Slope Stability Map of Massachusetts

Compiled by Stephen B. Mabee and Christopher C. Duncan

Prepared for the Massachusetts Emergency Management Agency, the Federal Emergency Management Agency and the Massachusetts Department of Conservation and Recreation

December 2013

This report is available on CD and online. Additional copies of this report and all accompanying documentation are available upon request by contacting the Massachusetts Geological Survey.

Address:
Department of Geosciences
University of Massachusetts
611 North Pleasant Street
Amherst, MA 01003
Telephone: 413-545-4814
Fax: 413-545-1200
Email: sbmabee@geo.umass.edu
World Wide Web: http://www.geo.umass.edu/stategeologist

Authors: Stephen B. Mabee, State Geologist, University of Massachusetts – Amherst
Christopher C. Duncan, Principal, GIS*matters*

Acknowledgements:

This work was funded by the Federal Emergency Management Agency through the Massachusetts Emergency Management Agency under Interagency Service Agreement CT-CDA-ISACDAHM189561UMS12A. Authors wish to thank the Massachusetts Department of Transportation engineers in Districts 1 and 2 for their cooperation on this project. Authors also want to acknowledge Cody Jones from the Geotechnical Group at the University of Massachusetts Department of Civil and Environmental Engineering for his help in researching and assembling the geotechnical data used in this study.

Cover: View looking up one of the large translational debris slides that occurred along Route 2 in Savoy, Massachusetts during tropical storm Irene on August 27-28, 2011. Pictured (from top to bottom) is Pete Connors, MassDOT, Steve Mabee (MA State Geologist) and Mike Yako (GEI Consultants). Photo by Joe Kopera.

Executive Summary

The purpose of this project is to prepare an updated map of potential landslide hazards for the Commonwealth of Massachusetts. The intent is to provide the public, local government and local and state emergency management agencies with a map showing the location of areas where slope movements have occurred or may possibly occur in the future under the right conditions of prolonged antecedent moisture and high intensity rainfall. It is hoped that this information will be included in the Statewide Hazard Mitigation Plan upon its next update. It is also anticipated that MassDOT and municipalities will find this information useful in planning upgrades and improvements to culverts and drainage along roadways in the future.

Three slope stability maps are provided at a scale of 1:125,000. Each sheet is 48 inches by 36 inches when printed. Sheet 1 covers western Massachusetts, Sheet 2, northeastern Massachusetts including the Boston area, and Sheet 3 covers southeastern Massachusetts, Cape Cod and the Islands. Data are also available as ESRI ArcGIS data files.

SINMAP, a deterministic model developed by Pack et al. (1998), which is a contraction for Stability Index Mapping, is used to identify areas that may be prone to shallow, translational landslides. SINMAP employs the infinite slope model to determine the propensity of a slope for failure. The model incorporates the severity of the slope (slope angle), information about the soil properties, including angle of internal friction and cohesion, and a relative wetness parameter. The wetness parameter includes flow direction, the upgradient area contributing to flow and the soil's ability to transmit water laterally in the shallow subsurface (transmissivity) in response to infiltration from rainfall (recharge). The friction angle, cohesion and transmissivity/recharge parameters can be altered by the user if site-specific data on the soil properties and hydrology are available or the default parameters can be used that are recommended by the authors of the SINMAP program.

For this study, both the default and local "calibrated" parameters are used to model slope stability. Results indicate that the default parameters provide the best results in a comparison of model results with the location of known landslides. Using the default parameters, 70% of 106 known landslides identified in a test area in the northwestern part of the state, are within 100 meters of an area designated as either a moderate or high slope stability hazard zone and 80% to 100% are within 200 meters. Results obtained using the site-specific, "calibrated" soil and hydrologic parameters result in a map where nearly 100% of the state is categorized as very stable and are unrealistic based on observations. In the site-specific, calibrated model runs, the cohesion values are too high and the transmissivity/recharge ratios is too low suggesting that the complexities of landslides cannot be modeled well using soil parameters obtained through correlation of the geotechnical literature with digital soils data, surficial geologic map unit descriptions and boring logs.

Translational debris slides, rotational slides and debris flows are the most common types of landslides in Massachusetts. Most are caused by a combination of bad geologic conditions (silty clay or clay layers contained in glaciomarine, glaciolacustrine or thick till deposits), steep slopes and excessive wetness leading to excess pore pressures in the subsurface. Examination of historic landslides in Massachusetts since 1901 indicate that most occur when preceded by two

or more months of higher than normal precipitation followed by a single, high intensity rainfall of several inches or more.

It should be made clear that the infinite slope model only applies to shallow translational slides. It does not apply specifically to rotational slides or slides associated with over steepening of banks from wave action or flooding. However, the model is very sensitive to slope and therefore, many head scarps associated with rotational slides and over steepened banks in coastal areas and along river banks are identified as potential hazard zones even though the infinite slope model assumptions are not met completely. Field verification confirms these findings.

The maps produced from this project should be viewed as a first-order approximation of potential landslide hazards across the state at a scale of 1:125,000. They are not intended for site-specific engineering design, construction or decision making. The maps are provided only as a guide to areas that may be prone to slope instability when subjected to prolonged periods of antecedent wetness followed by high intensity rainfall. The maps do not guarantee or predict that a landslide will occur. In addition, there also may be instances where vertical bedrock outcroppings appear on the map as an unstable slope in the model output. However, the maps certainly provide an important first step by highlighting areas that may warrant additional, site-specific investigation if high or moderate slope stability hazard zones are located near major roadways, utilities or critical facilities.

Contents

Slope Stability Map of Massachusetts

Compiled by Stephen B. Mabee and Christopher C. Duncan

INTRODUCTION

The Massachusetts Geological Survey (MGS), in cooperation with GIS*matters*, has prepared a slope stability map for Massachusetts. This is the first statewide coverage of potential landslide hazards that incorporates detailed data sets of the topography, soils and surficial geology. This project was supported by a grant from the Federal Emergency Management Agency under the Hazard Mitigation Grant Program. The grant was awarded to the University of Massachusetts through the Massachusetts Emergency Management Agency under Interagency Service Agreement CT-CDA-ISACDAHM189561UMS12A.

Purpose and Scope

The purpose of this project is to prepare an updated map of potential landslide hazards for the Commonwealth of Massachusetts. The intent of this work is to provide the public, local government and local and state emergency management agencies with a map showing the location of areas where slope movements have occurred or may possibly occur in the future under the right conditions of prolonged antecedent moisture and high intensity rainfall. It is hoped that this information will be included in the Statewide Hazard Mitigation Plan when the plan is scheduled for its next update. It is also anticipated that MassDOT and municipalities will find this information useful in planning culvert and drainage improvements in the future.

This project covers the entire geographic extent of the Commonwealth and addresses specifically landslides that involve earth materials. Rockfalls, involving bedrock, are not part of this study. It should also be noted that the modeling approach utilized in this study applies strictly to translational debris slides where thin earth material and soil slides on a bedrock surface or some other internal failure plane within the soil that has contrasting geotechnical properties. However, as explained later, the approach selected depends on slope and thus the method does a reasonable job of identifying head scarps associated with rotational slides and over steepened slopes along coast lines and waterways that also may be vulnerable to sliding.

Previous Work

The previous landslide hazard map of Massachusetts contained in earlier versions of the statewide hazard mitigation plan is based on a very small-scale map. The map[1], produced in 1982, was prepared by evaluating formations or groups of formations shown on the geologic map of the United States (King and Beikman, 1974) at a scale of 1:2,500,000 and classifying them as having high, medium, or low landslide incidence (number of landslides) and being of high, medium, or low susceptibility to landsliding. Thus, those map units or parts of units with

[1] Radbruch-Hall, D.H. et al. 1982. Landslide overview map of the conterminous United States. Geological Survey Professional Paper 1183, 25p.

more than 15 percent of their area involved in landsliding were classified as having high incidence; those with 1.5 to 15 percent of their area involved in landsliding, as having medium incidence; and those with less than 1.5 percent of their area involved, as having low incidence. Final map production was completed at a scale of 1:7,500,000. Because some generalization was necessary at the smaller scale, several small areas of high incidence and susceptibility were slightly exaggerated in order to retain them on the map. Therefore, the 1982 map is generalized and inadequate for more detailed emergency preparedness and planning. Larger scale digital data (1:24,000 scale and larger) now exist for topography, geology and soils that can improve the resolution and detail shown on the map.

Data Products

In response to this need, the following products have been prepared.

1. Three slope stability maps at a scale of 1:125,000 (PDF format). Each sheet is 48 inches by 36 inches when printed. Sheet 1 covers western Massachusetts, Sheet 2, Northeastern Massachusetts including the Boston area, and Sheet 3 covers southeastern Massachusetts, Cape Cod and the Islands. There is ample overlap between sheets.
2. ESRI ArcGIS shapefiles of the slope stability classifications. All GIS data are referenced to North American Datum of 1983 (NAD 83) and projected in the Massachusetts State Plane coordinate system. These files also have accompanying metadata. The shapefiles can be displayed with any other MassGIS compatible data layers.
3. A report (this document) summarizing the methods and process used to compile the map information.

Intended Use and Limitations of the Slope Stability Map

The new 1:125,000 scale maps provided here are intended for use only as a guide. They are not intended for site-specific engineering design, construction or decision making. They can be used for community level planning and for prioritizing areas that might be examined for targeted remediation or future monitoring. However, the maps in no way guarantee that a landslide will occur but recognizes the possibility of slope movement under the right conditions of antecedent moisture, steep slope and high rainfall intensity.

Although the data used to make these maps have been processed successfully on a computer, no warranty, expressed or implied, is made by the Massachusetts Geological Survey regarding the utility of the data on any other system, nor shall the act of distribution constitute any such warranty. Every reasonable effort has been made to ensure the accuracy of the information on which the maps are based; however, the Massachusetts Geological Survey does not warrant or guarantee that there are no errors or inaccuracies. Efforts have been made to ensure that the interpretation conforms to sound geologic and cartographic principles. No claim is made that the interpretation shown is correct. The Massachusetts Geological Survey disclaims any responsibility or liability for interpretations from these maps or digital data, or decisions based thereon. Any enlargement of this map larger than 1:125,000 scale could cause misunderstanding in the detail of mapping and may result in erroneous interpretations.

How to Read the Map

The color-coded map delineates relative hazard rankings (high, moderate, low and very low) for the initiation of naturally occurring, shallow, translational slope movements (debris flows, debris avalanches, mudslides). These rankings are based on the severity of the slope, various soil parameters and the response of that landscape to rainfall that leads to saturated conditions (relative wetness index). The four relative hazard rankings are generalized from six stability zones. Table 1 provides the stability zones, relative hazard rankings, and the corresponding stability index ranges. The slope stability maps do not predict that slope movements will occur, but forecasts that if they do, where they are more likely to initiate given the assumptions and input parameters used in the analysis. Slope movements originate where thin soil (1 to 6 feet thick) overlies low permeability layers such as glacial till or bedrock on steep slopes typically those >20° (22° = 40% slope). Areas with high to moderate hazard rankings are areas where further slope stability analysis and assessment, including field verification, is recommended before any ground disturbance.

Column 1 in Table 1 shows the color associated with each relative slide ranking. For simplicity, red represents areas associated with a high slide ranking, pink is a moderate ranking, yellow low ranking and green represents a slide ranking of very low, which means the area is stable and not prone to landslides.

Column 2 is the Predicted Stability Zone and is based on the factor of safety (FS)(see Column 5 below).

Column 3 is the Relative Slide Ranking and designates the relative hazard ranking for the initiation of shallow slides on unmodified slopes. It includes high, moderate, low and very low.

Column 4 is the Stability Index Range and is a numerical representation of the relative hazard for shallow translational slope movement initiation based on the FS computed at each point on a 9 meter (~30 foot) digital elevation model grid derived from the National Elevation Dataset. The stability index is a dimensionless number based on factors of safety generated by the slope stability model that indicates the probability that a location is stable considering the most and least favorable parameters for slope stability when they are entered as part of the model input. Each surficial geologic map unit or soil type has an associated range of values for the angle of internal friction, cohesion, and a transmissivity vs. rainfall parameter (a relative wetness index). These values are used as input to provide a range of model outcomes. The breaks in the ranges of values for the stability index categories are the default values recommended by the model program developers.

Column 5 is the Factor of Safety (FS) and is a dimensionless number computed by the slope stability model using a modified version of the infinite slope equation (Pack et al., 1998). The infinite slope equation represents the ratio of the stabilizing forces that resist slope movement to destabilizing forces that drive slope movement. A FS > 1 indicates a stable slope, a FS < 1 indicates an unstable slope, and a FS = 1 indicates a marginally stable situation where the resisting forces and driving forces are in balance.

Map Color Code	Predicted Stability Zone	Relative Slide Ranking[1]	Stability Index Range[2]	Factor of Safety (FS)[3]	Probability of Instability[4]	Predicted Stability With Parameter Ranges Used in Analysis	Possible Influence of Stabilizing or Destabilizing Factors[5]
	Unstable	High	0	Maximum FS<1	100%	Range cannot model stability	Stabilizing factors required for stability
	Upper Threshold of Instability		0 - 0.5	>50% of FS≤1	>50%	Optimistic half of range required for stability	Stabilizing factors may be responsible for stability
	Lower Threshold of Instability	Moderate	0.5 - 1	≥50% of FS>1	<50%	Pessimistic half of range required for instability	Destabilizing factors are not required for instability
	Nominally Stable	Low	1 - 1.25	Minimum FS=1	–	Cannot model instability with most conservative parameters specified	Minor destabilizing factors could lead to instability
	Moderately Stable		1.25 - 1.5	Minimum FS=1.25	–	Cannot model instability with most conservative parameters specified	Moderate destabilizing factors are required for instability
	Stable	Very Low	>1.5	Minimum FS=1.5	–	Cannot model instability with most conservative parameters specified	Significant destabilizing factors are required for instability

Table 1. Explanation of stability rankings shown on the Slope Stability Map of Massachusetts.

Column 6 is the Probability of Instability and shows the likelihood that the FS computed within this map unit is less than one (FS < 1, i.e., unstable) given the range of parameters used in the analysis. For example, a <50% probability of instability means that a location is more likely to be stable than unstable based on the range of parameters used in the analysis.

Column 7 is the Predicted Stability With Parameter Ranges Used in Analysis. For example, in the Unstable Predicted Stability Zone (Column 2) the Predicted Stability With Parameter Ranges Used in Analysis (Column 7) is “range cannot model stability”. What this means is that even when using the most favorable soil parameters for stability (high angle of internal friction, high cohesive strength, etc.) the FS is still less than one and stability cannot be attained for that map unit. Likewise for the Moderate Relative Slide Ranking (Column 3), the Predicted Stability With Parameter Ranges Used in Analysis (Column 7) is “pessimistic half of range required for instability”. This means that when the less favorable soil parameters are used to model stability for that map unit, only then does the slope have a FS < 1 and this occurs less than 50% of the time. In the Low to Very Low Relative Slide Ranking (Column 3) category, however, Column 7 indicates that the map units “cannot be modeled for instability” even when the least favorable soil parameters are used in the analysis. The computed FS is not less than one.

Column 8 is the Possible Influence of Stabilizing and Destabilizing Factors. What this means is that certain activities could be undertaken to improve stability or certain conditions may occur that produce instability. Stabilizing factors include increased soil strength, root strength, or improved drainage. Destabilizing factors include increased wetness or loading, or loss of root strength.

BACKGROUND

Landslide Classification and Causes

Landslides are classified by the type of movement involved (falls, topples, slides (rotational or translational), lateral spreads, flows, or combinations of all the above), and by the type of material involved in the landslide, whether it is bedrock, predominantly coarse soil material or predominantly fine soil material. Another factor affecting the classification scheme is the amount of water involved in the landslide. Classification and examples of types of slides are shown in Figures 1 and 2, respectively. The most common types of landslides in Massachusetts are rotational and translational debris slides and debris flows (Figure 2A, B and F). Rockfalls and topples are also common but for the purposes of this project, landslides involving bedrock (rockfalls) are not considered.

There are three main causes of landslides: 1) geologic, 2) morphologic and 3) human induced.

Geologic – Geologic causes are related to weak or sensitive materials such as clays that are prone to failure; weathered materials; sheared, jointed or fissured materials; and, juxtaposition of earth materials with contrasting strength, stiffness or permeability.

Morphologic - Morphologic causes refer to uplifts due to seismic or volcanic activities; fluvial (river), glacial or wave erosion of the toes of slopes or lateral margins; subterranean erosion such

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	ROTATIONAL	Rock slide	Debris slide	Earth slide
	TRANSLATIONAL			
LATERAL SPREADS		Rock spread	Debris spread	Earth spread
FLOWS		Rock flow (deep creep)	Debris flow (soil creep)	Earth flow (soil creep)
COMPLEX		Combination of two or more principal types of movement		

Figure 1. General classification of landslides (from Varnes, 1978).

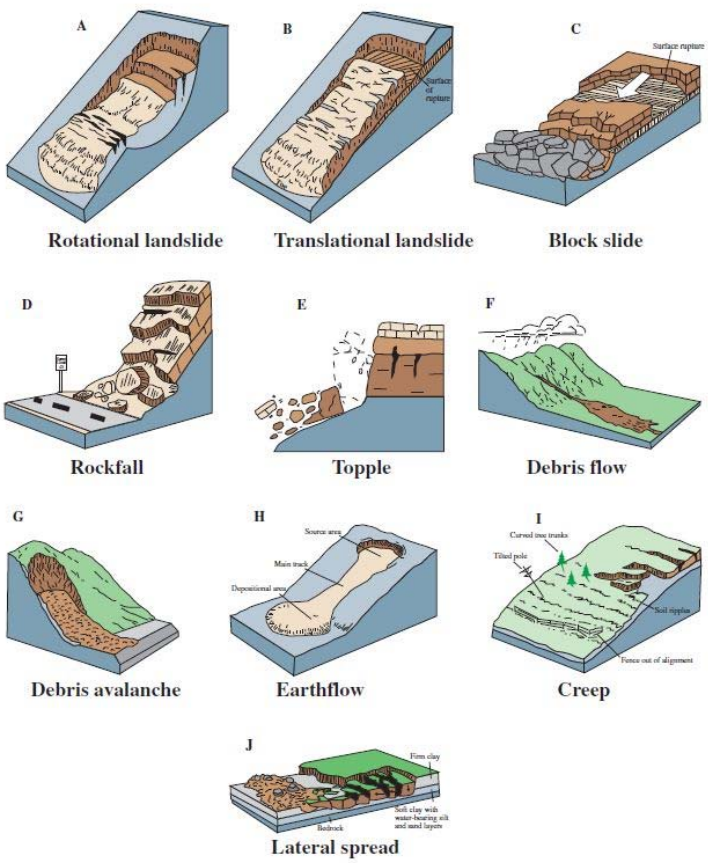


Figure 2. Types of landslides (from Varnes, 1978).

as dissolution and piping; loading of slopes or slope crests by deposition; removal of vegetation by fire or extended drought; alternating cycles of freezing and thawing; and, shrinking and swelling due to alternating cycles of wetting and drying.

Human-Induced - Human induced causes include over steepening of slopes or the toes of slopes due to excavation; loading of slopes or slope crests due to deposition of artificial fill or erection of structures; drawdown of reservoirs; deforestation; irrigation, which can add additional loads to slopes; mining operations; artificial vibrations created by blasting or other construction activities; and, water leakage.

Types of Landslides in Massachusetts

Slope saturation by water is a primary cause of landslides in Massachusetts. This effect can be in the form of intense rainfall, snowmelt, changes in groundwater level and water level changes along coastlines, earth dams and the banks of lakes, rivers and reservoirs. Water added to a slope can not only add weight to the slope, which increases the driving force that leads to failure, but can also increase the pore pressure in fractures and soil pores, which decreases the internal strength of the earth materials needed to resist the propensity to fail.

Landslides in Massachusetts can be divided into four general groups: 1) construction related, 2) over steepened slopes caused by undercutting due to flooding or wave action, 3) adverse geologic conditions and 4) slope saturation. Construction related failures occur predominantly in road cuts excavated into glacial till where topsoil has been placed on top of the till. This juxtaposition of materials with contrasting permeability often causes a failure plane to develop along the interface between the two materials resulting in sliding following heavy rains. Examples can be found along the Massachusetts Turnpike. Other construction related failures occur in utility trenches excavated in materials that have very low cohesive strength and associated high water table (usually within a few feet of the surface). This occurs in sandy deposits with very few fine sediments to give the material cohesive strength and can occur in any part of the state.

Undercutting of slopes during flooding or coastal storm events is a major cause of property damage. Streams and waves erode the base of the slopes causing them to over steepen and eventually collapse. This is particularly problematic in unconsolidated glacial deposits, which covers the majority of the state. Areas where this type of failure is occurring include Cape Cod, Nantucket, Martha’s Vineyard, Scituate, Newbury and along some of the major river valleys.

Adverse geologic conditions exist anywhere there are lacustrine (lake), marine clay or thick glacial till deposits. When over steepened or exposed in excavations and then saturated by high groundwater levels or heavy rainfall, these deposits often produce classic rotational landslides (Figure 2A). Rotational slides are deep seated failures where the failure plane occurs along a curvilinear path several feet or 10’s of feet below the land surface. The slide forms a characteristic scarp at the head of the slide and a very irregular, hummocky surface at the toe of the landslide where the displaced debris spreads out over the land surface (Figure 3). Clay and silty clay rich materials such as thick glacial till, lacustrine (lake), and marine sediments are often associated with rotational slides because they have lower permeability and therefore excess pore fluid pressure can develop within or on a clay layer causing a reduction in the forces that resist sliding. Clay and silty clay are common in Massachusetts because they formed in the deepest parts of many of the glacial lakes that existed in Massachusetts following the last glaciation. Till deposits are ubiquitous in Massachusetts (Figure 4). Some of the major glacial lakes include Bascom in the northwestern corner of Massachusetts, Hitchcock in the Connecticut River valley, Nashua, Sudbury, Concord, and Merrimack to name a few. The greater Boston area is also underlain by the Boston Blue Clay, a glaciomarine clay as are parts of the north shore. Figure 5 shows a recent example of a classic rotational slide on Route 2 caused by an underlying lake bottom deposit 15 to 19 feet below land surface.

Another occurrence of landslides in Massachusetts results from slope saturation. This occurs following heavy rains and dominantly in areas with steep slopes underlain by glacial till or bedrock. Bedrock is relatively impermeable relative to the unconsolidated material that overlies it. Similarly glacial till is less permeable than the soil that forms above it. Thus, there is a

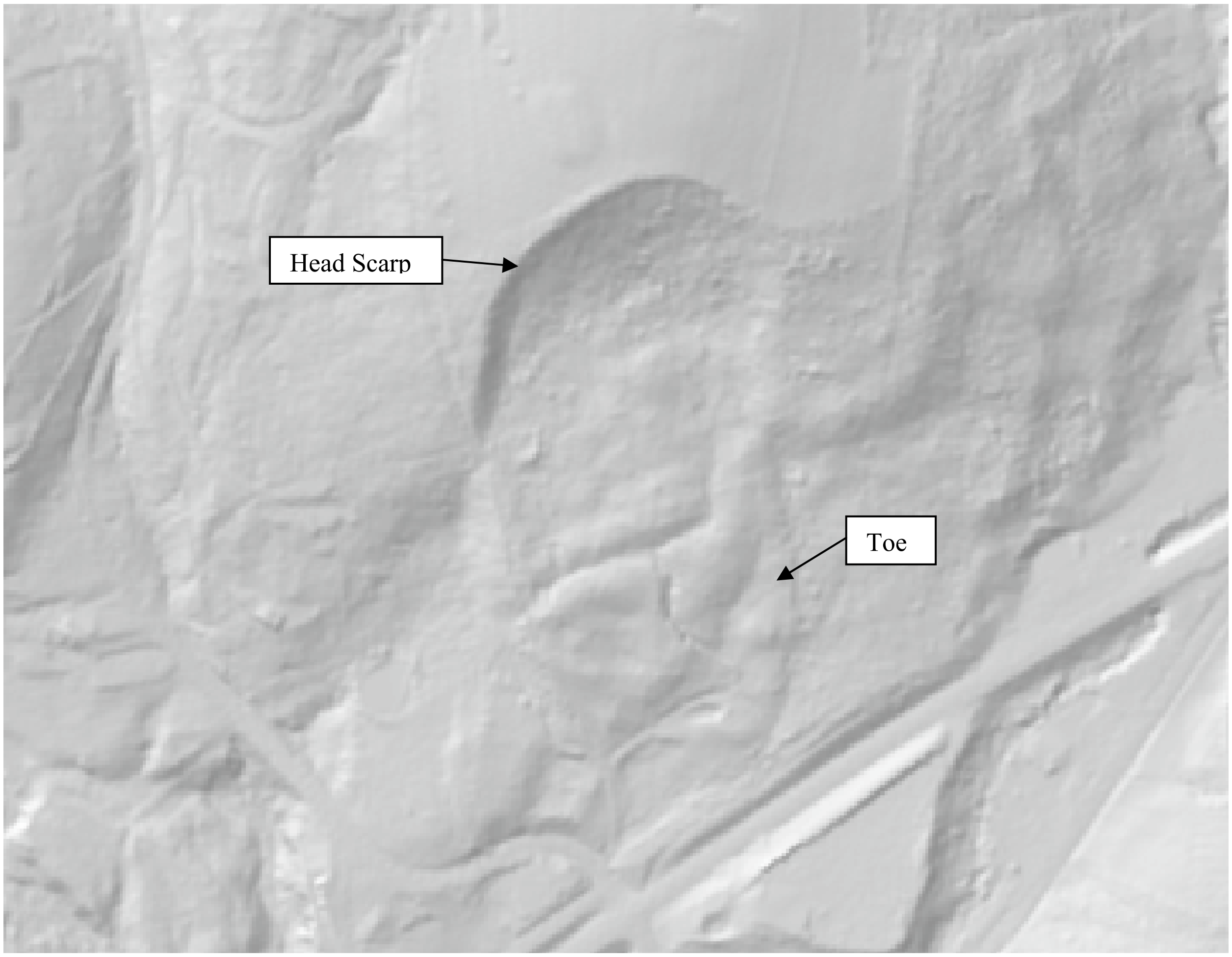


Figure 3. LiDAR image of a rotational landslide in glacial till north of Route 2 in Shelburne, MA. Note the steep scarp at the head of the landslide and elevated, somewhat hummocky surface at the toe of the landslide.

permeability contrast between the overlying soil and the underlying, and less permeable, till and/or bedrock. Water accumulates on this less permeable layer increasing the pore pressure at the interface. This interface becomes a plane of weakness particularly if the water is unable to drain away as fast as it is recharged by rainfall. If conditions are favorable failure will occur. Though slope saturation can result in rotational slides, such conditions can create the shallow translational debris slides (Figure 2B), which are common on Mount Greylock and in many other areas in the Berkshires. Figure 6 shows an example of a translational debris slide caused by slope saturation.

.

History of Landslides in Massachusetts

Nationwide landslides constitute a major geologic hazard as they are widespread, occurring in all 50 states, and cause $1-2 billion in damages and more than 25 fatalities on average each year. Landslides pose serious threats to highways and structures that support fisheries, tourism, timber harvesting, mining, energy production, utilities and transportation. Landslides commonly occur with other major natural disasters such as earthquakes and floods that impede relief and

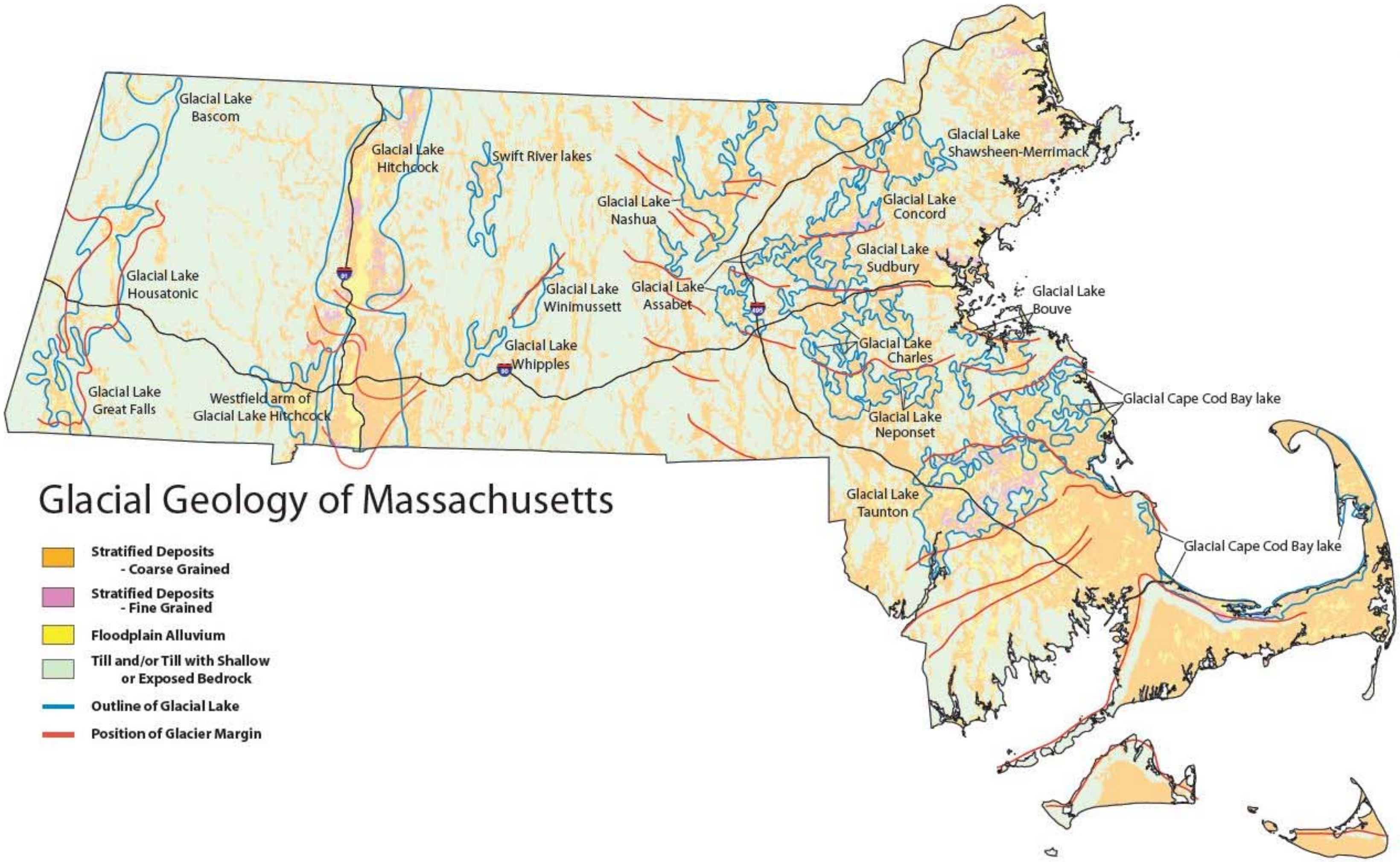


Figure 4. Map showing some of the major glacial lakes that existed in Massachusetts 14,000 to 10,000 years ago. The purple color represents areas where silty clay and clay lake bottom sediments are exposed at the surface. However, they may also occur at depth. Purple areas in the Boston area and north shore are marine clays. Green areas show the extent of glacial till deposits (surficial geology from MassGIS, lake boundaries adapted from Stone and Peper, 1982).

Figure 5. Damage to Route 2 in Charlemont, MA during tropical storm Irene caused by classic rotational slide where Trout Brook enters the Cold River. Head scarp formed over a period of weeks after the storm. Lake bottom sediments located 15-19 feet below ground surface probably formed the failure surface of the slide. Erosion of the toe of the slope by floodwaters on the Cold River most likely initiated the failure (photo by Pete Connors).

reconstruction efforts. Expanded development and other land use changes have increased the incidence of landslide disasters.

Landslides do occur in Massachusetts with regular frequency, and until recently, were often minor. Nevertheless, they do constitute a nuisance and do have a public cost for cleanup and remediation. According to the Massachusetts Department of Transportation (MassDOT) during the five-year period extending from 1986 to 1990, the estimated average annual cost of highway contracts let to correct landslide problems was $1,000,000. In addition, the average annual MassDOT maintenance expense needed to keep highways safe from landslide related activities was $2,000,000. These estimates only apply to state highways. The cost associated with remediation work and cleanup of debris from only four landslide-related events during the October 2005 rain event that affected Massachusetts was $2,300,000[2] (Figure 7). The damage to a 6-mile stretch of Route 2 caused by tropical storm Irene in 2011, which included debris flows, four landslides, and fluvial erosion and undercutting of infrastructure, cost $23 million for the initial repairs[3] (Figures 8, 9 and 10). Accordingly, landslides have a real cost to taxpayers yet

[2] Nabil Hourani, Mass Highway Department, written communication, December 18, 2006
[3] Daily Hampshire Gazette, December 15, 2011, Storm-ravaged stretch of Route will reopen today.

Figure 6. Example of a translational debris slide along Route 2 in Savoy, MA caused by tropical storm Irene. View is from the top of the slide. Slide is 900 feet long, average slope angle is 28 to 33°, area involved is about 1.5 acres and the elevation difference from the top of the slide to the bottom is 460 feet. Estimated volume of material moved is 5000 cubic yards. Only the top 2 to 4 feet of soil material was displaced (photo by J. Kopera).

Figure 7. Stabilization of slope at bend on Route 2 in Savoy, MA adjacent to Cold River. Mass wasting caused by flooding during the October 2005 rainstorms (photo by Nabil Hourani).

this hazard is not well known because most earth movements occur during extreme rainstorms and it is the rain and associated flooding that receives the majority of the publicity.

In addition, several landslides occurred along the east face of Mount Greylock (Figure 11) after heavy rains in 1901[4]; 1 home was destroyed and six others evacuated during a slide in North Adams in 1936[5]; a debris flow on Money Brook on the west side of Mt. Greylock that occurred on August 7, 1990 mobilized 3,100 cubic yards of material and a translational slide of rock and soil occurred on May 13, 1990 in the same area as the 1901 slides and mobilized an estimated 17,000 cubic yards of material[6]; debris from translational slides covered River Road in Florida requiring bucket loaders to remove the debris; and an ice contact delta collapsed into Pelham Brook in Rowe in 2006 silting the brook and the Deerfield River (Figure 12). There have been at least 30 or more landslide related events in the 10 to 20 years prior to 2006[7]. MassDOT has just started remediation along Route 116 in Amherst and South Hadley where minor slides have been

[4] Cleland, H. F. 1902. The landslides of Mt. Greylock and Briggsville, Massachusetts. *Journal of Geology*, v. 10, pp. 513-517.
[5] Associated Press. 1936. Landslide slowly pushes over North Adams street. *New York Times*, March 20.
[6] Dethier, D.P. et al., 1992, Rainfall-induced mass movements on Mt. Greylock, Massachusetts during 1990, *Northeastern Geology*, v.14, no.4, pp.218-224.
[7] Nabil Hourani, Mass Highway Department, written communication, December 18, 2006.

Figure 8. Example of debris flow along Route 2 caused by tropical storm Irene. These coarse debris flow deposits were transported by a small, first order stream that quickly overwhelmed the culvert (photo by S. Mabee).

Figure 9. Translational debris slide on Route 2 in Savoy, MA caused by tropical storm Irene. Note the smooth bedrock surface. That is the failure plane along which the soil slid (photo by S. Mabee).

Figure 10. Example of mass wasting in glacial till caused by undercutting of bank by floodwaters. Photo taken along the Cold River in Savoy, MA 1 week after tropical storm Irene (photo by J. Kopera).

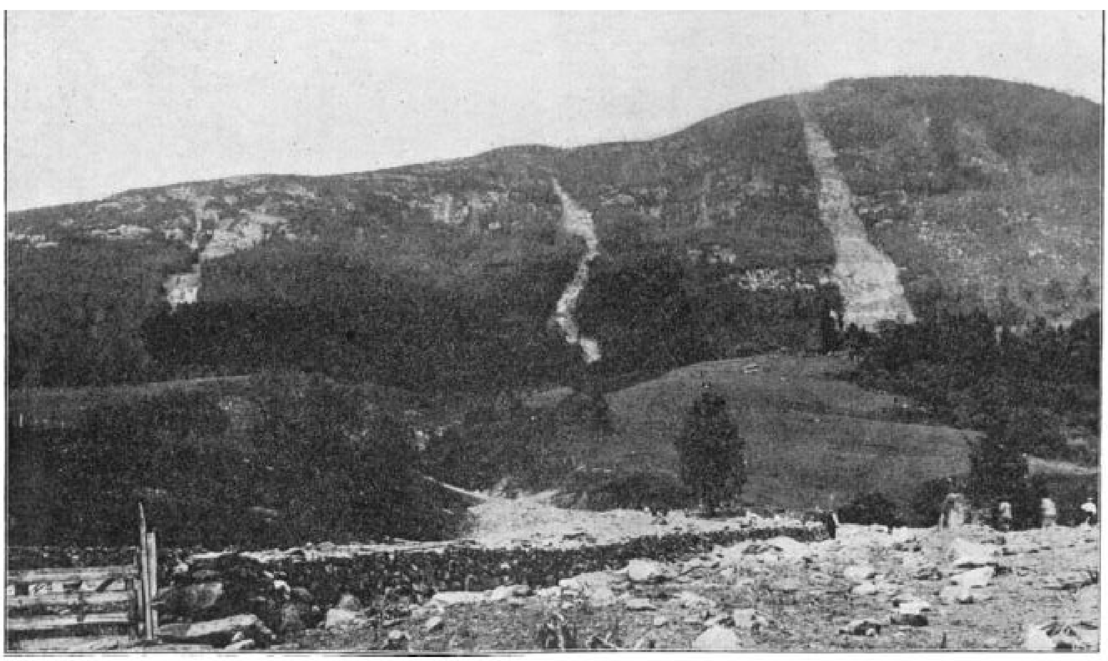


Figure 11. Photograph of at least 3 translational debris slides on the east face of Mt. Greylock in western Massachusetts that occurred on August 20, 1901. Note the debris flow deposits in the fields in the foreground (from Cleland, 1902).

Figure 12. Mass wasting of a glaciofluvial delta deposit by undercutting along Pelham Brook caused by heavy rains in May 2006 (photo by S. Mabee).

a problem and they are currently evaluating remedial actions on another recent slide in Topsfield[8]. Additional slides also occurred in Deerfield, MA after the October 31, 2011 snowstorm causing clogging of culverts under the railroad and Route 5 leading to siltation of a wetland and subsequent flooding of nearby homes[9] (Figure 13).

The frequency and intensity of storms is increasing as a result of climate change[10]. New construction (development, clearing, access roads) is now occurring in areas that previously were considered marginal for development. Both of these factors are likely to increase the severity of landslide risks in the future.

Most natural landslides in Massachusetts are caused by a combination of adverse geologic conditions, steep slopes and extreme wetness. Most are precipitation induced and seem to occur in years that have experienced prolonged antecedent wet periods. For example, in 1901, prior to the slides on Mt. Greylock, Cleland (1902) reported that between July 1, 1901 and August 20,

---

8 Peter Connors, Mass Department of Transportation, written communication, October 12, 2010.
9 Kopera, J. and S.B. Mabee, December 12, 2011, Preliminary field report on the November 13-14, 2011 landslide near Steam Mill Road, Deerfield, Massachusetts, Massachusetts Geological Survey.
10 Northeast Climate Impact Assessment Team. 2006. Climate change in the U.S. Northeast. Union of Concerned Scientists, 52p (http://www.northeastclimateimpacts.org).

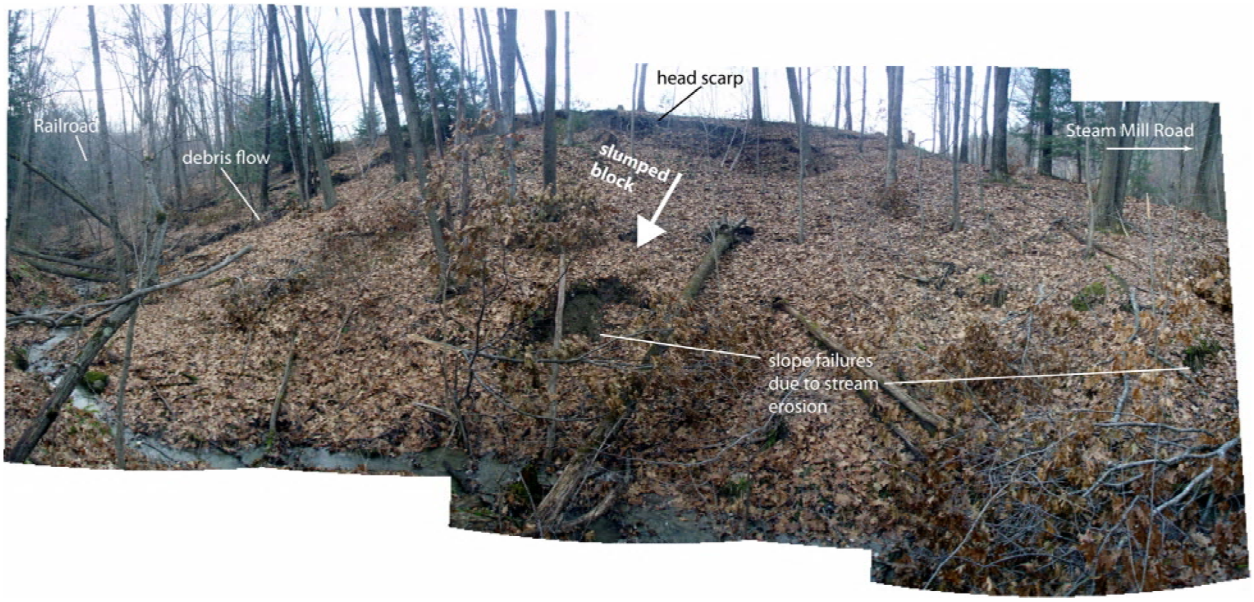


Figure 13. Photo panorama of a rotational slump block in lacustrine clay deposits in Deerfield, MA. Slide occurred following the Halloween snow storm in October 2011. Photo taken on November 27, 2011 by J. Kopera.

1901 approximately 13 inches of rain fell, which is well above normal. This was followed by a 2 to 3.4 inch cloudburst that occurred over a period of 4 hours on August 20. The combination of wet antecedent moisture conditions resulting in saturated soil followed by a high intensity rainfall was suggested as a likely cause of the slides. Dethier et al. (1992) also suggested that the Money Brook debris flow of August 7, 1990 on Mt. Greylock was the result of increased pore pressure through saturation by intense rainfall and shallow springs and that the large rock slide on May 13, 1990 on the east side of Mt. Greylock was preceded by nearly 10 inches and 22 inches of rain in the 30 days and 120 days, respectively, prior to the slide.

The landslides associated with tropical storm Irene were also preceded by very wet antecedent conditions. Examination of long term water level records from Well CSW 8 in Colrain located about 11 miles east of the large translational debris slides in Savoy, MA along Route 2, showed the highest recorded water levels in the 48 year record in the preceding 4 months before tropical storm Irene (Figure 14) and was in the 90 percentile 5 months (April) before the storm. Similarly, real time soil moisture records maintained by the National Resources Conservation Service (NRCS) at Lye Brook, VT, located 27 miles north of the Savoy landslides, showed rising soil moisture levels throughout August of 2011 (Figure 15), which is contrary to what is typically observed (Figure 16). Clearly, the spring and summer seasons of 2011 were very wet. Furthermore, in the 10 days prior to Irene the Savoy area received 5-7 inches of rain and then was hit with approximately 9 inches of rain over an 18 hour period on August 27-28, 2011 initiating the landslides.

The anecdotal evidence suggests that periodic high intensity rainfalls preceded by long term antecedent wet periods and high water tables are needed to initiate both rotational and translational debris slides as well as debris flows in Massachusetts. The rotational slide along

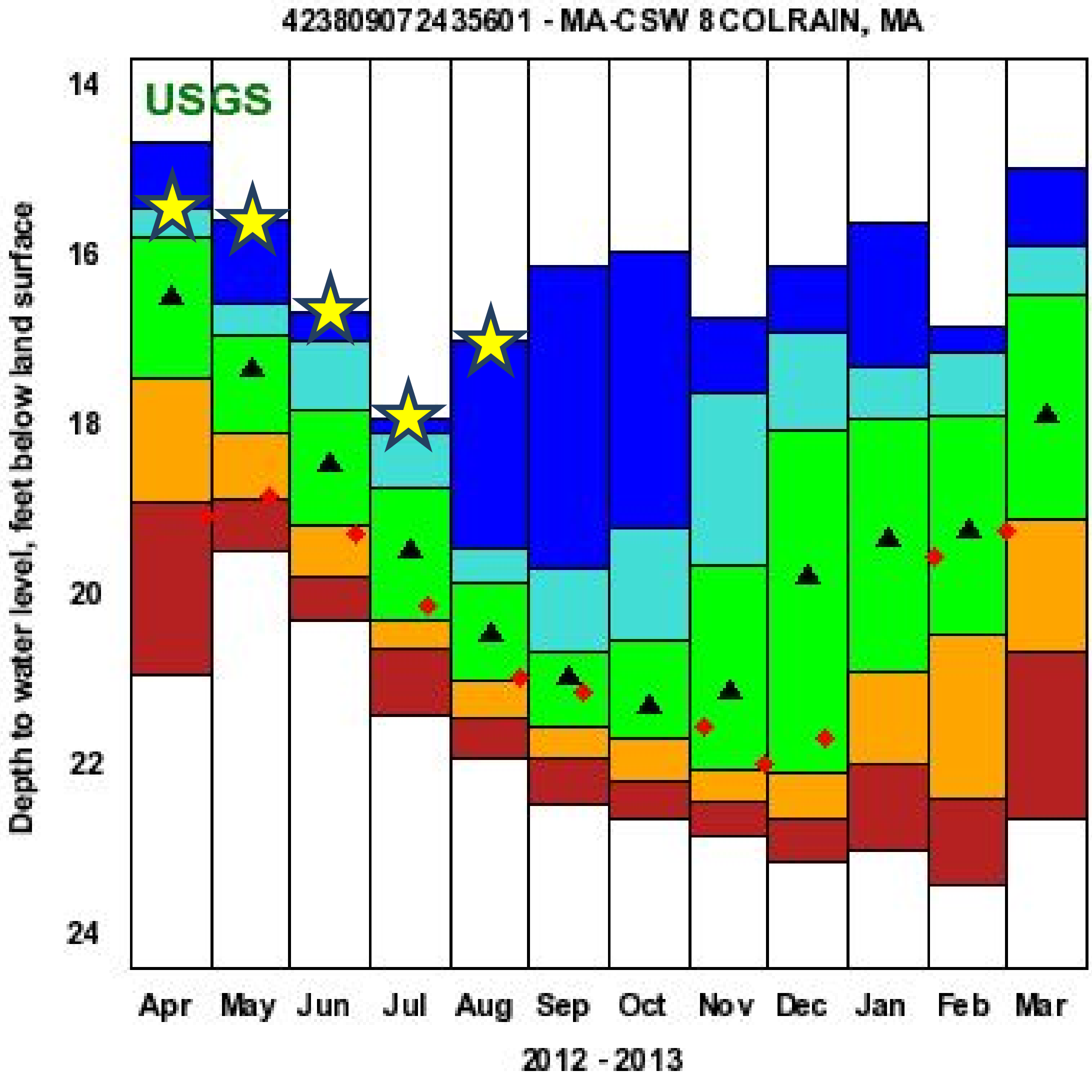


Figure 14. Graph showing water levels in well CSW 8 in Colrain. Stars are the measured water levels for 2011. Note that May, June, July and August measurements are the highest ever recorded in the well over the 48-year record. April reading is at the 90 percentile. Green is the middle 50% of all monthly readings with the triangles representing the median water level (from USGS).

Route 2 in Charlemont, MA,where Trout Brook enters the Cold River (Figure 5), has been a chronic problem on this section of roadway since 1938. It provides a good barometer for the frequency of sliding events at this location. In all cases, sliding is initiated by extreme wetness. Taking all the known landslide events from 1938 to 2011, landsliding events seem to occur on average once every 7-8 years. Examination of landslide events that have occurred since 1977 shows a frequency of occurrence of once every 3 to 4 years. This is certainly not a scientific analysis of the probability of occurrence and cannot be used as a predictor of future events but it does give some qualitative expression of frequency based on past observations.

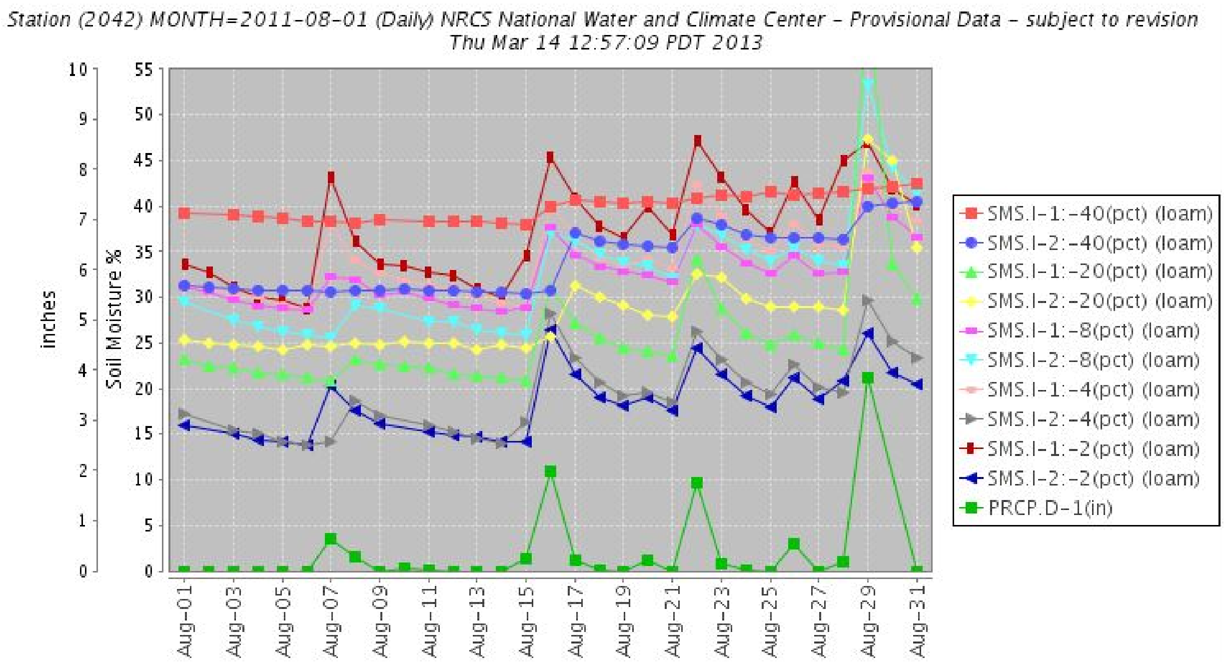


Figure 15. Soil moisture profiles at Lye Brook, Vermont for August 2011. Note the general increase in soil moisture throughout the month at multiple depths indicating very wet conditions prior to Irene (from NRCS).

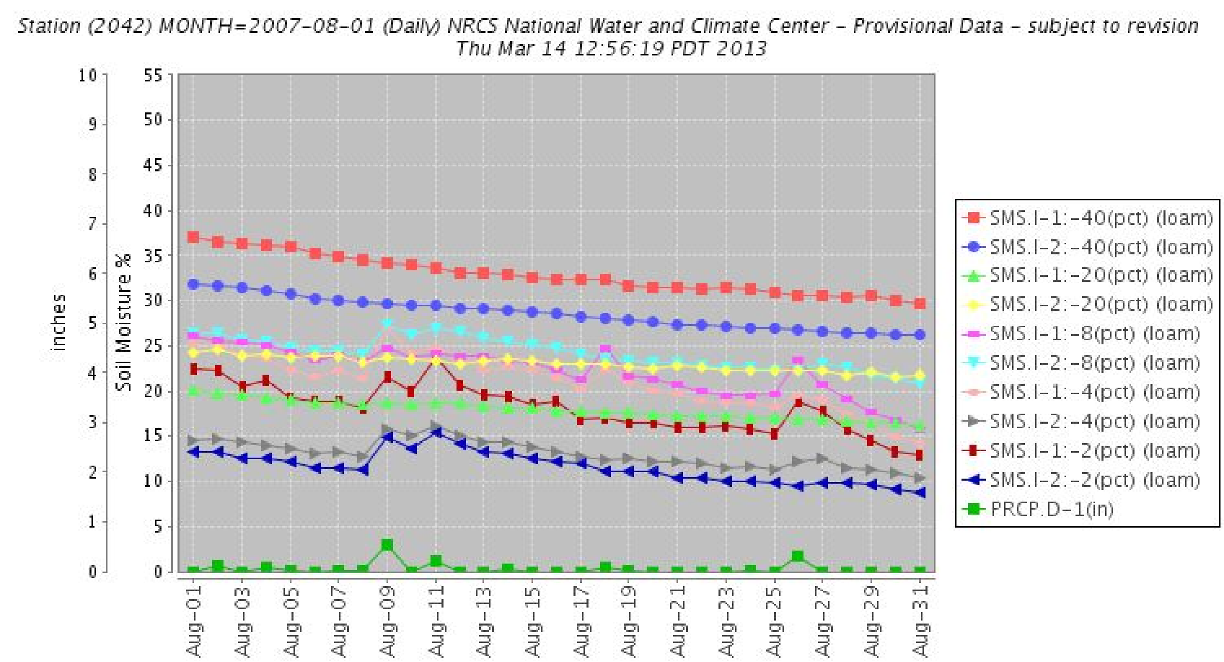


Figure 16. Soil moisture profiles at Lye Brook, Vermont for August 2007. Note the general decline in soil moisture throughout the month at multiple depths indicating dry conditions and is more typical of summer soil moisture conditions (from NRCS).

Summary of Different Approaches to Modeling Slope Stability

A variety of techniques can be employed to map landslides and slope stability. The Vermont Geological Survey recently released a Protocol for Identification of Areas Sensitive to Landslide Hazards in Vermont (Clift and Springston, 2012). In that document and the references contained therein, they review different approaches to modeling landslide susceptibility. The approaches can be summarized in three groups: 1) heuristic models, 2) deterministic models and 3) statistical models.

Heuristic models involve expert knowledge and the use of weighting factors to map areas that might be susceptible to landslides. This is a subjective process that requires professional judgment and experience in making decisions about where landslides might occur and how to weight the various factors.

Deterministic models involve the use of a computer program that requires slope as the primary input and information about the geotechnical properties of the earth materials such as hydraulic conductivity, angle of internal friction, cohesive strength, and unit weight, among others. There are many models that use this approach including SINMAP, LISA and STABL. The main drawback of this method is the uncertainty of the geotechnical parameters as these can vary significantly from place to place and are not always well constrained with site-specific field data.

Statistical models include probabilistic and multivariate methods such as fuzzy logic, frequency ratio, artificial neural networks and logistical regression methods. However, the use of statistical methods requires more field work. First, landslides are mapped in the field at known locations and characteristics about each landslide recorded. Parameters are selected from the data set that statistically characterize the landslides. The parameters (e.g., slope angle) are then lumped into classes and statistical methods used to calculate weights (i.e., level of importance) for each parameter. A typical example would be to use a regression equation where the dependent variable is the presence or absence of a landslide and the independent variables are the various weighted parameters. The weights are adjusted or parameters are added or removed from the regression until the majority of the observed landslides can be explained. This information is then displayed on a map. The main drawback is that statistical methods require a substantial amount of data to obtain reliable results. Yilmaz (2009) provides a summary of statistical approaches. Vermont selected the frequency ratio method for their protocol (Clift and Springston, 2012).

For the Massachusetts study, we decided to use SINAMP which is a deterministic model to map slope stability for the following reasons:

1. The model is relatively easy to use and has been employed in landslide mapping programs in North Carolina and, more recently, Virginia, so there is a track record of successful use by other states.
2. Slope is the main driver of most landslides along with wetness and the SINMAP model can incorporate detailed elevation and hydrologic response into the model in an ArcGIS environment.

3. While it is recognized that the geotechnical properties of the soil materials involved in the landslides are not as well constrained, it was felt that enough general geotechnical data could be gleaned from digital soils data and the literature that soil properties could be bracketed reasonably well if calibrated with data about the location of known landslides.
4. Extensive field work could not be completed as part of this project, therefore, the use of statistical models was precluded.

Overall, we consider the use of SINMAP to be better than any heuristic model but not necessarily as complete as field-based statistical models. Thus, the choice of SINMAP is a compromise. However, the intent of this project is to provide a statewide, first order approximation of areas that might experience slope stability problems under conditions of high intensity rainfall and prolonged antecedent wetness. We believe SINMAP accomplishes this goal and identifies areas where more detailed site characterization may be warranted.

METHODS

Stability Index Mapping (SINMAP)

The principal tool used in this project to estimate landslide risk is SINMAP, a contraction of **S**tability **IN**dex **MAP**ping. SINMAP is an add-on component to ESRI's ArcView 3.x GIS[11] application developed by Pack et al. (1998, 2001). This add-on software employs a theoretical model for hill slope stability that uses detailed data about the landscape and parameters to characterize local hydrologic and soil conditions. The model computes a grid of stability index values that indicates the variation in relative stability across the landscape. The output is a detailed map of relative hill slope stability showing where shallow, translational landslides are more or less likely to occur.

The theoretical underpinning for SINMAP is the infinite slope model (Hammond et al., 1992; Montgomery and Dietrich, 1994). This model assumes a constant hill slope of infinite extent underlain by a failure surface, parallel to the ground, on which motion (failure) will occur whenever the destabilizing force of gravity operating on the surface layer exceeds the restoring forces of cohesion and friction on the failure surface (Figure 17). The balance of these forces varies with both time and location; for example, rainfall tends to increase the destabilizing force by increasing the weight of the surface layer while decreasing cohesion and friction through an increase in pore pressure. The magnitude of these changes depends on several factors including the slope angle, the porosity and hydraulic conductivity of the soil, antecedent moisture, and so on. SINMAP incorporates both fixed values (e.g., hill slope angles) and parameters that vary over a range of values (e.g., soil properties) and computes local stability index values for each cell on a digital elevation model (DEM).

[11] SINMAP is also available as an extension for ArcGIS 9.x as well, but that version proved unstable and crashed frequently; functionally it is identical (same inputs and outputs) as the ArcView 3.x version, so we reverted to that without loss of functionality.

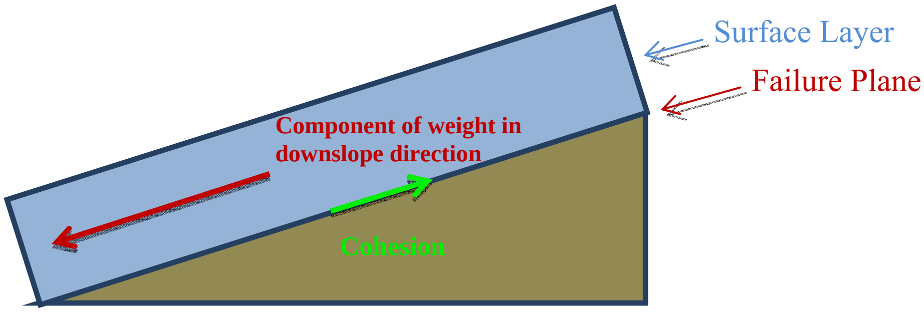
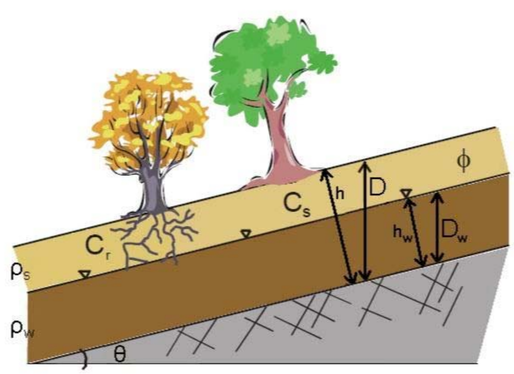


Figure 17. Basic elements of the infinite slope model.

The model assumes that rainfall on the landscape enters the ground, where its flow is determined by the shape of the landscape: channels, hollows, and other concave landscapes concentrate flow due to the convergence of flow lines, whereas ridges and promontories disperse flow due to divergent flow lines. The DEM is then used to derive a number of factors that drive the model behavior at each point: local hill slope angles, flow directions, and upstream catchment areas. The modeled flows are then used to compute soil saturation at each point based on parameters for soil conductivity, storm-related rainfall rates, soil cohesion, and soil friction angle. Finally, these flow and saturation rasters are used to compute a slope stability index at each point based on the factor-of-safety value. These indexes are further classified into a small set of landslide risk categories, which are described in Table 1 (see the section on How to Read the Map for a detailed description of Table 1).

The basic equation for the infinite slope model and the parameters used in the SINMAP model to compute factors of safety are given below.

$$FS = C + \cos\theta\,[1 - \min\{Ra / T \sin\theta, 1\}\, r] \tan\phi$$



FS = factor of safety
a = topographic catchment area
C = dimensionless cohesion, where,
$C = (C_r + C_s) / (hp_s g)$
C_r = root cohesion
C_s = soil cohesion
h = soil thickness
p_s = soil density
g = gravity constant
h_w = height of water
R = recharge
r = water density (p_w) to soil density (p_s) ratio
T = soil transmissivity = soil hydraulic conductivity x h
ϕ = soil internal angle of friction
θ = slope angle
h_w/h = relative wetness = min $\{Ra / T \sin\theta, 1\}$

It should be made clear that the infinite slope model only applies to shallow translational slides. Not all landslides are translational. However, for this study, the model has been applied to the entire state. The rationale for this is as follows. The model is very dependent on slope. Therefore, head scarps associated with rotational slides are identified through the modeling process because of the steep slopes even though the infinite slope model assumptions are not met completely. In addition, over steepened banks along rivers and eroding coastlines are also identified in the model for the same reasons. Field verification confirms these findings. The model may not identify all potential rotational slides and areas of bank erosion but the slope conditions inherent in the model give a reasonable first order approximation. There are instances where vertical bedrock outcroppings may appear on the map as an unstable slope in the model output. Again, this simply suggests caution and a site visit to confirm soil condition if such areas pose a risk and are located near roads or utilities.

Input Data and Processing

Topography – The model requires topographic data in a raster (gridded) format, with each grid cell containing a mean elevation value for the landscape at that location (DEM). The quality of the model output depends strongly on the quality of the input DEM. While some very high-quality and high-resolution (small cell size) DEMs exist from LiDAR surveys done in portions of the state, the best available DEM with uniform coverage state-wide is the National Elevation Dataset (NED). The NED is itself a number of different rasters of varying resolution but for Massachusetts there is statewide coverage at a 1/3-arc-second cell size.

The NED cells are defined on a grid of uniform increments of latitude and longitude – in this case, cells are 1/3-arc-second by 1/3-arc-second. While this is a natural and convenient format for storing data about the earth's surface, it is not well-suited for hydrologic uses such as SINMAP modeling because the surface area represented by each cell varies over the surface of the earth because of the convergence of lines of longitude from the equator to the poles; the surface area of cells as defined by a uniform longitude spacing decreases towards the poles. Equal-area cells are needed for SINMAP computations so the first processing step is to re-project the DEM cells into the Massachusetts State Plane coordinate system, and re-grid the elevation values onto a raster whose cell sizes are spaced evenly in meters rather than in degrees of latitude and longitude. For this project, the 1/3 arc-second DEM was re-projected on a regular cell spacing of 9 meters in both north-south and east-west directions (at the latitude of Massachusetts a 1/3 arc-second grid is about 10.3 meters in the north-south direction and 7.6 meters in the east west direction, so (10.3 + 7.6) / 2 gives a good average cell size of about 9 meters).

A number of processing steps are performed on and with this new elevation raster. This processing is done within SINMAP in a series of sequential steps, as outlined in the SINMAP User's Manual. These steps are designed to produce a complete and consistent set of rasters characterizing the hydrologic drainage system of the landscape. The first step involves removing depressions or "pits" – small areas that are completely surrounded by higher elevations; any such pits are "filled" by adding elevation values to the cells in the pit until they equal the lowest value of the surrounding cells, thereby ensuring that modeled water will flow continuously across the land surface and not become "trapped" in a pit.

The next step is to take the “filled” DEM version and estimate local slope angle, local flow direction (direction of steepest descent), and the area of the catchment upstream of each point on the DEM. These computations are all standard operations in a GIS environment, each yielding a new raster of values on the same grid as the underlying DEM. These three derived rasters (hill slope, local flow direction, and upstream catchment), together with the model parameters described in the next section, are then used to compute rasters of soil saturation (a function of catchment area, slope, and the soil transmissivity vs. recharge rate parameter) and stability index (a function of all of the terrain and parameter values).

Final processing involved the classification of the stability index values according to Table 1. Once classified, the data were then down-sampled for display on a printed map. While the data were processed at the 9 meter resolution of the DEM, these cells would not be readily visible when printed due to the small map scale and limitations of the human eye to distinguish pixels at such high dot density. We down-sampled the 9-meter cells in blocks of 5x5 cells to create a 45-meter resolution version for printing. To preserve unstable slopes through this down-sampling, each 45-meter cell is assigned the value of the least-stable cell in the 25-cell block.

Hydrologic and Soil Parameters - SINMAP uses three parameters to model the effects of soil properties on the slope stability: internal friction angle, cohesion and a soil transmissivity vs. recharge rate or T/R parameter. Internal friction angle can be obtained by direct measurement in the lab or correlation with other measured geotechnical properties. Cohesion is a combination of both the inherent cohesive strength of the soil and the cohesive strength afforded by the root system, referred to as root cohesion. Soil cohesion can be measured directly in the lab or through correlation with other measured geotechnical properties whereas root cohesion is usually estimated from the literature. The soil transmissivity vs. recharge parameter (T/R) is part of the relative wetness index in the infinite slope equation. The relative wetness index incorporates the slope angle, the upgradient contributing area and the T/R parameter, that is, the ratio of the soil’s ability to drain water away (T) to the rate of recharge from rainfall (R). T is transmissivity (m^2/hr), which equals the hydraulic conductivity (m/hr) of the soil times the thickness (m) of the soil and describes how easily water can be transmitted laterally down the slope through the shallow soil. The rate of recharge has units of m/hr.

These parameters can be adjusted by the user if desired but each parameter is specified as a range, with a minimum and a maximum value, so that the stability can be judged against "best-case" and "worst-case" scenarios of the factors affecting stability. As outlined in Table 1 above, hazard classes are delineated in part by their relationship with whether "best-case" or "worst-case" parameter values are required for stability/instability.

The SINMAP model provides default ranges for the three parameters based on a number of landslide studies; alternatively, any of the parameter values can be changed if there are observations suggesting the default values are inappropriate for a particular landscape. Furthermore, it is possible to define sub-regions of the study area and assign distinct parameter ranges to each sub-region to model variations based on knowledge about local soil, geologic, or hydro-climatic conditions.

We performed the SINMAP analysis using both the default parameter ranges applied uniformly throughout the state, as well as "calibrated" runs in which parameter values were computed from available measurements of local soil properties (Tables 2 and 3). For these calibrated runs, representative soil parameters were derived from digital soil data available from NRCS. In addition, the U.S. Geological Survey has new 1:24,000 scale surficial geologic maps for 75% of the state. These maps provide detailed unit descriptions upon which soil properties can be estimated. For the remaining 25% of the state, 1:250,000 scale maps available from MassGIS were used.

Description	T [m^2/hr]		T/R [m]		Soil Density [kg/m^3]			Cohesion (dimensionless)		Internal Angle of Friction, ϕ (deg)	
	Min	Max	Min	Max	Min	Mean	Max	Min	Max	Min	Max
Calibrated Runs											
Alluvium	0.00036	0.36	0.0378	37.795	1406.7	1773.7	2140.7	0	2.174	30	20
Sand and Gravel	0.36	360	37.7953	37795.28	1834.9	2089.7	2344.5	0	0.278	40	30
Large Sand Deposits	0.0036	3.6	0.3780	377.95	1437.3	1641.2	1845.1	0	0.355	35	15
Fine Grained deposits	3.6E-08	0.000036	0.0000	0.0038	1916.4	1998.0	2079.5	0.245	2.394	30	15
End moraine deposits	0.000036	3.6	0.0038	377.95	1437.3	1758.4	2079.5	0	1.844	36	28
Sandy Till over Sand	0.000036	0.36	0.0038	37.80	1406.7	1840.0	2273.2	0	3.261	36	24
Till and/or Bedrock	3.6E-07	0.0036	0.000038	0.378	1916.4	2079.5	2242.6	2.273	10.904	45	34
Model Defaults			2000	3000				0	0.25	30	45

Assumptions used in the calibrated model run:

R = Rainfall Rate = 0.009525 m/hr (9 inches in 18 hours similar to TS Irene)

Soil Thickness = 1 m

Gravity = 9.81 m/s^2

Cr = root cohesion = 0 kPa (min) and 5 kPa (max)

Table 2. T/R, cohesion and friction angle used in calibrated and default model runs. Calibrated run parameters are computed from the soil properties gleaned from digital soils data, boring logs, surficial geologic maps unit descriptions and the geotechnical literature. The parameters were grouped based on the map unit descriptions found on both 1:24,000 scale and 1:250,000 scale surficial geologic maps of Massachusetts. Default model parameters recommended by the SINMAP authors were employed statewide. Note the very low T/R and high cohesion values in the calibrated model run parameters compared to the values in the default model runs. The calibrated values result in a slope stability map that shows >99% of the state as being stable.

The soil parameters needed for the model can be extracted from published literature or estimated by correlation with soil descriptions or other soil geotechnical properties. For this study, the relevant soil properties that we examined include: cohesive strength, internal friction angle, unconfined compressive strength, unit weight, and hydraulic conductivity. For each surficial geologic map unit, a range of potential values was determined for the selected soil parameters (Table 3).

Description	Cohesive Strength, c (kPa)		Internal Friction, ϕ (deg)		Unconfined Compressive Strength (kPa)		Unit Weight (kN/m^3)		Hydraulic Conductivity (cm/s)	
	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min
Alluvium	25	0	30	20	40	0	21.0	13.8	1.00E-02	1.00E-05
Sand and Gravel	0	0	40	30	50	0	23.0	18.0	1.00E+01	1.00E-02
Large Sand Deposits	0	0	35	15	50	0	18.1	14.1	1.00E-01	1.00E-04
Fine Grained deposits	40	5	30	15	170	100	20.4	18.8	1.00E-06	1.00E-09
End moraine deposits	21	0	36	28	100	0	20.4	14.1	1.00E-01	1.00E-06
Sandy Till over Sand	40	0	36	24	120	0	22.3	13.8	1.00E-02	1.00E-06
Till and/or Bedrock	200	50	45	34	190	45	22.0	18.8	1.00E-04	1.00E-08

Table 3. Soil properties for different surficial geologic map units estimated from digital soils data, boring logs, surficial geologic map unit descriptions and correlations with soil properties from the geotechnical literature. These data were used to derive the calibrated model parameters, T/R, cohesion, and friction angle. kPa = kilo Pascals; kN = kilo Newtons; m = meters; cm/sec = centimeters per second; deg = degrees.

The range was developed using boring logs with a focus on correlating the N-values from Standard Penetration Tests (SPT data) with map unit descriptions, custom maps created in ArcMap using available digital soil parameters (e.g., Atterberg Limits and grain size distribution data), and comparing other published values correlating similar soil types to engineering parameters.

Available borehole logs were grouped by surficial geologic map unit. As many as twenty-five borehole logs were examined for each map unit to observe a range of behaviors. The field descriptions of the upper sediments were compared within each map unit to verify consistency. The N-values from Standard Penetration Tests (SPT) conducted in the upper 5 feet were also recorded for further analysis. If the field description from the boring logs failed to reasonably match the map unit description, or if the N-value stood out as markedly different than the average, the boring log was classified as unrepresentative of the map unit and removed from the analysis. Empirical correlations were made with the remaining N-values and soil properties following recommendations from Peck et al. (1974) for angle of internal friction, Meyerhof (1956) for unconfined compressive strength, Louden (1952) and Casagrande and Fadum (1939) for hydraulic conductivity, and Bowels (1996) for unit weight. Most borehole logs did not record the hammer type employed during the boring, so N-value corrections were not applied. The validity of the range of soil parameter values obtained from empirical correlation was verified with standard accepted values in geotechnical engineering texts, including Holtz (2011) and Murthy (2003).

In areas where boring logs were unavailable, soil properties were estimated by mapping specific parameters using the digital soil survey data. These included properties such as the liquid limit (LL), plasticity index (PI), and gravel, sand, silt and clay percentages.

As a final check, the range of recommended soil property values were compared with other published correlations associating geologic soil descriptions and engineering parameters, including Koloski et al. (1989), Stephenson et al. (1988), and Allred (2000).

SINMAP parameters were then computed from these soil properties (Table 2). The soil friction angle was already one of the soil properties and was used directly. The SINMAP cohesion parameter range was derived from the soil cohesion and unit weight, with minimum and maximum "root cohesion" values drawn from published studies. Finally, the SINMAP transmissivity/recharge rate parameter (T/R) was computed from the soil hydraulic conductivity and a rainfall rate of 9 inches in 18 hours (similar to the tropical storm Irene rain event). Because the soil properties are associated with mappable polygons either from the geologic maps or the digital soils data, the SINMAP range parameters could be computed separately for each map unit.

Hydrography - SINMAP has a limit on the size of the DEM it can process; to work within those limits while minimizing problems with computed catchment areas, the DEM was divided by watershed using the Major Watersheds data layer from MassGIS. By breaking the topography along the divides between drainage basins, the hydrologic integrity was maintained for all catchments. There were 5 major watershed basins that were still too large for SINMAP; these were broken at a point along the trunk drainage into "upper" and "lower" sub-watersheds that also followed drainage divides to avoid affecting catchment area calculations.

Map Presentation – To provide location context for map users, the following data layers from MassGIS were included on all maps: Community Boundaries (Cities and Towns); MassDEP Hydrography (1:25,000); Networked Hydro Centerlines; and MassDOT Roads. The 9 meter NED topography was also used to create a hillshade layer to provide visual clues about the relative ups and downs of the landscape.

Calibration and Verification

Modeling landslides from digital data requires some form of "ground truth" – independent observational data for assessing the performance of the model and/or for calibrating the model to match the observations. Information about existing landslides was obtained from two sources: discussions with the Massachusetts Department of Transportation (MassDOT) Districts 1 and 2, covering the western part of the state, and inspection of high resolution (2 meter cell) LiDAR-based DEMs covering the Deerfield and Hoosic watersheds in the northwestern part of the state.

The discussions with MassDOT personnel yielded reports of 21 trouble spots along state roads in western Massachusetts (Figure 18). These ranged from the obvious (e.g., the large slides that damaged parts of Route 2 in Savoy, MA, during tropical storm Irene) to the subtle (minor but persistent cracking in road surfaces due to very localized stability issues, often associated with water flow problems). These few, qualitative observations were located as best as could be done by asking the MassDOT staff to point to the locations in Google Earth imagery, and in several cases the roadway was obscured by tree canopy and locations were very approximate.

The LiDAR data, processed to remove the elevations of trees and buildings – a so-called "bare earth" model or "digital surface model" (DSM), provided vividly detailed landforms from which it was possible to readily identify existing landslide scars. Within the LiDAR data area, covering roughly 36 mi x 18 mi in the northwest portion of the state, 85 probable landslide events were identified from their geomorphic signature (Figure 18).

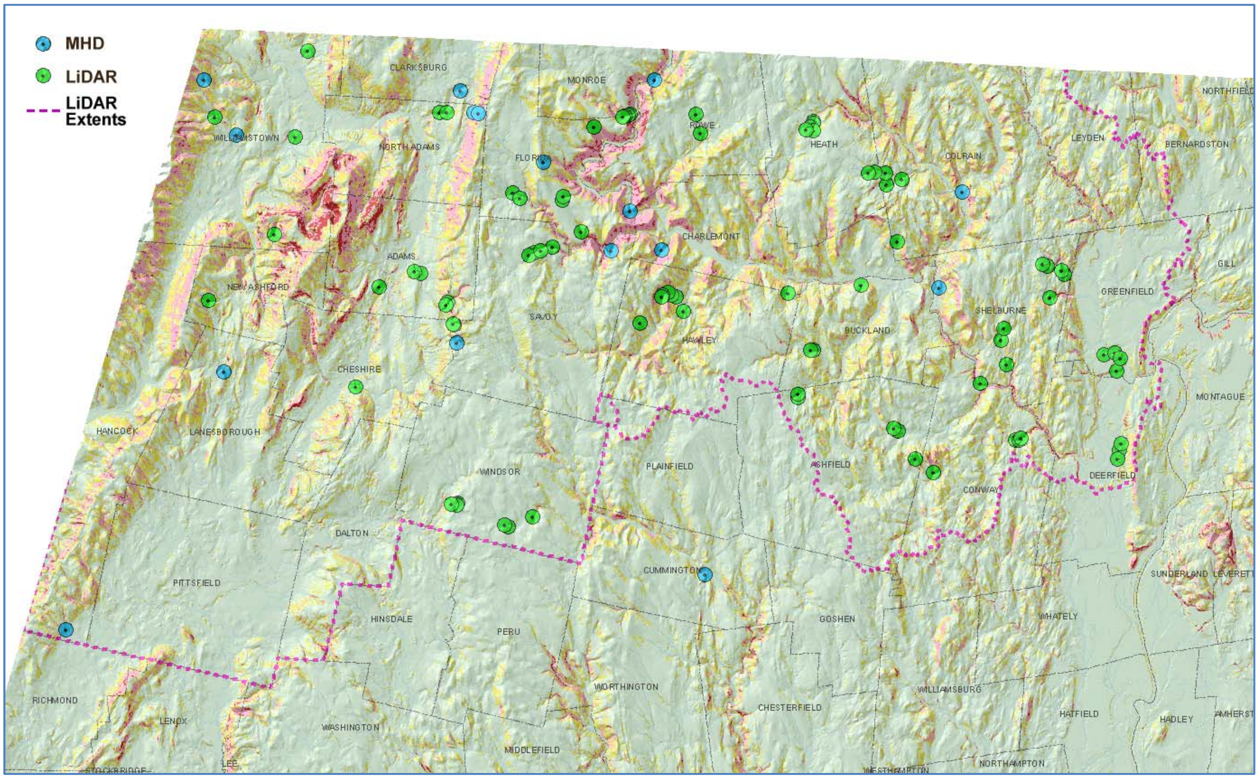


Figure 18. Locations of known landslides from MassDOT discussions and LiDAR visual inspection.

RESULTS AND DISCUSSION

Following the recommendations outlined in the SINMAP User's Manual the model was run using the default parameters for the entire state. Using visual inspection of individual known landslide locations as well as the built-in tools provided by SINMAP for analyzing known slide locations against computed stability indexes, the extent to which the model "predicted" the instabilities was assessed. That is, to what extent were the computed stability classes for known slide locations in the "High", "Moderate", "Low" or "Very Low" categories.

The visual inspection showed a number of promising results. For example, the majority of the hill slopes around the Irene landslides on Route 2 in Savoy, MA, are in the "Moderate" hazard category, with smaller strips of "High" hazard extending up the slopes along gullies (Figure 19). Likewise, reported problems along Route 2 above and below the hairpin switchback to the east of North Adams corresponded to a general "Moderate" hazard hillside with local strips of "High" hazard near the problem areas (Figure 20). All slides on Mt. Greylock are identified in the model as well.

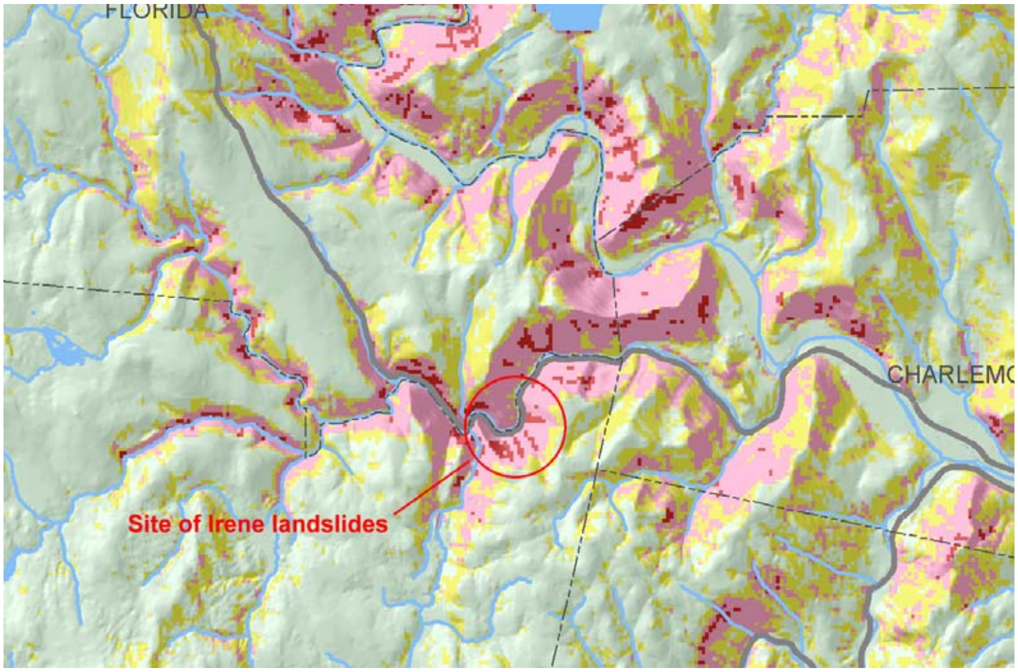


Figure 19. Default SINMAP results along Route 2 where landslides occurred during Irene.

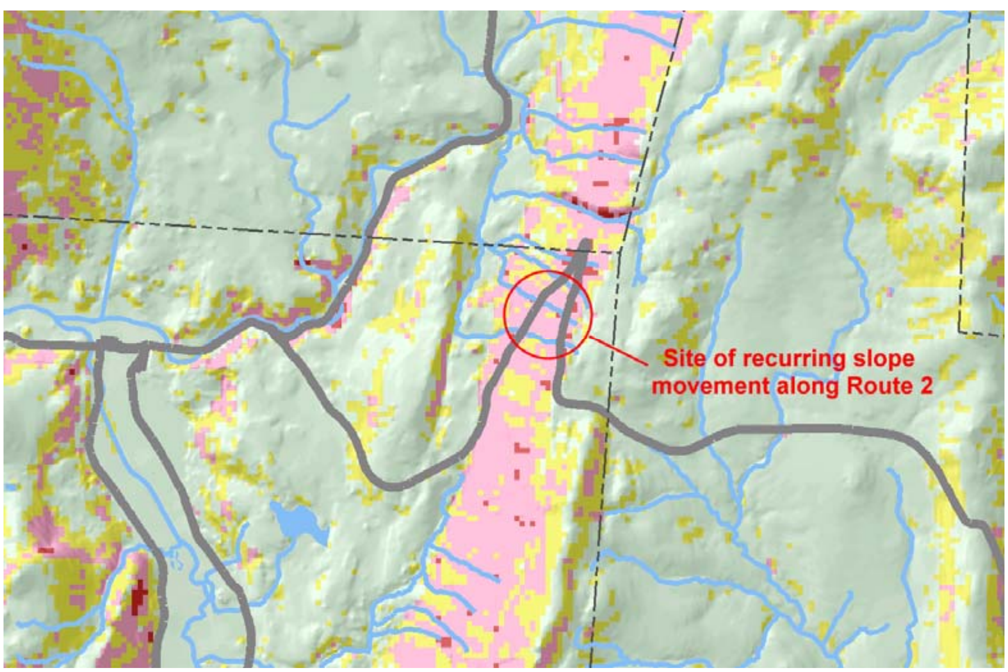


Figure 20. Default SINMAP results at Route 2 hairpin turn in North Adams, MA where MassDOT reports ongoing problems.

Other areas of the state where the model results showed a visual correlation with known landslides in coastal areas include Gay Head in Aquinnah, the Nashaquitsa and Wequobsque cliffs in Chilmark, the east shore of the outer Cape and portions of the coastline in Plymouth, among others. Areas where rotational slides are common in glacial lake Hitchcock lacustrine sediments include portions of Deerfield along the Deerfield River. The steep slopes of these potential problem areas are also recognized in the modeling. However, some of the unstable slopes are bedrock outcroppings such as those along Mt. Toby and Sugarloaf Mountain in Sunderland and South Deerfield, respectively.

In contrast, a plot of known landslides against the stability classes in a slope-area plot generated within SINMAP (Figure 21) indicates that only 20% of known slides occur within High or Moderate zones and 33% occur in Very Low hazard zones. This would suggest the need to adjust the model parameters to increase the likelihood of sliding everywhere, and thus place a greater proportion of the known slides into the High or Moderate hazard zones. To move all of the known landslides into at least the Moderate hazard range, however, resulted in a landscape that was almost entirely devoid of Very Low (that is, highly stable) hill slopes – an untenable result given the historical stability of the majority of the land.

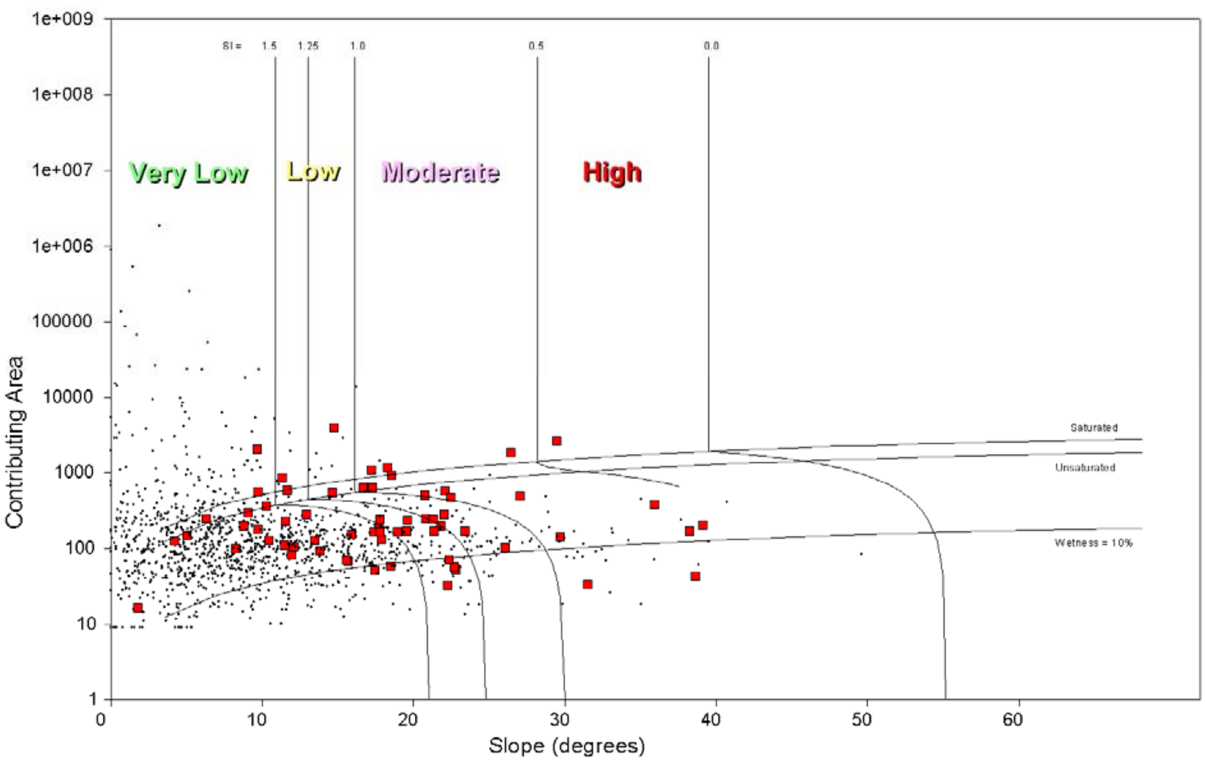


Figure 21. Slope-Area plot of known landslides (red) and non-landslide points (black) vs. stability index classes

Further analysis revealed that the low percentage of known slides falling within the High or Moderate hazard classes on the slope-area plot is the result of over-sensitivity to the landscape point positions within the plot. In other words, each individual landslide point on the plot in figure 21 is based on the stability index value of the single 9-meter cell upon which the marker was placed during discussions with MassDOT or during visual inspection of the LiDAR data. But these locations are not precise to the 9-meter level, and in any case many of the landslides are larger than a single 9 meter cell, so the positions of the known slides in the slope-area plot are not representative of the landslides.

To gain a better understanding of the model results with respect to known slides, we analyzed the distance from each mapped slide position to the nearest cell computed as a High or Moderate landslide hazard. This proximity analysis (Figure 22) revealed that with the default SINMAP

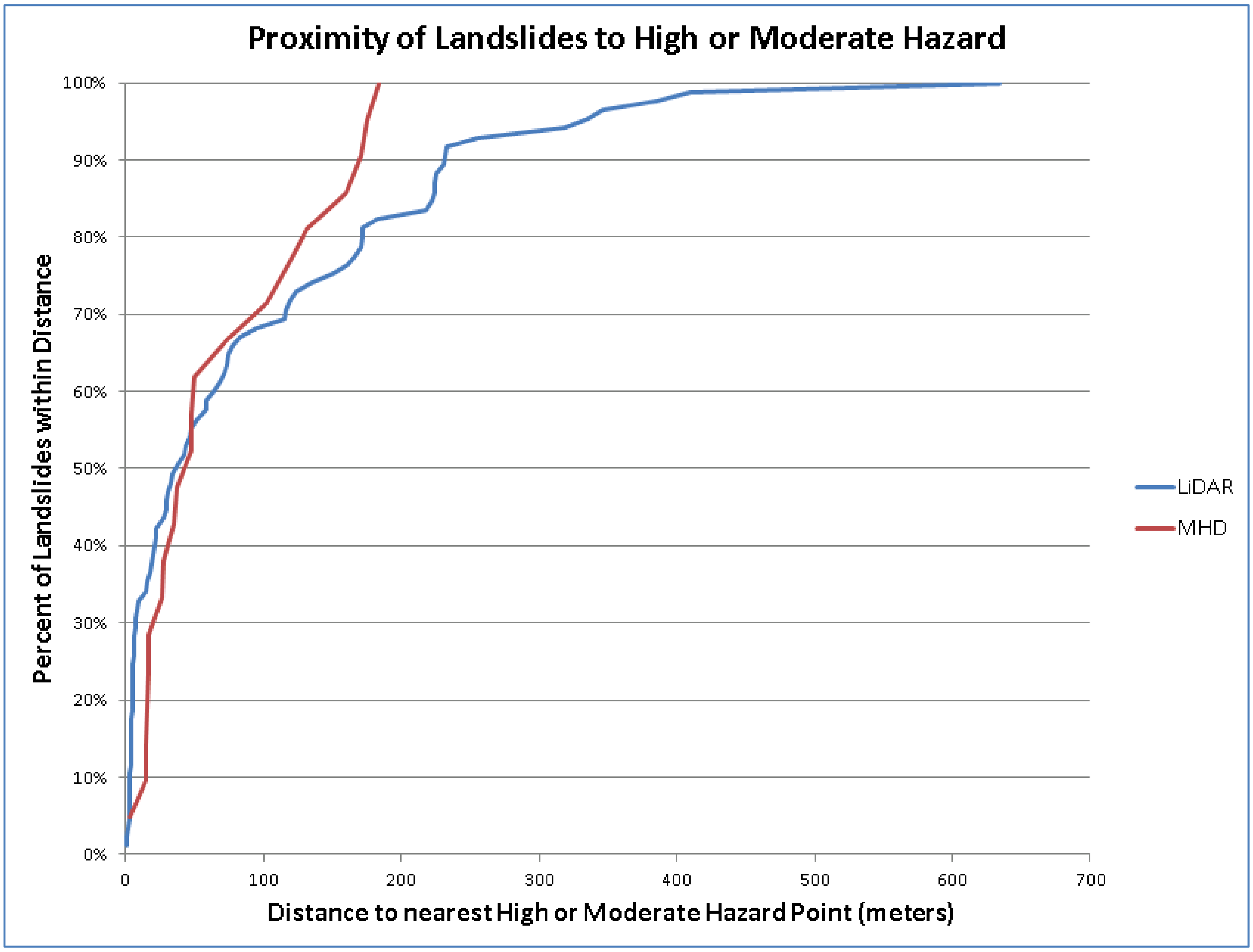


Figure 22. Proximity of known slides to High or Moderate hazard locations, red are slides identified by MassDOT and blue are slides determined from LiDAR data.

parameters, 70% of all slides are within 100 meters of High or Moderate hazard locations, and 80-100% of known slides are within 200 meters. Given the lack of locational precision in mapping the known slides, the size of typical slides (10's of meters), and the final map scale, this suggests a reasonable degree of agreement between the SINMAP results and the known slides.

Vegetation also might be affecting slope stability. However, SINMAP was given no data about vegetation patterns. To explore whether vegetation and the additional cohesion that roots might provide in stabilizing the slope, land cover class was compared with the location of all the known slides. Approximately, 90% of the slides identified by MassDOT and 86% of slides observed on the LiDAR imagery occurred in forested zones suggesting that the presence of a strong root system afforded by forests is not a significant factor in reducing landslide occurrence (Figure 23).

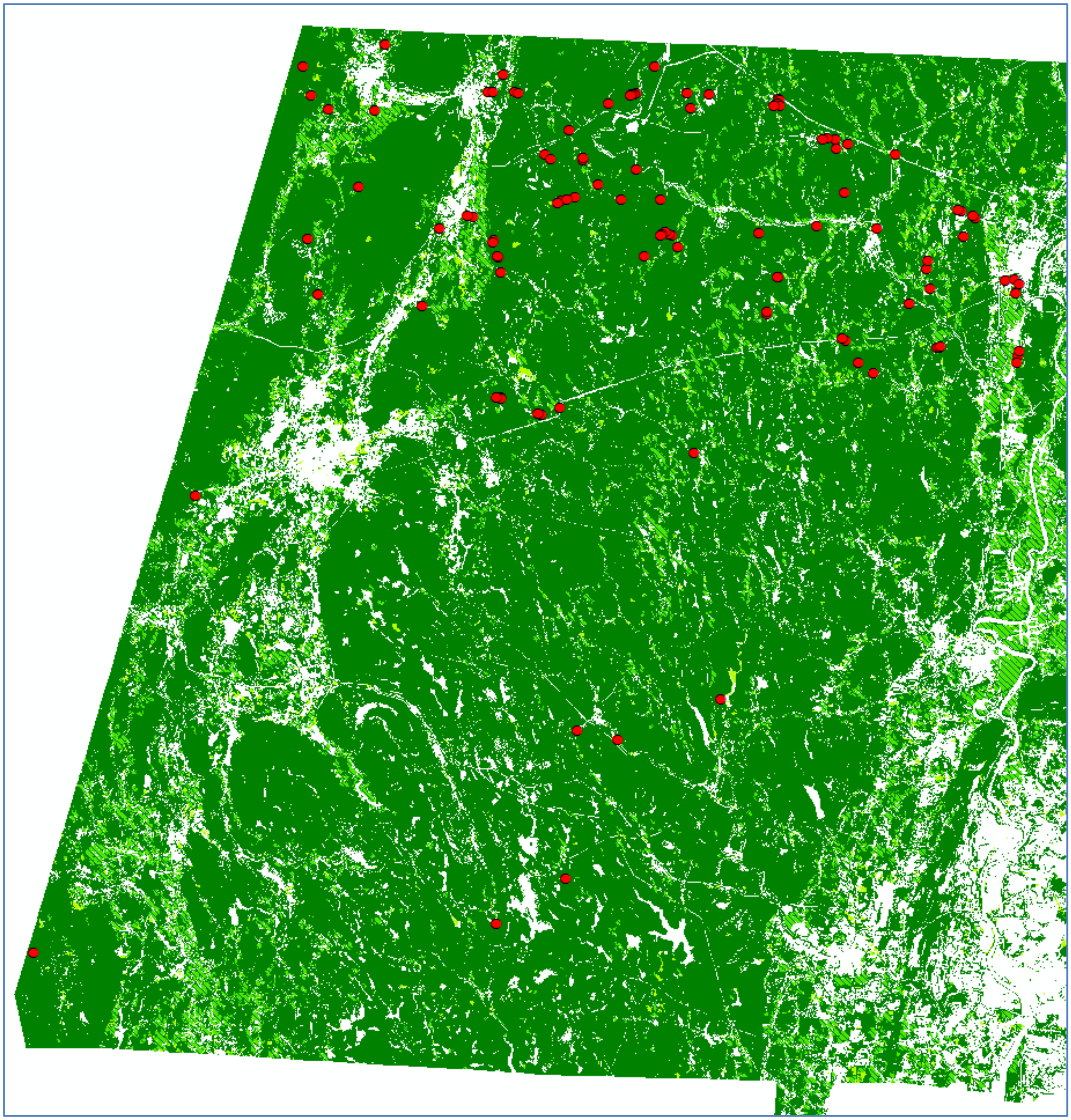


Figure 23. Forest (dark green) and pasture/brush (light green) land cover compared with known slide locations (from MassGIS).

A second run of SINMAP was completed using the soil-based parameters (Table 2). The results showed >99% of the state as a Very Low slope stability hazard zone. This result was puzzling and disappointing – it was assumed that using data-driven parameters based on known soil properties would yield the most reliable hazard estimate. Through personal communication with one of the SINMAP authors, however, it was made clear that similar attempts by others have also failed due to the complexity of the factors involved in landslides that cannot be captured by extrapolating from simple laboratory measurements or correlation of soil properties with map unit descriptions, borehole log descriptions, Atterberg Limits, grains size data or N-values from standard penetration tests.

As a final approach to verifying the validity of the SINMAP results using the default parameters, a handful of sites were field-checked that SINMAP indicated were prone to instability but had not been tagged as a probable landslide based on discussions with MassDOT or through inspection of the LiDAR imagery. In several instances, evidence of recent slope failure was observed. For example, Figure 24 shows the location of a slide caused by tropical storm Irene on Brook Road in Shelburne, MA. This slide occurred in till. A debris flow and channel scour were observed in Hawley MA along the Chickley River well above the floodplain (Figure 25) and a slide occurred in glacial till along East Mountain Road in Adams (Figure 26).

CONCLUSIONS

The maps produced from this project provide a first-order approximation of potential landslide hazards across the state at a scale of 1:125,000. This is an upgrade from previous landslide susceptibility mapping that was based on much smaller scale national data sets. The maps delivered in this study are provided only as a guide to areas that may be prone to slope instability when subjected to prolonged periods of antecedent wetness followed by a period of high intensity rainfall that exceeds several inches. The maps do not guarantee that a landslide will occur under these extraordinarily wet conditions, but they certainly indicate areas that may warrant additional, site-specific investigation if they are located near major roadways, utilities or critical facilities.

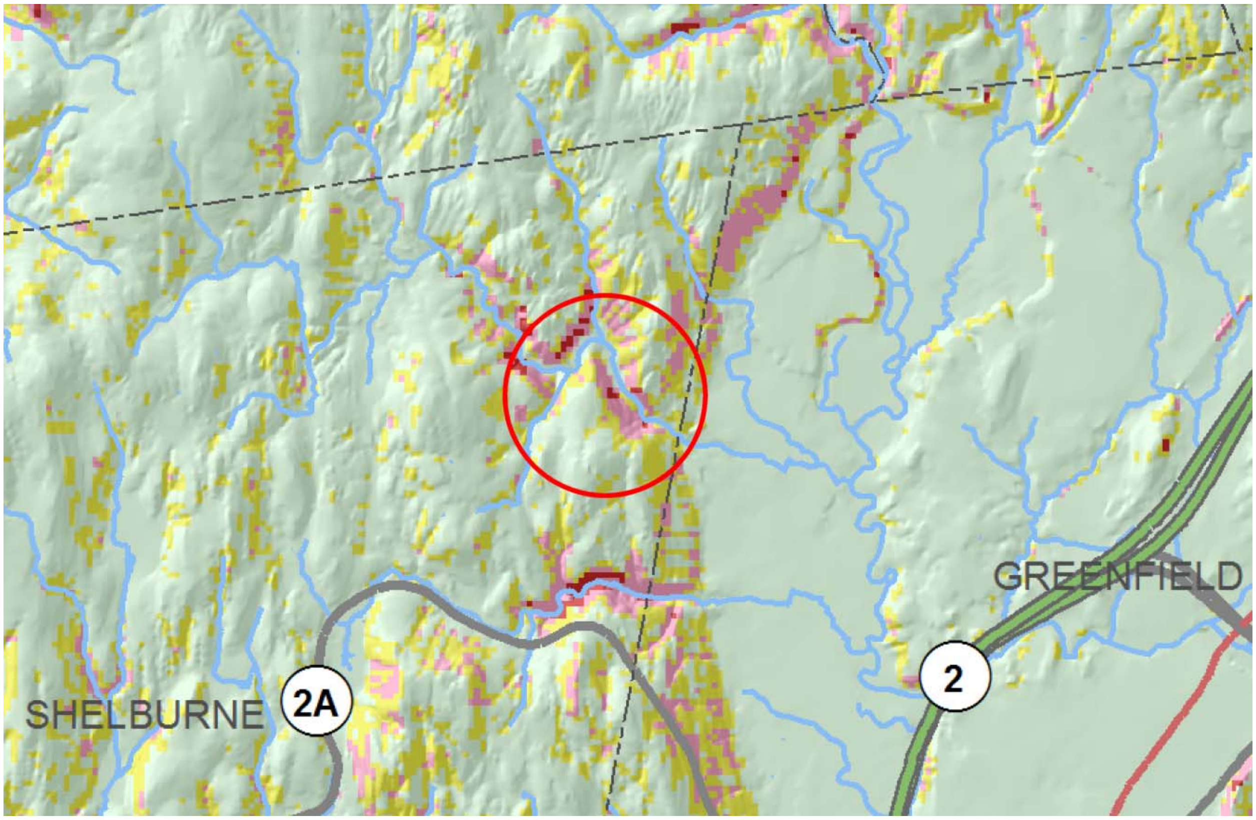


Figure 24. Landslide on south side of Brook Road in Shelburne, MA. Upper figure shows the location of the landslide on the slope stability map for western Massachusetts. Lower figure is a photograph showing the head scarp of one of the landslides found at this location (photo by C. Duncan).

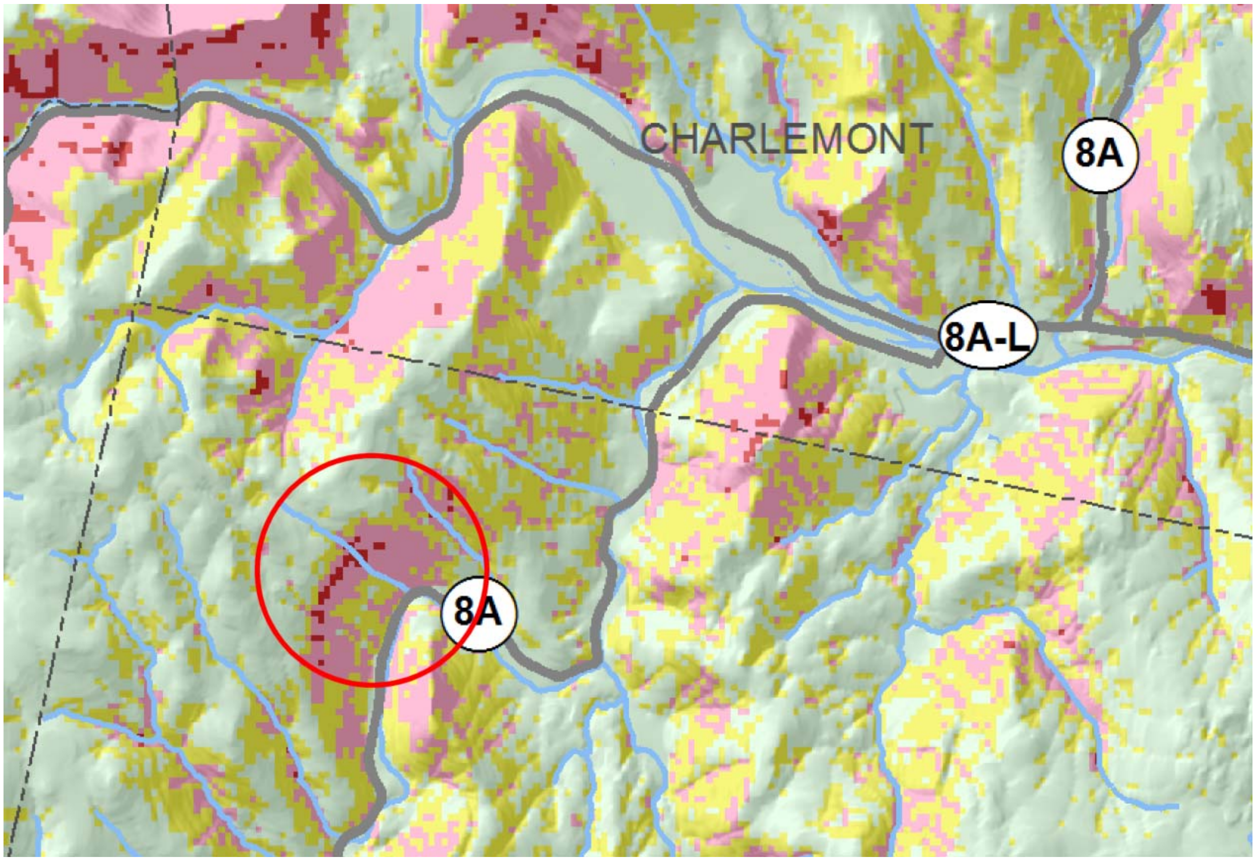


Figure 25. Scoured channel and debris flow material in small first-order stream located along Route 8A in Hawley, MA. Upper figure shows the location of the debris flow on the slope stability map for western Massachusetts. Lower figure is a photograph showing the amount of scour in the stream. Channel is located above the Chickley River floodplain (photo by C. Duncan).

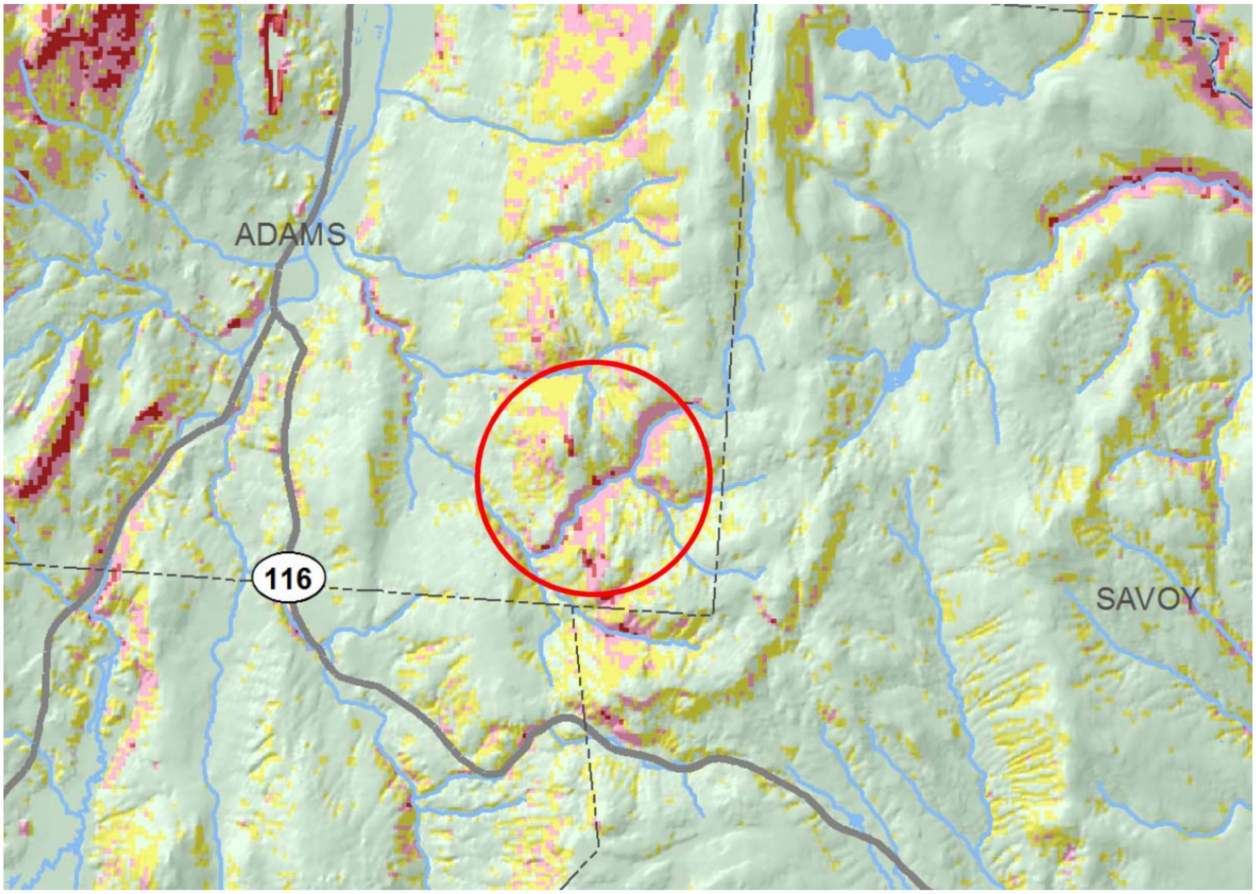


Figure 26. Landslide located along East Mountain Road in Adams, MA. Slide occurred in glacial till. Upper figure shows the location of the slide on the slope stability map for western Massachusetts. Lower figure is a photograph looking up from the toe of the slide (photo by C. Duncan).

REFERENCES CITED

Allred, B.J., 2000, Survey of fractured glacial till geotechnical characteristics: hydraulic conductivity, consolidation, and shear strength, Ohio Journal of Science, v.100, issue 3, pp.63-72.

Bowels , J.E., 1996, Foundation analysis and design, 5th edition. McGraw-Hill, New York.

Casagrande, A. and Fadum, R.E., 1940, Notes on soil testing for engineering purposes, Soil Mechanics Series, Graduate School of Engineering, Harvard University, Cambridge. M.A., Vol. 8.

Cleland, H. F. 1902. The landslides of Mt. Greylock and Briggsville, Massachusetts. *Journal of Geology*, v. 10, pp. 513-517.

Clift, A.E. and Springston, G., 2012, Protocol for identification of areas sensitive to landslide hazards in Vermont, Vermont Geological Survey Technical Report VGTR2012-1, 102p. http://www.anr.state.vt.us/dec/geo/pdfdocs/TechReports/LandslideProtocol2012.pdf

Dethier, D.P., Longstreth, B, Maxwell, K., McMillin, S., Scott, Jr., J., Small, E., and Weng, K., 1992, Rainfall-induced mass movements on Mt. Greylock, Massachusetts during 1990, *Northeastern Geology*, v.14, no.4, pp.218-224.

Hammond, C., Hall, D., Miller, S., and Swetik, P., 1992, Level I stability analysis (LISA) documentation for Version 2.0, General Technical Report INT-285, U.S. Department of Agriculture, Forest Service, Intermountain Research Station, 190 p.

Holtz, R.D., Kovacs, W.D., and Sheahan, T.C., 2011, An introduction to geotechnical engineering, 2nd edition, Pearson Education Inc., Prentice Hall, Upper Saddle River, NJ.

King, P. B. and Beikman, H. M., 1974, Geologic map of the United States (exclusive of Alaska and Hawaii) on a scale of 1:2,500,000: U.S. Geological Survey, 3 color plates.

Koloski, J.W., Schwarz, S.D., and Tubbs, D.W., 1989, Geotechnical properties of geologic materials, Washington Division of Geology and Earth Resources Bulletin, v.78.

Kopera, J. and S.B. Mabee, December 12, 2011, Preliminary field report on the November 13-14, 2011 landslide near Steam Mill Road, Deerfield, Massachusetts, Massachusetts Geological Survey.

Louden, A.G., 1952, The computation of permeability from soil tests, Geotechnique, v.3, no.4.

Meyerhof, F.F., 1956, Penetration tests and bearing capacity of cohesionless soils, *Journal of Soil Mechanics and Foundation Division*, American Society of Civil Engineers, Vol. 82, SM1.

Montgomery, D. R. and Dietrich, W. E., 1994, A physically based model for the topographic control on shallow landsliding, *Water Resources Research*, v.30, no.4, pp.1153-1171.

Murthy, V.N.S., 2003, Geotechnical engineering: principles and practices of soil mechanics and foundation engineering, Marcel Dekker, Inc., New York, NY.

Pack, R. T., Tarboton, D. G. and Goodwin, C. N., 2001, Assessing terrain stability in a GIS using SINMAP, *in* 15th annual GIS conference, GIS 2001, Vancouver, British Columbia, February 19-22.

Pack, T.T., Tarboton, D.G., and Goodwin, C.N., 1998, Terrain stability mapping with SINMAP, technical description and users guide for version 1.00, Tetratech Consulting Ltd., Salmon Arm, BC, Canada, Report Number 4114-0, 68p.

Peck, R.B., Hanson, W.E., and Thornburn, T.H., 1974, Foundation engineering, John Wiley and Sons Inc., New York.

Radbruch-Hall, D.H., Colton, R.B., Davies, W.E., Lucchitta, I., Skipp, B.A., and Varnes, D.J., 1982, Landslide Overview Map of the Conterminous United States, Geological Survey Professional Paper 1183, U.S. Geological Survey, Washington.

Stephenson, D.A., Fleming, A.H., and Mickelson, D.M., 1988, The geology of North America, Geological Society of America, v. O-2, ch. 35, pp.301-313.

Stone, B.D. and Peper, J., 1982, Topographic control of the deglaciation of eastern Massachusetts: Ice lobation and the marine incursion, in Larson, G.J. and Stone, B.D., eds., Late Wisconsinan glaciations of New England. Dubuque, Iowa: Kendall Hunt Publishing Company, pp.145-166.

Varnes D. J., 1978, Slope movement types and processes, *in* Schuster R. L. and Krizek R. J., Eds., Landslides, analysis and control. Transportation Research Board Special Report No. 176, National Academy of Sciences, pp. 11–33.

Yilmaz, I., 2009, Landslide susceptibility mapping using frequency ratio, logistic regression, artificial neural networks and their comparison: A case study from Kat landslides (Tokat-Turkey): Computers and Geosciences, vol. 35, p. 1125-1138.