

Historical Landslide Inventory for the Twin Cities Metropolitan Area

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Executive Summary

Minnesota's wettest recorded month in June 2014 led to widespread gravitational failure of sediment and rock in the metropolitan area of Minneapolis-St. Paul. The failure beneath Fairview Riverside Hospital Minneapolis would have been costly enough to push Hennepin County past the threshold to qualify for a federal disaster declaration with just this single event. Two years prior, a similarly rainy period resulted in loss of life as well as property damage. Hennepin County was motivated by these events to develop a better predictive model for when and where failures occur. Their overarching goal for such a model is to inform hazard response plans, best management practices and to develop model ordinance language. This collaborative project between the County, DNR, University of Minnesota and the National Weather Service represents the first step in this larger goal.

All attempts to understand the susceptibility of a landscape to gravitational failure begins with an inventory of historical failures and analysis of the slide types. This allows the regions that are susceptible to be identified. Historical failures were inventoried in an area centered on Hennepin County that included much of the Twin Cities metropolitan area by searching online sources and print newspaper archives. The 7-county metropolitan area has records of mass movement going back to 1879.

Failures were mapped onto a 1m-hillshade DEM created with LiDAR data and assembled into a slide distribution database. Failure scars discovered on the DEM and not through the historical archives were noted and municipalities contacted for more information on the timing of these slides. Slides were grouped by style and geology.

The failures were primarily located along the Mississippi and Minnesota River corridors which expose glacial sediment of varying textures and the underlying flat-lying Paleozoic sedimentary rock units. Each geologic unit provides its own unique stability issue, resulting in various styles of failure. In these locations, shallow stormflow increases flow at seeps and springs and provides a low-friction failure plane where pore water is high. Overland flow erodes ravines, accelerates head-cutting and steepens side slopes.

The earliest record of failure was in 1879. Wet periods in the late 1890s, early 1900s, 1980s and 1990s are reflected in an increase in reporting of slides. The increase in slides reported since 2010 may reflect the wetter climate as well as the ease of searching online records. The antecedent precipitation for the period prior to the failure was extracted from climate archives for well dated slides. Nearly all of the slides

occurred between May and October with peaks in June and August, both periods of higher incidence of rains associated with convective storms in Minnesota.

Introduction

June 2014 was Minnesota's wettest June, and wettest month, of the modern record. The state-averaged monthly rainfall total for June 2014 in Minnesota was 8.03 inches with some areas in the Twin Cities receiving more than 13 inches. The total was well more than the previous record of 7.32 inches set in July 1897 and again in June 1914. There were two large rainy periods in the month. The first 7-day rainy period ended June 4 and only three failures were documented during this period. However, this widespread rain event may have established the antecedent moisture conditions for the subsequent failures that occurred in association with the second rainfall event. This second period brought more widespread failure. The second round of storms hit southern Minnesota particularly hard.

Critical infrastructures, including 2 major hospitals, were threatened by hillside failure and flooding in Hennepin County during the extraordinary rains of June 2014. Suspending patient services at two large hospitals, even if temporary, would have serious impacts across the entire region. The Riverside Hospital failure was the single-most expensive and complex event of the disaster and directly led to Hennepin County receiving a federal disaster declaration. Hennepin County was motivated by the events of 2014 to develop a tool to better predict landslides. Their goals are to assess life-safety risk, determine threat to critical infrastructure, develop a tool to support land-use and environmental planning decisions, inform emergency management mitigation planning efforts, and create an exportable assessment model that could be used in other Minnesota jurisdictions.

Background

Changes in the general factors that increase the shear force (stress) on a slope or decrease the shear strength of the material will result in failure (Table 1). In the real world, layered or poorly sorted geologic materials have enough variability in grain size, packing arrangement and moisture content that the inhomogeneity has a strong effect on the style and location of slope failure. However, it is useful to keep some underlying physical principles that are based on ideal cases in mind. Gravitational force is directed downward, but it is typically visualized as having a component directed perpendicular to the slope (normal force) and a component parallel to the slope (shear force). Gravitational attraction is proportional to the mass of the object. It is the main driving force. There are resisting forces that keep gravity from resulting in a flat and featureless landscape. Fundamentally, friction resists gravity. In a granular material or rock the internal friction or strength of the material is related to size, shape and packing arrangement of the grains. For a rock layer, strength is also affected by the nature of the cement and any planes of weakness (faults, joints or bedding planes).

FACTORS THAT INCREASE SHEAR STRESS (FORCE APPLIED)	FACTORS THAT DECREASE SHEAR STRENGTH (RESISTANCE OF MATERIAL)
Removal of lateral support: <i>erosion (by rivers, ice, waves); human activity (quarries, road cuts)</i> Addition of mass: <i>natural (talus, rain); human (fill, stockpiles, buildings)</i> Ground shaking: <i>natural (earthquakes); human (mechanical vibration)</i> Regional tilting: <i>(glacial rebound)</i> Removal of underlying support: <i>natural (undercutting, solution, weathering); human (mining, tunneling)</i> Lateral pressure: <i>natural (swelling, expansion by freezing, water addition); human (watering; construction)</i>	Weathering and other physiochemical reactions (<i>disintegration, hydration [lowers cohesion], base exchange, solution, drying</i>) Pore water (<i>buoyancy, capillary tension</i>) Structural changes (<i>remolding, fracturing, bioturbation, changes in soil structure</i>).

Table 1. These are the primary factors that influence stress and resistance in slope materials. Adapted from Ritter et al., 1995.

Angle of repose

The slope of a pile of uniform granular material has a stable angle of repose that depends on the grain size and shape. This is because the angle of repose is fundamentally dependent on the packing arrangement of the grains. Some materials are stable at a 90° slope under the right conditions, but most have a much lower stable slope angle because the grains do not interlock or stack well.

Stability is increased by cohesive properties of a substance. This may occur at the molecular level and includes weak attractive forces between ions or polar molecules. A small amount of water will create an attraction as will the presence of salts in clays. These resistive forces increase the angle of repose.

Anything that reduces friction between grains or pushes them apart reduces the angle of repose. For example, pore water can reduce grain-to-grain contact and therefore decreases the stable slope angle.

Infiltration capacity of soils

Water that is not intercepted by vegetation, or that does not run off, has the potential to infiltrate the soil. The infiltration rate is dependent on the soil texture, structure, thickness, and antecedent moisture conditions. Infiltration capacity can be subdivided into three steps: 1) absorption, 2) storage, and 3) transmission downward. Infiltration is greatest on gently sloping coarse material and is least on fine-grained steep material (Ritter et al., 1995 p. 139).

Infiltration changes over the course of a rain event; it typically starts out high and decreases over time. For example, if certain clay minerals are present that swell when wetted or if pores become clogged with fines,

infiltration will decrease. Given time between wetting events, the soil has the potential return to its initial infiltration capacity but frequent wetting will not allow this to occur (Ritter et al, 1995, p. 139-140). Other limiting factors may be an impermeable layer at depth that affects total storage.

All of the slopes that were investigated for this report have had human and other invasive species impacts to the soil. Earthworms change soil structure by creating macropores that increase infiltration rate, at least initially, to the depth of the burrows (Tomlin et al., 1995). But they also decrease the organic duff layer and incorporate it lower in the soil profile. This alters the understory plants that typically grow in a worm-invaded area. The presence of the invasive plants such as the European buckthorn is linked to bare soil (Whitfield et al., 2012). This may alter infiltration by reducing vegetation interception and by possibly changing the soil structure. Tillage has a complicated impact on infiltration depending on management practices. Compaction from trails reduces infiltration. If any of these factors substantially changed the infiltration capacity of the soil, the equilibrium slope will be changed as a result.

Through-flow and subsurface stormflow

We typically think of infiltrated water as moving downward until it reaches the water table. But in storm situations, where the infiltration capacity of the soil may be exceeded during an intense rainfall event, water may flow laterally before it reaches the water table. This is through-flow. The water table may also rise and steepen its gradient during a storm event and result in an increase in base-flow to a stream. Together, these factors are called subsurface stormflow (Ritter et al., 1996, p. 140-141) and have the effect of increasing seepage pressure on slopes. The lateral flow-path has reduced strength owing to high pore-water pressure and may become a failure surface. The place where seepage daylights on the slope can be a site of piping or sapping, wherein grains of sediment are removed as a small cavity works its way up the pressure gradient (Figure 5). These cavities may collapse and create sinkholes or create a focus for overland flow. Sinkholes may form near a bluff top that are related to sediment piping.

Geology

Large drainage events dating to the end of the glacial period approximately 13,000 years ago have created deep trenches that modern rivers now occupy (Figure 1). The walls of the main glacial drainageway (the Minnesota and Mississippi below the confluence with the Minnesota) have stabilized during the varying climate and vegetation regimes of the past 13,000 years. It appears that the slopes were very active initially. Change is still ongoing in tributaries to this main channel.

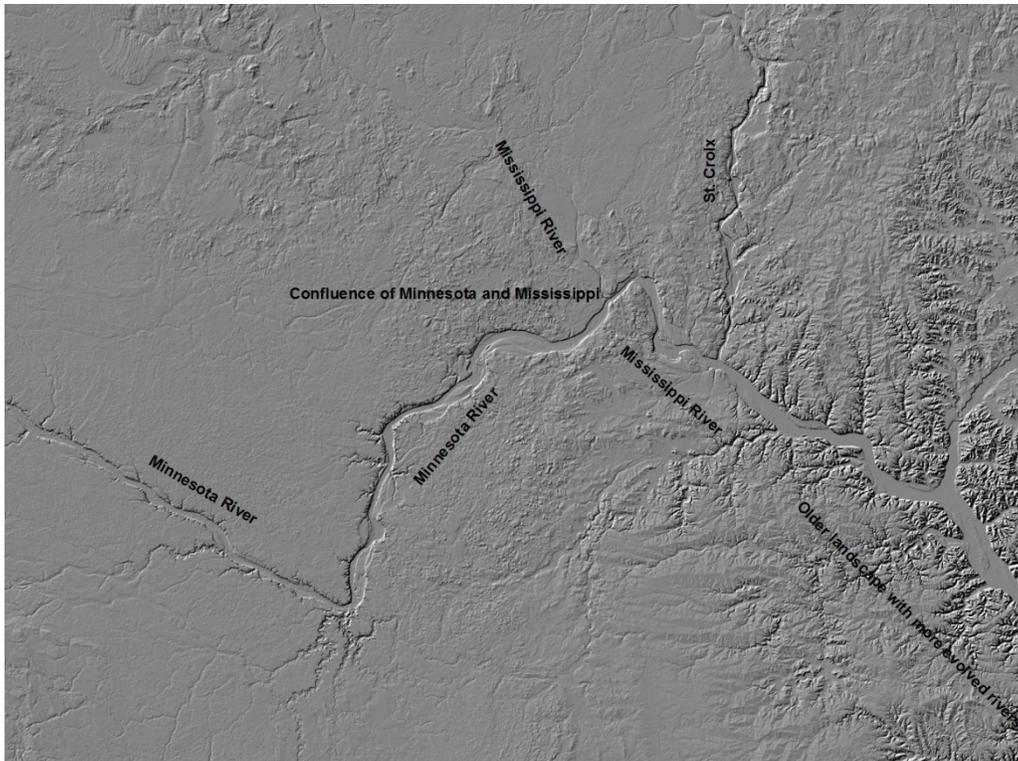


Figure 1. Shaded relief showing topography in southeastern Minnesota.

Late glacial events created a broad, deeply incised valley now occupied by the Minnesota River. It exposes layers of glacial sediment and rock.

Tributaries to the main channel, including the Mississippi upstream of the confluence with the Minnesota, are still actively adjusting to the river incision event of 13,000 years ago. None of the tributary watersheds has reached a stable configuration. The change in elevation of the main channel (base-level lowering) is working its way up into tributary watersheds through migration of nick points. The nick points may appear as waterfalls if hard substrates are encountered but may also be steep reaches in the stream profile. Sediment production is greatest in the nick zone (Gran et al., 2011).

Hennepin County has steep slopes along its river borders: Minnesota River to the south, Mississippi to the east and Crow River to the northwest (Figure 2). Broad glacial terraces lie on the upper surfaces of the Minnesota and Mississippi river corridors, in places supported by flat-lying bedrock. The western portion of Hennepin County is hummocky topography created by ice stagnation. Lakes, some very large, have steep slopes of glacial sediment.



Figure 2: Hennepin County Hillshade Map

Map of Hennepin County hillshade indicates steep riverine slopes lie along most of Hennepin County's borders. Hummocky topography created by ice stagnation covers the interior and also creates steep slopes in glacial sediment.

Stratigraphy

The glacial-river incision and the subsequent, ongoing erosion that it initiated have exposed sediment and rocks layers along the river corridors. The varying permeability of these geologic layers creates areas of persistent lateral flow (springs). Persistent springs in the metropolitan area have been discussed by G. Brick (1997) and are being systematically inventoried by him for the Minnesota Department of Natural Resources. He observed that spring lines were located at seven predictable levels, and for the most part were associated with perched water at the contact between a porous formation and an impermeable one. They are listed here from highest to lowest:

1. Galena Limestone-Decorah Shale contact; e.g. high on the wall in the Lilydale clay mines.
2. Glacial sediment-Decorah Shale contact; e.g. springs in the neighborhoods from the St. Paul Cathedral, looping south around Highland Park and north to the Lake Street bridge.
3. Glacial sediment-Platteville Limestone contact; at the level of Mississippi River Boulevard in St. Paul in ravines, the most notable being Shadow Falls by St. Thomas.
4. Located at a seam of bentonite (volcanic ash weathered to clay) in the Platteville Limestone; e.g. Cold Spring near Fort Snelling and Chalybeate Springs below St. Anthony Falls in Pillsbury Park and downriver at the location of the former Bohemian Flats community where the "Weeping Wall", as it is known to Minneapolis Public works employees, used to ice the road over.

5. Platteville Limestone-Glenwood Shale contact; only a few minor seeps at this elevation.
6. Where the water table in the St. Peter intersects the river gorge wall; e.g. Carver Cave and Fountain Cave.
7. Where the Mississippi intersects buried valleys in the bedrock surface; e.g. St. Paul Fish Hatchery below Dayton's Bluff and the Pine Bends where springs feed Spring Lake.

Methods

The Minnesota History Center has archives of print newspapers that were searched by students from the University of Minnesota. They also conducted online searches and found them most helpful for very recent slides. Slide locations were determined by the news source and plotted on LiDAR base maps. Where the location was uncertain, the location was estimated based on an interpretation of the slopes that had failure scars. In very old slides, histories of repairs obscured slide locations; they are more approximate. The Minnesota History Center has archives of print newspapers and that were methodically reviewed for articles on historic landslides.

Online databases and searches

The Minnesota Digital Newspaper Hub was the most helpful for landslides prior to 1925. It contained records of many old newspapers and could be searched in a way similar to the online databases. The advanced search found mentions of landslides or mudslides in many of the records, and displayed them in order sorted either by newspaper name, county of origin, city of origin, or date published.

Most online databases were searched using their internal search engine using keywords such as "landslides" or "mudslides". News sites, weather sites or government or research sites were good places to search. For example, city planning sites, the USGS and other geological or environmental databases yielded good results.

Results of Google searches mainly identified recent reports of large events that made the news by being costly or causing loss of life. The key to using Google more effectively was to use as specific a keyword as possible to help narrow the search. For example, instead of searching "Landslides MN" they searched instead for "Landslides Eden Prairie MN" or "Landslides MN 2014" or combined the two searches. The use of "landslide" to describe elections was the most likely search result. To help avoid these articles, the advance search tool was used to eliminate terms related to elections such as election, Republican, Democrat, presidential, and senate.



Figure 3: Stillwater, MN slide from May 9, 1894. (Photo Courtesy of the Washington County Historical Society)

Minnesota History Center microfiche collection

The Minnesota History Center has a collection of newspapers from across the state from the early 1900s to the present. Most of the records in the database came from this collection or the previously mentioned Minnesota Digital Newspaper Hub. Although this database has tremendous potential, it is also the hardest to use because there is no easy search tool. To speed up the process of going through decades of daily newspapers, searches were narrowed to certain months, from spring to mid-fall and focused on periods after large rain events. References to slides were more likely to occur in the A or B sections of the paper (or equivalents depending on paper), followed by the weather and C sections. They were likely to first be mentioned in the first 10 pages of any one day's paper and along with major rainfall events or floods. Usually the landslides were mentioned in articles that have some connection to weather, natural events, roads, or trains. For other physical paper archives a similar method was followed with exceptions based on each location. Some had a search index book that allowed the search to be narrowed down to specific periods.

Locating sites for landslides mentioned in articles

Sites mentioned in articles had to be accurately located on a map. This was difficult if articles gave only general locations. The DNR MNTOPPO site <http://arcgis.dnr.state.mn.us/maps/mntopo/> is a tool that provides easy access to high resolution LiDAR elevation models. It was used with a road map to find the named locations. Older slides where the terrain was altered were plotted approximately and a relatively steep slope in the vicinity was used for the reference slope. Older articles also referred to roads, railways or other features that are no longer in place that required further research on historic place names. Latitude, longitude, elevation and the US National Grid coordinates were recorded for each site.

The slide profiles were examined using the cross section tool in ArcMAP to determine the steepness of the pre-failure slope. If the LiDAR was taken after the failure, the post-failure slope and a nearby reference slopes were recorded (Figure 4).

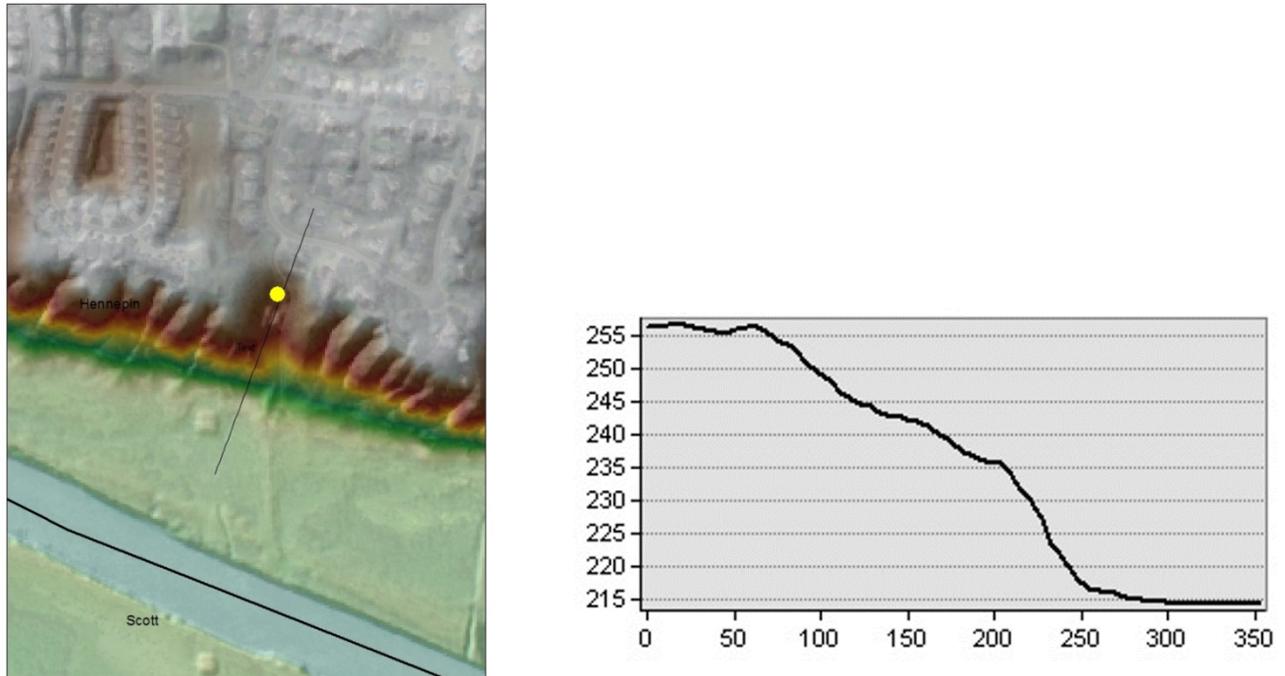


Figure 4. LiDAR DEM and Extracted Profile.

Failure sites were located on the elevation model and slopes (in meters) extracted using the profile tool of MnTOPO.

Precipitation Records

Other causative factors that lead to slides include soil moisture. Precipitation is a proxy for soil moisture and also results in enhanced spring flow. Storm water runoff can create new ravines, deepen and widen existing ravines and destabilize slopes. Soil moisture is usually gauged by looking at precipitation in a period leading up to the slide (antecedent moisture) and intensity of rainfall in a shorter period immediately preceding the slide.

Typically moderate to intense rainfall causes failure to occur (Coe et al., 2014). However, the antecedent rainfall prior to the intense event is also important because if soils do not have time to recover, to a normal moisture state, they are more vulnerable. Antecedent rainfall not only controls the initial moisture content of the sediment or rock but affects the subsequent rate and depth of wetting. Rainfall intensity, cumulative precipitation and the timing of rainfall all have a role in slope failure.

We searched historical archives and contacted municipalities for information on timing. The antecedent precipitation for two to four weeks prior to the failure and soil moisture conditions at the time failure were initially extracted from climate archives for the periods identified. We later extended the period that we reviewed.

We looked at precipitation records for well dated slides but also used known, high rain periods to focus the searches in the newspapers. Monthly data from every year dating back to about 1880 between March and September were reviewed to find relatively high totals (upwards of 9 or 10 inches). Within those months, dates or a set of dates that had high rainfall totals were reported to the student looking for news of landslide events. For well-dated landslide events, rainfall totals for those days as well as the cumulative totals from two weeks prior to the event were recorded. The stations closest to the slides were used. If nearby stations did not have long enough records, those in Minneapolis or St. Paul that had data that went back to the date of the slide were used.

Results

We focused our search on the metropolitan area centered on Hennepin County (Figure 5). However, this figure includes records for a single storm event in southeastern Minnesota in 2007.

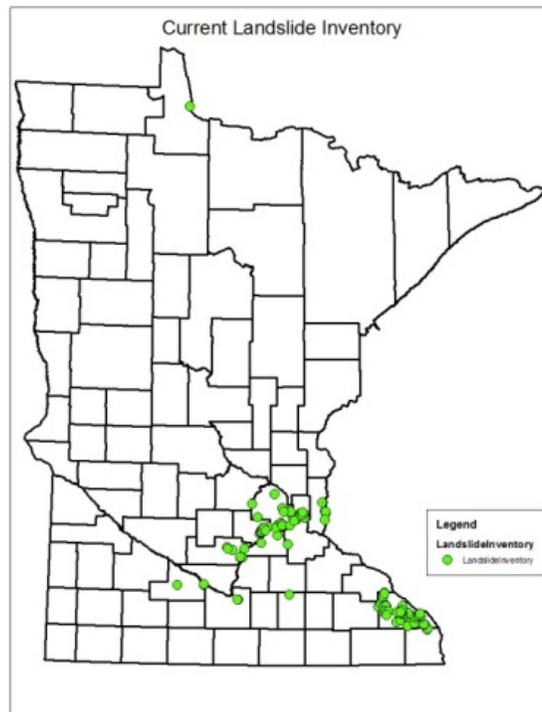


Figure 5. Landslide Inventory

The current distribution of historical slides. See Appendix A for the landslide database attribute table.

Reported slides occur between April and September with peaks in the months of May, June and August that have more convective storms and large rainfall totals. Wetter periods in the last century and a half had more reports of slides (Figure 6). Some of this distribution may be affected by the quality of records and the ease of searching paper or microfiche records versus electronic databases. The apparent recent increase is certainly in part affected by online news sources and search tool

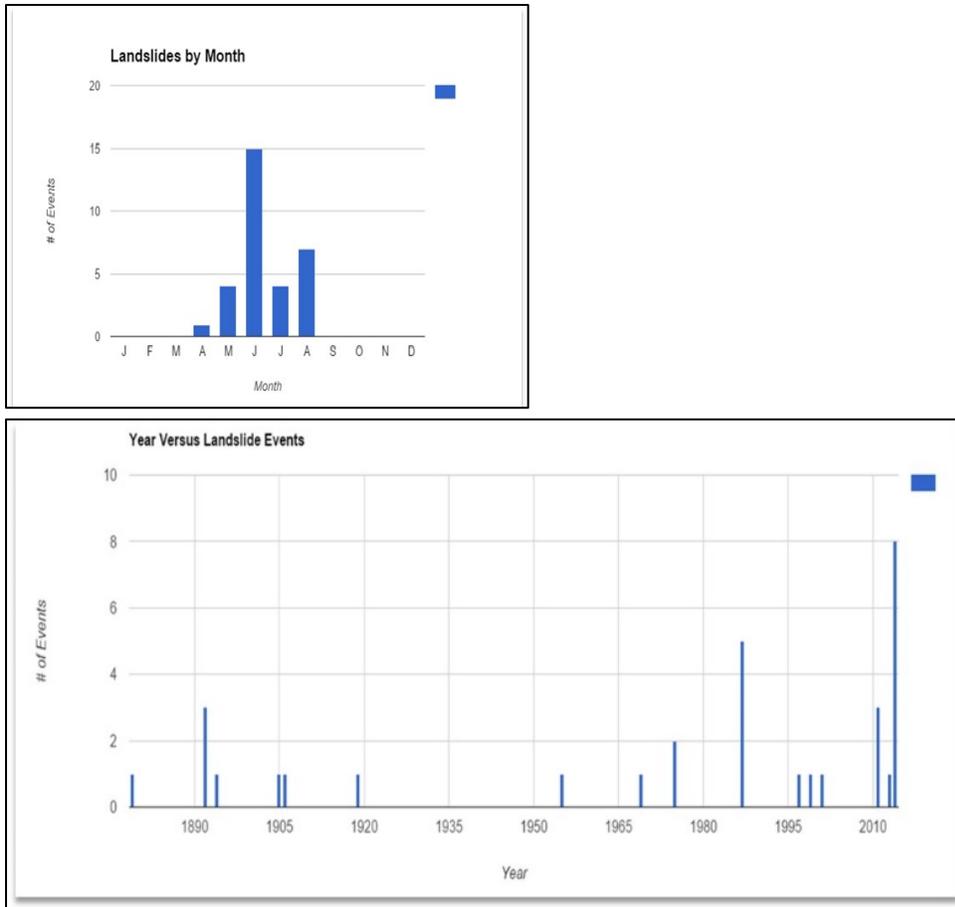


Figure 6. Distribution of failures over time

More failures were reported for the months with more intense rainfall events. Decades with wetter conditions stand out in the historical search.

Slopes

The greatest number of slopes that failed were at a 40% grade, however, slopes began to fail at lower grades (Figure 7). For convenience in our final product, we highlighted slopes of at least 30% because a coverage had already been developed with this threshold by Dr. Stephanie Day for a contract with the Minnesota Pollution Control Agency (S. Day, written comm., 2015) (Figure 8). A conservative approach may be to include slopes of approximately 20% or greater in a general susceptibility map. For site-specific rules, slopes associated with particular geologic units should be reviewed.

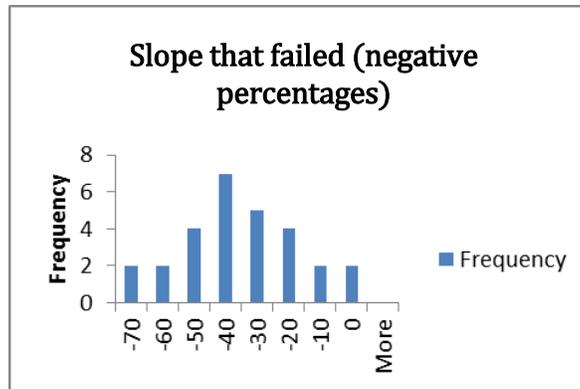


Figure 7 Range of Pre-Failure Slopes

Slopes greater than 20% are more likely to fail. A cutoff of 30% was chosen for presentation with project because a slope analysis was already available.

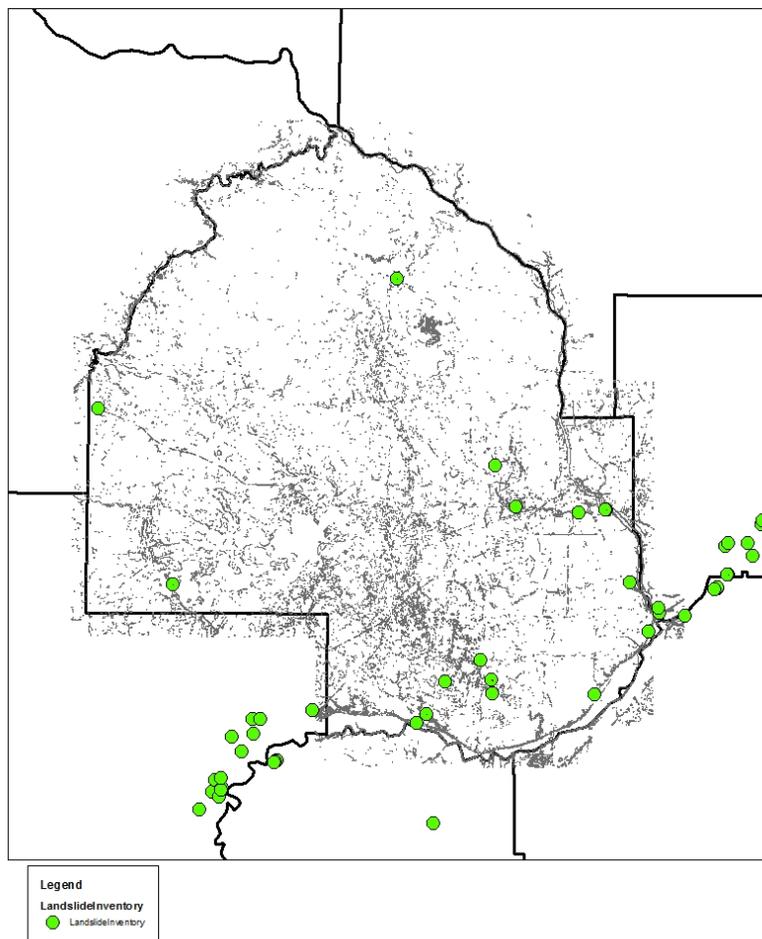


Figure 8. Landslide locations plotted on 30% slopes or greater (gray)

Artificial and natural slopes were extracted from a LiDAR DEM (S. Day, written comm.) and compared to slide locations.



Figure 9. Purgatory Creek in Eden Prairie

This river valley is outlined by steep slopes. The material exposed is primarily dry sand and gravel. The green dot represents a failure location where a house had to be removed in 2014. Additional setbacks of 30' from the tops of slopes are encouraged by the Lower Minnesota River Watershed District (Linda Loomis, written comm., 2016).

Setbacks of different widths from the top of steep slopes may be required depending on the style of failure and geologic material (Figure 9). If a different slope threshold is desired, a new coverage can be extracted from the LiDAR DEM using the bluff analysis tool in ArcMAP. The specific steps are given below.

- Bluff Toolbox
 - Focal statistics
 - Greater than equal (3)
 - Con (1)
 - Raster to Polygon
- New field for area (area) - float
- Geometry tool to calculate area
- Export bluffs greater than 100 m²
- Export bluffs within 35 m of channel centerline
- Buffer bluffs 6m
- Zonal statistics as table for buffered bluffs (range)
- New field for height (height) - float
- Join zonal stats table
- Field calculator to populate height field
- Remove join
- New field for surface area (surf_area) – float
- Field calculator to find surface area = $0.5 * \text{area} * \text{height}$
- All bluffs for watershed found
- Merge bluff shapefiles
- Intersect bluffs and subwatershed polygons
- Dissolve based on HUC8ID
- Statistics for area (sum), surf_area (sum), and height (mean)

Types of failures

Slides were assigned a type (Ritter, 1995) and classified as either rotational, dry flow or bedrock topple. Some slides were a combination of types, for example, if a bedrock slab fell, releasing the sediment above it. Some older slides are classified as unknown. This project included only limited field work so these classifications were made with geologic maps, photos and news descriptions.

Failures in fine-grained glacial sediment

Loamy glacial sediment layers experienced rotational failure that resulted in a steep head scarp with a wedge of rotated sediment. In some cases the sediment at the toe was saturated enough that it flowed and formed a lobe of debris that slowly dewatered. Vegetation typically moved with the sediment, sometimes remaining nearly upright. Because of the location of this study, the units that failed typically were till of the New Ulm Formation, the Twin Cities Member of the New Ulm Formation or the Cromwell Formation. For complete descriptions of the texture and extent of these units the reader is directed to a recent publication of the Minnesota Geological Survey (Johnson et al., 2016). However, this volume does not include engineering properties. Older glacial units that failed in lower positions along the valley walls in Carver and Scott counties and western Hennepin County are similar in texture but may have different consolidation states (Figure 10).



Figure 10. Scott County rotational failure in glacial sediment. Photo credit: Carrie Jennings, MN DNR.
 This loamy New Ulm Formation till failure has a steep scarp and the sediment has liquefied to flow across a road. Vegetation has moved with the sediment.

The lack of detailed field work did not permit identification of a clear relationship between failure depth and contacts between glacial units. However, in Bloomington, there are two spring horizons in the glacial sediment that may mark significant material contacts (Greg Brick, pers. comm.) (Figure 11). This is the location of a very large slide that probably occurred shortly after the formation of the river valley (approximately 13,400 years ago). It is not known whether the area is currently moving. It is a location to watch.

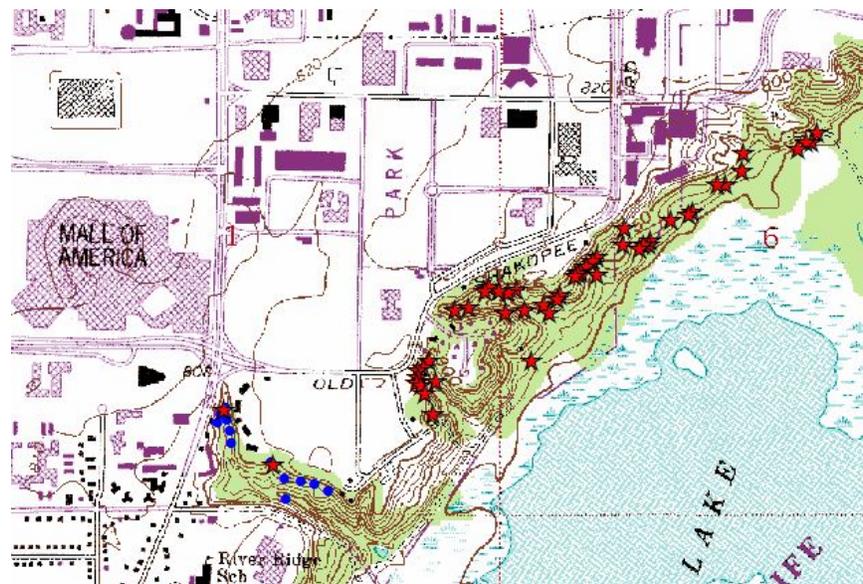


Figure 11. Draft map from the ongoing DNR Spring Inventory Project
 Red stars indicate where springs discharge from the bluff face. There are two distinct horizons and water appearance (and therefore chemistry) is different. Greg Brick, DNR, pers. comm., 2016.

Head-cutting of ravines that were formed entirely in glacial sediment occurred owing to the infiltration capacity of the soil and glacial sediment being overwhelmed resulting in overland flow or from stormwater being focused by pipes. This resulted in newly created, oversteepened reaches of the ravines that were susceptible to failure on the side slopes (Figure 12). Shallow storm flow also weakened saturated slopes or led to failure by sapping. Ravines may be preferentially located where springs emerge from sediment layers. Once a deepening occurs, groundwater will discharge laterally into ravines.



Figure 12. Ravine erosion creating unstable side slopes in Le Sueur County.

Water directed to a ravine will cause the headwall to move upstream ravine and the ravine may deepen. This creates the potential for the sides of the ravine to fail. Photo credit: Kristina Krklec

Human impact on the slopes includes municipal and agricultural drainage, roadways and railroads cut into the hillsides and construction of retention structures without adequate drainage which allow water to build up behind them. In a few places along lakeshores and riversbanks, erosion of the toe slope occurred. In some locations, water storage above a steep slope, either natural or artificial, was responsible for the glacial sediment failure.

Failures in dry, non-cohesive sediment

Dry sand and gravel lack cohesion and typically seek an angle of repose of approximately 30 to 45° depending on the average grain size and mixture. If stormwater is focused and creates a ravine in dry sediment, newly formed steep slopes quickly fail to the angle of repose. This style of failure has occurred along the high terraces of the Minnesota River in Eden Prairie both recently and historically (Figure 13).



Figure 13. Dry sand and gravel slopes in Eden Prairie undergoing repair.

This deposit forms a high, flat terrace along the Minnesota River and Purgatory Creek. It is vulnerable to failure when incised by stormwater. Photo credit: Mary Presnail, MN DNR.

Failures in bedrock

The bedrock exposed in the Mississippi River corridor in St. Paul is a sequence of flat-lying to gently dipping marine sedimentary units. The style of bedrock failure occurs where the St. Peter Sandstone forms a reentrant in the bluff face, leaving an overhanging ledge of the Platteville Formation. Undercutting can be facilitated by springs, sapping and mechanical erosion. The overlying slab eventually topples, in some cases releasing glacial sediment layers lying above (Figure 14).

In the Twin Cities metropolitan area, springs and seeps discharge at predictable horizons from the Paleozoic bedrock. The horizons are controlled by the vertical and horizontal hydraulic conductivity of the layers. Vertical fractures allow water to move down at high rates and bedding- plane fractures and finer-grained beds allow water to move horizontally and exit the bluff face at predictable horizons (Runkel et al., 2015).



Figure 14. Slabs of the Mifflin member of the Platteville Formation beneath Indian Mounds Park, St. Paul.

The St. Peter Sandstone is visible in the lower portion of the exposure. It is easily eroded, which leads to undercutting of the fractured members of the Platteville Formation. Photo credit: Carrie Jennings, MN DNR.

Springs that have been mapped in the Platteville emanate predominantly from the contact of the Magnolia and the underlying Hidden Falls member and (48%) and the Hidden Falls and the underlying Mifflin member (25%). There is some indication that dissolution along these fractures has widened them.

The hydraulic conductivity of the four members comprising the Platteville Formation varies with lithology and fracture density. Each member has a characteristic fracture pattern that terminates at its contact. The high density, vertical to sub-vertical fractures in the Magnolia Member give it a blocky appearance. The widely spaced, vertical fractures of the Mifflin Member make it break off in larger slabs. The Hidden Falls member has high density, curvilinear fractures (Runkel et al., 2015).

Buried valleys in the bedrock that are filled with glacial sediment will receive groundwater moving laterally. The valley fill may show enhanced rotational failure. This is well displayed in the bluff beneath Indian Mounds Park in St. Paul. The near-vertical bedrock face that is susceptible to topple is replaced by bowl-shaped hollows to the east where a valley in the bedrock is filled with glacial sediment (Figure 15).

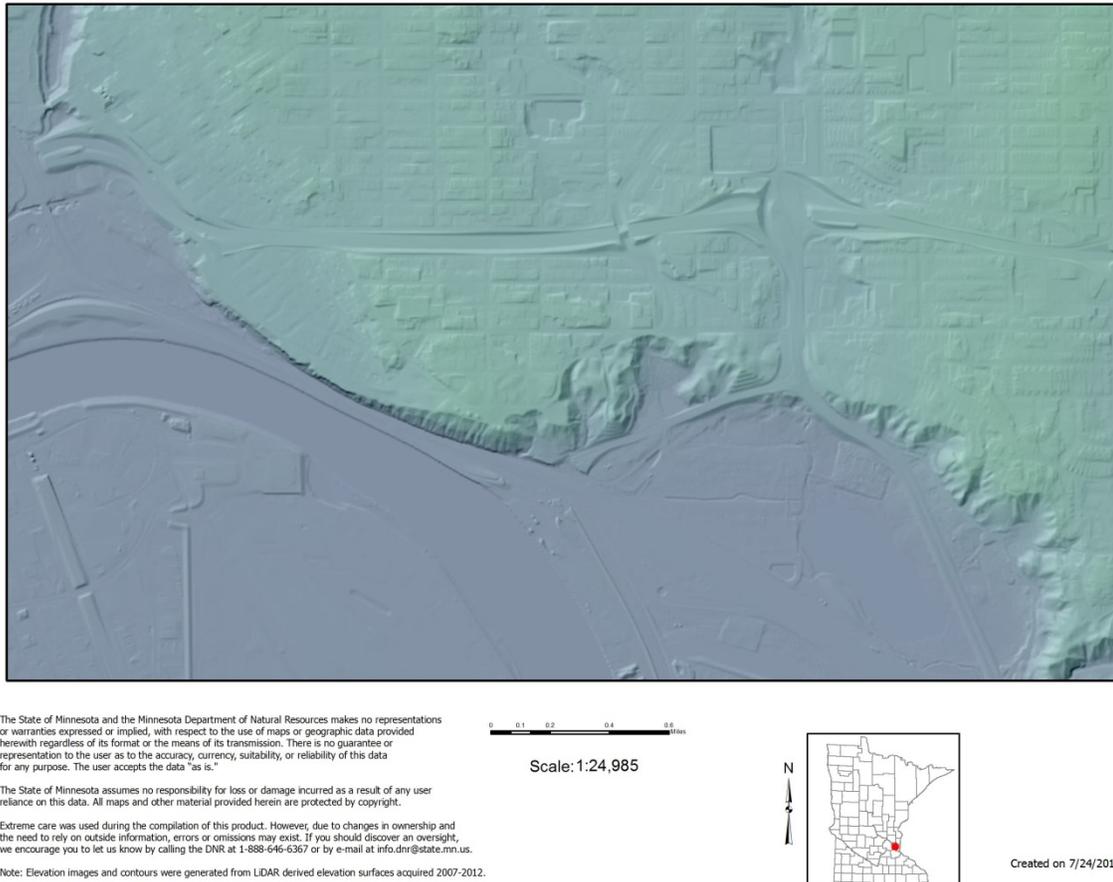


Figure 15. Bluff below Indian Mounds Park, St. Paul

The near-vertical bedrock face that is susceptible to topple is replaced by bowl-shaped hollows to the east where a valley in the bedrock focuses groundwater flow and causes rotational failure of the glacial sediment

Slide Domain Mapping

For geomorphic context, we use the DNR Ecological Classification System subunit called Land Type Association <http://www.dnr.state.mn.us/ecs/index.html>. Land Type Associations are units within Subsections that are defined using glacial landforms, bedrock types, topographic roughness, lake and stream distributions, wetland patterns, depth to ground water table, soil parent material, and pre-European settlement vegetation. Minnesota has 291 land type associations. A GIS cover of land type associations is

available on the Minnesota Geospatial Commons. When the landslides are displayed on this thematic layer draped over a hillshade DEM (Figure 16), it clearly shows the association of the failures with the river valleys and other steep slopes and helps group them by geology and geomorphology.

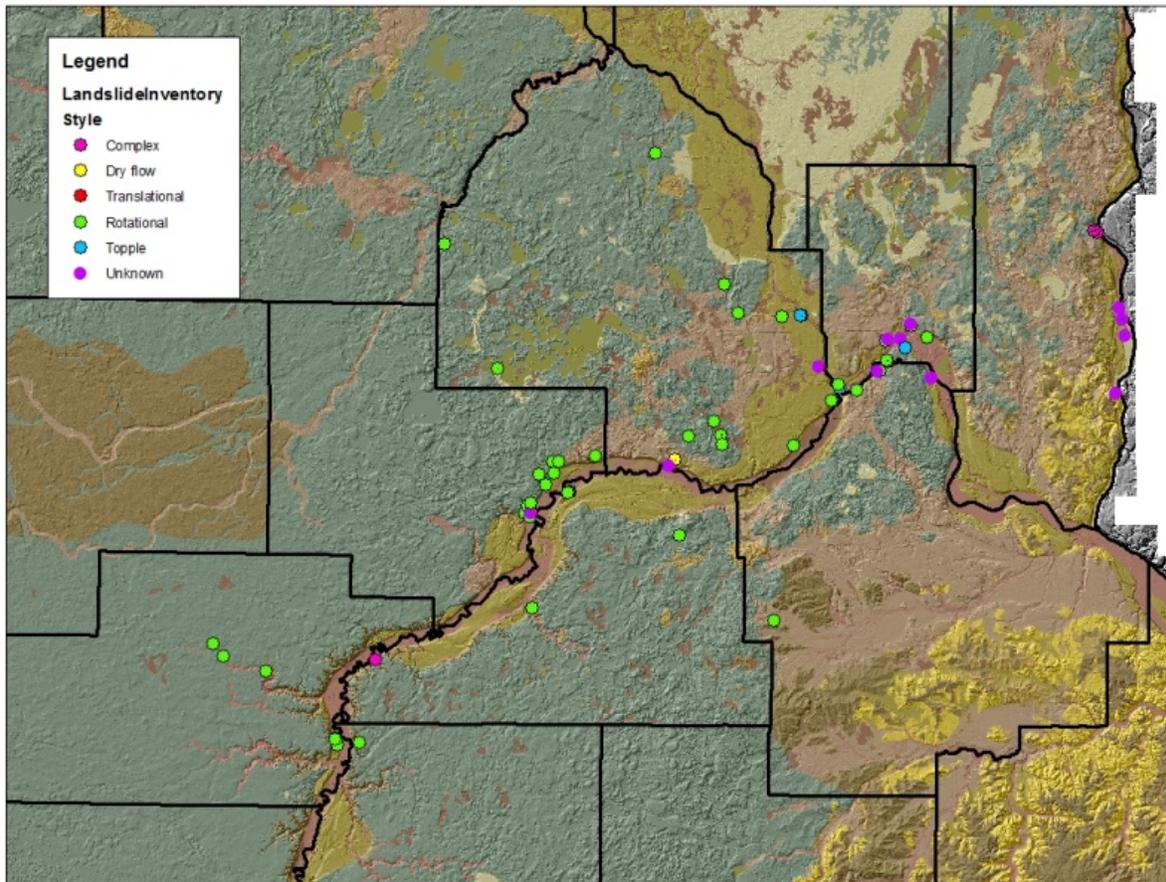


Figure 16. Slide Domain Map

Slides are colored by type and overlain on a Land Type Association map that is draped over a hillshade DEM. Green is glacial till, gold is glacial stream sediment in high terraces. Steep valleys between St. Paul and Minneapolis expose bedrock.

Steep till slopes in glacial sediment (green unit, green dot) along the Minnesota River and its tributaries and around Lake Minnetonka experience rotational failure. High glacial stream sediment terraces along the Minnesota and Mississippi (gold unit, yellow dot) do not become saturated. They fail when stormwater is not well controlled and is allowed to create a new gully or ravine. The nick zones of the steep tributaries to the Minnesota through this unit are especially vulnerable locations because these rivers are actively adjusting to the lower base level of the Minnesota River by incising and headcutting. Any extra water that they get speeds the process up (Gran et al., 2009).

Bedrock topples are located along the Mississippi between the two metropolitan areas where glacial rivers have removed the till and formed strath terraces (places where the downcutting was impeded by bedrock).

Precipitation

We had hoped to identify the critical rainfall intensity and recovery interval for slope failure by accumulating data or comparing this region to similar settings (e.g., Guzzetti et al., 2007, 2008). Hennepin County would like to be able to forecast areas of potential failure. Our expectations were shaped by work done by the [USGS](#) for Seattle where a robust relationship was found between 15-day antecedent precipitation and 3-day precipitation (Godt et al., 2006). Unfortunately, the differences in topography and rainfall patterns between the Pacific Northwest and Minnesota preclude this direct comparison. Heavy rainfall in Seattle tends to occur over multiple days from large scale storms, and are enhanced by mountain ranges that rise up in a perpendicular manner to the mean flow. Heavy rainfall in Minnesota tends to be more convectively driven, meaning smaller scale storms that drop incredibly heavy rainfall over small areas over small time scales, reducing the predictability of soil response in any particular location.

In England, the British Geological Survey found that rainfall deviating from the long-term average was important. They typically considered a period 7-90 day prior to the slide versus 7 day high-intensity events. They also found that even though rainfall might exceed a threshold, failure was not likely if there had been dryness in preceding 18 months. However, smaller rain events might lead to a slide if the previous 3-4 months had been wet (Pennington et al., 2014).

Norway takes a different approach to their hydrometeorological data, and tries to simulate soil saturation through their interactive [website](#). They also compare landslide to no-landslide days to better constrain their threshold events.

The National Weather Service uses the Sacramento Soil Moisture Accounting Model (SAC-SMA) in their operational river forecasts, which provides an estimate of soil moisture at various levels below the surface on a large scale. We investigated the feasibility of utilizing the SAC-SMA in this study, but found that while it attempts to model soil moisture for long term river forecasting, it does not provide modeled information for the small scale we desire, nor any actual measurement of soil moisture that we are seeking.

The Standardized Precipitation Index (SPI) looks at long term precipitation patterns and may provide reasonable approximation for antecedent soil moisture. Once SPI reached a yet-to-be-determined threshold, we could then look for short-term (1-3 day) precipitation to act as a trigger. We compared three different July failure events for which we could find SPI data, and the SPI increased markedly toward the event time for the 6- and 9- month timescales as opposed to the shorter timescales. The SPI was very positive for two of the events, but not for one (which occurred in a very extreme short-term rainfall event). There was not always a short-term trigger. The SPI and trigger idea deserves more study in the future, especially if compared to NOAA Atlas 14 information (see next section) (Figure 17).

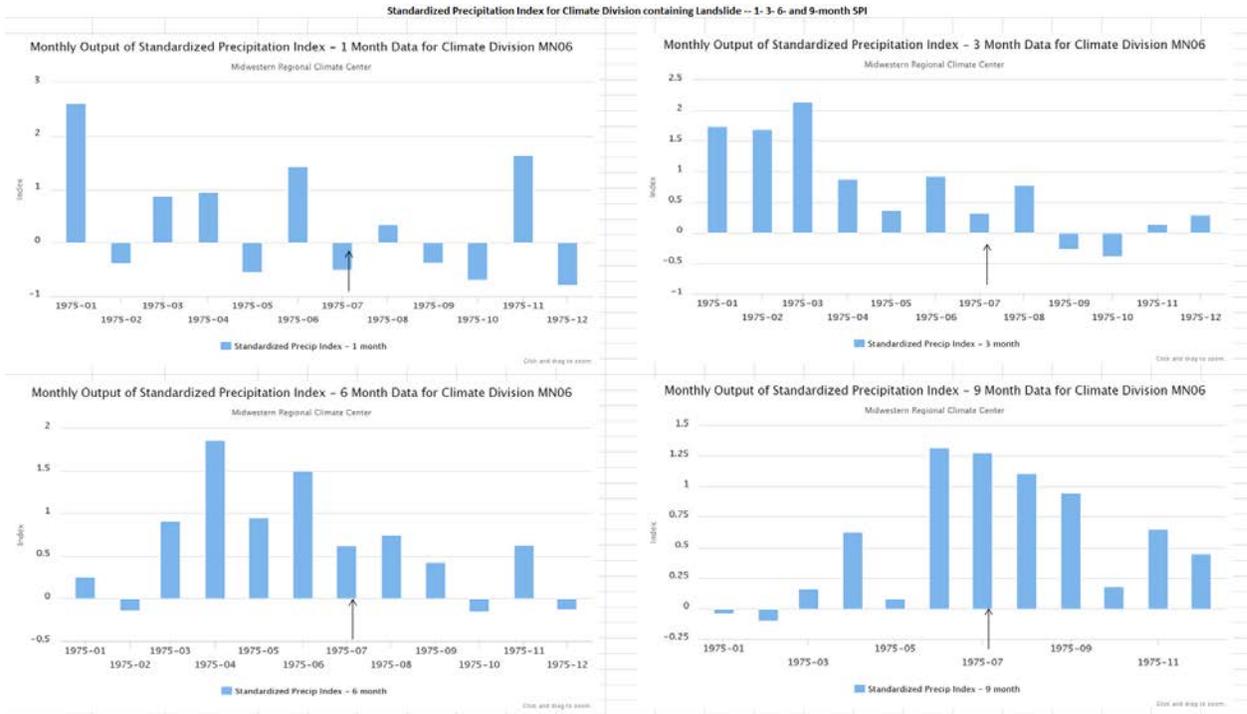


Figure 17a. SPI indexes for July 1975 slide for 1 month, 3 months, 6 months and 9 months. Timing of slide event is indicated by the black arrow.

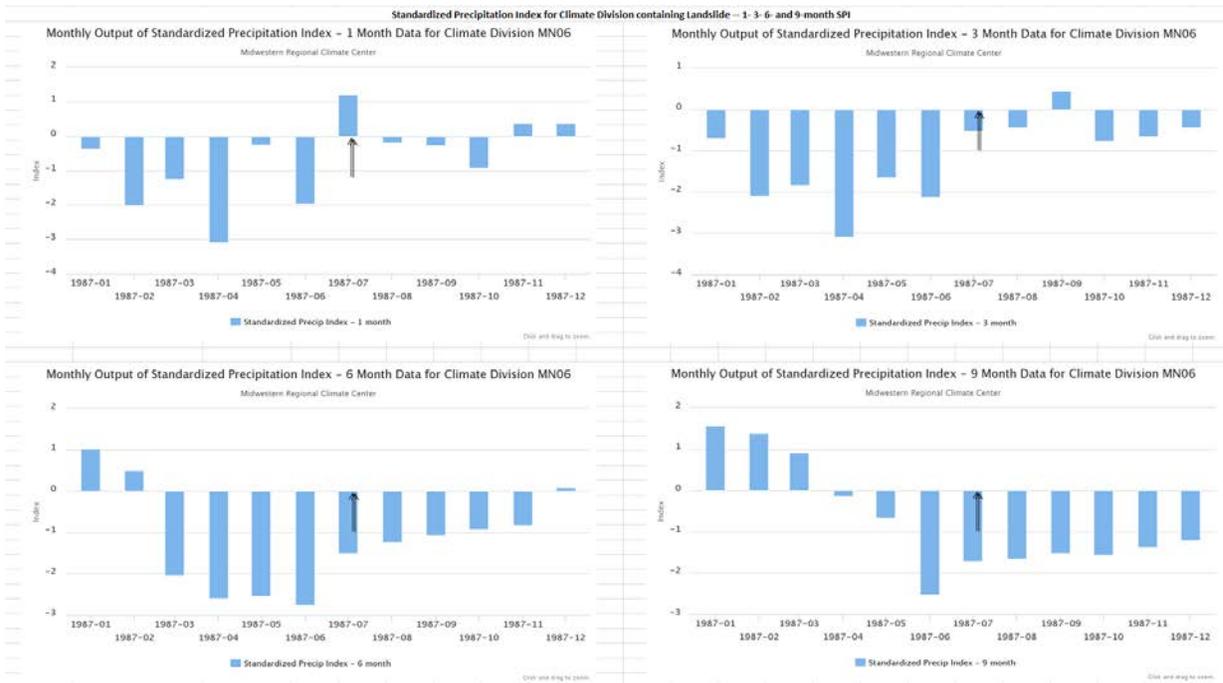


Figure 17b. SPI indexes for July 1987 slide for 1 month, 3 months, 6 months and 9 months. Timing of slide event is indicated by the black arrow.

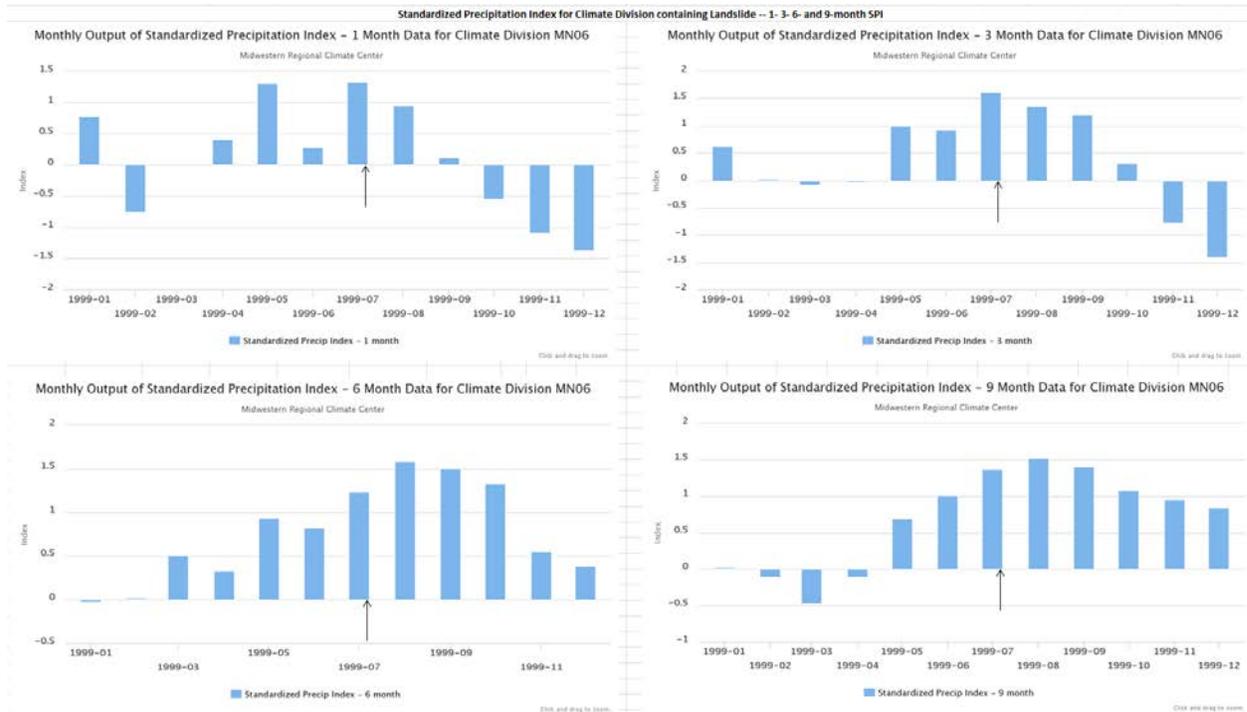


Figure 17c. SPI indexes for July 1999 slide for 1 month, 3 months, 6 months and 9 months.

Timing of slide event is indicated by the black arrow.

Another approach is to [put the rainfall in historical context using the NOAA Atlas 14](#). For the events since 1975 that are listed on the Hennepin tab in the Excel file, Dr. Kenneth Blumenfeld made the following notes (Figure 18, written comm., 2016).

Hennepin County Sites		24-hr rainfall amount (in)	24-hr Recurrence Interval	4-day rainfall	4-day recurrence interval	10-day rainfall amount	10-day recurrence interval	30-day rainfall amount	30-day recurrence interval(only for 2014,2011)
FID_0	6/19/2014	2.71	1 or 2 year	3.44	1 or 2 year	4.8	1 or 2 year	7.64	1 or 2 year
FID_36	5/21/2011	3.03	2 or 5 year	3.27	1 or 2 year	4.21	1 or 2 year	6.87	1 year
FID_36 (2)	5/22/2011	1.82	<1 year	5.09	5 or 10 year	6.03	5 or 10 year	8.53	2 or 5 year
FID_37	6/1/2014	2.76	1 or 2 year	4.25	2 or 5 year	4.37	1 or 2 year	7.24	1 or 2 year
FID_39	7/18/1975	0	<1 year	0	<1 year	0	<1 year	6.03	1 year
FID_40	7/22/1987	11.05	500 or 1000 year	14.75	500 or 1000 year	15.01	500 or 1000 year	17.56	500 or 1000 year
FID_41	6/19/2014	1.82	<1 year	2.43	<1 year	3.71	<1 year	9.02	2 or 5 year
FID_42	7/24/1987	4.31	5 or 10 year	11.88	500 or 100 year	11.97	200 or 500 year	13.82	50 or 100 year
FID_43	7/24/1987	8.02	100 or 200 year	10.43	200 or 500 year	10.54	100 or 200	13.46	50 or 100 year
FID_44	7/24/1987	0	<1 year	11.05	500 or 1000 year	15.01	500 or 1000 year	17.34	500 or 1000 year
FID_107	7/24/1987	0	<1 year	11.05	500 or 1000 year	15.01	500 or 1000 year	17.34	500 or 1000 year
FID_110	7/24/1987	0	<1 year	11.05	500 or 1000 year	15.01	500 or 1000 year	17.34	500 or 1000 year
FID_111	7/24/1987	0	<1 year	11.05	500 or 1000 year	15.01	500 or 1000 year	17.34	500 or 1000 year

Figure 18. Historical Context of Rainfalls since 1975

- July 18, 1975 (FID39). I do not see any recent precipitation associated with this event. The station they pulled had no measurable rain for over 10 days, and even MSP had been dry since the 9th. A

mini heat wave was in progress, with highs in the low-mid 90s and lows in the mid-upper 70s. No heavy precipitation had fallen in the area since the very end of June. June 1975, however, was a very wet month, with about 8 inches at MSP.

- July 20-21 1987 (FID 40). This was the first event of the two shown below (Figure 18a) which dropped between 3.5 and 9 inches of rain on Eden Prairie. Heavy rains fell from around 6 PM to 2 AM, with the highest intensities from 7 PM to midnight. Northeastern parts of Eden Prairie

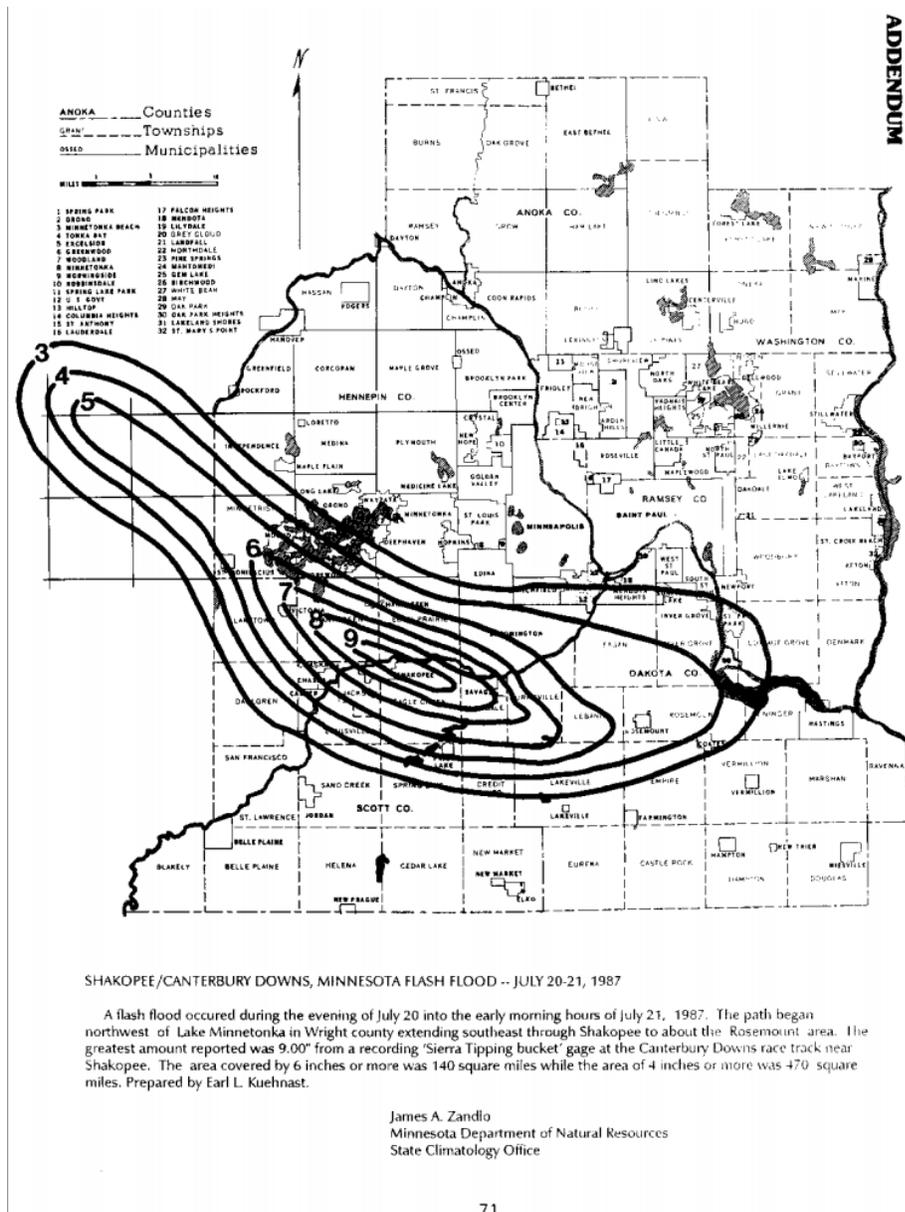
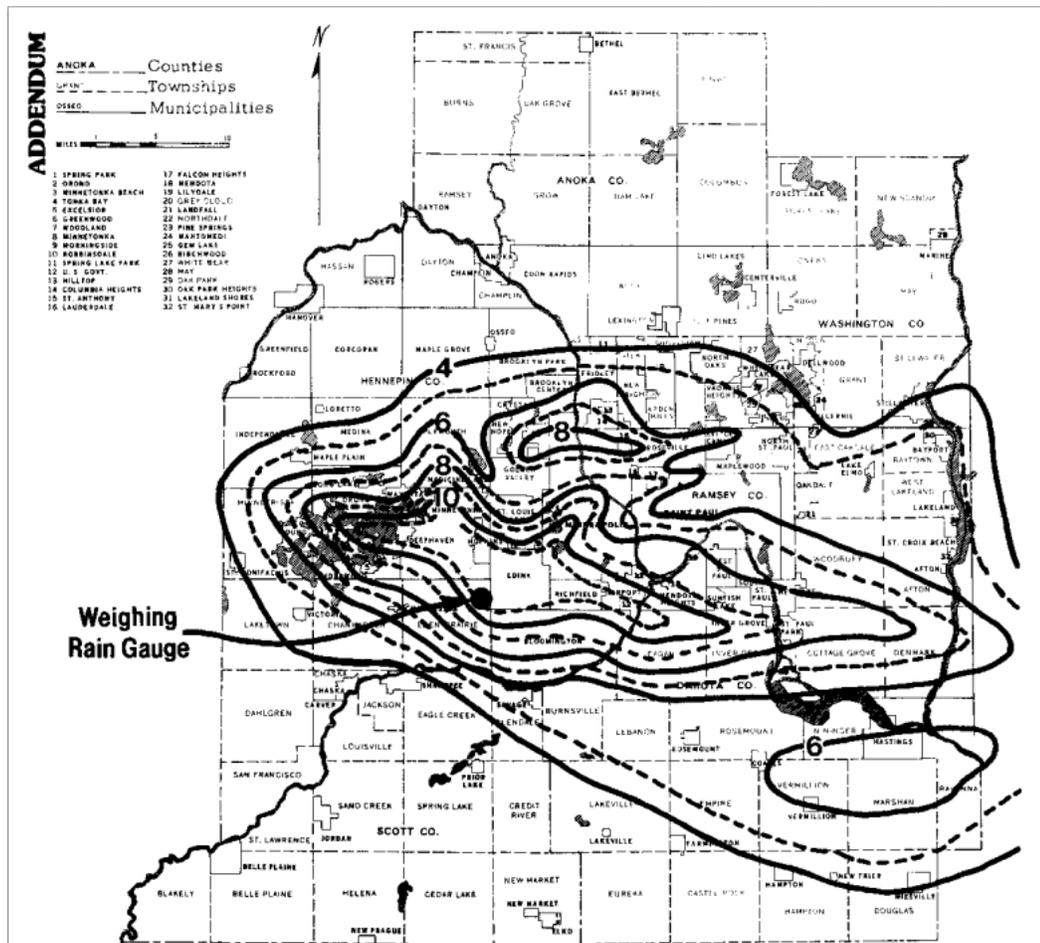


Figure 18a. Precipitation totals for July 21, 1987.

- July 23-24, (FIDs 42-44). The infamous "superstorm," ... with widespread 6-10" values across the central and southwestern TC area. Heavy rains fell from 7PM to 1 AM, with highest intensities from 7-10 PM. Three-hour totals of 7.58 inches were right around 500-year threshold for 3-hour rainfall, from NOAA atlas 14 (Figure 18b).



WESTERN AND SOUTH CENTRAL TWIN CITIES FLASH FLOOD - JULY 23-24, 1987

The flash flood occurred generally between 7PM 23 July to 1AM 24 July, 1987. It's path was on a line from Lake Minnetonka east-southeast through Edina, Inver Grove Heights and into Wisconsin; with rain fall amounts from 6 inches to more than 11 inches. The greatest amount was 11.32 inches documented on a standard weighing rain gage. There were some greater unofficial amounts. Some 335 rainfall reports were used to draw the isohyet map. The area covered by 10 inches or more of rainfall was 93 square miles; 6 inches or more was 574 square miles and by 4 inches or more was 1460 square miles. Much of the 6 inch and greater rainfalls occurred over residential parts of the Twin Cities. To date an estimated 7000 homes have reported water damage. At this time the known costs of damages are approximately 25 million dollars.

This storm was preceded by 72 hours by a similarly oriented storm with totals exceeding 9 inches. The earlier storm fell mostly in adjacent areas to the south and west. However, two storm totals exceeded 16 inches in some areas.

The greatest official 24-hour rainfall amounts for the Twin Cities are as follows: 10.00" on July 23-24, 1987 ranks first, 7.80" in June 1892 ranks second, and 7.36" on August 30, 1977 ranks third. Prepared by Earl L. Kuelhnast.

James A. Zandlo
 Minnesota Department of Natural Resources
 State Climatology Office

Figure 18b. Precipitation totals for July 23-24, 1987.

- July 26-27, 1999 (FID 47). This was a late night event associated with a slow-moving thunderstorm complex, and it dropped 2-4 inches in about 1.5 - 2 hours.
- May 21-22, 2011 (FID 36). This was a 2-headed event. On the evening of the 21st, an isolated severe thunderstorm sat over northwestern Hennepin County, producing very heavy rains for a few hours. Additional storms in the late morning and early afternoon of the 22nd produced heavy rainfall, over a shorter duration, however. 2-day totals in parts of the county were 4-5 inches.

- June 12, 2014 (FID 37). This was only a minor rainfall event on the 11-12th, with totals well under 0.50" in Eden Prairie (and the rest of Hennepin County, for that matter). There had been heavier rains ending on the 1st, but the heaviest totals would come later in the week, after this landslide event.
- June 19, 2014 (FID 0, 41). This was a very heavy rainfall event that occupied most of the morning and early afternoon, with a report of over 5 inches in Eden Prairie, and many 3-5" reports around the county. Heavy rains of 1-2" affected the area June 14-15 also, so the ground would have been very wet.

We do not feel that we currently have enough data to make a robust conclusion regarding rainfall thresholds. We still have questions regarding:

- What window of time is needed to capture the long-term deviation from the average;
- If there is a better way to estimate soil moisture, such as gridded soil moisture modeling;
- If there are better records of rainfall intensity near our slide locations, including radar data;
- Or if there are other things we should be considering.

We do think that the collection of more data is warranted because climatologists show that the recent trend has been towards larger precipitation events (Figure 19). This suggests that precipitation-driven landslides will become more common until hillslopes stabilize in the new climate regime.

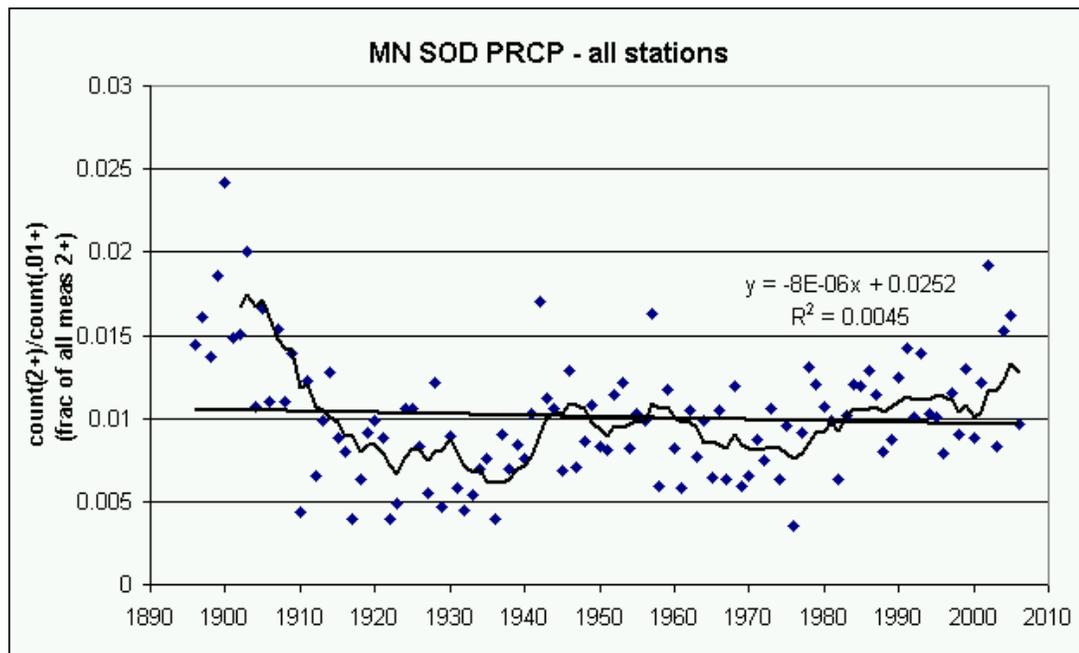


Figure 19. Precipitation events greater than 2" compared to all events vs. time
 There is a recent increase in the proportion of rainfall events that are greater than 2"

Summary

The first step in assessing the susceptibility of a landscape to slope failure is to inventory the locations of historical slides. We reviewed news archives to create an inventory centered on Hennepin County. The slide locations were interpreted in a geologic context. There are three primary styles of failure in Twin Cities metropolitan area: shallow rotational failure in saturated, loamy glacial sediment; dry flow of sand and gravel that has been incised beyond the angle of repose, and topple or fall of joint-delineated slabs of the Platteville Formation that have been undercut. The first two are clearly related to rainfall events; the latter can be induced by rainfall but is also linked to spring flow and would therefore depend on groundwater movement have a delayed response to rain events.

We reviewed a few proposals for bluff repair and million-dollar price tags are not uncommon. Successful lawsuits for damages also reached the million-dollar threshold. The prudent and more economic approach to susceptible slopes is to reduce risk. Slope susceptibility should be reflected in zoning and stormwater policy. As part of this project, FEMA partnered with STANTEC to create a user guide for landslide mitigation strategies that could be distributed to local planning and zoning offices to help guide development and use in areas that are susceptible to landslide failure. Ordinance language examples were included in the document to help Hennepin County develop their own ordinance language. The hope is that this language can be exported to other counties and cities in the metropolitan area for them to use. The next step is to hopefully take the inventory state wide. A team of faculty at The University of Minnesota and the USGS are applying for a grant from the Legislative-Citizen Commission on Minnesota Resources (LCCMR) for a 3 year state wide project.

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Appendix A

Landslide Inventory Database:

Estimated Slide Date	County	City	Style	Material
6/1/2014	Blue Earth	Mankato	Unknown	Unknown
6/1/2014	Blue Earth	Mankato	Unknown	Unknown
6/1/2014	Brown	New Ulm	Unknown	Unknown
6/1/2014	Brown	Sleepy Eye	Unknown	Unknown
6/1/2014	Brown	New Ulm	Unknown	Unknown
6/1/2014	Carver	Carver	Rotational	Glacial sediment (till)
6/1/2014	Carver	Carver	Unknown	Unknown
6/1/2014	Carver	Carver	Rotational	Glacial sediment (till)
6/1/2014	Carver	Carver	Rotational	Glacial sediment
6/1/2014	Carver	Carver	Rotational	Glacial sediment (till)
6/1/2014	Carver	Carver	Unknown	Glacial stream sediment
6/1/2014	Carver	Carver	Rotational	Glacial sediment (till)
6/1/2014	Carver	Chanhassen	Rotational	Glacial sediment (till)
6/1/2014	Carver	Chaska	Rotational	Glacial sediment (till)
6/1/2014	Carver	Chaska	Rotational	Glacial sediment (till)
6/1/2014	Carver	Chaska	Rotational	Glacial sediment (till)
6/1/2014	Carver	Chaska	Rotational	Glacial sediment (till)
6/1/2014	Carver	Chaska	Rotational	Glacial sediment (till)
6/1/2014	Dakota	Lakeville	Rotational	Glacial sediment (till)
6/19/2014	Dakota	Mendota Heights	Rotational	Glacial sediment (till)
7/28/1892	Dakota	South St. Paul	Unknown	Sediment
5/1/1975	Dakota	Lilydale	Rotational	Glacial sediment (till)
6/2/2014	Dakota	Mendota Heights	Rotational	Complex
6/5/1906	Dakota	Mendota Heights	Unknown	Rock and sediment
6/19/2014	Hennepin	Minneapolis	Rotational	Fill
5/21 and 5/22 2011	Hennepin	Maple Grove	Rotational	Glacial sediment and fill
6/1/2014	Hennepin	Eden Prairie	Dry flow	Glacial stream sediment
5/19/1894	Hennepin	Minneapolis	Unknown	Rock and sediment
7/18/1975	Hennepin	Golden Valley	Rotational	Sediment and fill
7/21/1987	Hennepin	Eden Prairie	Rotational	Glacial sediment (till)
6/19/2014	Hennepin	Minnetrista	Rotational	Glacial sediment (till)
7/24/1987	Hennepin	Eden Prairie	Unknown	Unknown
7/24/1987	Hennepin	Fort Snelling	Topple	Platteville Fm
7/24/1987	Hennepin	Bloomington	Rotational	Glacial sediment (till)
4/5/1919	Hennepin	Independence	Rotational	Glacial sediment (till)
7/27/1999	Hennepin	Minneapolis	Rotational	Sediment
7/24/1987	Hennepin	Bloomington	Rotational	Glacial sediment (till)
5/30/1943	Hennepin	Minneapolis	Topple	Rock or boulder

Estimated Slid eDate	County	City	Style	Material
5/30/1942	Hennepin	St Louis Park	Rotational	Sediment
7/24/1987	Hennepin	Bloomington	Rotational	Glacial sediment (till)
7/24/1987	Hennepin	Bloomington	Rotational	Glacial sediment (till)
6/1/2014	Hennepin	Minneapolis	Rotational	Glacial sediment
8/25/2006	Houston	Mound Prairie	Unknown	Unknown
8/25/2006	Houston	La Crescent	Unknown	Unknown
6/1/2014	Le Sueur	Henderson	Rotational	Glacial sediment (till)
6/1/2014	LOTW	Baudette	Unknown	Unknown
6/19/2014	Ramsey	St. Paul	Rotational	Glacial sediment (till)
6/19/2014	Ramsey	St. Paul	Rotational	Sediment
7/28/1892	Ramsey	St. Paul	Unknown	Unknown
8/21/1892	Ramsey	St. Paul	Rotational	Glacial sediment
7/24/1987	Ramsey	Saint Paul	Rotational	Glacial sediment
5/13/1879	Ramsey	Saint Paul	Unknown	Rock and sediment
5/22/2013	Ramsey	Saint Paul	Complex	Rock and sediment
5/1/2011	Ramsey	Saint Paul	Rotational	Glacial sediment and fill
4/8/2011	Ramsey	Saint Paul	Topple	Rock
Winter 1969	Ramsey	Saint Paul	Unknown	Sediment
6/1/2014	Scott	Blakely	Complex	Glacial sediment and fill
6/1/2014	Scott	Prior Lake	Rotational	Glacial sediment (till)
6/19/2014	Scott	Jordan	Rotational	Glacial sediment (till)
8/2014 (estimate)	Scott	Shakopee	Translational	Fill (railroad embankment)
8/2014 (estimate)	Scott	Shakopee	Rotational	Glacial sediment (till)
8/2014 (estimate)	Scott	Shakopee	Rotational	Glacial sediment (till)
6/1/2014	Sibley	Arlington	Rotational	Glacial sediment
6/1/2014	Sibley	Arlington	Rotational	Glacial sediment (till)
6/1/2014	Sibley	Arlington	Rotational	Glacial sediment (till)
6/1/2014	Sibley	Henderson	Rotational	Glacial sediment (till)
6/1/2014	Sibley	Henderson	Rotational	Glacial sediment (till)
6/1/2014	Sibley	Henderson	Rotational	Glacial sediment (till)
6/1/2014	Steele	Medford	Unknown	Unknown
5/2/1882	Washington	Stillwater	Complex	Rock and sediment
7/30/1892	Washington	W Lakeland Twp	Unknown	Sediment
4/29/1893	Washington	Lakeland Shores	Unknown	Sediment
6/5/1897	Washington	Lakeland	Unknown	Sediment
9/26/1903	Washington	Afton	Unknown	Unknown
5/13/1852	Washington	Stillwater	Complex	Sediment
Spring 2003	Wright	Otsego	Unknown	Unknown

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