Protocol for Identification of Areas Sensitive to Landslide Hazards in Vermont

Prepared for the Vermont Geological Survey by

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On the cover: A large landslide on the Missisquoi River, Sheldon, Vermont. Photo taken by George Springston, May, 2009.

Executive Summary

The purpose of this project is to advance the state of landslide mapping and landslide hazard assessment in Vermont by developing and testing a protocol to map potential hazard areas. The results of this project will be incorporated into the State Hazard Mitigation Plan, which will be updated in 2013.

This project was divided into three parts. Part 1 involved set up of the project, creation of a landslide database, and selection of test sites. Part 2 involved development of the protocol. Part 3 involved preparation of the protocol for incorporation in the State Hazard Mitigation Plan.

Seven site areas were selected in an attempt to represent conditions throughout Vermont. As a bare-earth lidar digital elevation model (DEM) was envisioned as being a key part of any resulting protocol (and the distribution of lidar data in Vermont was more limited when this study was conceived) the study sites are mostly within Chittenden County. Other considerations in site area selection included map coverage, geology, elevation, types of terrain, urban disturbance, and types of landslides expected. The site areas range in size from 1.28 to 12.58 km^2 for a total of 41.3 km^2. Site areas include parts of Alder Brook in Essex, Bartlett Brook in South Burlington, Clay Point in Colchester, Indian Brook in Colchester, Joiner Brook in Bolton, La Platte River and McCabe's Brook in Shelburne, and Smugglers Notch in Cambridge.

Data collection included a literature review, photo interpretation, and field reconnaissance. Landslide characteristics were collected using a field data sheet developed as part of this project. Data were input into an ArcGIS project for each site area.

Fourteen potential parameters were considered as to their effect on landslide hazard. These included location with respect to the marine limit of the Champlain Sea, aspect, distance to stream, elevation, hydrologic group, NDVI, profile curvature, roughness, slope angle, slope height, soil type, stream power index, surficial geology, and topographic wetness index.

A frequency ratio model was used to analyze the site areas and the landslides identified there. At most site areas, the most important parameters were determined to be slope angle and roughness, although soil type and topographic wetness index are also important at some site areas. Slope angle and distance to stream/lake were found to be the most important parameters along Lake Champlain shoreline. The important parameters were then combined to produce a landslide susceptibility map. These results were verified with field checking.

A heuristic method was used to complete the delineation of areas sensitive to landslide hazard. This included consideration of the frequency ratio maps, surficial geology, slope angle, profile curvature, topographic contours, outcrops, and mass failure sites identified by the DEC River Management Program during their Stream Geomorphic Assessments.

A protocol was written for analyzing susceptibility to landslide hazards at other sites using this method. This process was found to work best for the high-angle landslides, which in these sites were predominantly translational slides. Based on the results of the frequency ratio analysis, the most important parameters for identifying these high-angle translational landslides are slope angle and roughness, although soil type and topographic wetness index are also

important at some site areas. Slope angle and proximity to the shoreline were found to be the most important parameters along Lake Champlain.

Low-angle rotational landslides were difficult to identify using the terrain analysis phase of the protocol. Frequency ratio analysis suggests that the most important parameters for the low-angle rotational slumps are likely to be soil type and topographic wetness index, although surficial geology will likely prove to be important too. However, as there were not many of this type of landslide available in the study sites, these conclusions are preliminary.

Debris flows and associated features in the Smugglers Notch area can be accurately mapped by a combination of field work and photointerpretation, but lidar data was not available to test whether or not terrain analysis could successfully identify the features.

Our trials indicate that an accurate bare-earth lidar digital elevation model is extremely helpful. Indeed, it is probably an essential prerequisite for successful terrain analysis using the frequency ratio method described in the protocol. That does not mean that hazard mapping cannot be undertaken without lidar terrain data. Frequency ratio analysis can be tried, and if field review indicates that it is inadequate, then the areas of high hazard potential can be identified by careful stereoscopic photointerpretation and field work. However, the work will proceed far more efficiently if an accurate bare-earth lidar DEM is available.

Based on the results of this study, it is suggested that in most parts of Vermont, areas of at least 25 to 50 sq. km. will probably yield enough landslides for a robust analysis. Alternatively, if the site of interest is smaller, the best results occurred when the following criteria were met: There is, on average, a minimum of one landslide per square kilometer in the site area; the average size of the landslides is at least 400 square meters; and at least 30% of the landslides are greater than 400 square meters.

If the landslides are small in area, then it becomes critical to use a mapping-grade GPS with sub-meter accuracy. Otherwise, mislocation of landslides may cause pixels to be mis-assigned during the terrain analysis, leading to a smearing out or reduction of the landslide terrain signature.

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Introduction

The purpose of this project is to advance the state of landslide mapping and landslide hazard assessment in Vermont by developing and testing a protocol to map potential hazard areas. The results of this project will be incorporated into the State Hazard Mitigation Plan (SHMP), which will be updated in 2013. The protocol will provide regional and municipal planning agencies with a methodology to assess landslide hazard in their respective areas.

This project was undertaken by the Vermont Geological Survey (VGS) with planning assistance from the Chittenden County Regional Planning Commission (CCRPC). The CCRPC provided land ownership information, guidance for meeting with the town officials of each project site, and offered suggestions to incorporate the protocol in the SHMP as well as make the protocol and maps useful as tools for planning in Vermont. The CCRPC also detailed how the protocol would be incorporated into its planned 2016 update of the Chittenden County Multi-Jurisdictional All-Hazards Mitigation Plan.

This report describes a protocol for mapping landslides in natural materials and for identifying areas in natural materials that are sensitive to slope failure or landsliding. It is not intended to quantify the risks posed to people or property that may result from landslides, nor is it intended to identify slope failures that may occur in artificial fill or other human constructions. Any inventories undertaken using the protocol are for planning purposes only and such inventories would not constitute site-specific geotechnical analyses.

Acknowledgements

Funding was provided to the VGS through a Pre-Disaster Mitigation (PDM-C) Grant awarded to Vermont Emergency Management from the Federal Emergency Management Agency.

Laurence Becker, Vermont State Geologist, has been involved in this project from the inception and has participated in many discussions on the grant concept and the methodology as it was developed. We are grateful to him for his ideas, support, and encouragement.

Daniel Albrecht and Pam Brangan, both Senior Planners at the Chittenden County Regional Planning Commission, provided helpful advice and reviews of draft materials. Pam provided landowner contact information.

Many individuals provided information on the nature and occurrence of landslides within the study area. We extend special thanks to Eric Goddard of Knight Consulting Engineers, John Lens of Geodesign, Inc. Thanks to the many town officials who shared information with us, including: Eric Andrews from the Town of Bolton; Al Voegele, Sarah Hadd, and Bryan Osborne, from the Town of Colchester; Dennis Lutz from the Town of Essex; Alex Weinhagen and Mike Anthony from the Town of Hinesburg; Bernie Gagnon and Dean Pierce from the Town of Shelburne; and Justin Rabidoux, Paul Connor, and Tom Dipietro from the City of South Burlington. Thanks also to the many landowners, who graciously allowed us to examine slopes on their properties.

We extend many thanks to the staff of the Vermont DEC River Management Program. Gretchen Alexander and Staci Pomeroy provided data on fluvial geomorphology of the site areas. Gretchen, Staci, and other staff from the program, including Chris Brunelle, Shayne Jaquith, Todd Menees, Sacha Pealer, Rebecca Pfieffer, Shannon Pytlik, and Patrick Ross participated in a field session to review the Slope Stability Datasheet and provided valuable comments and suggestions.

Laurence Becker, Pam Brangan, and Daniel Albrecht each reviewed all or part of the manuscript and provided many constructive comments. Any remaining shortcomings remain the responsibility of the authors.

General Information about Landslides

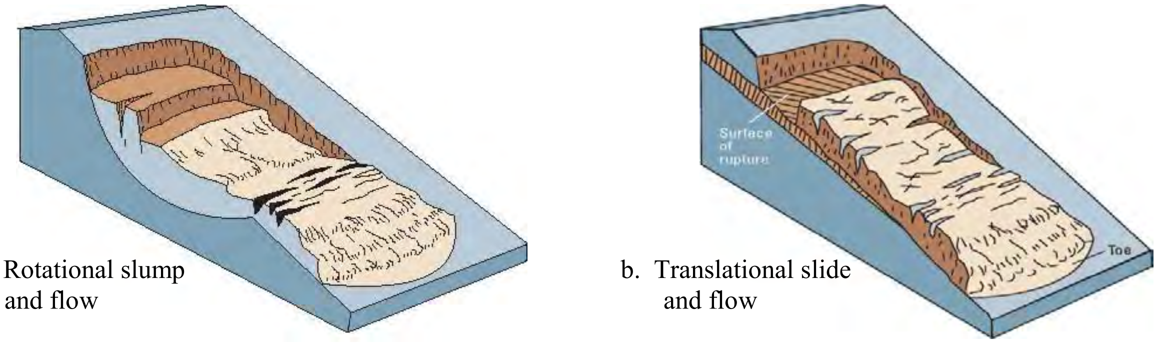
The term "landslide" describes a wide variety of processes that result in the downward and outward movement of slope-forming materials including rock, soil, artificial fill, or a combination of these. The materials may move by falling, toppling, sliding, spreading, or flowing. For a general introduction to landslides, Highland and Bobrowsky (2008) provide a good introduction to classification, causes, and associated hazards. Turner and Schuster (1996) and Sidle and Ochiai (2006) provide very complete overviews of landslide analysis, including detailed summaries of landslide types, field investigation methods, and strength and stability analysis. Table 1 shows a classification of slope movement types, with the common landslide types in Vermont emphasized.

Table 1 - Simplified classification of slope movement types
Modified from Varnes (1978). Types common in Vermont are in bold.

Type of Movement	Type of Material		
	Bedrock	Engineering Soils	
		Predominantly coarse	Predominantly fine
Falls	**Rock fall**	Debris fall	**Earth fall**
Topples	**Rock topple**	Debris topple	**Earth topple**
Slides*	**Rock slide**	**Debris slide**	**Earth slide or slump**
Spreads	Rock spread	Debris spread	Earth spread
Flows		**Debris flow**	**Earth flow**
Complex	**Combinations of two or more types of movement**		
Creep	**Several types**		

*Slides may be subdivided into rotational and translational types. Rotational slides in relatively homogeneous materials are commonly called "slumps". The term "rotational slump", although somewhat redundant, will be used here to emphasize the distinction from translational slides.

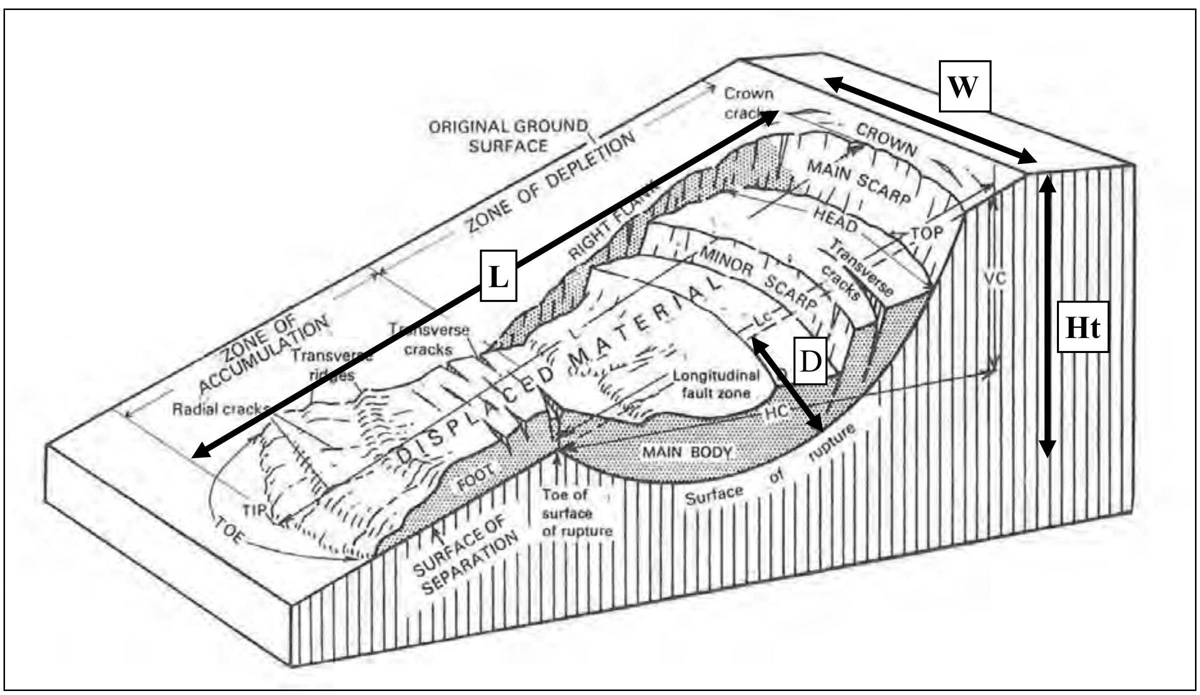
Figure 1 shows the two most common types of landslides in Vermont: Rotational slumps and translational slides. Figure 2 is a graphic illustration of a landslide, with the commonly accepted terminology describing its features.



a. Rotational slump and flow

b. Translational slide and flow

Figure 1 - Two Common Types of Landslides in Vermont. a) rotational slump and flow, b) translational slide and flow. From Highland and Bobrowsky (2008).



<u>Figure 2 - Generalized Complex Rotational Slump/Flow Showing Principal Features.</u> Landslides with this overall form are common on clayey to sandy lacustrine deposits throughout Vermont. In many cases the displaced material has been at least partially eroded away by stream flow. Length (L) refers to the total slope length from crown to the tip of the toe. Width (W) refers to the width of the feature measured across the slope at the location of greatest width. Depth (D) is measured in a vertical plane and perpendicular to the original slope. Height (Ht) refers to the vertical height from the toe up to the top of the slide. Modified from Cruden and Varnes (1996, Figure 3-3).

Landslides can be triggered by one or a combination of factors, including fluvial (stream) erosion, soil saturation from snowmelt or heavy rains, human modification of a slope by excavation of the toe or increasing of the load on top of the slope, and several others. Fluvial erosion leads to landslides by removal of material at the toe of a slope (resulting in steepening), or by lowering of the stream bed (effectively increasing the height of the slope).

Fluvial erosion is considered the most important contributing factor to landslides. In the past, unless the area was identified as hazardous through a fluvial geomorphic assessment and a river corridor plan, areas susceptible to landslides were sometimes not identified as hazardous if they were located well above the elevation that would be designated as hazardous under Federal Emergency Management Agency flood hazard area maps. This landside mapping protocol is intended to address this shortcoming.

Landslides Types Common in Vermont

The most common types of landslides in Vermont are slides, which take two general forms; rotational slumps and translational slides. The translational slides occur on a wide variety of unstable slopes underlain by weathered, dense till, as well as slopes underlain by sandy to clayey lacustrine deposits, whereas the rotational slumps are more common on unstable slopes underlain by sandy to clayey lacustrine deposits. Both rotational and translational failures imply that the material has internal cohesion; otherwise the material would disintegrate into some sort of flow. They are described in more detail in the following paragraphs and in Appendix A.

Rotational Slumps

Rotational slumps are common in the stratified deposits that are widespread in the larger stream valleys of Vermont, especially the cohesive glaciolacustrine silts, silty clays, and clays, although they may also occur in glacial till following especially severe episodes of stream erosion. The characteristic form of the rotational slump has a curving fracture or shear surface that intersects the ground either on the bank or behind the top of the bank. It is then seen to curve down to a bed or lamination either within the bank or at the base. The shear may extend all the way out to the free face or, more commonly, curve upward to take a path of least resistance to the free surface. Slump material often undergoes considerable deformation during failure and as the displaced material moves downward, the lower parts of this must, if they stay at least partly together, ride up over the lower end of the rupture surface (where the rupture broke up toward the old ground surface). It is also common for pieces of the displaced material to stack up on top of or push over earlier blocks or masses of displaced material. Seen in plan view from above, such rotational shear surfaces are commonly arcuate and concave out toward the stream. Earth flows in the lower portions of rotational slump/flows are in some places so extensive that they mask the original brittle nature of the slope failure.

A special type of rotational slump was encountered in the La Platte River site area. Besides a number of translational slides, three areas of low-angle rotational slumps were discovered. In these low-angle slumps, the overall slide angle is less than about 10°. This contrasts with the normal rotational slumps which usually have overall slide angles of 25° or more. All three low-angle slumps are within the elevation range of the late-glacial Champlain Sea and have fine-grained silt-clay deposits at depth. This type of landslide was not encountered in the other site areas and appears to be relatively uncommon. However, because these landslides are quite large, it is important that the possibility of occurrence of these low-angle slumps is considered in landslide inventory efforts.

Translational Slides

Unstable slopes that are underlain by the dense till that is common throughout Vermont commonly fail through relatively shallow landslides. These slides are also common in stratified lacustrine and marine sands, silts, and clays. On wooded slopes that have not experienced landsliding for a considerable time, the upper several feet is typically some combination of surficial material that has weathered in place and/or colluvial material derived from the surficial deposits. In both cases the material retains the wide range in grain sizes of the parent material and is significantly weaker than the underlying unweathered deposit. This upper material is often relatively impermeable and thus slow to drain. If the toe of such a slope is eroded by a stream, the contrast in strength between the weathered surficial material above and the dense, relatively unweathered material below results in the slope having a tendency to fail along the boundary. Thus, although the slides can extend great distances up and down the slopes and along the slopes, the slides rarely "bite" into the hillside deeper than 3 meters (10 feet) or so at a time.

Age of Landslide Activity

An active landslide is one that has moved within the last year. The sides and upper margin of such a landslide are generally sharp and any exposed slide surfaces are bare of vegetation or have only the beginnings of pioneer vegetation on them.

An inactive landslide has not moved within the last year, but it is in a setting in which it could be reactivated (Cruden and Varnes, 1996). One that has been inactive for several years may be largely revegetated, at least with pioneer vegetation. Inactive landslides are common near actively migrating stream meander bends where the site of landslide activity has shifted downstream as the stream meander has shifted downstream. The inactive slides may very well be reactivated if another meander bend migrates down from upstream.

We define a relict slide as one where there is no evidence of movement for many years and the likely causative agent is no longer present. An example would be a former stream cut bank formed by stream erosion in early Holocene time. If the stream has since cut down vertically and moved away in such a fashion that it is now trapped by bedrock and would be unable to move back to the old cut bank, that cut bank could be considered relict. Such a feature is generally completely revegetated and the edges have been softened by erosion.

Description of Project

The project was divided into three phases. Part 1 involved set up of the project, creation of a landslide database, and selection of test sites. Part 2 involved development of the protocol. Part 3 involved preparation of the protocol for incorporation in the State Hazard Mitigation Plan.

Part 1 –Set Up

A. Obtain equipment, maps, photos

Set up of the project included obtaining equipment, maps, and aerial photographs. The following table explains what equipment was purchased and its use.

Item	Use
Computer w/ Microsoft Office & Monitor	An updated computer was necessary to perform the photogrammetric analyses for this project.
Mikrotek Scanmaker 1000 XL to do high quality scanning of large aerial photos	The scanner was used to do high quality scans of paper aerial photographs from the 1940's, 1960's, and 1970's.
Software - Renewal of ERDAS-Imagine license and addition of Stereo Analyst Extension to digitize landslide polygons and other features directly into GIS.	ERDAS-Imagine was used to analyze the historical aerial photographs in stereo, identify landslides, and digitize their outlines for input into ArcGIS. Because of the complexity of rectifying adjacent photos, this process was found to be time-consuming and was only performed on the historical photos in the La Platte River site.

The maps and GIS layers necessary for this project were available primarily from the Vermont Geological Survey (VGS), the Vermont Center for Geographic Information (VCGI), the Vermont Mapping Program (part of the Vermont Department of Taxes), State GIS servers, Natural Resources Conservation Service of the Department of Agriculture (NRCS), and the U.S. Geological Survey (USGS) website.

Recent orthophotos were available from the sources listed above. Older aerial photographs were available at the VGS and borrowed from the Agency of Natural Resources, Water Resources Division and the Department of Forests, Parks & Recreation.

B. Landslide database

A landslide database was created on ArcGIS. The format of the database is similar to a field data sheet for landslides, which was also created. The data sheet and instructions for its completion are included as Appendix A. Details of the fields in the database are included as Appendix B. Briefly, the fields in the database include the following:

Location information
Observers
Date of data collection
Style of slope failure (landslide, gully, etc)
Type of landslide and material
Activity (active, inactive, relict)
Geometry (length, width, depth, height, slope angle, aspect)
Surficial materials

Presence of bedrock, seeps, piping, toe erosion, etc.
Comments (including extent of damage, if any)

C. Literature Review

A review of literature pertaining to landslides in general, methods for assessing landslide susceptibility, and particularly landslides in Vermont was conducted. The results of this literature review are incorporated in this report.

Highland and Bobrowsky (2008) provide a good introduction to classification, causes, and hazards associated with landslides. Turner and Schuster (1996) and Sidle and Ochiai (2006) provide very complete overviews of landslide analysis, including detailed summaries of landslide types, field investigation methods, and strength and stability analysis.

A USGS study of slope stability issues in Vermont, undertaken in cooperation with the Vermont Geological Survey, resulted in several publications that contain useful information on slope stability. Much of this work is summarized in Baskerville and others (1993) and Baskerville and Ohlmacher (2001). Of particular note is the cluster of at least four debris avalanches that occurred on Dorset Mountain on August 10, 1976. Such events, although comparatively rare in Vermont, have the power to cause tremendous damage. Where they have occurred in stream valleys, the signs may be discernible for many decades thereafter. Note that the Dorset slides extended up to 4.2 kilometers from their source areas. Similar debris avalanches or debris flows also swept down the valleys of Mill Brook in Fayston in 1827 and Slide Brook in Fayston in 1897 (Baskerville and others, 1993).

Several studies of debris flows and/or debris avalanches in the mountainous terrain of Vermont and surrounding states have been undertaken in recent decades, including Flaccus (1958), Kull and Magilligan (1994), and Milender (2004) in New Hampshire, Bogucki (1977) in the Adirondacks, and Dethier and others (1992) on Mount Greylock in Massachusetts. Springston conducted a detailed analysis of rockfall and debris flow hazards in Smugglers Notch in northwestern Vermont (Springston, 2009).

The close association between landslides and stream erosion has been investigated in a number of recent studies. Barg and Springston (2001), Springston and Barg (2001) and Springston and Barg (2002) studied the fluvial geomorphology and surficial geology of the Great Brook watershed in central Vermont. This work included mapping of over 20 large landslides. Springston and others (2004) conducted a detailed analysis of a large rotational slump in lacustrine sediments on the Mad River in Waitsfield. Since approximately 2000, extensive studies of fluvial geomorphology in Vermont watersheds have been undertaken by the River Management Program of the Vermont DEC. Some of the results of these studies are summarized in Kline and Cahoon (2010). These assessments include mapping locations of mass failures that can be seen walking along the stream and will be utilized extensively in this protocol. Springston (2010) summarized existing knowledge of bank stability issues in Vermont and included a literature review of previous landslide studies in the state. Landslide activity in the wake of Tropical Storm Irene (August 2011) is the subject of ongoing assessment. Preliminary work suggests that many pre-existing landslides were reactivated during the flooding (Springston and others, 2012).

D. Site Area Selection

The optimum goal of this project was to select site areas to try to represent conditions throughout the state because the protocol will be applied throughout the state. However, all the test site areas are in Chittenden County, because of the lidar coverage there. The bare-earth lidar 3.2m DEM is the best elevation data in the state, however it is only available in some parts of Vermont at this time. Other DEMs, such as the USGS 10m DEM, are available throughout the state and should be used with the protocol if lidar is unavailable, but the results would not be expected to be as accurate as the results with lidar.

Other considerations in site area selection included map coverage, geology, elevation, types of terrain, urban disturbance, and types of landslides expected. Because the existence of landslides was necessary to develop a protocol, sites were chosen where landslides had been previously identified, either by the USGS or in the Stream Geomorphic Assessments performed by the DEC River Management Program.

The steps in selection of site areas were:

1. Collect and use the following GIS overlays to locate preliminary areas of interest. Suitable site areas were chosen to include a variety of terrain (urban, rural, and mountainous) and a variety of geologic materials (till, clay, and other materials).
    - Chittenden County Boundary
    - VT Political
    - Roads
    - Rivers and Lakes VHD Cartographic (1.5K)
    - Lake Champlain
    - Surficial geology layers for Burlington, Charlotte, Colchester, Hinesburg, Williston
    - Surficial geology statewide (1970)
    - USGS Landslide layers (recent, recent to prehistoric rockfalls, recent to old debris flows, recent to old slope failures)
    - Soils – Department of Agriculture, Natural Resources Conservation Service (NRCS) Soil Survey
    - Stream Geomorphic Assessment layers - DEC River Management Program
    - Shallow overburden outcrops
    - Lidar Bare Earth DEM (3.2 meter)
    - NAIP 1m Color orthophotography (2009)
    - NAIP 1m True and Color Infrared orthophotography (2008)
    - NAIP 1m Color orthophotography (2003) - SDE
    - Chittenden County .1667m Color Orthophotos (2004)
    - Topographic Maps (1:24,000)

2. Evaluate possibilities for landslides within the different preliminary areas, based on comparison with previous mapping projects and professional expertise. Locations of mass failures and gullies identified by the DEC Rivers Management Section were considered. From this, preliminary site areas were chosen.

3. To gather first-hand input on the preliminary site areas, the CCRPC provided information on current mitigation plans and relevant staff contacts in each of the respective towns with potential site areas. Meetings were then held with each prospective

municipality to inform them of the project and to gather information about slope failures in that municipality.

Town of Bolton - Eric Andrews, Highway Foreman
Mr. Andrews pointed out several problem areas along Joiner Brook.

Town of Colchester - Al Voegele, Town Manager; Sarah Hadd, Planning Director; Bryan Osborne, Public Works Director
Town officials suggested several other areas of interest – along Lake Shore Drive, along the Winooski River, and around Mill Pond. These suggestions were taken into consideration, and the Indian Brook site area was changed to include the area around Mill Pond.

Town of Essex - Dennis Lutz, Public Works Director
Mr. Lutz showed us areas of gullying and erosion in Alder Brook. He suggested that the water table was artificially raised in this area, because the area is on public water, but has no public sewer system. He feels this may contribute to the instabilities and erosion being experienced in Alder Brook. He stated that no future development was scheduled for the Alder Brook area due to these problems.

Town of Hinesburg - Alex Weinhagen, Director of Planning; Mike Anthony, Road Foreman
Discussions at the meetings suggested that Hinesburg did not have enough slope failures at this time to warrant a site in that town. As a result, preliminary site areas in the town were dropped from consideration.

Town of Shelburne - Bernie Gagnon, Public Works Director; Dean Pierce, Planning Director
A large rotational failure, which occurred in 1863 and affected about 5 acres of land near the post office, was discussed at the meeting.

City of South Burlington - Justin Rabidoux, Public Works Director; Paul Connor, Planning Director; Tom Dipietro, Stormwater
Mr. Conner and Mr. Dipietro confirmed that Bartlett Brook was currently the most problematic area in the city because of the flooding and erosion due to increased development.

4. Using the information gathered, final site areas were selected.

The original proposal suggested that four site areas between 10 and 20 km^2 each would be selected. In the end, six site areas ranging in size from 1.28 to 12.58 km^2 for a total of 41.3 km^2, were selected for detailed development of the protocol. These site areas ranged from natural Lake Champlain shoreline to the western Green Mountains.

Locations of the site areas are shown in Figure 3. A synopsis of the site area characteristics is given in Table 2.

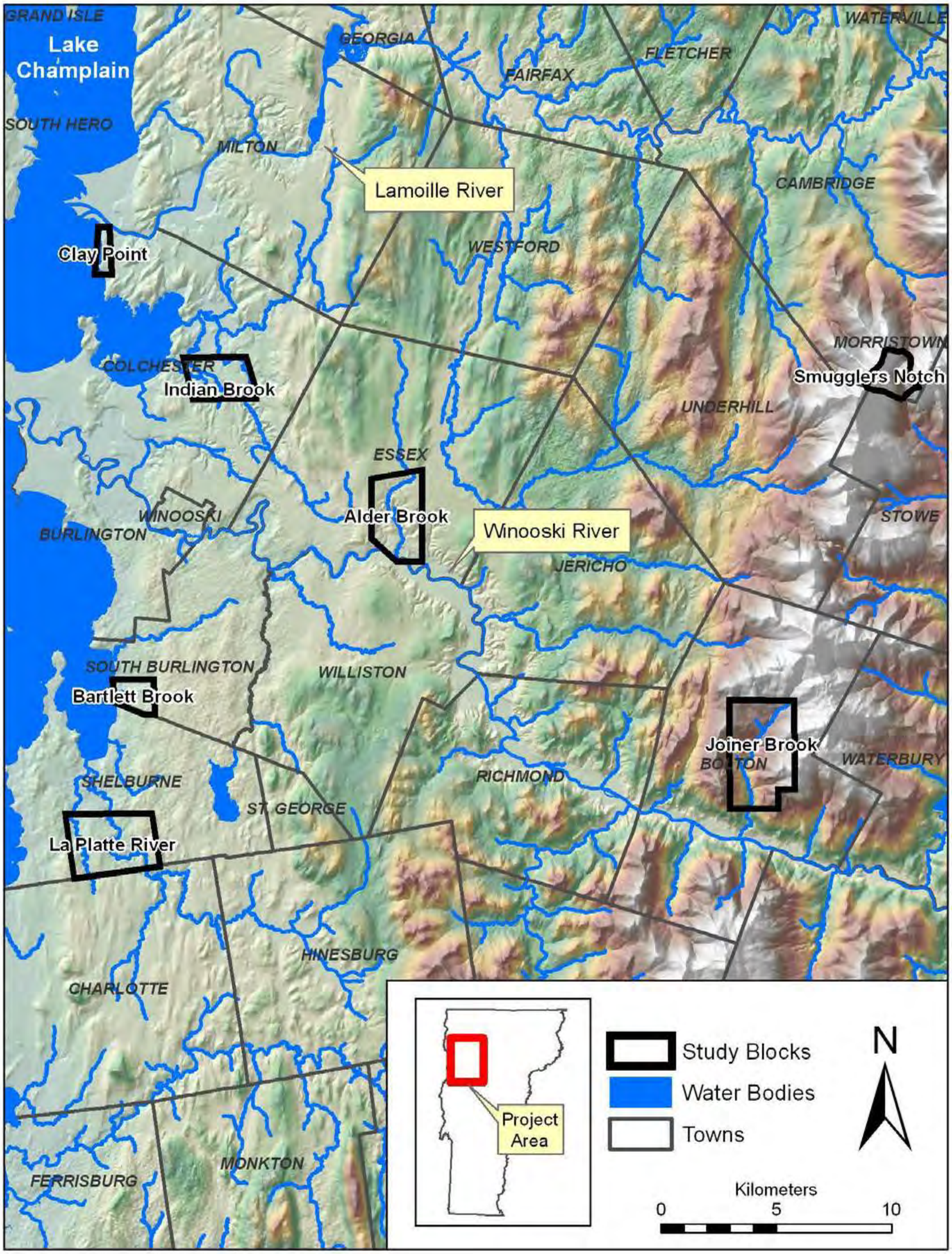


Figure 3. Site Area Location Map.

Table 2 – Summary of Site Area Characteristics

Site Area	Town	Urbanization/ Terrain	Surficial Materials	Area in km^2	Within limit of Champlain Sea?	Elevation in meters
Alder Brook	Essex	Rural/suburban, plains	Delta sand (Doll, 1970)	7.8	No	84-158
Bartlett Brook	South Burlington	Urban, plains/ shoreline along Lake Champlain	Till, medium fine sand, silt and clay (Wright et al., 2009a)	2.4	Yes	30-102
Clay Point	Colchester	Rural shoreline along Lake Champlain	Champlain Sea delta deposits. Pebbly medium coarse to medium fine sand (Wright et al., 2009b)	1.3	Yes	30-54
Indian Brook	Colchester	Rural plains and lowlands	Marine clay, pebbly marine sand (Wright et al., 2009b)	7.6	Yes	14-254
Joiner Brook	Bolton	Rural mountainous	Till (Doll, 1970)	12.6	No	200-800
La Platte River	Shelburne	Rural plains	Boulders in clay, marine beach gravel, delta sand, till (Doll, 1970)	9.6	Yes	30-130

A seventh site area at Smugglers Notch was added, but as the project proceeded, it became clear that the terrain analysis phases of the procedure could not be implemented there due to the lack of lidar topographic data. Also, the landslides at Smugglers Notch are a combination of rock falls and debris flows, landslide types that are relatively uncommon throughout the rest of the state. The landslides at Smugglers Notch were mapped by Springston (2009) using a combination of field assessment and aerial photo interpretation. This site area will be discussed further in the descriptions of the site areas.

Part 2 – Develop Protocol

A. Collect GIS layers

A GIS project was created for each site area. The following layers were added to the projects.

- Digital Elevation Model (DEM) – The 2004 3.2m lidar DEM was used at all of the site areas except for Smugglers Notch, where the terrain analysis phase was not performed.

- Orthophotos – Orthophotos used on this project, included:
    - 1999 black & white orthophotos from the Vermont Mapping Program
    - 2004 color orthophotos from the Vermont Mapping Program
    - 2009 color orthophotos from National Agriculture Imagery Program (NAIP)

- Aerial photographs – Photo interpretation of the 1962 black & white photos was performed for all site areas. In addition, photo interpretation of the 1942 black & white aerial photographs was performed at the La Platte River site area.

- Geologic Maps – The 1:62,500 scale surficial geologic maps were added to the projects. These are the maps used to compile Surficial Geologic Map of Vermont (Doll, 1970).

  The Colchester and Burlington surficial geology maps at a scale of 1:24,000 were added and cover approximately the northern quarter of the La Platte River site area, and all of the Bartlett Brook, Indian Brook, and Clay Point site areas (Wright et al., 2009a, 2009b).

Outcrop maps were available for some of the site areas (Bartlett Brook, Clay Point, and Indian Brook) and were added to those projects (Wright et al., 2009a, 2009b).

- Old Landslides – GIS layers compiled by the USGS showing areas affected by landslides were added to the projects. These layers include recent landslides, recent to prehistoric rockfalls, recent to old debris flows, and recent to old slope failure areas. (Baskerville and Ohlmacher, 2001)

- Soils Data – Soil survey data from the U. S. Department of Agriculture, Natural Resources Conservation Service was added to the projects. Soils survey data is derived from a combination of field work and aerial photo interpretation. Soil Series are defined based on soil horizon characteristics such as grain size (texture), organic matter content, color, structure, chemistry, etc. As soils are generally based on the upper parts of the surficial deposits (the top 50 inches or 1.3 meters), they are of somewhat limited utility for understanding the deeper parts of the surficial deposits. At times, it is possible to get partially past this shortcoming, if the soils on the side slopes of a terrace seem to reveal the material underlying the terrace. Many soil attributes were considered and tested as aids in identifying landslides, but this study did not identify a way to incorporate the soils data directly into the terrain analysis phase. The data remains very useful for the later phases of the protocol.

- Outcrop Data – A statewide outcrop map was compiled from four statewide or nearly statewide datasets showing outcrops and very shallow bedrock locations. The four datasets used were bedrock outcrops from the GeologicSurficial_SURFICIAL62K polygon layer, rocklines from feature class Geologic_SURFICIAL62K_line, soil polygons with shallow depth to bedrock or exposed bedrock derived from the soil layer Geologic_SO_poly, and a set of outcrop locations along highways compiled for a rockfall hazard study of the state. The resulting compilation appears to show the extent of bedrock outcrops and very shallow bedrock reasonably well for most of the state at small scales (1:100,000 or smaller). The exception is Essex County, where no soils data was available at the time of compilation. With the addition of shallow soils data from Essex County, this will be a statewide dataset. These layers were combined into a common raster dataset: vtoutcrops, which is available at the VGS.

- Fluvial Geomorphology Data – Data from the Stream Geomorphic Assessments conducted by the Rivers Management Section of the Vermont DEC was added to the projects. The data include the locations of mass failures, eroding stream banks, and channel alterations. It was found that the locations of mass failures were accurate and useful for this project. The mass failure locations are of key importance in conducting landslide inventory.

- Surface Water Data – The Vermont Hydrography Dataset, derived from 1:5000 orthophotos showing rivers, streams, lakes, and ponds was added to each project. This layer is available through VCGI. In addition, a layer showing the extent of Lake Champlain was added to the projects that border Lake Champlain (Bartlett Brook and Clay Point).

- Limit of Champlain Sea Marine Sediments – Marine sediments from the Champlain Sea have been found to create unstable conditions, however the extensive low angle earth flows, such as those in Quebec, are not known to have occurred in Vermont (Lefebvre, 1996; Scott, 2003). Low angle rotational slumps that affect acres of land do occur in Vermont and seem to be limited to areas within the marine sediments of the Champlain Sea. Therefore, the marine limit is an important consideration for landslide investigations in Vermont. A GIS layer of the marine limit of the Champlain Sea deposits was compiled by Springston in 2012 and is available at the VGS.

- Topographic Maps – USGS topographic maps at a scale of 1:24,000 were obtained as layer files from VCGI.

- Political Boundaries – These layers (BoundaryOther_BNDHASH) showing state, county, city, town, and village boundaries were obtained from VCGI.

- Roads – There are several roads layers available from VCGI**.** EmergencyE911_RDS layer was used for this project.

- Outline of the site areas of interest – Another important layer was the outline of the site areas of interest for this project. These polygon layers were created to show the boundaries of study for this project.

B. Investigation of Site Areas

The locations of mass failures delineated by the River Management Program during their Stream Geomorphic Assessments were used as a guide to find landslides to visit. In addition, orthophotos and aerial photographs were interpreted to identify landslides at the site areas. A sample of these landslides was visited at each project site area. Additional landslides encountered during the course of our field visits were also located using GPS and characterized for inclusion in the database.

In order to facilitate the organization and analysis of field information, a landslide database was developed. This includes general site information, as well as data on landslide classification, geometry, surficial materials and stratigraphy, and possible causes of the landslides. The database and the associated field data sheet are included in Appendices A and B.

Parcel ownership information was provided by the CCRPC. A description of the sites follows.

Alder Brook

Description of Site Area: The Alder Brook watershed flows from Milton through Westford and Essex into the Winooski River at the border of Essex and Williston. The Alder Brook site area for this project is in south central Essex and includes the area from the intersection of Jericho and Center Roads in Essex Center to the mouth of Alder Brook at the Winooski River. Figure 4 shows a map of the Alder Brook site area.

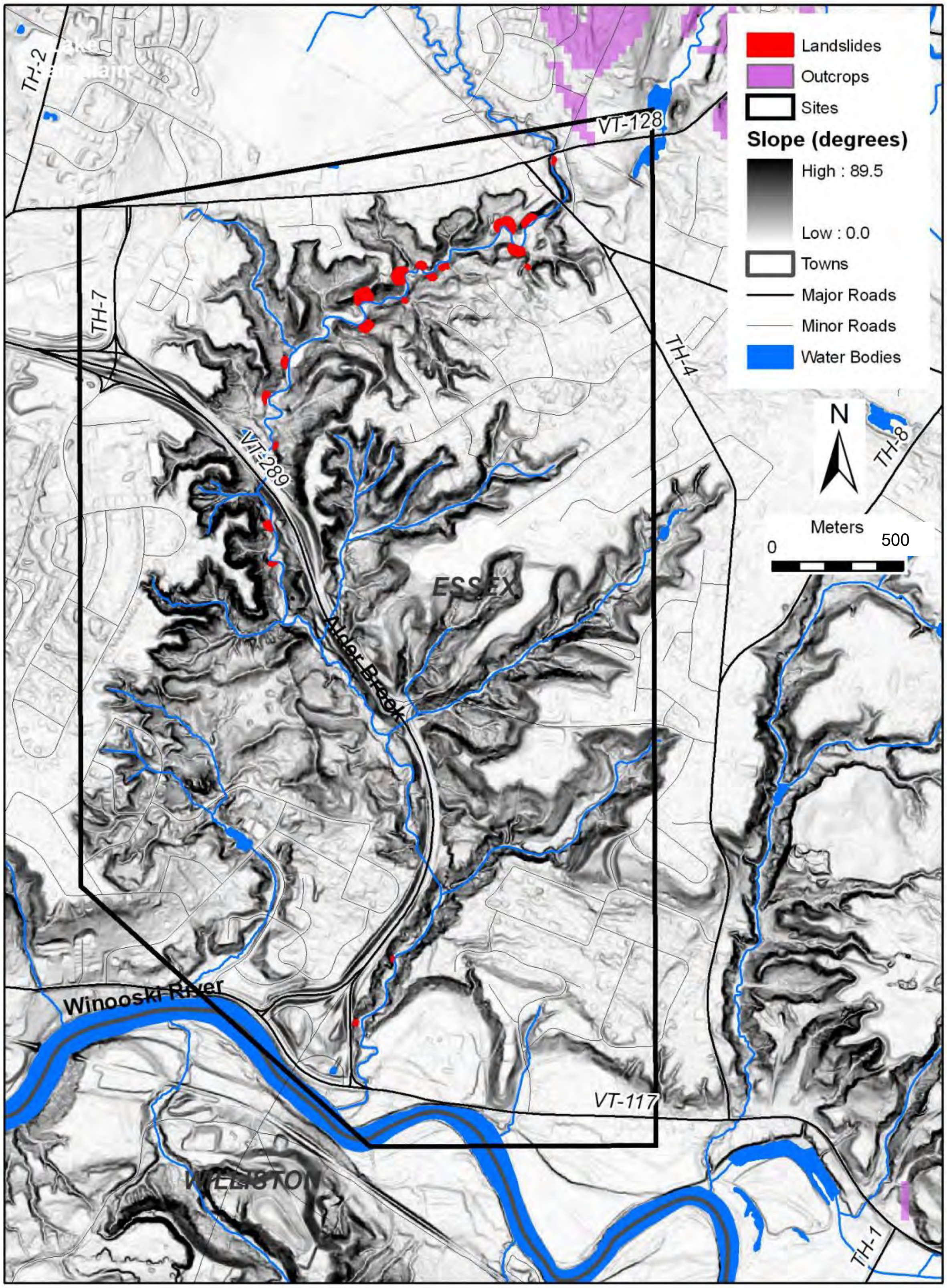


Figure 4. Alder Brook Site Area Location Map

Geology in the majority of the site area was mapped as delta sand on the 1970 state surficial geologic map (Doll, 1970). At the downstream end, the brook flows through an area mapped as pebble marine sand. As it reaches the Winooski River, the area is mapped as alluvium. There is no bedrock mapped in the site area.

Alder Brook has had an interesting history. Prior to 1830, it flowed east from Essex Center into Browns River, whose mouth is in the Lamoille River to the north. The following account is given by Frank Bent, editor of *The History of the Town of Essex*, published in 1963. The sawmill discussed was on Alder Brook in Essex Center.

"In 1804, Mr. Pelton leased of Daniel Morgan the right to plow land on Alder Creek, and built a sawmill on the bank of the brook ... This brook ... was then a very small stream, quite shallow, emptying into Brown's River... This brook Mr. Pelton diverted for his purposes, from its natural courses, carrying the water into a flume to a reservoir dam a few rods below the present causeway. ... The brook was a small affair. But in the freshet of 1830, it became a mighty power, swept off bridges, dams, and mills. It cut for itself a new channel, well toward a hundred feet below the original bed, and forced its way over all opposing obstacles till it mingled its waters with the Winooski in an entirely opposite direction from its original mouth."

Alder Brook has drained into the Winooski River since that time.

As part of this project, Mr. Dennis Lutz, the Director of Public Works for the Town of Essex, was contacted. Discussions with Mr. Lutz indicated that gullying and bank erosion have been major problems on Alder Brook and its tributaries, which are heavily influenced by development. Mr. Lutz stated that there would be no more development near Alder Brook at this time, due to these issues.

The River Management Program identified 41 mass failures in the site area. Ten landslides and one area of gullying were visited during the initial phase of this project.

The slides visited were predominantly translational. Along the brook, a thick layer of sand overlies a silty clay layer. The clay tends to fail in translational blocks, which causes the overlying sand to erode beneath the root layer and undermine the trees on the slope. The trees slide down the slope, tilting and falling, and uncovering more of the erodible sand. The site area is above the marine limit of the Champlain Sea, so large rotational slumps are not expected and no rotational slumps were identified.

Bartlett Brook

Description of Site Area: The Bartlett Brook site area is in southwestern South Burlington along the Route 7 urban corridor and is heavily developed with parking lots, business complexes, hotels, and housing. As such, the stream is experiencing downcutting and erosion due to the increase in stormwater runoff from the impermeable surfaces. Bartlett Brook flows directly into Lake Champlain. Figure 5 shows a map of the Bartlett Brook site area.

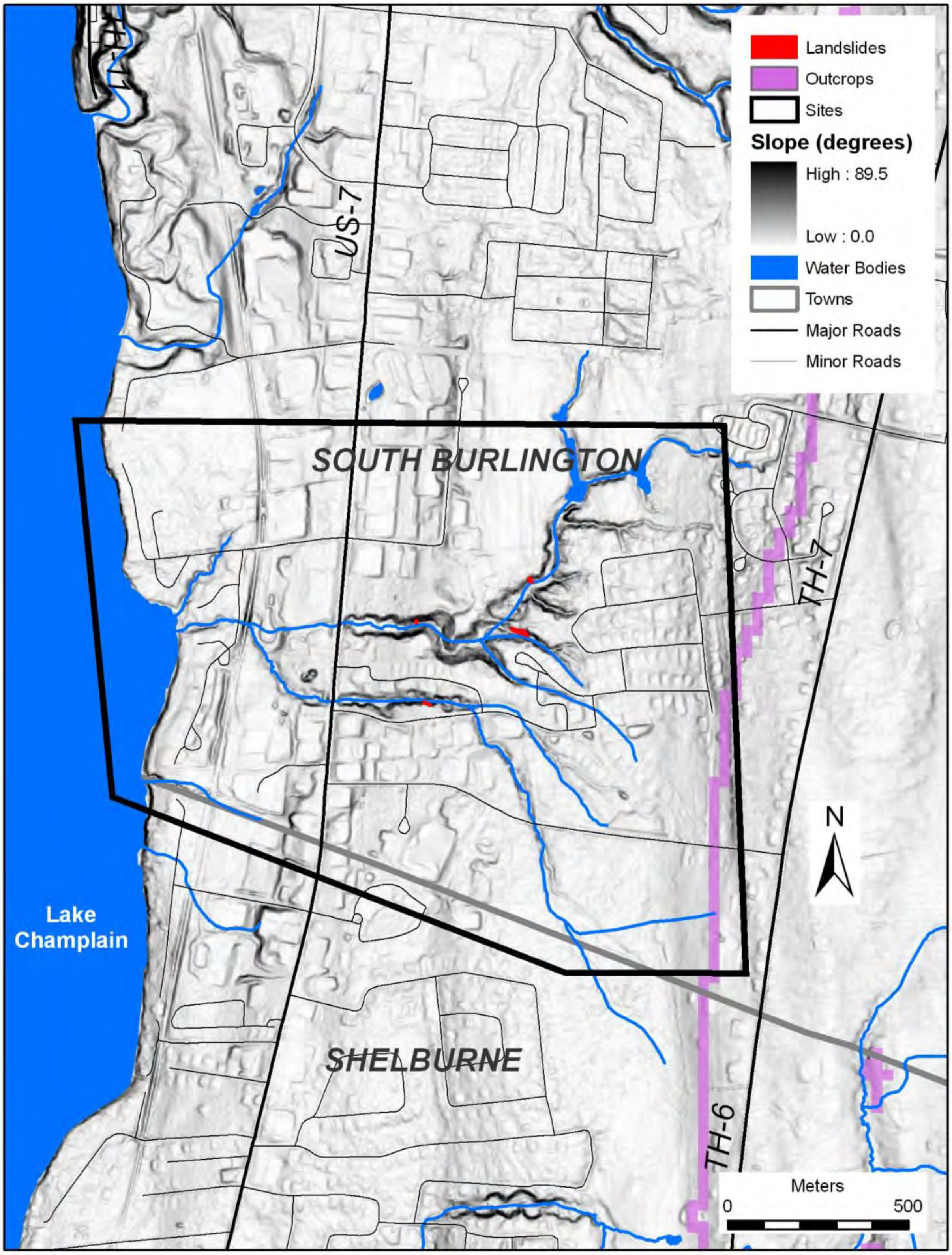


Figure 5. Bartlett Brook Site Area Location Map.

The River Management Program identified 4 mass failures in the site area. Five landslides were visited during the initial phase of this project. Four of the slides exhibited translational movement and one exhibited rotational movement. All of the slides were small in area (less than 700 sq. m.) and difficult to find on the orthophotos and aerial photographs.

The northeastern third of the site area is mapped as medium fine sand (Wright, 2009a). Field work found that this area was underlain by sand and silty clay, which flowed when saturated adding to the likelihood of slope erosion and failures. Four landslides were identified in this geologic unit – three translational and one rotational. The remainder of the site area is mapped as till (Wright, 2009a). One translational slide was identified in this unit.

Although the site area is within the marine limit of the Champlain Sea, no large low angle rotational slumps were identified. The small rotational slump at SBB-02 is more likely to be the result of downcutting of the brook due to increased stormwater than the effect of Champlain Sea sediments.

Clay Point

Description of Site Area: The Clay Point site area lies along the shoreline of Lake Champlain in northern Colchester just south of the mouth of the Lamoille River. This site area was included because it is located along a stretch of relatively natural shoreline that has not been heavily developed. Figure 6 shows a map of the Clay Point site area.

The site area is relatively flat with steep bluffs down to the lake. The bluffs are approximately 20 meters high at a 35 to 40^{o} angle. Lake terraces, about 10 meters above lake level, are also present along the shore and through the site area. The terrace slopes are 6 to 10 meters high at a 20 to 25^{o} angle.

Wright (2009b) maps the surficial geology at the site area as pebbly medium coarse to medium fine sand. Stratigraphy of the bluffs showed a layer of sand, about 15 meters thick, overlying a 5m thick clay layer. Sporadic outcrops of till occur at the base of the bluffs.

Because of its location along the shore, the River Management Program has not identified any mass failures within the site area. One slide in the site area was identified by a colleague who lives in that area and knew of the project. Three other slides were identified by employees at Camp Kiniya. All landslides occurred in the bluffs along the shoreline.

The shoreline in this area is subject to wind and wave erosion from the lake to the west and erosion and sedimentation from currents exiting the mouth of the Lamoille River. It should be noted that in the spring of 2011 when the field work at Clay Point was conducted, rainfall was higher than normal and lake levels were approximately 6 feet above normal, so the toes of the bluffs were experiencing more erosion than normal. This undoubtedly caused the initiation of most of the slides. When the lake level is normal, a sloping sandy beach separates the bluffs from the water. The beach provides some measure of protection from erosion, however, some land owners have installed rock walls to further protect the bluffs.

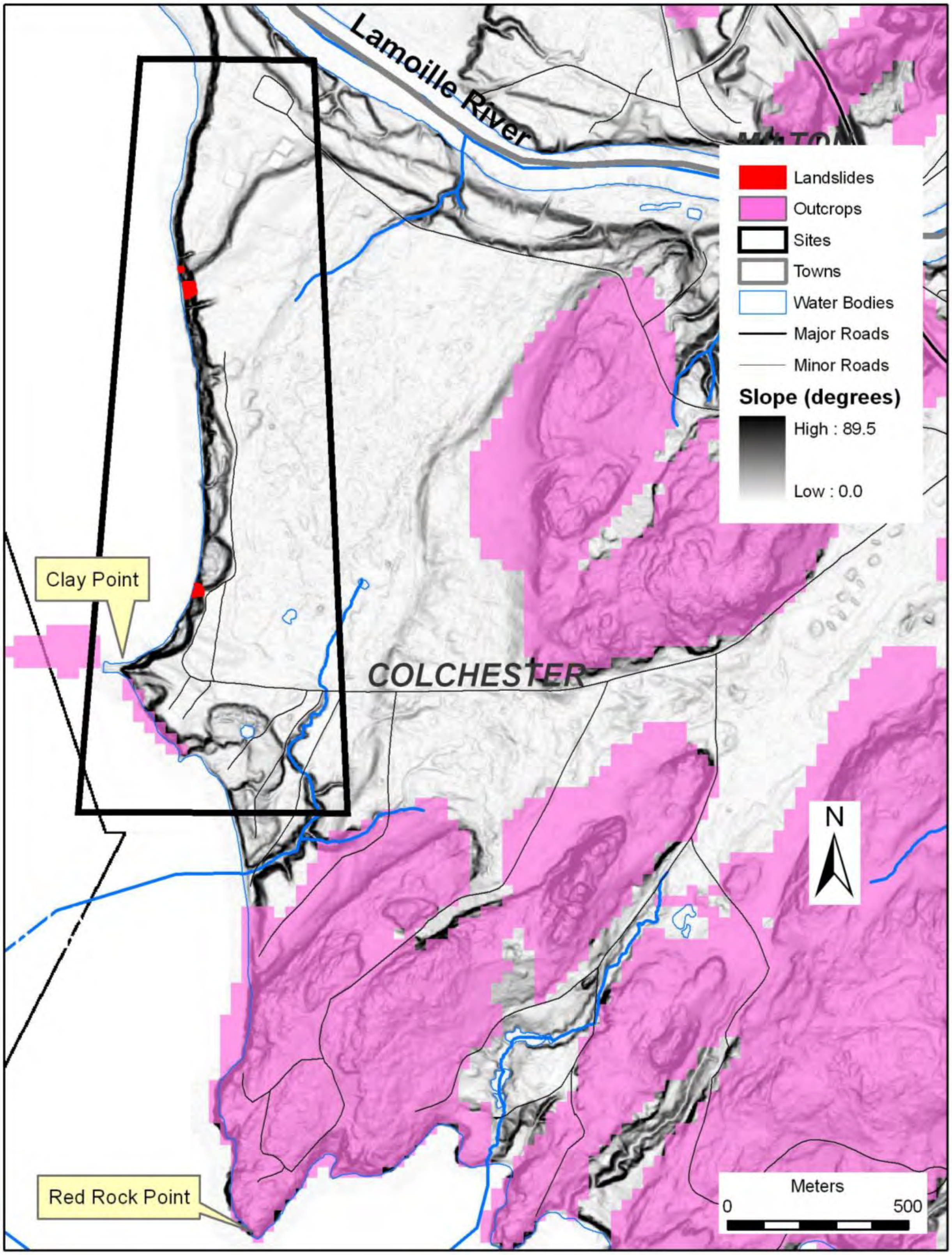


Figure 6. Clay Point Site Area Location Map.

The three larger slides in the area exhibit primarily translational movement, and affect the entire bluff. One smaller slide at Camp Kiniya seems to be rotational, affecting only the lower part of the slope.

Indian Brook

Description of Site Area: Indian Brook is in central Colchester and drains into Malletts Bay. Route 127 crosses the middle of the site area and Interstate 89 is just to the west of the site area. Figure 7 shows a map of the Indian Brook site area.

Indian Brook is a meandering stream in the site area with a flood plain about 75 m wide. Sediments in the valley are mapped as alluvium by Wright (2009b) with medium to fine sand and clay mapped in the slopes bordering the flood plain and the flatter areas above the slopes. Till and silt-clay deposits are mapped in the upland regions of the site area.

The site area is within the boundary of the marine deposits of the Champlain Sea. However, the large, low-angle rotational slumps that were identified in the La Platte River site area were not identified during earlier surficial geologic mapping of the Indian Brook area (Wright, 2009b), or in this study. Stephen Wright (email communication, December 2012) pointed out that the sandy deposits exposed in the Indian Brook valley are deltaic deposits formed by the Lamoille River as it emptied into the Champlain Sea. The deposits at the La Platte River site area, although of a similar age, have considerable fine-grained silt and clay in the deeper parts. The sandy deposits at Indian Brook are thus unlikely to be subject to low-angle landsliding.

Six mass failures were identified in the site area by the River Management Program. Five landslides were visited as part of the initial assessment of the site area. The slides were translational slides with one rotational slump seen at the northwestern part of the site area.

Joiner Brook

Description of Site Area: The Joiner Brook watershed is on the west side of the Green Mountains in central Bolton above the limit of the marine deposits of the Champlain Sea. Joiner Brook flows into the Winooski River. The Bolton Valley Resort lies in the upper part of the drainage and affects the drainage in terms of runoff, sedimentation, and erosion. The Bolton Valley Access Road roughly parallels Joiner Brook on its way up to the resort. Figure 8 shows a map of the Joiner Brook site area.

Joiner Brook flows south across the site area in a dendritic/rectangular pattern. One major tributary flows east into Joiner Brook from the east central part of the site area. Bedrock outcrops dominate the uplands in the site area. The remaining surface is covered with glacial till (Doll, 1970).

Eleven mass failures were identified in the site area by the River Management Program. Thirteen translational slides were investigated as part of the initial field reconnaissance for this project. All of the slides occur on the valley walls of Joiner Brook, primarily on the east side of the valley. The reason for this is not clear.

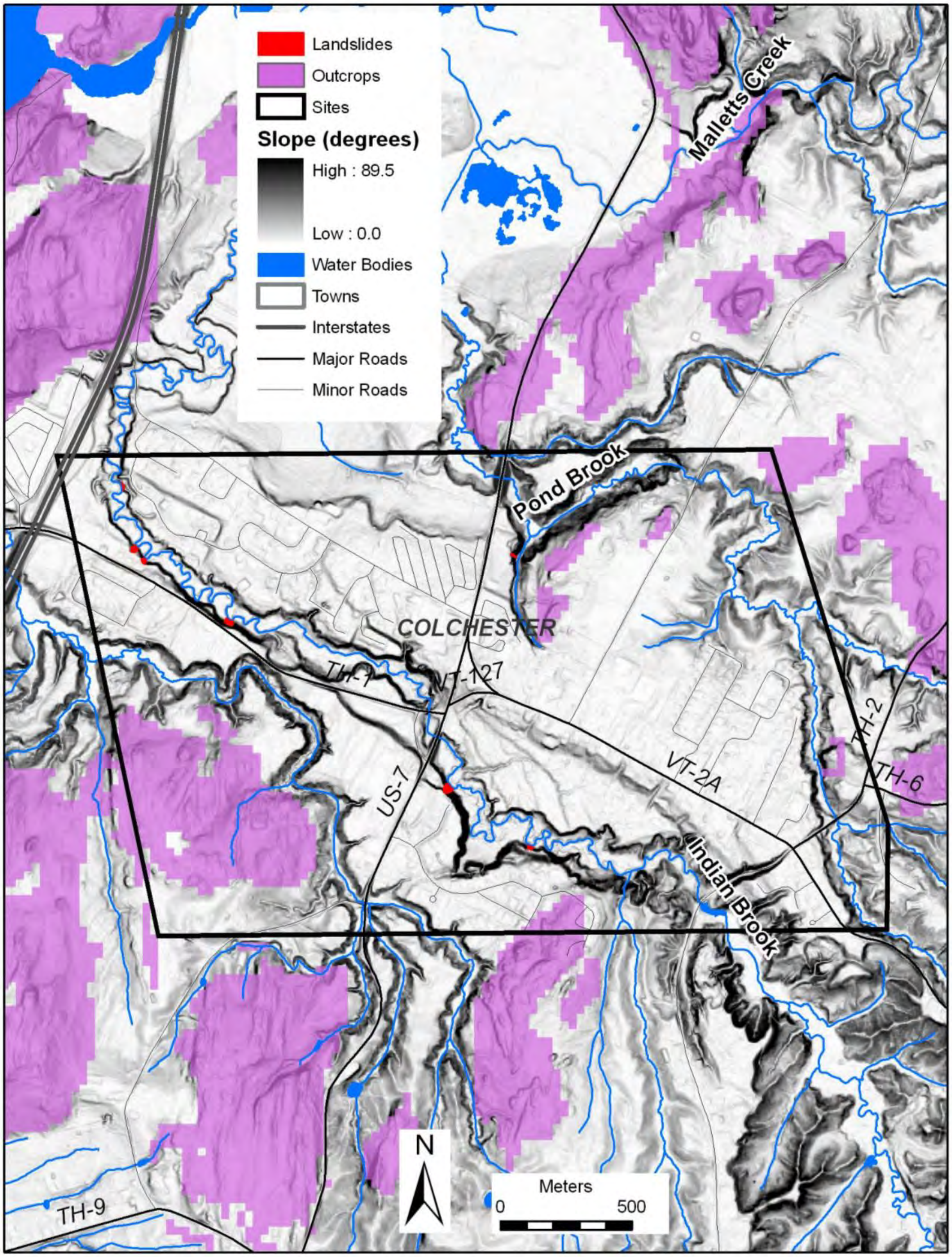


Figure 7. Indian Brook Site Area Location Map.

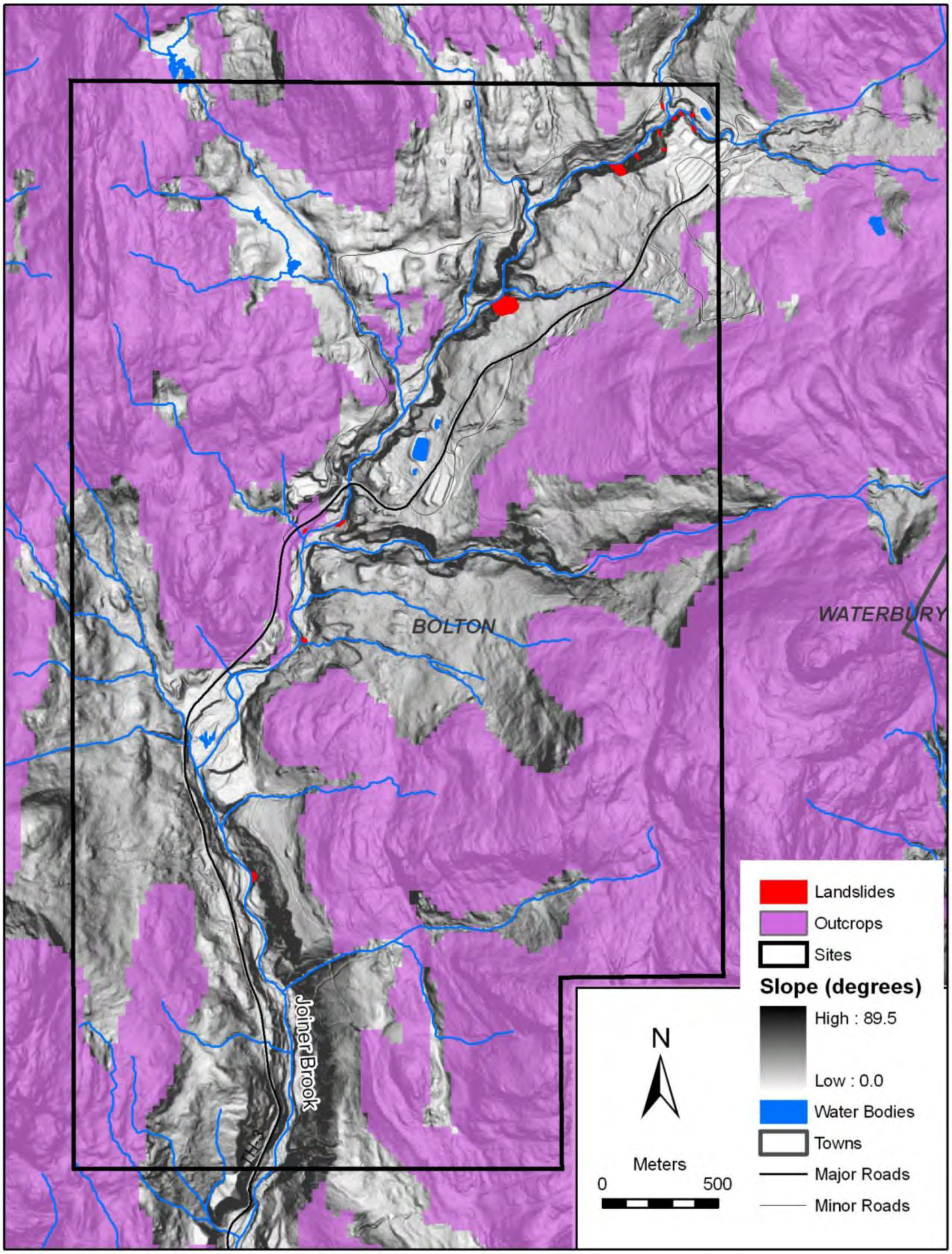


Figure 8. Joiner Brook Site Area Location Map.

La Platte River

Description of Site Area: The La Platte River site area is in the south central part of Shelburne. The site area includes two branches of the river, the main stem of the La Platte River and McCabe's Brook, which roughly parallels the river to the west. Route 7 traverses the western third of the site area and the village of Shelburne is in the central part of the site area. Figure 9 is a map of the La Platte River site area.

Geology in the northern quarter of the site area was mapped as part of the Burlington quadrangle by Wright (2009b). It is predominantly till with areas of medium to fine sand around the La Platte River and McCabe's Brook. Geology in the southern part of the site area is shown on the 1970 state surficial geologic map (Doll, 1970). It is predominantly till with some marine beach gravels mapped in the McCabe's Brook area. Bedrock outcrops are mapped in the center of the site area at Shelburne Falls and in the northeastern third and west central edge of the site.

The La Platte River site area lies within the limit of the marine Champlain Sea deposits. Several active and relict large, low angle rotational slumps were identified in the site area. One of these is located east of the post office off the community gardens on La Platte Circle. Movement on this slump was reported in 1863 (Cole, 2009) and likely continues today as exhibited by the hummocky topography, sag ponds, tilting trees, and flaking at the toe. These slumps are generally characterized by slopes less than 10^{o} and have affected as much as 0.05 sq. km.

The River Management Program identified 8 mass failures along the La Platte River and 7 along McCabe's Brook. Eight translational slides and three rotational slumps were visited during the initial phase of this project.

Smugglers Notch

Description of Site Area: Smugglers Notch is a narrow mountain pass located in the towns of Cambridge and Stowe in Lamoille County (Figure 10). It is flanked by Mount Mansfield on the west and Spruce Peak on the east and is largely within the Mount Mansfield State Forest. Vermont Route 108 winds through the narrow floor of the Notch, which is studded with large talus blocks and overhung by tall cliffs.

Details of the mapping of landslides in Smugglers Notch are contained in Springston (2009). Two very distinct types of landslides or slope failures occur in the Smugglers Notch area. The first is the broad class of landslide that includes rock falls and slides, and which consists of one or more large pieces of rock detaching from a cliff and falling or sliding down a slope. Most of the boulders in the floor of the Notch appear to be the result of such rock falls and slides. The second class of landslides includes the debris flows, which are slurries of water, mud, pebbles, cobbles, and boulders that flow within shifting channels on the talus slopes below the cliffs. In the Notch, they are activated by heavy rainstorms and/or snowmelt.

The large boulders that litter the floor of the Notch are strong evidence that rock fall hazards are high. Although the well-developed soil and vegetation on some indicate that they fell long ago, there is abundant evidence that they continue to come down today.

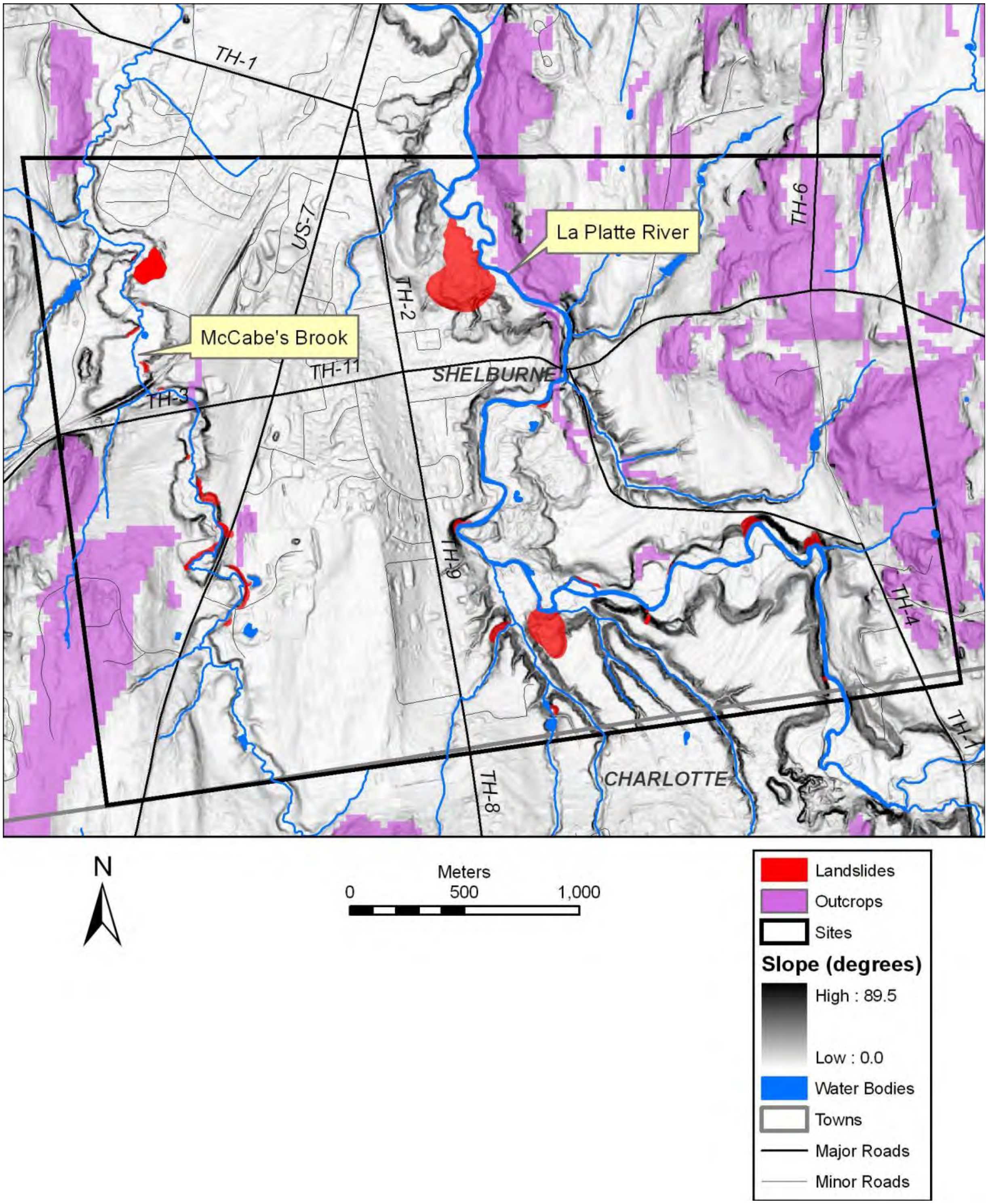


Figure 9. La Platte River Site Area Location Map.

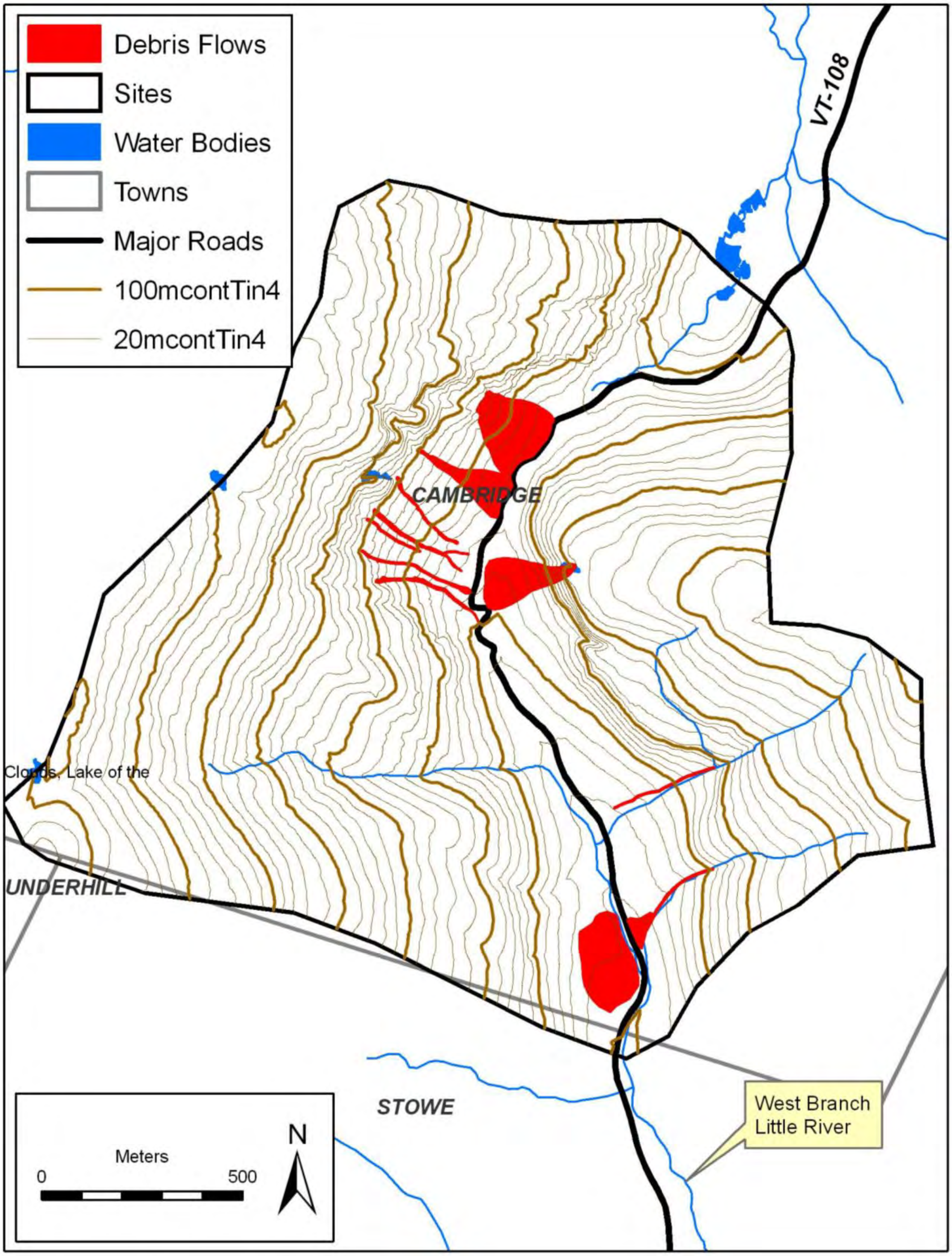


Figure 10. Smugglers Notch Site Area Location Map.

The level of debris flow activity appears to be accentuated on the west side of the Notch due to the increased height of the mountain slopes and the concave topography on that side, a combination that results in enlarged catchments for the rock chutes. By contrast, the east side of the Notch is lower and much of the east side has a convex topography, resulting in smaller catchments. Note, however, that the largest recorded debris flow event occurred on the eastern side at the southernmost debris flow near the Stowe-Cambridge town line. This is not surprising as this feature has one of the larger catchments in the site area.

The Smugglers Notch site area serves to illustrate the landslides of the debris flow type that can be expected in some of the high-elevation parts of Vermont. The landslides shown in Figure 8 were mapped using techniques similar to those in Phases 1 and 4 of the protocol. The mapping techniques are described in detail in Springston (2009). If lidar data was available, procedures similar to those in Phases 2 and 3 could be implemented. It is likely that identification of debris flows in high-elevation areas using the terrain analysis techniques can be successful, although the parameters may need to be modified. For example, it is likely that aspect may emerge as a dominant parameter. However, as Phase 2 and 3 analyses were not undertaken in the Smuggler Notch area due to the lack of lidar data, this site will not be discussed in the subsequent sections.

The level of detail available with modern lidar data suggests that at the very least these features can be identified efficiently by viewing slope or contour data derived from lidar. Combined with a modest amount of field work, this could be an effective way of identifying debris flows and related features in the mountainous parts of the state.

C. Literature review to choose model for analysis

A literature search was undertaken to identify landslide susceptibility models which could be applied in Vermont. Turner and Schuster (1996) provide a general overview of the different modeling types. A synopsis of these models is presented below.

Heuristic Models: These types of models are primarily qualitative and rely on weighting factors based on expert opinions (Sarkar and Kanungo, 2004). According to Yilmaz (2009), the main drawbacks with these methods are the following:

- Knowledge of the area of interest is essential to make accurate judgments on weights.
- Weighting is subjective.
- Results are often not reproducible, because experts' opinions may vary.

Deterministic Modeling: These methods involve computer modeling of geotechnical conditions at specific sites to calculate the factor of safety for a specific slope (Haneberg, 2000). Programs of this type include SINMAP, LISA, and STABL. These methods work best at specific sites where geotechnical data have been collected for that site. Based on statements by Yilmaz (2009), the main drawbacks for using this method on a project like the landslide protocol project are the following:

- Geotechnical data from one site may not be applicable at another site. Generic data from standard tables and charts can be used, but would not be accurate for all sites and would likely lead to erroneous conclusions.
- Because the necessary geotechnical data is generally collected via subsurface drilling and lab testing, the costs involved in obtaining accurate data throughout the state would be prohibitive.

Statistical Modeling: A review of probabilistic and multivariate methods of analysis was conducted to determine applicability to this project. (Haneberg, 2000; Lee and Pradhan, 2007; Yilmaz, 2009) The process of statistical modeling includes the following steps:

1. Landslides are mapped and data about the characteristics of each landslide in the area of interest are collected.
2. Parameters are selected from the data collected which characterize the landslides. Each parameter is divided into appropriate classes for that parameter (i.e. the slope angle parameter could be divided into 6 classes: 0 to 10^o, 10 to 20^o, 20 to 30^o, 30 to 40^o, 40 to 50^o, and $>50^o$).
3. Statistical methods are used to calculate weights for each of these parameters. In general, these methods relate the dependent variable (presence or absence of LS) and the independent variables (different parameters).
4. The weighted parameter maps are then combined to produce a map which shows the susceptibility to landslides. The map shows areas of known landslides as well as areas with similar conditions, in which landslides have not yet been identified.

According to Yilmaz (2009), the main drawback for using this method is the amount of data needed to obtain reliable results. As with most projects, more data yields better results.

Other techniques: Some other techniques, such as fuzzy-logic and artificial neural networks were considered. Yilmaz (2009) compared the artificial neural network, frequency ratio, and logistic regression methods and found them to be similarly accurate with artificial neural networks the best, but stated that the frequency ratio method was useful because it was easier to use.

Conclusions - Based on the above information, statistical models were determined to be the best to analyze the data in this project. Two types of statistical models, logistic regression and frequency ratio, were investigated further for use in this project. Following numerous trials of both modeling methods, it was concluded that for a general protocol, the frequency ratio method is more understandable and easier to use than the logistic regression model and will be used in this project. Frequency ratio modeling is discussed in detail in Dhakal et al., 1999; Jadda et al., 2009; Lee, Choi, and Min, 2004; and Yilmaz, 2009.

The products of this modeling are maps showing high, moderate, low and very low susceptibility to landslide hazard. Polygons showing areas sensitive to landslides are then delineated heuristically using this information and other sources of information. This process will be described more in Phase 2, Task G of this report.

D. Select parameters

Parameters were selected based on those used in previous work, knowledge of the site areas in this project, and available data. Some of the references used include Dhakal et al., 1999; Ercanoglu and Gokceoglu, 2004; Lee, Choi, and Min, 2004; and Yilmaz, 2009. Many parameters were tried, but not all were useful for this project. A description of all parameters considered is discussed below.

Above/Below Marine Limit of Champlain Sea – The approximate shoreline elevation for the highest level of the late-glacial Champlain Sea was derived from the work of Rayburn (2004). This shoreline, which is tilted up and to the north at approximately 0.7 m/km, was projected onto the recent 10 meter DEM from USGS and a polygon layer was produced, which is available through the VGS (Springston, 2012).

This layer was used more as a guide in the protocol than a parameter. Areas below the marine limit in the Saint Lawrence Valley of Canada that are underlain by soft marine clay deposits have been subject to devastating landslides. Once the material is disturbed at the onset of a landslide event, the soil loses most of its shear strength and the landslide can expand rapidly, resulting in large, low-angle rotational slumps that can affect many acres of land. Although these true soft marine clay deposits do not appear to occur in Vermont, large low-angle rotational slumps have been identified in the Shelburne area and may be related.

Areas above the marine limit are not likely to experience these types of failures. Because a site area is either above or below the limit, this is not a very discriminating parameter, but if a site of interest is below the limit, it indicates that the researcher should consider the possibility of these large-area low angle slumps in the site of interest.

Aspect – Researchers have used aspect as a parameter for mapping landslide susceptibility in Nepal (Dhakal et al., 1999), Korea (Lee et al., 2004), Malaysia (Lee and Pradhan, 2007) and Turkey (Yilmaz, 2009). Ohlmacher and Davis (2003) also included aspect in their landslide susceptibility study in northeastern Kansas, but determined no statistically significant relationship between aspect and landslide occurrence.

The results of frequency ratio modeling in this project showed aspect to be of lesser importance than other parameters, except at the Joiner Brook site area. Joiner Brook flows south and most of the landslides occurred on the east-facing slope. Aspect was a dominant parameter and was useful in explaining many of these landslides. However, areas in the Joiner Brook tributaries, which did not trend north-south were not adequately modeled using this parameter. One such area was the tributary flowing into Joiner Brook from the east in the east central part of the site area. Modeling using aspect as a primary parameter showed moderate hazard on the south slope, but field checking in this area indicated stable to low hazard slopes. The conclusions using aspect in Joiner Brook indicate that it is not likely to be a good parameter for landslide work in Vermont.

Distance to Stream – Landslides occur most frequently along waterways, therefore the distance of a slope to the nearest waterway was thought to be an important parameter.

Results showed that in general, distance to stream was not a very important parameter. The only exception to this was at the Clay Point site area, where all landslides occurred on the slopes bordering Lake Champlain. At this site area, the proximity to the shoreline (called "distance to stream" for consistency with the other study sites) was calculated from the lake and from the Lamoille River to the north. Wave and wind erosion from the lake are the dominant triggers for slides at this site area, so it follows that distance to 'stream' would be an important parameter here.

Elevation – Review of the literature suggested that elevation might be an important parameter in landslide susceptibility (Ayalew and Yamagishi, 2005; Dhakal et al., 1999; Duman et al., 2006; Gorsevski et al., 2006; Lawther, 2008). However, it was found that the elevation changes in Vermont are not great enough to affect landslide susceptibility.

Hydrologic Group (Soil Drainage) – Soils that have similar runoff properties, such as rates of infiltration and runoff, are combined into 'hydrologic groups' by the NRCS. Qualities that affect this are depth to high water table, saturated hydraulic conductivity, and depth to a very low permeability layer. (NRCS, 2003, National Soil Survey Handbook, p. 618-24) Four groups, A, B, C, and D, are delineated and described below.

A: Low Runoff Potential - These soils consist primarily of deep well drained sands or gravels which have a high rate of infiltration, and therefore low runoff.
B – These soils are primarily moderately deep and moderately well drained with a moderate rate of water transmission. Soils in this category are generally medium to coarse grained.
C – These soils drain slowly and have a low rate of infiltration. Soils in this category are generally fine grained.
D: High Runoff Potential – These soils consist of clay or soils with a permanent high water table. Infiltration is very slow and runoff very high.

Results showed that hydrologic group was not as influential as other parameters at the site areas in this project.

Profile Curvature – Profile curvature is a measure of the curvature of the slope in the vertical plane, either convex, concave, or neither. The numerical quantity given by terrain analysis is actually the second derivative of the slope. According to ESRI, profile curvature units are one hundredth (1/100) of a z-unit. Z-unit is a unit of elevation, so because the lidar DEM is in meters, profile curvature units are in 1/100 of a meter. For a hilly area, the values would be expected to vary from -0.5 to 0.5; whereas a steep, rugged mountainous area, the values would be expected to vary from -4 and 4.

Because profile curvature shows best at the top and bottom of a slope, and not within the landslide area, this parameter was used during the final step of the protocol to verify the frequency ratio results and delineate areas of sensitivity.

Roughness – The roughness parameter is the standard deviation of the slope angle. It is a measure of how variable the topography is over short distances. Smooth, even slopes have low roughness values and jagged surfaces have high values. The standard deviation is calculated for each pixel location by finding the standard deviation of the slope for all pixels within a 3 x 3 pixel block centered on the pixel. The units for both slope and roughness are degrees.

It should be noted that this parameter could lead to confusion with bedrock outcrops, which would also exhibit a 'rough' surface. Therefore, having some kind of outcrop map during the verification of frequency ratio results is important.

Slope Angle – Slope angle was found to be the most important parameter at most of the site areas. Translational slides commonly occur on high angle slopes (slopes greater than 30^{o}), so it follows that since the majority of slides were translational, slope angle would be important.

Slope Height (Elevation above Channel) – 'Elevation above channel' was used as a proxy for slope height. Results from the modeling indicated that it was not an important parameter at any of the site areas. Whether this is because it was not a good proxy for slope height or because slope height is not a good parameter is not clear.

It was decided that slope height would be considered in the final step of the protocol to verify the frequency ratio results. This would not be done using the 'Elevation above channel' proxy, but was visually factored in with slope angle and profile curvature to confirm areas of moderate and high susceptibility to slope failure.

Soil Type – NRCS digital soil data was extensively explored to see if it could serve as a useful terrain parameter by itself or as a proxy for surficial geology. Part of the problem with using soils to identify areas susceptible to landsliding is that landslides can occur in any soil type.

Soil type, which is a characteristic of soil series, was tried as a parameter for this project. Soil series is identified by the name of soil type (based on grain size or texture, organic matter content, color, structure, chemistry, etc.) and a slope angle delineation. An example of this is AdA, which indicates Adams and Windsor loamy sands on 0 to 5% slopes. For this project, soil 'type' was investigated as a parameter, which is the soil series name without the slope angle designation. Although the slope designation of soil type has been used as an identifier of unstable slopes in the past, the availability of DEM-derived topographic data renders this particular parameter obsolete for landslide identification.

This parameter was most important in the modeling of the large low angle rotational slumps at the La Platte River site area. Overall, the modeling for these types of slides was unsuccessful (that is, mapped large low angle rotational slumps were not in high or moderate susceptibility areas on the maps produced by the frequency ratio modeling). However, the fact that soil type was so important may point out that surficial geology may also be important and should be considered as a possible parameter for this type of slide. Unfortunately, most of the surficial geologic mapping at the La Platte River site area was done for the state map published in 1970 at a scale of 1:62,500 and is inadequate for this type of analysis.

Stream Power Index (SPI) – Stream Power Index is a measure of the erosive power of the water flowing through an area or stream. This parameter depends on the area upstream of the point of interest and slope angle and thus indicates areas of erosion. It is calculated by (Wilson and Gallant, 2000):

$$SPI = a \tan \beta$$

Where a= specific area = local upslope area draining through a certain length of contour
$\tan \beta$ = the local slope

Stream Power Index seemed to be too insensitive to conditions on the slopes and thus it did not have predictive value for finding landslides.

Surficial Geology – An understanding of the surficial geology is certainly critical in understanding slope stability. However, it is not a matter of finding some subset of the surficial geologic units that is subject to landslides. To the contrary, our experience in this and other study areas has clearly demonstrated that landslides occur in all types of surficial geologic materials.

There are two reasons why surficial geology was not included in the terrain analysis phases (Phases 2 and 3 of the protocol). One reason is that there was not enough detailed mapping available for all of the study blocks. Another is that the blocks where surficial geologic information had very little variability in surficial units and thus would not provide good tests (larger study areas would probably help with this issue).

Although we do not use surficial geology in Phases 2 and 3 of the protocol, we do use it in Phase 4, which is the delineation of sensitive areas. In this phase, the surficial geology serves as a critical data layer which is used to help extrapolate out from the areas identified in the terrain analysis phase.

Topographic Wetness Index (TWI) – Topographic Wetness Index is a measure of the water draining into an area or 'steady-state wetness'. It depends on the slope angle and drainage area uphill of the point of interest. The rationale for using topographic wetness index to identify areas susceptible to slope instability is that parts of the landscape that have consistently high pore-water pressure in the soil may be more subject to slope failure. It is calculated by (Wilson and Gallant, 2000):

$$TWI = \ln (a/\tan \beta)$$

Where a= specific area = local upslope area draining through a certain length of contour
$\tan \beta$ = the local slope

For a given slope angle, topographic wetness index increases as the contributing area increases. Higher values represent valleys and depressions and lower values represent upper hill slopes, crests, and ridges (Wilson and Gallant, 2000).

This parameter was somewhat influential at many of the site areas, but was the second most important in the modeling of the large low angle rotational slumps at the La Platte River site area. Although the modeling for these types of slides was unsuccessful (that is, mapped large low-angle rotational slumps were not in high or moderate susceptibility areas on the maps produced by the frequency ratio modeling), it is interesting that TWI was important for low-angle rotational slumps, but not for translational slides. This fact verifies that drainage at low-angle sites is influential in landslide susceptibility.

Vegetation/ Land Use (NDVI) – NDVI stands for Normalized Difference Vegetation Index. This GIS layer was developed from NAIP data by the Vermont Agency of Natural Resources, Information Technology Division and was intended to help distinguish areas of bare soil and pavement from vegetation

For this project, discrimination of vegetated landslides from non-landslide areas was not viable, so this parameter was not used. With further study, it may be possible to identify the bare soil of large non-vegetated landslides, but that remains to be seen.

For use in the Frequency Ratio model, the parameters were divided into increments or 'classes'. An example of this is slope, which was divided into 10^o increments. Table 3 is a list of the parameters considered for this project, their classes, and whether they were used in the final analysis.

Table 3 - Landslide-Related Parameters

Primary Parameters	Classes	Brief Description	Source	Result
Above / Below Marine Limit of Champlain Sea		Limit is approximately 107 m, but varies with latitude; Parameter only applicable in Champlain lowland	Champlain Sea Limit layer*	Used in Phase 2-G
Aspect (degrees)	1-45 181-225 46-90 226-270 91-135 271-315 136-180 315-360	Compass direction of slope in degrees	DEM- Lidar 3.2m	Not used as parameter in final analysis; see Phase 2-D
Distance to nearest stream (meters)	0-30 180-210 31-60 210-240 61-90 240-270 90-120 270-300 120-150 300-500 150-180 500-700	Different width buffers around 1:5000 surface waters in meters	DEM- Lidar 3.2m	Used in final analysis
Elevation		Elevation of point in DEM	DEM- Lidar 3.2m	Not used as parameter in final analysis; see Phase 2-D
Hydrologic Group (Soil Drainage)	A B C D	Runoff potential which depends on infiltration and transmission rates of the soil; Group A is coarse-grained (sand and gravel) with a high infiltration and transmission rate and therefore a low runoff rate; Group D is fine-grained (clay) or poorly sorted (till) with a low infiltration and transmission rate and therefore a high runoff rate.	NRCS	Used in final analysis
Profile Curvature (1/100 of a meter)	-6723 to -98; -98 to -63 -63 to -6; -6 to +6 +6 to +41 +41 to +76; +76 to +6754	Shape of slope indicating concave, planar slope, or convex. The coding is intended to help distinguish concave upward terrain at the base of slopes from planar slopes and concave downward terrain at the tops of slopes. Bright colors in the high and low ranges and neutral or no colors in the central ranges proved to be most effective.	DEM- Lidar 3.2m	Used in Phase 2-G
Roughness (degrees)	0-2, 2-4, 4-6, 6-8,8-10,10-12,12-24	Roughness is the standard deviation of the slope angle. Units are in degrees.	Slope map derived from DEM- Lidar 3.2m	Used in final analysis
Slope Angle (degrees)	0-10 30-40 10-20 40-50 20-30 50-90	Steepness of slope in degrees	DEM- Lidar 3.2m	Used in final analysis
Soil Type	Depends on what soil types are in the area of interest	Labeled as 'musym' on NRCS GIS layer, but does not include slope angle reference; indicates only Soil Series (see Phase 2-D)	NRCS	Used in final analysis
Stream Power Index		Measure of the erosive power of the water flowing through an area or stream	DEM- Lidar 3.2m	Not used as parameter in final analysis; see Phase 2-D
Surficial Geology		From detailed surficial mapping where available; units should delineate origin as well as grain size and texture (examples: lacustrine/marine fine-grained deposits, ice-contact deposits, till, alluvial fan, etc.)	Geologic mapping - VGS	Used in Phase 2-G
Topographic Wetness Index (TWI) (square meters)	0-3 12-15 3-6 15-18 6-9 18-21 9-12 21-24	Measure of water draining into the area; function of the local upslope area and the slope gradient; units in square meters; see Phase 2-D	DEM- Lidar 3.2m	Used in final analysis
Vegetation / Land Use		NDVI – Normalized difference vegetation index	ANR-GIS	Not used in final analysis; see Phase 2-D

* Springston, George, 2012, Champlain Sea Limit in Vermont GIS layer, available from Vermont Geological Survey

E. Run models

Frequency ratio analysis is a ratio of the area of landslides in the different parameter classes to the area of the parameter classes in the site area of interest. Area in GIS can be described in pixels. In order to do frequency ratio analysis for this project, a spreadsheet was created for each site area. The columns, labeled here as *a* through *j*, contain the following information:

a. Parameter
b. Class number – artificial number; starts at 1, goes to however many classes there are for that parameter
c. Classes – Each parameter is divided into classes. An example of this is the slope angle parameter, which is divided into 0-10°, 10-20°, 20-30°, 30-40°, 40-50°, and 50-90° or hydrologic group parameter, which is divided into A, B, C, and D. The classes should represent the distribution of data for the whole site.
d. Area of Landslides - number of pixels in class within landslide areas
e. Total number of landslide pixels within site area
f. % of class pixels within landslide areas = number of pixels in class within landslide areas / total number of landslide pixels within site area (column *d* / column *e*)
g. Number of pixels in class within site area
h. Total number of pixels in site area
i. % of class pixels in site area = number of pixels in class within site area / total number of pixels in site area (column *g* / column *h*)
j. Frequency Ratio = % of class pixels within landslide areas *1000 / % of class pixels in site areas (column *f* *1000 / column *i*)
(*Note that raster values in GIS raster must be whole numbers, so the frequency ratio values have been multiplied by 1000. Because all of the frequency ratio values are treated similarly, it does not affect the outcome of the analysis.)*

Data are entered into each column from the GIS layers. Frequency ratios are then calculated in the spreadsheet. These values show the quantitative importance of each parameter class with respect to landslides at that site area.

Below is an example of the spreadsheet for the hydrologic group parameter. Not shown here is column *a*, which is the parameter, in this case hydrologic group.

b	***c***	***d***	***e***	***f***	***g***	***h***	***i***	***j***
Class Number	**Classes**	**# of pixels in class within landslide areas**	**Total # of landslide pixels within site area**	**% of class pixels within landslide areas**	**Number of pixels in class within site area**	**Total # pixels in site area**	**% of class pixels in site area**	**Frequency Ratio**
1	A	284	298	95.3	255199	456541	55.9	***1705***
2	B	14	298	4.7	47844	456541	10.5	***448***
3	C	0	298	0	24553	456541	5.4	***0***
4	D	0	298	0	128945	456541	28.2	***0***
	Total	298		Total	456541			

The amount of influence of each parameter on landslide susceptibility is given by the highest frequency ratio values for that parameter at each site area. Table 4 shows the maximum frequency ratio numbers for each parameter at each site area. For example, at the Indian Brook site area, the most important parameters are slope angle and roughness, as shown by the high frequency ratio values in Table 4.

Table 4 – Highest Frequency Ratio Values for Each Parameter at Each Site

Parameter	Alder Brook	Bartlett Brook	Clay Point	Indian Brook	Joiner Brook	Shelburne - all slides	Shelburne - translational	Shelburne - rotational
Aspect	1379	5785	nc	3164	6704	nc	3465	2462
Distance to Stream	6057	5908	10398	5885	3212	1769	5448	1836
Hydrologic Group	1746	2880	7102	1705	2309	2960	1216	3159
Roughness	8844	142795	9548	85076	4215	10349	34484	3045
Slope Angle	34340	133275	32180	169488	6558	8859	32050	1691
Soil Type - Musym without slope angle designation	8942	nc	nc	1806	nc	5246	21278	4088
Topographic Wetness Index	7661	10688	5781	5648	3384	4721	7292	3890

nc – not calculated

Susceptibility maps are produced by combining the parameters with the highest frequency ratio values for each site area. Calculated frequency ratios for each class of the most important parameters are input into a GIS layer. For example, for Indian Brook, two frequency ratio maps (slope angle and roughness) are produced. On one map (slope angle), the parameter classes (0-10^{o}, 10 -20^{o}, 20-30^{o}, 30-40^{o}, 40-50^{o}, 50-90^{o}) are reclassified to show the calculated frequency ratio values. On the other map (roughness), the parameter classes are also reclassified to show the calculated frequency ratio values. Combining these two maps (or adding them together in GIS terms) produces a landslide susceptibility map.

In the case of Indian Brook, adding the frequency ratio values of other parameters to this combined map would not change the susceptibility much because frequency ratio values for slope angle and roughness are at least one to two orders of magnitude higher than other parameters. In the case of Alder Brook, slope angle is the most important parameter, but the second most important parameter is not as clear-cut. Soil type and roughness are the second most important parameters and are quite close in value. For this site area, several maps should be constructed, such as a slope angle-soil type combination, slope angle-roughness combination, or a combination of all three parameters. The map that best shows the mapped landslides as susceptible should be used.

F. Field Calibration

The results of the terrain modeling were checked by conducting field visits to verify the presence of unstable slopes. Over 80 field locations were visited within the six site areas in Chittenden County. An attempt was made to visit site areas delineated as stable on the susceptibility maps as well as to verify site areas shown as high hazard on the susceptibility maps.

G. Delineation of Sensitive Areas

Areas sensitive to slope instability and landsliding were delineated at a scale of approximately 1:3000 to produce hazard potential maps. The sensitive areas include areas of active and inactive landslides, relict landslides that can foreseeably be reactivated, areas susceptible to future landslides, active and inactive gullies, and areas susceptible to future gullying. The details of this procedure are contained in the attached protocol.

Artificial cut and fill slopes were excluded from the delineations. It is outside the scope of this work to evaluate stability in artificial materials and on engineered slopes. Areas underlain by exposed or shallow bedrock were excluded. The terrain analysis methods used here should not be used to distinguish stable and unstable bedrock slopes. That would require more detailed, field-based analysis.

H. Write Protocol

A protocol was written to delineate landslide susceptibility throughout the state, based on the work done to delineate susceptibility at the six site areas in this project. Each step of the delineation process is discussed in detail in the protocol. The protocol is included in a later section of this report.

I. Meet with CCRPC to Develop the Most Useful Product

As a partner on this project, CCRPC reviewed the protocol and maps. The wording of the protocol was checked and verified to produce the most easily understood document. The maps were reviewed to produce the best product for planning purposes.

J. Finalize Protocol and Compile Final Maps

Changes suggested by CCRPC were incorporated into the protocol and maps were adjusted as appropriate. Final maps for this project show both the results from the frequency ratio analyses and from the delineation of sensitive areas. Moderate and high susceptibility areas from the frequency ratio analyses are grouped and shown in raster form on the maps. The sensitive areas, which include those areas of moderate/high susceptibility as well as the areas which could be affected by mass failures (landslide runouts, etc.), are shown as polygons.

Part 3 – State Hazard Mitigation Plan Update

The Vermont Geological Survey will coordinate with the Vermont Emergency Management Agency to incorporate the protocol into the 2013 State Hazard Mitigation Plan. A Vermont Association of Planning and Development Agencies (VAPDA) meeting was attended in May 2012 to inform them of the protocol and in February 2013, the final draft of the protocol was distributed by CCRPC to VAPDA and to the municipalities with site areas for their review. The protocol will be available for use by regional planning commissions and municipalities to delineate areas susceptible to slope failure.

Results of Analysis

The results of the frequency ratio analysis are discussed below and shown in Figures 11 through 17. The frequency analysis is reported in percent on the figures.

Alder Brook

Results of the frequency ratio modeling shown in Table 4 indicate that slope angle is the most influential parameter at this site area. Also important are soil type, roughness, and topographic wetness index. Different combinations of maps were compiled and examined, including slope angle-soil type, slope angle-roughness, slope angle-roughness-topographic wetness index-distance to stream maps.

Slopes in the western part of the site area exhibited moderate to high potential on the maps and were verified as such in the field. The best map found to show the landslide susceptibility at this site area was the slope-roughness map. This map is shown on Figure 11.

Bartlett Brook

Results of the frequency ratio modeling shown in Table 4 indicate that roughness and slope angle are the most influential parameters for landslide susceptibility. Figure 12 shows the resulting map.

Five landslides were mapped at this site area. Intuitively, it would seem that an active landslide should show a high hazard potential. However, this is not the case in Bartlett Brook. The table below shows some characteristics of these landslides.

Four of the landslides are translational with areas less than 200 sq. m. Only one of these (SBB-04) is rated as having high potential on the frequency ratio map. The other translational landslides (SBB-01, SBB-03, and SBB-05) show very low to low hazard potential.

Landslide ID	Type	Area (sq. m.)	Hazard Potential based on Frequency Ratios
SBB-01	Translational	172	Very low to low
SBB-02	Rotational	610	Very low to low
SBB-03	Translational, inactive	60	Very low to low
SBB-04	Translational	198	Moderate to high
SBB-05	Translational	94	Very low to moderate

The fact that small active translational landslides are shown as having very low to low hazard potential on the frequency ratio maps is a problem for landslide susceptibility mapping. This problem is likely due to the inaccurate location of the landslides because of the following reasons.

- Polygons for small landslides are difficult to draw in the correct location, because the slides are difficult to identify on orthophotos and aerial photographs.

- The accuracy of the GPS instrument used for this project was ± 3 to 4 m. This error is sometimes greater than the size of the small landslide itself, which could also add to incorrect location of the slide.

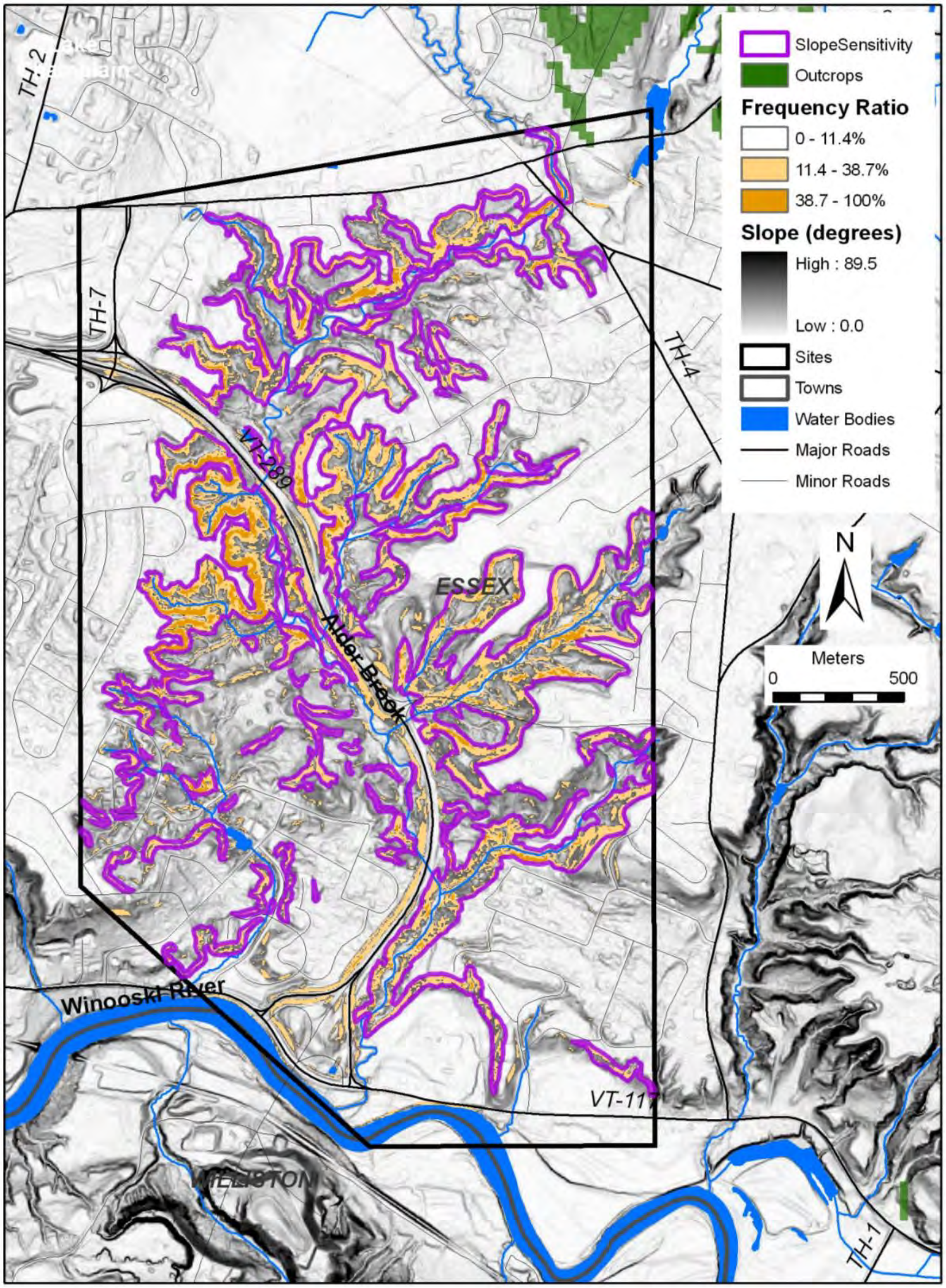


Figure 11. Alder Brook Site Area. Results of Frequency Ratio Analysis in Percent and Areas of Slope Sensitivity.

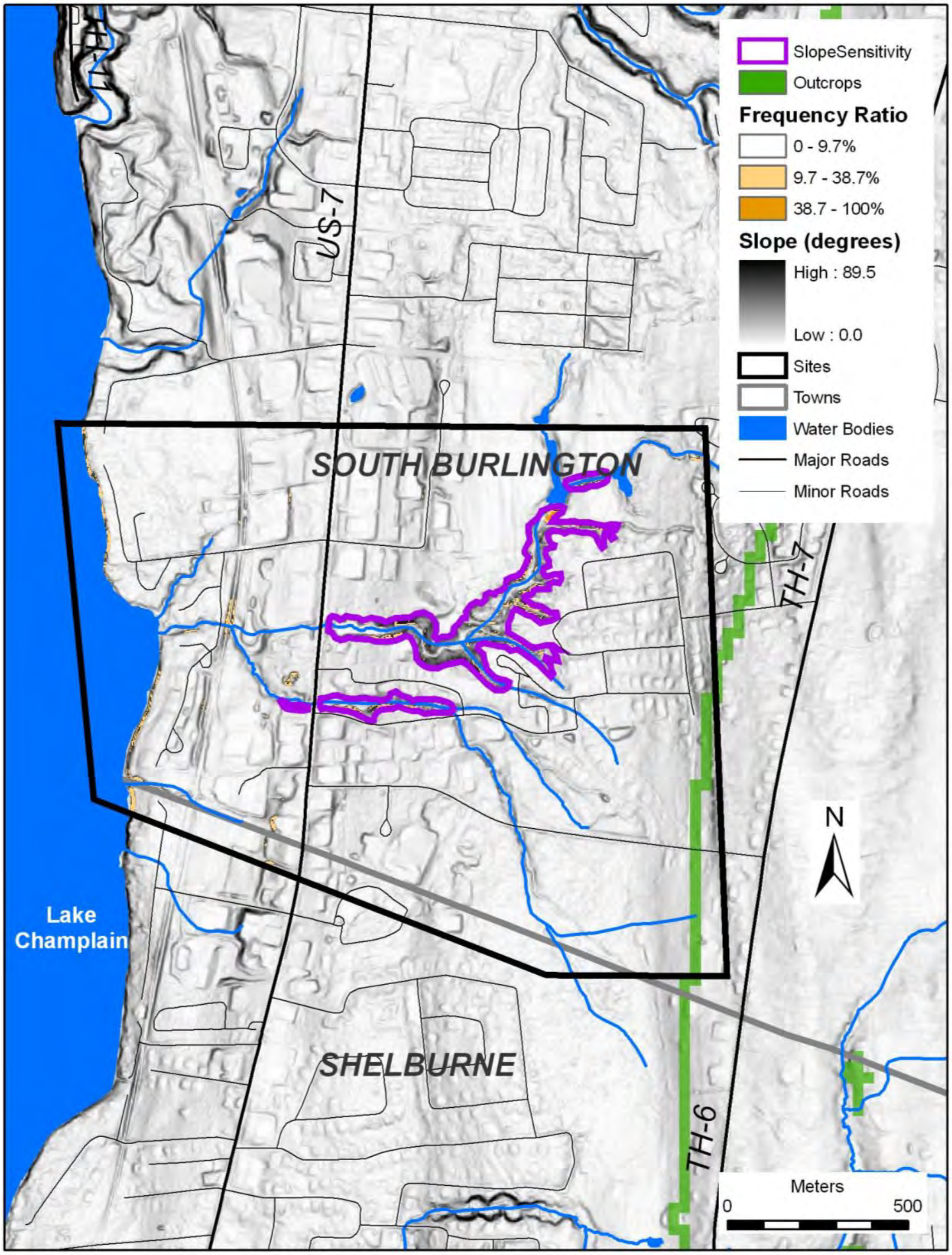


Figure 12. Bartlett Brook Site Area. Results of Frequency Ratio Analysis in Percent and Areas of Slope Sensitivity.

This location inaccuracy will lead to errors when calculating the frequency ratios, because pixels within the incorrectly located landslide polygon will be counted in a different parameter class. If the hazard potential of the site area is based on the frequency ratios calculated using primarily small landslides, this could render the entire hazard potential map inaccurate.

The other landslide in Bartlett Brook (SBB-02) is a larger rotational slump, but it also shows as very low to low hazard potential on the frequency ratio map. The difficulty with rotational slumps is that they are often not distinct from the surrounding landscape, because the area involved has just slipped down and not been uncovered except at the head scarp. This is true especially if they are recent and not large as is the case of SBB-02. In this case, they may not exhibit the classic hummocky topography that could potentially be shown by 'roughness', or the sag ponds that could potentially be shown by 'topographic wetness index'. Even the slope of a rotational slump such as this (20^o), is not distinctive from the surrounding landscape. This may explain why SBB-02 is rated as low hazard on the map.

Clay Point

Results of the frequency ratio modeling shown in Table 4 indicate that slope angle is the most important parameter at this site area, followed by distance to stream/lake and roughness. These parameters were combined to make three maps:

- slope angle-roughness
- slope angle-roughness-distance to stream/lake
- slope angle-distance to stream/lake

The maps were then compared to the landslides identified initially during this project. Existing active landslides should be shown within a moderate to high susceptibility area on the map. The following table shows results of this comparison.

Results of Comparison of Existing Landslides to Frequency Ratio Maps

Landslide Number LS_ID	**Notes**	**Hazard Potential Based on Type of Hazard**	**Hazard Potential Based on Frequency Ratio Map** *File: Slope angle & Roughness*	**Hazard Potential Based on Frequency Ratio Map** *File: Distance to Stream, Slope angle & Roughness*	**Hazard Potential Based on Frequency Ratio Map** *File: Distance to Stream & Slope angle*
CCP-01	Translational slide	High	Moderate to high	Moderate to high	Moderate to high
CCP-02	Translational slide	High	Moderate to high	Moderate to high	Moderate to high
CCP-03	Rotational slump	High	Low to high	Moderate to high	Moderate to high
CCP-04	Translational slide	High	Moderate to high	Moderate to high	Moderate to high

The table shows that the slope angle-roughness map does not show the existing landslides as well as the slope angle-roughness-distance to stream/lake map and the slope angle-distance to stream/lake map. Other considerations at this site area are the terrace slopes. The terrace slopes are not considered moderate or high hazard. They are lower angle (20 to 25^o) and not as high (6 to 10 meters) as the bluff along the lake (35 to 40^o, ~20 meters high). The terraces are shown on the slope angle-roughness map as low to moderate, on the slope angle-roughness-distance to stream/lake map as low, and on the slope angle-distance to stream/lake map as very low to low. Therefore, it was concluded that the best map to show landslide susceptibility at this site area is the slope angle-distance to stream/lake map. This map is shown in Figure 13.

Indian Brook

Results of the frequency ratio modeling shown in Table 4 indicate that the most influential parameters were slope angle and roughness. A map combining these was made and is shown in Figure 14.

Joiner Brook

The frequency ratio modeling shown in Table 4 indicates that aspect, slope angle, and roughness are the most influential parameters in Joiner Brook. Because Joiner Brook flows south across the site area and most of the landslides are on the eastern side of the valley, aspect was a dominant parameter and was able to explain many of the landslides. However, areas in valleys not trending north-south, such as the tributary flowing into Joiner Brook from the east were not adequately modeled using this parameter. Therefore, the best map found to identify most landslides at this site area was a combination of slope angle and roughness. This map is shown in Figure 15.

La Platte River

The La Platte River site area is interesting because it contains both translational and large low-angle rotational slumps. This site area was modeled in three ways:

- Using all the slides identified in the site area
- Using only the translational slides
- Using only the low-angle rotational slumps

This was done because translational and rotational slumps are very different and it was thought that the difference might be important in the frequency ratio analysis. Translational slides occur on higher-angle slopes and generally affect less area than rotational slumps. Twenty-seven translational slides were identified at the site area, whereas only two low-angle rotational slumps were identified. Several relict low-angle rotational slumps were also identified, but were not used in the analysis.

Based on the frequency ratio analysis as shown in Table 4, the most influential parameters for both the translational slides and all combined slides are slope angle and roughness. The maps for this site area are shown as Figures 16 and 17.

The most influential parameters for the low-angle rotational slumps are soil type, topographic wetness, and hydrologic group. The resulting map is perplexing, because although the two known low-angle rotational slumps show an unusual signature, they do not show up as high landslide potential. Because no other large active rotational slumps were identified at this site area, it is difficult to determine the validity of the results of this modeling. It seems that additional work is required to fully understand the influential parameters for these types of slides.

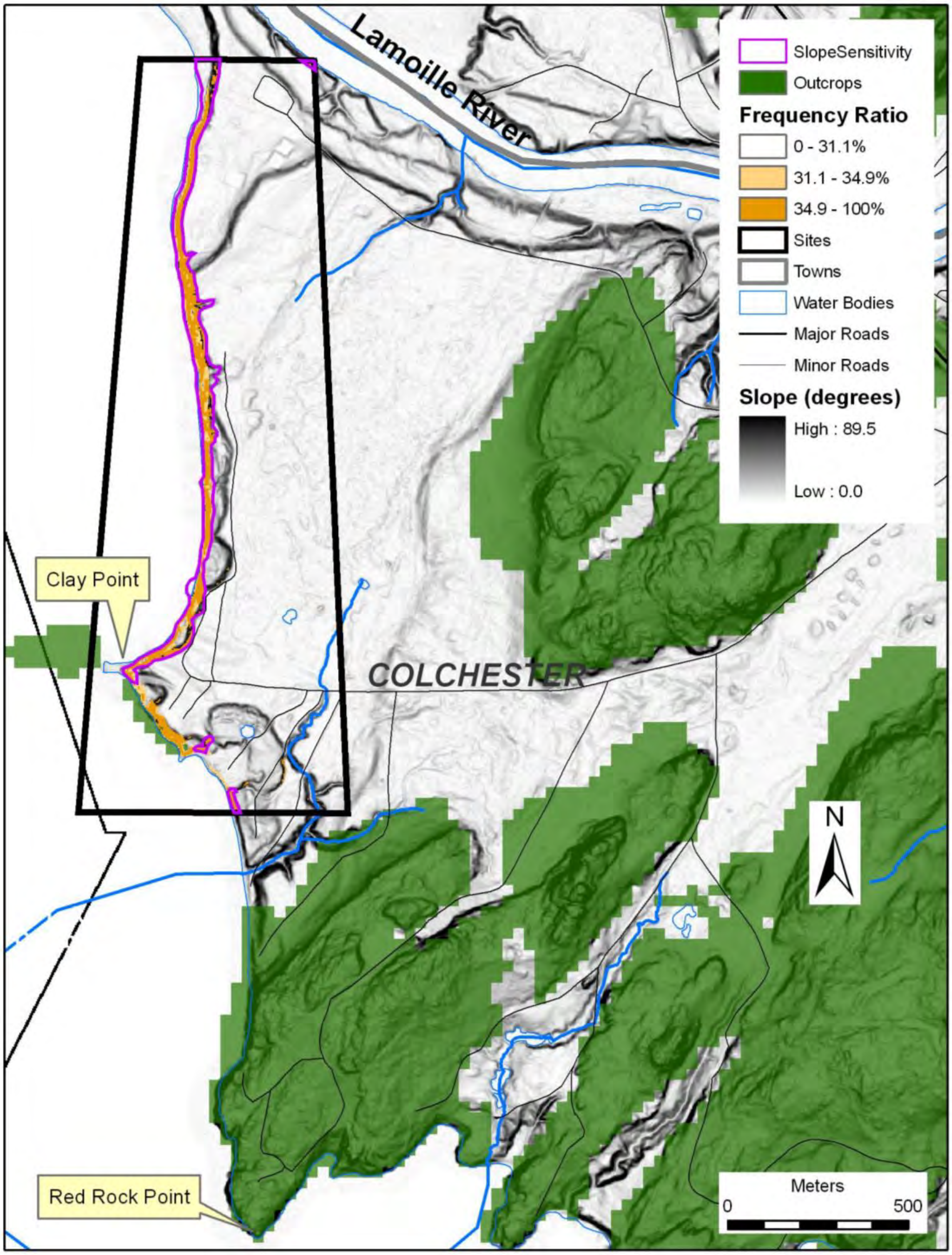


Figure 13. Clay Point Site Area. Results of Frequency Ratio Analysis in Percent and Areas of Slope Sensitivity.

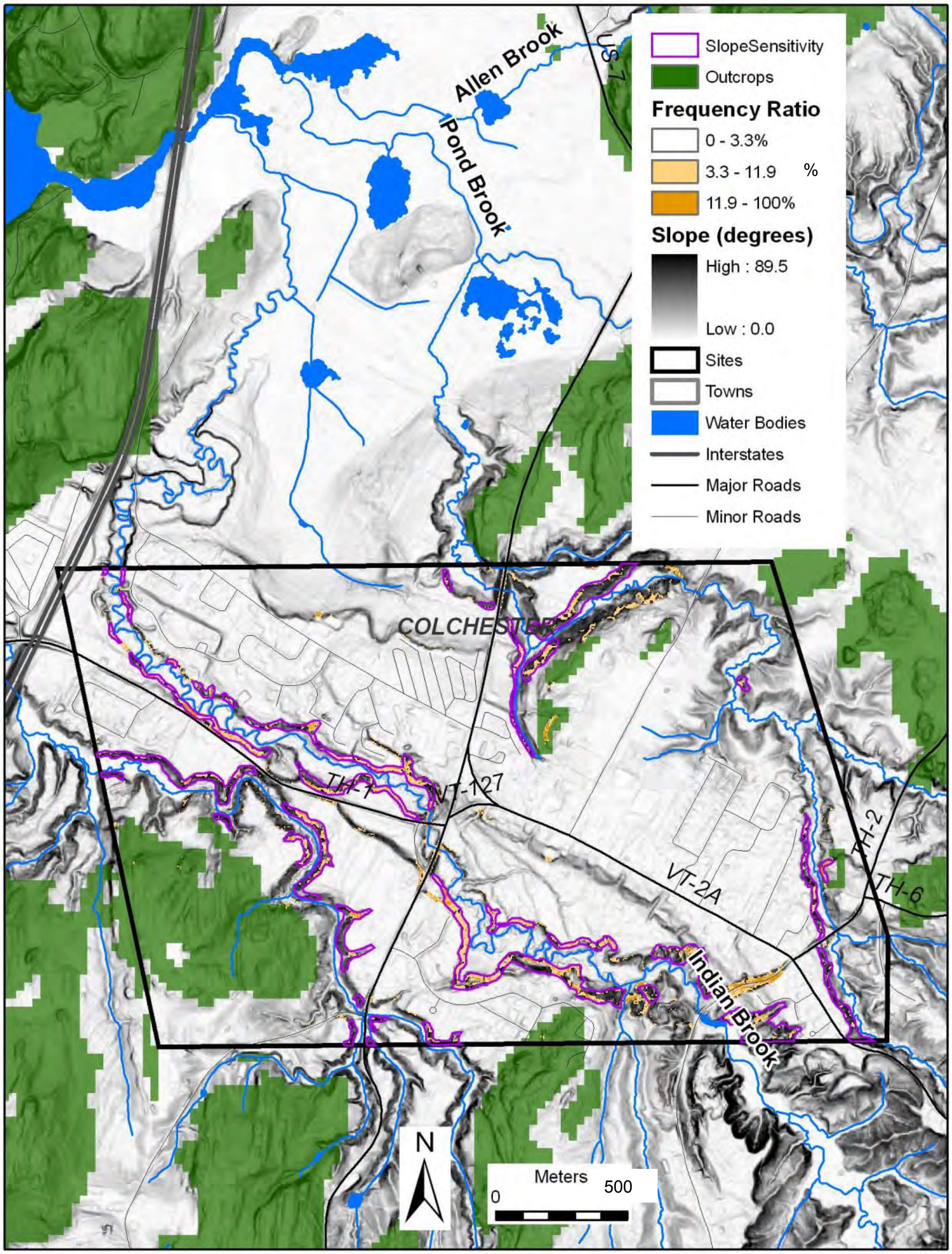


Figure 14. Indian Brook Site Area, Results of Frequency Ratio Analysis in Percent and Areas of Slope Sensitivity.

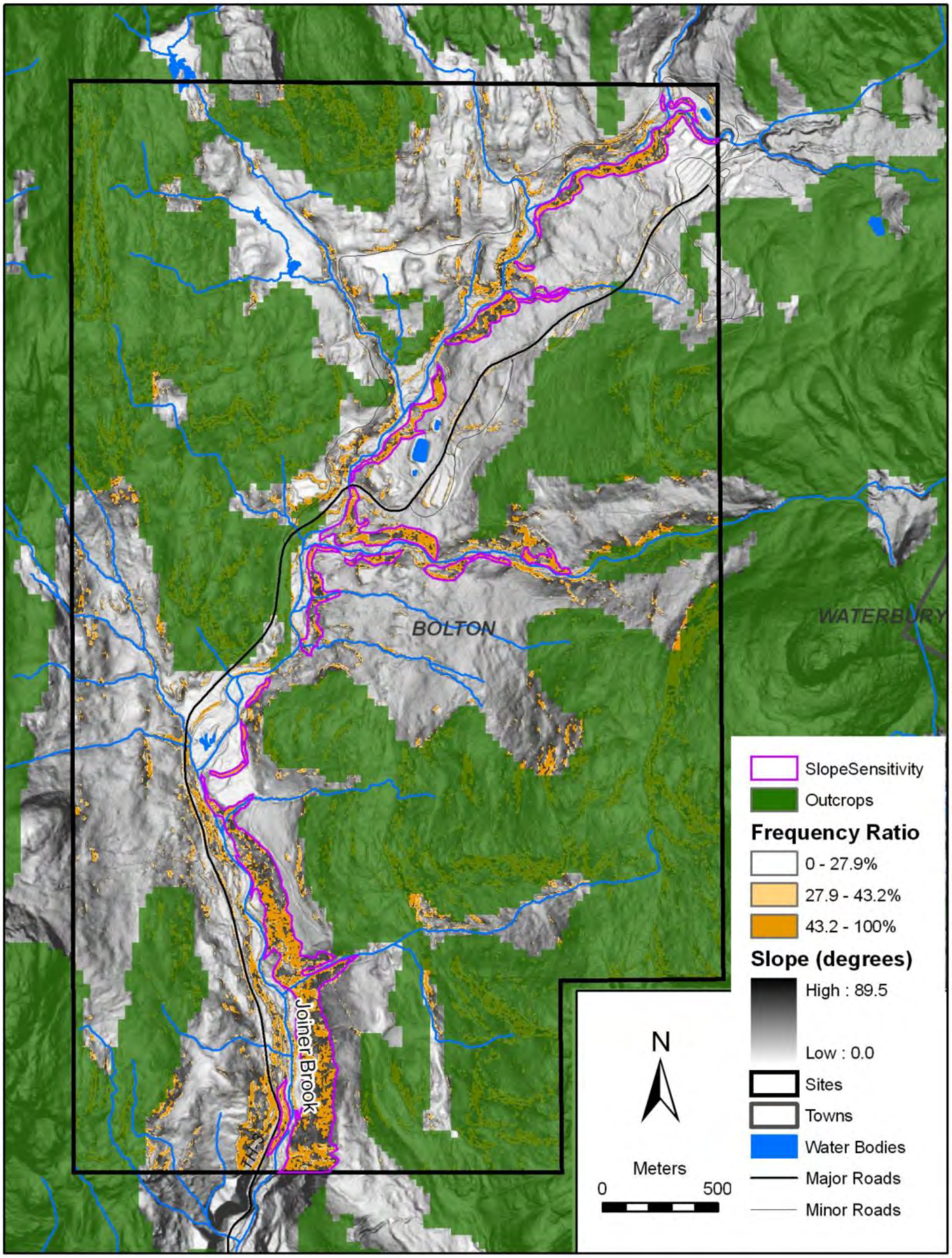


Figure 15. Joiner Brook Site Area. Results of Frequency Ratio Analysis in Percent and Areas of Slope Sensitivity.

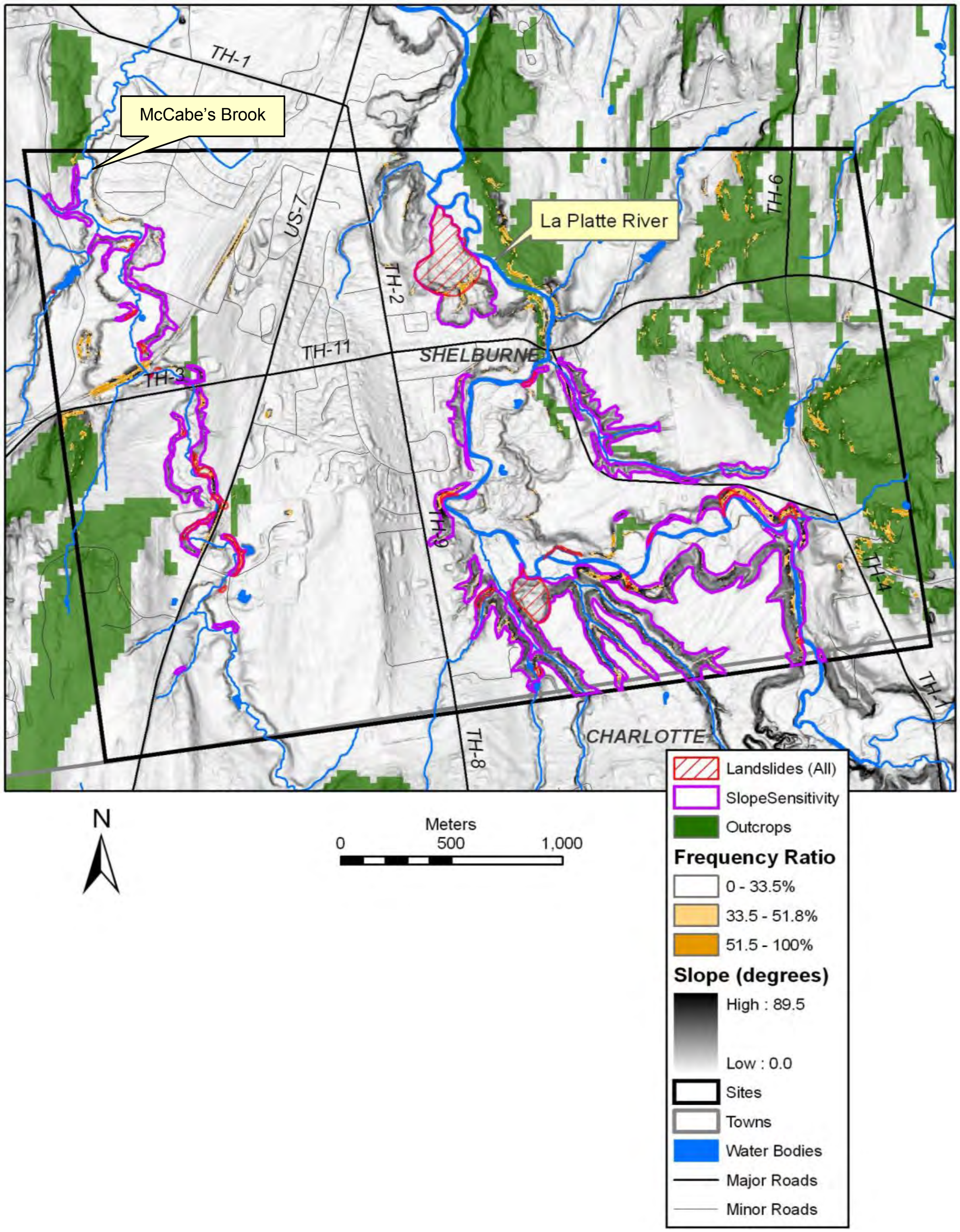


Figure 16. La Platte River Site Area (All Slides). Results of Frequency Ratio Analysis in Percent and Areas of Slope Sensitivity.

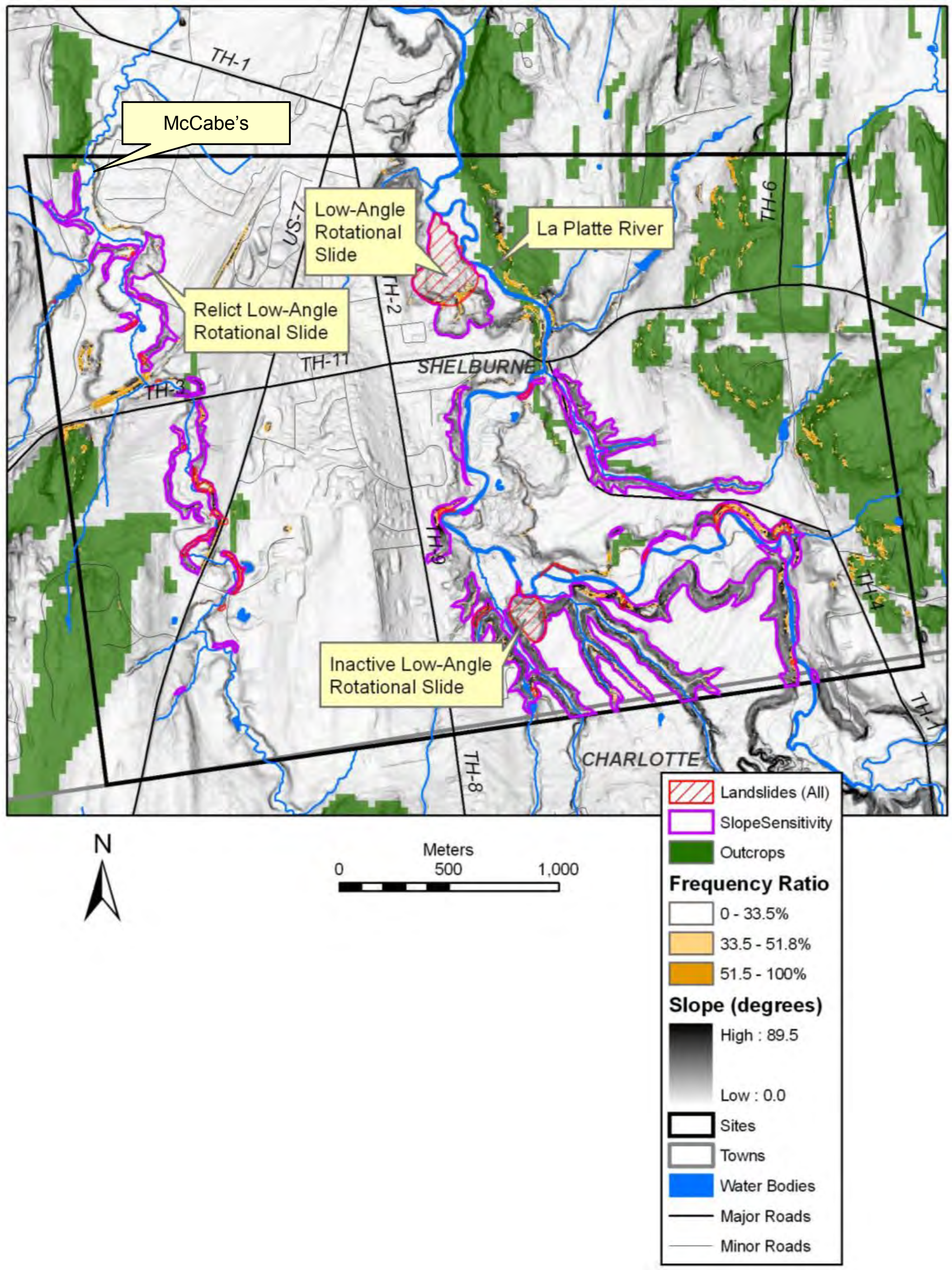


Figure 17. La Platte River Site Area (All Slides with Low-Angle Slides Highlighted). Results of Frequency Ratio Analysis in Percent and Areas of Slope Sensitivity.

Comparison of Lidar 3.2m DEM to USGS 10m DEM for Use in Protocol

Elevations for the entire state of Vermont are available in a 10 meter DEM prepared by the USGS. This DEM was constructed using the elevations on the 1:24,000 topographic quadrangle maps. Recently (within the past 10 years), lidar imagery has become available for parts of the state. This imagery is produced by laser imaging from the air. The resulting DEM is 3.2 meters. Currently parts of Chittenden and Essex counties are covered by lidar.

The protocol for identifying areas sensitive to landslide hazards is intended to be useful throughout the state of Vermont. It was developed using the 3.2m lidar DEM to identify the best process for the protocol. Because lidar is not available throughout the state, the protocol was then tested using the 10m DEM at the Indian Brook site area in Colchester.

In one 10m grid of the 10m USGS DEM, there are about nine 3.2m lidar grids, so the lidar data is more detailed. Therefore it is intuitive that the landslide protocol will be most accurate when the 3.2m lidar DEM is used. Table 5 shows a comparison of the slope angle data derived from the 3.2m lidar and 10m USGS DEMs in the Indian Brook site area. This comparison shows that the maximum reported slope is much lower for the 10m USGS DEM than for the 3.2m lidar DEM. The higher standard deviation in the 3.2m lidar DEM reflects the increased detail and higher variability in the elevation values.

Table 5- Comparison of Slope Angle Statistics of 3.2m Lidar and 10m USGS DEMs in Indian Brook Site Area

Statistics	3.2m Lidar DEM	10m USGS DEM
Number of Pixels	498027	51038
Minimum	0	0
Maximum	52.3	37.8
Mean	6.3	5.5
Standard Deviation	7.5	6.2

Figure 18 shows a comparison of the slope angle data in the part of the Indian Brook site area southeast of the intersection of Route 7 and Main Street. Although the general form is the same, the details are not. Table 6 is a comparison of the slope angle data at selected points on the two DEMS.

Table 6 – Comparison of Slope Angle Points as Derived on the 3.2m and 10m DEMs

Points of Comparison	Comments
A	More of the landslide and different parts of the landslide are shown as high angle in the 3.2m lidar DEM image; the slope angle shown is also higher in the 3.2m lidar DEM image.
B	Field reconnaissance showed the area across the river from the landslide as flat. The 10m USGS DEM image shows the slope angle in this area as 30 to 40^{o}. The lidar shows the slope in this area as 0 to 10^{o}.
C	The general shape of the slopes in the area is somewhat similar, but lower slope angles are shown in the 10m DEM.
D	Maximum slope angles in the two landslides in the southeast corner of the map are shown as 465^{o} on the 3.2m DEM and 22^{o} on the 10m DEM.

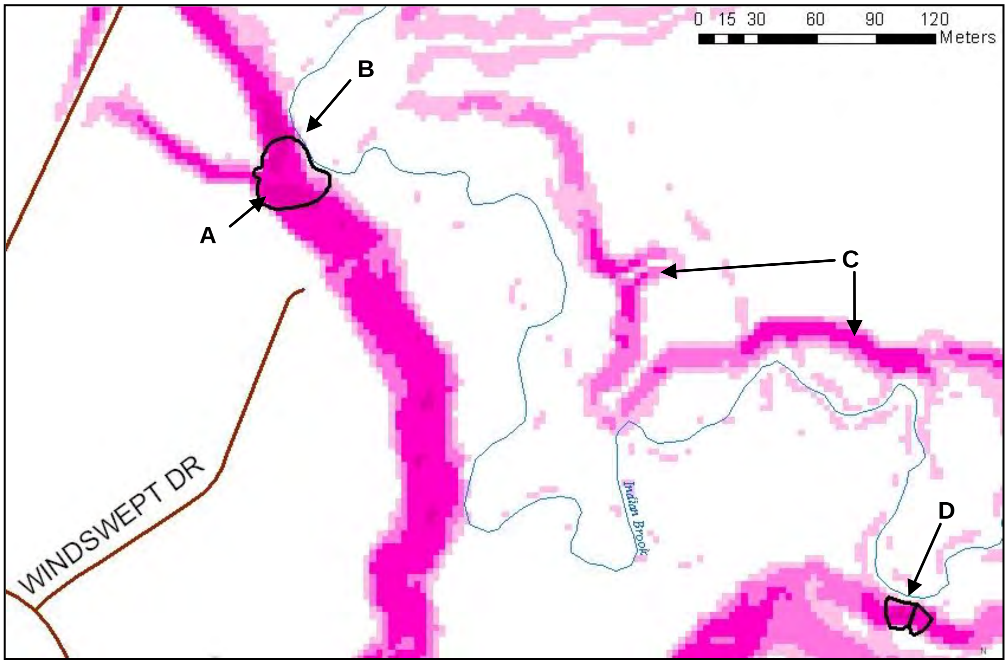
A comparison of the frequency ratio analysis results for the same area is shown in Figure 19. Slope angle and roughness were used to calculate the frequency ratio values for this site. Table 7 is a comparison of the frequency ratio results at selected points on the two DEMs.

Table 7 – Comparison of Frequency Ratio Results on the 3.2m and 10m DEMs

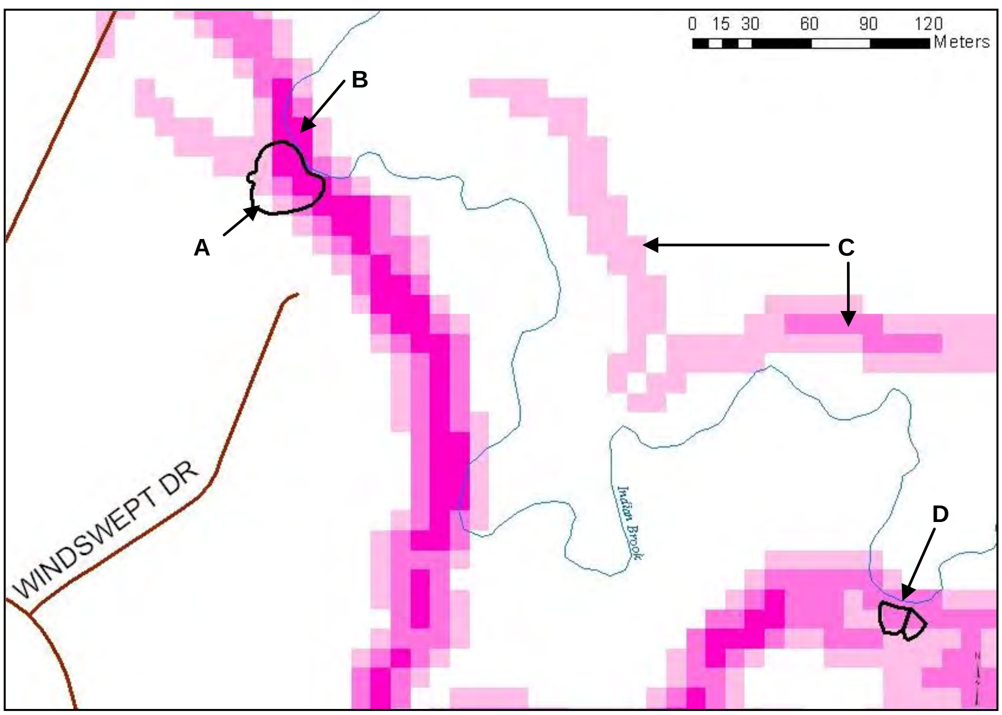
Points of Comparison	Comments
A	Results are comparable.
B	The 10m USGS DEM image shows the area as high hazard potential. The lidar shows the area as low hazard potential.
C	The area to the south of C is shown as moderate potential in both DEMs, but the area to the west of C shows as moderate in the 3.2m DEM and low in the 10m DEM.
D	Results for the 3.2m DEM show high and moderate hazard. Results for the 10m DEM show moderate hazard.
E	The 3.2m DEM shows moderate hazard potential in this area, however this slope is rated as high hazard potential in the 10m DEM.

Based on this analysis the 10m DEM does not seem to be nearly as suitable for terrain analysis as the 3.2 m DEM. The hazard potential of the large slide at point A is well-represented on both maps in Figure 19. However, the hazard potential at point B is shown as low on the 3.2m DEM map and high on the 10m DEM map. Based on field reconnaissance, that area is known to be flat with little hazard potential. The area at point E to the south-southeast of the large slide is also not represented equally on the maps. The 3.2 m DEM shows moderate hazard potential, whereas the 10m DEM shows high hazard.

Our trials indicate that an accurate lidar DEM is probably an essential prerequisite for successful terrain analysis using the frequency ratio method. That does not mean that hazard mapping cannot be undertaken without lidar terrain data. Frequency ratio analysis can be tried, and if field review indicates that it is inadequate, then the areas of high hazard potential can be identified by careful stereoscopic photointerpretation and field work.



a. Slope angle as measured in 3.2m lidar DEM



b. Slope angle as measured in 10m USGS DEM

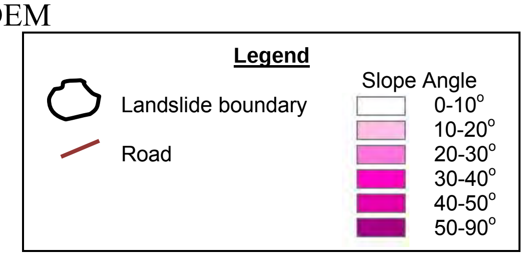
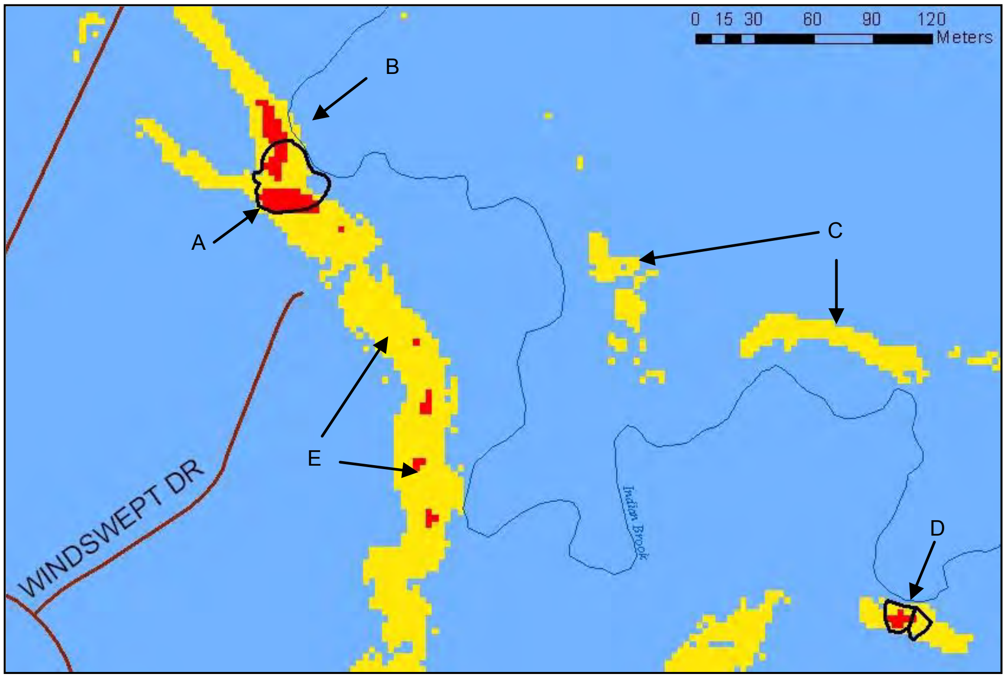
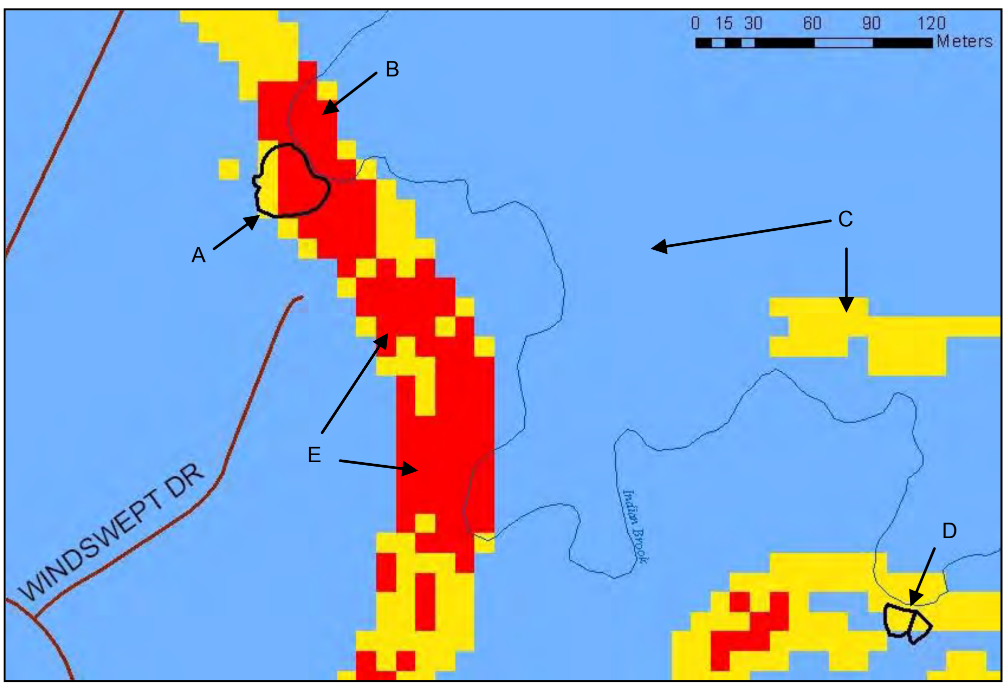


Figure 18. Comparison of Slope Angle derived from 3.2m Lidar DEM and 10m USGS DEM.

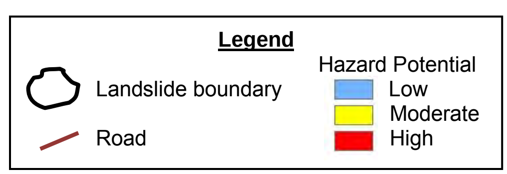


a. Frequency ratio results for slope angle and roughness on 3.2m lidar DEM



b. Frequency ratio results for slope angle and roughness on 10m USGS DEM

Figure 19. Comparison of Frequency Ratio Results for 3.2m Lidar DEM and 10m USGS DEM.



Protocol
for Identification of Areas Sensitive to Landslide Hazards in Vermont

A protocol for identifying potentially unstable slopes has been developed and tested at six site areas in Chittenden County. The analysis on the tested site areas utilized ESRI's ArcGIS Standard with the Spatial Analyst extension. While other GIS software could be used, the protocol outlined below assumes the analysis uses ESRI ArcGIS software. The protocol is divided into five phases:

Phase 1. Selection of a site area of interest; preparation of the project in ArcGIS; initial data collection on existing landslides; photo interpretation of orthophotos and aerial photographs; field reconnaissance of a sampling of landslides; and compilation of the landslides identified from different sources at the site area.

Phase 2. GIS-based terrain analysis using the best-available Digital Elevation Model (DEM) parameters in the protocol include distance to stream, hydrologic group, roughness, slope angle, soil type, and topographic wetness index.

Phase 3. Frequency ratio analysis. Each parameter is divided into classes (e.g. slope angle 0-10^o, 10 -20^o, 20-30^o, 30-40^o, 40-50^o, and 50-90^o). Within the site area, the number of landslide pixels in each class is compared to the total number of pixels in that class and a frequency ratio is calculated. The parameters that show the highest frequency ratios are then added together to produce a preliminary map of potentially unstable areas.

Phase 4. Random areas and questionable areas in the site area are field checked to verify and calibrate the maps. Maps are compared to the surficial geology, bedrock outcrops, topographic contours, and profile curvature to delineate sensitive areas.

Phase 5. Final maps showing potentially unstable areas and areas sensitive to landslide hazard are prepared.

Two GIS programs are considered in this protocol. Most of the analysis is undertaken with ArcGIS with the SpatialAnalyst extension. Familiarity with this program is assumed. Part of the terrain analysis in Phase 2 is undertaken with SAGA. This is free and open source software available at http://www.saga-gis.org/en/index.html. Other GIS programs such as ArcGIS can be used for the terrain calculations such as topographic wetness index, but SAGA has the advantage of having built-in algorithms that simplify the steps needed to run the calculations. Once the data is loaded, it is a one-step process to set the "Basic Terrain Analysis" module running. It is not essential to use SAGA, but we found it to be a useful tool for the terrain analysis.

Note that a large number of GIS files are created in this protocol. Consistent naming conventions should be used throughout. Document file names and processing steps in a spreadsheet as discussed in Phase 2 below.

Phase 1 – This phase involves selection of the site area of interest, creation of the project in ArcGIS, initial data collection, creation of a landslide database for the site area, photo interpretation, field reconnaissance, and resolution of the landslide polygons.

A. Selection of the site area of interest – In the work to develop the protocol, site areas were selected in part of a watershed based on the availability of lidar data and the presence of a variety of geologic and land-use characteristics.

There is no set size for a site area, although the site area should be large enough to include a good representation of the landslides there. The area should be at least 25 to 50 sq. km. This would probably yield enough landslides for a robust analysis. For best results at smaller site areas, the following criteria should be met: There is an average of at least one landslide per square kilometer in the site area; the average size of the landslides is at least 400 square meters; and at least 30% of the landslides are greater than 400 square meters.

The site areas for the initial protocol development ranged from 1.3 to 12.6 sq. km. Note that the areas were kept small in order to facilitate testing of multiple approaches in a limited amount of time. Areas of at least 25 to 50 sq km. are much more likely to be suitable in practice.

When possible, the study area should include complete subwatersheds. This will facilitate accurate calculation of Topographic Wetness Index (TWI, described in Phase 2 below). If it is not possible to include complete watersheds for the 1st order streams in the study area, a larger block of terrain data should be analyzed for TWI. The outputs for the study area can then be extracted. This will ensure that the correct contributing area is used in the TWI calculation (see Phase 2 below). The complete watersheds of the larger streams in a block are not needed as TWI is more sensitive to the steep slopes of local side valleys than it is to large contributing areas of the floodplain pixels.

B. The ArcGIS Data Frame properties and all data layers should be in Vermont State Plane coordinates (meters), NAD 83. The initial data layers needed to start the project in ArcGIS are listed below in Table 8. Some data layers will be used in the analysis. Others will not be used in the analysis, but will provide overall knowledge of the site area.

Existing geologic data should be reviewed. Surficial geologic maps of the site area should be reviewed to identify known landslides. Bedrock geologic maps may provide locations of areas of bedrock exposures. The GIS data files should be downloaded and incorporated into the GIS project. Check the VGS website for updated information on these and other geologic hazard datasets.

A wide variety of other sources may contain information regarding landslides. Local libraries and historical societies be helpful. The University of Vermont Special Collections and the Vermont Historical Society library contain extensive collections of newspapers, maps, and other documents that may contain information on past landslides.

Historic views of landslides in or near the study area may be available from the extensive image collection maintained at the Vermont Landscape Change Program at http://www.uvm.edu/landscape/ .

Table 8 – GIS Layers Needed to Start Landslide Susceptibility Assessment

Layer Content	File Type	Source*
Political boundaries that may be useful (state, county, city, town, village)	Polygon	VCGI
Roads	Line	VCGI
Surface Waters from Vermont Hydrography Dataset (VHD)	Line/Polygon	VCGI
Outline of the site area of interest	Polygon	User defined
Lake Champlain – you must have this layer if your site area borders Lake Champlain, otherwise not.	Polygon	VCGI
Topographic maps (USGS 1:24,000)	TIF file	VCGI
DEM (At this point, the 2004 lidar bare-earth 3.2m DEM is preferable, however this is only available in a few parts of Vermont. The USGS 10m DEM is usable and would be an alternative, although it will not give as accurate results.)	Raster	VCGI
Surficial Geology (from 1970 statewide map and 1:24,000 quadrangles if available)	Polygon	VGS
USGS mapped landslides – includes recent landslides, recent to prehistoric rockfalls, recent to old debris flows, and recent to old slope failure areas)	Point/Line/ Polygon	VGS website
Location of marine limit of Champlain Sea (if your site area is in a county bordering Lake Champlain)	Polygon	VGS
NRCS Soils Data (This covers the whole state, so it is a very big file. You may want to make it smaller, using the Geoprocessing 'clip' tool. You can 'clip' it to the county boundary or site area or whatever suits you best.)	Polygon	VCGI
Outcrop maps as available	Polygon/raster	VGS
Statewide Stream Geomorphic Assessment Layers (These layers indicate which streams have been assessed by the Rivers Program and the type of assessment)	Point/Line/ Polygon	RMP
Stream Geomorphic Assessment FIT Layers (These layers show the stream features identified during field work along the assessed stream. Mass failures noted as the assessor walked along in the stream are documented. Bank erosion is also noted.) (FIT=Feature Indexing Tool)	Point/Line	RMP
Available orthophotos for the site area (possibilities include 1999 black and white, 2004 and 2007 color); Leaf-off imagery is the most helpful. The years vary for different areas of the state. Vermont Orthophoto Program imagery found on VCGI's website is suggested.	TIF file	See text, Phase 1A

* RMP – River Management Program - Geomorphic Assessment data can be obtained from the Agency of Natural Resources, River Management Program, at http://www.vtwaterquality.org/rivers/htm/rv_geoassess.htm
VCGI – Vermont Center for Geographic Information, at www.vcgi.vermont.gov
VGS – Vermont Geological Survey, at http://www.anr.state.vt.us/dec/geo/hazinx.htm

Meeting with site area town/city officials and road crew to learn about landslides and unstable slopes in their area.

Interpretation of orthophotos, which were loaded into the GIS project. Orthophotos are available through the Vermont Center for Geographic Information (VCGI) at www.vcgi.vermont.gov.

Interpretation of older aerial photographs. These are not orthorectified, but are often very useful to identify areas of recurrent instability. Older aerial photographs, which can be used in stereo are available through:

- UVM Government Documents Office
- U. S. Department of Agriculture, Natural Resources Conservation Service (NRCS) Offices located around Vermont
- Vermont Agency of Natural Resources (ANR) Water Quality Division
- ANR Department of Forest, Parks, and Recreation

The photographs will probably need to be viewed in-house, but the stereoscopic analysis is a critical step in the landslide inventory process. Even when lidar data is available, it is extremely useful to examine sharp, leaf-off photography in stereo.

C. Create a landslide database in which you give each landslide a unique name (LS_ID) and tabulate its characteristics. This includes general site information, as well as data on landslide classification, geometry, surficial materials and stratigraphy, and possible causes of the landslides. The database and the associated field data sheet are described in detail in Appendices B and A, respectively.

D. Interpretation of the orthophotos and stereoscopic interpretation of the older aerial photos should be performed to identify existing and past landslides. Landslides identified on the orthophoto layers in ArcGIS can be drawn as landslide polygons directly into the data layer file. Landslides identified on the older aerial photographs (presumably paper copies in stereo) will have to be located in ArcGIS and drawn in as polygons. It works well to have different landslide polygon layers for each source. All landslides should be identified by their unique identification number (LS_ID) in the landslide database and polygon layers. *If a landslide is identified in the same place in multiple sources (e.g. orthophotos, aerial photographs, field), the LS_ID number will be the same in all layers. The polygons will likely overlap in this case, as shown in Figure 20.*

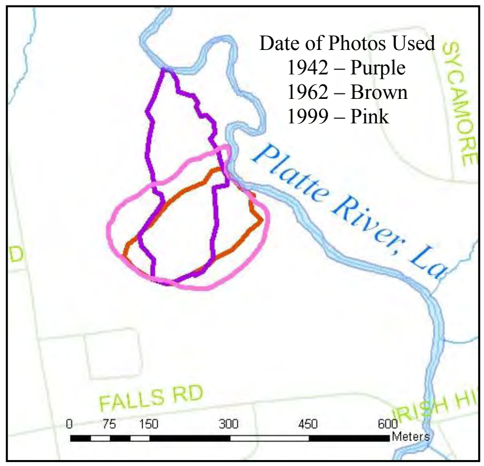


Figure 20 - Example of Overlapping Polygons of the Same Landslide. Each different colored outline was made during photo interpretations of aerial photographs from different years. All of these landslides are the same and therefore have the same LS_ID number SLP-02.

E. Field reconnaissance of some of the landslides should be performed to document their boundaries using GPS and tabulate pertinent characteristics, such as those in Appendices A and B. The locations of mass failures delineated by the River Management Program during their Stream Geomorphic Assessments were used as a guide to find landslides to visit. The River Management Program only identifies the locations of slides along waterways. Because the size and characteristics of mass failures they have identified are not part of their data collection process, it is necessary to visit some of these locations and collect GPS points and characteristics to add into the landslide database. Unstable areas identified by the city/town officials should also be visited. If these areas are confirmed to be unstable, they should be identified by a polygon or a GPS point in the GIS project, because slope failures tend to recur in the same place (Giraud and Shaw, 2007). Remediated slides, even if they are stable now, are in sensitive areas and should be included in the database.

IMPORTANT: It is probably not feasible to visit every landslide in the site area, but it is critical to visit a sampling of the slides to get the basic characteristics of the slope failures in the site area. Given the highly variable distribution of landslides in Vermont, it is difficult to specify how many landslides need to be visited, but it is important to keep in mind the criteria outlined in Phase 1A of the protocol.

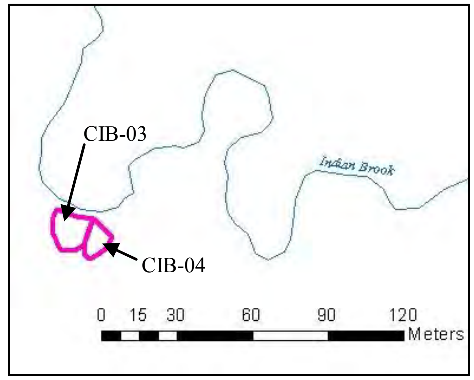
The following layers should now be in the GIS project.

Layer Content	**File Type**
Landslide database w/ landslide ID number (LS_ID) and pertinent information about the landslides	Point
Landslide extent (one or several files showing extent of landslide areas from field reconnaissance, orthophoto and aerial photo interpretation) Be sure that the landslides have a unique identification number LS_ID, unless they are the same landslide.	Polygon
GPS Points (any GPS points recorded during field reconnaissance may be useful later to delineate landslide locations or boundaries)	Point

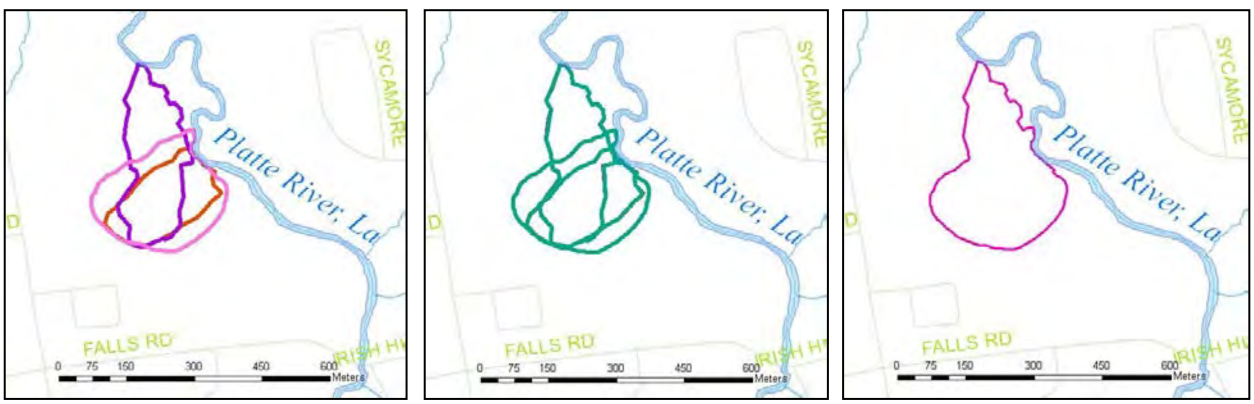
F. At this point, you may have several files of landslide polygons identified from different sources. In order to use the landslides in the analysis, they must be resolved into one file. *Landslides in different places should have different identification numbers. Landslides in the same place could have different boundaries if they are the same landslide identified in aerial photographs of different years. In this case, they should have the same landslide identification number because they are the same landslide. An example of this is shown in Figure 19. If two different landslides are adjacent, but they share a boundary, they should have different LS_ID numbers, as shown in Figure19.*

Figure 21 shows the outlines of two translational slides in the Indian Brook site area. The slides share a boundary, but are distinct slides and therefore have different LS_ID numbers, CIB-03 and CIB-04.

Figure 21 – Example of Different Landslides That Share the Same Boundary



The goal is to have all the landslide polygons from the different sources in one 'merge' layer, if the landslides do not overlap, or one 'dissolve' layer, if the landslides overlap. The dissolve tool will remove or 'dissolve' the boundaries of the same landslide with overlapping boundaries, so that landslide (same LS_ID) will now have one outer boundary. Examples of this process are shown in Figure 22. The steps in this process are listed below.



a. Boundaries of landslide SLP-02 from 1942, 1962, and 1999 aerial photographs

b. Merged – Landslide boundaries for SLP-02 are merged into one file

c. Dissolved – Outermost landslide boundary for SLP-02 remains

Figure 22 - Example of Merging and Dissolving Landslide Boundaries.

a. Look in the attribute tables for the landslide polygon files you have. Make sure that each landslide has an identification number (LS_ID). All of these identification numbers should coordinate with data in the landslide database.

<u>Note</u>: If all the landslides in a site area are in one layer file and they do *not* overlap, go directly to Phase 2. You do not need to do the next two steps (steps b and c below).

If you have several files of landslide polygons from different sources, do the next two steps (steps b and c below).

If all the landslides at your site area are in one layer file and there are overlapping boundaries, do the dissolve step only (step c below).

b. Use the Geoprocessing Tool\Merge to get all the landslide polygons into one file. The resulting merge layer will contain many landslide polygons, some of which may have the same identification number, if they are the same landslide, as shown in Figure 24.

   Input Datasets: All landslide polygon layers (Each landslide polygon should have a corresponding LS_ID number)
   Output Dataset: Use a consistent naming convention
   Field Map: No change

   If all the polygons in the merge file are discrete and do not overlap, you do not need to do the dissolve step (step c below). You can go directly to Phase 2.

c. Because the landslides were identified using different sources, boundaries of the same landslide may differ, as shown in Figure 20. Use the Geoprocessing Tool\Dissolve to combine these landslides into one slide of the same name. In order to do this, you must have a property common to the same landslide in the Merge layer. In this case, it is LS_ID, so when you run Dissolve, be sure to click on LS_ID.

   Input Features: Merged layer from step b
   Output Dataset: Use a consistent naming convention
   Dissolve_Field: Click on LS_ID
   Statistics Field: No change
   Create multipart features: Leave as checked
   Unsplit lines: Leave as unchecked

   The output feature from the Dissolve tool should now contain landslides identified from many sources, but only one polygon for each landslide identification number (LS_ID). The boundary of each landslide is now the maximum extent of all the failures at that particular area identified using different sources, as shown in Figure 22c.

<u>Phase 2</u> – This phase involves conducting terrain analysis on the best DEM available for the site area to produce layers which will be used for frequency analysis later in the process. Our trials indicate that an accurate bare-earth lidar DEM is probably an essential prerequisite for successful terrain analysis using the frequency ratio method. That does not mean that hazard mapping cannot be undertaken without lidar terrain data. In many parts of Vermont no lidar data is currently available. In these areas, the best available DEM may be the USGS 10 m DEM. In such areas the procedures outlined in this phase can be attempted, and if field review indicates that it is inadequate, then the areas of high hazard potential will need to be identified by careful stereoscopic photointerpretation and field work. However, the work will proceed far more efficiently if an accurate bare-earth lidar DEM is available.

If your site area does not include an entire watershed, it is suggested that you first analyze a ‘study block’ larger than your site area because of ‘edge effects’ that might occur when analyzing the exact extent of the site area. For example, if the site area is only a portion of a watershed, it is important to include the upper part of the watershed in the larger block because some parameters depend on upstream characteristics (e.g. topographic wetness index). The block must be at least large enough to encompass the first order tributaries that are in the site area. After calculation of parameters, the pixels within the site area can then be extracted from the larger block file.

Details to accomplish the terrain analysis are explained below. It is suggested that a log of the files be kept as the project progresses. An Excel spreadsheet can be very useful to keep file names organized. Other important entries in the spreadsheet are the subdirectory in which the file can be found and the process by which it was created.

A. Layers should be created for each of the following parameters: distance to stream, hydrologic group or soil drainage, profile curvature, roughness, slope angle, soil type, and topographic wetness index. A brief description of each parameter is below.

Distance to Stream – Landslides occur most frequently along waterways, therefore the distance of a slope to the nearest waterway is an important parameter.

Hydrologic Group (Soil Drainage) – Soils that have similar runoff properties, such as rates of infiltration and runoff, are combined into ‘hydrologic groups’ by the NRCS. Qualities that affect this are depth to high water table, saturated hydraulic conductivity, and depth to a very low permeability layer. (NRCS, 2003, National Soil Survey Handbook, p. 618-24) Four groups, A, B, C, and D, are delineated and described below.

A: Low Runoff Potential - These soils consist primarily of deep well drained sands or gravels which have a high rate of water transmission.
B – These soils are primarily moderately deep and moderately well drained with a moderate rate of water transmission. Soils in this category are generally medium to coarse grained.
C – These soils drain slowly and have a low rate of infiltration. Soils in this category are generally fine grained.
D: High Runoff Potential – These soils consist of clay or soils with a permanent high water table. Infiltration is very slow and runoff is very high.

Profile Curvature – Profile curvature is a measure of the curvature of the slope in the vertical direction. Profile curvature is a quantity indicating whether the slope is convex, concave, or neither. Because the highest values for profile curvature were at the top or bottom of a slope, the values within the landslide areas were similar to the values in flat areas (neither concave nor convex). Although profile curvature is more useful in the final step of the protocol to verify the frequency ratio results, the layer should be calculated during the terrain analysis process.

Roughness – The roughness parameter is the standard deviation of the slope angle. It is a measure of how variable the topography is over short distances. Smooth, even slopes have low roughness values and jagged surfaces have high values. The standard deviation is calculated for each pixel location by finding the standard deviation of the slope for all pixels within a 3 x 3 pixel block centered on the pixel. The units for both slope and roughness are degrees.

It should be noted that this parameter could lead to confusion with bedrock outcrops, which would also exhibit a 'rough' surface. Therefore, having some kind of outcrop map during the verification of frequency ratio results is important.

Slope Angle – Translational slides commonly occur on high angle slopes (slopes greater than 30^o), so it follows that since the majority of slides were translational, slope angle would be important.

Soil Type – Soil type, which is a characteristic of soil series, is used as a parameter for this project. Soil series is identified by the name of soil type (based on soil horizon characteristics, including grain size or texture, organic matter content, color, structure, chemistry, etc.) and slope angle delineation. An example of this is AdA, which indicates Adams and Windsor loamy sands on 0 to 5% slopes. For this project, soil 'type' was investigated as a parameter, which is the soil series name without the slope angle designation, so in the previous example, only 'Ad' would be used.

Topographic Wetness Index (TWI) – Topographic Wetness Index is a measure of the water draining into the area. It depends on the slope angle and drainage area uphill of the point of interest. It is calculated by (Wilson and Gallant, 2000):

$$TWI = \ln (a/\tan \beta)$$

Where a = specific area = local upslope area draining through a certain pixel per unit contour length

β = the local slope

Methods of creation of these layers are listed in Table 9. Each of the parameters considered were abbreviated to help with file naming during the frequency ratio analysis (e.g. 'ds' for distance to stream, 'hg' for hydrologic group, 'pc' for profile curvature, 'ro' for roughness, 'sl' for slope angle, 'so' for soil type, and 'tw' for topographic wetness index). These seven files should be created for each site area.

Table 9 – Method of Creation of Parameter Layers

Parameter	Method of Creation	Input File
Distance to Stream (ds)	ArcGIS\Spatial Analyst\Distance\Euclidean Distance (make sure the output cell size is the same as the DEM size you are using; e.g. Lidar cell size = 3.2m; you do not need to specify maximum distance)	Rivers – stream layer clipped to larger study block
Hydrologic Group (indicative of soil drainage) (hg)	a. Geoprocessing Tool\Clip NRCS Soils layer to site area b. Open Properties; choose Display tab; change Display Expression to HYDROGROUP c. Choose Symbology tab; click on Categories; change Value Field to HYDROGROUP; click on 'Add All Values' d. Choose Labels tab; click on Text String/Label Field; change to HYDROGROUP	NRCS layer

	e. Click okay at bottom of window; If labels are not showing, right-click on layer name and click on Label Features f. Use ArcGIS\Conversion Tools\To Raster\Polygon to Raster to convert hydrologic group polygons to a raster file (Input file: hg layer clipped to site area; Value Field: 'HYDROGROUP'; Cell Size: whatever size DEM is being used (3.2m for lidar). g. Use ArcGIS\Spatial Analyst\Reclass\Reclassify to change water pixels to Hydrologic Group D and Not Rated pixels to NoData	
Profile Curvature (pc)	ArcGIS\Spatial Analyst\Surface\Curvature (choose profile curvature)	DEM
Slope Angle (sl)	ArcGIS\Spatial Analyst\Surface\Slope (specify degrees; z factor = 1 for lidar; check and change accordingly for other DEMs)	DEM
Roughness (standard deviation of slope) (ro)	ArcGIS\Spatial Analyst\Neighborhood\Focal Statistics (choose standard deviation)	Slope file 'sl' in degrees previously generated (see below)
Soil Type (so)	Soil type in the GIS layer is indicated by 'musym'. These soil types generally have 3 letters, such as AdA. The first two indicate the soil type; in this case, Adams and Windsor loamy sands. The third letter indicates slope in a general way. Slopes 'A' through 'E' vary from flat more steep. This slope designation must be removed. a. Geoprocessing Tool\Clip NRCS Soils layer to site area (may have already been done for Hydrologic Group) b. Open Properties; choose Display tab; change Display Expression to MUSYM c. Choose Symbology tab. If hydrologic group symbols are displayed, change Value Field to MUSYM; click on 'Add All Values' d. Choose Labels tab; click on Text String/Label Field; change to MUSYM e. Click okay at bottom of window; If labels are not showing, right-click on layer name and click on Label Features f. Go into Editor and start editing soils layer. g. Open attribute table; right-click on the 'musym' column and sort ascending; delete the third letter of each of the 'musym' entries to get rid of the slope designation. Do not change anything if there is no third letter on the musym designation. Save edits and stop editing when complete. Close attribute table. g. Use ArcGIS\Conversion Tools\To Raster\Polygon to Raster to convert musym polygons to a raster file (Input file: soils layer showing musym clipped to site area; Value Field: 'MUSYM'; Cell Size: whatever size DEM is being used (3.2m for lidar).	NRCS layer
Topographic Wetness Index (tw)	This can either be created in the SAGA GIS program (see Glossary) or as a script in ArcGIS.	DEM

B. If the site area of interest is not along the shore of Lake Champlain or a large water body, proceed to step C.

If the site area of interest is on the shore of Lake Champlain or a large water body, you will need to remove that water body before proceeding. This is because the terrain analysis does not distinguish between land surface and water surface, so the parameters (distance to stream, profile curvature, roughness, slope angle, and topographic wetness index) will be calculated on the water surface as well as the land surface and will skew the frequency ratio results.

Follow the steps below to remove the water body area from the site area.

a. Open ArcCatalog.
Right-click on the file you want to change (in this case, Lake Champlain layer).
Click on Properties.
Go to Fields tab.
Go to the first empty line of Field Name and click on it.

Type in 'Id'.
Under Data Type, click in the space and find the pull down menu.
Click on Long Integer.
Click OK at the bottom of the window.
Close ArcCatalog

b. Open ArcMap; start editing the Lake Champlain layer.
Right click on Lake Champlain in the Table of Contents and click on Open Attribute Table.
Change the Field labeled 'Id' to 1.
Save Edits and Stop Editing.

c. Open Geoprocessing Tools
Click on Union to join polygon files together (File showing the outline of your site area and Lake Champlain layer).
Input Features: Outline of Your Site area file and Lake Champlain layer
Output Feature: Outline of Your Site area_noLakeChamp
Select ALL for join attributes; so Lake Champlain Id_1=1, and land area in the site area Id_1=0.

d. Open ArcMap; start editing Outline of Your Site area_noLakeChamp
Right click on Outline of Your Site area_noLakeChamp and click on Open Attribute Table
Delete the Lake Champlain areas; (FTYPE=LakePond) (If you scroll right to the end of the table, these will have Id_1 = 1)
Select these lines by clicking on the box at the far left to highlight the line; then right-click on this box and select 'Delete Selected'
Save Edits and Stop Editing

e. This file will show your new site area. It only includes the land part of the site area.

C. Cut the site area out of each of the larger block files created above in step A. With the exception of Hydrologic Group and Soil Type, which should already include just the site area, it is necessary to cut the site area out of each of the block files.
Process: ArcGIS\ Spatial Analyst\Extraction\Extract by Mask.
Input file: Block file for parameter.
Mask file: Site area boundary file (if your site area borders Lake Champlain, use the Outline of Your Site area_noLakeChamp file just created above)

D. Since the number of pixels in areas affected by landslides is necessary to do frequency ratio analysis, layers showing just the parameters in the landslide-affected areas will now be created. This will be done by using ArcGIS\Spatial Analyst\Extraction \Extract by Mask. The input files are the files created in Phase 2-A. The mask file is the dissolve layer created in Phase 1-Gc.

At this point, you should have the following layers for *both your site area and the previously identified landslides* within your site area.

a. Distance to stream
b. Hydrologic group
c. Roughness
d. Slope angle
e. Soil type
f. Topographic wetness index

Phase 3 – Frequency ratio analysis will be conducted during this phase. Frequency ratio is basically a comparison of the landslide pixels in the site area to the total number of pixels in the site area for each parameter. The following steps will explain how to calculate and understand frequency ratio.

A. Divide each topographic parameter (distance to stream, roughness, slope angle, and topographic wetness index) into classes that represent the distribution of points. *Nothing should be done with the soil parameters (hydrologic group and soil type) at this time.* To see the distribution of points within a parameter,
   a. Right-click on one of the layers, for example, the slope angle layer for the site area.
   b. Click on Properties.
   c. Click on the Symbology tab.
   d. Click on Classified (left-hand side of box).
   e. Click on the 'Classify' button in the right middle of the box.
   f. You should see the distribution of points.
   g. To change the number of classes in the parameter, you click on the 'Classes' pull-down menu at the top left and select the number of classes. If you cannot change the number of classes there, click on 'okay' at the bottom right and go back to the last window. You will be able to change the number of classes there.
   h. On the point distribution graph window, you should look at the 'break values' on the right side of the window.
   i. You can change the break values for the classes there by clicking on the break value and typing in a new one.
   j. Table 10 illustrates the break values for the classes used in the test run of this protocol. *The goal is to have the classes reflect the distribution, so if these class breaks do not describe the distribution adequately, change them.* (For example, Topographic Wetness Index can be classed by either twos or threes, depending on how the distribution looks.)

Table 10 – Class Breaks for Parameters

Parameter*	Class Number	Classes
Distance to Stream (m)	1	0-30
	2	30-60
	3	60-90
	4	90-120
	5	120-150
	6	150-180
	7	180-210
	8	210-240
	9	240-270
	10	270-300
	11	300-500
	12	500-700

Hydrologic Group	1 2 3 4	A B C D
Roughness - standard deviation of slope; units are in degrees	1 2 3 4 5 6 7 8	0-2 2-4 4-6 6-8 8-10 10-12 12-14 14-18
Slope Angle in degrees	1 2 3 4 5 6	0-10 10-20 20-30 30-40 40-50 50-90
Soil Type	Depends on how many soil types are in the site area	Soil Type names in site area
Topographic Wetness Index (can be classified by twos or threes, depending on distribution – threes shown here); units are in sq. m.	1 2 3 4 5 6 7 8	0-3 3-6 6-9 9-12 12-15 15-18 18-21 21-24

*Profile Curvature will not be used in the frequency ratio analysis. It will be used in Phase 4 to verify the results of the frequency ratio analysis.

k. Change the break values for the classes for the continuously distributed parameter layers (distance to stream, roughness, slope angle, and topographic wetness index) for the site area and also for those parameter layers for the landslides. Class breaks for each parameter should be the same in both the site area and landslide layers.

B. The parameter layers need to be reclassified into their respective classes to obtain the number of pixels in each class. Do this by using ArcGIS\Spatial Analyst\Reclass\Reclassify.

Input raster: parameter layer to be reclassified
When you put in the raster name, the old values will show with new numerical values (class numbers). These values do not need to be changed.
Output Raster: Name of your choice
Click 'OK'

Do this for the continuously distributed parameter layers (distance to stream, roughness, slope angle, and topographic wetness index) for the site area and for the landslides. Nothing should be done with the hydrologic group and soil type layers at this time.

C. To calculate frequency ratios, set up a spreadsheet in a program like Excel with the headings shown in Table 11.

Table 11 – Spreadsheet Setup for Calculation of Frequency Ratio Values

a	b	c	d	e	f	g	h	i	J
Parameter	Class Number	Classes	# of pixels in class within landslide areas	Total # of landslide pixels within site area	% of class pixels within landslide areas	Number of pixels in class within site area	Total # pixels in site area	% of class pixels in site area	Frequency Ratio
					Column *f* = column *d* *100 / column *e*			Column *i* = column *g* *100 / column *h*	Column *j* = column *f* *1000 / column *i*

D. Populate the columns of the spreadsheet as follows:

a. Parameter – name of parameter (distance to stream, hydrologic group, roughness, slope angle, soil type, topographic wetness index)

b. Class Number – artificial number; starts at 1, goes to however many classes there are for that parameter; use values from Table 10

c. Classes – Each parameter is divided into classes, which represent the distribution of data for the whole site. Use values from Table 10 for all the parameters, except Soil Type.
- For Soil Type, classes corresponding to each class number are listed in the attribute table of the soil type raster layer masked to the site area boundary. To get these classes:
  - Right-click on the soil type raster layer for the site area
  - Click on 'Open Attribute Table'
  - Classes are listed in the column labeled 'MUSYM'
  - Type these into column *c* in the spreadsheet next to the corresponding class number
  - Close attribute table

d. Populate columns *d* and *e* at the same time.
For column *d*: Number of pixels in class within landslide areas
- Right-click on reclassified parameter layers for landslides (distance to stream, roughness, slope angle, and topographic wetness index created in Phase 3-B). For hydrologic group and soil type, use the landslide raster files created in Phase 2-D.
- Click on 'Open Attribute Table'
- The number of pixels in each class number (column labeled 'VALUE') is in column labeled 'COUNT'
- Put these count values in column *d* of the spreadsheet, making sure that the count values are placed in the correct class number. Note that for hydrologic group, the class numbers 1, 2, 3, 4 do not necessarily correspond to A, B, C, and D classes.

For column *e*: Total number of landslide pixels within site area
- Right-click on the 'COUNT' column.
- Click on Statistics
- The sum is given in the Statistics box on the left side of the window.

- Put this number in column *e* of the spreadsheet. Note that hydrologic group and soil type may not have the same total number of pixels as other parameters due to missing data.

e. Total number of landslide pixels within site area – See column *d* instructions

f. % of class pixels within landslide areas = column *d* *100 / column *e*

g. Populate columns *g* and *h* at the same time.
For column *g*: Number of pixels in class within site area
- Right-click on reclassified parameter layers for site area (distance to stream, roughness, slope angle, and topographic wetness index created in Phase 3-B). For hydrologic group and soil type, use the raster files for the site area created in Phase 2-D.
- Click on 'Open Attribute Table'
- The number of pixels in each class number (column labeled 'VALUE') is in column labeled 'COUNT'
- Put these count values in column *g* of the spreadsheet, making sure that the count values are placed in the correct class number. Note that for hydrologic group, the class numbers 1, 2, 3, 4 do not necessarily correspond to A, B, C, and D classes.

For Column *h*: Total number of pixels in site area
- Right-click on the 'COUNT' column.
- Click on Statistics
- The sum is given in the Statistics box on the left side of the window.
- Put this number in column *h* of the spreadsheet. Note that hydrologic group and soil type may not have the same total number of pixels as other parameters due to missing data.

h. Total number of pixels in site area – See column *g* instructions

i. % of class pixels in site area = column *g* *100 / column *h*

j. Frequency Ratio = column *f* *1000/ column *i*
GIS raster values are whole numbers, therefore the raw frequency ratio values must be multiplied by 1000 in order to use them in a raster format. This will not change the results of the analysis, provided *all* frequency ratio values are changed.

Below is an example of the spreadsheet for the hydrologic group parameter. Not shown here is column *a*, which is the parameter, in this case hydrologic group.

b	*c*	*d*	*e*	*f*	*g*	*h*	*i*	*j*
Class Number	**Classes**	**# of pixels in class within landslide areas**	**Total # of landslide pixels within site area**	**% of class pixels within landslide areas**	**Number of pixels in class within site area**	**Total # pixels in site area**	**% of class pixels in site area**	**Frequency Ratio**
1	A	284	298	95.3	255199	456541	55.9	***1705***
2	B	14	298	4.7	47844	456541	10.5	***448***
3	C	0	298	0	24553	456541	5.4	***0***

4	D	0	298	0	128945	456541	28.2	***0***
	Total	298		Total	456541			

E. Create a new table which will show the highest frequency ratio values for each parameter at the site area. An example table is shown in Table 12 below.

<u>Table 12 – Example List of Highest Frequency Ratio Values* for Each Parameter</u>

Parameter	Indian Brook	Joiner Brook
Distance to stream	5885	3212
Hydrologic group	1705	2309
Roughness	85076	4215
Slope angle	169488	6558
Soil type	1806	nc
Topographic wetness index	5648	3384

* Frequency ratio values are multiplied by 1000 to get whole numbers to enter into the raster (See Phase 3-Dj in the Protocol for more information).
nc = not calculated

For the slides in Indian Brook, it is easy to see that slope and roughness are the most important parameters and will dominate the landslide potential when added together. The remaining factors will have little influence.

For the slides in Joiner Brook, all of the frequency ratios are in the same order of magnitude. This makes it much more difficult to determine what influences landslide potential. Although it is important to try adding the highest values together first, it may make sense to try combining a number of different factors too.

F. In order to finish the frequency ratio analysis, the frequency ratios of the parameters of highest influence will be added together. The steps for this are as follows:
   a. For the parameter having the *highest* frequency ratio value, it is necessary to reclassify the classes with frequency ratio values.
      - Open ArcGIS/Spatial Analyst/Reclass/Reclassify
      - Input raster: reclassified layer of the parameter with the highest frequency ratio value (Phase 3-B)
      - In the column labeled 'New values', input the frequency ratio values from the spreadsheet for each class.
      - Output raster: file name of your choice
      - Click 'OK'

   b. Repeat previous step with the parameter layer having the *second highest* frequency ratio value.

   c. Add the two frequency ratio files together.
      - Open ArcGIS/Spatial Analyst/Math/Plus
      - Input raster or constant value 1: parameter layer with the highest frequency ratios, created in Phase 3-Fa
      - Input raster or constant value 2: parameter layer with the second highest frequency ratios, created in Phase 3-Fb
      - Output raster: file name of your choice
      - Click 'OK'

d. The result is a first-cut of a landslide potential map. In order to easily view the map, it is necessary to change the colors and classification breaks.
   - Right-click on the file name.
   - Click on Properties
   - Click on the Symbology tab
   - Click on Classified on the left side of the window.
   - Click on the button that says classified in the right middle part of the window
   - Change the Classification Method at the top and change to Natural Breaks (Jenks)
   - Change the classes just below that to 10.
   - After changing these values, Click 'OK' to get back to the main Layer Properties window. Click on the right end of the color ramp in the middle of the window. Choose a color ramp that helps you to see the different hazard potentials. Red to yellow to blue was used for this study to mean high to very low hazard potential. If the brightest color is on the lowest hazard potential after you choose your color ramp, you may want to make the brightest color on the highest hazard potential. To do this, click on the word 'symbol', then click on 'flip colors' and the colors will flip, so the brightest is now at the highest hazard potential.
   - Click 'OK' to view your map.
   - Open the dissolve layer with the outlines of the existing landslides and compare the high and moderate hazard areas with those landslides.
   - Change the colors in the 10 categories to three distinct colors, such as red, yellow, and blue, representing high, moderate, and low potential hazard respectively. By changing some of the intermediate colors, try to find high, moderate, and low frequency ratio categories that best reflect the hazard potential in the site area. The moderate and high category areas should fall predominantly within the mapped landslides, whereas the low category areas should fall predominantly outside of the mapped landslides.

   If you are satisfied with this map, make a note of the break values. Then return to the Properties window and click on Symbology.
   - Click on the classify button at the right middle of the window.
   - Change the number of classes to three.
   - Change the break values to the numbers you have selected from your analysis. Click on the % button to the right of break values to change those numbers to percent.

   If you are not satisfied and want to add the parameter with the third highest frequency ratio, follow the steps in Phase 3-Fa to produce the frequency ratio layer for that parameter. Then add these values to the other frequency ratio map by adding the maps together as outlined in Phase 3-Fc. Finish the map by following the steps in Phase 3-Fd.

Phase 4 – Calibration of the maps and construction of the hazard potential maps

A. Field Calibration of Maps - A sampling of sites from the frequency ratio map should be field-checked to verify the results and calibrate the maps for each site area. Include both areas mapped as high hazard and stable areas identified in the field. This provides a more objective view of how well the sites are being classified.

a. Choose sites - include a sampling of sites that the Phase 3 outputs have identified as high hazard as well as those identified as stable.

b. Conduct field visits

c. Fill out slope stability data sheets for the sites (Appendix A)

d. Enter data into LSPoint database (Appendix B).

B. Construction of Hazard Potential Maps - Areas sensitive to slope instability and landsliding should be delineated to produce hazard potential maps. The sensitive areas are intended to include areas of active and inactive landslides, relict landslides that can foreseeably be reactivated, areas susceptible to future landslides, active and inactive gullies, and areas susceptible to future gullying. Artificial cut and fill slopes should be excluded from the delineations. It is outside the scope of this work to evaluate stability in artificial materials and on engineered slopes. Areas underlain by exposed or shallow bedrock are also to be excluded. The terrain analysis methods used here should not be used to distinguish stable and unstable bedrock slopes.

The following steps outline the method to delineate sensitive areas.

Working at a scale of approximately 1:3,000, delineate areas of high susceptibility to include all known landslides and mass failure locations and to include areas with high frequency ratio index. These will generally be steep areas that are in close proximity to streams and drainages, although areas with steep, high, non-bedrock slopes that are distant from the streams should also be considered. Areas of low susceptibility that are entirely enclosed within an area of high susceptibility should be delineated and coded as such. In order to produce the sensitivity maps, the following data layers can be used:

- Best map of combined frequency ratio values for each site area
- Field calibration stations
- Outlines of landslides identified in previous phases of this work
- Shallow soils and outcrops (vtoutcrop plus available outcrop locations from bedrock and surficial mapping)
- Mass Failures from Stream Geomorphic Assessment data of the DEC Rivers Program
- Surface Waters from Vermont Hydrography Dataset (VHD)
- Slope layer from DEM (lidar or best available substitute)
- Profile curvature from DEM (lidar or best available substitute)
- 2 meter contours from lidar or best available substitute
- Recent ‘leaf-off’ orthophotos.

Field data should be consulted for site conditions. On reaches which have Stream Geomorphic Assessment data, the mass failure locations are used to identify the bases of near-stream landslides. The VHD streams layer is helpful for quickly reading the terrain. Stream erosion is the major cause of slope failures in Vermont, and thus many landslides can be found on steep slopes adjacent to streams. However, it is important to realize that the VHD layer does not show all perennial and intermittent streams. Check the slope and contour maps for additional small drainages and consider the stability of their side slopes.

The shallow soils and outcrop data can be used to exclude bedrock areas from delineation. The vtoutcrop layer is derived largely from the NRCS soil surveys and small-scale (1:250,000) surficial geologic mapping. It is intended as a rough indication of the presence of shallow or exposed bedrock, not as a precise delineation. Thus, use this layer with caution and fully consider the other data layers.

Bedrock outcrop locations from detailed (1:24,000) bedrock and surficial geologic mapping projects are generally quite accurate, but it should be realized that these maps only show outcrops that the researcher actually visited and thus there may be many additional outcrops that are not shown. If detailed surficial geologic mapping is available, check to see if areas of thin till over bedrock were delineated. If available, these should provide a good idea of the location of shallow soils, which should not be included in the areas delineated as sensitive for landslide hazard.

Surficial geologic data is used to help extrapolate the extent of sensitive areas. For example, if a steep slope has abundant areas of moderate to high frequency ratio values and is underlain by similar surficial material with no signs of bedrock, then it is probably reasonable to extend the sensitive polygon across the slope, connecting up the areas of moderate to high frequency ratio values.

The combination of the slope and the profile curvature layers is a powerful tool for reading the landscape. The slope layer, coded with a standard deviation classification serves to accentuate subtle changes in slope. Profile curvature is used to define bottoms and tops of sensitive areas. The combination of the slope and the profile curvature layers accentuates the steep slopes and their bottoms and tops and serves as one of the key tools in delineating the sensitive areas.

The contours derived from lidar provide a detailed view of the shape of the terrain and help in defining the extent of the sensitive areas. A 2-meter contour interval provides a sufficiently detailed view of the terrain. By viewing the contours, the higher slopes can be readily distinguished from isolated steep but low areas (bank erosion). If lidar is not available, it is unlikely that any of the other contour layers will be sufficiently detailed to be of much assistance in delineating the sensitive areas.

Orthophotos can be very helpful in picking out significant landslides, but only if they have relatively high resolution and are produced from leaf-off aerial imagery. Use the most recent available.

Terrace tops are generally excluded from the sensitive areas, although small sections of the terrace tops can be included when they are surrounded by sensitive slopes on three sides and have necks that are narrower than about 15 meters, that is, the distance across the top of the terrace is at some point less than about 15 meters.

Areas at the base of high, sensitive slopes should generally be included in the delineation as slides from the slopes above are very likely to extend down onto them. Thus, some of the sensitive areas will include lower frequency ratio and lower slope areas at their bases. Isolated areas with high frequency ratio and/or slope that are less than 4 meters high that are not adjacent to streams should be excluded as they are unlikely to lead to significant slope failures.

<u>Phase 5</u> – Preparation of maps showing potentially unstable areas

Final maps will show the moderate/high hazard zones and the areas designated as sensitive to landslide effects. The scale of presentation is optional, but this protocol is intended to produce maps that can be used for planning purposes at scales of about 1:10,000 or smaller (that is, less detailed). Additional buffering of the sensitive areas may be undertaken based on planning considerations.

Suggestions for Future Work

1. Conduct landslide mapping over larger areas in order to have more landslide polygons for analysis. One of the principal difficulties encountered in this study was the small number of landslide pixels available for analysis. This would be solved by investigating site areas of 25 to 50 sq. km. in size or larger.

2. Identify special procedures to be used in small study areas and/or those with small landslides. Locations given by the GPS used for this project are accurate to within no better than ± 3 to 4 m. As a result, small landslides may not be accurately located on the maps. Table 13 below shows statistics about the site areas and landslides. Note the small average size of the landslides in the Bartlett Brook site area. Mismatches between the true location of the landslides and the pixels identified as being within the landslides could cause inaccurate characteristics to be input into the frequency ratio analysis and thus weakening the terrain signatures of the landslides. This may well have been the case at Bartlett Brook.

Table 13. Statistics about the size and number of landslides in the study sites investigated in this project.

Site	Average Size of Landslides (sq.m)	# LS Identified	Area of Site (km^2)	# LS / km^2 of site area	Correlation of Landslides with Results of Frequency Ratio Analysis	%LS >400sq.m.
Alder Brook	1009	19	7.8	2.44	Worked okay	63
Bartlett Brook	227	5	2.4	2.08	Did not work well	25
Clay Point	484	4	1.3	3.08	Worked well	75
Indian Brook	398	8	7.6	1.05	Worked okay	37
Joiner Brook	3556	17	12.6	1.35	Worked well	35
La Platte River – all slides	4311	29	9.6	3.02		65
La Platte River – translational slides	1145	27	9.6	2.81	Worked well	62

La Platte River – rotational slumps	47052	2	9.6	0.21	Did not work well	100

Several conclusions can be made based on the information in this table. For best results from the frequency ratio analysis,

- The site area should have, on average, a minimum of 1 landslide per square kilometer.
- The average size of the landslides used in the analysis should be greater than 400 sq. m.
- At least 30% of the landslides should be greater than 400 sq. m.

3. Investigate the occurrence of low-angle rotational slides, which currently appear to be limited to areas below the upper shoreline of the Champlain Sea deposits in the Champlain Valley.

Conclusions

A protocol was developed to map landslide susceptible areas in the state of Vermont. The protocol requires use of a GIS system for compiling and analyzing the data. Below is a brief synopsis of the steps involved in the protocol.

1. Select site area to be studied
2. Collect literature about slope failures at the site area of interest; meet with town officials to obtain first-hand information about slope failures
3. Develop GIS project with basic mapping layers
4. Obtain orthophotos and aerial photographs relevant to the site area of interest
5. Conduct field reconnaissance on a sample of landslides within the site area of interest to collect landslide boundaries and characteristics
6. Conduct stereoscopic photo interpretation of aerial photos to identify additional landslides within the site area
7. Perform GIS terrain analysis on the site area
8. Run frequency ratio models
9. Verify accuracy of maps by field checking random areas and questionable areas within the site area of interest
10. Draw polygons around sensitive areas, including areas that have not currently failed, but have moderate to high potential to do so and areas that would be affected if adjacent land failed
11. Produce final maps of landslide susceptibility and sensitive areas

Our trials indicate that an accurate bare-earth lidar DEM is probably an essential prerequisite for successful terrain analysis using the frequency ratio method. That does not mean that hazard mapping cannot be undertaken without lidar terrain data. Frequency ratio analysis can be tried, and if field review indicates that it is inadequate, then the areas of high hazard potential can be identified by careful stereoscopic photointerpretation and field work. However, the work will proceed far more efficiently if an accurate bare-earth lidar DEM is available.

During development of the protocol, it was found that this process currently works best for high-angle landslides. In these study sites most of the high-angle landslides were translational. Based on the results of the frequency ratio analysis, the most important parameters for identifying these high-angle landslides are slope angle and roughness, although soil type and topographic wetness index are also important at some site areas. Slope and proximity to the shoreline were found to be the most important parameters along the Lake Champlain shoreline.

Low-angle rotational slumps were encountered in the La Platte River site area. These low-angle rotational slumps were challenging to identify using the terrain analysis phase of the protocol. This is probably because the terrain lacks a distinctive rough character displayed by the high-angle landslides. Although a head scarp and bulging toe may be apparent, the bulk of the slumped area may not be heavily disturbed. They are thus difficult to distinguish from the surrounding terrain. However, it should be noted that three of these features were identified during the field work and photo-interpretation. Those in the La Platte River site area did not provide enough area to come to significant conclusions. The low-angle sites observed to date are all below the upper Champlain Sea shoreline and are underlain by fine-grained silt/clay deposits. Surficial geology may thus serve as a key to identifying areas that could be subject to these large low-angle rotational slumps. Further research is needed.

Debris flows and associated features in the Smugglers Notch area can be accurately mapped by a combination of field work and photointerpretation, but lidar data was not available to test whether or not terrain analysis could successfully identify the features. The level of detail available with modern lidar data suggests that at the very least these features can be identified efficiently by viewing slope or contour data derived from lidar.

Based on the results of this study, it is suggested that in most parts of Vermont, areas of 25 to 50 sq. km. will probably yield enough landslides for a robust analysis. Alternatively if the site of interest is smaller, the best results occurred when the following criteria were met: There is, on average, a minimum of one landslide per square kilometer in the site area; the average size of the landslides is at least 400 square meters; and at least 30% of the landslides are greater than 400 square meters. It is probably best to consider 25 to 50 sq. km. as a minimum size for implementation of the frequency ratio method.

If the landslides are small in area, then it becomes critical to use a mapping-grade GPS with sub-meter accuracy.

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Abbreviations Used in this Report

CCRPC – Chittenden County Regional Planning Commission
DEC – State of Vermont, Agency of Natural Resources, Department of Environmental Conservation
DEM – Digital elevation model
km - kilometers
m – meters
mm -- millimeters
NAIP - National Agriculture Imagery Program
NRCS – U. S. Department of Agriculture, Natural Resources Conservation Service
SHMP – State Hazard Mitigation Plan
VAPDA – Vermont Association of Planning and Development Agencies
VCGI – Vermont Center for Geographic Information
VGS – Vermont Geological Survey
USGS – United States Geological Survey

Glossary

Block file – for the purposes of this report a block file is a block if terrain data that may be larger than the *Ssite area* (see below) in order to avoid 'edge effects' that might occur analyzing the exact extent of the site area. For example, if the site area is only a portion of a watershed, it is important to include the upper part of the watershed in the larger block because some parameters depend on upstream characteristics (e.g. topographic wetness index). The block must be at least large enough to encompass the first order tributaries that are in the site area. After calculation of parameters, the pixels within the site area can then be extracted from the larger block file.

Class – a division of a parameter. An example is the parameter slope, which can be divided into classes or increments, such as 0 to 10^o, 10 to 20^o, 20 to 30^o, 30 to 40^o, 40 to 50^o, 50 to 90^o or whatever classes are appropriate for the work.

Hazard potential/Susceptibility – hazard potential has been rated using this protocol as high, moderate, and low. High zones are generally steep areas that have failed in the past or are exhibiting characteristics that indicate a high potential for failure in the future. Moderate zones may be less steep, but could potentially fail if landscape conditions change. This might be increased erosion at the toe of a slope from a nearby stream, additional development in the area, which could increase stormwater runoff, or construction which could jeopardize the slope.

Parameter – a measurable terrain, hydrologic, geologic, or cultural factor that will be evaluated. Some examples of parameters in this study that were found to affect the hazard potential of an area are slope angle, roughness, distance to stream, hydrologic group, and topographic wetness index.

SAGA – A GIS program used for part of the terrain analysis in Phase 2 of the Protocol. It is a free and open source software available at http://www.saga-gis.org/en/index.html. Other GIS programs such as ArcGIS can be used for the terrain calculations such as topographic wetness index, but SAGA has the advantage of having built-in algorithms that simplify the steps needed to run the calculations. Once the data is loaded, it is a one-step process to set the "Basic Terrain Analysis" module running. It is not essential to use SAGA, but we found it to be a useful tool for the terrain analysis.

Sensitive area — an area that could be affected by slope failure. This includes areas of active and inactive landslides, relict landslides that can foreseeably be reactivated, areas susceptible to future landslides, active and inactive gullies, and areas susceptible to future gullying.

Site area– the area of interest
The site area can be an irregularly-shaped block or an entire watershed. If the site area does not encompass an entire watershed, it is important to analyze a larger area of terrain data that will encompasses at least all of the watersheds of first-order tributaries (see *Block file* above).

Appendix A

Vermont Geological Survey Slope Stability Data Sheet

Location ___________________________________

Observer___________________________________

USGS Map _________________________________

Site No.______________ Date_________________

Town_______________________________________

Stream Reach/Segment ID ____________________

Style of slope failure: *None / Soil creep / Gullying / Landslide / Landslide-gully complex / Streambank erosion (low bank)*

Landslide type: *Fall / Topple / Rotational slump / Rotational slump-flow / Translational slide / Translational slide-flow / Flow / Other*

____

Landslide material: *Rock / Debris / Earth*

Activity: *Active / Inactive / Relict / None*

Date of most recent failure _______________________

Dimensions (in meters):

Width (across)______ Depth _________

Length ______ Height_______ Aspect _______°

Overall slide angle_____° Original slope angle _____°

Area estimate: <100 m^2 / 100 - 1000 m^2 / >1,000 m^2

Condition of toe: Intact/Partly removed/Totally removed

Bedrock present on slope? Yes / No / Unsure

Bedrock grade control in stream? Yes/ No/ Unsure/ NA

Is slope on outside of a stream meander? Yes / No

Headcuts in bottom of stream ? Yes / No / Unsure/ NA

Springs? Yes / No Seeps? Yes / No Piping? Yes / No

Photos

Photo #	Description

Points on Feature. UTM NAD83. Grid Zone: 18 / 19 (circle one).

Waypoint	Easting	Northing	Comments (NW corner of slide, center of slide, base of gully, etc)

Dominant Surficial Material (circle one): dense till, loose till, till, boulder gravel, cobble gravel, pebble gravel, gravel/sand, sand, sand/silt, silt, silt/clay, muck, peat, unknown. For complex stratigraphy, describe in Stratigraphic Log.

Stratigraphic Log (with thickness of layers in meters). Surficial material choices include dense till, loose till, till, boulder gravel, cobble gravel, pebble gravel, gravel/sand, sand, sand/silt, silt, silt/clay, muck, peat, unknown.

Thick-ness	Surficial Material	Cohesive (yes / no)	Description (texture, color, sorting, consistency, moisture, bedding, structures, roots, etc.)	Environment of Deposition

Profile of Slope. Specify scale and orientation. Site No. ____

Show major breaks in slope, the extent of any displaced mass, and the extent of any toe deposit. Show stratigraphy of the deposit as far as it can be determined.

Map View. Include scale and orientation.

Causes of Slope Failure *(circle dominant cause and underline subordinate causes):*

- Stream erosion
- Heavy rainfall
- Rapid snowmelt
- Wave erosion
- Water diversion onto slope
- Water level drawdown
- Loading on slope or crest
- Excavation at toe or on slope
- Other
- Unknown

Comments ____

____

____

____

____

Instructions for the Vermont Geological Survey Slope Stability Data Sheet

Introductory Matter
Location: Name of river, landslide complex, study area, etc.
Observer: List principal observers.
Site No: Original researcher's site ID number. These are likely to be project-specific and take many forms.
Date: Date of field visit.
Town: Town or city.
Stream Reach/Segment ID: VT DEC Identification code.

Classification
Style of slope failure: Choose the appropriate broad class or style of feature from the list. This sheet is not intended for analysis of rock slope failures or erosion of low streambanks (those less than about 3 meters high).
None:
Soil Creep: The process operates to varying degrees on almost all slopes, whether of rock or soil. Creep may affect the upper few centimeters of soil on a bank or operate at depths of one or perhaps several meters. However, creep processes are commonly observed at the incipient stages of landslide activity at a site and/or at the margins of an active landslide.
Gullying: Areas of active or former gully formation should be noted. When a gully has distinct landslides at the head or on the sides, it can be classified as a landslide-gully complex (see below) .
Landslide: Classify using the landslide types described below.
Landslide-Gully complex: A gully that is actively expanding may have prominent landslides at the head or on the sides. Classify the landslides using the landslide types described below.
Streambank Erosion: The processes leading to streambank erosion are essentially identical to those that result in landslides. Both are indications of unstable slopes. However, features below approximately 3 meters in height are here classed as streambank erosion and are not a focus of this manual.
Landslide type: Although fresh landslides may have forms that correspond reasonably well to those in Table 1, the slides that occur on stream banks tend to be rapidly altered by the stream at the base, by ground water sapping or piping, by surface runoff down from the top, and by surface earth flows. The end result of a bank failure that is more than a few months old may be somewhat difficult to classify. However, if there are other nearby slides in similar materials that are at different stages in their evolution, these may be used to interpret the older slides.

A typical rotational slump-flow landslide is shown in Figure 1.

Table 1. Simplified classification of slope movement types. Modified from Varnes (1978). Types common in Vermont are in bold. Spreads have not been encountered in Vermont.

Type of Movement	Type of Material		
	Bedrock	Engineering Soils	
		Predominantly coarse	Predominantly fine
Falls	**Rock fall**	Debris fall	**Earth fall**
Topples	**Rock topple**	Debris topple	**Earth topple**
Slides*	**Rock slide**	**Debris slide**	**Earth slide or slump**
Spreads	Rock spread	Debris spread	Earth spread
Flows		**Debris flow**	**Earth flow**
Complex	**Combinations of two or more types of movement**		
Creep	**Several types**		

*Slides may be subdivided into rotational and translational types. Rotational slides in relatively homogeneous materials have commonly been called "slumps". The term "rotational slump" although somewhat redundant, will be used here to emphasize the rotational nature of the slump

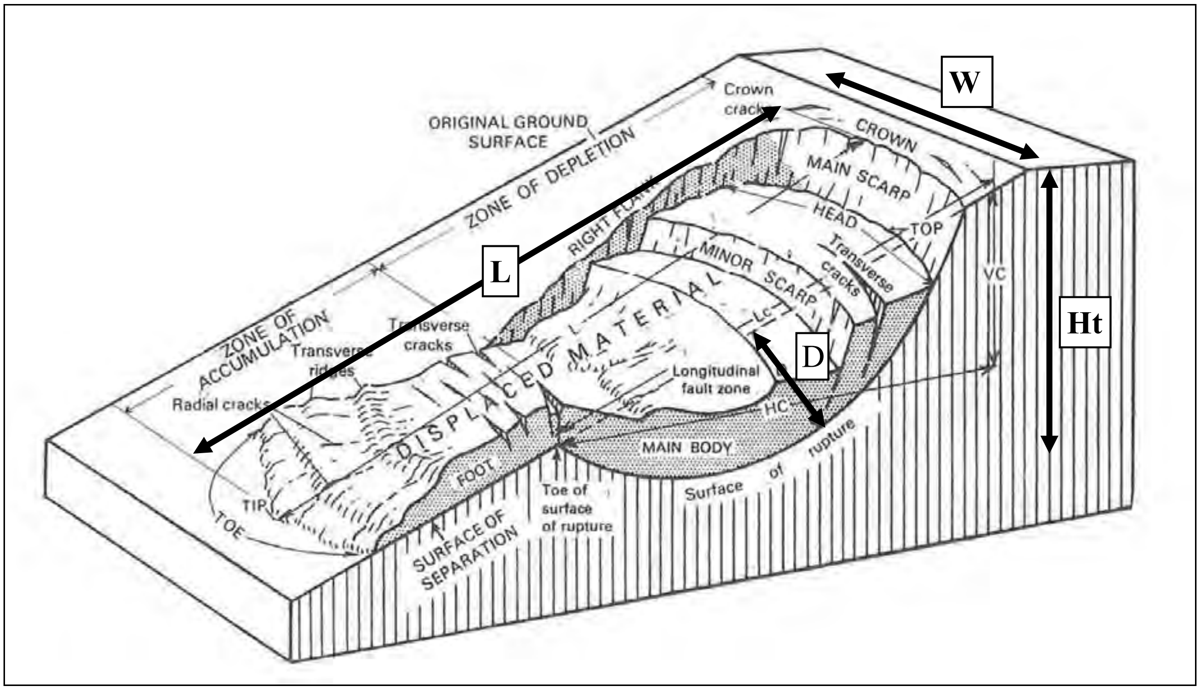

Figure 1. Generalized complex rotational slump/flow showing principal features. Landslides with this overall form are common on clayey to sandy lacustrine deposits throughout Vermont. In many cases the displaced material has been at least partially eroded away by stream flow. Length (L) refers to the total slope length from crown to the tip of the toe. Width (W) refers to the width of the feature measured across the slope at the location of greatest width. Depth (D) is measured in a vertical plane and perpendicular to the original slope. Height (Ht) refers to the vertical height from the toe up to the top of the slide. Modified from Cruden and Varnes (1996, Figure 3-3).

The most common types of landslides in Vermont are the slides, which take two general forms as shown in Figure 2; rotational slides (here called rotational slumps) and translational slides. The translational slides generally occur on unstable slopes underlain be weathered, dense till, as well as slopes underlain by sandy to clayey lacustrine deposits, while the rotational slides (here called rotational slumps) are more common on unstable slopes underlain by sandy to clayey lacustrine deposits. Both rotational and translational failures imply that the material has internal cohesion, otherwise the material would disintegrate into some sort of flow. They are described in more detail in the following sections.

Note that no classification of velocity of landslide movement is included. In the experience of the authors, information on velocity is so rarely available for Vermont landslides that it will be sufficient to incorporate it as a comment in the few cases where it is available.

Rotational Slumps

Rotational slumps are common in the stratified deposits that are widespread in the larger stream valleys of Vermont, especially the cohesive glaciolacustrine silts, silty clays, and clays, although they may also occur in glacial till following especially severe episodes of stream erosion. The characteristic form of the rotational slump, as shown in Figure 1, has a curving fracture or shear surface that intersects the ground either on the bank or behind the top of the bank. It is then seen to curve down to a bed or lamination either within the bank or at the base. The shear may then extend all the way out to the free face or, more commonly, curve upward to take a path of least resistance to the free surface. Slump material often undergoes considerable deformation during failure and as the displaced material moves downward, the lower parts of this must, if they stay at least partly together, ride up over the lower end of the rupture surface (where the rupture broke up toward the old ground surface). It is also common for pieces of the displaced material to stack up on top of or push over earlier blocks or masses of displaced material. Seen in plan view from above, such rotational shear surfaces are commonly arcuate and concave out toward the stream. Earth flows in the lower portions of rotational slump/flows are in some places so extensive that they mask the original brittle nature of the slope failure.

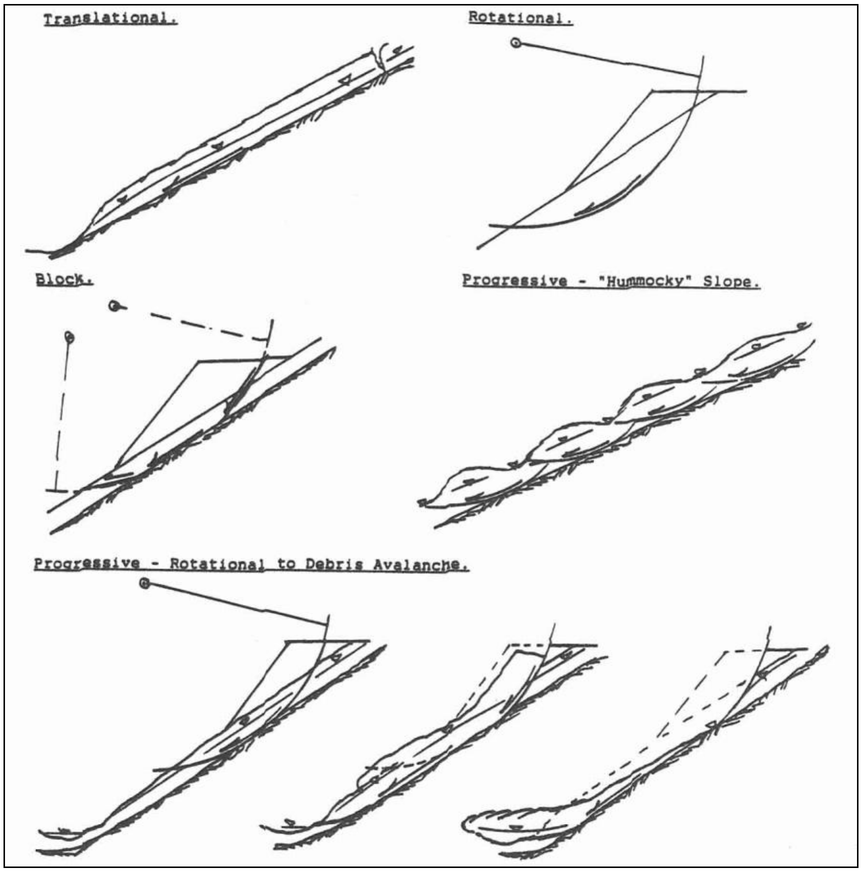

Figure 2. The translational and rotational forms of slope failures and composite forms. The pure translational slide would have a tension crack at the top and be completely translational from there down. Actual translational slides will often have some shearing motion in the upper part and may well break out in the lower parts as one or more rotational shears. The lower set of three sketches shows a rotational slide progressively changing to a debris avalanche or flow as a result of the disaggregation of the sliding mass. From Prellwitz and Remboldt (1994, Figure 5A.2).

Translational Slides: Unstable slopes that are underlain by the dense till that is common throughout Vermont commonly fail through relatively shallow landslides. These slides are also common in stratified lacustrine and marine sands, silts, and clays. On wooded slopes that have not experienced landsliding for a considerable time, the upper several feet is typically some combination of surficial material that has weathered in place and/or colluvial material derived from the surficial deposits. In both cases the material retains the wide range in grain sizes of the parent material and is significantly weaker than the underlying unweathered deposit. This upper material is often relatively impermeable and thus slow to drain. If the toe of such a slope is eroded by a stream, the contrast in strength between the weathered surficial material above and the dense, relatively unweathered material below results in the slope having a tendency to fail along the boundary. Thus, although the slides can extend great distances up and down the slopes and along the slopes, the slides rarely "bite" into the hillside deeper than 3 meters (10 feet) or so at a time.

More than one process may operate in a translational slide. The cohesion due to roots may help hold the slope together in large patches, yet failure has to happen somewhere. The first visible fractures will be in the form of tension cracks at the upper boundaries and perhaps fractures along the sides of the failing area. Some blocks will slide intact all the way down to the base of the slope while others will disaggregate into flows.

Flows

Flow-type slope failures are found in two main settings in Vermont. The displaced material of translational and rotational slides is commonly disaggregated into small- or medium-scale earth or debris flows or channelized debris flows on steep mountainsides. The channelized debris flows may originate from slope failures on the slope or be initiated by rock fall from a cliff above.

A Note on Mechanisms of Detachment

During floods, the fluvial shear stress operating on the base of a slope (especially on the outside of a meander bend) can tear away individual grains and irregular chunks of material, oversteepening the bank, and leading to slope failure that extends far above the reach of the flood waters.

Detachment of irregularly shaped blocks is especially common on dense till slopes. Slopes of unweathered dense till commonly have sufficient short-term shear strength to stand as vertical or even overhanging slopes for some months after a flood. Blocks will continue to detach from such a slope for many months after the erosion event. The blocks may fall, roll, or slide downslope. Eventually, weathering will soften the remaining material and the failure mechanisms will shift toward the more common slides and flows. In these cases the landslide type should be recorded as "other" and this should be described in the comments as "irregular block detachment."

Landslides comprised primarily of loose, non-cohesive material (primarily loose sands and gravels) may, in the response to fluvial erosion, fail by detachment of separate particles. The landslide type should be recorded as "other" and this should be described in the comments as "grain detachment."

Landslide Material

The definitions in this section are after Cruden and Varnes (1996). *Rock* consists of an intact mass of hard or firm material. We will further restrict this here to mean solid bedrock. Thus, if a solid rock mass detached from a cliff and slid down a slope, it would be called a rock slide. *Debris* contains a large amount of coarse material greater than 2 mm in diameter (20 to 80%). *Earth* consists of material that has 80% or more of particles smaller than 2 mm. Debris and earth together constitute the materials that engineers conventionally describe as soil.

Activity

An *active* landslide is one that has moved within the last year. The sides and upper margin of such a landslide are generally sharp and any exposed slide surfaces are bare of vegetation or have only the beginnings of pioneer vegetation on them.

An *inactive* landslide has not moved within the last year, but it is in a setting in which it could be reactivated (Cruden and Varnes, 1996). One that has been inactive for several years may be largely revegetated, at least with pioneer vegetation. Inactive landslides are common near actively migrating stream meander bends where the site of landslide activity has shifted downstream as the stream meander has shifted downstream. The inactive slides may very well be reactivated if another meander bend migrates down from upstream.

We define a *relict* slide as one where there is no evidence of movement for many years and the likely causative agent is no longer present. An example would be a former stream cut bank formed by stream erosion in early Holocene time. If the stream has since cut down vertically and moved away in such a fashion that it is now trapped by bedrock and would be unable to move back to the old cut bank, that cut bank could be considered relict. Such a feature is generally completely revegetated and the edges have been softened by erosion.

If dates of landslide activity are known, they should be noted. This information can be critical to understanding the frequency of landslide activity at a site. Precise dates can help to evaluate connections between times of snowmelt or heavy precipitation and landslide activity.

Slope Failure Geometry: Note that all dimensions should be measured in meters.
Width: Measured across the toe of the landslide. Shown as W in Figure 1.
Depth: Measured perpendicular to the original slope. Shown as D on Figure 1.
Length: Slope length. Shown as L on Figures 1 and 3. Measurement is optional as it can be calculated from the height and overall slide angle.
Height: The vertical height should be obtained, when possible, by actual measurement. This may be done by tape and clinometer, rangefinder and clinometer, or by hand-leveling up the feature. Shown as Ht on Figures 1 and 3.

One way to calculate the height is use the formula Ht = Lsin(va), where Ht = height, L = slope distance, and va = the vertical angle from the top of the slide to the toe. The slope length L can be measured with either a tape or a laser rangefinder. The vertical angle needs to be measured with a clinometer. If the measurements are made by a person standing at the bottom of the slope, then the eye-height (eh) of the person needs to be added to the calculated height as follows: Ht = (Lsin(va))+eh.

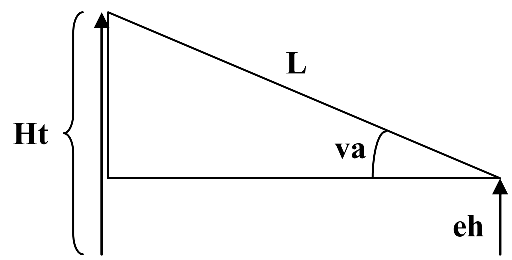

Figure 3. Calculation of height of a landslide. L = slope distance, va = vertical angle, eh = eye height, Ht = total height of landslide.

Example: L = 18.6 m, va = 36°, and eh = 1.8 m.
Ht = (18.6sin(36°))+1.8
Ht = ((18.6)(.5878))+1.8
Ht = 12.7 m

Another way to measure the height of a slope is to use a hand level to measure a succession of eye-heights up the slope. The number of steps is tallied and multiplied by the eye height. Fractions of an eye height can be either estimated or measured using a survey rod, folding rule, or Jacobs staff.

Example: If a person's eye height is 1.75 m, and a succession of 6 eye heights plus an additional 0.5 m are measured from top to bottom, the total height is 10.5+ 0.5 = 11.0 m.

Aspect: The direction that is most nearly directly down the slope of the feature. This should be measured relative to true north and values should run from 1 to 360 degrees.
Overall Slide Angle: The vertical angle from the toe to the crown.
Original Slope angle: The vertical angle of the slope on which a landslide subsequently formed. The original slope angle can often be approximated by measuring the slope of the land to the side of the slope failure. However, in cases where there have clearly been successive slope failures, measure the slope on which the most recent failure occurred.
Area Estimate: A rough estimate of the area in square meters. Although polygons will be delineated using the GPS points for the larger landslides during the GIS analysis, this will not always be feasible for the smaller landslides.

Other Features:
Condition of Toe: An indication of how much the landslide has been modified since it was last active. Is the toe intact? Has it been partly eroded by a stream at the base or by human activity? Has it been removed entirely?

Bedrock present on slope?: Look to see if bedrock is exposed anywhere on the slope. The presence of bedrock might limit the extent of possible slope failures.
Bedrock grade control in stream? The presence of a grade control in the stream bed may limit the possibility for incision and thus reduce the severity of future landsliding or, alternatively it may mean that the stream may be prone to lateral shifts in planform, which may aggravate any slope stability problems. Be sure to check up and downstream from the site and to review available stream geomorphic assessment data.
Is slope on outside of a meander bend? Landslides in proximity to streams are commonly found at these locations. Keep in mind that an inactive or relict slide may well have formed at a meander bend, even though the stream has since shifted position. If that is the case, note the fact in the comments rather than by checking yes for this question.
Headcut in bottom of stream? Headcuts or knickpoints are locations where the bed abruptly lowers. They are a sign that the stream is changing grade in response to changes in sediment supply, flood frequency, or flood magnitude. If a stream segment is undergoing active headcutting, the adjacent slopes can be expected to become less stable.
Springs? Seeps? Piping? The presence of any of these features provides important information about the presence of groundwater on the slope. Springs are areas of groundwater discharge with visible flow. Seeps are persistently wet areas on the slope where groundwater comes to the surface. Pipes are areas where outward subsurface flow of groundwater has eroded a subterranean channel back into the slope.

Photos: The photographs that you take at a site can be among the most valuable pieces of field information, but only if they are sharp and well-documented. Make sure there is a person or survey rod or other scale in each photo. Record the number and what the photo shows. Fewer photos with good documentation are preferable to a large number of undocumented ones.

Points on Feature: Obtain GPS positions in order to facilitate delineation of the landslide in GIS. At the very least, obtain one position at the bottom, top, or center of the feature (specify which). Use UTM Grid, NAD 83. Specify UTM Grid Zone (18 or 19 in Vermont). When an LSPOINT record is created for the landslide, the position of the approximate center of the feature will be estimated. This task is made considerably easier if GPS positions have been taken at 3 or more points on the margin. **Mapping-grade GPS receivers and post-processing of the data to a sub-meter level of accuracy are preferred**, but a recreation-grade receiver can be used if it meets the contract requirements.

Dominant Surficial Material: This may be one of the following: dense till, loose till, till, boulder gravel, cobble gravel, pebble gravel, gravel/sand, sand, sand/silt, silt, silt/clay, unknown. Make an attempt to identify the dominant material. Note that this is primarily a material description, not an interpretation of environment of deposition. It is necessary to distinguish toe deposits and later deposits of materials that have sloughed down from above from the in-place surficial material. Look for gullies and eroded spots where this material is exposed. Judicious shoveling and scraping can often expose a series of spots that will give you a good idea of the underlying material. Almost all sites will have two or more units, which should be described in the stratigraphic log.

Stratigraphic Log: This is intended to be a flexible way of recording detailed observations of the units encountered. Although the log only gives columns for thickness, basic type of material, cohesion, texture, color, sorting density/stiffness, moisture, bedding, structures, and interpretations, additional features can be included in comments section.

Thickness: Vertical thicknesses of the units in meters. The surficial units will generally be bounded by upper and lower surfaces that are approximately horizontal. If that is not the case, then this should be noted on the profile sketch and in the comments. Even in the case of steeply dipping delta foreset beds, the foreset beds will commonly be bounded below by roughly horizontal bottomset beds and above by either topset beds or they will have been planed of along an approximately horizontal erosion surface and overlain by fluvial deposits.

Cohesion: Surficial materials can be either cohesive or non-cohesive. This parameter is very important for understanding the stability of slopes. Cohesive materials are those with a substantial clay content, such as clayey silt or silty clay, while coarser grained soils such as the coarser sands and gravels and sandy till are to be classed as non-cohesive. Till should only be classed as cohesive if it has a clay-rich matrix. This is a rough field classification and would not necessarily stand up to laboratory scrutiny.

Texture: In soil science terminology, the term "texture" refers to grain size distribution. The grain size of materials is important for understanding the geotechnical behavior of the bank, because of the influence on soil shear strength, the influence on hydraulic ease of ground water movement, and surface water erosion. The standard classification for geologic analysis is the Udden-Wentworth scale described in Table 2.

Table 2. Udden-Wentworth grain size classification. Modified from Boggs (1995,Table 4.1).

Millimeters	Udden-Wentworth Size Class	
>256	Boulder	Gravel
16 - 256	Cobble	
4 - 16	Pebble	
2 - 4	Granule	
1 -2	Very coarse sand	Sand
.5 - 1	Coarse sand	
.25 - .5	Medium sand	
.125 - .25	Fine sand	
.0625 -.125	Very fine sand	
.031 - .0625	Coarse silt	Silt
.0156 - .031	Medium silt	
.0078 - .0156	Fine silt	
.0039 - .0078	Very fine silt	
<.0039	Clay	Clay

Color: The color of surficial materials can be helpful in interpreting the environment of deposition and the soil drainage conditions. The standard technique is to use a Munsell color chart. It is best to compare a sample to the chart while in a moist state and in direct sun when possible. Besides the matrix color, also record the color, distinctness, and abundance of mottles and other redoximorphic features.

Sorting: Sorting is the degree to which grains are of a uniform size (Figure 3). A very well sorted material has a uniform grain size while a very poorly sorted material has a wide range in grain sizes. The soil engineer's term "grading" is the inverse of sorting, with well graded soils having a wide variety of grain size and uniformly/poorly graded soils being of uniform size.

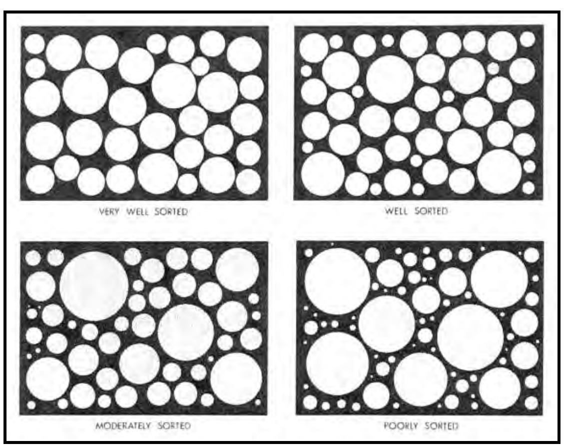

Figure 3. Sorting of particles. Very well sorted materials have uniform grain size (upper left) while poorly sorted materials have a wide variation in grain size (lower right). From Boggs (1994).

Consistency: This term is used to refer to the geotechnical terms density and consistency. These are material characteristics that essentially refer to the ability to resist penetration. In standard geotechnical usage the term density is used to refer to coarse grained deposits and the term consistency refers to fine grained materials: silts and clays. The standard geotechnical classifications for these are given in Tables 3 and 4.

Table 3. Relative density classification. N-values refer to the Standard Penetration Test (a commonly used field test performed while conducting split-spoon augering). From Renteria (1994).

N-value	Relative Density
0 - 4	Very loose
5 - 10	Loose
11 - 29	Medium dense
30 - 49	Dense
>50	Very dense

Table 4. Consistency classification for fine-grained soils. Unconfined compressive strength of clay can be roughly determined by penetrometer or torvane tests. From Renteria (1994).

N-value	Unconfined compressive strength (tsf)	Consistency
0 - 2	< 0.25	Very soft
3 - 4	0.25 - 0.50	Soft
5 - 8	0.50 - 1.0	Medium
9 - 15	1.0 - 2.0	Stiff
16 - 30	2.0 - 4.0	Very Stiff
> 30	>4.0	Hard

*Moisture: D*ry material feels dry to the touch, moist material feels damp but there is no visible water, and wet materials have visible water.

Bedding or Stratification: Surficial materials display a wide variety of physical features at a scale larger than the individual grains. Some of these features formed as sediment was deposited while others formed long afterwards. "Stratification" is the general term for the primary depositional layering of sediments. As described in Table 5, strata can vary from thick beds to thin laminae. It is possible for a deposit to be massive, that is, completely uniform throughout. This is most commonly encountered in deposits of till, although it is quite common that a careful search will reveal signs of stratification even in these.

Table 5. Stratification. From Boggs (1995).

Very thickly bedded	>100 cm thick
Thickly bedded	30 - 100 cm thick
Medium bedded	10 - 30 cm thick
Thinly bedded	3 - 10 cm thick
Very thinly bedded	1 - 3 cm thick
Laminated	< 1 cm thick

Structures: The term "structure" has unfortunately been used in three very different senses. Geologists use structure in two senses. They define primary sedimentary structures as the features formed during and shortly after the deposition of sediments, such as bedding, lamination, cross bedding, ripple marks, rain drop prints, faults and folds resulting from collapse, water escape structures, etc. By contrast, secondary structures form at some time after deposition. These include a wide variety of faults and folds that form long after deposition, as well as concretions formed through chemical interaction of ground water and sediments. In each of these geologic senses of the term "structure" the terms have strong genetic connotations. In contrast to the wide variety of structures recognized by geologists, soil scientists describe the structure within soil horizons using a fairly simple geometric classification (Table 6). Some of these have their origin as sedimentary features while others are the result of soil-forming processes. These terms provide a rough way to describe how the individual grains in the deposit form aggregates or bodies as they are broken out of the side of the bank.

Table 6. Soil structure. Modified from Schoeneberger and others (2002).

Massive	Individual soil particles entirely bound together into one aggregate
Single-grain	Individual soil particles not bound to one another at all
Granular	Spheroidal peds or granules usually packed loosely
Blocky	Irregular, roughly cubelike peds with planar faces (angular to subangular)
Platy	Flat peds, usually roughly horizontal
Prismatic	Vertical, pillarlike peds with flat tops

Contacts: If exposed, contacts between units should be described by specifying whether the lower contact of each unit is sharp (<= 2 cm thick) or gradational (> 2 cm). If gradational, note the thickness of this transition interval.

Stratigraphy: Describe the overall depositional patterns, viewed both in cross-section and in planform. These shifting patterns are due to changes in source areas and changes in the energy distribution within the depositional system (changes in water velocity, flow depth, turbulence, etc.). Patterns include the small-scale rhythmic sedimentation of varved lacustrine deposits, large-scale coarsening of grain size upward within lacustrine deposits as the water body fills in over time, and fining upward of fluvial deposits due to changing from bed load to suspended or wash load.

Roots: These can have a considerable strengthening effect. Both the distribution and size of roots should be noted. On most freshly eroded stream banks, the roots will be seen to be concentrated in the upper meter or so of the bank, although cases of very deep penetration are encountered.

Other Features: The features listed below can be important for interpreting the slope stability at a site.
Plasticity: A rough field classification of plasticity that can be performed by kneading a sample, rolling it out in the hand into a rod, and seeing if it can hold together when suspended. The criteria are listed in Table 7.

Table 7. Field criteria for determining the plasticity of cohesive soils (Schoeneberger and others (2002).

Will not support 6 mm diameter roll if held on end.	Non-plastic
6 mm diameter roll can be repeatedly rolled and supports itself, 4 mm does not.	Low plasticity
4 mm diameter roll can be repeatedly rolled and supports itself, 2 mm does not.	Medium plasticity
2 mm diameter roll can be repeatedly rolled and supports itself	high plasticity

Fractures: Surficial deposits may be fractured, in places to depths of several meters. Prominent fractures should be described as encountered. The features to observe include the geometry of the fractures, the fracture density, continuity, and cross-cutting relationships. As the fractures are developed in non-lithified materials below the surface of the ground, great attention should be paid to fracture infillings and alterations along the walls of the fractures. A good description of the general terminology for fracture description is in Bureau of Reclamation (1998, Chapter 5).

Weathering: Are freshly exposed parts a different color or consistency from parts long-subjected to weathering? This can have profound effects on the strength of surficial materials.

Reaction to HCl: A simple test for the presence of carbonate minerals is made by placing a drop of dilute (10%) hydrochloric acid on a sample. Fizzing indicates the presence of carbonate. Carbonate-rich parent materials will often show strong leaching in their weathered upper horizons.

Clasts: In the sense of these field descriptions, the clasts are the large particles that stand out in a finer matrix. Their size, shape, arrangement, and lithology may be useful in interpreting the source area and environment of deposition. Clast characteristics are particularly important to note in till or diamict deposits.

Fabric: This refers to the orientation of the particles in a sedimentary deposit. Examples include the imbricated arrangement of pebbles, cobbles, or boulders arranged by flowing water so as to face upstream or the preferred alignment of the long axes of clasts parallel to the glacial flow direction as seen in some tills.

Environment of Deposition: Make an effort to objectively describe the characteristics of the layers and the landforms. If you don't feel confident that you understand the origin of a particular unit or landform, refrain from speculating and just describe it. The characteristics listed below are all, important for the understanding of slope stability and should be selectively included in the interpretations and comments as the situation requires.

Profile of Slope and Map View: The profile and sketch map are very important. On one or both of these include details on the major breaks in the slope, the extent of any displaced mass, the extent of toe deposits, stratigraphic breaks, zones of groundwater flow, etc.

Causes of Slope Failure: There is commonly more than one cause for a slope failure. The most common ones are listed on the data sheet. For a more detailed discussion of causes see Wieczorek (1996).

Comments: The comment section can include more detail as to location, type of landslide, movement history, velocity of movement, landscape position, stream geomorphology, causes of slope failure, and geologic interpretation. This is a very important part of the data sheet where characteristics that are unique to the site in question can be recorded.

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Appendix B

Fields to Be Used for Landslide Point Database (LSPoint)

Attribute Name	Data Type	Description	Gen.
LS_ID	Text (15)	Landslide name composed of the 4 or 5 character quad abbreviation plus a four digit sequential number, e.g. Burl0022	
LS_COMPLEX	Text (20)	Name of landslide complex, if applicable	
ORIG_SITE_ID	Text (15)	Original researcher's site ID number	
OBSERVER	Text (15)	Researcher name	
ORGANIZATION	Text (15)	Researcher organization	
LS_DATA_SOURCE	Text (20)	Data source (map, publication, report, air photo, oral communication, field)	drop-down
FIELD_VISIT	Text (3)	yes/no	drop-down
VISIT_DATE	Date	Date of field visit; assumes that observer did the work	
CREATION_DATE	Date	Date of record creation	
REVISION_DATE	Date	Date of latest record revision	
TOPOMAP	Text (20)	7.5 minute quad name(s)	auto
TOWN	Text (20)	Town name with initial capitals	auto
UTM_NORTHING	Float	UTM coordinates, NAD83	
UTM_EASTING	Float	UTM coordinates, NAD83	
UTM_GRID_ZONE	Short integer	Valid choices for Vermont are 18 or 19	
RchptID	Text (12)	Tie-in to Stream Geomorphic Assessment data from the DEC River Management Program)	auto
RchsegID	Text (12)	Tie-in to Stream Geomorphic Assessment data from the DEC River Management Program)	auto

LS_TYPE	Text (25)	Fall, topple, slide (undifferentiated), rotational slide, translational slide, complex slide/flow, flow, other	drop-down
TALUS	Text (5)	yes/no/unknown	drop-down
LS_DEPTH	Text (20)	Shallow (<3 m; deep (>3 m); unknown	drop-down
MATERIAL	Text (10)	Rock, debris, earth	drop-down
ACTIVITY	Text (10)	Active, inactive or dormant, relict	drop-down
DATE_FAILURE	Date	Date of most recent failure; see comments for dates of previous failures	
LS_CERTAINTY	Text (12)	Certainty that feature is a landslide (definite, probable, questionable)	drop-down
LENGTH_M	Float		
WIDTH_M	Float		
HEIGHT_M	Float	Elevation difference between top and bottom of slide	
SLOPE	Float	Angle of the original slope in which the slide occurred, in degrees down from horizontal	
ASPECT	Float	Aspect of original slope, in degrees, measured to the right from true north; valid values are 1 to 360, zero is not used	
ELEV_CROWN_M	Float	NVD, 1988	
ELEV_TOE_M	Float	NVD, 1988	
PROFILE_GEOM	Text (15)	Original slope profile geometry (convex, planar, concave, complex)	drop-down
PLANFORM_GEOM	Text (15)	Original slope planform geometry (convex, planar, concave, complex)	drop-down
VEGETATION	Text (20)	In landslide source area (trees, saplings or shrubs, herbaceous, mixed, bare)	drop-down
LAND_USE	Text (10)	Standard USGS land-use/land cover classification	

SURF_MATERIAL1	Text (20)	Material in uppermost layer (dense till, loose till, till, boulder gravel, cobble gravel, pebble gravel, gravel/sand, sand, sand/silt, silt, silt/clay, muck, peat, unknown)	drop-down
SURF_MATERIAL2	Text (20)	Material in layer underlying SURF_MATERIAL1 (dense till, loose till, till, boulder gravel, cobble gravel, pebble gravel, gravel/sand, sand, sand/silt, silt, silt/clay, muck, peat, unknown)	drop-down
SURF_MATERIAL3	Text (20)	Material in layer underlying SURF_MATERIAL2 (dense till, loose till, till, boulder gravel, cobble gravel, pebble gravel, gravel/sand, sand, sand/silt, silt, silt/clay, muck, peat, unknown)	drop-down
SURF_MATERIAL4	Text (20)	Material in layer underlying SURF_MATERIAL3 (dense till, loose till, till, boulder gravel, cobble gravel, pebble gravel, gravel/sand, sand, sand/silt, silt, silt/clay, muck, peat, unknown)	drop-down
SURF_MAP_UNIT	Text (25)	Classification on a surficial geologic map at a scale of 1:24,000 or larger, if available (e.g. Pleistocene esker deposit, Holocene stream terrace deposit, etc.)	
SURF_MAP_SOURCE	Text (25)	Map used to identify geologic materials at the surface	
GULLIES	Text (6)	yes/no/unknown	drop-down
SEEPS	Text (6)	yes/no/unknown	drop-down
PIPING	Text (6)	yes/no/unknown	drop-down
TOE_EROSION	Text (6)	yes/no/unknown	drop-down
DAMAGE	Text (6)	yes/no/unknown	drop-down
INJURIES	Text (6)	yes/no/unknown	drop-down
COMMENTS	Text (100)		
DOMINANT_SURF_M	Text (20)	Dominant surficial material: dense till, loose	drop-

		till, till, boulder gravel, cobble gravel, pebble gravel, gravel/sand, sand, sand/silt, silt, silt/clay, muck, peat, unknown	down
SLIDE_ANGLE	Float	Overall angle from top of slide to toe	
TOE_CONDITION	Text (16)	Intact/partly removed/totally removed	drop-down
BEDROCK_SLOPE	Text (6)	Bedrock present on slope: yes/no/unknown	drop-down
BEDROCK_STREAM	Text (6)	Bedrock grade control present in stream bed: yes/no /unknown	drop-down
MEANDER_BEND	Text (6)	Slope on outside of meander bend: yes/no / unknown	drop-down
SPRINGS	Text (6)	yes/no/unknown	drop-down