Landslides along the Winooski River in Burlington, Vermont: Landscape change and slope instability

Shayla Triantafillou, Anne Morrison, Emily Mischler, Jason Drebber
Department of Geology, University of Vermont, Burlington, VT, USA

Abstract (179 words)

Riverside Avenue in Burlington, Vermont has been the site of frequent landslides over the past 100 years. We investigated the history of the site on geologic and human timescales to understand the causes of these landslides and make management suggestions to limit their potentially devastating effects. The purpose of our investigation was ~~specifically~~ to ~~aid in~~ assess~~ing~~ the geologic hazards as they relate to human infrastructure and safety. We examined how the runoff, hydrogeology and surficial geology affect slope stability along Riverside Avenue. Additionally, we analyzed how humans have altered the landscape since significant urbanization began at the onset of the 20th century. Our findings attribute slope destabilization and subsequent landslides to increased impervious surface area, extensive deforestation, construction of a wider road, and the addition of loose fill and garbage along Riverside Avenue. The effects of climate change threaten to increase landslide events as large precipitation events become more frequent, further exacerbating the already critical geologic hazard. Moving forward, we suggest that management of Riverside Avenue focus on long term de-urbanization and natural ecosystem restoration along the slope.

Introduction (1200 words)

We investigated causes of landsliding along Riverside Avenue in Burlington Vermont (Figure 1). As a main road running parallel to the river, Riverside Avenue is important for businesses, homes, and transit. We aim to understand how hydrogeology, runoff, and surficial geology control landslides along Riverside Avenue.

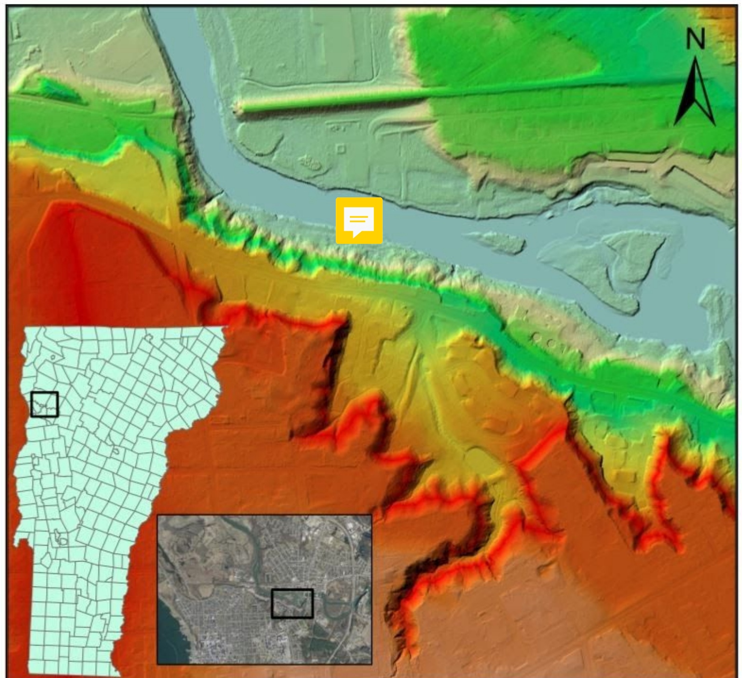

Figure 1. Shaded relief map of the study area. Inset of location within Burlington and Vermont. Amphitheatre shaped landslides are clearly visible along the bank of Riverside Avenue.

Landslide controls

River channel morphology and human landscape change are two primary controls on the spatial distribution of landslides ~~here~~ (Fig. 1). Already narrow and steep river margins were worsened by development. Human induced landscape change results in a higher amount of runoff, decreasing cohesion and changing slope stability force balance equations (Fig. 2). Upstream of Riverside Avenue, the channel is confined by bedrock and the level ground is made up of ancient terraces (Wright).

Glacial history, hydrology, and human induced changes all contribute to landsliding along Riverside Avenue. Significant road work began in 1930; filling and widening the road by over five feet (Fig. 3A, *Street Department, 1931*). Historical aerial photos reveal houses, businesses, and parking lots constructed on both sides of the road between 1930 and 1955 prior to the first documented landslide in 1955 (Fig. 3B). The issue was exacerbated in the late 1970s and early 1980s when trash was illegally dumped down the slope between the road and river (Melvin, 1983). Fill is incohesive and decreases slope stability by creating a lower angle of internal friction as well as limiting drainage, causing the water table to rise.

Natural and anthropogenic causes of landslides

Landslides are natural or human induced events when a stability threshold is surpassed (Barg & Blazewicz, 2003). Construction, slope alterations, and hydrologic changes can trigger landslides (Barg & Blazewicz, 2003). Riverside Avenue underwent significant human alterations throughout the 20th century changing the slope angle, soil cohesion and hydrology, increasing landslide frequency.

Slope material influences slope stability. Sand and gravel fill do not generate much friction between grains; slope angles above a specific threshold value are prone to failure. Trash and construction waste (Reilly, 1981) dumped onto slopes further reduces internal friction and simultaneously increases slope thickness which intensifies shear stress. Cohesion is a measurement of a material's ability to stick to itself. The surficial soil on Riverside Avenue is fill deposited by humans in the 20th century. Therefore, cohesion of the slope material is likely low.

Low cohesion indicates a higher probability of slope failure by resisting shear stress (See Appendix).

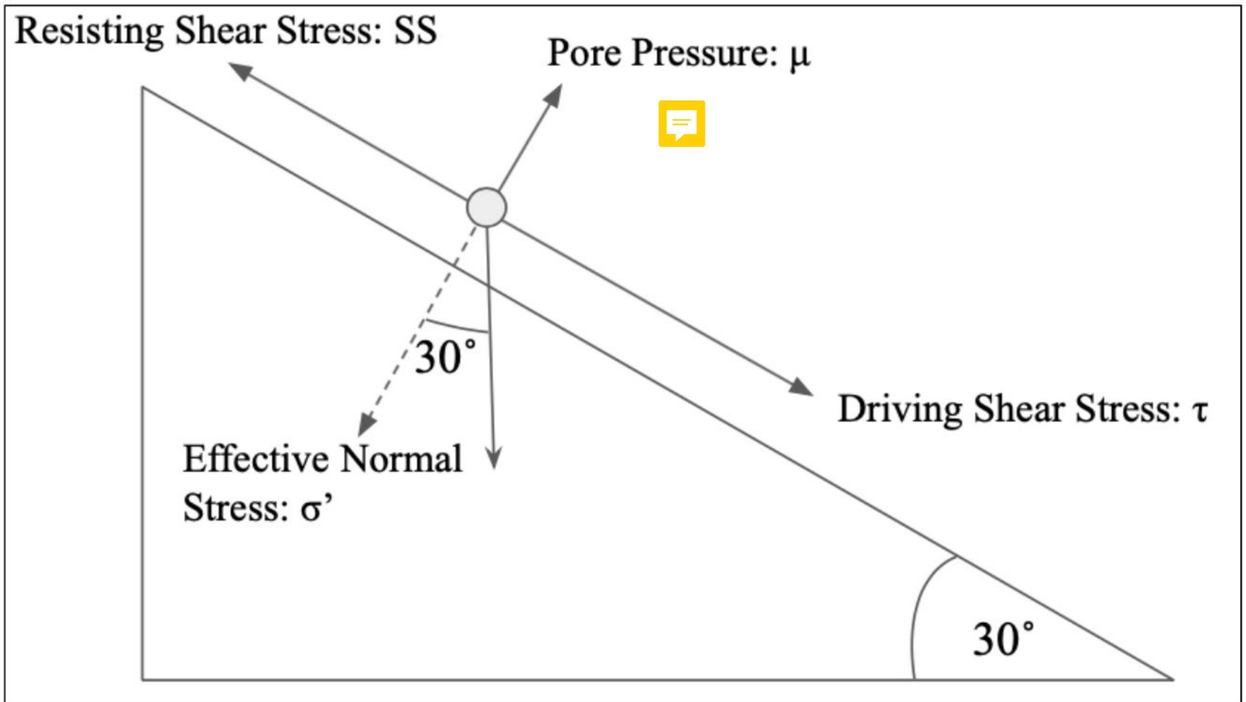

Figure 2. Slope stability force diagram. Vectors represent 4 principle forces contributing to the stability of a slope. Unbalanced vectors indicate greater driving shear stress than resisting shear stress and likely slope failure of a slope with failure plane 30˚ above horizontal. See Appendix for further explanation. Figure adapted from Bierman and Montgomery.

Figure 3: Historic images of Riverside Ave (Source: uvm.edu/landscape). Image A depicts road widening with wooden shorings and fill in progress between 1930 and 1955. Image B is of the 1955 landslide.

Vegetation increases effective soil cohesion (Hales et al., 2009). Effective cohesion increases with increasing depth, number and tensile strength of roots (Hale et al., 2009). Deforestation throughout the 20th century reduced root concentration on the hillslope and further limited soil cohesion, contributing to slope instability (See Appendix). New growth trees do not provide the degree of cohesion that may have dominated the hillslope prior to deforestation.

The driving shear stress increases with increasing density and slope thickness. Dumping of additional fill and trash contributes to this force vector. Evidence of this was recorded by Paul Bierman (Bierman, Personal Communication) prior to the 2019 landslide. Past landslides have been triggered by dumping additional fill or construction waste onto the slope (Reilly, 1981). Any event that causes the driving shear stress to exceed the resisting shear stress will result in slope failure (Fig. 2).

Hydrology

Surface water

We discovered a substantial increase in paved and other impervious surface area over the past century coinciding with increased urbanization (Nichols et al., 2003). Artificial surfaces decrease infiltration which increases runoff. The site's drainage basin topography is depicted in Figure 1. Impervious surfaces from new developments intensify runoff volume and speed as it flows towards the site. Approximately 757,664 ft^2 of Riverside Avenue and surrounding neighborhoods within this drainage basin consist of paved or impervious surfaces (Fig. 4). Shifts in runoff response due to changes in land use are visible in a basin's hydrograph (Hackett, 2008). The October 2019 storm (Fig. 5) triggered the most recent landslide. The Winooski River hydrograph looks "flashy," showing a sharp increase in discharge over a relatively short time period, especially for a drainage basin over 2700 km² (Fig. 5). Hydrographs of this nature correspond with basins that are less permeable, as infiltration allows for a more gradual peak. This rain event was key in destabilizing the Riverside Avenue slope on November 1, 2019.

Figure 4: Map of impervious surfaces on Riverside Avenue contributing to high volumes of runoff within the study area.

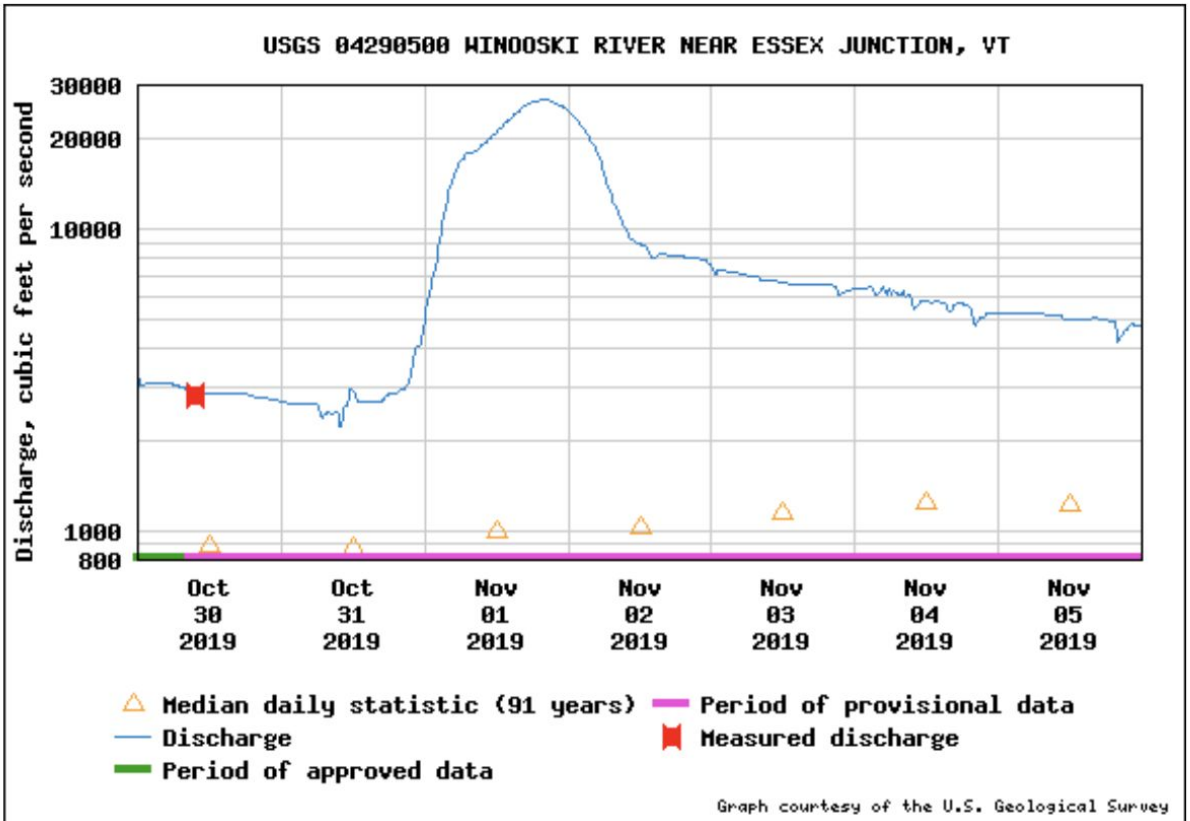

Figure 5: Winooski River hydrograph of the November 2019 storm with peak flow of 23,300 cfs at Essex Junction, VT.

Groundwater

Groundwater hydrology plays an essential role in landslides. Water table height (h), is linearly related to pore pressure within soil (See Appendix). Pore pressure opposes effective normal stress, so increases in water table height destabilize slopes (Fig. 2). Large precipitation events provide a catalyst for this. Most recently the October 31st, 2019 storm (Fig. 5) saturated the soil past a threshold triggering a landslide. Additionally, an increase in the groundwater height will reduce the effect soil density has on resisting slope failure (See Appendix).

The density and connectivity of pores is important for groundwater hydrology. Well drained soils do not accommodate rising pore pressure since the water is unable to accumulate in the soil (See Appendix) and slopes are less prone to failure. Deforestation decreases the effect of evapotranspiration on groundwater further increasing the water table. Most landslide events are associated with large storms (*Driving Rain Causes Landslide*, 1959; *Washout Rips Riverside Ave.*, 1955).

Glacial History

Glacial processes have been shaping our study area for thousands of years. During the Last Glacial Maximum, the entirety of Vermont was covered by the Laurentide Ice Sheet. Soil evidence indicates the presence of a lake occupying the Champlain valley during the ice sheet's retreat northward. The ice sheet acted as a dam for Glacial Lake Vermont; the lake expanded as the ice sheet moved north until it finally failed and the lake drained rapidly (Wright). Isostatically depressed following the final retreat of the ice sheet and the draining of Glacial

Lake Vermont, the St. Lawrence and Champlain valleys were soon inundated by the Atlantic Ocean creating the Champlain Sea (Cronin et al, 2008).

Unconsolidated sediment deposited during the glacial retreat and subsequent hydrological processes covered the underlying bedrock and previous river channels. The Winooski River incised new channels into these sediments and deposited them into Lake Champlain. The flat step-like terraces visible on and above Riverside Avenue are relicts of historical water levels (Wright). The steep slopes alongside Riverside Avenue are likely these relict water levels. Slope angle, which partially determines stability, and landslide potential by extension, is therefore related to paleoglaciations. The unconsolidated materials deposited by this glaciation have also increased landslide potential because these sandy materials have low friction between grains, decreasing the cohesiveness of the material.

Conclusion

The most recent landslide at Riverside Avenue was triggered by an intense precipitation event (Fig. 5). While this storm was large across Vermont, it had a recurrence interval of only 3.44 years at the Essex Junction stream gage. There is a 29% chance of this event occurring in any given year. Simple models show that the hillslope along Riverside Avenue surpass threshold conditions resulting in slope failure. We should prepare for more frequent landslides. Based on our analysis, solutions must be implemented immediately.

Corrective measures should preserve the Winooski stream channel morphology and reduce the hazard to human health and infrastructure. Engineering solutions on the landscape have been employed in the past (Melvin, 1983), but shoring, cribbing, and buttressing (Eckel, 1958) risk damaging the walking path alongside the river. Abandonment and relocation (Eckel, 1958) are feasible only on a longer timescale given the likely economic consequences of upending both housing complexes, businesses and important highway infrastructure. Revegetation of the hillslope, utilizing pervious pavement, and increasing the drainage infrastructure should be prioritized for more rapid mitigation. In the event that future landslides occur, further investigation into the causes and revegetation should take place to stabilize the slope. Given the potential catastrophic consequences of future landslides, the City of Burlington should prioritize swift and thoughtful action.

Acknowledgements We would like to thank Dr. Paul Bierman, Christopher Halsted, and Bella Bennett for providing guidance and instruction on this project.

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Appendix:

Force Diagram Equations

Eq. 1 $SS = \mathbf{C} + \{\boldsymbol{\rho}_s - [1000kg/m^3 * (\mathbf{h}/\mathbf{z}_s)]\}9.8m/s^2 * \mathbf{z}_s * \cos(30°) * \tan\boldsymbol{\phi}$

Eq. 2 $\tau = \boldsymbol{\rho}_s * 9.8m/s^2 * \mathbf{z}_s * \sin(30°)$

Eq. 3 $\mu = 1000kg/m^3 * 9.8m/s^2 * \mathbf{h} * \cos(30°)$

Eq. 4 $\sigma' = \{\boldsymbol{\rho}_s - [1000kg/m^3 * (\mathbf{h}/\mathbf{z}_s)]\}9.8m/s^2 * \mathbf{z}_s * \cos(30°)$

Unknown variables are bolded. C is the soil cohesion, a measure of the tendency of the soil to resist separating. ρ_S (rho s) is the soil bulk density, a relationship between the mass and the volume of the soil. The expression h/z_S is the ratio of the height of the groundwater to the thickness of the failed slab. Well drained soils will have a lower ratio due to their increased ability to drain. The variable z_S is the thickness of the failed surface. The ϕ (phi) angle is the angle of internal friction which is related to the resistance to shearing between individual grains and is related to the maximum slope angle that will remain stable for a given material. The variable h alone is the height of the groundwater and is dependent on the amount of precipitation, vegetation and the type of surficial sediment on a slope. Well drained slopes will require significantly more precipitation much more quickly to increase the groundwater height.

Equation 1 demonstrates that increases in the soil cohesion, slope thickness and phi angle will all reduce the risk of slope failure. An increase in any of these individual factors will result in increased risk of slope failure. Additionally, increasing the ratio of the height of the groundwater to the thickness of the slope reduces the effect that increasing the density has on resisting slope failure.

Equation 2 demonstrates that increasing the thickness or density of the slope material will increase the driving shear stress and increase the risk of slope failure.

Equation 3 demonstrates that an increase in the height of height of the groundwater will increase the pore pressure, effectively reducing the normal shear stress on the bed and increasing the change of slope failure.

Equation 4 demonstrates that an increase in the density, or slope thickness will increase the slope stability. An increase in the ratio of the height of the groundwater to the thickness of the slab will result in a decrease in the slope stability related to an increase in the pore pressure (Eq. 3).