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

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Abstract (153 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. We assessed the geologic hazards as they relate to human infrastructure and safety. We examined how runoff, hydrogeology and surficial geology affect slope stability along the north slope of 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. Moving forward, we suggest that management focus on long term de-urbanization along the north side of Riverside Avenue and natural ecosystem restoration along the slope.

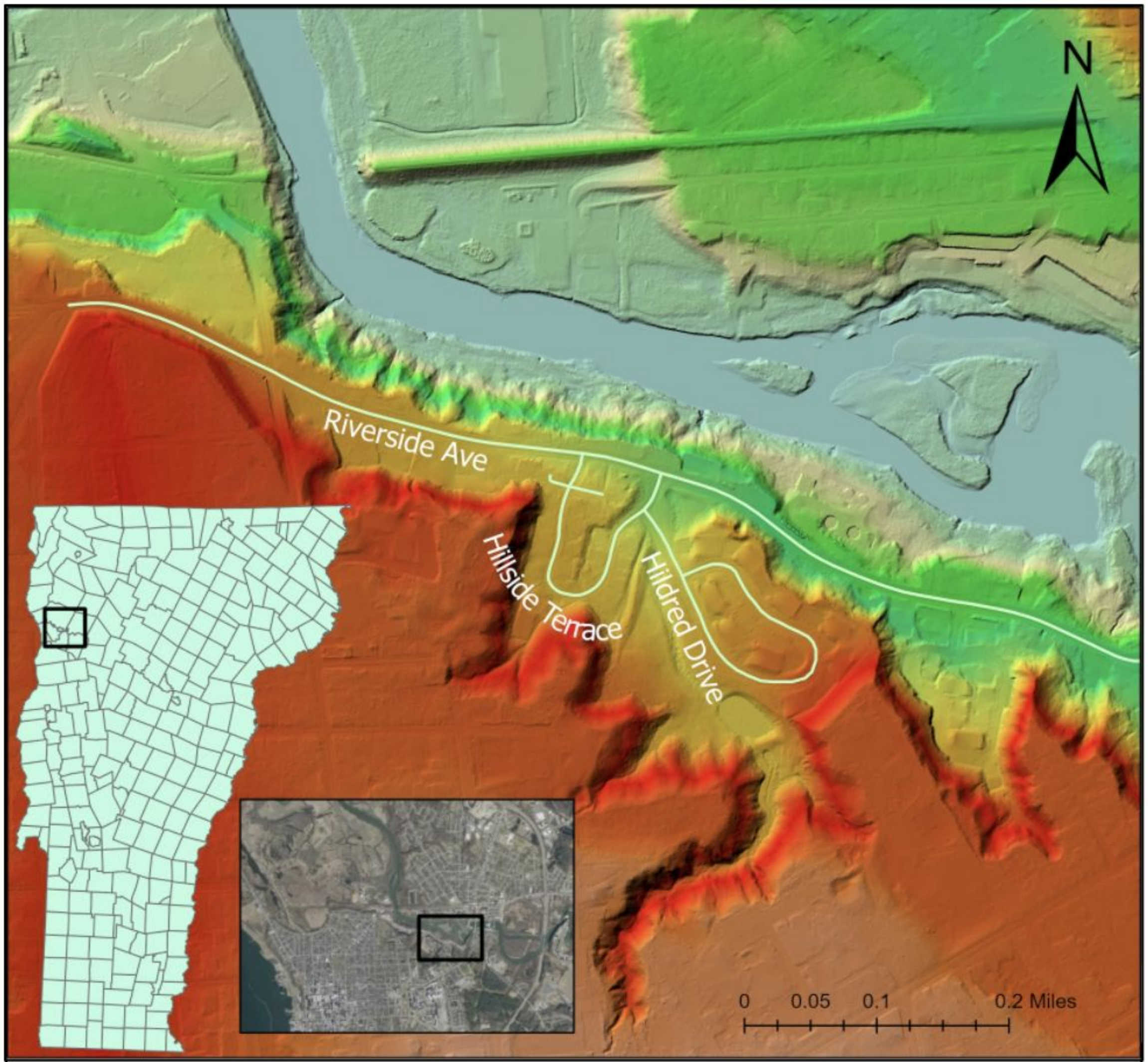

Figure 1: Shaded relief map of the study area. Inset of location within Burlington and Vermont. Higher elevations are depicted in reds and lower elevations in blues. Amphitheatre shaped landslides are visible along the slope of Riverside Ave. Data sourced from VCGI and VTrans.

Background (1158 words)

Introduction

Landslides are triggered when a stability threshold is surpassed (Barg & Blazewicz, 2003); this can be the result of natural causes or human landscape alterations. Construction, slope alterations, and hydrologic changes all contribute to slope destabilization (Barg & Blazewicz, 2003). We will use Riverside Avenue in Burlington, VT as a case study to understand the underlying causes of landslides (Fig. 1).

Glacial history

Glacial processes have been shaping our study area for thousands of years. During the Last Glacial Maximum, Vermont was entirely covered by the Laurentide Ice Sheet. The ice sheet retreat first created Glacial Lake Vermont and later the smaller Champlain Sea within the St. Lawrence and Champlain Valleys (Cronin et al., 2008). The sediments deposited from this deglaciation process make up much of the natural surficial geology along Riverside Avenue.

Surface water

The United States has experienced an immense amount of urbanization within the last century. Between 1982 and 1997 alone, the estimated area of developed land increased by 32% (Alig, Kline, & Lichtenstien, 2004). This increase in urbanization inevitably impacts drainage in watersheds, as water is less able to infiltrate into the ground through artificial surfaces like pavement. Therefore, impervious surfaces intensify runoff volume and speed.

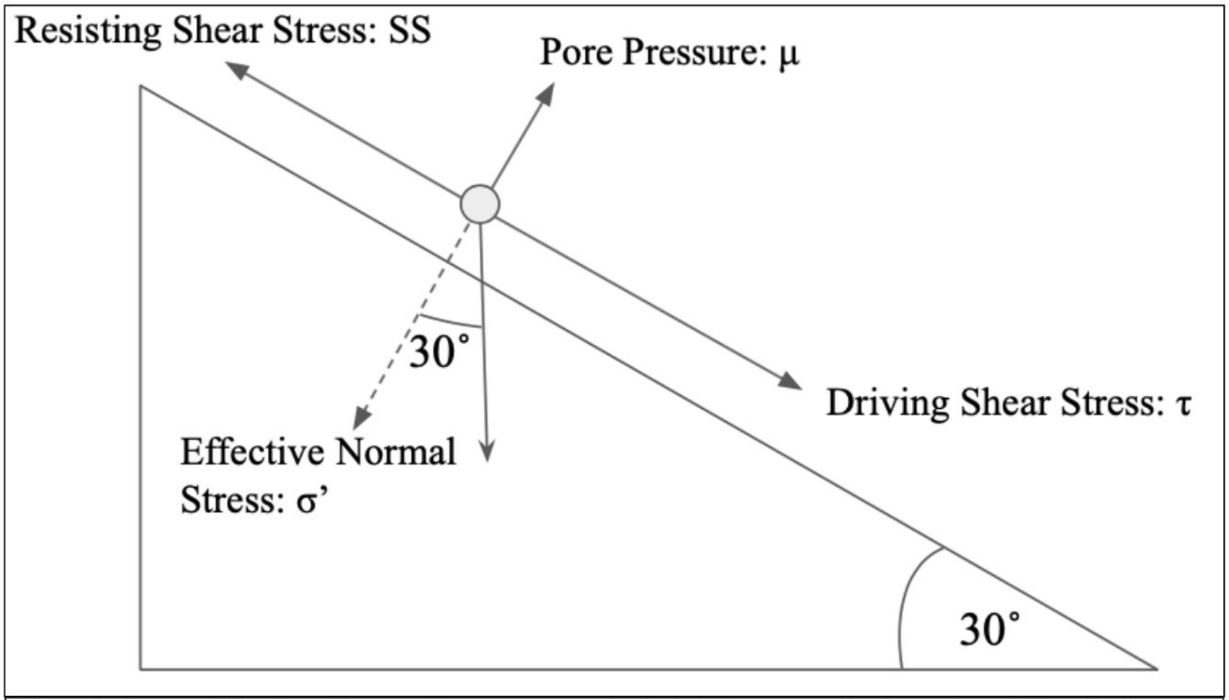

Figure 2. Slope stability force diagram. Vectors represent 4 principle forces contributing to the stability of a slope. Unbalanced vectors indicate greater driving shear stress than resisting shear stress and likely slope failure of a slope with failure plane 30˚ above horizontal. See Appendix for further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

Groundwater

Groundwater hydrology plays an essential role in landslides. Water table height (h), is linearly related to pore pressure within soil (See Appendix, Eq. 3). Pore pressure opposes effective normal stress, so increases in water table height destabilize slopes (Fig. 2). Plants evapotranspire water reducing groundwater height; deforestation decreases this effect increasing pore pressure. The density and connectivity of soil pores is also important for groundwater hydrology. Water in well drained soils is unable to accumulate and does not result in rising pore pressure, lowering risk of slope failure (See Appendix). Additionally, an increase in the groundwater height will reduce the effect soil density has on resisting slope failure, by disrupting grain connectivity (See Appendix, Eq. 4).

Landslide controls and causes

River channel morphology and human landscape change are two primary controls on the spatial distribution of landslides (Fig. 1). Human induced landscape change results in more runoff, and also results in decreased cohesion, changing slope stability force balance (Fig. 2). Any event that causes the driving shear stress to exceed the resisting shear stress will result in slope failure (Fig. 2).

Slope material influences slope stability. Cohesion is a measurement of a material's ability to stick to itself. Sand and gravel fill have inherently low cohesion which reduces the slope's resisting shear stress and indicates higher probability of slope failure (See Appendix). Effective cohesion increases with increasing depth, number and tensile strength of roots (Hales et al., 2009). Vegetation increases effective soil cohesion (Hales et al., 2009). Deforestation throughout the 20th century reduced root concentration on the hillslope, further reducing soil cohesion, contributing to slope instability (See Appendix). New growth trees do not provide the same apparent cohesion that may have dominated the hillslope prior to deforestation.

Figure 3: **A)** Historic photograph of road widening with wooden shorings and fill from early 1930 on the north side of Riverside Avenue. **B)** December, 1955 Riverside Avenue landslide. Sourced from the UVM Landscape Change Program website. Photo credit: A) L.L. McAllister, B) James Detore

Riverside Avenue

Figure 4: Map of impervious surfaces (pavement, buildings, etc.) on Riverside Avenue contributing to high volumes of runoff within the study area. Approximately 27% of the area that drains in the direction of the study area is impervious. Sourced from ESRI World Imagery basemap and VCGI road data.

We investigated causes of landslides along the north slope of Riverside Avenue in Burlington, Vermont (Fig. 1). As a main road running parallel to the Winooski River, Riverside Avenue is important for businesses, homes, and transportation. We aim to understand how hydrogeology, runoff, surficial geology and landscape change control landslides here.

Unconsolidated glacial till deposited during the glacial retreat and subsequent hydrological processes covered the underlying bedrock and previous river channels. These sandy deposits have increased landslide potential because they have low cohesion. The Winooski River incised new channels into these sediments, creating the flat step-like terraces with intermittent steep slopes visible on and above Riverside Avenue (Wright, 2009). Slope angle and landslide potential by extension, is therefore related to deglaciation.

Anthropogenic landscape changes are the primary cause of landsliding along Riverside Avenue by altering the force balance of the slope (Fig. 2). Significant road work began in 1930: filling and widening the road by over 1.5 meters (Fig. 3A, *Street Department, 1931*). Historical photos reveal houses, businesses, and parking lots were constructed on both sides of the road between 1930 and 1955 (Fig. 3A,B). Eventually, the surficial geology alongside Riverside Avenue became primarily sandy fill deposited by humans. The first documented landslide occurred in 1955 (Fig. 3B). The slope instability was exacerbated in the 1970s and 1980s when trash was illegally dumped down the slope on the northern side of Riverside Avenue triggering landslides (Melvin, 1983). Trash and construction waste (Reilly, 1981) on the slope increase slope angle and soil-slab thickness which intensify driving shear stress (See Appendix).

Hydrology

The site's drainage basin topography is depicted in Figure 1. Approximately 27% of Riverside Avenue and surrounding neighborhoods within this drainage basin consists 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 triggered the most recent landslide. The Winooski River hydrograph looks "flashy," showing a sharp increase in discharge over a relatively short time period (Fig. 5), especially for a large drainage basin over 2700 km² (Fig. 5). Hydrographs with rapid spikes like this correspond with basins that are less permeable, as infiltration allows for a more gradual peak.

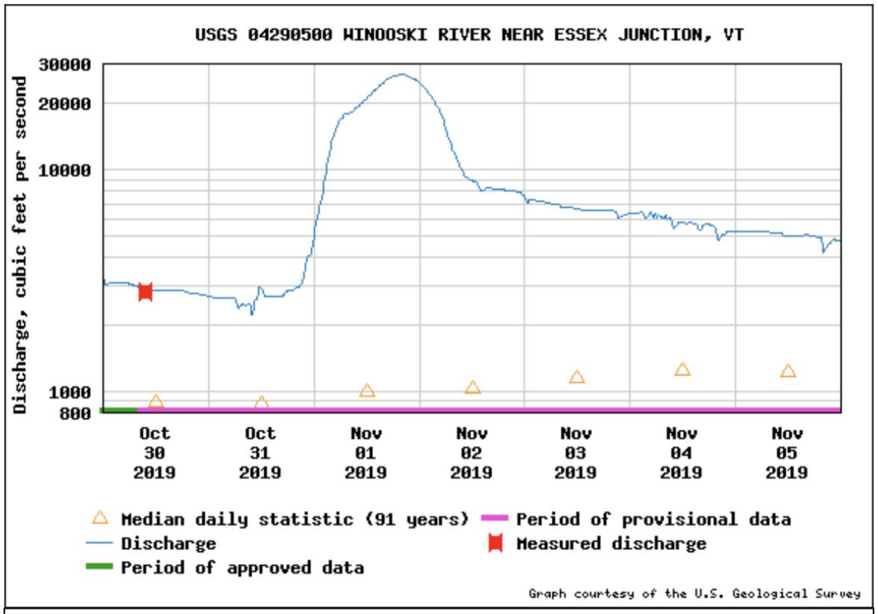

Figure 5: Winooski River hydrograph of the November 2019 storm with peak flow of 23,300 cfs (659.78 m³/s) at Essex Junction, VT.

Most landslide events are associated with large storms as a catalyst (*Driving Rain Causes Landslide*, 1959; *Washout Rips Riverside Ave.*, 1955). Most recently, the October 31st, 2019 storm (Fig. 5, Fig. 6) saturated the soil past a threshold triggering a landslide. This storm event was of high intensity and duration and produced ten centimeters of precipitation from the afternoon of October 31st to the morning of November 1st (Fig. 6). While this was a large storm in Vermont, we calculated a flow recurrence interval of only 3.44 years at the Essex Junction stream gage. Therefore, there is a 29% chance that an event of this size will occur in any given year.

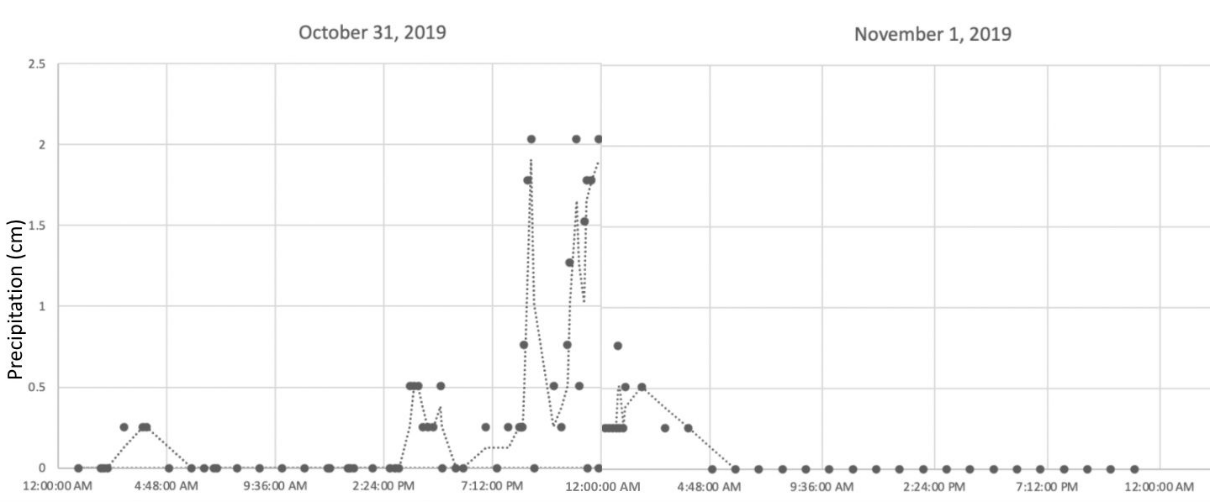

Figure 6: Precipitation measurements including a moving average of precipitation at the Burlington International Airport weather station on the night of the Riverside Avenue landslide in 2019. Data sourced from Weather Underground, VT Weather History.

Management

Corrective measures should preserve the Winooski stream channel morphology and reduce the hazard to human health and infrastructure. Engineering solutions on the landscape were 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 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.

Conclusion

Riverside Avenue has undergone land use change in the last century resulting in decadal scale slope failure. Landslide scars are visible on digital elevation models (DEMs), and newspaper articles record the timing of these events. Historical photos show that much of the surficial geology is formed by sandy fill dumped on the slope to widen the road. Aerial imaging and remotely sensed data show increased urbanization over time, increasing runoff volume and speed onto the slope. Deforestation on the hillslope abutting the road reduced effective cohesion where it was already weak from fill dumping. Illegal dumping onto the slope increased the downslope driving shear stress. Large precipitation events have the potential to weaken the slope by increasing pore pressure. Slope stability estimates show that the slope is close to a threshold condition, so small changes in the groundwater hydrology and surface runoff can result in slope failure. Unstable slopes on Riverside Avenue will result in slope failure more frequently, risking human life and property in the process. Given the potential catastrophic consequences of future landslides, the City of Burlington should prioritize swift and thoughtful action.

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Appendix:

Force Diagram Equations

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

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

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

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

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, soil-slab 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 soil-slab 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).