A century of urban landslides: the legacy and consequences of altering riverbank landscapes

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ABSTRACT

Urban landslides are a deadly and costly hazard. Human actions, such as altering the grade, composition, and vegetation-cover of hillslopes, can increase the threat of mass movements. Here, we use an interdisciplinary approach to examine the spatial distribution, timing, and cause of landslides affecting a state highway and adjacent buildings along the top of a steep, urban riverbank in the mid-latitude, humid-temperate state of Vermont. Using over 100 years of mapping, photographs, and written records, we demonstrate that most mass movements in our field area occurred on slopes over-steepened by the addition of uncompacted artificial fill – added without engineering considerations. Emplaced atop glacial and post-glacial sediment with low hydraulic conductivity, the fill, having little to no cohesion, expanded buildable areas, but the new infrastructure sat on unstable ground. Over the following decades, repeated failures, (n=20), mostly shallow translational landslides in fill material along with several deeper-seated rotational slides, sent buildings, trees, and segments of road into the river below. Solutions include incentivizing the removal of structures built on fill and limiting further filling activities through changes in zoning regulations and more effective enforcement of existing municipal codes. The approach we use provides a framework for similar geographic settings and can inform urban planning and risk assessment.

Supplementary material including a list of references for all historic photographs and maps used in this study is available at.

Landslides are a globally pervasive geologic hazard, occurring in all geologic settings and climate zones (Highland and Bobrowsky 2008; Clague and Stead 2012). Among natural hazards, Wallemacq *et al.* attribute at least 17% of global fatalities to landslides (2018). Between 1998 and 2017, landslides caused 18,000 deaths worldwide (WHO 2021; Wallemacq *et al.* 2018). Estimating landslide losses is difficult due to temporal and regional variability, as well as inconsistencies in reporting. In 1980, Fleming and Taylor (1980) estimated that landslides in the United States cause more than 25 fatalities and more than a billion dollars in direct costs annually. Adjusted for inflation, this is about 3.65 billion dollars in annual losses today (2023) (CoinNews, 2023). More recent studies suggest similar annual fatalities (25-50) and direct financial losses (1-3 billion) in the United States (Schuster and Fleming, 1986; Regmi *et al.* 2014; Mirus *et al*. 2020). One particularly deadly example, the 2014 Oso landslide in Washington, USA, caused 43 fatalities and more than 170 million dollars in damages (Kargar *et al.* 2021).

Beyond the direct cost of damages, the indirect costs of landslides at the regional, community, and familial levels can be severe, long lasting, and difficult to estimate (Fleming and Taylor 1980; MacLeod *et al.* 2005; Mirus *et al.* 2020). Globally, landslides pose the greatest direct threat to human life and infrastructure when they occur in areas with high population and infrastructure density (Lacasse *et al.* 2009). Land-use changes associated with urbanization, including forest clearing, slope steepening, the addition of uncompacted fill material, and expanding infrastructure and impermeable surfaces, all increase the likelihood of landslide occurrence (Highland and Bobrowsky 2008).

Landslides are caused by a combination of factors, including topography, stratigraphy, hydrology, land-use, and heavy or extended precipitation events (Regmi *et al.* 2014). In regions shaped by glaciation, glacial sediment type and distribution can contribute significantly to landslide vulnerability (Van Westen *et al.* 2003). Glacial outwash deposits, especially those dominated by sand, lack cohesion, and thus, without root reinforcement, hold slopes no higher than the angle of repose (Perkins *et al.* 2017). Along river valleys, incisional processes compound the already unstable nature of these materials. Fluvial incision results in slope oversteepening and destabilization along cut banks on the outer edge of meanders (Lévy *et al.* 2012).

Human actions play a significant role in determining the vulnerability of communities to landslides. As people reshape landscapes for agriculture, urban development, natural resource extraction, and energy and transportation infrastructure, they often destabilize natural systems, causing a cascade of effects. While landslides are naturally occurring geomorphic phenomena in undisturbed environments, the alteration of natural systems can increase land instability, resulting in more frequent and larger landslides (Selby 1993; Montgomery *et al.* 2000; Johnston *et al.* 2021; Bozzolan *et al.* 2023). Deforestation removes root structures that stabilize slopes, and urbanization increases run-off from impermeable surfaces during storm events (Cohen and Schwarz 2017; Johnston *et al.* 2021). For example, the deforestation of much of Vermont's old growth hardwood forests during the American colonial period caused the highest rates of hillslope erosion in the regional, post-glacial sedimentary record (Bierman *et al.* 1997).

In urban settings, poor slope management can intensify the erosional response to deforestation. Uncompacted fill is common, often emplaced informally and without engineering design in urban areas (Watts and Charles 2015). Riverbanks have long been an available and culturally acceptable location to place soil removed during excavation as well as construction and woody debris (Nanton and Merriman-Shapiro n.d.). The geologic material disposed of on riverbanks is typically coarse-grained and has little if any cohesive strength. Extreme hydrologic events, such as storms and rapid snowmelt, can raise pore pressure and saturate the shallow subsurface, increasing the potential for slope failure.

Here, we present an interdisciplinary case study of urban landslide hazards exacerbated by human activities over the past 100 years. Specifically, we examined the impact on slope stability caused by the repeated addition of fill materials (including soil excavated for foundations, construction waste, wood waste, demolition waste, and automobiles) to the top of an incised slope. Using maps, historical photographs, and newspaper reports, we reconstructed the spatial and temporal pattern of filling and subsequent slope-instability history of a 1.4 kilometer-long riverbank that is up to 30 meters tall (Figure 1). This waste, emplaced informally and without engineering controls or compaction, failed at least 20 times in landslides of different sizes starting in 1952 (Table 1). These historical data allow us to identify patterns and zones of potential future hazards. This study contributes to the growing body of work that uses open access visual data to assess slope stability (Nefros *et al.* 2023; Mirus *et al.* 2020; Fiorucci *et al.* 2010; Bierman *et al*, 2005). Our approach provides a template for risk reduction in similar studies here and elsewhere.

BACKGROUND AND FIELD SITE

Our field area is located in northern Vermont (USA) along the lower reaches of the Winooski River, a major east-west flowing drainage (~2700 km^2, mean flow 67 m^3 s^{-1}). The climate is strongly seasonal and characterized as Koppen classification *Dfb* (Humid Continental, Cool Summer) with dry, cold winters and wet, warm summers. Over the past century, the climate in northern Vermont has warmed and moistened. Mean annual precipitation (30 year normal, 92 cm) has increased about 15% over the nearly 100-year-long record and mean annual temperature (now 7.2 C) has risen about 2.9 degrees C since 1923 ("Statewide Time Series" 2023). The Vermont 30-year normals indicate a June peak in precipitation with a secondary peak in September and October, while February is the driest month.

Starting about 24,000 years ago, the retreating Laurentide Ice Sheet deposited glacial till and glacial lake sediments throughout northeastern North America. The ice sheet left northern Vermont about 14,000 years ago (Halsted *et al.* 2023). After the ice retreated, rivers cut terraces and deposited sand and silt in deltas. Radiocarbon dating suggests that within several thousand years, forests began to recolonize the region (Jennings *et al.* 2003). In the time since, vegetation has played an important role in stabilizing the rolling hills and incised valley landscapes of New England by providing apparent cohesion to otherwise cohesionless, uncompacted deposits of sand and gravel (Bierman *et al*. 2005; Bierman *et al.* 1997; Clarke 2018). The slopes that we study here are now mostly forested with hardwood species, the roots of which provide at most 10 kPa of effective cohesion (Cronkite-Ratcliff *et al.* 2022; Chok *et al.* 2015). Today's trees have regrown after several cycles of cutting and deforestation.

Once the land of the Abenaki Native Americans, European settlers began to colonize Vermont in the 1700s, clearing land for timber, agriculture, and construction. The settlers constructed what are now the cities of Burlington and Winooski on two prominent bodies of water, Lake Champlain and the Winooski River. Today, these cities are connected by a heavily trafficked two-lane road: Riverside Avenue. True to its name, Riverside Avenue runs parallel to the Winooski River, separated by a 20 to 30-meter-high slope. From the road, the slope drops steeply to the riverbank below. The river floodplain at the base of the slope is narrow, at most 10 meters wide, and several meters above water level during average discharges. During floods, slack water reaches the toe of the riverbank slope.

Development along the river terrace between Riverside Avenue and the Winooski River began prior to 1872, at which time there were 12 small structures along the eastern section of the road, 10 of which were constructed in the area now occupied by a Burlington City wastewater treatment facility (Pierce, 1872). Riverside Avenue remained sparsely developed until 1930, when the highway department began widening the road (Figure 2) ("Contract Awarded" 1930). By 1962, people had cleared much of the forest along the eastern section of the slope, and built at least 24 structures within the narrow strip of level land that runs along the top of the slope (VCGI, 1962). At present, most of this land is privately owned by a variety of people and businesses. There are seven commercial buildings and four residences spread across a total of 19 parcels, one of which is a city-owned water treatment plant. In total, parking makes up 9070m^2, 6070 m^2 of which is paved; the remainder is dirt. The lower slope and the floodplain are easements ceded for a public walking trail.

The steep riverbank is underlain by glacial and fluvial sediment and covered with a slope-parallel layer of colluvium, much of which is artificial fill emplaced periodically after 1931 (Figure 3). Between 1931 and 2023, both the city and private landowners used fill to extend the developable land north of the roadway as much as 30 m in some places (Figure 4). Below this fill, the uppermost native materials are bedded fluvial sand, deposited in a delta complex built into glacial lakes impounded in the Champlain Valley by the retreating Laurentide Ice Sheet to the north and into the Champlain Sea, a brackish water body created when ocean water flooded the isostatically depressed basin after deglaciation. These fine-grain marine and freshwater sediments result from deeper water deposition (Wright, n.d.). Exposures of these materials are rare. Three soil boring logs from 2021 suggest that the artificial fill is on average 2.5 m thick and underlain by more than 13 m of soft, silty fine-grained sediment, below which is dense, unstratified sand and gravel, which we interpret, on the basis of these drill holes, to be glacial till (Figure 3) (Sanborn, Head & Associates, Inc. 2021).

METHODS

To understand the history of human modification and resulting hillslope instability, we used an interdisciplinary research approach. We compiled historical maps, archival photographs, zoning documents, and newspaper records to establish past changes to the landscape caused by people and landslides, and used Geographical Information Systems (GIS) and field observations to examine and interpret the physical and spatial features of the slope.

Historic Records and Imagery

We used local newspaper archives to constrain relevant events temporally and spatially, including documented landfilling projects, landslides, and slope stabilization efforts along Riverside Avenue after landslides. Our search variables included a key term, location, year, and newspaper. We constrained our search to Burlington, Vermont, and applied search terms including “landslide,” “failure,” “damage,” “slide,” “mudslide,” “washout,” and “repair,” with and without “Riverside Ave”. We constrained searches further by year and/or date where applicable, but kept searches intentionally broad to maximize results.

For additional context, we used historic photographs, maps, and aerial images. The University of Vermont’s Howe Library Special Collections and Landscape Change Program database provided historical photographs of our field area (Landscape Change Program, 2011). We used these photographs to evaluate landscape and land-use change, and where possible, to locate and corroborate events described in newspapers (Bierman *et al*. 2005). We used historic maps and imagery to evaluate change over time, through map overlays and visual comparison (Supplementary Data). We also used a series of black and white and/or infrared aerial photographs, black and white ortho-photos, color ortho-photos, satellite imagery, and a bare-earth digital elevation model (Supplementary Data). We present these images using a publicly accessible, geolocated digital repository accessible at https://go.uvm.edu/4gvil (Owens, 2019).

City records provided slope stability assessments from both 1984 and 2020 (Knight Consulting Engineers, Inc. 1984; Hoyle, Tanner & Associates, Inc. 2020) and zoning records provided a 2021 engineering report including subsurface data from three boreholes (Sanborn, Head & Associates Inc. 2021). The 1984 slope stability assessment provides recent landslide scarp locations and scaled dimensions, from which we infer slide area and corroborate slide locations suggested by other records. The 2020 slope stability report identifies areas of slope activity and suggests monitoring strategies. The boring report provides material descriptions, depth, and thickness of each unit, which we used to construct a schematic cross section (Figure 3) (Sanborn, Head & Associates, Inc. 2021).

<u>Spatial Analysis</u>

We identified landslide scarps both above and below Riverside Avenue using 2014 Light Detection and Ranging (LiDAR) imagery of the study area (VCGI, 2017). We then used spatial references included in newspaper clippings and landmarks in historic photographs of landslides to match the scarps visible on the LiDAR imagery to the reported event dates where possible, creating a map of landslides and assigning ages of last activity (Figure 5, Table 1).

Slope assessment

To assess the slope stability and identify landslide scarps, we have conducted intermittent visual observations along the public sections of the slope beginning in early 2019. Using both the sidewalk at the top of the slope and a public walking path at the base of the slope, we visually observed, recorded, and photographed the slope, documenting changes including the addition of fill and slope instability. We used re-photography to identify changes to the slope and/or infrastructure between photographs of the same location through time (Figure 4).

RESULTS

Using a combination of archival sources, interviews, and well-documented, geolocated historic photographs, we found definitive evidence of 20 landslides along the 1.4 km length of Riverside Avenue that we studied. The first slide occurred in 1952; the most recent in 2019, with an average recurrence interval of 3.4 years (range <1 – 11 years) (Table 1). We found that slides occurred in all months except January. The months with the highest slide occurrence (2-4) were August through October (Figure 6). Landslide area ranged from a few square meters to thousands of square meters. Volumes are more difficult to estimate (because the depth of failures are rarely reported and difficult to estimate retroactively) although some were reported in newspaper articles, including that of the 1976 slide, which was reported to displace "4,000 yards" of material ("Mudslide Cleanup" 1977). Field observations and newspaper reports, considered along with historic ground and aerial photography, consistently suggest that most if not all of the material that slid was placed as fill informally, without permits or engineered designs.

Archival photographs and maps show unambiguously that forest covered much of the undeveloped riverbank as recently as the late 1920s. Then, in 1931, engineers removed the streetcar tracks from Riverside Avenue and widened the road by two meters using fill, before being paved for the first time (Figures 2 and 4) ("Street Department" 1931). The extent of the fill increased between 1931 and 2023, though inconsistently across the slope surface and often illegally and without written record. Where historic photos exist, we can estimate the extent of this filling. Toward the western end of the field area for instance, the present-day slope bank extends more than 15 m beyond the modern sidewalk and supports a building where steeply sloping forest existed less than 100 years ago (Figure 4).

The largest landslide to date on Riverside Avenue occurred in 1955. This slide was preceded by several smaller slides (Figures 4 and 7; Table 1). The 1955 slide destroyed more than 90 meters of roadway and displaced at least two structures four meters below their initial position (Figure 7C, D). Newspaper records indicate that the first slide at this location occurred in August 1955, causing road damage that was subsequently patched. A week later, the slope failed again, this time undermining the road and creating a six by five-meter hole in the road ("Burlington Youths" 1955). In late September, a bypass road was constructed ("Emergency Road" 1955) and the repair work was contracted by early November for $37,500 (over $400,000 in 2023 dollars) ("St. Johnsbury Men" 1955). Weeks later, on November 18th, the largest slide occurred, displacing thousands of tons of material (“Washout Rips Riverside” 1955). After this slide, the city closed Riverside Avenue and constructed a new asphalt road to bypass the area while the landslide damage was repaired (Knight Consulting Engineers Inc. 1984) (Figure 7A, B).

This series of landslides occurred despite preemptive management work two years earlier, in 1953. That year, the Burlington Public Works Department installed 72 meters of underdrains below the road in an attempt to address “treacherously wet subsoils, among buried utility lines and plugged ancient underdrains,” with the intention of “eliminat[ing] conditions which caused a slide to take away sizable portions of the pavement there last spring” (“Mild Winter” 1953).

Almost 30 years and 11 landslides later (1981), illegal dumping of recently excavated landfill material onto the slope edge triggered a landslide 13 meters across that partially blocked the Winooski River below (Reilly, 1981; “Debris Slides” 1981; “Dismissal requested” 1981). This slide occurred on private land after the owner requested the fill placement. The reported volume of the slide was “several thousand cubic yards” and local authorities reported concerns for river pollution resulting from the contents of the dumped material (“Dismissal requested” 1981).

The most recent fill was placed in 2018 and 2019 without permitting or engineering controls (Figure 8D). Property owners added truckloads of sand, gravel, wood chips, and demolition waste directly to the top of the terrace at multiple proximal locations. These materials settled at the angle of repose over the cut face of the riverbank (Figure 8B). Within a year of emplacement, this material failed in three locations in shallow translational landslides, one of which ran out nearly to the river’s edge (Figure 9; Table 1 #18, 19, 20). Several months before the 2019 landslides, *en echelon* ground cracks, several cm wide and meters long, opened parallel to the face of the slope (Figure 8A). The cracks grew wider over time and some slide blocks near the face of the slope were displaced downward 10-20 cm (Figure 8E).

The 2019 landslide occurred during the night of October 31 and/or the early morning of November 1 (Figure 9). It was coincident with a record-breaking late October storm, which developed in an exceptionally warm and moist late fall air mass. The storm delivered about 8 cm (3.3 inches) of rain to the Burlington, Vermont area within a 10-hour period. Several bands of precipitation delivered rain at rates of 1.25 to 2.5 cm per hour (0.50 to 1.0 inch per hour). The heavy rain triggered urban flash flooding and swift rises in the stage of area rivers. Given the quantity of water delivered in this storm, we infer that a rapid and substantial increase in sediment pore pressure contributed to the slope failure. Using aerial imagery of the slide, we determined that the failed volume was between 3600-5000 m^3.

The coincidence of intense precipitation and slope failure is one of several patterns in the recorded history of Riverside Avenue. Four of the 11 landslides with identified causes in the newspaper record were attributed to large rain events (Table 1). An additional two mass movements were attributed to underground seepage and/or inadequate drainage, while the remainder were attributed to dumping, development, and/or deforestation. Landslides were most common in August, September, and October, and least common in the winter months (Figure 6). There were no landslides in January, and only one each in December and February (Table 1; Figure 6). We know that three of the seven fall slides were caused by significant rainstorms, another was attributed to recent deforestation, and the September 6, 1955 slide occurred in the same location as a slide the week before, suggesting ongoing slope instability following a late August storm (Table 1). By comparison, there were only three recorded landslides during the spring months, one of which was attributed to subsurface water seepage (1958), and another to dumping of fill (1968) (Table 1).

Many of the articles about these landslides mention the contents of the fill material, which includes sand, gravel, landfill material, tires, junked vehicles, and appliances. Newspaper articles about both the 1968 and 1976 landslides mention junked cars becoming dislodged from the slope, falling into the river, and their subsequent removal from the river ("Landslide Repair" 1976; "Firm Foundation" 1968). Following the 1981 landslide, concerns about river pollution arose due to the "several thousand cubic yards" of material that entered the river and included multiple truckloads of excavated landfill material that were responsible for destabilizing the slope ("Dismissal Requested" 1981).

In other instances, the addition of fill has increased slope stability. Following the 1958 landslide, an estimated 5,000 cubic yards of gravel-to-boulder-sized crushed stone fill was placed at the base of the slope (Table 1) ("Crews Begin" 1958). Ten years later, following the 1968 landslide, the Burlington Free Press reported the emplacement of "tons of crushed stone" to stabilize the base of the slope close to 411 Riverside Ave ("Firm Foundation" 1968). We have not found evidence of a landslide upslope of this intervention. Today, those boulders are still in place at the base of the slope, meanwhile remnants of junked vehicles and appliances visibly protrude from the slope elsewhere and on either side. A local resident reported that the 1955 slide was filled using hundreds of junk cars.

In 2020, the Department of Public Works (DPW) released a slope stability report that identified six addresses along Riverside Avenue in need of urgent repair and/or further assessment (Figure 5; Table 2) (Hoyle, Tanner & Associates Inc. 2020). Among these, we found that two were the sites of one previous landslide each (471 and 389 Riverside Avenue), one was the site of two previous slides (411 Riverside Avenue), and one is likely atop the slope reconstructed following the November 1955 landslide (356 Riverside Avenue).

Of the six parcels listed, five are commercial lots with active businesses, and one is an active residential rental. The report deemed two parcels in urgent need of repair and in close proximity to buildings (505 and 389 Riverside Avenue). It also provided annual assessment plans for the remaining four, all of which included geotechnical borings to evaluate fill thickness, soil types and densities, and groundwater levels as well as the installation of inclinometers to monitor slope movement, and repeated inspection for surficial erosion, cracking, and debris dumping (Table 2). This report recommended annual inspections for these sites beginning in September 2021. As of October 2023, there is no formal follow up report. However, in 2024 the DPW plans to fix a stormwater outfall at 505 Riverside Avenue and buy out the house at 389 Riverside Avenue to convert the property to green space (Table 2).

DISCUSSION

Human activities, principally the addition of uncompacted fill to steep riverbank slopes, catalyzed almost 70 years of landsliding along a high riverbank in temperate, humid northeastern North America. Unplanned and uncoordinated alteration of this slope has made the area vulnerable to slope failure. The combined effect of fill loading the slope, heavy rainfall events which increase pore pressure, and alteration of natural drainage patterns, has resulted in 20 landslides along 1.4 km of busy urban roadway. At least seven of these slides have damaged the road, while others have impacted buildings and/or the river below (Table 1). At present, six properties along Riverside Avenue have active slope characteristics (Table 2) (Hoyle, Tanner &

Associates, Inc, 2020). The record of human modification of this landscape and the multiple and on-going landslides that modification triggered, support our hypothesis that the material disposed as non-engineered fill to expand buildable areas is a major cause of the ongoing instability along this slope (Selby, 1993; Bierman *et al.* 2005).

The series of slides in 1955 are the largest we have identified on Riverside Avenue and were almost certainly caused by the placement of artificial fill. In the area that failed, the 1872 topographic map clearly shows a stream valley blocked by the embankment carrying Riverside Avenue. The map shows the embankment was at least 40 ft high and culverted (because the stream daylights directly below the road). The 1906 and 1948 maps show the stream but not the embankment, likely a simplification because the 1937 and 1942 air photos show the embankment and a forested riparian zone both up and downstream (Supplemental Data). A city landfill operated in this small drainage basin between 1950 and 1961. A local resident reported that the stream was culverted and fill was placed over it as part of the landfilling operation. It was this fill and the embankment that failed in 1955. We suspect that the embankment, being an aquitard, retained groundwater in the valley fill, raising pore pressure and triggering the failure of both fill and native materials upstream. Photographs show that the 1955 slides removed the embankment, re-establishing the original grade of the stream that existed prior to the construction of Riverside Avenue (Pierce 1872; Supplemental Data).

The data we compiled reveal seasonal influences on landslide occurrence, most likely the effect of precipitation on pore pressure and therefore slope stability. Vermont's climate is summer wet and winter dry. The paucity of winter landslides (December, January, and February) is driven by low precipitation volumes (Figure 6) and the storage of that precipitation in the seasonal snowpack. Although summer precipitation amounts are greater (U.S. Climate Data, 2023), trees in their growing season are transpiring water and evaporation rates are high; which can lower soil water content, minimizing slope destabilizing pore-pressure spikes when heavy rains do occur (Ng *et al.* 2016; Sidle 1992). There are only four ground water wells in Vermont with long, publicly available records and while all show overall lower water tables in the fall and higher water tables in the spring, the highest water tables are driven by precipitation events not by season (USGS 2023). Thus, we conclude that the prevalence of fall landslides is driven by long and especially intense fall rainstorms. In Vermont, such precipitation events are associated with tropical air masses that have large amounts of precipitable water, and tropical storms, including hurricanes.

Newspaper articles, aerial images, and ground photographs provide the foundation of this study. Some written materials include important qualitative details such as the suspected cause of slope failure, a record of recent landscape alterations, and quantitative data including an estimated slide volume and cost of damages and/or reconstruction. Unfortunately, many of these stories mention only one or two of these details (Table 1). Given the nature of historic record keeping and accessibility, the data we present should be regarded as an minimum record of mass movement activity in our field area. When considered along with municipal records, we suspect that the landslide inventory we present here captures most if not all of the substantial mass movements in our field area since about 1930, after which numerous ground and aerial photographs were taken. As such, the composite record serves to provide insight into the relative frequency of landslides, their scale and impacts, and in some cases, the causes and resulting costs that these events have imposed on the city and state responsible for maintaining the slope and the highway located above it.

Throughout the written record of mass movements along Riverside Avenue, newspaper articles report the local government's desire to find a long-term solution to the slope instability, as well as their inability to acquire funding adequate to do so. As a result, the city has patched and repatched the most unstable sections of the road and attempted to stabilize the slope below using engineered and informal methods including the emplacement of rip-rap, and the installation of wooden cribbing and drainage systems. The costs of this work, while sparsely mentioned in these articles, have been significant. For example, in 1983, the mayor sought $350,000 (the equivalent of more than a million dollars in 2023) in state funding to find a long-term solution for the road following the 1981 landslide ("Burlington Board" 1983). Instead, the state allotted limited funding to address only immediate concerns, which were estimated to cost $100,000 ($300,400 in 2023), and the slope remained active (CoinNews 2023).

The recurrence of landslides requiring costly repairs demonstrates the importance of roadway and road-adjacent land management in our field area. Riverside Avenue (Figure 1) is part of the Vermont State Highway system; yet, it is owned by the city in order to facilitate maintenance (Melvin 1983 Sept. 3; Dec. 8; Dec 29). Historic records provide insight into the funding problems caused by this arrangement, as both the city and state repeatedly failed to allocate the funds necessary to finance a long-term solution to the Riverside Avenue slope instability. Meanwhile, property owners, either seeking to extend their properties or to dispose of unwanted material, continue to illegally dump materials down the slope, exacerbating the problem.

In more recent years, several buildings have been condemned after landslides have undermined their foundations. One building was condemned in the late 1990s when much of it was undercut by a landslide; it was demolished soon after. This happened again in 2007, when one of two homes at 389 Riverside Avenue was undermined and deemed unsafe for habitation (Table 1). Now, the state is in the process of purchasing the remaining residential rental on that parcel (389 Riverside Avenue), using funds appropriated by the Federal Emergency Management Agency (FEMA) hazard mitigation assistance grants (Table 2).

The 2020 slope stability report (Hoyle, Tanner & Associates Inc. 2020) revealed the increasingly precarious position of the few remaining structures along this slope, and demonstrated the continuation of a reactive rather than proactive slope management strategy. The report communicated urgent need for repairs and monitoring at six locations; yet, the city has limited ability to apply the suggested monitoring and evaluation strategies due to private property ownership (Table 2).

According to the DPW, landowners are not obligated to allow the city to install the suggested monitoring equipment and/or drill test borings. The potential implications of slope monitoring for landowners include diminished property values and the possibility that their property may be deemed unsafe for use. However, ongoing slope activity may result in reduced property values and/or usability with or without intervention. As such, there is not currently an incentive – beyond safety – for property owners to implement the suggestions provided in the slope stability report. Paired with our finding that four of these parcels identified as high risk are associated with one or more historic landslides (Tables 1 and 2), ongoing slope instability at each demonstrates the lack of adequate slope stabilization following prior slides. Together, these data indicate that without intervention, erosion and landslide activity along this slope will continue to occur at locations affected by past instability as well as others for which there is so far no record of slope failure (Figure 5, Table 1).

Meanwhile, as of 2023, there are two apartment complexes proposed for development along Riverside Ave (GB Architecture & planning, 2021; Gustin, June 2021; July 2021). These apartment buildings, proposed for 237 and 356 Riverside, would supply 65 and 64 units respectively, situating housing for hundreds of people atop or directly across the street from locations of historic landslides (Figure 5) (Gustin, June 2021; July 2021). The project at 356 Riverside Ave was approved by the zoning board in July 2021, and the borehole reports utilized in this study are a product of the slope stability evaluation for this project. The project review for the complex at 237 Riverside Ave was scheduled for August 2021. As of October 2023, there are no further public records related to either project. While it is unclear whether either project will move forward, the location selection and zoning consideration of each project demonstrates the need for a more informed record of the history of instability along this slope.

Rather than increase the number of residents living along Riverside Avenue, we suggest that the persistence of landslide hazards should preclude large-scale residential developments. While there is a valid counterargument for slope stabilizing interventions prior to development, interventions such as slope reinforcement, resloping, and restructuring and/or refurbishing existing buried drainage networks, are costly and environmentally invasive. In the past 80 years, each of these methods has been applied to part of the Riverside Avenue slope at least once. While we found that culverts or improper drainage were cited as probable landslide triggers in at least five slides, the city has also found on multiple occasions that many of these culverts are in good condition when excavated.

Reinforcement and resloping have been applied situationally and following landslide events along Riverside Avenue. Following the 1968 landslide, the city reinforced the base of the slope by adding “tons of crushed stone” as a buttress (“Firm Foundation” 1968). Then in 1983, following the 1981 slide, the city reinforced the active slope area with boulders and rip rap (Knight Consulting Engineers, Inc. 1984). Initially, the property owner hired a contractor to reslope the unstable slope at a two-to-one angle; however, that plan quickly failed when the contractor built a road across the scarp, causing additional slope instability. Boulder size rip-rap has proven successful to date; however, widespread installation would not be a practical, environmentally sound, or cost-effective method for stabilizing the entire 1.4 km slope which is now almost fully forested.

The lowest cost and least invasive hazard-reduction strategy is for the city and/or State to preclude further development along the top of slope, purchase the buildings at highest risk (regardless of their residential or commercial designation), demolish the structures, and transform the slope into a thickly-forested natural area with long-term monitoring in place. Analysis of geologically similar slopes (underlain by non-cohesive materials) shows that vegetation provides critical effective cohesion preventing failure when heavy rainfall or runoff saturates the materials (Dolidon *et al.* 2009; Bierman *et al.* 2005). The removal of buildings and impermeable surfaces that concentrate precipitation runoff, paired with the addition of structural stability and effective cohesion provided by tree roots, constitute a low impact, low-cost solution (Fan & Lai, 2014; Genet *et al.* 2010). The reclaimed and forested land could be converted into a public green space, which could benefit both the community and the city.

Looking forward, regional climate change predictions suggest a 10% increase in mean annual rainfall by 2100, over and above a nearly 15% increase since 1920. Paired with predicted increases in storm event frequency and intensity, future precipitation events will exacerbate slope hazards by raising ground water tables and thus pore pressure in the uncompacted fill. As the climate changes and the intensity and variability of weather events increase in this region, action to increase slope stability beside and below Riverside Avenue is increasingly crucial to ensure the stability of the slope and the safety of people who currently live or work there.

CONCLUSION

We found that the emplacement of uncompacted fill material along Riverside Avenue in Burlington, Vermont has caused at least 20 landslides over the past century. Using newspaper archives, we found that seven of these slides were caused by poor drainage and/or large rainfall events. Throughout the past century, the city has developed the roadway from an unpaved two-lane road surrounded by forest, to a paved two-lane state highway with bike lanes, sidewalks, and homes and businesses on either side. In many areas, this expansion sits on uncompacted artificial fill. While we found evidence of attempts to stabilize segments of the slope after landslides, most of these efforts did not adequately address future risks of slope failure. Without significant intervention, the uncompacted fill supporting this slope will continue to fail, causing landslides that endanger the road and adjacent homes and businesses. To avoid further landslides along this slope, remaining buildings along the top of the slope could be removed and replaced with deep-rooted native vegetation.

Here, we demonstrate that written and/or photographic records of historic land use are a powerful tool in interdisciplinary approaches to understand the legacy effects of land-use change. The consideration of historical documents in slope stability research provides crucial information for mitigating future hazards, such as slope failure causes and recurrence intervals. The landslide chronology we developed provides both evidence of repeated anthropogenic slope destabilization and the knowledge needed to inform future slope management strategies, including the identification of causation and locations of repeated activity. Together, such an approach can reduce the risk of future slope instability.

ACKNOWLEDGEMENTS

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FIGURE CAPTIONS

Figure 1 caption: *This study focuses on a 1.4 km stretch of sloping river terrace in Burlington, Vermont that separates a Vermont State Highway, Riverside Avenue, from the Winooski River below. (a) includes relevant local features and addresses, which are referenced in the text and Table 1. (b) provides a three-dimensional visualization of the slope looking south-southwest and includes the location of the cross section (red A-A') landslides 18 (left) and 19 demarcated by light pink shading, and 5 m contour lines (yellow, labeled in 10 m increments).*

Figure 2 caption: *Installation of wooden cribbing material along the northern bank of Riverside Avenue near 114 Riverside Avenue to widen the road (a, b). (c, d) the subsequent addition of fill material on top of that cribbing. (a) and (c) are looking west, (b) and (d) are looking east. Photo source: McAllister Collection, University of Vermont, Special Collections, 1931.*

Figure 3 caption: *Schematic cross section bisecting the 365 Riverside Avenue parcel. Using data from borehole SH-2 and local stratigraphic descriptions, we developed a schematic cross section of the slope at 365 Riverside Avenue (Sanborn, Head & Associates Inc. 2021; Wright n.d.). We synthesized material descriptions (b) from Sanborn, Head & Associates Inc. (2021).*

Figure 4 caption: *Comparison of a historic photograph and rephotograph (at 505 Riverside Ave) demonstrates development and width of fill emplacement between 1931 and 2023. The image on the left (1931) shows the recently paved road and the fill emplaced on the left side and along the slope. Note the mature trees on the slope. The right image (2023) shows the modern extent of fill and development that has been emplaced on the slope over the preceding 90 years. The red building sits entirely on fill material. Historic photo source: McAllister Collection, University of Vermont, Special Collections, 1931.*

Figure 5 caption: *Map of landslide and active slope locations along Riverside Avenue, Burlington, VT. We compared available location information with the 2014 regional Digital Elevation Model to estimate the location of each landslide (see location certainty in figure legend) and outlined the visible scarp most proximal to each location description. The numbers associated with each location are in chronological order and correspond to the landslides as listed in Table 1. Due to overlapping landslides and reactivation, these scarp outlines are not definitive, with the exception of 5, 18, 19, and 20, which were well documented and georeferenced. Active slope areas from the 2020 Slope Inspection are outlined in red (Hoyle, Tanner & Associates Inc. 2020; VCGI 2017). Two proposed locations for 64+ apartment buildings are highlighted in yellow (Gustin, 2021 June, July).*

Figure 6 caption: *Landslide seasonality by month and associated average precipitation. Landslide occurrences (orange) organized by month (or season where month is unknown, indicated by a double-ended arrow), with associated average monthly precipitation (inches) between 1950-2019 below (National Weather Service 2019). Landslide numbers correspond to those used in Table 1. Landslides 14, 15, and 17 are left blank due to lack of seasonality data.*

Figure 7 caption: *Images of the 1955 landslide. (a) the landslide area looking east along Riverside Avenue, showing the bypass road and the landslide damage to the upper left. (b) Close up of the bypass road looking west. (c, d) images of the landslide scarp and displaced buildings. Photograph source: University of Vermont, Special Collections, James Detore Photograph Collection, images taken for American Fidelity on December 8, 1955.*

Figure 8 caption: *Photographs taken during a six-month period demonstrate the increased activity proximal to 389 Riverside Avenue. (a) Photograph of fill emplaced adjacent to home* *with tensional ground cracks parallel to the free face. The Winooski River is visible between the trees, which are growing on the steep riverbank. (b) Photograph of fill dumped over the bank and at the angle of repose. (c) Photograph of vertically displaced ground cracks to the right of the automobile. (d) An example of modern illegal dumping on this slope at 411 Riverside Avenue. In this photo, dumped material is primarily composed of woodchips and other organic material, and was placed on top of ground cracks at the edge of the slope. (e) Photo taken in the same location as (c) after additional fill was added to the slope surface in August, showing cracks reforming in the fill. Note the same tree in both photographs.*

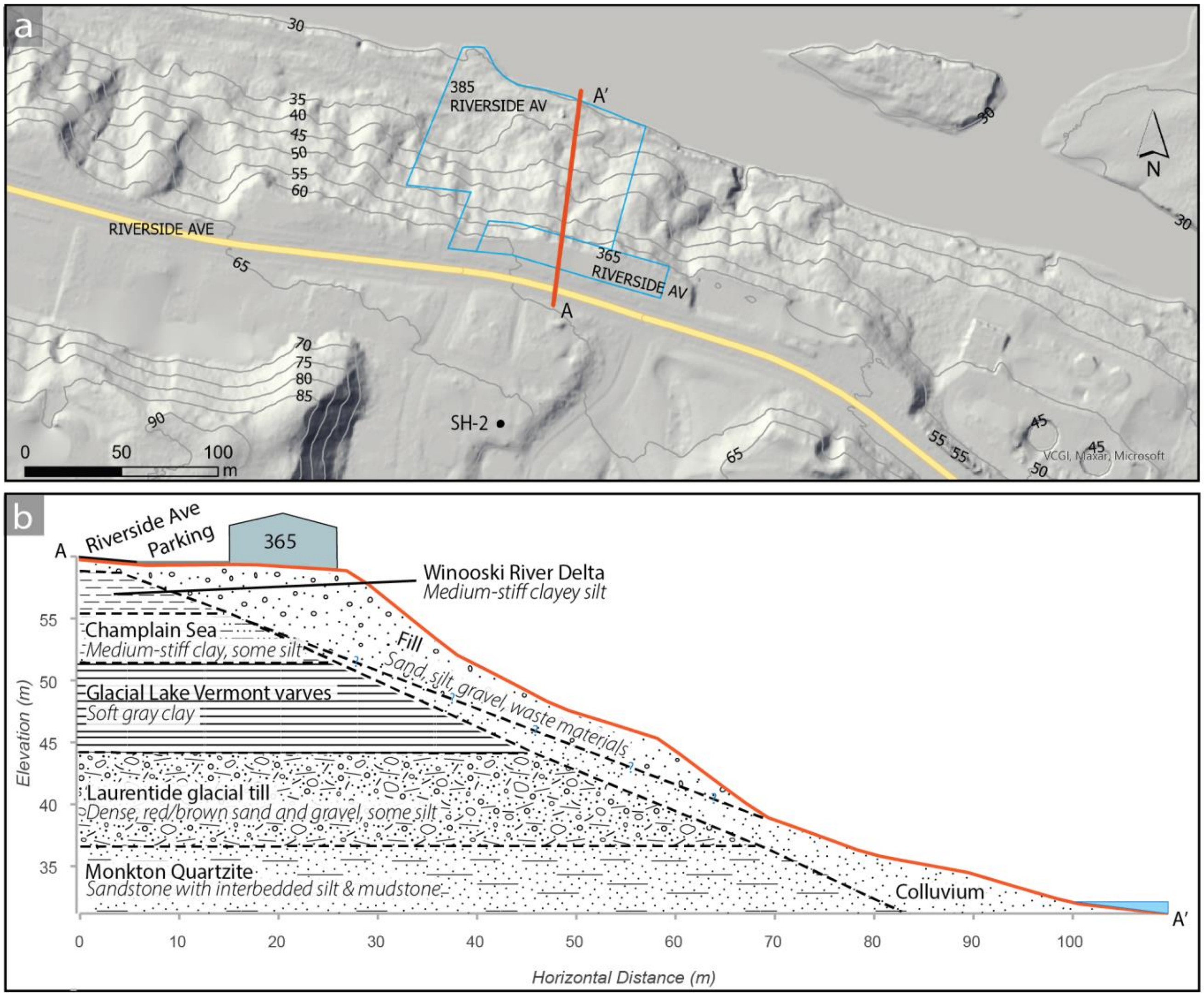
Figure 9 caption: *(a) Aerial imagery of the landslide with members of the UVM Spatial Analysis Laboratory visible above the riverbank (circled in red for scale). Image provided by the UVM Spatial Analysis Laboratory (2019). (b) Photograph of the landslide looking upslope taken from the base of the slide, from the location of the shaded blue circle in image (a).*

FIGURES

Fig. 1.

Fig. 2.

Fig. 3.


a
385
RIVERSIDE AV
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SH-2
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0 50 100
m
b
Riverside Ave Parking
365
Winooski River Delta
Medium-stiff clayey silt
Champlain Sea
Medium-stiff clay, some silt
Fill
Sand, silt, gravel, waste materials
Glacial Lake Vermont varves
Soft gray clay
Laurentide glacial till
Dense, red/brown sand and gravel, some silt
Monkton Quartzite
Sandstone with interbedded silt & mudstone
Colluvium
Elevation (m)
Horizontal Distance (m)

Fig. 4.

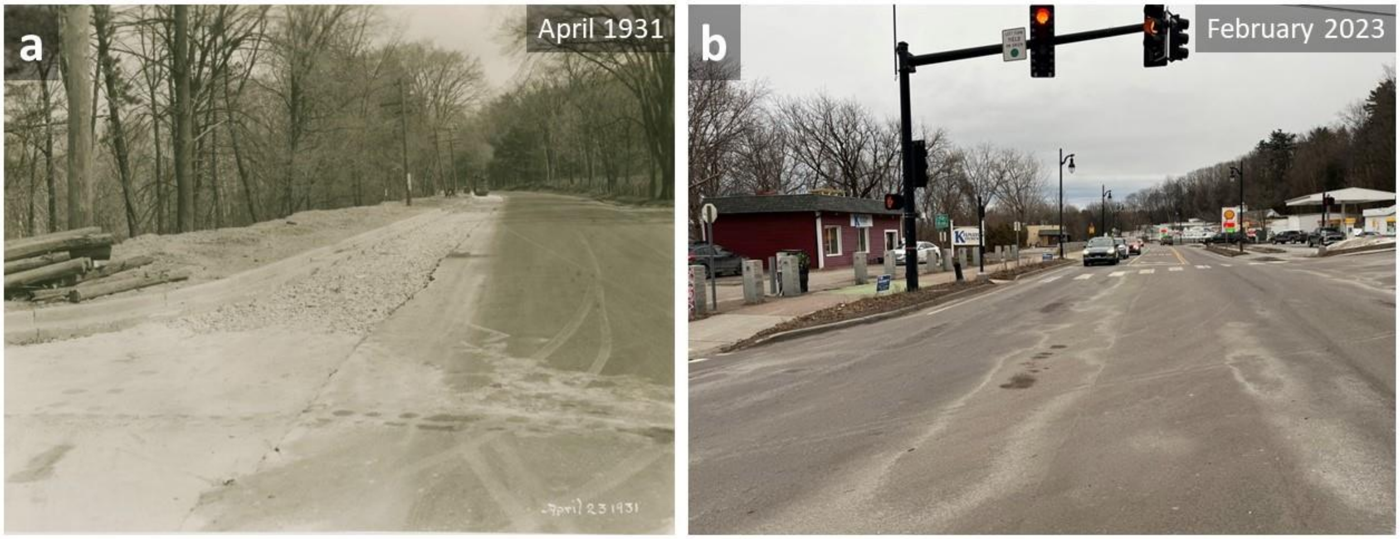
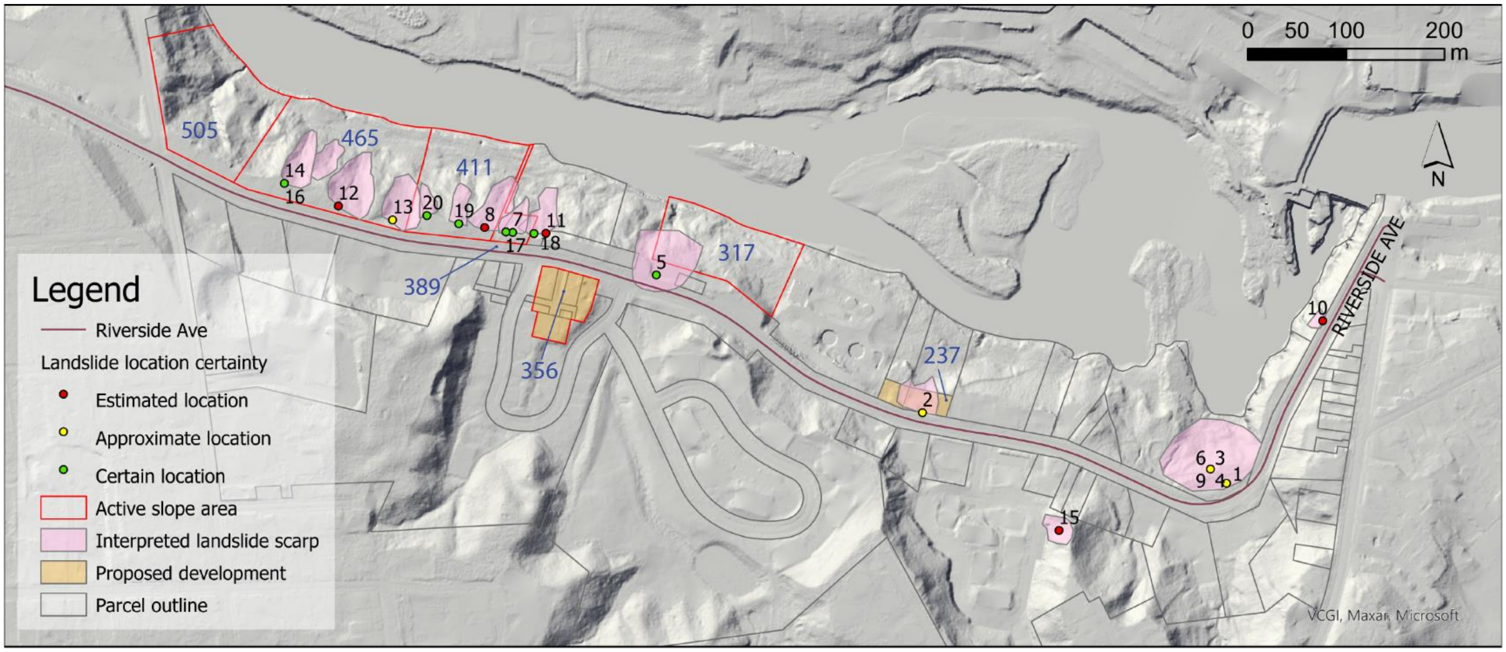


Fig. 5.


0 50 100 200 m
N
505
465
411
389
356
317
237
RIVERSIDE AVE
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20
Legend
Riverside Ave
Landslide location certainty
Estimated location
Approximate location
Certain location
Active slope area
Interpreted landslide scarp
Proposed development
Parcel outline
VCGI, Maxar, Microsoft

A century of landslides
Bennett & Bierman, 2023

Fig. 6.

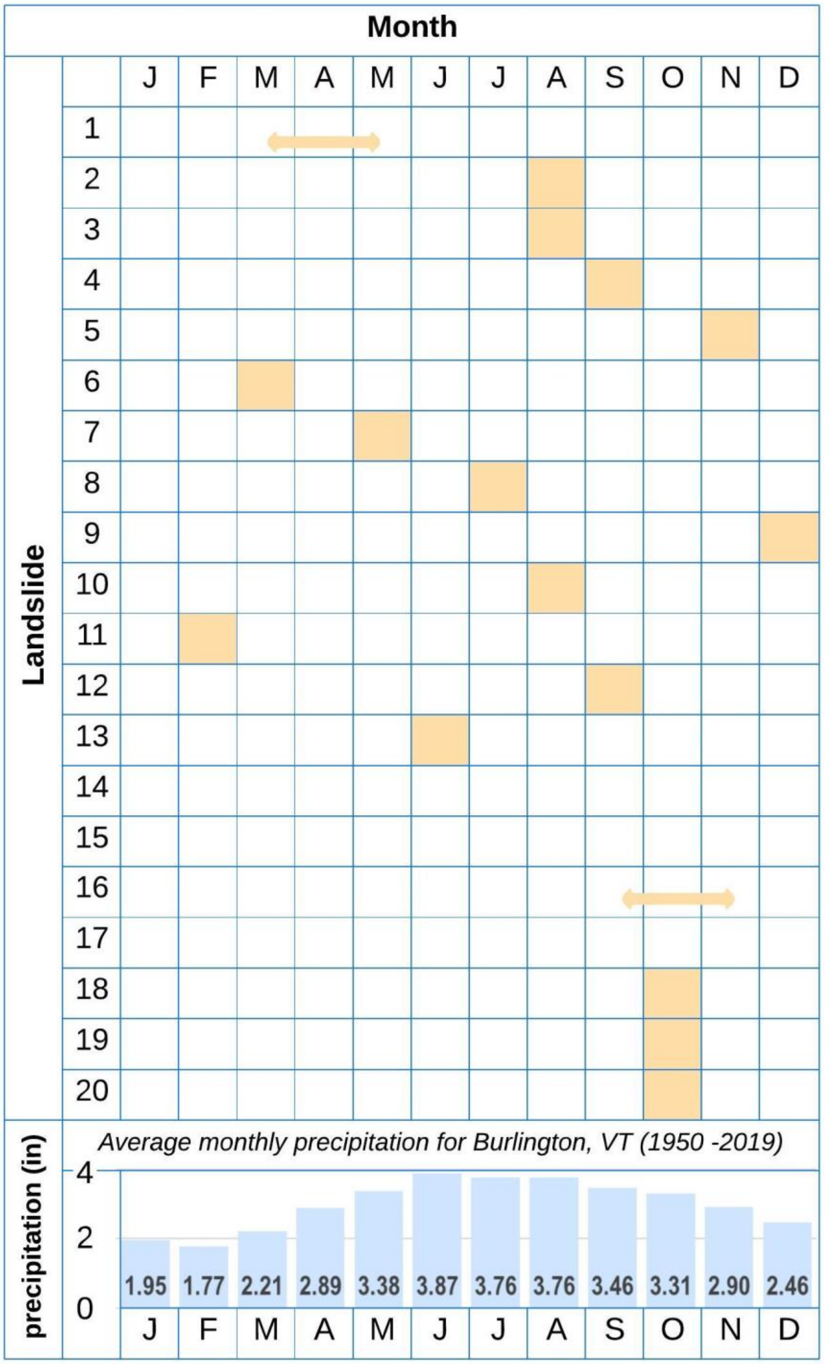


Fig. 7.

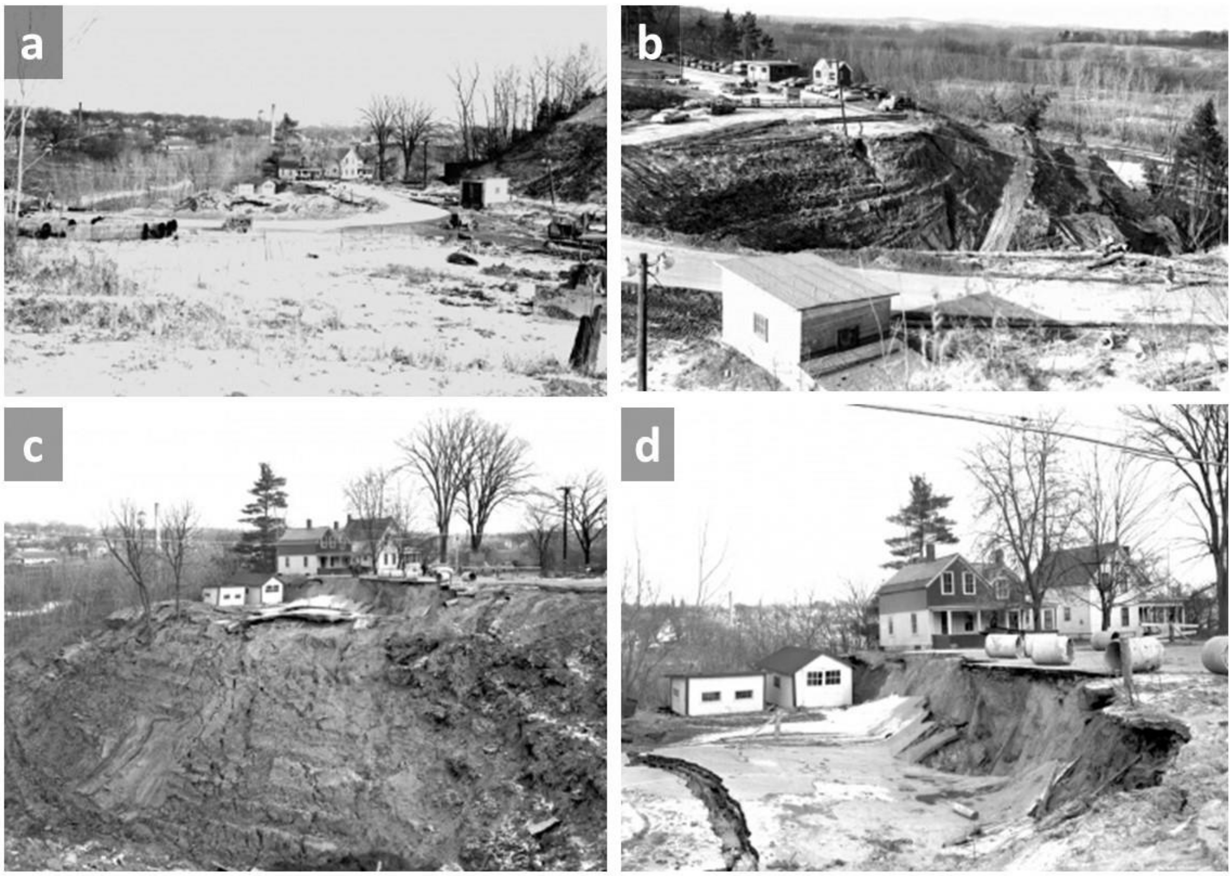


Fig. 8.


a
April 30, 2019
b
May 24, 2019
c
June 20, 2019
d
September 20, 2019
e
October 11, 2019

Fig. 9.

Table 1: *Chronological list of all known landslides along Riverside Avenue as of October 2023*

Slide	Year	Date	Size information	Location & Notes	Repair Cost	Cause	Source(s)
1	1952	Spring	Unknown; "[Took] away sizable portions of the pavement."	Near Fairview garage (114 Riverside Ave). Prompts 1953 winter street project.	Unknown	Unknown	("Mild Winter" 1953)
2	1955	August 17	Unknown; "The water took away much fill underneath the [side]walk."	Just east of 239 Riverside Avenue. "Washout Wednesday."	Unknown	2.37 inch rain storm on August 17 caused flooding, drainage problems across city.	("Storm is worst" 1955; "City Light" 1955)
3	1955	End of August	Unknown; Articles suggests multiple washouts along Riverside Ave following storm.	Occurred 1 km from the intersection with N. Winooski Avenue. Across from Fairview Garage (114 Riverside Ave).	$37,500	Unknown	("Burlington Youths " 1955' "Washout Rips Riverside" 1955; "St. Johnsbury" 1955)
4	1955	September 6	A section of road and sidewalk slid down the embankment, creating a 20 x15 ft hole in the road and breaking a water main.	Same location as slide #3, which had just been patched. Across from Fairview Garage (114 Riverside Ave).	$35,000	Unknown	("Burlington " 1955; "Washout Rips Riverside" 1955)
5	1955	November 18	Thousands of yards of fill.	Across from Hillside Terrace Development (365, 385 Riverside Ave). Composed of fill, half dozen big pine trees.	Unknown	Potentially the excavation for a new culvert along the bank of the old washout.	("Washout Rips Riverside" 1955; Detore Collection 1955, Landscape Change Program)
6	1958	March 31	Unknown	Within 10 ft of sidewalk, caused it to drop "some". Across from Fairview garage (114 Riverside Ave), same location as September 6, 1955 slide.	Cost of 5,000 cubic yards of rock fill required to stabilize bank.	"Underground water seepage that undermines the fill" and inadequate drainage.	("Small Landslide" 1958; "Crews Begin" 1958)
7	1968	May 9	"Tons of earth and junked cars…"	389 Riverside Ave; came within 15 ft of road.	Unknown	Occurred after fill was dumped.	("Landslide Threatens" 1968)
8	1968	July 1	Unknown	Caused cars to fall into river; stabilized with "tons of crushed stone." Stone located below 389-411 Riverside Ave.	Unknown	Unknown	("Firm Foundation" 1968)
9	1969	December 31	Unknown	Salmon Hole Park. "Historic slide; 'collapse of medium to fine sand, gravel above	Unknown	Unattributed . Historical storm occurred Dec. 25-28th delivering 30 inches	VT Open Geodata Portal Landslide Inventory.

				liquefied undifferentiated silt/clay sediments and till'" (across from 114 Riverside Ave).		of snow in 60 hours ahead of this landslide.	("December" 1969)
10	1972	Before August 29	Unknown; minimal information available.	Right above the Winooski Salmon Hole. Images show an undermined sidewalk and road.	Unknown	Unknown	Landscape Change Program images LS57951-LS57954
11	1974	Early February	Unknown; large enough that material entering the Winooski River altered its flow.	Across from the Winooski Sewage treatment plant. Concern that it might change the course of the Winooski River by altering its bed.	Unknown	Unknown	(Wolff 1974)
12	1976	September	Article estimated 4,000 yards of material; caused increased scouring of the riverbanks.	"Occurred about 35 ft from Riverside Avenue near B.J.'s Variety Market." (454 Riverside Ave).	Estimate: $45,000	"May have been caused by heavy rains in August and September, and resulting high river levels which undercut the supporting banks."	("Mudslide cleanup" 1977; "Landslide Repair" 1976)
13	1981	June 12	40 ft across, "Several thousand cubic yards" that "partially blocked" the Winooski.	Across from Koffee Kup Bakery (436 Riverside Ave). Mayor requested $350,000 to stabilize.	Work in 1983 cost between $80,000-$100,000.	Illegal dumping of landfill material on private property.	("Workers Begin" 1983; "Debris Slides" 1981; Reilly 1981; "Dismissal requested" 1981)
14	1983	Unknown	"[The property owner] told the board he has lost 20 feet of land in the last year."	Undermined the Riverside Glass and Mirror Inc building (463 Riverside Ave) "The back of that building is handing in the air over the eroding bank."	$5,000 to hire a consultant. "Shoring up the entire problem area, which extends from the Winooski Bridge to Intervale Road… Would cost hundreds of thousands of dollars."	Potentially caused by illegal dumping; determined that it was not caused by drainage issues.	(Melvin 1983)
15	1989	Fall	Unknown	Within the Salmon Run apartments construction area (220 Riverside Ave)	Unknown	Trees were cut for development, destabilizing the slope.	("Ward 1" 1990)
16	1998	Unknown	Unspecified; Visual	Undermined the Riverside	Unknown	Attributed to	("Retail Roundup"

			estimate: 50 ft wide by 23 ft deep	Glass and Mirror Inc building at 463 Riverside Ave.		"underground water problem"	1998; Melvin 1983).
17	2007	Unknown; prior to inspection on July 12	Unknown	Undermined single bedroom house at 389B Riverside Avenue	Unknown	Unknown	(Department of Planning and Zoning 2008)
18	2019	October 31	More than 100 ft wide at the top of the scarp, 3600-5000 m^3 of material displaced	385 Riverside Ave; Just west of Hall's Hitches & Welding.	Unknown	3.3 inches of rain in 6-10 hours exacerbated slope instability caused by illegal dumping	(Baird 2019; Hastings & Taber n.d.; Google Earth 2023)
19, 20	2019	October 31	Each wider than 50 ft at the top of the scarp	Two landslides (smaller than #18) occurred on either side of the Burlington Collision Center (411 Riverside Ave)	Unknown	3.3 inches of rain in 6-10 hours exacerbated slope instability caused by illegal dumping	(Hastings & Taber n.d.; Google Earth 2023)

Caption: *Comprehensive list of landslide events along Riverside Avenue, in Burlington, Vermont, to date. We compiled this information primarily from Burlington Free Press Newspaper archives and photography accessible from the Vermont Landscape Change Program. The Burlington Free Press uses Imperial or United States Customary Units, while we use metric units in our measurements.*

Table 2: *Ongoing slope instability on Riverside Avenue identified in the 2020 Slope Stability Report (Hoyle, Tanner & Associates Inc.)*

Street Number	**Condition** *(stable, needs further assessment, or urgent repair needed)*	**Activity description**	**Suggested approach**	**Previous activity**	**Updates**
505	Urgent repair needed	Active slope movement and surface erosion close to a structure	• Field investigation program, review of historic boring logs and aerial photography • Test borings, assessment of repair options • Install inclinometers, strain gauges, and/or survey benchmarks • Redirect roof drainage and armor exposed soil surfaces behind building with crushed stone and geotextile fabric to limit ongoing surface erosion	Unknown	DPW is working to address an eroded stormwater outfall at the corner of Intervale Road and Riverside Avenue
471	Needs further assessment	• Significant erosion at pipe outlet • Evidence of active slope movement	• Drill test borings to determine thickness of fill, in-situ soil densities and soil types, and groundwater levels • Install inclinometers	May have been impacted by slide #16 (Table 1)	None as of September, 2023
411	Needs further assessment	• Evidence of active slope movement Crown cracking • Continued dumping on property	• Annual visual monitoring • Monitor crown cracking • Drill test borings to determine thickness of fill, in-situ soil densities and soil types, and groundwater levels • Install inclinometers • Restrict dumping of bark mulch, soil and vegetative debris along slope	2019 landslides (Table 1, #19)	None as of September, 2023
389	Urgent repair needed	• Active slope movement and surface erosion close to a structure • Exposed scarp between 356 and 389	• Field investigation program, review of historic boring logs and aerial photography • Test borings, assessment of repair options • Install inclinometers, strain gauges, and/or survey benchmarks • Redirect roof drainage and armor exposed soil surfaces behind building with crushed stone and geotextile fabric to limit ongoing surface erosion	1968 & 2007 landslides (Table 1, #7, 17)	This property is being purchased by the city of Burlington through the Federal Emergency Management Agency (FEMA) Hazard Mitigation Grant Program. The house

					will be demolished and converted to green space in 2024.
356	Needs further assessment	• Evidence of active slope movement • Exposed scarp between 356 and 389	• Annual visual monitoring • Monitor scarp development between 389 and 356. • Drill test borings to determine thickness of fill, in-situ soil densities and soil types, and groundwater levels • Install inclinometers	Likely within the area reconstructed after the November 1955 slide.	None as of September, 2023
317	Needs further assessment	Evidence of active slope movement	• Annual visual monitoring • Drill test borings to determine thickness of fill, in-situ soil densities and soil types, and groundwater levels Install inclinometers	Unknown	None as of September, 2023

Caption: *A summary of the 2020 Slope Stability Report released by the Burlington Department of Public Works (DPW) in 2021. To date, this survey has not been updated. Members of the DPW provided the information in the "updates" column through verbal and written communication.*