

Debris Flow Hazard Identification and Monitoring

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Abstract

Over the past few years, considerable roadway damage has occurred in Vermont due to intense precipitation, leading to upslope landslides and debris flows (mixtures of boulders, trees and slurries) spilling onto roadways. Although landslide occurrence has a long history in the State, the debris flow phenomenon addressed in this work is relatively new to Vermont and needs further attention. The work is focused on non-channelized debris flows, that is, debris flows not specifically associated with gullies and channels developed through fluvial processes. Identifying areas susceptible to such debris flows and monitoring of these areas will facilitate asset management, improve roadway safety, potentially reduce the need for emergency road closures and help reduce long-term costs associated with repeated emergency responses. The susceptibility to debris flow is influenced by several factors such as slope angle, slope materials and rainfall intensity. The key outcome of this study was to create a map identifying high-hazard areas (susceptible to debris flow) for awareness, asset management and monitoring. We considered rainfall as the triggering factor to initiate debris flow and merged rainfall data with topographic and soil parameter data to produce a debris flow factor of safety map for a study area comprised of a 152 m (500 ft) buffer zone on either side of national and state routes. Three factor of safety groupings categorize the terrain in the buffer zone into stable, marginally unstable, and unstable, and thereby the debris flow potential in the design rainfall triggering scenario.

The map development consisted of a high resolution (75 cm $\times$ 75 cm) digital elevation model available through the Vermont Center for Geographic Information resampled into 15m grid size and then converted into a statewide slope map. A total of 16 soil types were extracted from the Natural Resources Conservation Service (NRCS) Gridded Soil Survey Geographic (gSSURGO) data set, and were assigned standard values of effective cohesion, effective friction angle, saturated unit weight, and porosity. Multiple storm event simulations in the slope stability model indicated that ground water level (G.W.L.) rise causes the most significant reduction in the slope stability factor of safety values. By considering 100% rainwater infiltration into slope the potential G.W.L. rise was calculated from individual soil porosity to estimate the G.W.L. rise from the bottom of a 3.04 m (10 ft) thick potential failure depth chosen for slope stability analysis.

An infinite slope stability model integrated with GIS (Geographic Information System) tools was used for slope stability analysis to classify the debris flow susceptibility in the study area into 3 categories (F.S. < 1: unstable; F.S. = 1-1.25: marginally stable; and F.S. > 1.25 = stable). Field-based validation was employed to assess performance of the debris flow hazard prediction model. Out of 14 validation sites, 12 sites showed good to excellent agreement with those of the developed susceptibility map.

Aside from traditional monitoring, feasibility of a satellite InSAR-based debris flow monitoring system was evaluated for assisting with hazard susceptibility identification and monitoring, based on detecting terrain movement. InSAR implementation is potentially viable but is not yet possible due to current limited availability of L-band SAR imagery over Vermont.

A combination of ground station-based rainfall recording and satellite based surficial soil moisture tracking methodology is proposed for monitoring debris flow susceptible areas as of the currently available hazard mitigation methodology. In addition, this report provides recommended structured and non-structured mitigation methods at debris flow prone locations.

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1 INTRODUCTION

1.1 Background and Motivation

Debris flows, sometimes referred to as mudslides, mudflows, or debris avalanches, are fast-moving landslides that can carry large items such as boulders, trees, and cars and can destroy objects in their paths (USGS). Typically, debris flows occur during periods of intense rainfall or rapid snowmelt and usually start on hillsides or mountain sides (USGS; Yang et al., 2020).

Considerable roadway damage occurred in July 2023 rains from uphill gully erosion and debris flows spilling onto roadways (Figure 1.1). This was a new phenomenon at this magnitude for VTrans which required them to engage outside expertise to develop standard details for rapid repairs, and in some cases, specific situation recommendations.

There are safety and cost-saving benefits in identifying the future hazard potential and developing strategies for preparing for, warning of, and responding to the debris flow hazard. Identifying higher hazard areas and monitoring these areas will facilitate asset management, improve roadway safety, reduce the need for emergency road closures, and reduce long-term costs associated with repeated emergency responses.

Debris flow hazard assessments generally apply a Geographic Information System (GIS), predominantly in combination with statistical analysis, and interpretation of aerial photographs or satellite images (e.g. Melelli and Taramelli, 2004; Hürlimann et al., 2019). One of the most significant applications of remote sensing is the observation and monitoring of geohazards following extreme events, particularly those tied to ground surface deformation (e.g. landslides, wildfires, earthquakes). One of the strongest capabilities of remote sensing is to detect changes over large spatial and temporal extents. In addition, airborne and terrestrial LiDAR (light detection and ranging) have been employed for creating digital elevation models (DEM) before and after an extreme event, or during such events, to monitor ground surface movements (e.g. Rathje et al., 2016; Kean et al., 2019). UAVs (unmanned aerial vehicles) carrying photographic equipment, and radar sensors have also been employed (Jet Propulsion Laboratory's UAVSAR (Delbridge et al., 2016)). Satellite photogrammetry and change detection processing of aerial imagery have been used to detect landslides following the Fish fire in Southern California (e.g. Kean et al., 2019).



(a)



(b)



(c)

Figure 1.1 Examples of roadway damage caused by uphill gully erosion and debris flow in Vermont's July 2023 flood event. (Source: VTrans)

1.2 Research Approach

This study aimed at carrying out debris flow hazard assessment, monitoring, and mitigation at the state level. A physics-based infinite slope stability model was used for regional-scale slope stability assessment as its simplified assumptions make it well suited to situations with limited real-time data. It should be noted that the study focuses on non-channelized debris flow, that is debris flows not specifically associated with fluvial processes where gullies and small stream channels accumulate runoff. A GIS-based integrated framework has been developed that incorporates parameters derived from LiDAR-derived DEMs (Digital Elevation Model), gridded soil databases (gSSURGO), National Oceanic and Atmospheric Administration (NOAA) rainfall records. A statewide combined slope failure database from the Vermont Agency of Natural Resources (ANR) was considered to create an overall landslide inventory map since few historical records of debris flow exist in Vermont. The analytical steps for slope stability analysis including data extraction, processing, and modeling were performed using ArcGIS Pro 3.6.2 software. Site inspections with VTrans personnel and the study team were carried out to obtain information on debris flow failure sites (e.g. dimensions, extent, vegetation, slope material, etc.) The suitability of an InSAR based monitoring system and its capability to detect debris flow potential in densely vegetated terrains such as in Vermont was also investigated. Although L-band InSAR images can penetrate tree canopy, due to lack of publicly available data for Vermont, InSAR technology cannot be implemented in a foreseeable timeframe. A combination of daily rainfall and satellite-based surficial soil moisture tracking tools are proposed for monitoring higher susceptibility hazard slopes. Hazard mitigation strategies for debris flow, both structural and non-structural, were evaluated for their suitability for Vermont.

1.3 Project Objectives

- Create a map identifying high-hazard areas for awareness, asset management and monitoring.
- Provide potential hazard mitigation measures and monitoring strategies for the State of Vermont.
- Develop technology transfer, and guidelines for implementation.

This study contributed to the following strategic goals of VTrans as detailed below:

VTrans Strategic Goal 1: Provide a safe and resilient transportation system that supports the Vermont economy.

- No unplanned road closures or restrictions due to conditions within VTrans' control,
- Increase the resilience of the transportation network to floods and other extreme weather and events.

VTrans Strategic Goal 2: Preserve, maintain, and operate the transportation system in a cost effective and environmentally responsible manner.

- Maintain pavement, structures, and other transportation system assets in a state of good repair.

VTrans Strategic Goal 3: Provide Vermonters with energy efficient travel options.

- Minimize traveler delay.

2 LITERATURE REVIEW

This chapter reviews the current approaches to debris flow hazard study, including the methodologies used for hazard assessment, identification of existing and potential debris flow-prone locations, analysis and spatial mapping of hazards, spatiotemporal monitoring of unstable slopes using InSAR technology, and the influence of surface runoff on debris flow hazards along with applicable mitigation techniques.

2.1 Debris Flow Hazard Assessment Methodology

Recent studies on storm-induced landslides and debris flows reflect a spectrum of geomorphic, empirical, and physics-based approaches, with growing integration of GIS and remote sensing for regional susceptibility mapping. Mohseni et al. (2018) grouped landslide hazard assessment methods into geomorphic, index-based, statistically based, and physically based categories, and demonstrated a physics-based, infinite-slope GIS model for storm-driven slope failures that couples LiDAR topography, gSSURGO soils, and NOAA Atlas 14 rainfall data to produce multi-class susceptibility maps for transportation corridors, showing good agreement with observed problem sites and supporting its use as a screening tool. Extending this line of work to debris flows, Pei and Qiu (2023) compared an infinite-slope factor-of-safety model with a multi-layer artificial neural network in the Colorado Front Range, using nine terrain, soil, and vegetation predictors, and found good model performance with both approaches ($AUC \approx 0.89$ vs 0.93), while emphasizing the stronger dependence of data-driven models on comprehensive debris-flow inventories for regional mapping. In parallel, Burns et al. (2022) formalized a protocol for channelized debris-flow susceptibility in the State of Oregon, organizing analysis into initiation, transport, and deposition stages, using inventories, terrain metrics (e.g., convergent slopes $> 35^\circ$, within ~ 30 m of channels), and Lahars hazard zonation (LAHARZ) based inundation modeling to assign standardized susceptibility classes, though without explicitly incorporating rainfall intensity or climate-change effects. At the slope-scale, Zito et al. (2024) illustrated the value of advanced monitoring and numerical modeling for complex cascading landslides, combining drone mapping, Interferometric Synthetic Aperture Radar (InSAR) and pixel-offset analysis, and Finite Element Method- Strength Reduction Method (FEM-SRM) stability simulations to show that high rainfall

and elevated groundwater strongly control multi-phase movements, motivating site-specific, sensor-based early-warning systems.

2.2 Debris Flow Hazard Identification

Recent studies have shown that high-resolution topographic datasets (airborne LiDAR and UAV-derived DEMs), combined with statistical and deterministic susceptibility or hazard models and explicit vulnerability analysis, provide a robust basis for hazard-informed planning and mitigation. Abdulwahid and Pradhan (2017) demonstrated that airborne LiDAR-derived terrain metrics (e.g., slope, curvature, wetness and roughness indices) can be effectively integrated in a logistic-regression framework to produce statistically robust susceptibility maps, which are then combined with precipitation-based temporal probabilities and detailed vulnerability indicators (cost, reconstruction time, population exposure) to derive quantitative hazard maps for multi-hazard urban settings. Their work underscores that effective susceptibility mapping requires both good spatial overlap between landslide inventories and zones of high modeled probability, and avoidance of overly extensive high-probability areas, while also noting that limitations in temporal landslide data, rainfall records, and land-use information still constrain hazard quantification.

Complementary advances in UAV remote sensing enabled airborne platforms capture short-term dynamics and process intensity for different landslide types relevant to debris-flow hazards. Ilinca et al. (2022) used multi-platform UAV imagery and structure-from-motion processing to generate high-resolution surface models under dense forest cover, manually tracking features such as tilted trees to resolve kinematics of a slow-moving landslide, and demonstrating that such methods can distinguish different movement regimes (e.g., earth slide vs. earthflow) despite vegetation constraints, while recommending multispectral or LiDAR-equipped UAVs to improve automation. Ahmad et al. (2024) further integrated UAV-based DSMs (validated with DGPS) with RAMMS debris-flow simulations, deterministic slope-infiltration factor-of-safety modeling, and rainfall statistics to produce spatially explicit debris-flow hazard maps, which were then combined with an AHP-based vulnerability assessment of different building types to generate hazard maps for a

mountainous region of northern Pakistan and to guide continuous UAV monitoring for early warning and land-use planning.

At the site scale, recent work in Vermont illustrates how repeated remote-sensing and field campaigns can quantify geomorphic change and sediment redistribution associated with large landslides. Myrick (2024) combined detailed field mapping of fractures, gullies, and bank erosion with LiDAR and photogrammetric DEMs to perform topographic change detection at the Cotton Brook landslide, documenting substantial sediment removal and accumulation over a multi-year period and linking these patterns to glacial sediment properties, bedrock structure, and hydrologic forcing. Together, these studies demonstrate that debris-flow and landslide hazard identification increasingly rely on high-resolution elevation data (LiDAR/UAV), susceptibility and hazard modeling (statistical, deterministic, and numerical), and explicit vulnerability analysis to produce hazard-informed products for urban planning, infrastructure management, and community-level mitigation.

2.3 Debris Flow Hazard Analysis & Mapping

Recent debris-flow and rainfall-induced landslide hazard studies combine deterministic geotechnical modeling, probabilistic event analysis, and machine-learning GIS methods, all supported by high-resolution topography. Delmonaco et al. (2003) showed that a distributed, physically based GIS framework-linking inventories, geotechnical characterization, Green-Ampt infiltration, and infinite-slope factors of safety-can successfully reproduce observed debris-flow patterns at basin scale, while cautioning that conservative strength assumptions and neglected controls (e.g., root reinforcement) may overestimate unstable areas.

Coe et al. (2004) used Poisson and binomial models on 90 years of Seattle landslide records to derive spatial patterns of recurrence and annual exceedance probability, finding higher exceedance probabilities on steeper slopes and demonstrating that binomial models better capture clustered landslide behavior despite inventory limitations. Alvioli and Baum (2016) parallelized TRIGRS with MPI, enabling rapid, large-domain simulations of transient pore-pressure

and factor-of-safety changes under varying rainfall scenarios and supporting applications to real-time hazard monitoring.

Regional hazard-mapping work such as Crawford et al. (2022), Baum et al. (2024), Liu et al. (2024), and Meng et al. (2024) confirms that lidar-based susceptibility inputs, quasi-3D stability analysis, and geographically partitioned machine-learning models (e.g., Random Forest, logistic regression) can produce accurate, interpretable hazard probabilities and susceptibility classes, even under limited data conditions, thereby providing practical screening tools for large-area landslide and debris-flow hazard assessment.

2.4 Debris Flow Hazard Monitoring with InSAR Technology

Debris-flow and landslide monitoring studies show that combining satellite-based deformation measurements, data-driven models, and rainfall information can capture the space–time evolution of slope motion and hazard, providing a stronger basis for early warning and continuously updated hazard maps. Tong and Schmidt (2016) used a coherence-based InSAR time-series method with L-band ALOS-1 data to track seasonal motion of the Cascade landslide complex, showing up to ~25 cm line-of-sight displacement over four years and a consistent acceleration in early winter, thereby demonstrating that hydrologically driven, non-linear slope behavior can be detected in densely vegetated terrain when interferograms are carefully processed and validated against GPS.

Building on this cited study, Xiong et al. (2024) proposed a hybrid spatiotemporal susceptibility framework in western Pennsylvania that couples static terrain and soil factors with time-varying rainfall metrics in machine-learning models (Logistic Regression, Support Vector Machine, Random Forest, Gradient Boosting Machine), using cross-validation and SHAP analysis to quantify the contributions of both geomorphic and antecedent rainfall controls and achieving high AUC for combined spatial-temporal landslide prediction under limited inventory data. Zocchi et al. (2024) applied multitemporal PS-InSAR processing (SARPROZ) to Sentinel-1 data over the DeBeque Canyon landslide, deriving dense velocity and displacement time series for thousands of scatterers and using vector decomposition and gradient analysis (including a C-factor metric)

to distinguish bulging, subsidence, and translational components of complex landslide kinematics. She et al. (2024) further showed in Wanzhou that combining susceptibility modeling (SVM on DEM and geology-based factors) with SBAS-InSAR surface-deformation time series and rainfall correlations can reduce bias from uncertain InSAR signals and yield hazard maps where landslide-prone areas expand systematically with increasing rainfall intensity, improving the reliability of spatial–temporal hazard assessment for hazard management.

2.5 Debris Flow Hazard Influenced by Runoff and Mitigation Techniques

Debris-flow hazard is strongly shaped by runoff, with catchment-scale hydrologic processes and engineered mitigation measures together governing debris-flow mobility and the severity of downstream impacts. Justice and Buech (2026) emphasize that debris-flow hazard mitigation should be based on a competent, site-specific assessment of both the physical hazard and the elements exposed to it. Because debris flows can travel rapidly over long distances and exert substantial impact forces, mitigation should not focus solely on initiation areas; it should also address potential flow paths, runout zones, and downstream consequences. The New Zealand Geotechnical Society (NZGS) guidance positions mitigation within a hazard-based framework that integrates geotechnical, engineering-geological, and hydrogeological evidence to support defensible management decisions. Liu and He (2024) developed a physically based, multi-process coupling model that links rainfall, vegetation interception, soil infiltration, runoff generation, and debris-flow propagation at catchment scale, showing that effective precipitation and runoff dynamics strongly modulate debris-flow initiation, velocity, and runout distance. In their Meilong case study, simulations indicated that water absorption into the debris mass decreases basal shear stress and supplies additional energy, so stronger runoff and more frequent rainfall pulses in larger, high-relief catchments enhance debris-flow mobility and extend runout, although limited field monitoring still constrains full calibration of the governing mechanisms.

Complementing these process insights, Roth et al. (2010) demonstrated that properly designed flexible ring-net barriers can effectively intercept and retain substantial debris-flow volumes, including fine-grained mudflows, when sited and engineered based on observed event loads, full-scale flume tests, and numerical simulations. Their results highlight the superior energy

absorption and terrain adaptability of ring-net systems compared with more rigid woven wire nets, while stressing the importance of maintenance (debris clean-out) and the residual hazard that extreme, unanticipated events may exceed barrier capacity, especially for broad, unconfined flows along transportation corridors. Table 1 presents a summary of literature review findings in this study.

Table 2.1 Summary of reviewed literature

Category	Authors	Methodology/ Tools	Comment
1) Debris Flow Hazard Assessment Methodology	Mohseni et al. (2018)	- Physically based method (Infinite slope model) - SSURGO DATASET for soil property - ATLAS-14 DATASET for rainfall data	The methodology incorporates topography, soil type, and expected rainfall extent through a GIS approach for susceptibility screening.
	Pei et al. (2023)	-Data driven method (artificial neural network) -Physics-based method (infinite slope model)	Both approaches are good for regional scale susceptibility mapping, where the data driven method shows higher accuracy due to high data input.
	William et al. (2023)	-CDF (Channelized Debris Flow) Susceptibility mapping. -LAHARZ modeling (GIS based python coding for slope analysis).	Standardized protocol for susceptibility analysis in valley areas.
	Zito et al. (2024)	-Coherence pixel technique (CPT) to process InSAR image. -Finite Element Method (FEM) and Stress Reduction Method (SRM) for slope stability under influence of groundwater fluctuation.	Proper assessment of complex slope movement can be done with the combination of traditional field activities, remote sensing techniques, and numerical modeling.
2) Debris Flow Hazard Identification	Abdulwahid et al. (2017)	-Logistic regression analysis. -Statistical Packages for Social Science (SPSS) software to evaluate the correlation between conditioning factors.	The efficiency of susceptibility maps can be validated in 2 ways. Maps should be overlapped with inventories, and the percentage of high-hazard prone areas should not be high.
	Ilinca et al. (2022)	-(DJI Phantom 4 and Phantom 4 RTK) drones are used to map the area.	Manual tracking of landscape features via UAV mitigates the vegetation error.

Category	Authors	Methodology/ Tools	Comment
		-structure-from-motion (SFM) techniques to generate high-resolution orthophotos, digital surface models, and digital elevation models	
	Ahmad et al. (2024)	-Normalized Root Mean Square Error (NRMSE) was used to evaluate the accuracy of UAV-DSM. -RAMMS numerical simulation tool was used to calibrate different debris flow scenarios.	The dynamics of debris flow are complex to understand in regions where human activities and fragile slopes intersect.
	Myrick (2024)	-Photogrammetric data to detect topographic changes.	Glacial sediments, bedrock structures, and the influence of surface water and groundwater are actively shaping the landscape.
3) Debris Flow Hazard Mapping	Delmonaco et al. (2003)	-Geotechnical analysis (field measurement and lab test). -Green-AMPT model to estimate the relationship between rainfall, soil saturation, and pore pressure generation.	Perched water table and metasedimentary rock influence the initiation of debris flow.
	Coe et al. (2004)	-Poisson model to estimate the probability of future occurrence of individual landslides. -Binomial model to estimate the probability of having a group of landslides. -ArcInfo software to connect areas of similar landslide density.	The Binomial model provides a more realistic portrayal of future landslide occurrence compared to the Poisson model.
	Alvioli et al. (2016)	-TRIGRS code to speed up running time.	Reduce time to simulate large data set.
	Crawford et al. (2022)	-Bagged tree model to predict weighted classification according to variables and rank importance. -Kernel density map to estimate the cost of damage.	Susceptibility-based hazard maps are more recommended than slope-based ones because of the quantity of data

Category	Authors	Methodology/ Tools	Comment
			computed to assess the entire area with more considerable factors.
	Baum et al. (2024)	-Integrate soil-depth modeling, consideration of parameter variability, and quasi-3D slope stability analysis into the assessments.	The Quasi-3D approach showed more continuous susceptibility zones with smoother, buffered boundaries.
	Liu et al. (2024)	-Support Vector Machines, Logistic Regression, Decision Tree, Random Forest are used to refine inductive bias and capture nonlinear relationships, enabling a quantitative estimation of hazard probabilities for each slope unit. -P-RF+ (P-value analysis with a Random Forest model) method, which combines spatial partitioning and consideration of multiple triggering factor.	Spatial heterogeneity in large-scale landslide hazard assessment can be overcome with machine learning tools.
	Meng et al. (2024)	- t-test and chi-squared test have been done for numeral and categorical data to estimate the significance of conditioning factors for landslide occurrence.	Only conditioning factors are taken into consideration for susceptibility analysis in large areas of extent without any remote sensing data.
4) Debris Flow Hazard Monitoring with InSAR Technology	Tong et al. (2016)	-GMTSAR software is used to process interferograms. -SNAPHU software is used to unwrap the interferograms with high coherence level. -InSAR data correlated with GPS data to validate displacement result.	Comparison of displacement with different rainfall periods, which shows a constant harmonic pattern of displacement.
	Xiong et al. (2024)	-Causative factors are classified into two categories i.e. static factors (elevation; slope; aspect; mTPI; TWI; SPI; profile curvature; Plane curvature; NDVI; clay content etc.) and time varying factors (rainfall intensity).	A Hybrid method to assess landslide susceptibility both spatially and temporally with a limited data set,

Category	Authors	Methodology/ Tools	Comment
		-SHAP method is used to make graphical representation of significance of each factor.	which has potential applicability to mitigate landslide hazard.
	Zocchi et al. (2024)	-SARPROZ (SAR processing tool by Perez) software is used for processing Sentinel-1 images which provide line of sight velocity.	C (percentage of ground displacement) factor can be used to better understand the complex kinematics of slope movement.
	She et al. (2024)	-Pearson's coefficient formula is used to determine the dependency of landslide occurrence on rainfall.	The combination of landslide hazard, surface deformation, correlation coefficient, deformation factors and final landslide hazard assessment enhances the accuracy of the method, which can be applied in large areal extent.
5) Debris Flow Hazard Influenced by Runoff and Mitigation Techniques	Liu et al. (2024)	-Physical-based multi process coupling model is used to quantify the effective precipitation that contributes to runoff. - Elevation based empirical formula to evaluate the spatial distribution of rainfall.	The integration of various processes like rainfall, vegetation interception, soil infiltration, and runoff generation enables us to understand the influence of surface runoff to initiate debris flow.
	Roth et al. (2010)	-Designed the flexible barrier to mitigate impact of debris flow hazard. -FARO modeling to test strength of ringlet barriers under different dynamic conditions.	Flexible barriers were installed in a project to protect highways in California performed well.
		- Hazard-based debris-flow assessment integrating source areas, channelized flow paths, and runout/fan zones. - Estimate debris-flow magnitude, peak discharge, flow	Provides a structured framework for converting debris-flow hazard assessment into mitigation design.

Category	Authors	Methodology/ Tools	Comment
	Buech and Justice (2026)	depth, velocity, and runout distance. - Assess exposure and vulnerability of elements at hazard, including buildings, roads, and lifeline infrastructure. - Compare mitigation alternatives against performance objectives, technical feasibility, cost, environmental effects, and residual hazard	Flow depth and velocity at the exposed asset are key parameters because they govern impact severity and the required performance of protective works.

3 METHODOLOGY

3.1 Analytical Workflow

This chapter presents an overview of the analytical framework of the adopted analysis and monitoring methodology for data input, and modeling. The study employs an infinite slope stability model, analyzing forces affecting stability and incorporating soil properties, slope angle, and rainfall as key factors. Figure 3.1 shows the analytical workflow, where the study began with a detailed evaluation of historical landslide inventories and a comprehensive review of relevant literature to identify the most appropriate methodology for debris-flow hazard mapping. The resulting hazard map was refined through multiple rounds of calibration and parameter adjustment to improve agreement with observed real site conditions. Field-based validation was then conducted to evaluate the reliability of the mapping results, and based on these findings, appropriate monitoring strategies and feasible mitigation measures were identified and recommended.

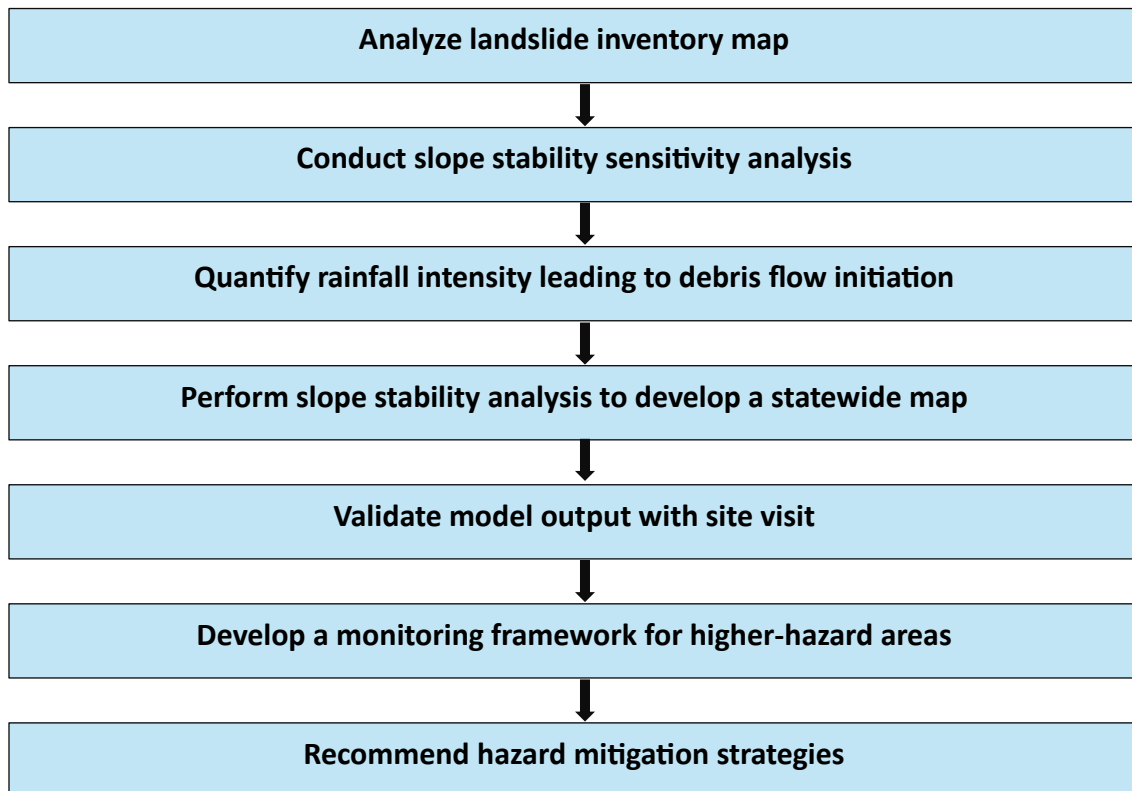


Figure 3.1 Analytical workflow of the study.

3.2 Landslide Inventory Analysis

Since debris flows are an emerging hazard in Vermont, no dedicated debris-flow inventory currently exists. A statewide landslide inventory containing approximately ~3,000 documented landslide locations were available and therefore adopted as a surrogate dataset. These landslide points were overlaid on a digital elevation model (Figure 4.1) to understand the spatial distribution of landslides and their correlation with topography.

3.3 Sensitivity Analysis

To evaluate the influence of slope stability parameters on the factor of safety, a sensitivity analysis was performed using average parametric values derived from initial site observations and model calibration (Table A1 in Appendix). The results of the sensitivity analysis indicated that groundwater-level rise (h_w) and increased failure depth (Z) cause the largest reductions in slope stability computed Factor of Safety (F.S.), with changes on the order of 40% within the tested ranges, indicating that increases in h_w and Z parameters most substantially destabilize the slopes. For example, two simulations were conducted under the scenario of failure depth 3.04 m (10 ft) and ground water level rise 1.82 m (6 ft) & 3.04 m (10 ft) as shown in Appendix Figure A1, A2. This showed the factor of safety value drops with increasing ground water level from 1.82 m (6 ft) to 3.04 m (10 ft) from bottom of slope surface. This shows reasonable consistency with sensitivity result.

A primary challenge in this project was the lack of real-time data on statewide groundwater-level and failure depth information. To address groundwater level rise in response to rainfall, soil porosity was incorporated to estimate groundwater-rise scenarios across the State.

Field observations at three visited debris-flow sites (Route 62-Railroad Street, Barre, Route 302-East Barre, and Route 103-Proctorsville) indicated a failure depth of approximately 3.04 m (10 ft). In contrast, Route 110 site in Washington County had shallow bedrock at approximately 1.52 m (5 ft). Comparison of the modeled results with conditions at the documented debris-flow sites indicated that a failure depth of 3.04 m (10 ft) provided the most reasonable agreement. Therefore, a constant failure depth of 10 ft across the State was considered in this study.

Following groundwater-level rise and increasing sliding zone thickness slope angle (β) has the next strongest effect on the factor of safety (F.S. change of 30%), followed by effective cohesion, C' (20% change), whereas effective friction angle (ϕ') and saturated unit weight (γ_{sat}) exhibit comparatively modest impacts on F.S. in this parameter space. Figure 3.2 shows these relationships.

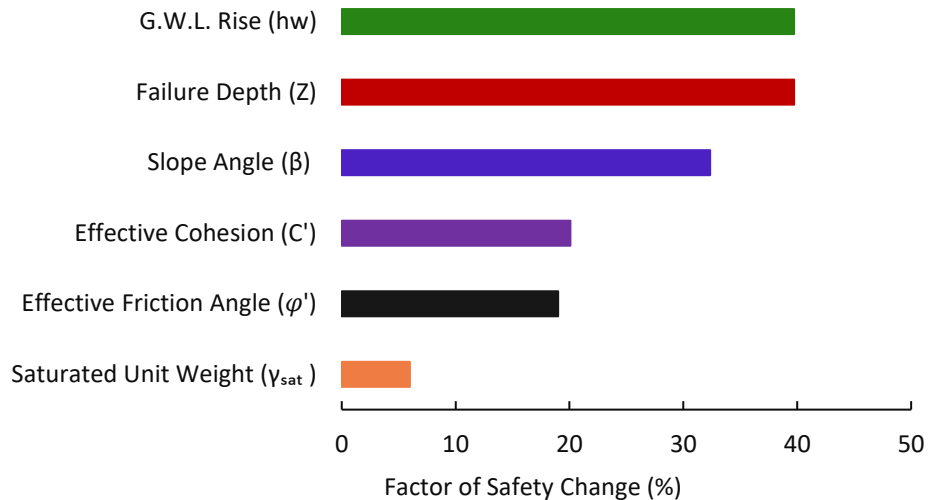


Figure 3.2 Sensitivity analysis for the influence of variables on the factor of safety for slope stability.

3.4 Rainfall Analysis

Daily precipitation data was used as rainfall input to calculate factor of safety. For the July 2023 storm event, the combined June-July monthly precipitation at the Montpelier-Edward F. Knapp State Airport station was 0.45 m (17.75 inches). This value represents the cumulative rainfall amount applied as the input to the slope-stability model. Across Vermont, the county wise comparison of average rainfall amounts for June-July 2023 shows the statewide mean of .43 m (16.92 inches) with a standard deviation of .04 m (1.54 inches). Therefore, the single weather-station record at Montpelier-Eward F. Knapp State Airport was used in this study for the entire state. Most sites used for model calibration in the study lie near this weather station.

3.5 Infinite Slope Stability and Factor of Safety

A physics-based approach for debris flow slope stability estimation was selected in this study. Based on multiple site inspections across the State of Vermont, it was found that the length of

sliding slope (L) is much larger than failure depth (Z). This specific slope failure geometry justified using infinite slope stability modeling approach to evaluate the stability of slopes, where the bottom of sliding surface runs parallel to the ground surface. It should be pointed out that in reality, the bottom of sliding surfaces is not smooth and does not necessarily maintain a parallel plane with the ground surface. The stability analysis examines a small soil slice using a free body diagram to determine the balance of forces as shown in Figure 3.3.

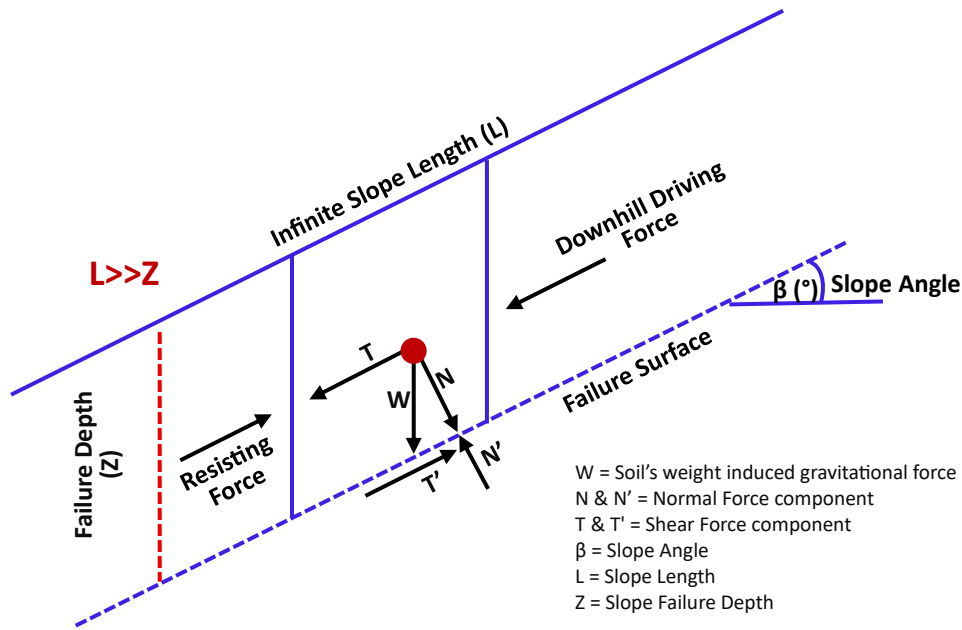


Figure 3.3 Schematic free body diagram of Infinite slope.

In the soil slice shown in Figure 3.3, the effective shear resistance T' arises from soil effective cohesion c' and effective friction ϕ' , both of which depend on the effective normal stress. The slope remains stable as long as the available resisting shear (T') exceeds the driving shear component (T). To initiate sliding along the failure surface, driving force must exceed the resisting force ($T > T'$). Slope stability is evaluated using the factor of safety (F.S.), defined as the ratio of resisting to driving forces, as presented in the following equation:

$$F.S. = \frac{C' + (\gamma_{sat} Z - \gamma_w h_w) \cos^2 \beta \cdot \tan \phi'}{\gamma_{sat} Z \cos \beta \sin \beta} \dots \dots \dots (Das, 2010)$$

Here,

F.S. = Factor of Safety

C' = Effective Cohesion (kPa)

h_w = Rise of G.W.L. (m)

β = Slope Angle ($^\circ$)

γ_{sat} = Saturated unit weight of soil (kN/m³)

γ_w = Unit weight of water (kN/m³)

Z = Depth of failure surface (m)

ϕ' = Effective friction angle of soil ($^\circ$)

If the factor of safety against sliding is less than one, then the slope is considered as unstable. For the slope stability analysis, we incorporated soil properties, slope angle, depth of failure surface, and rise of the ground water level, (based on rainfall) in raster format to calculate the factor of safety. The rasterized F.S. output has been categorized to identify potential high-hazard zones for future debris flow.

In this analysis, a conservative assumption was made that the entire amount of rainwater infiltrates into the ground on the slopes (Figure 3.4). It should be acknowledged that this assumption is conservative, but the groundwater level rise associated with this assumption correctly predicted through a back-analysis of the observed debris flows at Route 62, Railroad Street and Route 110 allows statewide scale analysis without site specific data.

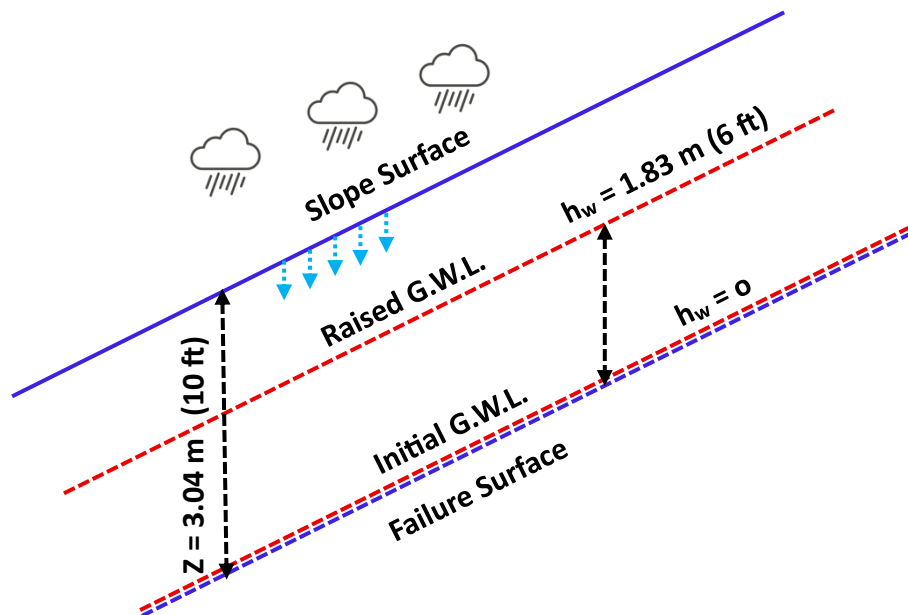


Figure 3.4 Schematic diagram of infinite slope with initial and raised G.W.L before and after rainfall.

3.6 Model Validation Approach

The resulting factor of safety map is used as an indicator of the susceptibility of slopes to future debris-flow initiation, rather than as a tool to predict the precise locations or runout extent of future slides. For model validation, we focused on site-specific validation through joint UVM-VTrans field investigations. A qualitative ranking scheme was developed to assign performance classes to the model based on how well the mapped F.S. patterns corresponded to the observed debris-flow evidence in the sites.

3.7 Monitoring Framework

Rainfall and soil moisture data was used as a decision-support tool for monitoring potentially high-hazard zones. The debris-flow factor of safety map developed in this study focuses on hazard areas with elevated potential for future debris-flows. Details of this monitoring framework are explained in chapter 6.

3.8 Mitigation Strategies

Mitigation strategies are recommended for the debris-flow characteristics observed in Vermont. The recommendations prioritize non-structural approaches, including tracking the debris-flow inventory through systematic event cataloging, improved hazard characterization, development of a prediction and early-warning system, and targeted site improvements. Details of this mitigation strategies are explained in chapter 7.

4 STATEWIDE DATA SOURCES

4.1 Historical Landslide Record in Vermont

The first step in the hazard analysis was to develop an inventory database of historic events. We started with known debris flow sites from 2023 and 2024 provided by VTrans. We extended the inventory with the Vermont Agency of Natural Resources (ANR) landslide database. This historical landslide data (Figure 4.1) is publicly available at ([Landslides | Vermont Open Geodata Portal Your source for geospatial data](#)) This database contains approximately ~3000 historical slope failure events, which include landslides, mud flows, and gully erosion. This inventory map (Figure 4.1) shows areas of identified slope failures in Vermont which was used as a guide for identifying where debris flow hazard areas may also be concentrated.

4.2 Digital Elevation Model (DEM)

The Digital Elevation Model (DEM) constitutes the primary topographic input governing slope stability within the study area. The DEM (Figure 4.1), with an original grid resolution of 75 cm × 75 cm was obtained from Vermont Open Geodata portal (<https://geodata.vermont.gov/pages/elevation>), was processed with ArcGIS geoprocessing tool to derive slope angles in degrees and subsequently resampled to a working grid resolution of 15 m × 15 m. Alternative grid sizes (3 m, 5 m, and 10 m) were evaluated to assess their influence on computed factor-of-safety values at known debris flows. To reduce computation time, we chose 15 m grids after using 3, 5, and 10 m grids to map low F.S. zones, where there were known debris flows. Using the geoprocessing tool, this DEM file was converted into a slope angle map (Figure 4.2).

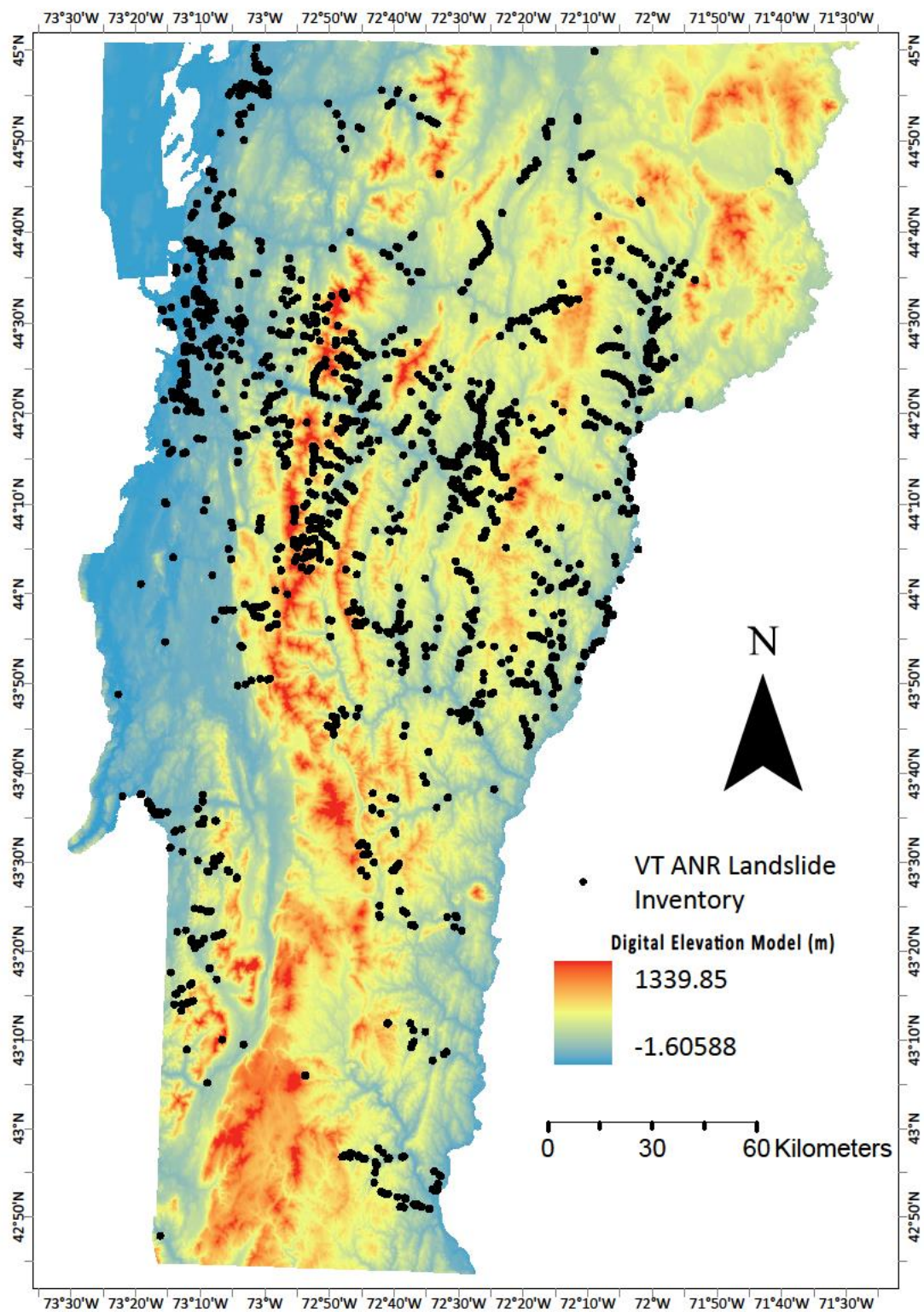


Figure 4.1 Digital Elevation Model overlaid with landslide inventory map of Vermont.
(Vermont Agency of Natural Resources)

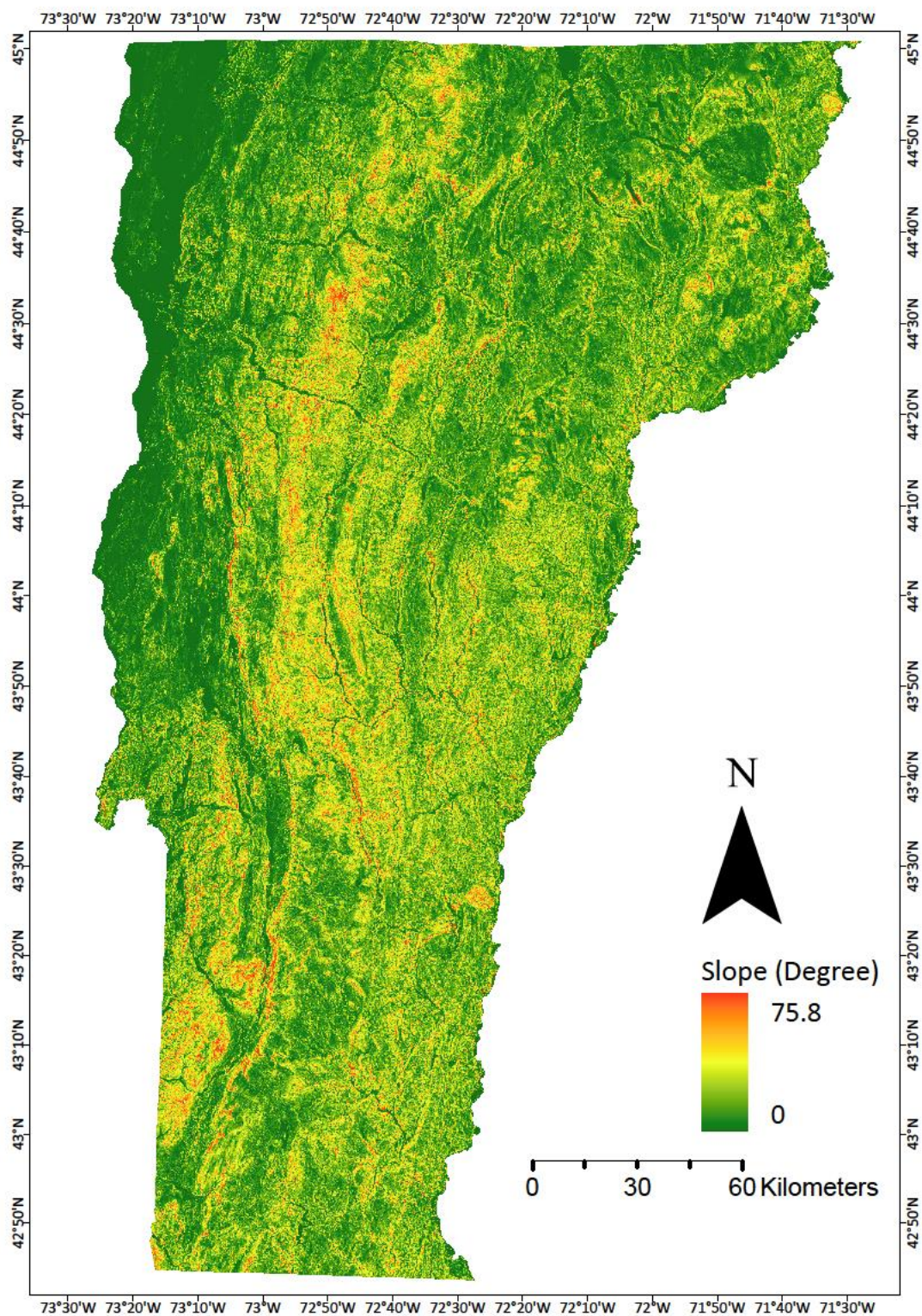


Figure 4.2 Resampled slope map of Vermont in 15m cell resolution.

4.3 Road Network Data

The state and national highways (Figure 4.3) in this study were based on VTrans preference to include Interstate and limited-access primary highways and major U.S., state, and county secondary highways. A total length of ~7608 km (4700 miles) roads are covered in this mapping model. Road network data were obtained from the national geospatial database (<https://catalog.data.gov/dataset/tiger-line-shapefile-current-state-vermont-primary-and-secondary-roads>). A buffer zone of 152 m (500 ft) was considered on both sides of the selected road segments, and only slopes located within this corridor were retained for subsequent stability modeling and hazard assessment.

4.4 Soil Data (gSSURGO)

The surficial geology map of Vermont indicates that a large portion of the state is underlain by glacial till deposits (Stewart & MacClintock, 1970). Following that characterization, we used constant values in glacial till geotechnical parameters of effective cohesion (C'), effective friction angle (ϕ'), and saturated unit weight (γ_{sat}) based on field observations and literature sources.. The resulting factor of safety map showed good agreement with known sites that had recent debris flows, but it was a conservative approach to use the same parameters. A grided soil data was subsequently chosen to account for spatial variation.

The Gridded Soil Survey Geographic (gSSURGO) database is a statewide gridded representation of the Soil Survey Geographic (SSURGO) database developed by the United States Department of Agriculture's USDA-NRCS National Cooperative Soil Survey (NCSS) program nrcs.usda.gov-database. The gSSURGO database consists of conventional SSURGO polygon map units, their corresponding relational attribute tables, and a gridded map unit raster layer. The gSSURGO dataset provides high-resolution soil-property information at raster resolutions ranging from 10 to 30 m, enabling characterization of soil conditions across large areas. The dataset indicates total soil thicknesses of approximately 1.7 to 1.9 m. For this analysis, a uniform soil profile was assumed.

Excluding exposed bedrock, 16 texturally distinct soil types were identified in the gSSURGO dataset across Vermont. Parameter ranges for soils, summarized in Table 4.1, were compiled from

published geotechnical correlations and engineering guidance documents, with representative values selected from those ranges (WSDOT, 2013; Iowa DOT, 2014; Verbrugge & Schroeder, 2018; Ameratunga et al., 2016). Across Vermont, C' varies approximately from 0 to 25 kPa, ϕ' from about 22° to 36°, γ_{sat} from 19 to 21 kN/m³, and n from 0.25 to 0.45. Rather than representing with a single constant property set, spatially distributed ranges of these parameters were assigned to 16 textural soil classes, so that the model input reflects the heterogeneity of surficial materials at the statewide scale.

4.5 Rainfall Data

Rainfall data was taken from State Climatologist - Applied Climate Information System (SC ACIS), which is a regional database for climate data (<https://scacis.rcc-acis.org/>). There are more than 135 weather stations (Figure 4.4) across the state, operated by several agencies including the USGS (United States Geological Survey), and NOAA (National Oceanic and Atmospheric Administration). The daily rainfall data for June and July 2023 are shown in Table 4.2. was used to calculate the approximate rise of ground water level in each grid ($h_w = 0.45 \text{ m/ porosity}$) in both Washington county and across Vermont.

Table 4.1 List of soils considered in the analysis along with corresponding parametric values

Textural Category	C' (kPa)	ϕ' (°)	γ_{sat} (kN/m ³)	n
Glacial Till	22	36	21	0.25
Coarse sand	0	35	20	0.45
Sand	0	34	20	0.4
Fine sand	0	32	20	0.35
Loamy coarse sand	2	34	20	0.3
Loamy sand	3	33	20	0.25
Loamy fine sand	3	33	20	0.3
Sandy loam	5	32	19	0.25
Fine sandy loam	5	32	19	0.25
Loamy very fine sand	4	32	20	0.3
Very fine sandy loam	6	31	19	0.25
Loam	12	28	19	0.35
Silt loam	10	26	19	0.3
Silty clay loam	18	24	19	0.25
Silty clay	23	23	19	0.25
Clay	25	22	19	0.25

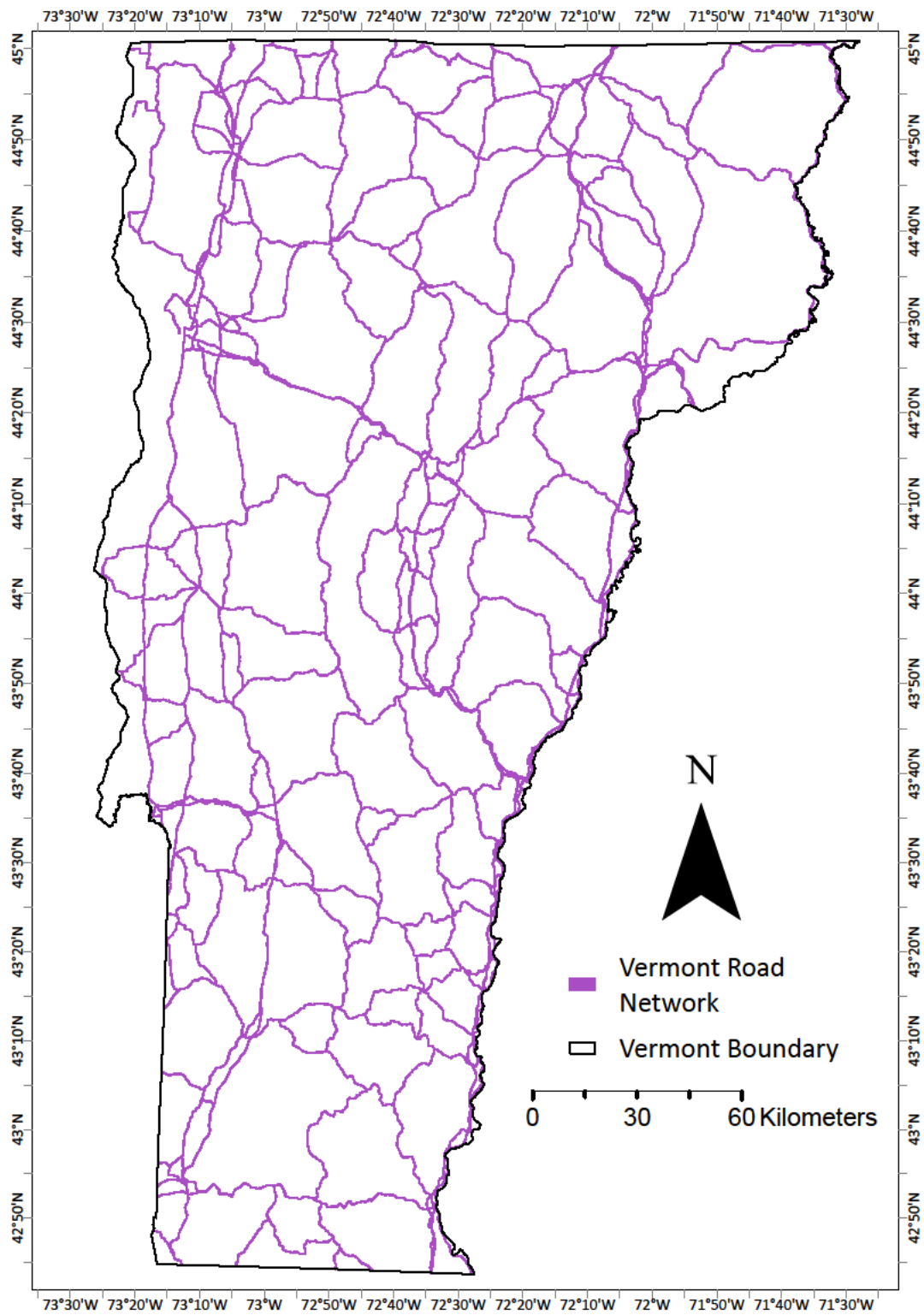


Figure 4.3 Vermont road network for debris flow analysis.

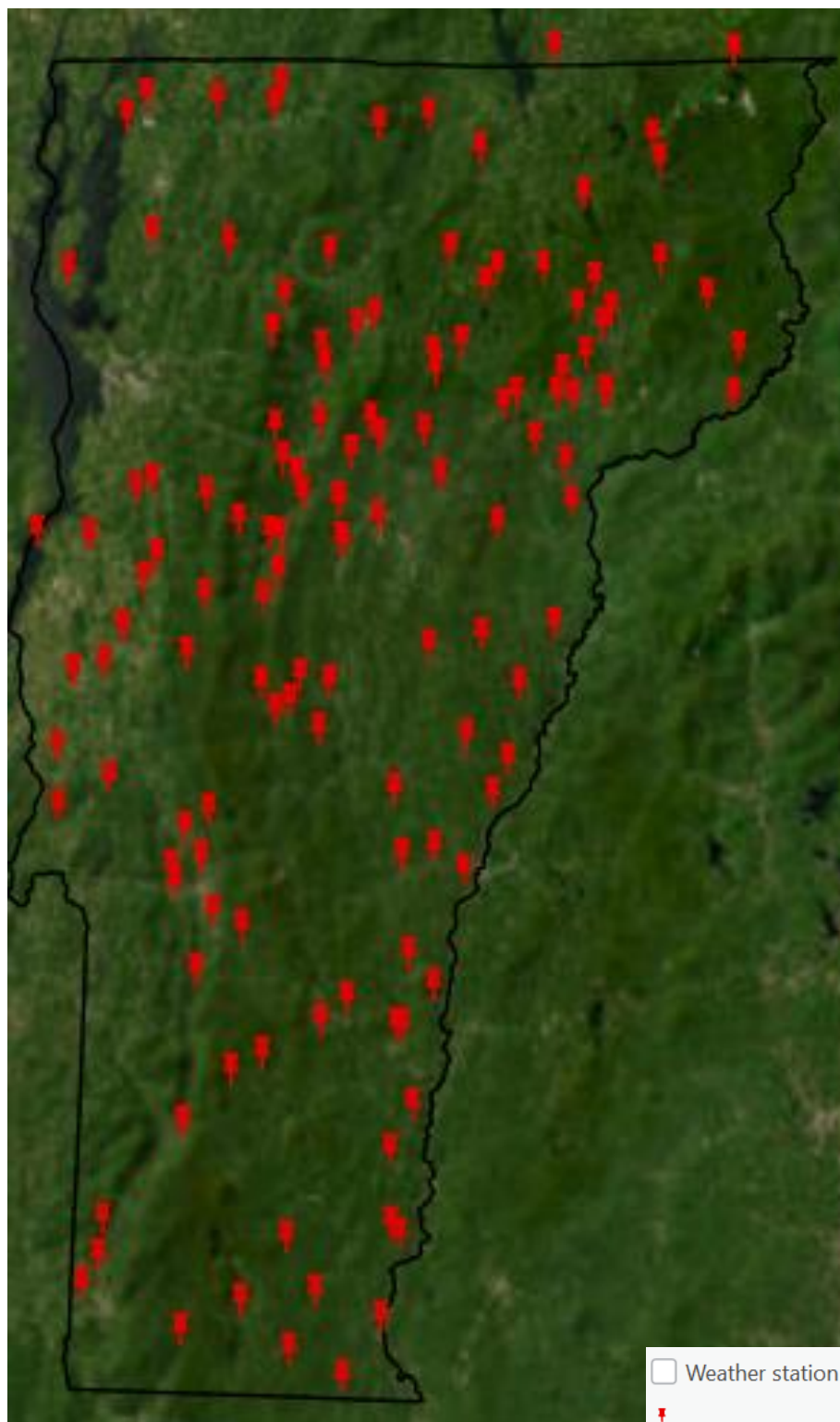


Figure 4.4 Spatial distribution of available weather stations in Vermont from the NOAA Applied Climate Information System (ACIS) platform.

Table 4.2 Daily rainfall data of June-July 2023 from MONTPELIER - EDWARD F. KNAPP STATE
AIRPORT weather station

Date	Rainfall (Inch)	Date	Rainfall (Inch)	Date	Rainfall (Inch)
6/1/2023	0	6/21/2023	0	7/11/2023	1.11
6/2/2023	0.29	6/22/2023	0	7/12/2023	0
6/3/2023	0.03	6/23/2023	0	7/13/2023	0.29
6/4/2023	0.05	6/24/2023	0.1	7/14/2023	0.28
6/5/2023	0	6/25/2023	0	7/15/2023	0
6/6/2023	0	6/26/2023	0.39	7/16/2023	1.51
6/7/2023	0.05	6/27/2023	0.25	7/17/2023	0
6/8/2023	0.16	6/28/2023	0.45	7/18/2023	0.1
6/9/2023	0.25	6/29/2023	0	7/19/2023	0
6/10/2023	0.13	6/30/2023	0	7/20/2023	0
6/11/2023	0	7/1/2023	0	7/21/2023	0.55
6/12/2023	0.07	7/2/2023	0.87	7/22/2023	0
6/13/2023	0.88	7/3/2023	0.04	7/23/2023	0
6/14/2023	0.37	7/4/2023	0.07	7/24/2023	0.51
6/15/2023	0	7/5/2023	0	7/25/2023	0
6/16/2023	0.41	7/6/2023	0	7/26/2023	0
6/17/2023	0.81	7/7/2023	0.33	7/27/2023	0.73
6/18/2023	0	7/8/2023	0	7/28/2023	0
6/19/2023	0	7/9/2023	0.47	7/29/2023	0.73
6/20/2023	0	7/10/2023	5.28	7/30/2023	0
				7/31/2023	0.09
				Total	17.75 inch
					0.45 m

5 RESULTS AND DISCUSSION

5.1 Statewide Factor of Safety Map

Initially, a constant G.W.L. rise (h_w) of 1.82 m (6 ft) and a constant soil porosity (n) were considered across the State to calculate the factor of safety (Figure 5.1). This represents a deliberately conservative scenario. Multiple parametric calibrations were performed to identify possible combinations of failure depth and G.W.L. rise that best match the observed slides in the sites. Trial simulations with $h_w = 1.52$, 1.82, and 3.04 m (5, 6, and 10 ft, respectively) produced markedly different F.S. maps. The scenario of $h_w = 3.04$ m (10 ft) yielded unrealistically extensive areas with $F.S. < 1$, implying widespread failures. Also, the scenario of $h_w = 1.52$ m (5 ft), failed to capture some known debris flow sites. Based on these findings, the factor of safety map was generated using a failure depth of $Z = 3.04$ m (10 ft) and a groundwater rise of $h_w = 1.82$ m (6 ft) from the base of the failure surface. The produced factor of safety map showed reasonable agreement with observed and catalogued slides.

Later, spatially variable porosity corresponding to different soils was considered to produce grid wise different values for ground water level rise. This adjustment provided a factor of safety map (Figure 5.2) that showed stronger agreement with known debris flow sites. The color coded factor of safety map is divided into 3 categories:

- Red cells: $F.S. < 1.0$ (Unstable)
- Yellow cells: $F.S. 1.0 - 1.25$ (Marginal)
- Green cells: $F.S. > 1.25$ (Stable)

The factor of safety map (Figure 5.2) highlights clusters of roadway segments intersecting slopes with a $F.S. < 1$, indicating potentially unstable and debris flow-prone conditions. Prominent concentrations of high-hazard zones ($F.S. < 1$) are observed in the southern, and central regions of Vermont. The figure 5.3 shows some zoomed in sectional views of different regions where the red clusters represents slopes with $F.S. < 1$ that might experience debris flow event after hitting heavy rainfall in future.

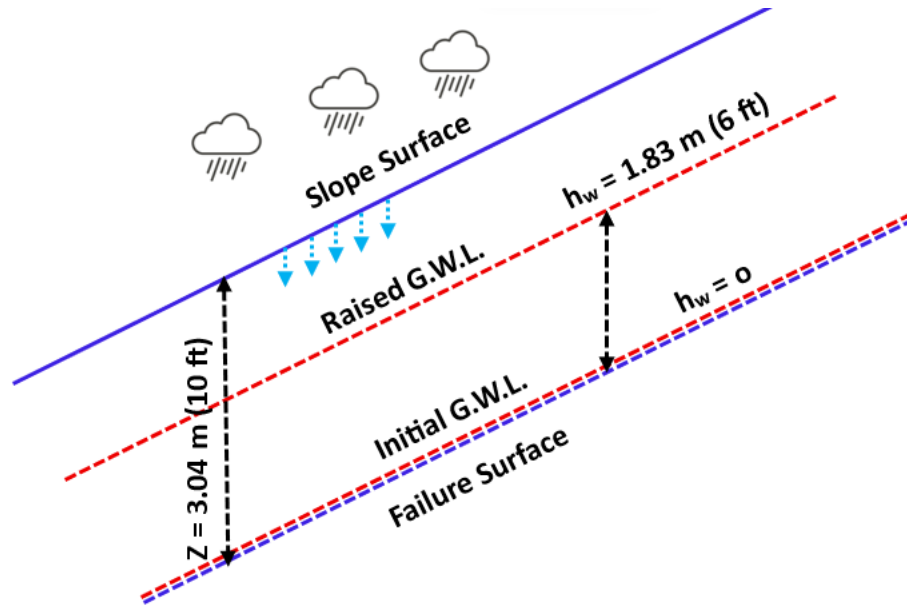


Figure 5.1 Schematic diagram of a 3.04 m (10 ft) thick infinite slope with 1.82 m (6 ft) raised G.W.L. used in the initial analysis

Available landslide inventory data were spatially filtered using a 152 m (500 ft) buffer and overlaid on the factor of safety map (blue points on the map in Figure 5.2). Despite some spatial inconsistencies in the inventory dataset, there is a reasonable level of agreement between mapped unstable areas and previously recorded slide events.

This map (Figure 5.2) serves as a visual decision-support tool for VTrans to identify and prioritize high-susceptibility areas ahead of emergency periods. In addition, an interactive ArcGIS web map was developed and delivered to VTrans. The web map is compatible with both iOS and Android devices and can be used similarly to a GPS-enabled application, allowing field personnel to efficiently locate and assess high-hazard areas during site visits.

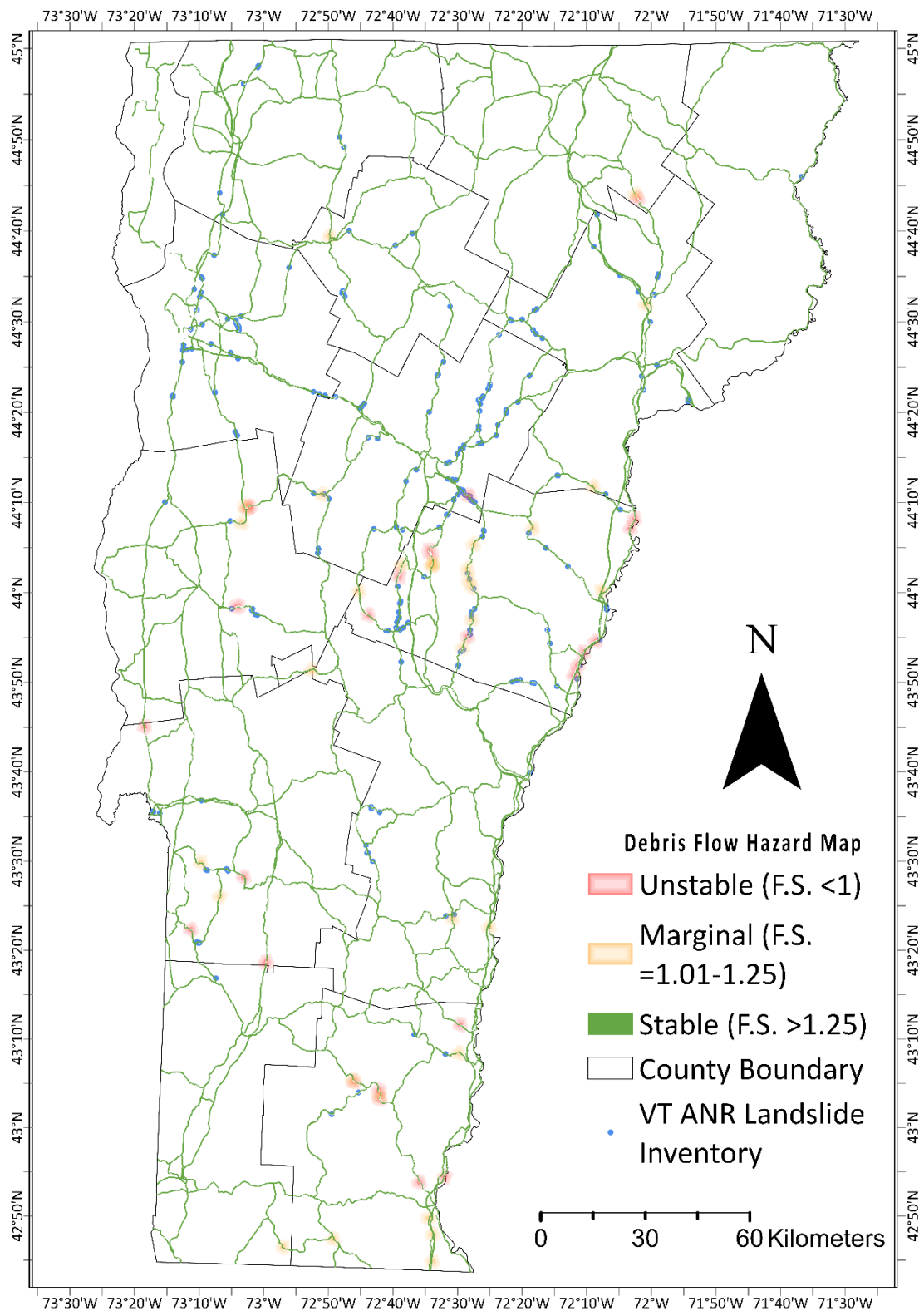


Figure 5.2 Statewide debris flow hazard map of Vermont.

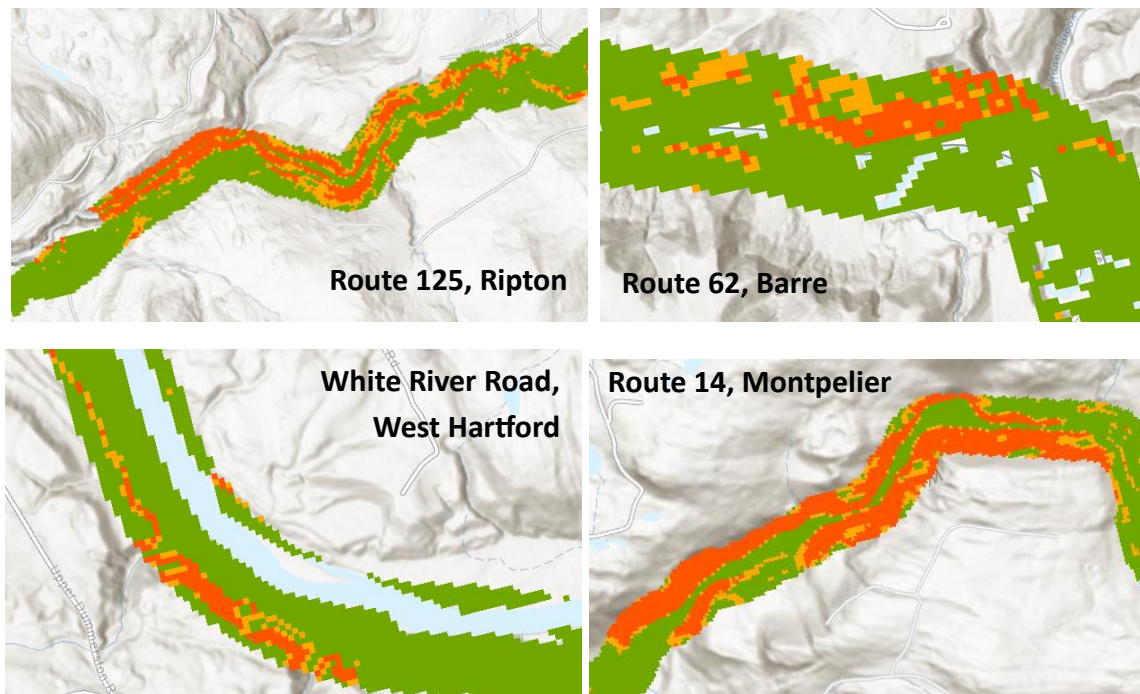


Figure 5.3 Zoomed sectional view of some potential sites for debris flow.

5.2 Site Validation

The factor of safety map produced to identify susceptible areas for future debris flow required validation. For this we made site visits along with additional site visits conducted by VTrans for:

- (a) inspection of both existing high-hazard slopes and known sites that had experienced debris flows in 2023 and 2024, and
- (b) comparing our map with actual site conditions.

Table 5.1 summarizes the information about visited sites and comparison of the debris flow hazard map with actual field conditions. Based on the site visits, a 1 to 5 ranking was assigned to the visited sites to quantify the prediction model performance. The ranking characteristics are as follows:

- **1 (Unreliable):** The model completely fails to capture the failure or the failure did not occur.

- **2 (Poor):** The model captures general failure but consistently over- or under-predicts the field observations.
- **3 (Moderate):** The model predicts the general behavior and magnitude of the field observations reasonably well but misses specific localized failures. It captures dominant failure patterns but lacks high precision.
- **4 (Good):** There is strong agreement between the model and the field observations. The model accurately captures trends, with only minor acceptable deviations.
- **5 (Excellent):** The model predictions closely mirror the field observations. The model captures both dominant failure patterns and localized fluctuations, remaining within the acceptable margin of measurement error.

The map was overlaid with a fishnet grid in ArcGIS using a uniform cell resolution of 15 m × 15 m. The precise locations of identified slope failures were first mapped onto the gridded F.S. dataset. Each corresponding grid cell was then assigned a ranking score (see Figure 5.4 as an example). Recognizing that areas surrounding the debris flows being addressed in this study often exhibit similar geomorphic and geotechnical characteristics, adjacent cells were considered part of the zone of influence. Accordingly, neighboring cells were assigned the same ranking score as the primary failure cells. An average ranking score was subsequently computed across these cells to represent the overall susceptibility level of each site.

Figure 5.4 shows the model evaluation for the the Railroad Street site in Barre (Site #1), which experienced a debris flow during the July 2023 storm event. The areas with F.S. < 1 closely match the spatial location of the debris flow, indicating excellent consistency with the susceptibility mapping. Sites #8, 9, 11 and 14 also show excellent spatial match between the model and site visit (Figure A6, A7, A9, A12 in the Appendix). Model evaluation for Route 110 (see Figure 5.5) & Route 14 sites and Route 302, East Barre (Sites #2, 4, 5 and 6) show good agreement, corresponding to a ranking of 4 (Figure A3, A4, A5 in the Appendix).

Table 5.1 Summary of the sites visited to compare the model predictions with the failures observed at the actual sites.

Site No.	Site Name	Coordinates	Average Ranking	Slide Type
1	Railroad street, Barre, VT	72° 31' 7" W 44° 12' 26" N	5	Debris Flow
2	Route 110, Washington, VT	72° 28'26.9" W 44° 02'55.4" N	4	Debris Flow
3	Route 14, Brookfield, VT	72° 27' 39" W 44° 5' 15" N	2	Landslide
4	Route 14, Brookfield, VT	72° 48' 50" W 44° 21' 42" N	4	Landslide
5	Route 14, Brookfield, VT	72° 46'25"W 44°21'7"N	4	Landslide
6	US 302, East Barre, VT	72°28'27"W 44°10'47"N	4	Gully Erosion
7	Proctorsville gulf slide, VT	72°38'00.8"W 43°21'27.2"N	1	Debris Flow
8	Taft Ave, Hartford, VT	72°18'43"W 43°39'55"N	5	Erosional failure
9	Black Piece Road, Route 100, Wardsboro, VT	72°49'29"W 43°1'31"N	5	Erosional failure
10	Peak Hill Road, Route 14, East Calias, VT	72°26'47"W 44°21'22"N	3	Erosional failure
11	Mill Hill Road, Highgate, VT	73°2'45"W 44°56'15"N	5	Erosional failure
12	Stony Hill Road, Bristol, VT	73°5'13"W 44°7'58"N	3	Landslide
13	Interstate 91N, Fairlee, VT	72°10'28"W 43°53'22"N	3	Rockfall Debris
14	Interstate 91N/US Route 5s, Fairlee, VT	72°8'56"W 43°54'30"N	5	Rockfall Debris

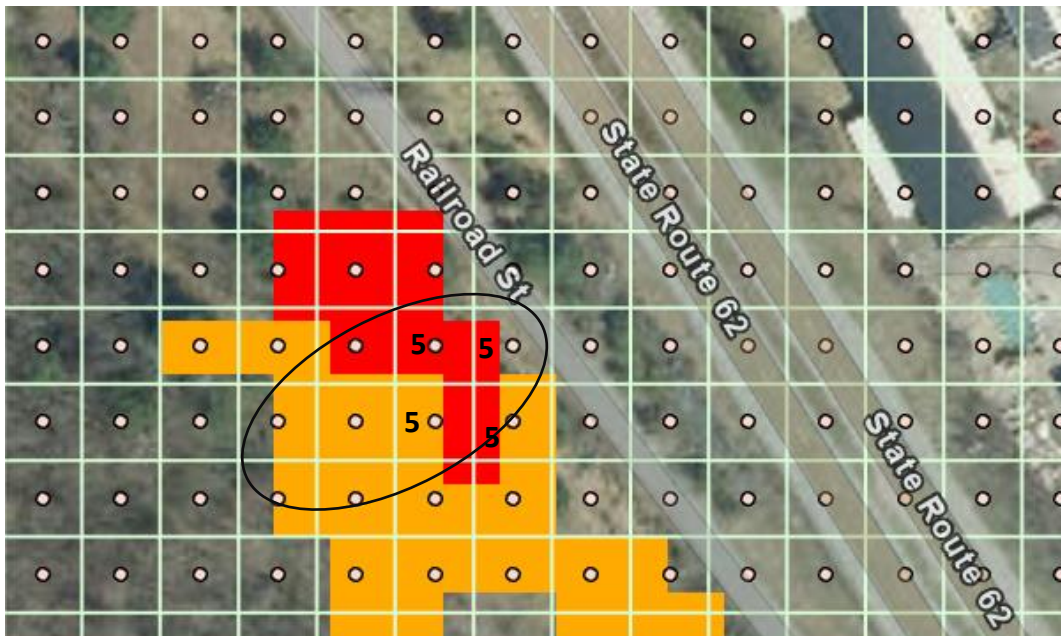


Figure 5.2 Site#1, Route 62, Railraod street, Barre, VT. (Ranking = 5)

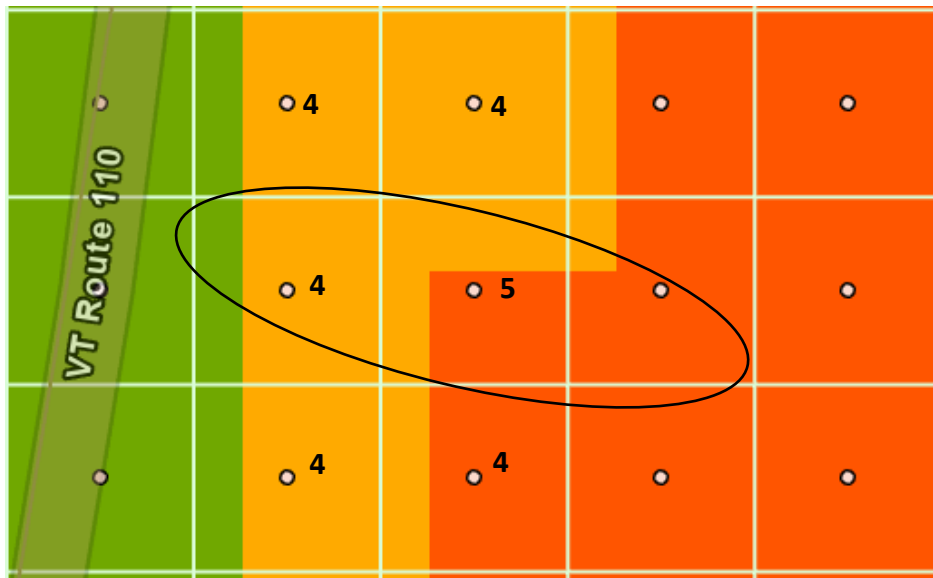
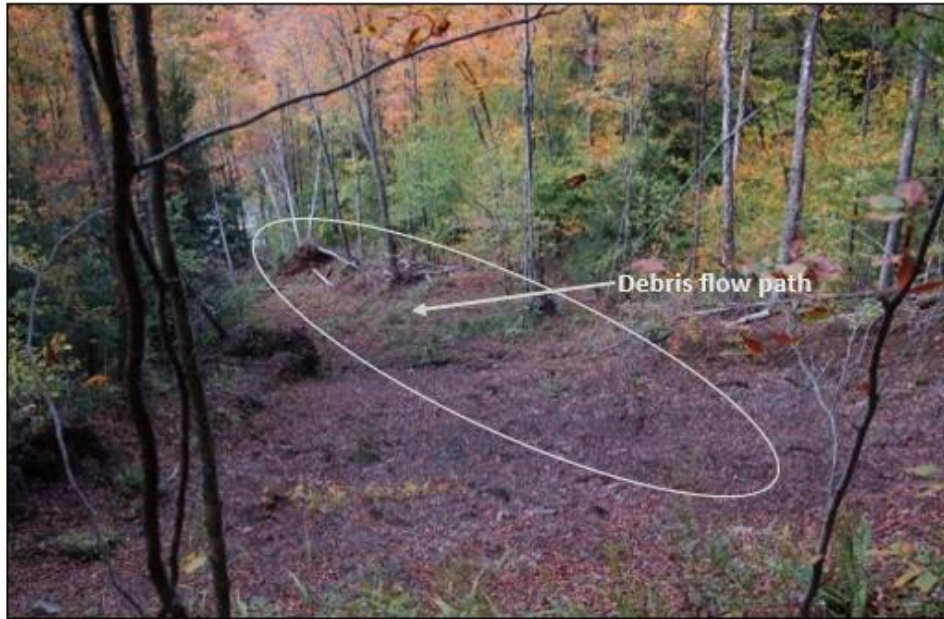


Figure 5.3 Route 110, Washington, VT. (Ranking = 4)

Sites #10, 12 and 13 shows moderate consistency with the developed map, although the mapped location is slightly offSet from the actual slide point (see Figure A8, A10, A12 in the Appendix).



Figure 5.4 Route 14, Brookfield, VT. (Ranking = 2)

Figures 5.6 and 5.7, show the model does not capture the failure location of sites #3 (Brookfield, VT) and #7 (Proctorsville gulf slide, VT). Inconsistencies on hydrological conditions (e.g. actual ground water level, amount of infiltrated water, etc) between model and actual ground conditions could have contributed to miss this failure.



Figure 5.5 Route 103, Proctorsville, VT. (Ranking = 1)

5.3 Discussion

5.3.1 Overall model performance

Under a representative rainfall scenario corresponding to the June and July 2023 storm event, 12 out of 14 validation sites exhibited good to excellent agreement with observed field conditions, indicating a high level of predictive accuracy. Overall, the model shows strong correspondence with documented slope failures under the chosen rainfall conditions, supporting its applicability for regional-scale hazard assessment. However, it should be acknowledged that, this model uses a simplified characterization of soil strengths and porosity.

5.3.2 Limitations of the developed model

The current model has been developed through multiple simulations under varying storm and subsequent G.W.L rise scenarios. The results demonstrated reasonable agreement with observed failure locations of the chosen rainfall conditions.

- The developed model cannot adequately distinguish slopes with shallow rocks below thin soil cover. The model could not capture at least one documented failure site.
- The statewide representation of soil parameters was derived from the Gridded Soil Survey Geographic (gSSURGO) database developed by the United States Department of Agriculture (USDA), which is primarily intended for agricultural applications. A uniform failure depth of 10 ft was assumed with homogeneous soil properties; however, this simplification neglects potential stratigraphic variability .
- The current model does not specifically include snow melting. For example, high soil moisture followed by rapid snow melting infiltrating into thawed soil and would cause G.W.L. to rise similar to summer scenarios. However, this could be accounted for using estimated soil moisture values and water equivalence in the snowpack.
- The final susceptibility map has been generated based on the June-July 2023 storm event that equals 0.45 m (17.75 inches) of cumulative rainfall of June-July. However, extreme storm events producing substantially higher rainfall may increase the debris flow hazard.
- A significant data limitation throughout the study was the lack of groundwater level information pre- and post-rainfall. In the absence of this data, a simplified assumption of

100% rainfall infiltration with groundwater at the base of the sliding zone thickness was adopted, resulting in the rise in the groundwater level calculated based on the corresponding soil porosity. Given the critical role of groundwater in affecting slope stability, it is recommended to install and monitor piezometers at representative sites in Vermont to develop a database of groundwater levels. Such field data would enable calibration and future refinement of the susceptibility model.

5.3.3 Future steps to improve model prediction

- Machine-learning (ML) methods have gained substantial attention in regional landslide and debris-flow susceptibility mapping because they can represent nonlinear relationships between failure occurrence and multiple topographic, geological, hydrological, vegetation, and anthropogenic conditioning factors (Liu et al., 2023; Zhang et al., 2024). We performed a preliminary analysis at Washington county incorporating the conditioning factors of elevation, slope aspect, curvature, topographic wetness index (TWI), distance to roads and rivers, geological units, soil moisture, and rainfall. The preliminary output using the ML approach for Washington county shows promise given the good agreement between our ML predictive model and catalogued slides. Future efforts by VTrans could consider this approach to developing more data driven statewide susceptibility maps.
- In addition, Non uniformity in the infiltration rates across the State is not considered in current study. TRIGRS (Transient Rainfall Infiltration and Grid-Based Regional Slope-Stability), developed by the U.S. Geological Survey, simulates transient rainfall infiltration and its effects on shallow slope stability on a grid, and is widely recommended for estimating rainfall-induced rises in groundwater levels and pore-water pressures ([usgs.trigrs](https://www.usgs.gov/science-topics/trigrs)). This model can potentially capture spatially heterogeneous ground water level rise. TRIGRS was initially explored in this study, but its full implementation was deferred to future work because of the time needed to set up and calibrate the model properly.

6 DEBRIS FLOW MONITORING

This chapter provides information on how to use the following to monitor for possible debris flows:

- Satellite soil moisture data
- Storm rainfall predictions
- Debris flow hazard susceptibility map

These three inputs were explained in the prior chapters, and the following section outlines how to use those inputs.

6.1 Monitoring of Debris Flow Hazard

Monitoring systems follow susceptibility mapping and are an integral part of a hazard management program. A variety of texturally different surficial soil, precipitation, and existing soil moisture combinations can lead to debris flow slope failure. A GIS-based susceptibility map has been developed that identifies potential slope locations susceptible to debris flows. Adding rain gage station-based and remote sensing data to this, a process was designed to combine rainfall predictions with and surficial soil moisture monitoring to identify where debris flow susceptible slopes exist for a particular combination of existing soil moisture and expected intense rainfall. This systematic monitoring process (i.e., identified susceptible slopes with rainfall and soil moisture monitoring) creates a debris flow hazard management program for VTrans.

6.2 Rainfall Monitoring

Rainfall causing ground water level rise was identified as a primary driver of debris-flow initiation in the study area. The following explains the rainfall monitoring aspect. As an example, 10 years of monthly rainfall data (2015-2024) from the Edward F. Knapp State Airport gauge in Montpelier were analyzed to coincide with the debris flows occurring nearby in Barre. Within this period, 2023 and 2024 exhibit distinct mid-summer monthly cumulative peaks associated with storm events that produced multiple debris flows, landslides, and flash floods, in the July 2023 storm (Figure 6.1). Since quantitative rainfall thresholds for debris-flow initiation have not yet been derived from event data and slope response, it is not possible to specify a critical rainfall intensity

that will trigger debris flows. However, on July 10, 2023, ~ 134 mm (~5.28 inch) rainfall was recorded within 24 hours at Edward F. Knapp State Airport gauge in Montpelier (Table 4.2) that led to multiple debris flows. It suggests that high intensity short duration rainfall has a strong influence in initiating debris flows.

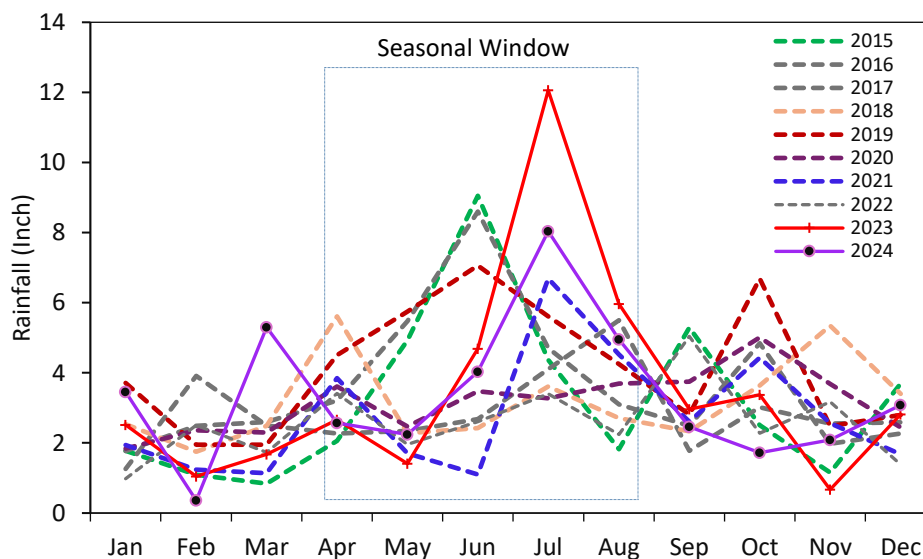


Figure 6.1 Monthly Rainfall Distribution at Montpelier-Edward F. Knapp State Airport, Vermont (2015-2024)

Rainfall data can be obtained from the Applied Climate Information System (ACIS) version 2 web services and its associated interactive client tools (<https://scacis.rcc-acis.org/>). ACIS is developed by the NOAA Regional Climate Centers and provides standardized access to historical as well as near-real-time climate observations. Within the interface, the user can select the desired product type from the upper-left menu; for this study, single-station daily precipitation data aggregated monthly were selected. The analysis period can then be specified through the available time-selection options. The stations nearest to 22 identified route locations with substantial areas susceptible to debris flows are listed in Table 6.1. Selecting an individual station allows the monthly precipitation record to be retrieved and reviewed.

This platform is a useful no-cost resource for rainfall monitoring and climate data extraction. Systematic tracking of cumulative rainfall coupled with soil moisture monitoring in debris flow susceptible areas is the first part of this hazard management plan.

Table 6.1 List of corresponding monitoring stations at some identified high susceptible routes

No.	Route	Town & County	Coordinate	Station Name
1	Drake Woods Rd, State Rt 17	Bristol, Addison County	73.0333054°W 44.1609360°N	NEW HAVEN 2.4 SE
2	Lake Dunmore Rd, State Rt 53	Salisbury, Addison County	73.0688330°W 43.9170290°N	CORNWALL
3	Ripton 125	Ripton, Addison County	73.0567974°W 43.9711265°N	MIDDLEBURY 0.3 N
4	Lynburke Rd, US Hwy 5	Burke, Caledonia County	71.9795771°W 44.5899550°N	LYNDONVILLE 1.1 W
5	State Rt 100	Granville, Addison County	72.8515763°W 43.9991477°N	BRAINTREE 2.8 SW
	State Rt 100	Jamaica, Windham County	72.7613933°W 43.0637470°N	JAMAICA 1.9 WNW
6	South Rd, State Rt 118	Montgomery, Franklin County	72.6209720°W 44.8072082°N	MONTGOMERY 4.1 ESE
7	VT Rt 5A	Westmore, Orleans County	72.0304065°W 44.7224853°N	BROWNINGTON 4.7 ESE
8	State Rt 14	Williamstown, Orange County	72.5699424°W 44.0738309°N	WILLIAMSTOWN 3.0 WSW
	State Rt 14	Hartford, Windsor County	72.4054529°W 43.7007902°N	QUECHEE 0.7 WSW
9	Forest Dale Rd, State Rt 73E	Brandon, Rutland County	73.0341991°W 43.8400342°N	CHITTENDEN 0.2 W
10	State Rt 22A	Benson, Rutland County	73.3085663°W 43.7503958°N	ORWELL 1.2 WNW
	State Rt 22A	Benson, Rutland County	73.3084817°W 43.7508066°N	ORWELL 1.2 WNW
11	State Rt 30	Hubbardton, Rutland County	73.1816932°W 43.7263681°N	BENSON 0.4 NW
	State Rt 30	Townshend, Windham County	72.7035060°W 43.0686152°N	WESTMINSTER 5.5 W
	State Rt 30	Wells, Rutland County	73.2053660°W 43.4575997°N	NORTH RUPERT 1.7 WNW
12	School st E, State Rt 140	Wallingford, Rutland County	72.9607762°W 43.4671885°N	WALLINGFORD 2.7 SSW
13	I-91	Rockingham, Windham County	72.4627303°W 43.1753026°N	ROCKINGHAM 1.1 NNE
14	East Barre Rd	Barre, Washington County	72.4721376°W 44.1789691°N	GROTON 4.4 WSW
15	Access Rd, State Rt 63	Barre, Washington County	72.5167119°W 44.1723417°N	WILLIAMSTOWN 3.0 WSW

No.	Route	Town & County	Coordinate	Station Name
16	State Rt 110	Washington, Orange County	72.4743268°W 44.0479732°N	WEST TOPSHAM
17	White river Rd	Brattleboro, Windham County	72°35.2676669'W 42°53.0010936'N	BRATTLEBORO 1.3 WSW
19	Marlboro Rd	Brattleboro, Windham County	72°38.7978980'W 42°52.3009966'N	BRATTLEBORO 1.3 WSW
20	Coolidge Hwy	Guilford, Windham County	72°33.8025125'W 42°47.7073866'N	BRATTLEBORO .7 S
21	Vt Rt 112	Whitingham, Windham County	72°48.9049357'W 42°47.1938550'N	ROWE 3NE
22	VT Rt 100	Whitingham, Windham County	72°49.8552374'W 42°48.1745026'N	ROWE 3NE
23	US Rt 4	Mendon, Rutland County	72°54.4696998'W 43°38.9646323'N	RUTLAND

6.3 Soil Moisture Monitoring

Surficial soil moisture approximately reflects the overall soil water content in upper soil strata, to understand the relative amount of accumulated soil moisture in an area. It represents the wetness state of the slope soils which strongly influences soil pore-water pressure and resulting soil shear strength (Wicki et al., 2020). Soil moisture can be measured locally by on-site measurement techniques such as groundwater monitoring wells, or remotely, by satellites or airborne systems (Ochsner et al. 2013). Because continuous in situ monitoring of soil moisture over large spatial extents is logistically challenging, remotely sensed soil moisture monitoring provides an effective alternative means to characterize the shallow soil wetness. The following explains the soil moisture monitoring through an example.

The July 10-11, 2023 storm triggered multiple debris flows, landslides, and flash floods. To assess and compare how soil moisture changed around this event, daily soil moisture data for May 7-14, June 7-14, and July 7-14, 2023 were compared. May and June represent pre-storm conditions, while July covers the days before and after the storm. The data was obtained from NASA's Satellite Soil Moisture Active Passive (SMAP). The Level 4 SMAP data have a grid resolution of 9 km with a 3-hour recurrent period (Figure 6.2). This satellite provides an approximately upper 5 cm volumetric water content (m³/m³) estimate in a range between 0 to 1 by measuring microwave

emission from soil surface. This satellite operates in the L-band microwave frequency which can penetrate dense vegetation cover.

Figure 6.3 shows that the moisture in the surface soil did not change by a large amount. However, soil moisture clearly went up as rainfall increased. On 10 July 2023, the moisture value reached $0.40 \text{ m}^3/\text{m}^3$ after about 134 mm (5.3 Inches) of rain fell in 24 hours. Before the storm on 9 July, soil moisture was between 0.20 and $0.32 \text{ m}^3/\text{m}^3$. During the storm, it rose to about 0.30 to $0.40 \text{ m}^3/\text{m}^3$. All the slides recorded in 2023 (landslides and debris flows) took place in areas with high soil moisture. This shows that soil moisture follows rainfall closely and can be used to track debris flows. The images also show that soil moisture was fairly high in May, dropped in June, and stayed low in early July.

Monitoring rainfall and soil moisture together is a useful way to screen debris-flow hazards. Both datasets are free and open to the public, and they need very little processing before they can be used to support decisions.

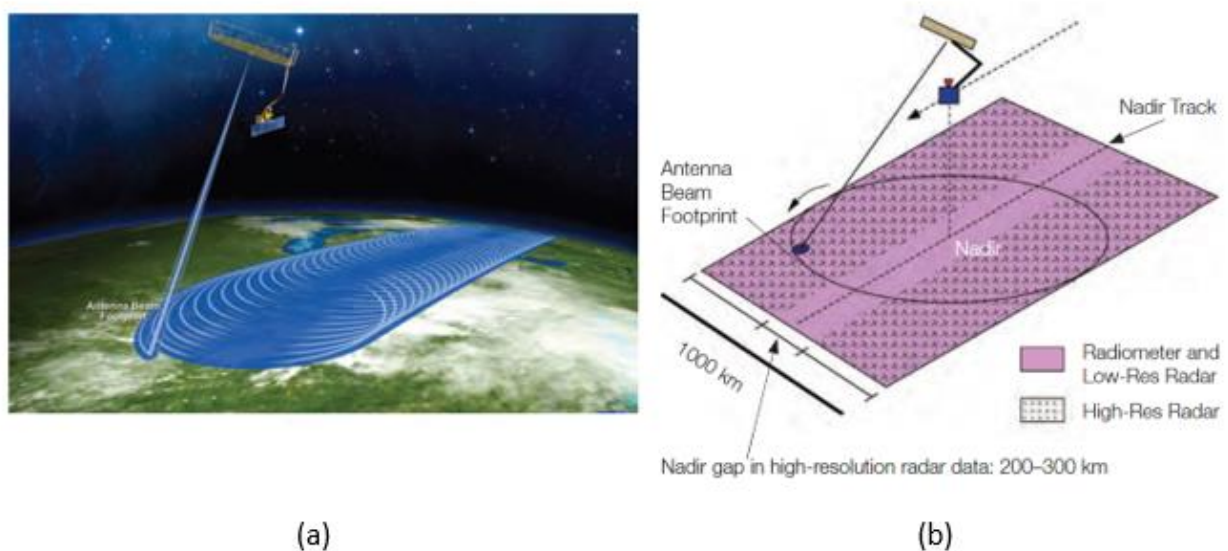


Figure 6.2 (a & b) Schematic diagram of SMAP radar data acquisition (NASA Jet Propulsion Laboratory (JPL). (2014). SMAP Handbook).

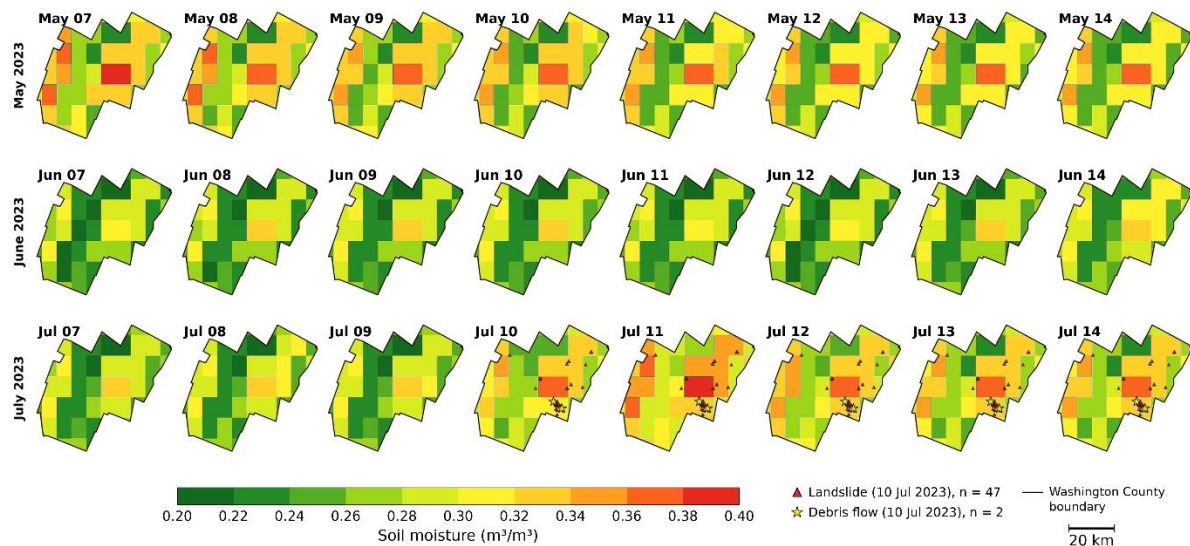


Figure 6.3 Daily surficial soil moisture tracking

6.4 Monitoring Steps for VTrans

A combination of rainfall and soil moisture tracking allows VTrans to monitor debris flow potential with limited resources. In spring through fall, the expected daily rainfall intensity should be watched when and where surficial volumetric water content and cumulative rainfall in debris flow hazard susceptible locations show trends of suggesting relatively wetter ground conditions. The soil moisture and cumulative rainfall patterns shown for the observed debris flow sites documented in this report are a starting point for defining what constitute wetter conditions. This definition of wetter conditions should be reviewed and evaluated as subsequent monitoring leads to a record wetness and rainfall patterns which are correlated to debris flow occurrences.

An example is shown here of this method. On July 11, 2023, a massive debris flow occurred at 62 Railroad street, Barre, VT (Figure 6.4). The flowing debris crossed the highway and pushed three cars over the road. We reviewed both rainfall and soil moisture data for this location to evaluate the correspondence with the slope failure. The rainfall data here is taken from the Edward F. Knapp State Airport weather station, Montpelier, Vermont approximately 4 miles from this site (scacis.rcc-acis.org/).



Figure 6.4 July 11, 2023, debris flow at Route 62, Railroad Street, Barre, VT. (Credit: VTrans)

Daily average soil moisture (Figure 6.5) and daily rainfall (Figure 6.6) from April to August of 2022-2025 are plotted from prior to following the debris flow date. July 11th shows a sharp peak in rainfall on that day. The soil moisture dropped from April to early June then remained almost constant to rising trend up to the time of the debris flow. This same trend occurred in 2024, which also had intense rainfall in mid-July. Both 2022 and 2025 kept dropping continuously from April to August which are consistent with corresponding rainfall records.

Limitations exist in using satellite-based soil moisture data. L-band microwave sensors estimate near-surface soil moisture by sensing emitted radiation from the Earth's surface and interpreting the returned signal through empirical models. This also has a large grid resolution of ~9km, covering a large area per grid. Consequently, variations may arise between in situ soil moisture measurements and remotely sensed surface soil moisture due to local variations not captured by the sensor resolution. Despite these limitations, the data exhibit strong correspondence with the precipitation when the debris flows evaluated in this report occurred.

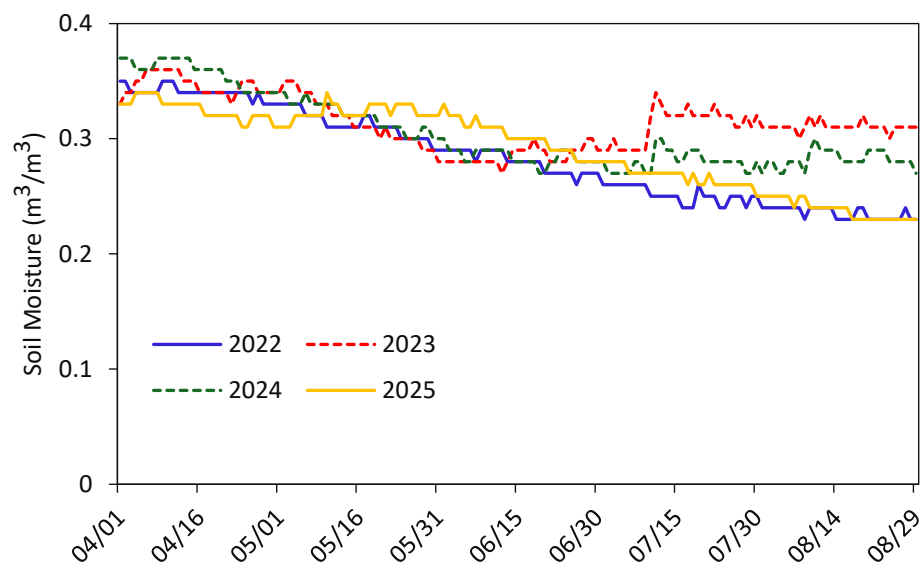


Figure 6.5 Daily Soil Moisture data for April-August 2022-2025 from Route 62, Barre City.

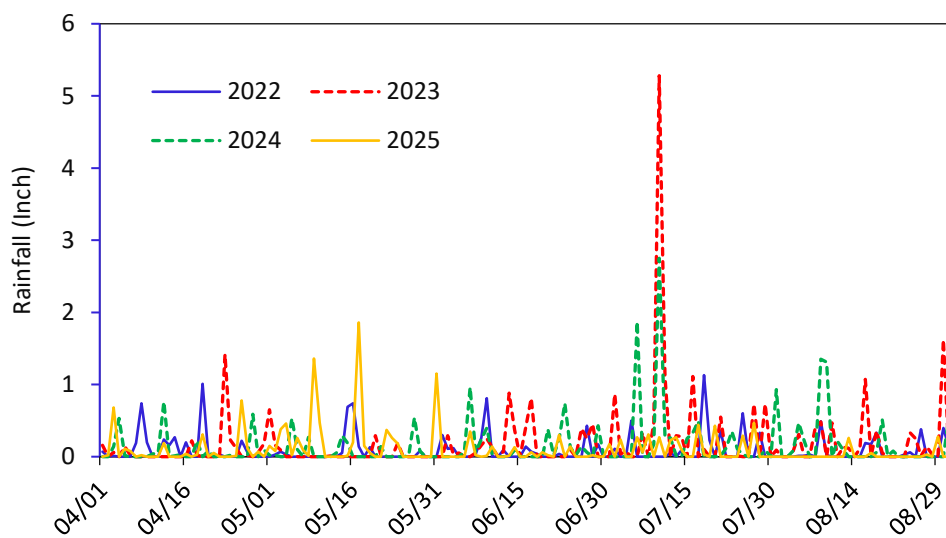


Figure 6.6 Daily rainfall data from April-August of 2022-2025 from a nearby weather station (Montpelier - Edward F. Knapp State Airport) of Route 62, Barre City.

6.6 InSAR Monitoring

In mountain areas where field surveying is difficult, time series InSAR (TS-InSAR), represented by small baseline subset InSAR (SBAS-InSAR), has become one of the preferred approaches for studying landslides or other geological disasters (Jie et al., 2018). The capacity of Differential Interferometric Synthetic Aperture Radar (DInSAR) for measuring surface movement caused by wildfire burning has been investigated following the 2017 Eagle Creek Wildfire in Oregon, USA (van et al., 2025). Small Baseline Subset InSAR (SBAS-InSAR) is used to identify slow deformation and acceleration that may precede debris-flow initiation (Zheng et al., 2025). From a literature study, it has been identified that L-band InSAR data is best suited for Vermont to accommodate dense vegetation and snow cover during winter.

We searched for active sources of L-band data currently available for Vermont and located the ALOS-2 (Advanced Land Observing Satellite-2), equipped with the PALSAR-2 (Phased Array type L-band Synthetic Aperture Radar) sensor, operated by the Japan Aerospace Exploration Agency (JAXA), as a high-resolution L-band SAR data source. We contacted JAXA about data access and learned that there are 2 categories of data:

1. Publicly available (~100 m spatial resolution, 350 km swath) <https://gportal.jaxa.jp/n>
2. Commercial data (3-10m resolution, 50-70 km swath) <https://satpf.jp/spf/>.

From the publicly available data, 4 scenes that had been captured on July 13, October 5, October 19 and November 30 of 2023 covering the selected area (red rectangle) of Vermont as can be seen in (Figure 6.7). These data were not sufficient to detect spatiotemporal changes on slopes of Vermont.

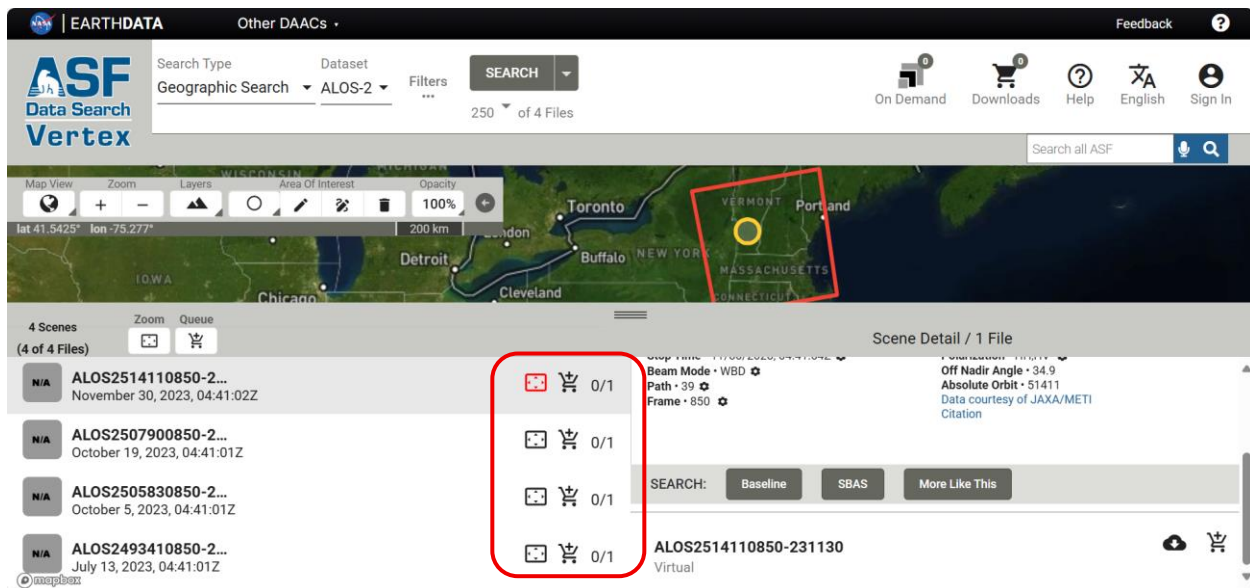


Figure 6.7 Available L-band data for Vermont from ALOS-2 satellite.

A newer satellite, NISAR (NASA-ISRO Synthetic Aperture Radar), was launched on July 30, 2025. NISAR has recurrent periods of 12 days which is specially designed to monitor geohazards in densely vegetated and snow covered areas with the L-band. NISAR released a calibrated provisional dataset (Figure 6.8) on July 20, 2026 that are validated with limited site (<https://search.asf.alaska.edu/>). For geohazards management programs such as debris flow monitoring, the NISAR can be a promising source of synthetic aperture radar data information for Vermont. NASA offers an excellent online training program through [NASA Earthdata](#) on InSAR technology, which provides a comprehensive introduction to its practical applications.

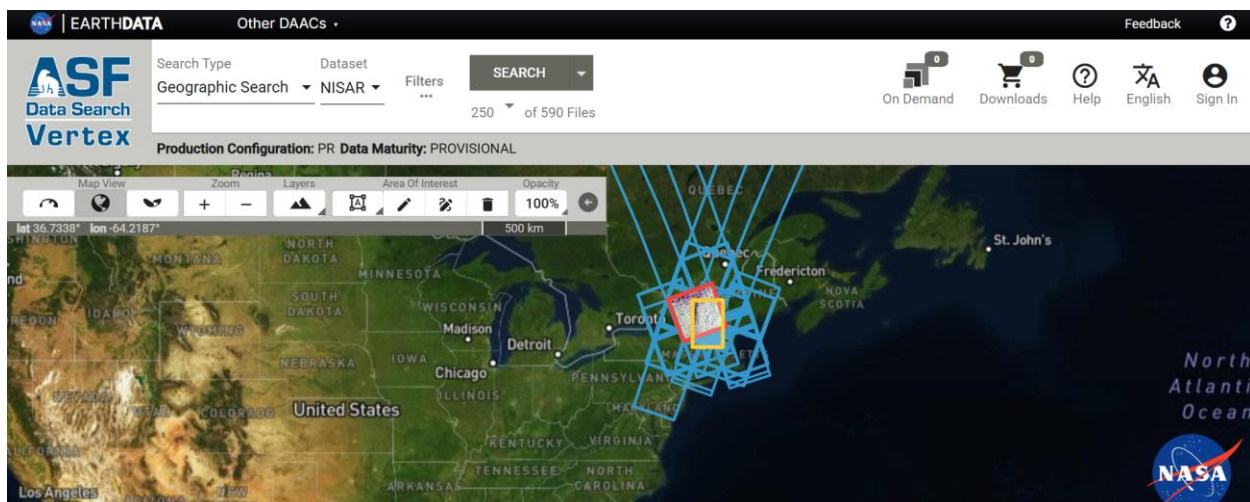


Figure 6.8 Available L-band provisional data for Vermont from NISAR.

7 MITIGATION STRATEGIES

7.1 Catalog of Hazard Mitigation Design Strategies

This section provides guidance for coupling measures to monitor for site and weather condition combinations which increase the potential for debris flows, associated motorist early warnings, and site improvements that reduce the potential for such flows reaching roadways.

The currently available record of debris flows reaching roadways in Vermont is small and mainly associated with flows following the July 2023 and 2024 storms. This record is likely to increase given the trend toward greater and more intense rainfall such as those experienced where debris flows occurred in 2023 and 2024. This guidance needs to be reviewed and updated by VTrans as more experience develops with debris flows in Vermont.

This guidance addresses predicting when and where debris flows are more likely to occur, roadway hazard and damaging limiting or prevention measures, and post-flow measures at slide scars to stabilize exposed ground to prevent erosion and further soil, boulders, and trees from reaching roadways from the freshly exposed ground.

7.2 Hazard Types

Two types of debris flow hazards occurred in the 2023 and 2024 storms. Channelized debris flows reaching roadways occurred in fluvial drainage networks along hillsides where runoff concentrated into existing channels carrying soil, rock, and woody debris. This report focuses on the debris flow type which is not channelized and occurs as shallow, rapid earth or mud flow. The record of these in Vermont is that they occurred on steeper slopes with sandy, loamy, silty and glacial till soils, in areas described in chapter 4 of this report, having a combination of factors making them more prone to sliding. It is critical to recognize that areas susceptible to the non-channelized debris flows can be identified with the methodology given in this report, but the exact locations of the debris flow within those areas are not as predictable as are channelized debris flow locations.

7.3 Prediction Strategies

Chapter 6 of this report explains recommended hazard prediction coupling hazard location mapping based on the combination of terrain, tracking seasonal soil moisture progression, and tracking expected heavy rainfall for higher hazard locations.

We also recommend implementing a long-term approach to prediction strategies, especially at higher hazard ranked sites, including real-time groundwater monitoring and installing movement tripping monitors as more history develops with debris flows and the availability and cost technology for such monitoring improves.

7.4 Warning Strategies

Debris flow hazard locations on roadways can be identified for drivers starting with installing fixed warning signs in the way that rock fall hazard locations currently are. That would need to include a general public information approach to informing drivers of what these hazard signs are intended for and how drivers should respond to them, as this is an emerging hazard which the general public is not familiar with. Additional options for informing drivers of debris flow hazards and their implications include using the VT Alert program (reference = <https://vem.vermont.gov/vtalert>) through the Vermont Emergency Management program. VTrans can evaluate the need for expanding on these warning strategies as part of their overall level of service planning. Expansion can include actively patrolling higher hazard routes when heavy rain conditions are expected and potentially temporarily closing routes during heavy rain if predictions indicate high potential for debris flows.

7.5 Site Improvement Strategies

A considerable body of design approaches and methodologies exists for designing channelized debris flow mitigation measures, such as in Figures 7.1, 7.2, 7.3. The “earth flow” types of debris flows which are the focus of this report have so far not been associated with terrain or soil features that can be traced to specific and distinct local trigger features that would allow for a practical site improvement strategy within an identified hazard area (see Section 6.1 in this report) for preemptive action. However, once debris flows occur they can become localized topographic low areas that develop into channels where runoff can concentrate, which coupled

with their disturbed and initially un-revegetated soils become susceptible to developing into channelized debris flow locations. Channelized debris flow site improvement strategies are applicable for those situations.

In the short term, immediately following an earthflow type debris flow it is critical to give attention to stabilizing the exposed soil and rock to prevent further mudflows and rock/boulder falls onto roadways. Principles for addressing channelized debris flows apply to these situations, if needed by using improvised barriers and diversion to restore safe passage on the affected route until more detailed evaluation and possible design and construction of permanent measures can occur. Similarly, it may be necessary to use tripwire or similar type monitoring in special situations which warrant precautions in addition to barriers and diversions. Examples of current methodologies are provided in Marchi, Coviello, and Hurlimann, 2024.

7.6 Channelized Debris Flow Sites

Typical site improvement strategies for channelized debris flows are flow impediments such as baffles, debris straining, and barrier walls, both parallel and perpendicular to the channel. An excellent compilation of practice methods was developed by the New Zealand Geotechnical Society (Buech, and Smith, 2026).

Engineering design and construction solutions for debris flow mitigation are intended to reduce the impact of fast-moving, water-saturated sediment and rock by intercepting, retaining, or safely conveying the flow (Chen et al., 2015). Such engineering interventions are generally considered long-term solutions for debris-flow hazard reduction. The selection of appropriate mitigation measures for a given area depends on site-specific factors, including topography, climatic conditions, and available financial resources.

7.6.1 Flexible Steel Net Barriers

Flexible steel net barriers catch coarse debris, letting some of the fine material and water pass through the net (Wendeler et al., 2019). The purpose of this metal net is to intercept mass volume of flowing debris from roadways. This method is best suited for concave slopes, where debris flows are likely to become channelized. The load-bearing capacity of the flexible barrier can typically be designed through numerical simulations (Figure 7.1).

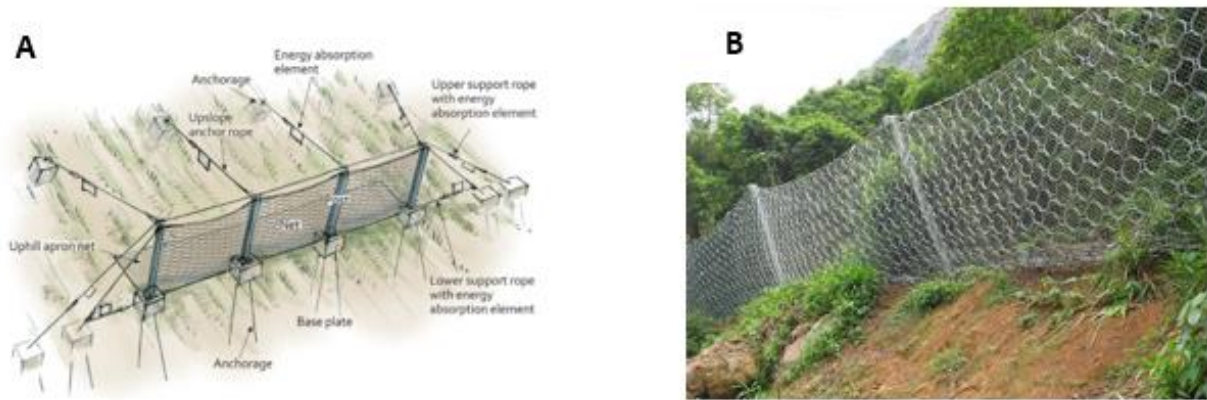


Figure 7.1 A) Schematic view of the components and arrangement of a hillslope debris flow protection net (Berger et al., 2021) & B) Installed ring net. (Rockcont, n.d.)

7.6.2 Barrier Walls

Barrier walls to physically impede future debris flows are typically concrete, or gabion block, or a combination of these. Their required heights and dimensions depend on slopes and expected flow volumes, with examples of design guidance available in Figure 7.2 and 7.3.

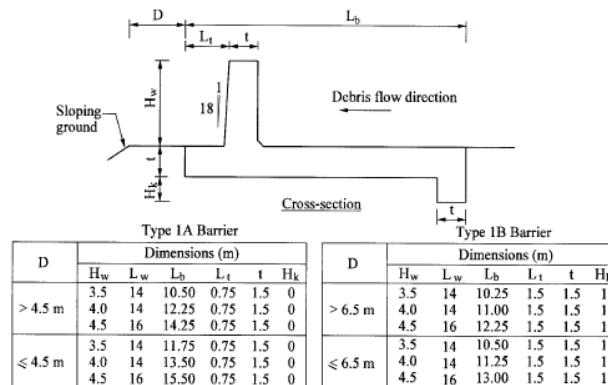


Figure 7.2 Barrier wall design guidance (Sun et al., 2005)

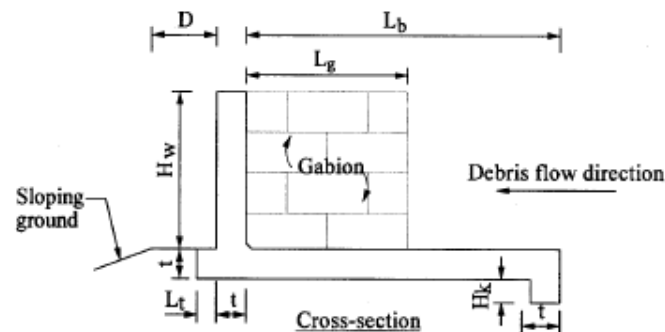


Figure 7.3 Schematic of Gabion walls (Sun et al., 2005).

8 SUMMARY AND RECOMMENDATIONS

8.1 Summary

- Debris flows are an emerging hazard in Vermont, and historical inventory data is limited. Instead, a combined dataset of slope failure records was utilized to support this analysis.
- Site visits were conducted during the study to characterize debris flow post-failure site conditions. These site visits aided model development and validation.
- Following the development of the debris flow hazard susceptibility map, field-based validation comprised of site reconnaissance was performed to evaluate model performance. The final map incorporates the field validation findings to obtain agreement in showing both documented debris flow and other landslide locations and locations without debris flows and landslides.
- Combining GIS data on terrain and soil type with satellite moisture data, and NOAA rainfall records correlated in most locations with debris flows identified by VTrans.
- The analysis employs a simplified physics-based infinite slope stability model to compute the factor of safety.
- The modeling to back-analyze observed debris flows evaluated for this work assumed complete rainfall infiltration (100%). The initial groundwater level was assumed at the base of the 10 ft thick sliding zone, with a rise of up to 6 ft based on July 2023 storm event simulations. This scenario produced a reasonable correspondence between modeled instability patterns and observed failure locations. Future analyses may incorporate more extreme rainfall scenarios to evaluate higher-magnitude hazard conditions. In addition, incorporating field-measured groundwater data into future model updates can improve susceptibility mapping.
- InSAR based susceptibility mapping is a possible future additional monitoring technology applicable for debris flows in Vermont once the satellite imagery becomes available across the state.

8.2 Recommendations

- The landslide susceptibility map should be utilized as a screening and prioritization tool to rank transportation routes and associated roadside infrastructure for further monitoring.
- Develop a consistent monitoring program with the methods provided in this report and update the data on debris flows along with developing debris flow triggering predictions using soil moisture and rainfall records from the developing body of debris flows.
- Groundwater conditions within steep terrains were uncertain throughout the study due to the absence of reliable, continuous groundwater level data. Variations in groundwater levels significantly influence soil pore water pressure, which in turn affects soil strength. It is essential to improve understanding of baseline groundwater levels and seasonal fluctuations, and rates of groundwater level rise during heavy rainfall. It is therefore recommended to install piezometer.
- Refine the prediction model with improved soil data as that becomes available.
- Periodic field inspections should be conducted along routes with more susceptible slopes to assess physical changes in slope conditions, ideally before and after major storm events.
- Field observations indicate the presence of residential buildings and commercial establishments located in close proximity to steep slopes. While relocation may involve economic constraints for property owners, it is important to raise awareness regarding potential hazards. Coordination with state planning authorities is recommended to develop and implement future land-use management guidelines.
- Vermont experiences substantial snow cover for approximately one-quarter of the year. Snowmelt can increase soil saturation, which may impact slope stability. Site inspections of vulnerable slopes should be conducted during early summer.
- Although tree roots are generally expected to enhance soil cohesion and overall stability, it was not explicitly part of this research. Research is recommended to quantitatively evaluate the influence of root systems on soil mechanical properties and resulting debris flow slope stability.
- The development of a rainfall threshold-based debris flow warning system is recommended to mitigate potential damage during extreme weather events. This will

require further investigation of available data and acquiring additional data on rainfall, moisture, and debris flows, potentially using machine-learning methods to analyze a larger body of potential factors associated with debris flows.

- The landslide inventory map should be regularly updated and utilized to track seasonal debris flow activity, in coordination with the Vermont Center for Geographic Information.
- The susceptibility map should be updated periodically with new available data, maintenance records, and field observations records, because the VTrans resilience framework is designed to support adaptive planning.

References

- Abdulwahid, W. M., & Pradhan, B. (2017). Landslide vulnerability and hazard assessment for multi-hazard scenarios using airborne laser scanning data (LiDAR). *Landslides*, 14(3), 1057–1076. <https://doi.org/10.1007/s10346-016-0744-0>
- Ahmad, N., Shafique, M., Hussain, M. L., & Ullah, I. (2024). Integrated debris flow hazard and hazard assessment using UAV data and RAMMS: A case study in northern Pakistan. *Natural Hazards*. <https://doi.org/10.1007/s11069-024-06862-0>
- Alvioli, M., & Baum, R. L. (2016). Parallelization of the TRIGRS model for rainfall-induced landslides using the message passing interface. *Environmental Modelling & Software*, 81, 122–135. <https://doi.org/10.1016/j.envsoft.2016.04.002>
- Ameratunga, J., Sivakugan, N., & Das, B. M. (2016). Correlations of soil and rock properties in geotechnical engineering. Springer. <https://doi.org/10.1007/978-81-322-2629-1>
- Baldwin, B. (1982). *Geology of Vermont*. Vermont Geological Survey.
- Baum, R. L., Brien, D. L., Reid, M. E., Schulz, W. H., & Tello, M. J. (2024). Assessing locations susceptible to shallow landslide initiation during prolonged intense rainfall in the Lares, Utuado, and Naranjito municipalities of Puerto Rico. *Natural Hazards and Earth System Sciences*, 24(5), 1579–1605. <https://doi.org/10.5194/nhess-24-1579-2024>
- Bennett, K., et al. (2021). Landslides along the Winooski River in Burlington, Vermont ,Conference poster, University of Vermont.
- Berger, C., Denk, M., Graf, C., Stieglitz, L., & Wendeler, C. (2021). Practical guide for debris flow and hillslope debris flow protection nets (WSL Berichte No. 113). Swiss Federal Institute for Forest, Snow and Landscape Research WSL.
- Buech, F., & Justice, R. (2026). Slope stability geotechnical guidance unit 6: Debris flow assessment, analyses and mitigation (Version 1). New Zealand Geotechnical Society.
- Burns, W. J., Calhoun, N. C., & Franczyk, J. J. (2022). Protocol for channelized debris flow susceptibility mapping (Special Paper 53). Oregon Department of Geology and Mineral Industries. https://pubs.oregon.gov/dogami/sp/SP-53/SP-53_report.pdf
- Chen, J., Chen, X., Li, Y., & You, Y. (2015). Engineering measures for debris flow hazard mitigation in the Wenchuan earthquake area. *Engineering Geology*, 194, 73–85. <https://doi.org/10.1016/j.enggeo.2014.10.002>
- Chen, X., Tessari, G., Fabris, M., Achilli, V., & Floris, M. (2021). Comparison between PS and SBAS InSAR techniques in monitoring shallow landslides. In N. Casagli, V. Tofani, K. Sassa, P. T.

Bobrowsky, & K. Takara (Eds.), Understanding and reducing landslide disaster hazard (WLF 2020). Springer. https://doi.org/10.1007/978-3-030-60311-3_17

Coe, J. A., Michael, J. A., Crovelli, R. A., Savage, W. Z., Laprade, W. T., & Nashem, W. D. (2004). Probabilistic assessment of precipitation-triggered landslides using historical records of landslide occurrence, Seattle, Washington. *Environmental & Engineering Geoscience*, 10(2), 103–122. <https://doi.org/10.2113/10.2.103>

Crawford, M. M., Dortch, J. M., Koch, H. J., Zhu, Y., Haneberg, W. C., Wang, Z., & Bryson, L. S. (2022). Landslide hazard assessment in eastern Kentucky, USA: Developing a regional-scale, limited-resource approach. *Remote Sensing*, 14(24), Article 6246. <https://doi.org/10.3390/rs14246246>

Cutter, S. L., Burton, C. G., & Emrich, C. T. (2010). Disaster resilience indicators for benchmarking baseline conditions. *Journal of Homeland Security and Emergency Management*, 7(1), 1–22. <https://doi.org/10.2202/1547-7355.1732>

Delmonaco, G., Leoni, G., Margottini, C., Puglisi, C., & Spizzichino, D. (2003). Large-scale debris-flow hazard assessment: A geotechnical approach and GIS modelling. *Natural Hazards and Earth System Sciences*, 3(5), 443–455. <https://doi.org/10.5194/nhess-3-443-2003>

Dong, J., Zhang, L., Tang, M., Liao, M., Xu, Q., Gong, J., & Ao, M. (2018). Mapping landslide surface displacements with time series SAR interferometry by combining persistent and distributed scatterers: A case study of Jiaju landslide in Danba, China. *Remote Sensing of Environment*, 205, 180–198. <https://doi.org/10.1016/j.rse.2017.11.022>

Encyclopaedia Britannica. (2025). Vermont. In *Encyclopaedia Britannica*. <https://www.britannica.com/place/Vermont>

Entekhabi, D., Yueh, S., O'Neill, P., Kellogg, K., Allen, A., Bindlish, R., Brown, M., Chan, S., Colliander, A., Crow, W., Das, N., De Lannoy, G., Dunbar, S., Edelstein, W., Entin, J., Escobar, V., Goodman, S., Jackson, T., Johnson, J., Xu, X. (2014). *SMAP handbook*. NASA Jet Propulsion Laboratory.

Federal Highway Administration. (2008). *Rock slopes: Design, excavation, stabilization* (FHWA-NHI-08-123). U.S. Department of Transportation.

Fell, R., Corominas, J., Bonnard, C., Cascini, L., Leroi, E., & Savage, W. Z. (2008). Guidelines for landslide susceptibility, hazard and hazard zoning for land use planning. *Engineering Geology*, 102(3–4), 85–98. <https://doi.org/10.1016/j.enggeo.2008.03.022>

Ferguson Waterworks. (n.d.). Gabions: Gabion wall structures for slope stabilization and erosion control. <https://www.fergusonwaterworks.com/product/gabions/>

- Ford, T. W., & Quiring, S. M. (2019). Comparison of contemporary in situ, model, and satellite remote sensing soil moisture with a focus on drought monitoring. *Water Resources Research*, 55(2), 1565–1582. <https://doi.org/10.1029/2018WR024039>
- Geotech d.o.o. (n.d.). Gabion walls: Function, application, advantage. <https://www.geotech.hr/en/gabion-walls/>
- Geotechnical Engineering Office. (2008). Guide to soil nail design and construction (Geo Guide 7). Civil Engineering and Development Department, Hong Kong Special Administrative Region Government. https://www.cedd.gov.hk/filemanager/eng/content_118/eg7_200803.pdf
- Gonzalez, F. C. G., Cavalcanti, M. C. R., Nahas Ribeiro, W., Mendonça, M. B., & Haddad, A. N. (2024). A systematic review on rainfall thresholds for landslide occurrence. *Heliyon*, 10(1), Article e23247. <https://doi.org/10.1016/j.heliyon.2023.e23247>
- Highland, L. M., & Bobrowsky, P. (2008). Introduction to landslide stabilization and mitigation. In *The landslide handbook: A guide to understanding landslides* (U.S. Geological Survey Circular 1325, Appendix C). U.S. Geological Survey. <https://pubs.usgs.gov/circ/1325/pdf/Sections/AppendixC.pdf>
- Ilinca, V., Şandric, I., Chiţu, Z., Irimia, R., & Gheuca, I. (2022). UAV applications to assess short-term dynamics of slow-moving landslides under dense forest cover. *Landslides*, 19(7), 1717–1734. <https://doi.org/10.1007/s10346-022-01877-9>
- Iowa Department of Transportation. (2014). Soils design and construction manual (Chap. 2, Engineering properties of soil and rock). iStock. (n.d.). Landslide road sign illustrations. <https://www.istockphoto.com/illustrations/landslide-road-sign>
- Li, S., Xu, W., & Li, Z. (2022). Review of the SBAS InSAR time-series algorithms, applications, and challenges. *Geodesy and Geodynamics*, 13(2), 114–126. <https://doi.org/10.1016/j.geog.2021.09.007>
- Liu, Q., Zhao, Q., Lan, Q., Huang, C., Yang, X., Tang, Z., & Deng, M. (2024). Regional dynamic hazard assessment of rainfall-induced landslide guided by geographic similarity. *Bulletin of Engineering Geology and the Environment*, 83(12), Article 501. <https://doi.org/10.1007/s10064-024-04001-4>
- Liu, S., Wang, L., Zhang, W., He, Y., & Samui, P. (2023). A comprehensive review of machine learning-based methods in landslide susceptibility mapping. *Geological Journal*, 58(6), 2283–2301. <https://doi.org/10.1002/gj.4666>
- Liu, W., & He, S. (2024). Influence of runoff on debris flow propagation at a catchment scale: A case study. *Landslides*, 21(8), 1757–1774. <https://doi.org/10.1007/s10346-024-02255-3>

- Meng, Q., Smith, S. A., & Rodgers, J. (2024). Geospatial analysis and mapping of regional landslide susceptibility: A case study of eastern Tennessee, USA. *Geohazards*, 5(2), 364–373. <https://doi.org/10.3390/geohazards5020019>
- Mohseni, O., Anderson, C., Strong, M., Conway, R., Hathaway, C., Grosser, A., & Mielke, A. (2018). Storm-induced slope failure susceptibility mapping (Report No. MN/RC 2018-05). Minnesota Department of Transportation.
- Myrick, E. P. (2024). Characterizing geomorphological change utilizing remote sensing and field-based methods at the Cotton Brook landslide, Waterbury, Vermont , Graduate thesis, University of Vermont. Graduate College Dissertations and Theses, 1932.
- National Aeronautics and Space Administration. (2025). NISAR science users' handbook (2nd ed.). NASA Jet Propulsion Laboratory. <https://science.nasa.gov/mission/nisar/nisar-handbook/>
- Natural History of Greenways. (n.d.). Natural history of Vermont greenways. University of Massachusetts. <https://www.umass.edu/greenway/Vt/History/VT-HG-nat.html>
- Ochsner, T. E., Cosh, M. H., Cuenca, R. H., Dorigo, W. A., Draper, C. S., Hagimoto, Y., Kerr, Y. H., Larson, K. M., Njoku, E. G., Small, E. E., & Zreda, M. (2013). State of the art in large-scale soil moisture monitoring. *Soil Science Society of America Journal*, 77(6), 1888–1919. <https://doi.org/10.2136/sssaj2013.03.0093>
- Pei, T., & Qiu, T. (2023). Debris flow susceptibility mapping in Colorado Front Range, USA: A comparison of physics-based and data-driven approaches. *E3S Web of Conferences*, 415, Article 01018. <https://doi.org/10.1051/e3sconf/202341501018>
- Reid, M. E., LaHusen, R. G., & Ellis, W. L. (1999). Real-time monitoring of active landslides (Fact Sheet F.S.-091-99). U.S. Geological Survey. https://pubs.usgs.gov/F.S./F.S.-091-99/F.S.091_99.html
- Rockcont. (n.d.). Ring net system for rockfall, debris flow and mudflow protection. <https://www.rockcont.com/products/ring-net-system.html>
- Rotte, V. M., & Viswanadham, B. V. (2013). Influence of nail inclination and facing material type on soil-nailed slopes. *Proceedings of the Institution of Civil Engineers: Ground Improvement*, 166(2), 86–107.
- Roth, A., Wendeler, C., & Amend, F. (2010). Use of properly designed flexible barriers to mitigate debris flow natural hazards. In *GeoFlorida 2010* (pp. 3207–3216). American Society of Civil Engineers. [https://doi.org/10.1061/41095\(365\)327](https://doi.org/10.1061/41095(365)327)

- She, X., Li, D., Yang, S., Xie, X., Sun, Y., & Zhao, W. (2024). Landslide hazard assessment for Wanzhou considering the correlation of rainfall and surface deformation. *Remote Sensing*, 16(9), Article 1587. <https://doi.org/10.3390/rs16091587>
- Sun, H.W., Lam, T.T.M., & Tsui, H.M. (2005). Design Basis for Standardized Modules of Landslide Debris-Resisting Barriers, GEO Report No. 174, Geotechnical Engineering Office, Civil Engineering and Development Department, Hong Kong SAR Government.
- Syazili, M., Bisri, M., Andawayanti, U., & Hendrawan, A. P. (2025). The safety factor and deformation on the slope by soil nailing reinforcement in the water saturation condition. *Civil Engineering and Architecture*, 13(4), 2914–2921. <https://doi.org/10.13189/cea.2025.130408>
- Tong, X., & Schmidt, D. (2016). Active movement of the Cascade landslide complex in Washington from a coherence-based InSAR time series method. *Remote Sensing of Environment*, 186, 405–415. <https://doi.org/10.1016/j.rse.2016.09.008>
- U.S. Department of Transportation, Federal Highway Administration. (2015). Soil nail walls: Reference manual (FHWA-NHI-14-007; FHWA GEC 007; NHI Course No. 132085). <https://www.fhwa.dot.gov/engineering/geotech/pubs/nhi14007.pdf>
- U.S. Geological Survey. (2011). Bedrock geologic map of Vermont (Scientific Investigations Map 3184).
- Urciuoli, G., & Pirone, M. (2013). Subsurface drainage for slope stabilization. In C. Margottini, P. Canuti, & K. Sassa (Eds.), *Landslide science and practice* (pp. 475–481). Springer. https://doi.org/10.1007/978-3-642-31319-6_74
- van der Heijden, R., Ghazanfari, E., Rizzo, D. M., Leshchinsky, B., & Dewoolkar, M. (2025). Applications of InSAR for monitoring post-wildfire ground surface displacements. *Remote Sensing*, 17(12), Article 2047. <https://doi.org/10.3390/rs17122047>
- Verbrugge, J.-C., & Schroeder, C. (2018). Geotechnical correlations for soils and rocks. John Wiley & Sons. <https://doi.org/10.1002/9781119482819>
- Vermont Agency of Natural Resources. (n.d.). Landslides. Vermont Open Geodata Portal. <https://geodata.vermont.gov/datasets/VTANR::landslides/about>
- Vermont Geological Survey. (2016). Landslide hazard assessment, Highgate, Vermont (Open-File Report VG2016-4). Vermont Agency of Natural Resources. <https://dec.vermont.gov/sites/dec/files/geo/HazDocs/HighgateLSOFRVG2016-4.pdf>
- Washington State Department of Transportation. (2013). Geotechnical design manual (M 46-03.08, Chap. 5, Engineering properties of soil and rock).

- Wendeler, C., Volkwein, A., McArdell, B. W., & Bartelt, P. (2019). Load model for designing flexible steel barriers for debris flow mitigation. *Canadian Geotechnical Journal*, 56(6), 893–910. <https://doi.org/10.1139/cgj-2016-0157>
- Wieczorek, G. F. (1996). Landslide triggering mechanisms. In A. K. Turner & R. L. Schuster (Eds.), *Landslides: Investigation and mitigation* (Transportation Research Board Special Report No. 247, pp. 76–90). National Academy Press.
- Wicki, A., Lehmann, P., Hauck, C., Seneviratne, S. I., Waldner, P., & Stähli, M. (2020). Assessing the potential of soil moisture measurements for regional landslide early warning. *Landslides*, 17(8), 1881–1896. <https://doi.org/10.1007/s10346-020-01400-y>
- Xiong, J., Pei, T., & Qiu, T. (2024). A novel framework for spatiotemporal susceptibility prediction of rainfall-induced landslides: A case study in western Pennsylvania. *Remote Sensing*, 16(18), Article 3526. <https://doi.org/10.3390/rs16183526>
- Zheng, Z., Teng, Z., Xie, C., Ma, Y., & Tang, H. (2025). Prediction of debris flow hazard based on multi-source remote sensing data: A case study of Dulongjiang Township, Yunnan Province. *Remote Sensing Applications: Society and Environment*, 39, Article 101719. <https://doi.org/10.1016/j.rsase.2025.101719>
- Zhou, J., Huang, J., Sun, Z., Yi, Q., & He, A. (2024). Machine learning approaches to debris flow susceptibility analyses in the Yunnan section of the Nujiang River Basin. *PeerJ*, 12, Article e17352. <https://doi.org/10.7717/peerj.17352>
- Zito, C., Mangifesta, M., Francioni, M., Guerriero, L., Di Martire, D., Calcaterra, D., & Sciarra, N. (2024). Cascading landslide: Kinematic and finite element method analysis through remote sensing techniques. *Remote Sensing*, 16(18), Article 3423. <https://doi.org/10.3390/rs16183423>
- Zocchi, M., Delchiaro, M., Troiani, F., Scarascia Mugnozza, G., & Mazzanti, P. (2024). PS-InSAR post-processing for assessing the spatiotemporal differential kinematics of complex landslide systems: A case study of DeBeque Canyon Landslide (Colorado, USA). *Earth Surface Processes and Landforms*, 49(14), 4862–4880. <https://doi.org/10.1002/esp.6002>

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Table A 2: Sensitivity analysis of variables on slope stability factor of safety

Variable Parameter	β (Deg)	C' (kN/m ²)	Z (m)	h_w (m)	γ_{sat} (kN/m ³)	ϕ' (Deg)	γ_w (kN/m ³)	F.S.	% change of F.S.
	30.0	20.0	3.0	1.5	20.0	30.0	9.8	1.47	Base Value
β (Deg)	30.0	20.0	3.0	3.0	18.0	30.0	9.8	1.15	21.5
	35.0	20.0	3.0	3.0	18.0	30.0	9.8	1.09	25.6
	40.0	20.0	3.0	3.0	18.0	30.0	9.8	1.00	31.9
	45.0	20.0	3.0	3.0	18.0	30.0	9.8	0.99	32.4
C' (kN/m ²)	30.0	18.0	3.0	3.0	18.0	30.0	9.8	1.17	20.1
	30.0	20.0	3.0	3.0	18.0	30.0	9.8	1.25	14.6
	30.0	22.0	3.0	3.0	18.0	30.0	9.8	1.33	9.2
	30.0	24.0	3.0	3.0	18.0	30.0	9.8	1.41	3.8
Z (m)	30.0	20.0	1.5	1.5	18.0	30.0	9.8	2.05	39.7
	30.0	20.0	2.1	1.5	18.0	30.0	9.8	1.75	19.2
	30.0	20.0	2.4	1.5	18.0	30.0	9.8	1.66	12.8
	30.0	20.0	3.0	1.5	18.0	30.0	9.8	1.53	3.9
h_w (m)	30.0	20.0	3.0	1.5	18.0	30.0	9.8	1.53	3.9
	30.0	20.0	3.0	1.8	18.0	30.0	9.8	1.47	0.2
	30.0	20.0	3.0	2.4	18.0	30.0	9.8	1.36	7.2
	30.0	20.0	3.0	3.0	18.0	30.0	9.8	1.25	14.6
γ_{sat} (kN/m ³)	30.0	20.0	3.0	1.5	17.0	30.0	9.8	1.56	6.0
	30.0	20.0	3.0	1.5	18.0	30.0	9.8	1.53	3.9
	30.0	20.0	3.0	1.5	19.0	30.0	9.8	1.50	2.0
	30.0	20.0	3.0	1.5	20.0	30.0	9.8	1.47	0.3
ϕ' (Deg)	30.0	20.0	3.0	1.5	20.0	30.0	9.8	1.47	0.3
	30.0	20.0	3.0	1.5	20.0	32.0	9.8	1.56	5.8
	30.0	20.0	3.0	1.5	20.0	34.0	9.8	1.65	12.0
	30.0	20.0	3.0	1.5	20.0	36.0	9.8	1.75	19.0

The baseline factor of safety was computed using the average standard parametric values derived from the initial site calibration, which are stated in the first row of each parameter category. Within each highlighted variable parameter, that parameter was varied while all remaining parameters were kept constant at their baseline values. The change in each resulting F.S. from the baseline value is expressed as a percentage change in F.S. attributable to the variation of that parameter. The maximum percentage change associated with each parameter is also presented in a bar plot as a measure of parametric sensitivity (Figure 3.4).

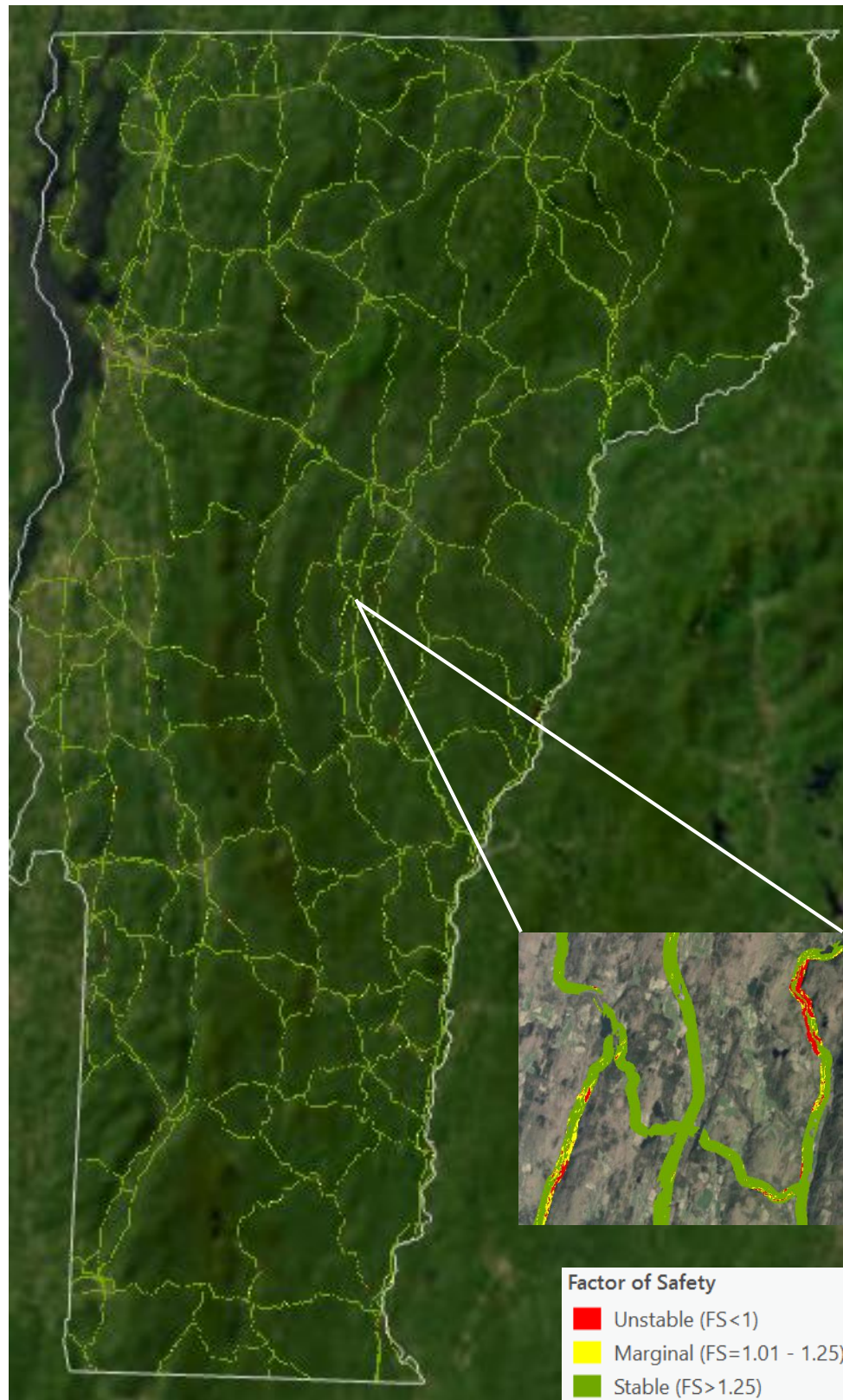


Figure A 7: Factor of safety map for G.W.L. rise of 1.82m (6 ft) with failure depth 3.04m (10 ft).

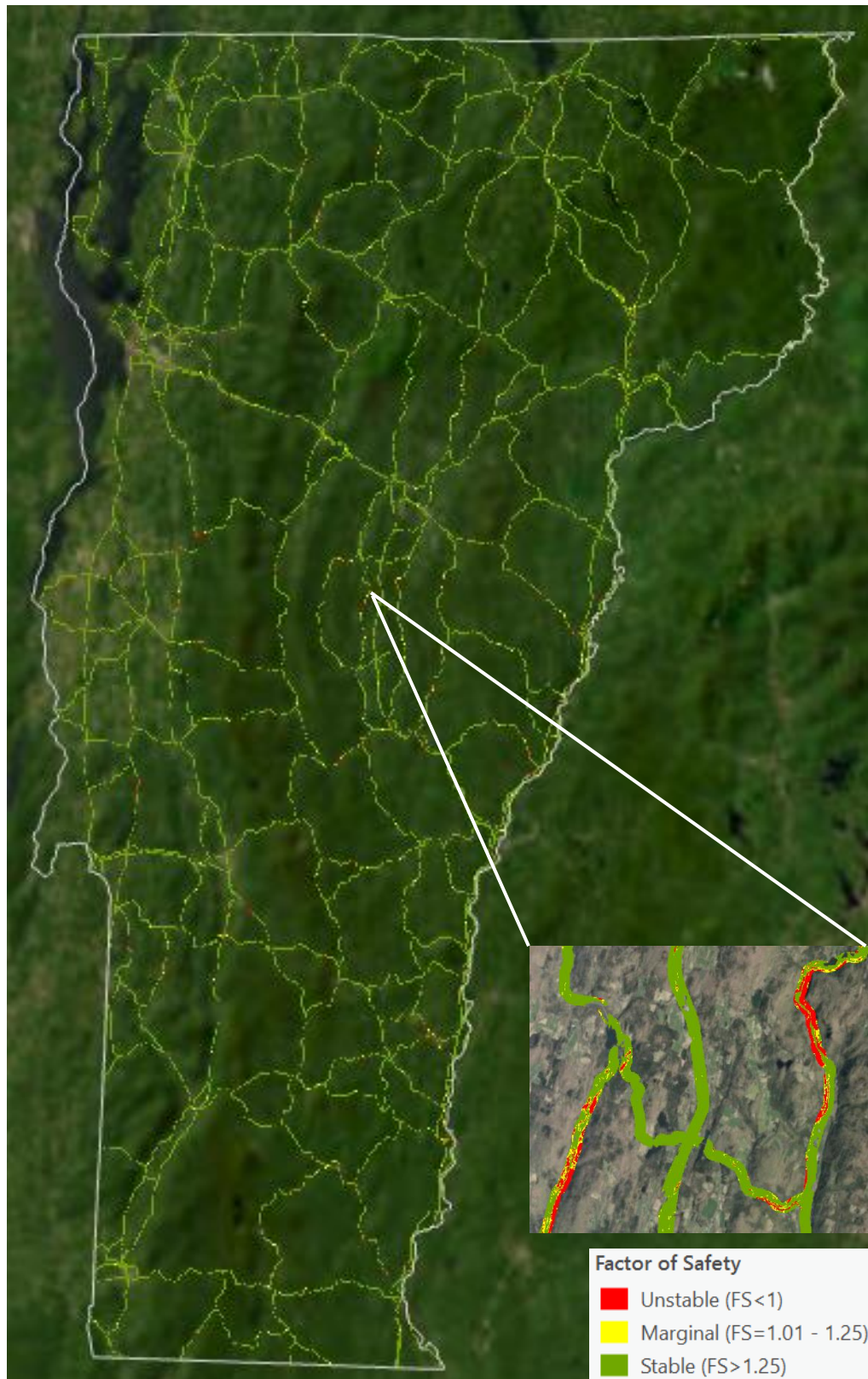


Figure A 8: Factor of safety map for G.W.L. rise of 3.04m (10 ft) with failure depth 3.04m (10 ft).

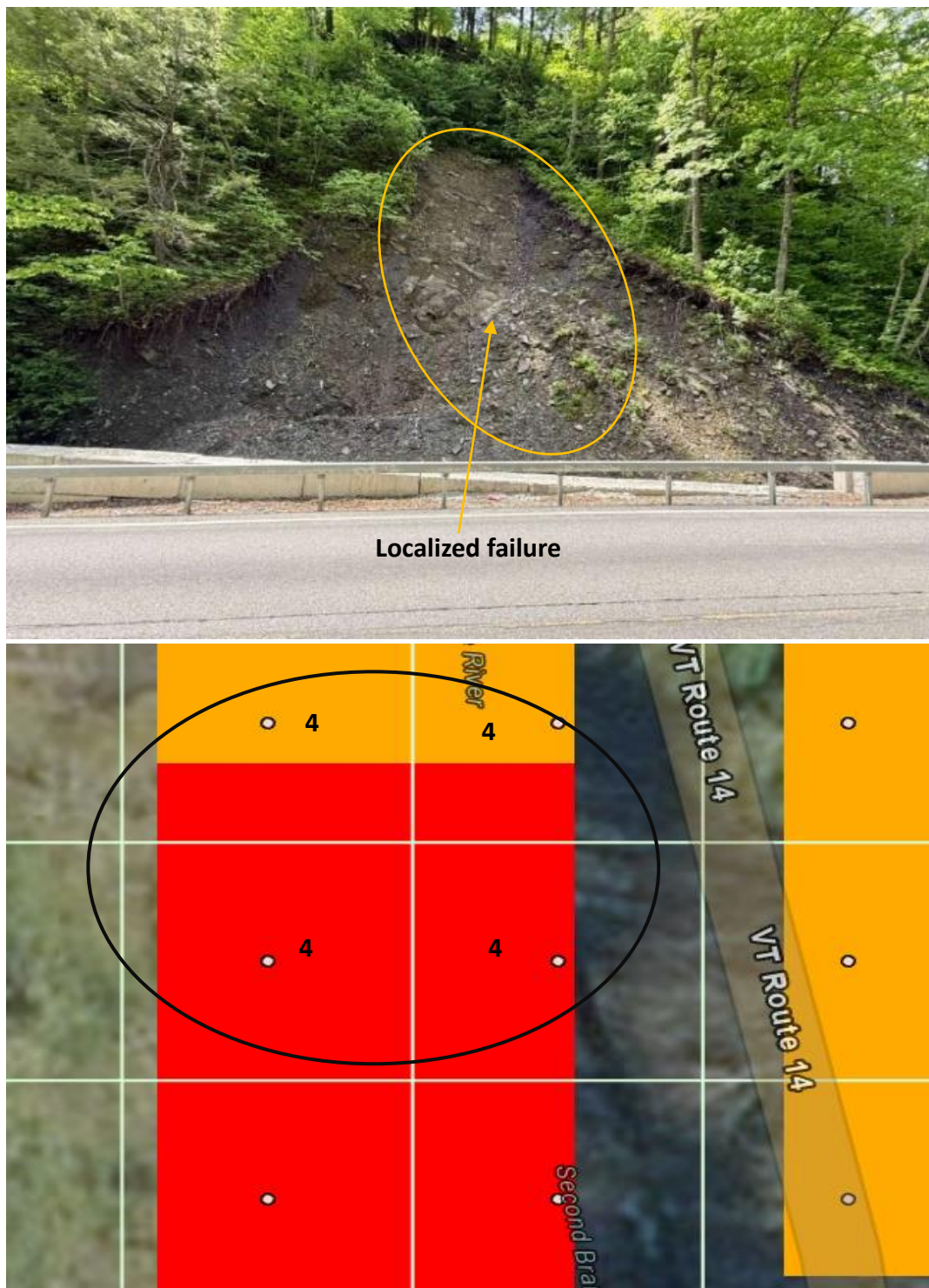


Figure A 9: Site#4, Route 14, Brookfield, VT (Ranking = 4).

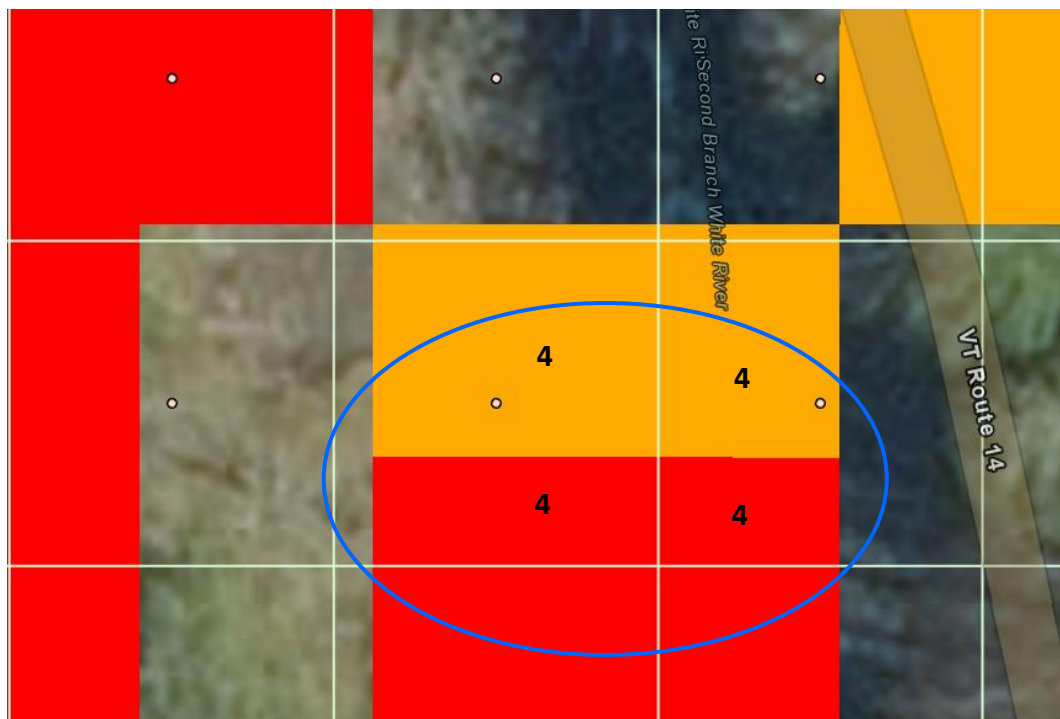


Figure A 10: Site#5, Route 14, Brookfield, VT (Ranking = 4).

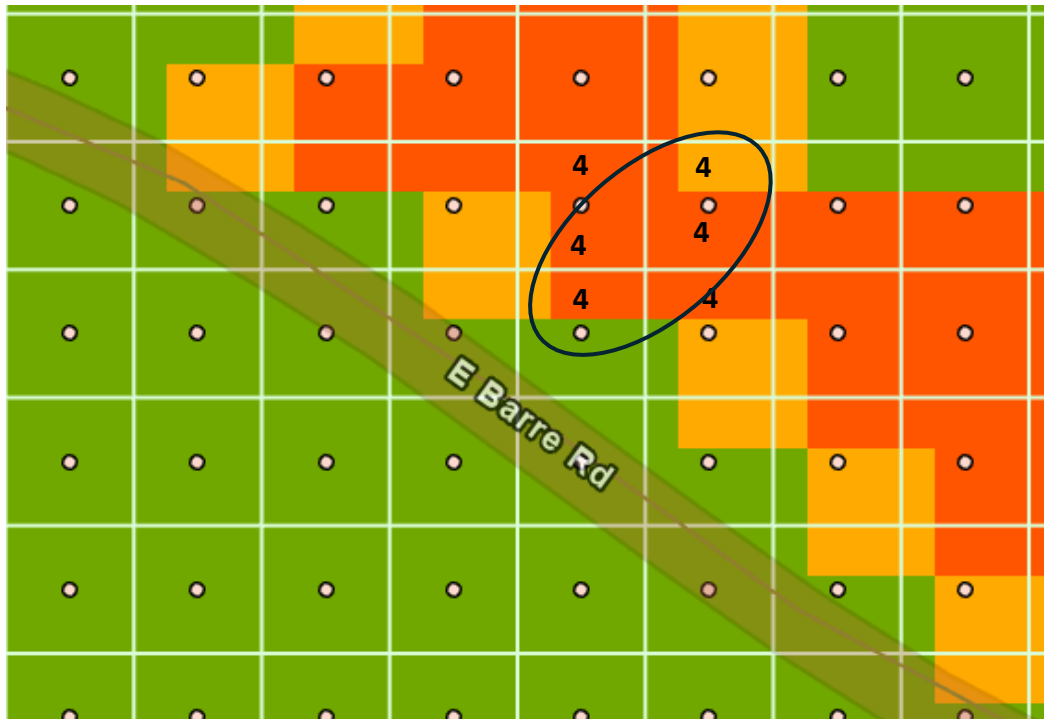


Figure A 11: Site#6, US 302, East Barre, VT (Ranking = 4).

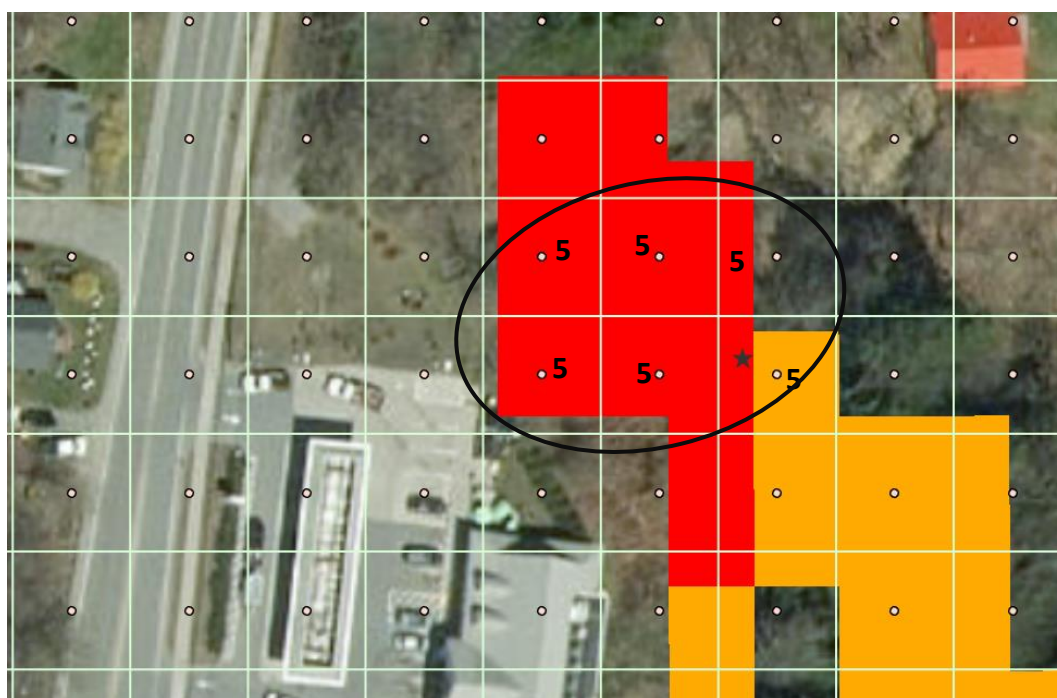


Figure A 12: Site#8, Taft Ave, Hartford, VT (Ranking = 5).

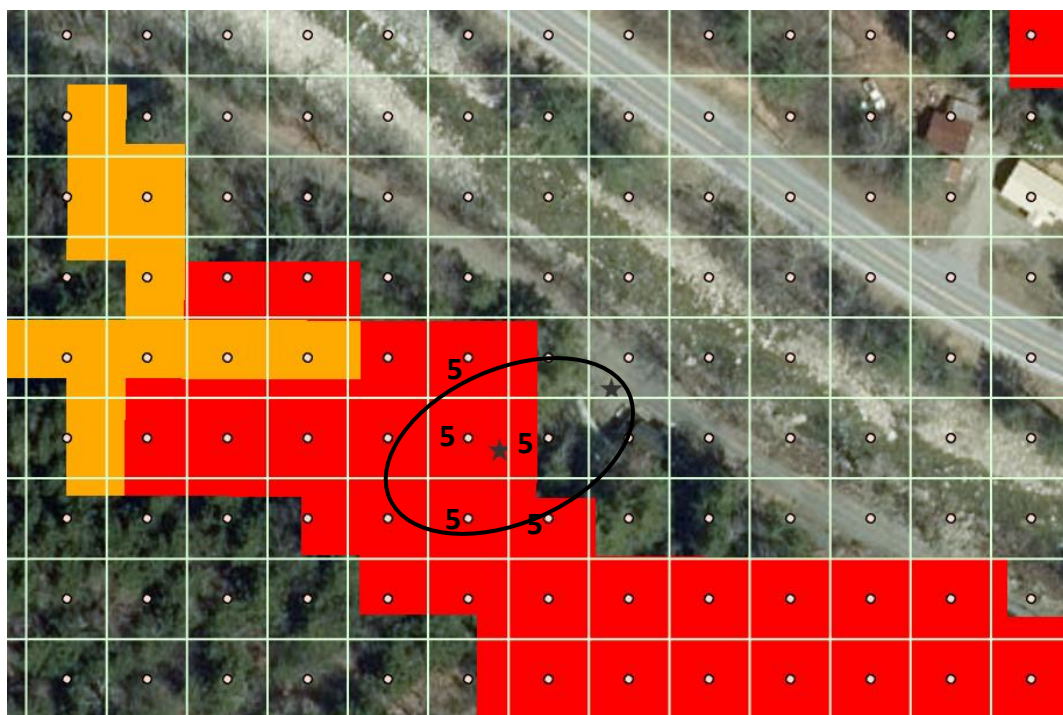


Figure A 7: Site # 9, Black Piece Rd, Route 100, Wardsboro, VT (Ranking = 5).



Figure A 8: Site#10, Peak Hill Rd, Route 14, East Calias, VT (Ranking = 3).



Figure A 9: Site#11, Mill Hill Rd, Highgate, VT (Ranking = 5).

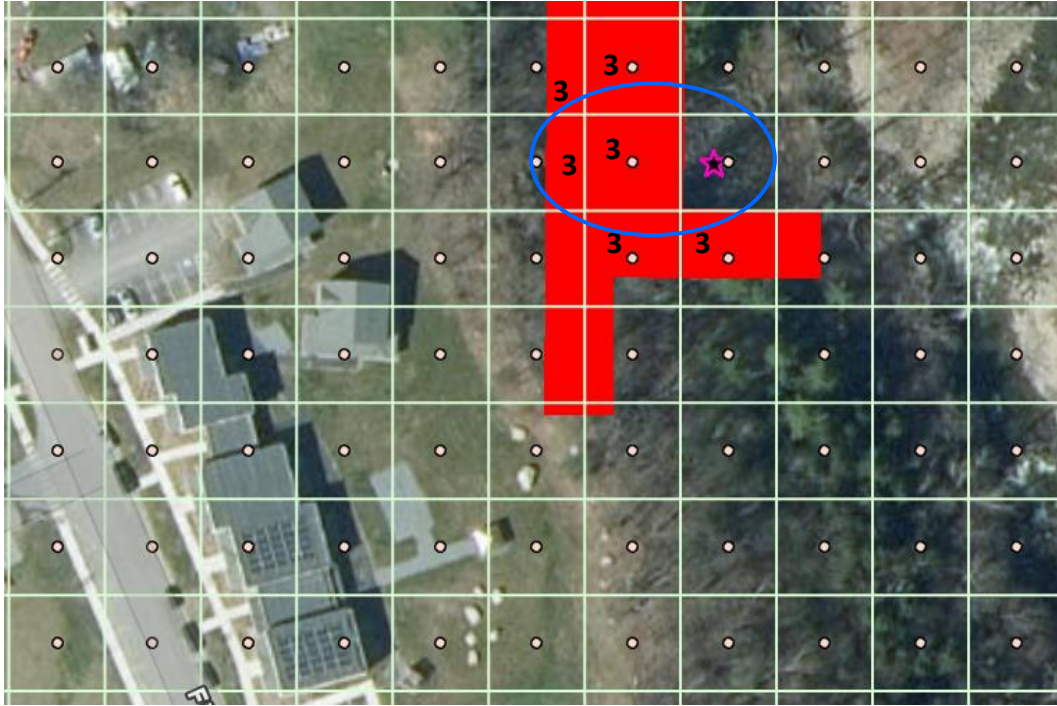


Figure A 10: Site#12, Stony Hill Rd, Bristol, VT (Ranking = 3).



Figure A 11 Site#13, Interstate 91N, Fairlee, VT (Ranking = 3).

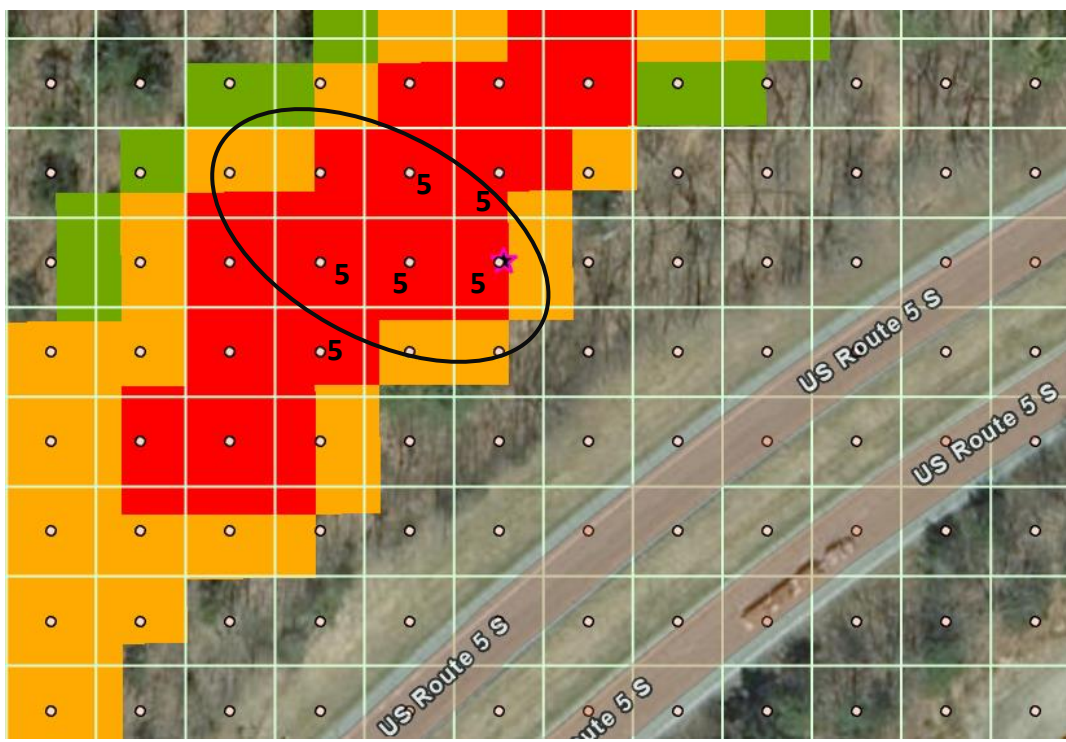


Figure A 12: Site#14, Interstate 91N/US Route 5s, Fairlee, VT (Ranking = 5).

Glossary

ALOS-2 - Advanced Land Observing Satellite-2.

Aspect -The compass direction toward which a slope faces.

AUC – Area Under Curve, a model performance validation approach.

CDF - Channelized Debris Flow; a debris-flow process that occurs within a defined channel or valley.

Cumulative Rainfall - The total amount of precipitation that has fallen over a specified period of time.

Curvature - A measure of the rate of change in slope across the terrain surface, describing the degree to which a slope is convex or concave.

DEM - Digital Elevation Model; a digital representation of the Earth's surface that provides elevation information.

Debris Flow - A rapid downslope movement of a mixture of water, soil, rock, and other debris driven primarily by gravity.

Geohazard - A geological or geomorphological condition or process capable of causing damage, injury, loss of property, or loss of life.

GSSURGO - Gridded Soil Survey Geographic Database; a digital soil database developed by the U.S. Department of Agriculture.

InSAR - Interferometric Synthetic Aperture Radar; a remote-sensing technique that uses the phase differences between radar images acquired at different times to measure surface deformation.

Inventory Map - A thematic map that records the location, extent, and characteristics of past slope failures or landslides within a specific area.

LAHARZ – Lahar’s hazard zonation, a GIS – based empirical computer program designed by United States Geological Survey to simulate potential debris flow accumulation site.

Landslide - The downslope movement of rock, debris, or soil under the influence of gravity, occurring at rates ranging from very slow movement to extremely rapid failure.

LiDAR - Light Detection and Ranging; a remote-sensing technology that uses laser pulses to measure distances and generate detailed information about the Earth's surface and terrain.

NISAR - NASA-ISRO Synthetic Aperture Radar; a joint Earth-observation satellite mission of NASA and the Indian Space Research Organization (ISRO) that uses synthetic aperture radar to monitor changes in the Earth's surface.

NRCS - Natural Resources Conservation Service.

Pixel - The smallest spatial unit of a raster dataset, representing a specific area on the Earth's surface and containing a value for that location.

Raster Data - A type of GIS data that represents geographic information as a regular grid of cells or pixels, with each cell containing a value representing a geographic attribute.

Susceptibility - A measure of the likelihood that a natural hazard, such as a landslide, will occur in a specific area based on its environmental and physical conditions.

TRIGRS - Transient Rainfall Infiltration and Grid-Based Regional Slope-Stability; a physically based model used to evaluate rainfall-induced changes in slope stability.

TWI - Topographic Wetness Index; an index used to estimate the spatial distribution of soil moisture and the tendency of water to accumulate based on topography.

UAV - Unmanned Aerial Vehicle; an aircraft operated without an onboard human pilot, commonly equipped with cameras and other sensors for remote sensing and surveying.

UAVSAR - Uninhabited Aerial Vehicle Synthetic Aperture Radar; an airborne synthetic aperture radar system designed for high-resolution remote sensing and measurement of surface changes.

USDA - United States Department of Agriculture.