Landslide Hazard Analysis of the Great Brook Watershed, Plainfield, Vermont

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On the cover: Large landslide at Site GB-3 on Great Brook near Plainfield Village. George Springston, July 11, 2013.

Executive Summary

This report presents the results of a detailed study of landslide hazards along Great Brook in Plainfield, Vermont. The project was conducted in response to catastrophic flood damage in 2011. Approximately 70 sites were examined as part of this study, including 47 active landslides, 3 inactive landslides, 7 streambank erosion sites, 15 sites with gullying (11 of these are landslide-gully complexes), and one stable site. This report examines a sample of seven of these sites in detail and provides a delineation of the landslide hazard zone.

Great Brook has a long history of flooding. Damaging floods are known to have occurred in the Great Brook watershed in July 1857, April and October of 1869, November 1927, September 1938, June 1973, June 1984, June 1989, August 1990, September 1999, and, most recently, in May and August of 2011.

Most of the currently active landslides are on or adjacent to slopes that have been unstable for many years. All are on steep slopes adjacent to the brook or its tributaries. Most of the large landslides (greater than 1000 square meters) are found along the downstream half of the brook (from Lee Road downstream), and only small landslides (less than 100 square meters) are found in the headwaters of the brook.

Gullies are common throughout the length of the stream corridor. Small gullies are common on the steep slopes near the brook and appear to be able to form in any of the surficial geologic materials. The extensive gullies of the MacLaren-Fowler gully-landslide complex are extremely unstable and are the subject of a separate study that has been conducted as part of a separate Ecosystem Restoration Program grant (Milone and MacBroom, Inc., 2013).

We attempted to apply Phase 3 of the Landslide Protocol of Clift and Springston (2012), which uses a statistical model based on the Frequency Ratio technique, to identify areas susceptible to slope failures. However Phase 3 of the Protocol was not practical to apply here because the USGS 10-meter Digital Elevation Model is too generalized. Instead, we proceeded to Phase 4b of the Protocol to delineate the landslide hazard zone using field data, orthophotos, and aerial photo interpretation, with only limited reliance on the digital terrain analysis outputs. Lidar topographic data would be needed in order to implement the full Landslide Protocol.

The landslide hazard zone is shown on Plate 1. Plate 1 also shows the landslides visited in this study, as well as landslides identified in a 2001 study (Barg and Springston, 2001.) The landslide hazard zone has been delineated to encompass all of the known landslides and gullies as well as areas with similar slopes that are underlain by similar surficial materials.

Given the patterns of landslide activity observed along the brook over more than 50 years, it will probably take many years for the major landslides that were active in 2011 to begin to stabilize. Rejuvenated landslides of a similar scale can be expected after any future large flood. The landslide hazard zone as delineated here is a first step toward developing a comprehensive Fluvial Erosion Hazard Zone for the Great Brook watershed.

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Introduction

This report presents the results of a detailed study of landslide hazards along Great Brook in Plainfield, Vermont. The work consisted of field visits to approximately 70 sites and delineation of a landslide hazard zone. The project followed a methodology developed for the Vermont Geological Survey by Clift and Springston (2012). The landslide hazard zone will be used by the Central Vermont Regional Planning Commission (CVRPC) and the Town in the development of a Fluvial Erosion Hazard Zone (FEH Zone) for the brook.

Great Brook is a tributary of the Winooski River and drains an area of about 14.5 square miles (Figure 1). The headwaters are in the hills of northern Orange and the western part of Groton, and the brook flows northward to its confluence with the Winooski River in the village of Plainfield. The brook is confined to a narrow valley and is generally touching one or both sides of the valley slopes. The highest point in the watershed is Signal Mountain at 3,352 feet above sea level and the lowest point is the confluence with the Winooski River at approximately 712 feet. The brook is approximately 8 miles long and has an average gradient of 3%. The largest concentration of houses is at the bottom of the watershed in Plainfield Village.

In order to understand the origins of the flooding problems in the Great Brook watershed it is helpful to understand some of the geologic background, the land-use history, and the flood history. For more detailed discussions of the geologic underpinnings and land-use history, see Barg and Springston (2001a and b) and Springston and Barg (2001). A brief summary of the surficial geology is included below. The flood history is also summarized below with an emphasis on the flooding of 2011.

Surficial Geology

Surficial materials include dense silt-matrix till, sandy till, ice-contact sand and gravel deposits, coarse and fine grained lacustrine deposits, stream terrace deposits, and modern alluvium.

The most abundant surficial geologic material is the dense silt-matrix till. This material is firm to very firm, is very poorly to extremely poorly sorted, and contains abundant boulders, cobbles, and pebbles in a matrix of silt and sand with minor clay. Sandy till is common in the southern portion of the watershed. This material has a loose consistency, is poorly to very poorly sorted, and contains boulders, cobbles, and pebbles in a matrix of medium to fine sand with some silt and little clay.

Ice-contact sand and gravel deposits consist mostly of moderately sorted to very poorly sorted, medium to fine sand and silty fine sand and gravel deposited in contact with glacial ice. Faulting and/or contortion of layers is common. These deposits are found at elevations up to approximately 1500 feet.

Lacustrine deposits are common in the lower parts of the watershed. These formed in one or more Late Pleistocene glacial lakes. Fine-grained lacustrine deposits consist of varved fine sand, silty fine sand, silty clay, and clay. Dropstones are abundant in these deposits. Coarse-grained lake bottom deposits that formed in glacial Lake Winooski, consisting of silty sand and

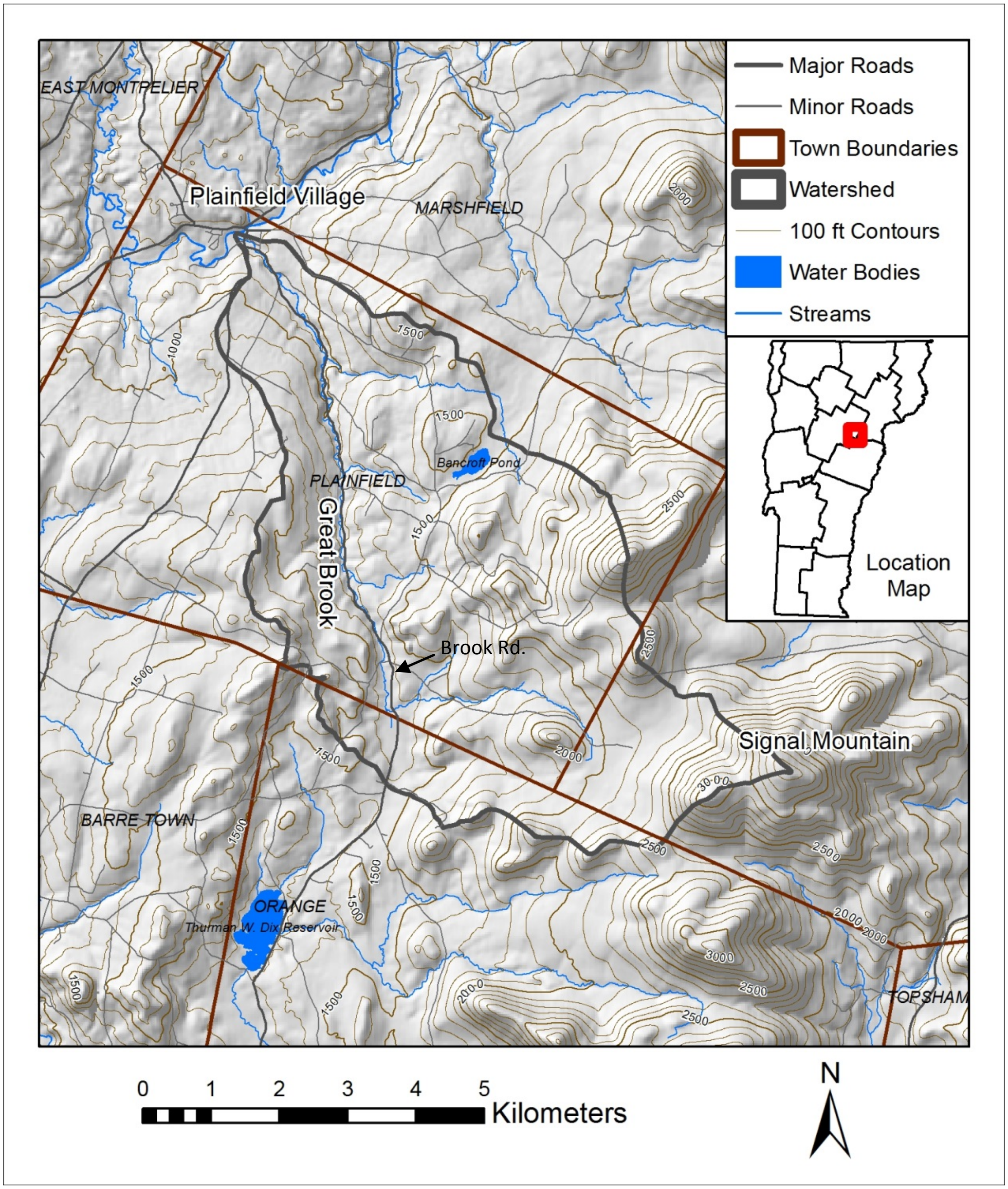

Figure 1. Overall map of the Great Brook watershed.

silty fine sand with ripple-drift cross lamination, are found at elevations up to at least 960 feet. A few of the exposures reveal lacustrine deposits that consist of many horizontal sets of the following: a lamination or bed of dense gray silt-matrix diamict overlain by a thin lamination of very fine to fine sand (sometimes absent), which is in turn overlain by a lamination or very thin bed of silty clay or clay. The term "diamict" refers to an unsorted to very poorly sorted material composed of a wide range of grain sizes. More than 100 of these sets are exposed at Site GB-3 (discussed below). These are interpreted to be lacustrine debris-flow deposits.

Alluvial deposits composed of loose boulder, cobble, and pebble gravels, coarse to fine sands, and silty sands are present both as Holocene stream terrace deposits and as modern alluvium throughout the length of the brook.

Based on glacial striations and an erratic boulder of the Craftsbury orbicular granodiorite, the glacial ice movement direction over the watershed was between 140° and 186°.

Evidence that is suggestive of a glacial readvance of presumed Late Wisconsinan age is seen at several sites. As analysis of the stratigraphy of these sites is ongoing, only a brief mention of two of the sites will be made here. At Site GB-3 the lacustrine debris flow deposits described above appear to be overlain by a thick, massive diamict that may represent lodgement till from a glacial readvance. Springston and Barg (2001) describe an exposure at their Site GB-44 (Site GB-1056 of this study), where lodgement till is overlain by at least 14 feet of varved fine lacustrine sediment, the upper 4.5 feet of which is deformed. This in turn is overlain by 14 feet of lodgement till. This location was revisited as part of this study, and although a careful search was made, erosion appears to have destroyed the portion of the exposure that contained the varved lacustrine sediment. No absolute date can be assigned to this possible readvance, but it may correlate with the Middlesex Readvance described by Larsen and others (2003).

Flood History

Damaging floods are known to have occurred in the Great Brook watershed in July 1857, April and October of 1869, November 1927, September 1938, June 1973, June 1984, June 1989, August 1990, September 1999, and, most recently, in May and August of 2011. High water levels in June and early July, 2013 resulted in some erosion of the banks and bed, but did not lead to extensive damage.

During the evening of May 26, 2011 a series of intense thunderstorms swept across central Vermont, resulting in a period of intense rainfall. The National Weather Service cooperative weather station at Plainfield had a storm total of 5.22 inches, the highest of all reported totals for this event. The rain began after 7 p.m. and most of the total had fallen by midnight. As the snowpack had been heavy in the late winter, and April and May had been very rainy, the ground was already saturated. Great Brook responded rapidly to the downpour, cresting in the village sometime around 2 a.m. The Winooski River took longer to respond, reaching its crest at Plainfield sometime between 6 and 7 a.m. Heavy erosion occurred on the banks of the streams in town, destabilizing the slopes in many locations. Erosion was especially severe along Great Brook from the village up to about Maxfield Road. This led to landslides, which in turn resulted in many trees falling into the brook. Damage in Plainfield and surrounding towns was extensive, with all of Plainfield's roads sustaining moderate to severe damage. The first bridge on the Brook Road (Town Highway Bridge 21) clogged with debris and washed out the Brook Road on the east side. A long stretch of Brook Road just downstream from the intersection with Fowler Road was washed out and took several weeks to repair.

The second flooding in 2011 was the result of Tropical Storm Irene. The rain began in Plainfield late on the evening of August 27 and ended around midnight on the 28th. Although damage in Plainfield was quite limited in comparison to many towns in Vermont, 5.12 inches fell within 24 hours at Plainfield and the streams rose to dangerously high levels. The flow on Great

Brook peaked in the late afternoon of the 28th and remained high through much of the 29th. A woody debris jam had begun to accumulate upstream of Town Highway Bridge 21 on the Brook Road, but it broke up and there was no repeat of the May washout. A small bridge higher up on the Brook Road (Bridge 13, the first one upstream of the Lee Road intersection) clogged with debris and sent water across the road. There were numerous washouts along the roads and several important culverts were washed out, but no major bridges went out. The banks of Great Brook were again eroded and slopes were further destabilized.

Previous Studies

Several studies of the Great Brook watershed have been undertaken since the 1990s. Baskerville (1991) reports on recent damage due to “catastrophic flooding” in the watershed. Writing in 1991, he attributes the damage to the 1989 flood rather than that of 1990. The Plainfield Conservation Commission conducted a detailed study of stream flow, water quality, and stream habitats from 1997 to 2001 (Plainfield Conservation Commission, 2002). This work was conducted in cooperation with the Vermont Department of Environmental Conservation and the Vermont-New Hampshire office of the U.S. Geological Survey, Water Resources Division. Part of the work was funded by a Watershed Grant from the Vermont Department of Environmental Conservation in 2000. In 2000, the Vermont Geological Survey funded an assessment of fluvial geomorphology and surficial geology in the watershed. The results of the fluvial geomorphology study are in Barg and Springston (2001a and b) and the surficial geology is in Springston and Barg (2002). These studies provided detailed information for guiding restoration work and assessing hazard potential on the mainstem of Great Brook and tributaries.

After completion of the geomorphic studies in 2001, stream channel restoration work was undertaken along parts of Great Brook in 2004 and 2005. Funding included a FEMA Hazard Mitigation Grant of $100,000 (with $25,000 of in-kind match from the town), which was combined with grants from the USDA Natural Resources Conservation Service (NRCS) Wildlife Habitat Incentive Program and the US Fish and Wildlife Service (USFWS) Partners in Fish and Wildlife Program totaling $16,000 with 25% in-kind match from the town. The project included work on 11 sites along about 3 miles of brook to provide grade control using large boulders. Two sites (one at the Recreation Field and the other 2.5 miles up brook) were treated with rock weirs designed by USFWS and NRCS. At the other sites boulders were added to stabilize headcuts. This was accomplished by adding boulders to existing boulder steps in the bed or else by scattering boulders in the bed. Stone was donated by landowners and donated labor served as local match. Much of this channel restoration work came through the two large floods of 2011 in good condition and although the floods still resulted in major changes to the bed and banks, the channel restoration work probably helped to reduce the impacts of the floods.

Following the 2011 floods, Bear Creek Environmental of Middlesex, Vermont was engaged by the CVRPC to conduct geomorphic assessments of the brook using the Phase 2 Stream Geomorphic Assessment Protocols of the River Management Program of the Vermont Department of Environmental Conservation. When this new data has been finalized it can be compared with the earlier studies by Barg and Springston (2001a) to see how the brook has changed in the intervening decade. Preliminary results were made available for this study (Pam DeAndrea, Bear Creek Environmental, personal communication, 2013).

Methods

About 70 sites were visited as part of this study. Data sheets from Appendix A of the Landslide Protocol (Clift and Springston, 2012) were filled out at most of the sites (due to time limitations a few minor landslides and streambank erosion sites were documented in less detail). The locations were determined using a hand-held GPS unit. Although we recognize the limited accuracy of these GPS units, by comparison of prominent features on digital orthophotos it appears that the locations of points were generally within 10 meters of their true position. The physical dimensions of the features were measured by laser rangefinder, tape measure, and pacing. Detailed notes were taken on the sedimentology and stratigraphy of the slopes and photos were taken at most sites.

The field data was entered into a spreadsheet and converted to a point coverage in ArcGIS shapefile format (*GreatBrookLSPointRevised03172014.shp*). A polygon coverage was created using a combination of GPS points on the margins of landslides and digital orthophotos (*GreatBrookLSPoly01102014.shp*).

Although the Landslide Protocol uses a statistical model based on the Frequency Ratio technique, it was not practical to apply the statistical model in this study area. This is because the USGS 10-meter Digital Elevation Model (DEM) is too generalized. In contrast to lidar data at 3-meter resolution or better, this 10-meter slope data does not capture the shape of the land accurately enough to reliably signal the presence of landslides. Instead, most irregular slopes displayed by the 10-meter data appear much flatter than they really are. Other terrain products derived from the 10-meter DEM, such as profile curvature and aspect, also suffer from this generalization. The end result is that the Frequency Ratio method described in Phase 3 of the Protocol could not be implemented as written. Instead, it was necessary to proceed to a Phase 4b delineation of the hazard zone using field data, orthophotos, aerial photo interpretation, and limited reliance on the terrain analysis outputs. The lack of detailed topographic data from lidar rendered the process difficult, but the density of field data did permit the accurate delineation of the hazard zone.

Results

The GIS database includes 47 active landslides, 3 inactive landslides, 7 sites with streambank erosion, 15 sites with gullying (11 of these are landslide-gully complexes), and one stable site. Two alluvial fan sites from Barg and Springston (2001a) are included below. Note that three additional gully sites and an alluvial fan were observed in the Phase 2 geomorphic assessments by Bear Creek Environmental and are included below.

Plate 1 shows the landslides visited in this study, as well as landslides from 2001 and 1963 identified by Barg and Springston (2001). The landslides mapped during the 2001 study are the result of field work and interpretation of mid-1990s orthophotos and aerial photos. The landslides from 1963 are the result of stereoscopic interpretation of aerial photos taken in the spring of 1963. Although each of these data sources has its limitations, taken together they establish a long-standing pattern of slope instability in the vicinity of Great Brook.

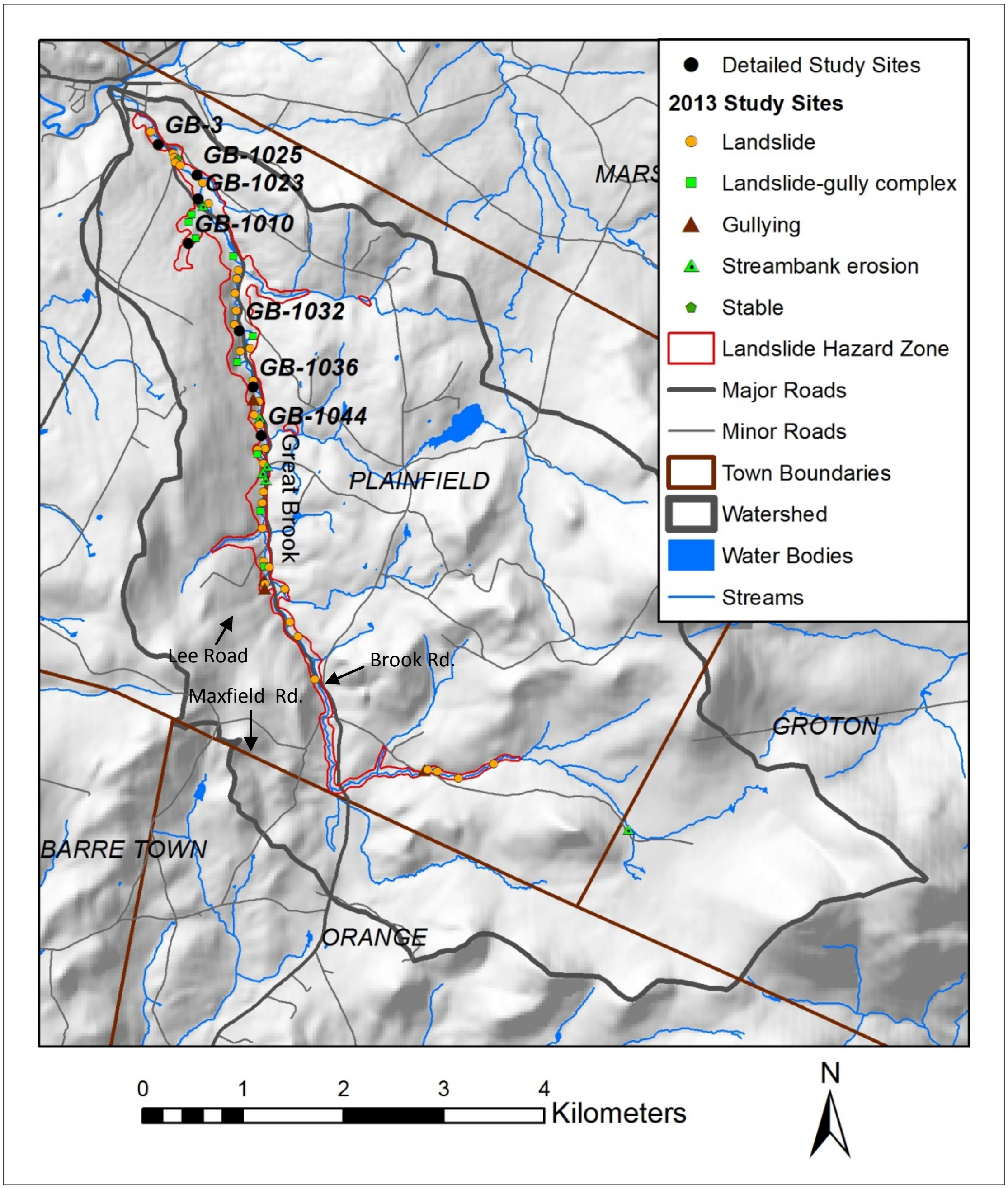

Figure 2. Study sites. Preliminary landslide hazard zone outlined in red. The detailed study sites are shown as black dots and labeled. The study sites are shown in more detail in Figures 3a and b.

The landslide hazard zone is shown on Plate 1 and several of the figures within this report. It has been delineated to encompass all of the known landslides and gullies and to also include areas with similar slopes that are underlain by similar surficial materials. The sites are broken out into several types in Figure 2, which shows the locations of the landslides, inactive landslides, landslide-gully complexes (all active), gullies. No relict landslides were encountered in this study. Gullies are scattered along the entire length of the brook. Note that in many cases only the lower ends of the gullies were mapped in the field. The landslide hazard zone was delineated to include all known gullies, but it is possible that some may extend even above the zone as presently drawn.

Severe gullying has occurred in the northern part of the watershed on the west side of the brook in an area of thick, ice-contact sands and silts. The gullies at the MacLaren Farm and Fowler sand pit are being studied by Milone and MacBroom of Waterbury, Vermont as part of a separate Ecosystem Restoration Program grant (Milone and MacBroom, Inc., 2013). As these gullies are the sites of very large landslides (some of which exceed 79 feet or 24 meters in height), they are within the landslide hazard zone as drawn.

Figures 3a and 3b show the site locations and the Landslide Hazard Zone in more detail and include station numbers.

Figure 4 shows the sites classified by estimated size. Note that most of the sites that are greater than 1000 square meters in area are downstream of Lee Road.

Figure 5 shows the locations of bedrock outcrops or ledge in or adjacent to the channel. The presence of bedrock limits the erosive possibilities of the stream. Channel spanning bedrock exposures begin just below Lee Road and effectively limit the amount of channel incision that is possible. No large landslides occur upstream of Maxfield Road. See page 30 for a discussion of the connections between the presence of bedrock grade controls, channel gradients, and the size of landslides..

Alluvial fans and gullies are shown on Plate 1 and in Figure 6. The alluvial fans are all relatively minor features on small streams. Most are at the mouths of active gullies, although there is one fan on a tributary located east of the main brook. As abrupt channel shifts are common on alluvial fans, these should be viewed as hazardous features and included in any FEH Zones. The gully sites included on this figure include all landslide-gully complexes as well as isolated gullies. These too should be included in FEH Zones.

Mechanisms of Slope Failure

The recent flood events in the Great Brook watershed led to extensive failures on the slopes along much of the brook, examples of which are illustrated below. The extensive documentation from the earlier stream geomorphic study (Barg and Springston, 2001) provides the starting point for an analysis of the mechanisms involved in these failures. Sites GB-3, GB-1025, GB-1023, GB-1010, GB-1032, GB-1036, GB-1044 (listed from downstream to upstream), are shown in Figures 7 through 13. Their physical characteristics and the slope failure mechanisms that operate at the sites are shown in Table 1. In order to illustrate how floods and slope processes have affected the slopes, time-series of photos are shown for Sites GB-3, GB-1032, and GB-1036 in Figures 7a-h, 11a-f, and 12a-f, respectively.

Site GB-3 is one of a pair of very large landslides near the bottom of the watershed. Both are on the outside of meander bends and both had been undergoing active slope failure in the years prior to the studies of Barg and Springston (2001a) and Springston and Barg (2001).

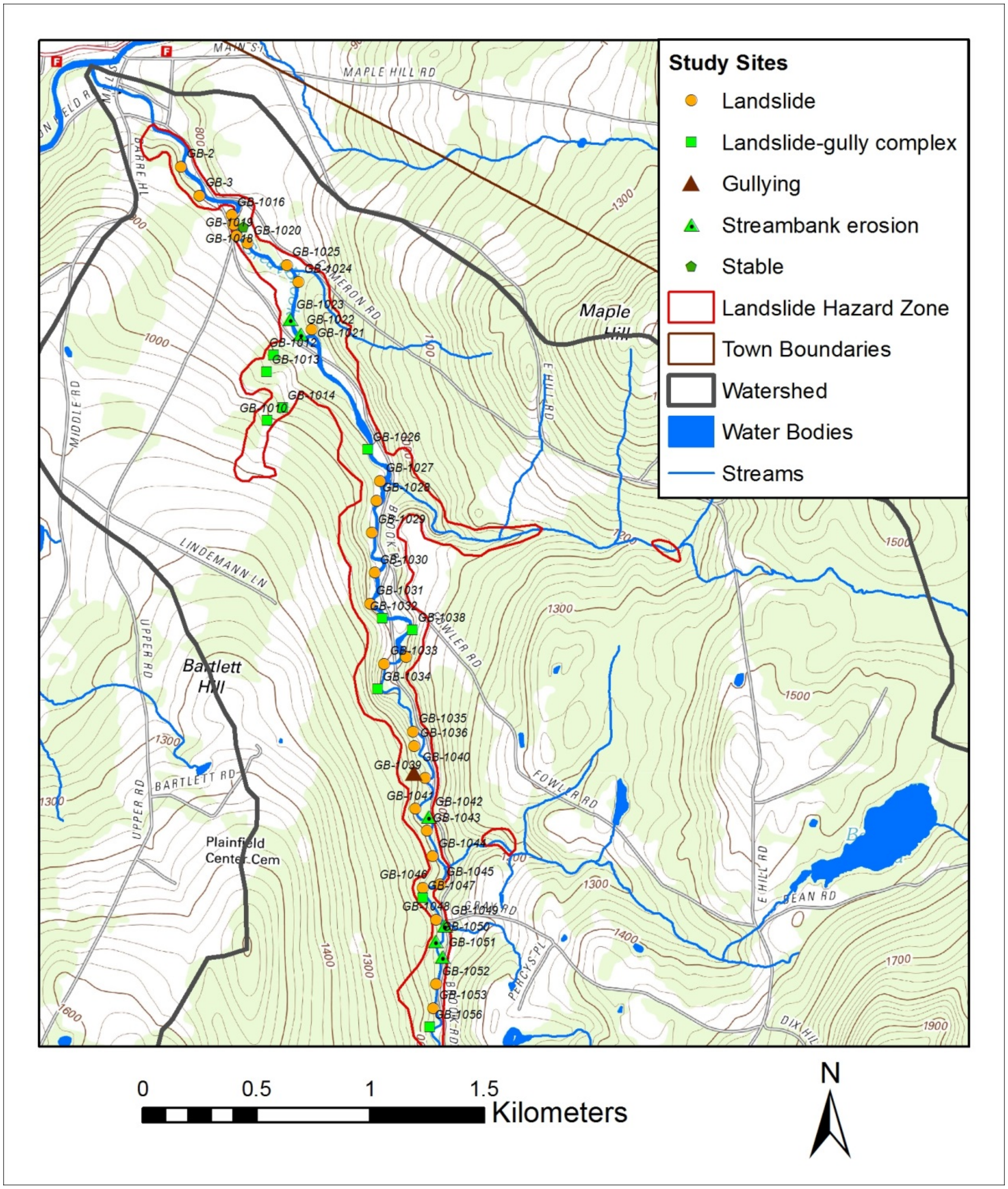

Figure 3a. Study sites in the northern part of the watershed. Base map from U.S. Geological Survey. Contour interval 20 feet.

Before those studies, the last major erosion event was probably the flood of either 1989 or 1990. Figure 7a shows the site as it was just prior to the May, 2011 flood. In the years between 2001 and 2011, much of the 105 foot (32 meter) slope had begun to revegetate, but the May 2011 flood caused heavy erosion at the base and undercut the slope at the downstream end of the landslide. The over-steepening of the lower slopes (probably combined with high pore-water pressures in the surficial material) resulted in renewed translational sliding.

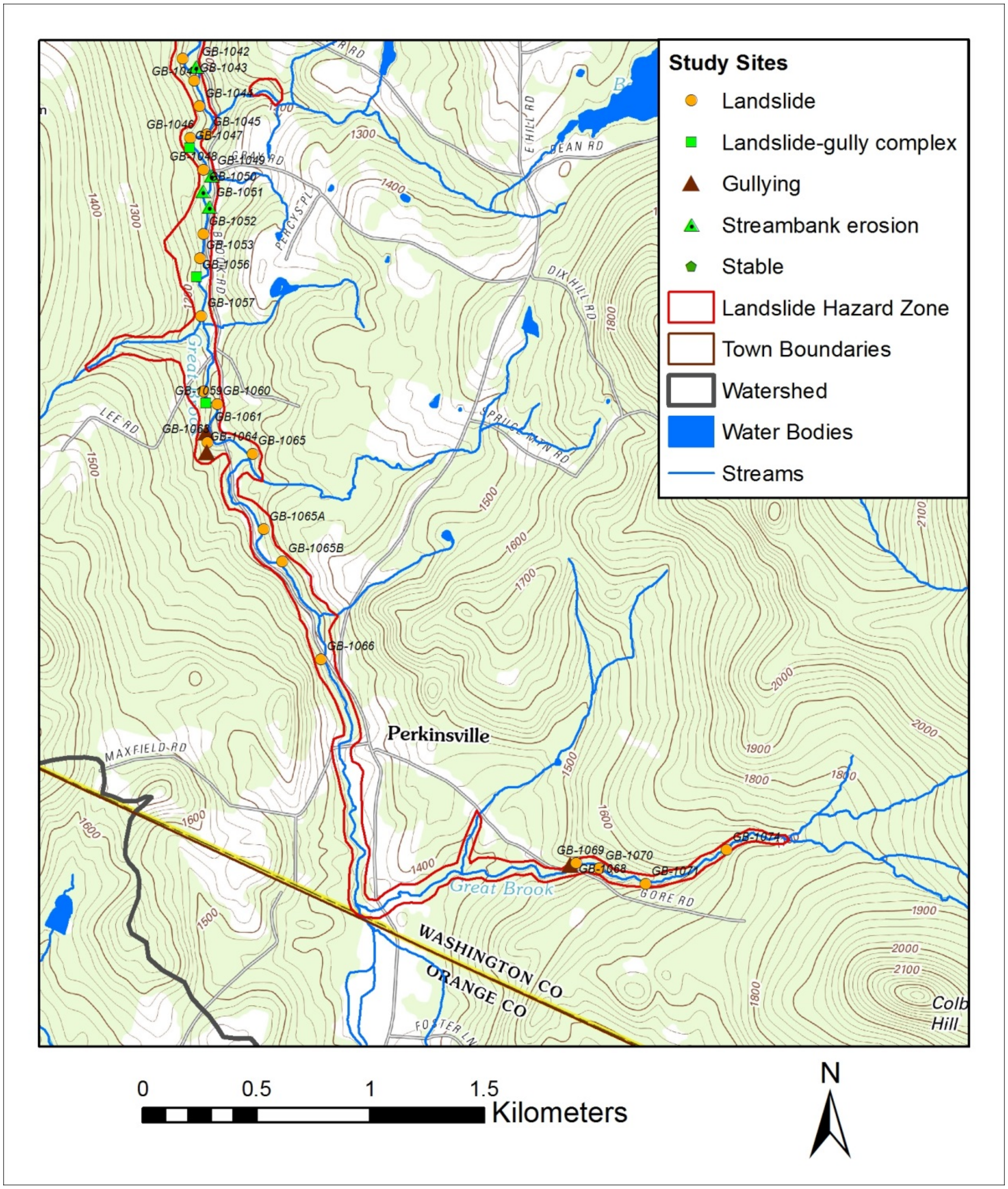

Figure 3b. Study sites in the southern part of the watershed. Base map from U.S. Geological Survey. Contour interval 20 feet.

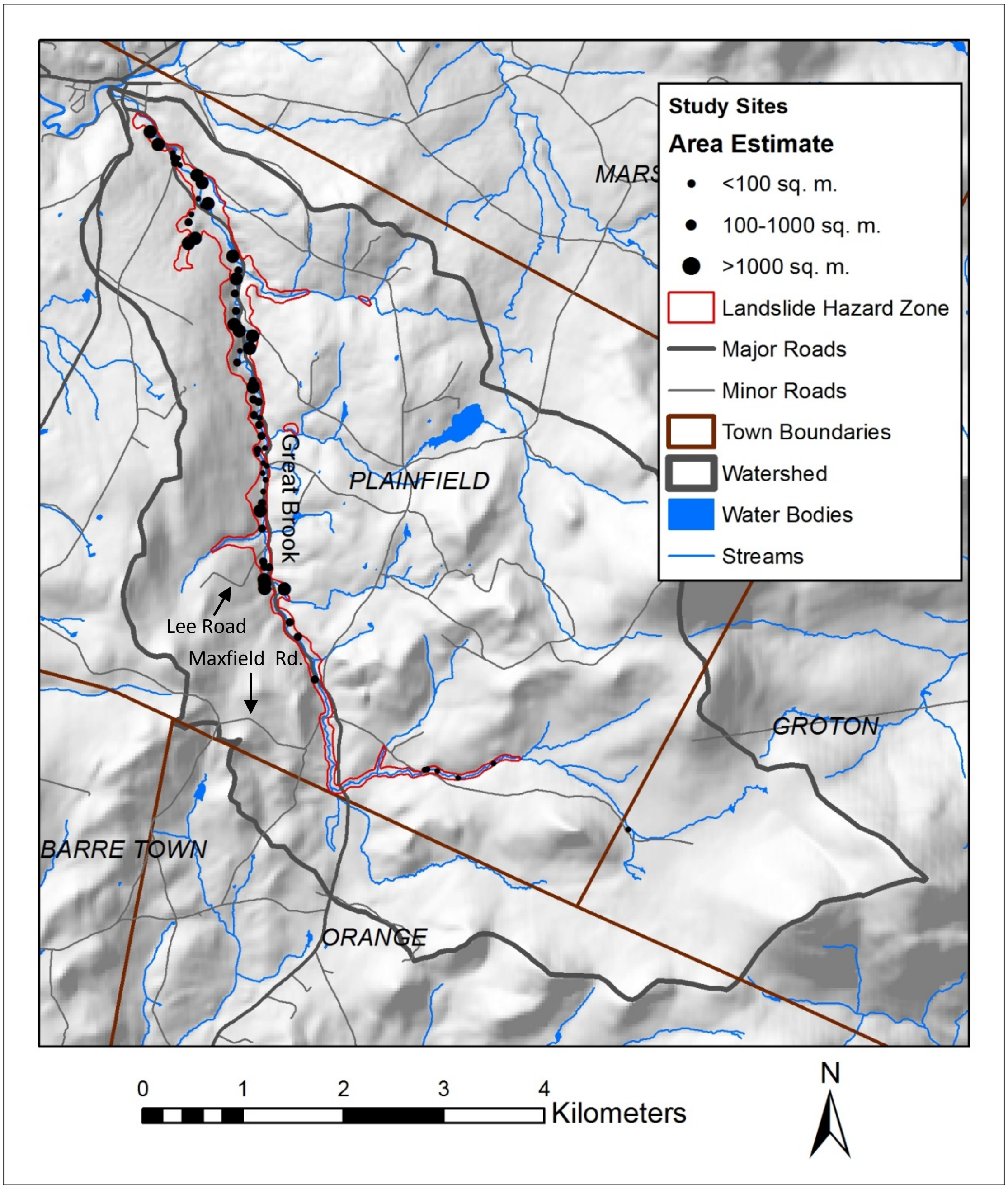

Figure 4. Study sites classified by estimated area. Note that almost all of the large sites are located downstream of Lee Road.

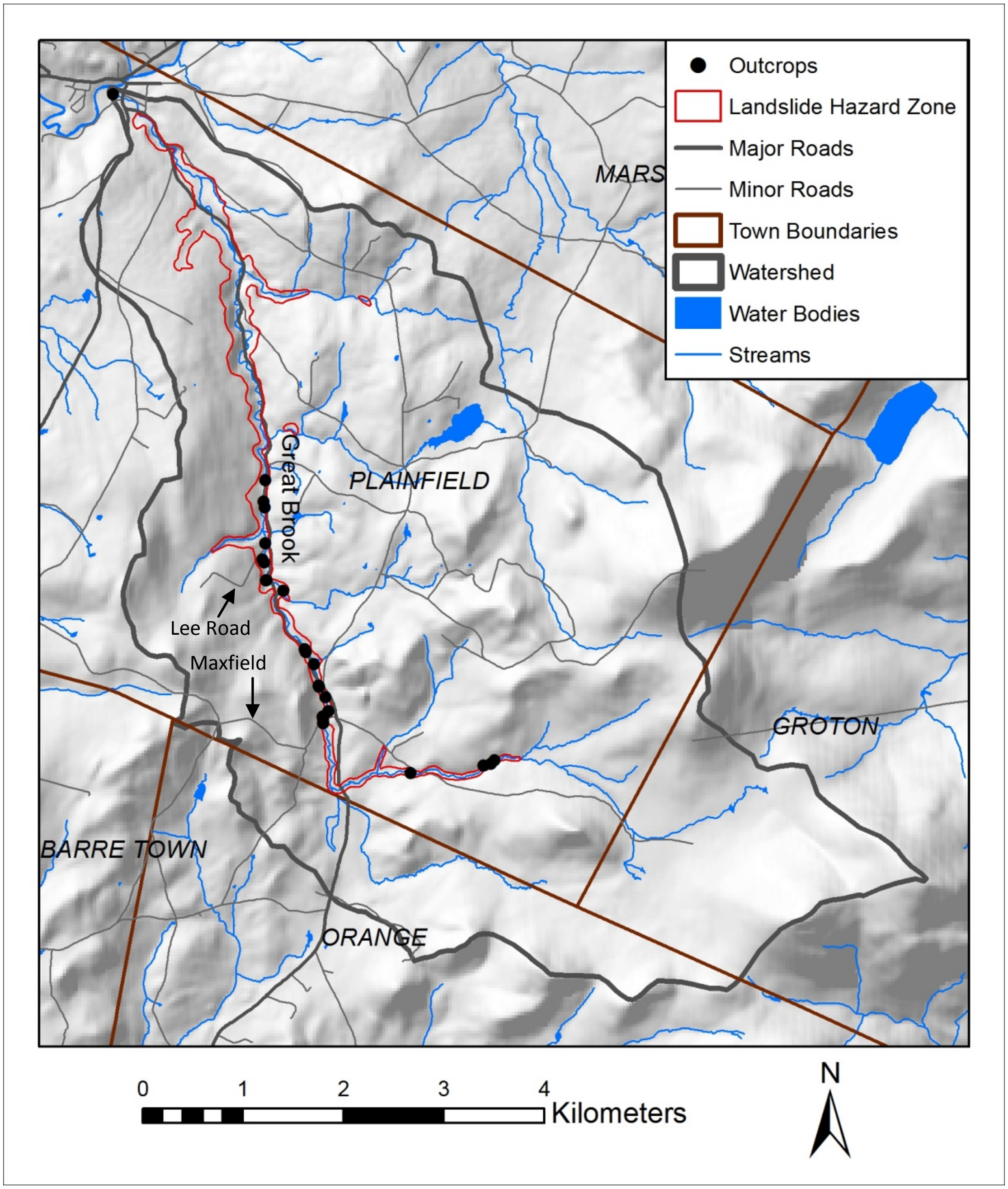

Figure 5. Bedrock outcrop (ledge) locations along Great Brook. Note that all are located in the southern (upstream) reaches and most are upstream of Lee Road. The first channel-spanning outcrops occur just downstream of Lee Road. Outcrop locations that are distant from the brook are not shown in this figure but are included in the GIS data.

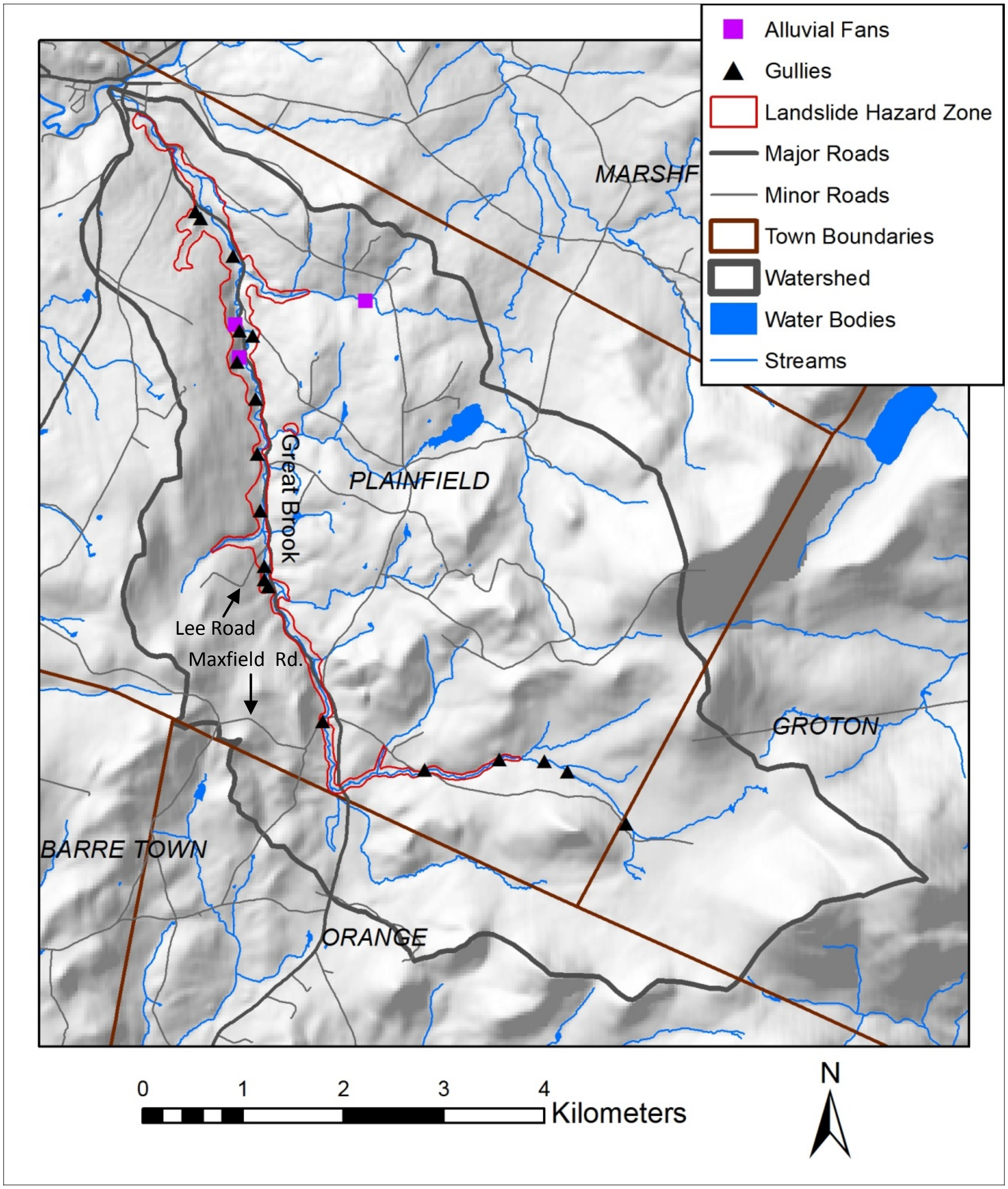

Figure 6. Locations of alluvial fans and gullies. The alluvial fans are all small features associated with first-order tributaries. The gullies range in size from quite small up to the large gullies at the MacLaren Farm and Fowler sand pit in the northern part of the watershed (see text).

Table 1. Characteristics of study sites. This table describes the physical characteristics and slope failure mechanisms for the seven sites discussed below.

Site	VSP North	VSP East	Elevation of Crown (ft)	Width (m)	Height (m)	Depth (m)	Toe to Crown (m)	Aspect (deg.)	Overall Slide Angle (deg.)	Area Estimate (m^2)	Major Slide?
GB-3	196895	506317	249.6	83.0	32.0	1-2	55.4	64	30	>1000	Y
GB-1025	196591	506701	257.9	51	17	1-2	14.8	195	49	>1000	Y
GB-1023	196354	506713	260	10	3.3	<1	2.8	125	50	<100	N
GB-1010	195910	506615	306.3	>100	22.2	2-5	12.3	304	61	>1000	Y
GB-1032	195040	507120	314.8	59	16.1	1-2	23.0	55	35	>1000	Y
GB-1036	194480	507260	327.3	65	15.6	<1	9.0	109	60	>1000	Y
GB-1044	193995	507341	338.6	44	4.9	<1	1.3	70	75	100-1000	N

Site	Major Slide?	General Material Class	Surficial Material	Slope Failure Types	Rilling?	Gullying?	Bedrock on slope?	Bedrock control in stream?	Seeps?	Outside of Meander?	Headcuts in stream?
GB-3	Y	Earth	dense diamict	TS and IBD	Y	N	N	N	Y	Y	Y
GB-1025	Y	Debris	sand / dense till	TSF, SGD, IBD	Y	N	N	N	N	Y	Y
GB-1023	N	Debris	pebble gravel	SGD	N	N	N	N	N	Y	Y
GB-1010	Y	Earth	sand	TSF, SGD	N	Y	N	N	N	Y	Y
GB-1032	Y	Debris	dense till	TSF, IBD, TSD	N	Y	N	N	Y	Y	Unsure
GB-1036	Y	Earth	dense till	TSF and IBD	Y	N	N	N	Y	Y	Y
GB-1044	N	Earth	dense till	TS, IBD, TSD	N	N	N	N	Y	Y	Y

Notes:

Coordinates are UTM, meters, NAD83

Landslide Types: IBD = Irregular Block Detachment, SGD = Single-grain Detachment, TS = Translational Slide, =
TSD = Thin Slab Detachment, TSF = Translational Slide-flow

Toe to crown distance is the horizontal distance from the toe of the landslide measured to the crown at the back of the slide.

The surficial materials at GB-3 have a very complex stratigraphy (see especially the photo on the cover and Figures 7e through h). Study of this site is still ongoing, but the lower 43 feet (13 meters) of the section consists of more than 100 sets of the following: A lamination or bed of dense gray silt-matrix diamict overlain by a thin lamination of very fine to fine sand (sometimes absent), which is in turn overlain by a lamination or very thin bed of silty clay or clay. The upper part of the section appears to consist of more massive dense silt-matrix diamict. The lower units appear to be multiple debris flows deposited in glacial Lake Winooski. The upper unit may be dense lodgement till deposited during a glacial readvance over the lake deposits.

Site GB-1025 is on the outside of a meander bend and has been the site of ongoing slope instability for many years. At the time of the field work in 2000 this was an active landslide. Since that time a house and garage have been built on the terrace a short distance back from the landslide and the slope has continued to fail (Figures 8a and b). The site is underlain by 18.0 feet (5.5 meters) of lacustrine, medium to fine sand over 8.9 feet (2.7 meters) of laminated silty clay and medium to fine sand over about 29.8 feet (9.1 meters) of dense, silt-matrix till. The over-steepened condition, the erodible materials, and the position on the outside of the meander bend make it highly likely that this slope will continue to fail and thus put the house and garage at greater and greater risk.

A typical slope failure in stream terrace deposits is located at Site GB-1023 (Figure 9a). The 10 foot (3.3 meter) section consists of loose boulder-cobble-pebble gravel overlain by loose, sandy pebble-cobble gravel. Figure 9b shows a similar exposure at Site GB-1027. The surficial materials at these sites were deposited by Great Brook at some time in the recent past. Given the extensive channel incision documented in this study and the earlier study by Barg and Springston (2001a), it is likely that the tops of these terraces represented the active floodplain of the brook sometime in the 20th Century (perhaps as recently as the 1960s).

Figures 10a and b show one of the sites within the extensive MacLaren-Fowler landslide-gully complex. The stratigraphic section at Site GB-1010 consists of over 70 feet (21 meters) of ice-contact sands and possible silt with lenses of pebble gravel (Table 2). The intermittent stream that flows in the bottom of this gully is actively incising into the bed and cutting laterally into the sand deposits, resulting in ongoing slope failures. The eroded sand is easily transported downstream to Great Brook and contributes a very heavy load of fine sediment to the brook.

Table 2. Stratigraphic section at GB-1010 in MacLaren-Fowler gully. Thicknesses and depths in feet. The upper part of the steep slope was largely inaccessible.

Top Thickness (ft)	Depth (ft)	Description
33	33	Very fine sand, fine sand, and silt(?) (inaccessible)
5.5	38.5	Very fine sand, fine sand, coarse-sandy pebble gravel, in alternating beds, dense, dry
6	44.5	Very fine sand, laminated, very dense, dry
1.8	46.3	Coarse-sandy pebble gravel bed of variable thickness, dense, dry, dips to northeast
6	52.3	Fine sand, laminated, very dense, dry
18	70.3	Covered

Site GB-1032 is located on the outside of a meander bend and has been the site of ongoing slope instability for many years. The material consists of a 52.5 foot (16.1 meter) section dominated by dense, gray silt-matrix diamict containing a 5.6 foot (1.7 meter) unit of laminated silty clay and silt with dropstones interbedded with dense, silt-matrix diamict. Figures 11a through f show how the site has changed since 2011. Heavy scour occurred during the May 26-27, 2011 flood, resulting in the undercutting of the slope to form an overhang. Large, angular blocks of dense till fell and toppled into the brook. After the initial undercutting, blocks of till broke off the slope and slabs of soil with trees toppled out onto the slope. By April of 2012 the overhang was no longer visible, having been erased by some combination of collapse of the roof of the overhang and accumulation of toe material at the base of the landslide. Although additional toe erosion took place during the high streamflows of June and early July of 2013, continued failure of the upper slopes has rebuilt the toe deposit. Figure 11f shows how thin slabs are breaking off the main face of the slide as it weathers.

Site GB-1036, also on the outside of a meander bend, has been the site of ongoing slope instability for many years. Figures 12a through f show how the site has changed since 2000. Following a long period of little change, slope instability accelerated during the 2011 floods, with slope failure mechanisms including fluvial shear at the base, translational sliding from the upper parts, toppling of the upper soil horizons and trees out onto the slope, and growth of the toe deposits as the upper slope fails back. In the future, the relatively loose toe deposits will probably be easily swept away by moderately high stream flows.

Site GB-1044 shows very clear evidence that the stream is cutting into fresh material, both in the bank and the bed (Figures 13a and b). This site experienced heavy scour in the 2011 floods. Since then, the dense till has begun to weather. The photos show a distinct scour line, below which the slightly weathered till has been sheared off by flowing water on the outer face of the landslide. Note that fresh till is also exposed in the bed, indicating active vertical incision.

Although much of the discussion here focuses on slope failure due to fluvial shear and the after-effects of the steepening of the slopes, increased pore-pressure in the surficial materials is very likely to have played a critical role in many of the slope failures in this watershed. Most of the sites showed evidence of at least occasional soil saturation and seepage. Given that soil moisture was quite high prior to both of the 2011 floods, it is very likely that this played a critical role in the subsequent slope failures.

Data Products

GIS outputs include the following: The landslide hazard zone is a polygon coverage in ArcGIS shapefile format as *GreatBrookLandslideHazardZone.shp*; the field data for each site is shown as a point coverage in *GreatBrookLSPointRevised03172014.shp*; landslide polygons are shown as *GreatBrookLSPoly01102014.shp*; alluvial fans from this study and from the recent Bear Creek Environmental studies were combined into a point coverage (*GreatBrookAlluvialFanPoints.shp*); gully sites from this study and from the Recent Bear Creek Environmental studies were combined into a point coverage (*GreatBrookGullyPoints.shp*); and bedrock outcrops are also shown as a point coverage (*GreatBrookBedrockOutcropsRevised2013.shp*).

Figure 7a. Site GB-3 on May 18, 2011, prior to the May 26-27 flood. No major landslide activity had occurred at this site since the 1989 or 1990 floods and although some bare soil was visible in the upper parts of the downstream portions, the slope was beginning to revegetate.

Figure 7b. Site GB-3 on May 27, 2011, the morning after the May flood. The brook is receding from the peak flow, but is still high and turbid. The base of the slide has been scoured and dramatically undercut and translational slides have removed material from the main face.

Figure 7c. Site GB-3 on June 13, 2011. The water level has receded and the scoured base is clearly visible. Additional vegetated sections have slid off of the main face and slumped material is accumulating at the base.

Figure 7d. Site GB-3 on August 29, 2011, one day after the peak flow from Irene. The toe deposits have been scoured away and some new scour and undercutting has occurred at the base. Photo courtesy of Bram Towbin.

Figure 7e. Site GB-3 on September 14, 2011, two weeks after Irene. Additional collapse of the greatly over-steepened base has occurred and new material has slid off of the main slope.

Figure 7f. Site GB-3 on April 26, 2012. Over the course of the winter and early spring the toe deposits have built up, covering over the over-steepened base and material has continued to slide off of the main face.

Figure 7g. Site GB-3 on July 2, 2013. High flows in June and early July led to renewed scour at the base and translational slides off of the main face.

Figure 7h. Site GB-3 on July 11, 2013. The waters have receded and the fresh toe deposits have partially collapsed.

Figure 8a. Site GB-1025. Active landslide on right bank. Lacustrine sand, silt, and silty clay over dense gray till. Note roof of garage visible just beyond top of landslide. Photo taken July 29, 2013.

Figure 8b. Site GB-1025 looking downstream and across. Note trees toppling over at top. Photo taken July 29, 2013.

Figure 9a. Site GB-1023 looking downstream. Typical exposure of coarse-grained stream terrace deposits on outside of bend. Material failed during high stream flows of 2011, primarily by singe-grain detachment. Photo taken July 29, 2013.

Figure 9b. Closeup of stream terrace deposits at Site GB-1027. Boulder-cobble-pebble gravel in lower part is overlain by sandy pebble-cobble gravel. Similar to material at GB-1023 but coarser-grained. Photo taken July 29, 2013.

Figure 10a. Site GB-1010. Looking down gully on July 16, 2013. This is part of the large MacLaren-Fowler gully system, which has developed in ice-contact sands.

Figure 10b. Site GB-1010 looking upstream. Headcuts are actively incising the valley bottom, the bases of the slopes are being undercut, and the side walls are continuously collapsing into the gully bottom. Some of the boulders in the channel have fallen in from gravel lenses within the ice-contact deposits exposed in the side walls while others have probably washed down from till exposures near the head of the gully.

Figure 11a. Site GB-1032 on May 29, 2011, two days after the May 26-27 flood. Dense till has been heavily eroded at the base, leading to the prominent overhang seen at right. Although this has been an active landslide for many years, no overhang was present prior to this flood. Note the angular blocks of till below the overhang and the large gray block of till in the brook.

Figure 11b. Site GB-1032 on September 14, 2011, about two weeks after Irene. Additional scour has occurred at the base, leading to the breaking off of irregular blocks from the over-steepened slope. Slumped material is accumulating at the base.

Figure 11c. Site GB-1032 on April 26, 2012. Additional material has slumped down from above.

Figure 11d. Site GB-1032 on October 18, 2012. Additional slumping has occurred. Photo courtesy of Bear Creek Environmental.

Figure 11e. Site GB-1032 on July 30, 2013. Slumping has continued and trees with roots have toppled out onto and down the slope.

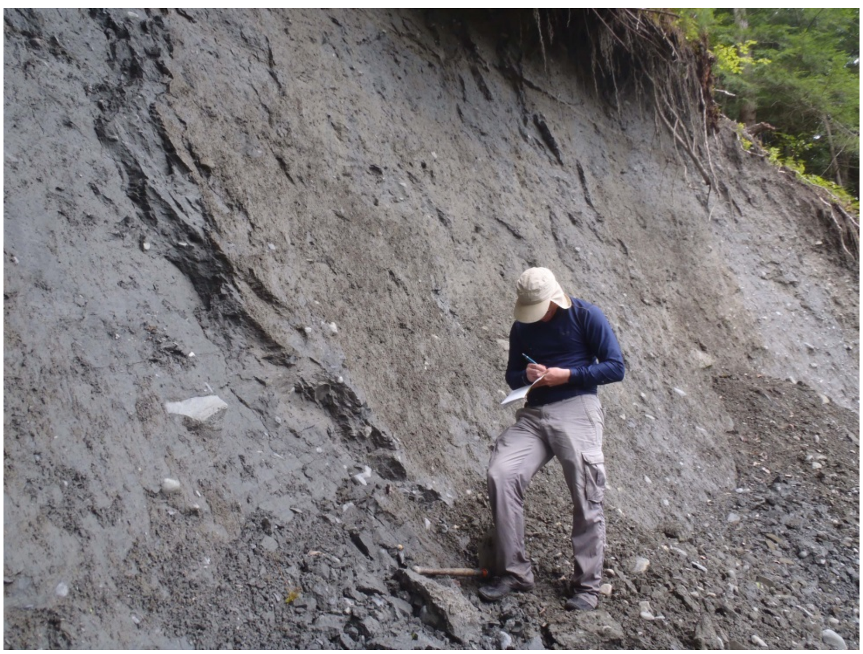

Figure 11f. Upper face at Site GB-1032 on July 30, 2013. Thin slabs of dense till are breaking off parallel to the face. This jointing parallel to the face of the landslide is apparently due to weathering.

Figure 12a. Site GB-1036, summer, 2000. Last major erosion was probably during Hurricane Floyd in 1999. Photo courtesy of Lori Barg.

Figure 12b. Site GB-1036 on May 12, 2011, prior to the May 26-27 flood. Changes since the summer of 2000 appear to be modest.

Figure 12c. Site GB-1036 on May 29, 2011, two days after the May flood. Heavy erosion at the base has resulted in translational slides and topples in the upper parts.

Figure 12d. Site GB-1036 on July 1, 2012. Note buildup of toe deposits at base.

Figure 12e. Site GB-1036 on October 12, 2012. Photo courtesy of Bear Creek Environmental.

Figure 12f. Site GB-1036 on July 30, 2013. Note the continued buildup of toe deposits.

Figure 13a. Site GB-1044. Looking upstream at freshly scoured dense till (up to hand) on August 1, 2013. Although this landslide was active during the 2011 floods, the fresh scour shown in these photos appears to be from the high flows of June and early July, 2013.

Figure 13b. Site GB-1044, looking downstream. Scour line at shovel head. Note fresh till visible below the water line. Removal of the material has occurred by irregular block detachment.

Discussion

A striking feature of the distribution of landslides along Great Brook is the recurrence of many of the landslides at or near the same locations over many years. By combining the results of aerial photo interpretation of photos from 1962 and 1974 with digital orthophotos from the 1990s to the present and the field work from 2000 and 2013, it is clear that the landslide locations tend to experience repeated cycles of destabilization due to catastrophic flooding, followed by (in the absence of another large flood) at least partial stabilization as the slope is eroded back to a more stable angle and vegetation re-establishes itself, only to have the slope once again destabilized by another large flood. Although there is a tendency for landslides to recur at the same locations, the landslide locations are subject to both relatively slow shifts due to normal stream meander migration processes and rapid, catastrophic shifts during large floods.

Most of the large landslides occur in dense till or dense lacustrine diamict. These materials are quite resistant to erosion in their unweathered state, although after one or two years of exposure at the surface they are beginning to weather and become more erodible.

The downstream reaches of Great Brook have steeper gradients, generally lack bedrock exposures, and have larger landslides. As noted on page 7 and as shown in Figures 4 and 5, all of the bedrock exposures are limited to the southern (upstream) reaches, with the first channel-spanning outcrops located just downstream of Lee Road and most of the large landslides located below Lee Road (there are no large landslides upstream of Maxfield Road). This concentration of the large landslides in the lower reaches may be at least partly due to the steeper stream gradient along the lower reaches. Barg and Springston (2001a) found that the stream gradient increased from 2.1 % in the reaches extending 2.06 miles upstream of Lee Road to 2.7% for the 2.85-mile-section extending downstream of Lee Road. The steeper gradient and lack of channel-spanning bedrock mean that the stream can incise vertically as well as laterally during large floods, thus destabilizing larger areas of the banks.

Gullies were observed at 15 of the sites (eleven were associated with landslides). Small gullies are common on the steep slopes near the brook and appear to be able to form in any of the surficial materials. The extensive gullies of the MacLaren-Fowler gully-landslide complex are extremely unstable and are the subject of a separate study that has been undertaken as part of a separate Ecosystem Restoration Program grant (Milone and MacBroom, Inc., 2013).

Observations of the landslides here and elsewhere in Vermont suggest the following as a common sequence of events in response to catastrophic flood events such as the flash flood of May 26-27, 2011 and Tropical Storm Irene on August 28 and 29, 2011. Note that the events described below will not always take place in a sequence of discrete steps. For example, a translational slide on the upper part of a landslide may be occurring at the same time that the base is being undercut by flood waters.

1. Fluvial shear results in erosion of the bank and/or bed, over-steepening the slope and, if bed erosion occurs, increasing the effective height of the slope. Dense till and lacustrine diamict typically are detached as irregular blocks. Loose materials typically are detached

as single grains. At sites where the material is very strong, the stream may undercut the bank, leaving an overhang.

2. Infiltration of rainfall results in an increase in pore-pressure in the surficial material, reducing the effective shear strength of the material.
3. Translational slides occur off the upper slope, commonly carrying blocks of soil and trees, with depths of 1.5 to 5 feet (0.5 to 1.5 meters). Parts of the sliding blocks may break up into flows. Although not observed in the Great Brook watershed, a rotational slump may occur in place of or following a shallow translational slide. This type of slope failure is more common in lacustrine or ice-contact or stream terrace deposits than in till, but a few examples of rotational slumps have been observed in dense till deposits that were severely undercut by catastrophic flooding.
4. Material reaching the base of the slope may either be swept away by the stream or accumulate to form a toe deposit.
5. The water level of the stream recedes, perhaps leading to additional slope failure as the support of the water on the lower face is removed.
6. Overhangs begin to fail and translational slides and flows remove material from the upper parts of the landslide.
7. With the passage of time, mass-wasting and weathering processes begin to alter the deposits. Material continues to fall, topple, slide, or flow off of the upper slopes. Weathering of the fresh deposits becomes evident after the first winter, with the outer 0.5 to 1 inch (1 to 2.5 cm) of even the densest till beginning to soften. Rills begin to dissect parts of the upper faces and the toe deposits. Even after only a single year, pioneer vegetation such as coltsfoot and horsetails begin to colonize the slopes.

Conclusions

Approximately 70 sites were examined as part of this study. The database includes 47 active landslides, 3 inactive landslides, 7 sites with streambank erosion, 15 sites with gullying (11 of these are landslide-gully complexes), and one stable site. Detailed characteristics, including mechanisms of slope failure are reported in the GIS data. This report examines a sample of seven of the sites in detail and provides a delineation of the landslide hazard zone.

All of the active landslides are on steep slopes adjacent to the brook or its tributaries. Most of the large landslides (greater than 1000 square meters) are found along the downstream half of the brook (from Lee Road downstream), and only small landslides (less than 100 square meters) are found in the headwaters of the brook. The concentration of landslides in the lower part of the watershed is at least partly a result of the thicker surficial materials there and partly due to the lack of bedrock exposures in the channel in the lower part of the watershed.

Most of the currently active landslides are on or adjacent to slopes that have been unstable for many years. The earlier studies on Great Brook clearly showed that the banks had been destabilized from earlier catastrophic floods. From 1999 up until 2011 there were no truly damaging flood events and some of the landslides and eroding streambanks were beginning to be stabilized by vegetation. However, the floods of May 26-27, 2011 and Tropical Storm Irene on August 28 and 29, 2011 resulted in extensive bed and bank erosion and reinvigorated many of the landslides, eroding streambanks, and gullies. High streamflows during June and early July, 2013 caused some additional erosion along the brook, but this appears to be quite minor in comparison to the 2011 events.

The principal causes of the slope failures appear to be the over-steepening of slopes due to fluvial erosion of banks and stream beds during the flash floods and decreases in shear strength of soils due to increases in soil water pore pressures due to the heavy rainfall.

The steeper gradient in the reaches downstream of Lee Road and the lack of channel-spanning bedrock mean that the stream can incise vertically as well as laterally during large floods, thus destabilizing larger areas of the banks.

Given the clear field evidence for unstable slopes in the Great Brook valley, it is important to delineate the areas most subject to landslide hazards. The combination of extensive field work and careful interpretation of orthophotos has enabled us to produce a reasonably accurate landslide hazard zone despite the lack of detailed lidar topographic data. The earlier work by Clift and Springston (2012) in Chittenden County for the Vermont Geological Survey showed that lidar data can be successfully used to identify areas underlain by surficial materials that are susceptible to slope failures (essentially areas susceptible to landslides and gully formation). In the Great Brook watershed the 10-meter DEM from the USGS was too generalized to produce an accurate slope map, which is a critical data layer in its own right and also is used to produce several other important layers.

The detailed (Phase 2) stream geomorphic data were critical to understanding the patterns of stream channel adjustment that are underway in the watershed. In this watershed we had the advantage of having the 2001 data from Barg and Springston as well as the up-to-date 2012 and 2013 data from Bear Creek Environmental. The mass failure locations from the Bear Creek work compared very well with our site locations. It would be highly desirable to have similar Phase 2 data available for the streams in any areas where landslide mapping is to be undertaken.

The detailed surficial geologic mapping work from Springston and Barg (2002) was also very helpful. This mapping identified areas of bedrock exposures, both adjacent to and further from the stream. The identification of abandoned stream terraces is also critical to understanding where the stream has moved in the past. The relative erodibility of materials in the banks and bed is important when analyzing channel adjustment patterns.

Given the patterns of landslide activity observed along the brook over more than 50 years, it is clear that it will take many years for the major landslides that were active in 2011 to begin to stabilize. Rejuvenated landslides of a similar scale can be expected after any future large flood.

The present study serves to reinforce the conclusions of the Barg and Springston study (2001a). That study found that many of the problems along the brook and its tributaries are related to anthropogenic causes. Channelization, removal of roughness from the channel, hard armoring of the banks, floodplain encroachment, and berming have all contributed to producing a more unstable river system in the lower watershed.

Barg and Springston (2001a) laid out actions that should be taken to reduce the instability of the stream and thus reduce the likelihood of catastrophic landslides in the future. These included avoidance of any additional floodplain encroachment, re-connection of the channel to floodplains via removal of berms or other techniques, improvement of bridge crossings to reduce channel constrictions, stabilization of gullies, proper construction and maintenance of logging roads, etc. As floodwaters from the tributaries pass rapidly down to the main channel, these steps should be applied to the tributaries as well as the main stream.

A carefully delineated Fluvial Erosion Hazard Zone will be a useful tool to help the Town of Plainfield undertake planning efforts so that the Town and its citizens can take steps to avoid the very real hazards along this stream. The landslide hazard zone as delineated here is a first step toward developing such a comprehensive Fluvial Erosion Hazard Zone.

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