**M.L. 2017 Project Abstract**
For the Period Ending June 30, 2021

**PROJECT TITLE: Landslide hazards and impacts on Minnesota's natural environment**
**PROJECT MANAGER: Karen Gran**
**AFFILIATION: University of Minnesota Duluth**
**MAILING ADDRESS: Dept. of Earth and Environmental Sciences, UMD, 1114 Kirby Dr.**
**CITY/STATE/ZIP: Duluth, MN 55804**
**PHONE: 218-726-7406**
**E-MAIL: kgran@d.umn.edu**
**WEBSITE: https://scse.d.umn.edu/about/departments-and-programs/earth-environmental-sciences**
**FUNDING SOURCE:** Environment and Natural Resources Trust Fund
**LEGAL CITATION: M.L. 2017, Chp. 96, Sec. 2, Subd. 03i** as extended by M.L. 2020, First Special Session, Chp. 4, Sec. 2

**APPROPRIATION AMOUNT: $500,000**
**AMOUNT SPENT: $494,583**
**AMOUNT REMAINING: $5,146**

## Sound bite of Project Outcomes and Results

Landslides in five regions across Minnesota were mapped and inventoried to identify geologic and topographic conditions vulnerable to slope failures providing resource and emergency managers with better predictive tools to guide land-use decisions. Landslides are a dominant source of sediment to regional waterways, occurring frequently along steep valley walls.

## Overall Project Outcome and Results

In June 2014, widespread landslides occurred in south-central Minnesota; a similarly rainy period in 2012 caused two deaths. In June 2012, a two-day rain event in Duluth generated hundreds of landslides, extensively damaging Jay Cooke State Park and surrounding areas. In August 2007, a year's worth of rain fell in 36 hours in southeastern Minnesota causing extensive landsliding. Weak clay soils in the Red River valley frequently fail, undermining homes and roads. All of these eroding, hazardous slopes present an acute natural resource and emergency management challenge, yet until now, the state lacked landslide hazard maps. Because mass wasting processes vary with geology, we defined five study areas in which we documented the distribution, failure mechanisms, and frequency of landslides in order to help resource managers make sound mitigation decisions.

Each region was mapped by a different partner institution using established data standards and protocols through: 1) historical research, 2) mapping known slides onto high-resolution lidar base maps, and 3) identifying additional landslides using lidar data; topographically-derived maps (slope, hillshade, and red relief); and aerial imagery. Slide sites were field-checked where possible for geology, hydrogeology, vegetation cover, and land use.

In northeastern Minnesota, where repeat lidar data were available, additional work was done. Repeat lidar data collected before and after a major 2012 storm event were properly aligned to allow erosion and deposition to be quantified, and Object-Based Image Analysis was used to define and classify types of change (erosion, deposition in different settings) across the landscape.

Landslide susceptibility modeling in that same, well documented area illuminated which landscape parameters were most important to slope stability: slope, distance to stream, and depth of glacial deposits overlying competent bedrock. The method developed in northeastern Minnesota can be applied to the other four areas of the state.

## Project Results Use and Dissemination

Project results were disseminated to local and regional stakeholders through presentations at meetings and to the scientific community through conference presentations. The full inventory database is being released through the U. S. Geological Survey with an accompanying U. S. Geological Survey Fact Sheet on Landslides in Minnesota. These products will be available to assist with emergency management planning and natural resource assessments of sediment loading in watersheds across the state. Details on landslide mapping methodologies and results across the state, and multitemporal lidar correction and Object-Based Image Analysis research in northeastern Minnesota will be published through publicly-available scientific papers.

# Environment and Natural Resources Trust Fund (ENRTF) M.L. 2017 LCCMR Work Plan Final Report

**Date of Submission: 08/16/2021**

**Final Report**

**Date of Work Plan Approval: 06/07/2017**

**Project Completion Date: 06/30/21**

**PROJECT TITLE: Landslide hazards and impacts on Minnesota's natural environment**

**Project Manager:** Karen Gran

**Organization:** University of Minnesota, Duluth

**Mailing Address:** Dept. of Earth and Environmental Sciences, UMD, 1114 Kirby Dr.

**City/State/Zip Code:** Duluth MN, 55812

**Telephone Number:** (218)726-7406

**Email Address:** kgran@umn.edu

**Web Address:** http://www.d.umn.edu/~kgran/

**Location: Statewide**

| **Total ENRTF Project Budget:** | **ENRTF Appropriation:** | **$500,000** |
|---|---|---|
| | **Amount Spent:** | **$494,583** |
| | **Balance:** | **$5,146** |

**Legal Citation: M.L. 2017, Chp. 96, Sec. 2, Subd. 03i** as extended by M.L. 2020, First Special Session, Chp. 4, Sec. 2

**Appropriation Language:**
*$500,000 the first year is from the trust fund to the Board of Regents of the University of Minnesota to create landslide susceptibility maps using a landslide inventory and quantitative analysis of LiDAR to provide tools and data for mitigation and restoration to reduce impacts on water resources. This appropriation is available until June 30, 2020, by which time the project must be completed and final products delivered.*

M.L. 2020 - Sec. 2. ENVIRONMENT AND NATURAL RESOURCES TRUST FUND; EXTENSIONS. [to June 30, 2021]

**I. PROJECT TITLE:** Landslide hazards and impacts on Minnesota's natural environment

**II. PROJECT STATEMENT:** The state of Minnesota faces threats to environmental sustainability due to excessive sediment that ***negatively affects water quality, riparian ecosystems, trout and other fisheries and recreational facilities.*** Recent research by members of this proposal team identified that ***the majority of sediment delivered to many watersheds comes from bluff erosion and landslides adjacent to stream channels***. Furthermore, landslides have caused considerable damage to infrastructure and even loss of life in Minnesota. Eroding, hazardous slopes present an acute natural resource management challenge, yet the state lacks a landslide hazards map and mitigation strategy. Our proposed research will provide information on the distribution, failure mechanisms, and frequency of landslides in order to make sound mitigation decisions. We will address this challenge through the following actions:

- **Inventory the locations of recent landslides in Minnesota**
- **Evaluate the types of landslides, their geologic and topographic settings and their causes**
- **Use high-resolution data (lidar) to map of landslide susceptibility quantitatively**
- **Provide tools for land managers to make informed decisions about mitigation and restoration.**

In June 2014, widespread landslides occurred in south-central Minnesota; a similarly rainy period in 2012 caused two deaths. In June 2012, a two-day rain event in Duluth generated hundreds of landslides, extensively damaging Jay Cooke State Park and limiting access to Thomson Dam, which was in jeopardy of failing. In August 2007, a year's worth of rain fell in 36 hours in southeastern Minnesota causing extensive landsliding. Weak clay soils in the Red River valley frequently fail, undermining homes and roads. These events defined our study areas:

- **Mississippi River in southeast Minnesota**
- **Minnesota River valley from New Ulm to Chaska**
- **Lake Superior watershed**
- **Red River Valley**
- **7-county Metropolitan area**.

**III. OVERALL PROJECT STATUS UPDATES:**

**Project Status as of** *March 5, 2018:*
As of March 5, 2018, the historical inventories are underway in all five of our study regions. Historical inventories are being conducted via a number of methods including 1) library research of newspapers, 2) research into newspapers at the Minnesota Historical Society, 3) research into online newspaper archives (especially in Winona County), 4) Soil Water Conservation District records, 5) MnDOT records, 6) local city records, and 7) consulting firm records. Different approaches have proved more useful in different parts of the state. Field mapping has begun in Hennepin County, the Minnesota River valley, and Southeastern Minnesota. Summer staff are being hired to complete field mapping in all five regions. We continue to meet monthly via phone to update progress to the full group and maintain communication between collaborators.

**Amendment Request** March 5, 2018:
We are requesting a rebudget of $19,500 that was originally allocated to pay for a "graduate research assistant" to instead go towards salary and fringe for a "post-doctoral research assistant". The post-doctoral research assistant will do the work originally intended for the graduate research assistant, and help with the development of a process domain model (Activity 2). No funds need to be shifted between activities. We simply want to hire a staff member with a different classification than was listed in the original budget.

**Amendment Approved by LCCMR 3/14/2018**

**Project Status as of** *July 30, 2018:*

Landslide mapping is well underway in all of our project areas (Metro Area, Minnesota River valley from Chaska to New Ulm, Red River valley in NW Minnesota, Lake Superior watershed in NE Minnesota, and SE Minnesota). Historical landslide inventories using available records are complete in many of the areas and should be complete in all of them by fall 2018. Most areas have moved on to mapping slides from lidar topography and aerial imagery and subsequent field verification of the results. Some regions are nearing completion of all field mapping (i.e. Upper Minnesota River valley), while others will require through the end of summer 2019 to complete field verification and field data collection.

We have begun discussions of landslide susceptibility mapping methodologies and have decided to use northeastern Minnesota in the vicinity of Duluth as the first test area because of the density of mapped and field verified landslides from the 2012 flood, as well as the availability of repeat aerial lidar in this region. We have acquired the entire raw observational lidar dataset from the original data vendor for the 2011 and 2012 Duluth area lidar that brackets the megastorm of June 2012, and are working to improve the processing of the lidar collections in order to minimize the significant internal alignment errors within each dataset. This is complete at a first pass, though we are still assessing the degree of improvement and may refine our work further. This important step will lead to improved change detection data across the region. The improved topographic change maps will feed into object-based image analysis to properly characterize the effects of the 2012 storm and to assist with landslide susceptibility analysis.

**Project Status as of** *January 30, 2019***:**
Landslide mapping continues in all of our project areas. Historical landslide inventories using available records we could find are complete in all areas as point files, and in most areas as polygons with full attributes. All areas have moved on to mapping slides from lidar topography and aerial imagery and subsequent field verification of the results. As a group we have begun doing comparisons between areas to ensure consistency in mapping. The project is on track to complete all mapping work, including field verification and identification of underlying geology and process by fall 2019. Individual groups have worked on identifying the underlying geologic units, stratigraphy, topography, and hydrology that leads to failures of different kinds in their regions. This work will continue with field work this upcoming summer.

We completed reregistration of repeat aerial lidar data in the Duluth area (before and after the 2012 flood). Internal tests have shown that the alignment between the two datasets has improved overall. Next steps involve comparing the repeat aerial lidar with field identified slides from the event and repeat terrestrial lidar data.

**Project Status as of** *July 30, 2019:*
Most of the work involving landslide mapping this period has involved finalizing remote mapping inventories and field checking them. We are also working on QA/QC for inventory datasets as they come in to ensure continuity between mapping groups and areas. The project remains on track to complete all mapping work, including field verification and identification of underlying geology and process by fall 2019. Individual groups have worked on identifying the underlying geologic units, stratigraphy, topography, and hydrology that leads to failures of different kinds in their regions. The repeat lidar alignment work has continued, with a more complete understanding of the inconsistencies and errors between datasets. In addition, work is progressing using object based imagery analysis (OBIA) as a way to map to better classify maps of topographic change.

The research group continues to hold monthly phone meetings. We met in Duluth in June 2019 to discuss updates in each group and processes driving landsliding in each area across the state. Mass wasting processes can be variable in different regions across the state due to the unique underlying bedrock and surficial geology. Part of this meeting involved a field trip to see some of the different types of slides in the Duluth area and discuss how we best incorporate observations from the field of site complexities into the geodatabase and process models.

**Project Status as of** *January 30, 2020*:
In the last six months, most of the groups have finished their historic landslide inventory maps and remote mapping from lidar and aerial photography. The Two Cities metro area and Minnesota River valley corridor are complete. Work is on-going now to QA/QC the Minnesota River valley and expand the mapping into upper tributaries in this area based on previously mapped eroding bluff databases. In the Red River, Northeastern Minnesota, and Southeastern Minnesota, mapping is almost complete. Groups are finalizing their maps and updating their attribute tables. Field checking is complete, although the fraction of slides field-checked varies by area. QA/QC has begun from all areas. All groups have tracked the locations mapped and locations field-checked to ensure good communication of data quality. Three of the lead investigators met in January to review work completed to date and assemble plans to complete the mapping portion of the project by mid-summer.

Analyses of repeat lidar in the Duluth area is also complete (Activity 3), and is now being used with Object Basin Image Analysis to better define and classify types of change (erosion, deposition in different settings) across the landscape. OBIA allows us to better understand what happened and how it might impact landscape processes like sediment transport in river corridors rather than just quantifying volumetric change.

Susceptibility mapping is also on-going. We have a better understanding of how the variability in bedrock geology and surficial deposits impacts slope hazards across the state and are using that to develop multiple susceptibility models that will be applicable in different areas.

Our group continues to meet monthly for updates, and present on-going results to stakeholders and to the scientific community at research meetings.

All mapping (historical, remote, and susceptibility) should be complete by mid-summer. We anticipate needing extra time beyond the original end date for internal QA/QC of the map product before it can be released. Because the USGS (United States Geological Survey) is a partner and author of the final maps, all data products will need to undergo internal review before they can be released. This will likely take longer than the August 15th, 2020, deadline for submitting our final report and mapping products.

**Project extended to June 30, 2021 by LCCMR 6/18/20** as a result of M.L. 2020, First Special Session, Chp. 4, Sec. 2, legislative extension criteria being met.

**Project Status as of July 1, 2020:**
As of the end of June, the historical inventory and all field-checking were complete. We have a team going through all of the mapped areas now for Quality Control purposes, to make sure that polygons are mapped with the same specificity across the state. Attributes are being calculated and updated across the state. The inventory is almost ready for internal review by the US Geological Survey, as the data release will be coming from them.

Landslide susceptibility modeling work was completed in northeastern Minnesota to assess the role of spatial scale and determine which landscape parameters were most important to slope stability in this region. In addition to slope, distance to stream and depth to bedrock both proved to be useful predictor variables, as relief in the system is driven in part by incision that is propagating upstream on all major rivers. The thickness of glacial deposits on top of competent bedrock was also important. The method used in NE Minnesota is now being spread to other areas of the state. Given the differences in both bedrock geology and surficial geology, it is expected that different parameters may emerge as important in other regions of the state.

The repeat lidar data in northeastern Minnesota are “fixed”, after realignment strip-by-strip. The repeat lidar change detection data are being analyzed using Object-based image analysis (OBIA) to assign interpretation to different patterns of change, adding more information to what is otherwise an accounting of volumetric change. This work expanded in scope to cover a much greater area than the initial test case in the southwest corner of the repeat lidar blocks in NE Minnesota.

Our group continues to meet monthly online. With the completion of the inventory mapping, many of our subcontracts have been completed. In May, we convened a session at the North-Central section meeting of the Geological Society of America, held virtually from Duluth, MN, where we gave a series of talks on the status of the project across the state. Those talks are available publicly and are linked to in section V below.

**Project Status as of January 1, 2021:**
Over the past six months, most of the work has focused on data QA/QC. Most of our subcontracts have ended and the field and remote mapping is complete. We have a supervisory crew (DeLong, Jennings, Gran) working with several staff who are going through all of the mapped data to ensure quality control. The data release should be ready by late spring for US Geological Survey internal review and then external release.

We have written a draft landslide Fact Sheet for Minnesota, which will be completed this spring. We have made progress on two publications: one will focus on the mapping and susceptibility modeling work across the state, and the second will focus on Object-based image analysis from repeat lidar analyses coupled with field mapping in northeastern Minnesota.

Lastly, susceptibility modeling is proceeding. Northeastern Minnesota was used to test different kinds of susceptibility models and different scales of analysis. As we complete QA/QC work on different subregions, we are moving on to develop susceptibility models for each subregion.

**Amendment Request** April 26, 2021:
We are requesting a rebudget of $9046 that was originally allocated for travel, supplies, and subcontracts that were not fully spent down into salary and fringe. Our plan originally was to present the bulk of our research findings at the North-Central Geological Society of America meeting in Duluth in May 2020. We did accomplish this, however the conference was virtual and required no travel expenditures. The specifics of the budgetary changes are
Travel expenses in Minnesota: Originally $4995. Change to $1683.
Rationale: Travel was severely curtailed due to the pandemic.
Supplies: Originally $1500. Change to $179.
Rationale: We were able to borrow much of the equipment we needed and thus have more funds than we needed for supplies.
Subcontracts: Originally $324,692. Change to $320,278
Rationale: All but one of the subcontracts have ended and two of them had unspent funds we would like to reallocate to on-going staffing needs.

Personnel: Originally $167,813. Change to $176,859
Rationale: We would like to be able to continue paying staff to complete final tasks for the project.

The other amendment request involves a slight change to our personnel classifications. We have funds set aside for Graduate Research Assistants and Undergraduate Research Assistants. Sometimes when our students graduate, we rehire them back under a “temporary and casual” appointment to enable them to continue working on the project. We would like to add “temporary and casual” to the Graduate Research Assistant salary pool to enable those employees to be covered by grant funding for the same work.

**Amendment Approved by LCCMR 5/7/2021**

**Overall Project Outcomes and Results:**

In June 2014, widespread landslides occurred in south-central Minnesota; a similarly rainy period in 2012 caused two deaths. In June 2012, a two-day rain event in Duluth generated hundreds of landslides, extensively damaging Jay Cooke State Park and surrounding areas. In August 2007, a year's worth of rain fell in 36 hours in southeastern Minnesota causing extensive landsliding. Weak clay soils in the Red River valley frequently fail, undermining homes and roads. All of these eroding, hazardous slopes present an acute natural resource and emergency management challenge, yet until now, the state lacked landslide hazard maps. Because mass wasting processes vary with geology, we defined five study areas in which we documented the distribution, failure mechanisms, and frequency of landslides in order to help resource managers make sound mitigation decisions.

Each region was mapped by a different partner institution using established data standards and protocols through: 1) historical research, 2) mapping known slides onto high-resolution lidar base maps, and 3) identifying additional landslides using lidar data; topographically-derived maps (slope, hillshade, and red relief); and aerial imagery. Slide sites were field-checked where possible for geology, hydrogeology, vegetation cover, and land use.

In northeastern Minnesota, where repeat lidar data were available, additional work was done.  Repeat lidar data collected before and after a major 2012 storm event were properly aligned to allow erosion and deposition to be quantified, and Object-Based Image Analysis was used to define and classify types of change (erosion, deposition in different settings) across the landscape.

Landslide susceptibility modeling in that same, well documented area illuminated which landscape parameters were most important to slope stability: slope, distance to stream, and depth of glacial deposits overlying competent bedrock.  The method developed in northeastern Minnesota can be applied to the other four areas of the state.

## IV. PROJECT ACTIVITIES AND OUTCOMES:

### ACTIVITY 1: *Landslide inventory data collection*

**Budget: $50,357**

**Description:** Conduct historical research; perform lidar and air photo analyses to identify slide locations.

Each of the five study areas has experienced landslides in the past. They have caused infrastructure damage and contributed to excess sediment loading in major rivers. The first activity involves developing an inventory of historic landslides. Each of the five regions in the state will be covered by a different partner using established data standards and protocols. Each partner institution will conduct historical research in local archives to find all documented landslides in their region. Stephanie Day at NDSU will cover the Red River valley, Dylan Blumentritt at Winona State University will cover SE Minnesota, Laura Triplett at Gustavus Adolphus College will cover the Minnesota River valley from St. Peter to Chaska, and Phil Larson at Minnesota State University Mankato will cover the Minnesota River from New Ulm to St. Peter. Preliminary work in the Minneapolis-St. Paul metropolitan area has been conducted by Carrie Jennings at the University of Minnesota. She will continue that work in collaboration with Jeni McDermott at the University of St. Thomas. Andrew Breckenridge at the University of Wisconsin-Superior has already mapped landslides associated with the 2012 flood in the Nemadji River area near Duluth. He will contribute those data and help with the integrated mapping. The rest of the Lake Superior watershed will be covered by Karen Gran at the University of Minnesota Duluth.

All of the historical landslides will be compiled into a master database containing information on when and where each event occurred, and contain information about the nature of the landslide. The geospatial database will be overlain on statewide aerial lidar data. The topographic and geologic settings of historically-documented slides will then be used to map other sites where slides are likely to have occurred.

The outcome of this activity will be a database covering the five regions of the state noted above (Red River valley, Minnesota River valley, SE Minnesota, Lake Superior watershed, and Metro area), a geospatial database with documented slide locations and locations of apparent past landslides as indicated by landscape morphology.

**Summary Budget Information for Activity 1:**

| | |
|---|---|
| **ENRTF Budget:** | **$ 50,357** |
| **Amount Spent:** | **$ 50,346** |
| **Balance:** | **$ 11** |

| Outcome | Completion Date |
|---|---|
| 1. Completed historical records search for the 5 landslide regions | July 2018 |
| 2. Compiled digital database of landslide locations to guide follow-up work | Oct. 2018 |

**Activity 1 Status as of** *March 5, 2018:*
As of March 5, 2018, the historical inventories are underway in all five of our study regions. Historical inventories are being conducted via a number of methods including 1) library research of newspapers, 2) research into newspapers at the Minnesota Historical Society, 3) research into online newspaper archives (especially in Winona County), 4) Soil Water Conservation District records, 5) MnDOT records, 6) local city records, and 7) consulting firm records. Different approaches have proved more useful in different parts of the state, depending on the records available.

**Activity 1 Status as of** *July 30, 2018***:**
There are two main parts to developing the initial landslide inventory: 1) mapping documented slides from historical archives and 2) mapping slides from lidar and air photos with similar topographic expressions. Phase 1

is nearly complete in all five mapping areas, with the number of historically-documented slides varying significantly depending on location and population.

Phase 2 is proceeding in all five areas. We held an internal training session in spring 2018 to standardize mapping procedures. We disseminated tiled maps of lidar topography and derivative products to entire project staff (e.g., shaded relief with multiple sun angles, slope maps, aspect, and curvature maps) to support landslide mapping in each of the five designated regions. Our group has developed and disseminated a working database structure for all landslide inventory observations. The database uses the ESRI geodatabase structure and is modified from existing landslide inventory databases used by the states of Oregon and Washington as well as that used in Hennepin County. During the course of the project all participants will populate this database and it will be published along with digital map products.

**Status by mapping area:**
**7-county Metropolitan area:** The existing inventory was updated to include slides that have occurred during the past year.

**Mississippi River in SE Minnesota:** Sub-group consists of one faculty member, one graduate student, and two undergraduate students, all from Winona State University. Completed: We have conducted historical landslide searches for six counties in southeast Minnesota (Goodhue, Olmsted, Wabasha, Winona, Houston, and Fillmore). These historical landslides were mapped into a GIS, wherever it was possible to get a general location from articles/photos. Ongoing: We are in the process of identifying and mapping possible landslides from lidar-derived topography imagery for all six SE Minnesota counties. Students are scanning each county in 1 square mile increments and mapping possible landslides in a GIS, which will be field verified. In addition to historical slide research and image analysis, we have also identified and mapped several recent slides by conducting field surveys, primarily along roadways.

**Red River Valley:** Historical record search was conducted for 8 counties (Clay, Polk, Marshall, Beltrami, Becker, Ottertail, Norman, and Kittson) in the watershed, and 12 landslides or significant erosion events were documented, located, and mapped in a GIS. Additional historic air photo analysis is ongoing to locate areas that require further investigation where landslides may have occurred, but did not turn up on the historic record search.

**Minnesota River Valley from New Ulm to Chaska:** We have begun populating the landslide inventory with historical landslides as identified in media reports, lidar imagery, and aerial photographs in the St. Peter to Chaska reach. In the New Ulm to St. Peter reach, o**ne** Minnesota State faculty member, one graduate student, two undergraduates and two Minnesota State classes have conducted field mapping (utilizing Trimble Geo7x GNSS units) and interpretation throughout study area. Field-based mapping and interpretation was cross-verified with remote datasets (e.g. LiDAR derived DEMs, historic aerial imagery) and historic records (e.g. historical societies, county and local government agencies). We have also identified and characterized failures within and near to our study area that have occurred during our investigation (e.g. http://mankatotimes.com/2018/07/01/highway-68-south-of-courtland-closed-due-to-mudslide/)

To date, 262 mass wasting sites have been identified, characterized and described. With each identified mass wasting event, the following attributes were incorporated into the attribute table within the geodatabase: 1) class-type of failure, 2) type of substrate/geologic material that failed, 3) headscarp height and width, 4) failure depth, 5) aspect of movement-bearing, 6) failure mass area-if observed in LiDAR, 7) estimated date of occurence or age range, 8) associated damage, 9) photograph of site, 10) slope of landscape where failure occurred.

We are nearing completion of field mapping and interpretation in the reach upstream of St. Peter, along with compilation of historic records and identification from remote datasets (e.g. LiDAR and aerial imagery). Limitations experienced thus far are: 1) a lack of robust historical record in any archives, 2) rejection of permission to investigate by landowners, and 3) occasional safety concerns on steep, failing slopes. These limitations may result in some "holes" in the mapped locations within our study reach, but the frequency of failures observed elsewhere could be used to interpolate what may be going on in places we are unable to visit in-person. Finalized inventory and a completed geodatabase is nearing completion - estimated to be finished by end of summer 2018.

**Lake Superior Watershed:** A historical inventory of newspaper reports of landslides was conducted for Carlton, St. Louis, Cook, and Lake Counties, focusing on time periods with recorded heavy rainfall. The flood of June 2012 was treated separately, so the historical search focused on other events. These records were augmented with files of projects from the NRCS (Natural Resources Conservation Service), and we are working on obtaining additional records from other local agencies as well as from a variety of surveys conducted for water quality assessments. All slides documented so far have been located on Google Earth imagery and plotted in a GIS database.

For the June 2012 flood, landslides were identified using several methods: 1) within and around the city of Duluth, volunteer streamwalk records and photos were used to identify slide locations, 2) in the St. Louis River estuary, slides were mapped using repeat aerial photography, and 3) within Jay Cooke State Park, slides were mapped based on repeat imagery as well as notes from park staff. Slide locations were verified using Google Earth imagery and lidar topography and are being added to the official geodatabase in GIS. We plan to finish the historical inventory by the end of summer 2018, and are starting phase 2 mapping of potential slides to be field-checked based on aerial imagery and lidar topography.

**Activity 1 Status as of** *January 30, 2019:*
There are two main parts to developing the initial landslide inventory: Phase 1 mapping documented slides from historical archives and Phase 2 mapping slides from lidar and air photos with similar topographic expressions. Phase 1 is complete in all five mapping areas, with the number of historically-documented slides varying significantly depending on location and population. Although the initial maping in Hennepin County demonstrated the value of historic media like newspapers, other areas of the state had more limited media resources. Instead, we relied more on historic air photos showing when events occurred, NRCS (National Resource & Conservation Service) or SWCD (Soil Water Conservation District) files of projects conducted following mass failures, consulting reports, and sediment stressor reports. We have kept track in each area which resources have been reviewed.

Phase 2 is proceeding in all five areas, and is nearing completion in most areas. We met in January 2019 through a 2-hour webinar to review mapping procedures from region to region, and updates are now proceeding based on protocols discussed in the meeting.

**Status by mapping area:**
**7-county Metropolitan area:** One University of St Thomas faculty member (Dr. Jeni McDermott) and four undergraduate students (Matt Endres, Victoria Orchard, Jordan VanBerkel, and Kate Mohn) finalized the historical inventory. The historical archives available in the metro area are quite extensive and date back to 1852; 64 slope failure events were documented from the historical archives, 51 of which were located in the field and mapped. Additional mapping has been carried out using LiDAR derived DEMs and derivatives (hillshade, slope, slopeshade) paired with satellite images. The attribute tables for the digital map files are still being populated. Based on interpretations of slide morphology, 358 additional undocumented landslides have been identified. The majority of the slope failures are concentrated in the valley walls of the Mississippi and Minnesota Rivers and their tributaries. Detailed mapping of these slope failures using LiDAR and field mapping has occurred on approximately 60% of identified slides (creation of slide polygons, population of attribute tables). Future work includes (1) continuing the detailed mapping of LiDAR-identified failure events along with completion of field mapping, and (2) evaluation of landslide type, documentation of substrate, and evaluation of the relationship of substrate on the location and type of slide events. Preliminary analysis indicates many slope

failures along river corridors correlate with deposits of friable, mixed glacial and fluvial sediment, while rockfall events correlate with locations where the Platteville limestone is exposed above soft St. Peter sandstone. We plan to complete the LiDAR inventory and fieldwork by the end of May 2019.

**Minnesota River valley St. Peter to Chaska:** The historical inventory is complete. There were limited historical records available in the area. Two Gustavus faculty (Dr. Julie Bartley and Dr. Laura Triplett) and two undergraduate students (Emily Fischer and Alex Senjem) have nearly completed a first pass of mapping slides in this region. Mapping of additional slides is primarily being conducted using remote datasets (e.g. LiDAR, derived DEMs); small areas are then field-checked. Several hundred slides have been identified, mostly of small extent, having slide, flow or complex movement, and positioned entirely within the glacial till. Next steps include revising some slide polygons to conform to new group-wide agreements about slide mapping and terminology and populating attribute tables. Finally, some progress has been made toward evaluating whether differences exist in landslide density/extent between the northern and southern parts of this region. We intend to provide a characterization of landslide types by the end of May 2019.

**Minnesota River Valley from New Ulm to St. Peter:** Historic mapping is complete. There were limited historic resources in this area. Historic air photos are being utilized to determine the timing of any historic mass wasting event.

Phase 2 mapping has proceeded in conjunction with field mapping efforts. In this reach and since our last report, one Minnesota State faculty member (Dr. Phillip Larson), one graduate student (Missy Swanson), one undergraduate student (Rainier Bergstrom-Conley) and a Minnesota State class (Geog 416/516: Fluvial Geomorphology) have conducted field mapping (utilizing Trimble Geo7x GNSS units) and interpretation throughout study area. Field-based mapping and interpretation was cross-checked with remote datasets (e.g. LiDAR derived DEMs, historic aerial imagery) and historic records (e.g. historical societies, county and local government agencies). We are utilizing historic aerial photographs to attempt to “frame” the timing of any historic mass wasting event. Those identified but not observed in historic aerial imagery will be classified as prehistoric mass wasting events.

We have populated and nearly completed the landslide inventory within this study reach. The database and inventory should be completed by mid-spring 2019. To date, 545 total mass wasting sites have been identified and mapped through a combination of field investigation and remote imagery analysis. With each identified mass wasting event catalogued with the following attributes in an attribute table within an ArcGIS geodatabase: 1) class-type of failure, 2) type of substrate/geologic material that failed, 3) headscarp height and width, 4) failure depth, 5) aspect of movement-bearing, 6) failure mass area-if observed in LiDAR, 7) estimated date of occurence or age range, 8) associated damage, 9) photograph of site, 10) slope of landscape where failure occurred. In addition, we note that volume estimates of slide masses have proven difficult as boundaries of slide masses are often diffuse or obscured in LiDAR and aerial imagery.

Lastly, progress is being made towards statistically correlating attributes catalogued at each mass wasting site with the type of mass wasting failure observed (e.g. complex, fall, flow, slide, topple). We hope that these data will help future work in assessing and predicting sites prone to future failure. We hope that this will be completed by July of 2019.

**Mississippi River Valley in SE Minnesota:** We have completed landslide identification in two counties (Goodhue and Wabasha). Slides were identified from lidar imagery and then field-verified or simply identified and mapped in the field. There were 116 total landslides in these two counties, the most common types being rock falls, debris falls, and translational slides. These mass wasting events occurred in eight different stratigraphic units, primarily in the St. Lawrence Fm and Oneota Dolomite. The remaining three southeastern Minnesota counties (Winona, Houston, and Fillmore) have ongoing work. Historical landslides have been identified from media sources, and identification from lidar imagery is ongoing. We will begin field verification this spring and into the summer. The completed Wabasha and Goodhue County work was presented at the Annual Geological Society of America Fall meeting in Indianapolis, IN.

**Red River Valley**: The historic inventory is being georeferenced and comparisons with digital data to expand to less populated areas has begun. While there are relatively few large scale landslides in this region, mudflows are quite common. Field verification of predicted activity will begin this spring.

**Lake Superior Watershed:** Our inventory of historically-documented landslide locations for Carlton, St. Louis, Lake and Cook counties is complete. After finding few landslide reports in the media, we expanded to include slides from NRCS records, North Shore sediment stressor reports, and completed graduate research theses. Many of these records contain locations of erosional hot spots from surveyed streams and rivers along the North Shore. We mapped all historically documented landslides in St. Louis, Lake and Cook counties. Historic slides along the shore are in the process of being converted from point to polygon files and attribute files are being updated.

We are maintaining a separate file of slides those recorded in Duluth from the 2012 flood separately to allow for cross-comparison with repeat lidar data. Landslides from the 2012 flood have been mapped as polygons in a GIS database and await field checking. We are actively mapping slides that can be detected from repeat lidar and air photos in St. Louis, Lake and Carlton counties. We plan to finish our digital landslide inventory (historical; active) by the end of May 2019 and will begin verifying and field checking our inventory over the summer.

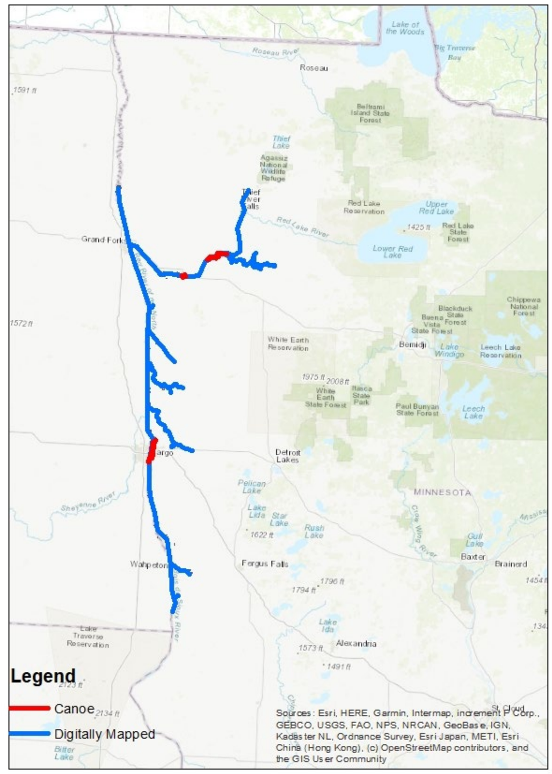
**Activity 1 Status as of** *July 30, 2019:*
**Status by mapping area:**
**7-county Metropolitan area:**
The historical inventory is complete. Population of the geodatabase attribute table is approximately 70% complete. Two new undergraduate students (Blake Mattie and Sophie Link) were hired to continue the LiDAR-derived mapping. C. Jennings, Z. Engle, and S. DeLong met with the new student hires at St. Thomas to orient them with the geodatabase and the methods being used. Current students are checking the completeness of the previously completed work, and adding new slides as identified.

**Minnesota River valley St. Peter to Chaska:**
Landslide mapping from LiDAR is nearly complete; a newly-trained undergraduate student (in consultation with faculty members) has been checking previously mapped slides and finishing incomplete areas. Limited field checking is underway and will likely be complete by the end of this year. Participation in a full group training session and field day in Duluth (June 2019) helped refine our definitions and identifications. A problem was fixed with the attribute table for this region, and populating the attribute table has begun.

**Minnesota River Valley from New Ulm to St. Peter:**
Historic mapping was completed previously using aerial photographs. The slide inventory has been delivered to project PIs for QA/QC and approval. We are now utilizing historic aerial photographs to attempt to “frame” the timing of any historic mass wasting event. Those identified but not observed in historic aerial imagery will be classified as prehistoric mass wasting events. More detailed updates from this study reach can be found in Activity 2.

**Mississippi River Valley in SE Minnesota:** Efforts continue to inventory landslides using lidar data and satellite imagery. Since our last update, we have scanned Winona and Houston Counties, and approximately 30% of Fillmore County. Many landslides have been identified throughout the study area, and are primarily concentrated on the steeper bluffs of the Mississippi River Valley and larger tributaries such as the Zumbro River and Root River.

**Red River Valley**: The historic inventory has been completed for all counties in the Red River watershed. This inventory was completed primarily by calling county offices to inquire about any records of landsliding they are aware of. Because populations are low, and the land area is large, there were relatively few historic landslides documented, and most that were documented were in or near towns. Mapping of landslides along the river corridor using aerial lidar data has revealed many more areas where landslides have occurred, and field checking has been used to verify some of these locations (see figure to right). These landslides were likely not picked up on the historic inventory because they had no impact on infrastructure. The current mapping and field checking is also being used to help reveal landslide type and processes. An additional student has been hired to assist with this continued effort.




**Lake Superior Watershed:**
Mapping of documented slides from historical archives is complete for all counties. Mapping of historic and active landslides from lidar and air photos is complete for St. Louis, Lake and Cook counties. We used Google Earth imagery and lidar to identify and map slides along rivers, roads, and the Lake Superior shoreline. To date, 1061 slope failure sites have been mapped in St. Louis, Lake and Cook counties and parts of Carlton County. As data collection continues, we are revising remotely mapped slides and populating slide attribute tables within the landslide geodatabase.

**Activity 1 Status as of** *January 30, 2020:*

**7-county Metropolitan area:**

Both historical and digital mapping in the 7-county Metro area is complete.

**Minnesota River Valley:**

Mapping is complete along the river corridor and a completed geodatabase was submitted to the PIs. Some attribute tables are still being compiled. The mapped database is currently undergoing QA/QC. Work is on-going to expand into major tributaries using previously mapped eroding bluff databases.

**Mississippi River Valley in SE Minnesota:** Mapping in Winona, Wabasha, and Goodhue counties have been completed. Mapping in Houston and Fillmore counties, particularly down the Root River and Mississippi River corridors, is being finalized. QA/QC of existing data is on-going.

**Red River Valley**:

Nearly 2000 landslides have been identified and 78 have been field checked. The majority of landslides are found along rivers or oxbows in this region and therefore the mapped area is reported in completed river valleys. The Red River main stem and 5 major tributaries have been mapped using lidar data and additional mapping is ongoing. Field mapping took place on the Red River mainstem and two major tributaries.

**Lake Superior Watershed:**

Remote mapping of historic and active landslides is complete in St. Louis, Lake and Cook counties. A total of 1515 slope failure sites have been mapped and submitted for QA/QC review. Slide attributes (i.e. location method/source, age, slide class, geologic material, geologic unit, slope, area, aspect, movement direction, class confidence, and location confidence) are populated for more than 50% of the inventory. 705 of our mapped slides were field verified during summer of 2019. Remote mapping in Carlton County is ongoing and is expected to be completed by March 2020.

**Activity Status as of July 1, 2020:**

All landslide mapping is complete in all areas. QA/QC'ing is proceeding across the entire area. As areas are checked, some polygons are being redrafted for consistency in detail. Attributes are being calculated and added to the landslide inventory database.

**Activity Status as of January 1, 2021:**

All landslide mapping is complete in all areas. QA/QC'ing is continuing across the entire area. As part of this effort, polygons are being refined for consistency across mapping subregions.

**Final Report Summary:**

All landslide mapping is complete in all areas (Red River valley, Minnesota River valley, SE Minnesota, Lake Superior watershed, and Metro area). Internal QA/QC'ing is complete across the entire mapping area. The ArcGIS geodatabase has been submitted to the USGS for internal review before being released as a published dataset to the public. It will be released to the public as a USGS data release as soon as internal review is complete.

The original plan was to map historical landslides from published media reports and then use that information to help map out landslides across a broader area using statewide high-resolution lidar topographic data. The historic slides could be used to identify known sites of hillslope instability, and the topographic fingerprint of those slides could be identified and used to identify other landslides that were not in historical records. We found that this approach worked well in the Twin Cities metropolitan area, where historical landslides were likely to be reported in the media. Historical newspapers are available in print and microfiche through the Minnesota History Center and online through the Minnesota Digital Newspaper Hub. Elsewhere in the state, records were more sparse. In northeastern Minnesota, we found other archives to be useful in locating landslides including reports by land management agencies like the county Soil Water Conservation Districts or the Minnesota Pollution Control Agency. Because many landslides occur along stream bluffs and are a major source of sediment to downstream water bodies, agencies tasked with protecting infrastructure or improving water quality both had reports that included information on bluff failures and landslides. The 2012 flood event in the Duluth area in northeastern Minnesota also provided a wealth of data to draw from including media reports as well as stream walks and photos collected by volunteers after the flood event. In some mapping areas, landslides and rockfalls occurred during the project. For example, in the Minnesota River valley, intense storms in 2018 triggered several landslides during the mapping project. These were added to the database. Elsewhere in the state, the historical landslide search was more limited and most mapping occurred using remote data.

After historical records were exhausted, landslide mapping occurred remotely using a combination of high-resolution lidar data and historical imagery. In areas like northeastern Minnesota, where a major storm event in 2012 triggered hundreds of landslides, these features were readily mappable from Google Earth imagery. Repeat lidar data collected before and after the 2012 even could also be used to help identify landslide areas (covered more in objective 3). Lidar derivative base maps used for remote mapping included slope maps, multi-directional hillshade maps, and a red relief map visualization that combines both slope and topographic openness. An example of Google Earth imagery, multidirectional hillshade, and red relief maps, with mapped landslide scarps and deposits is shown below.

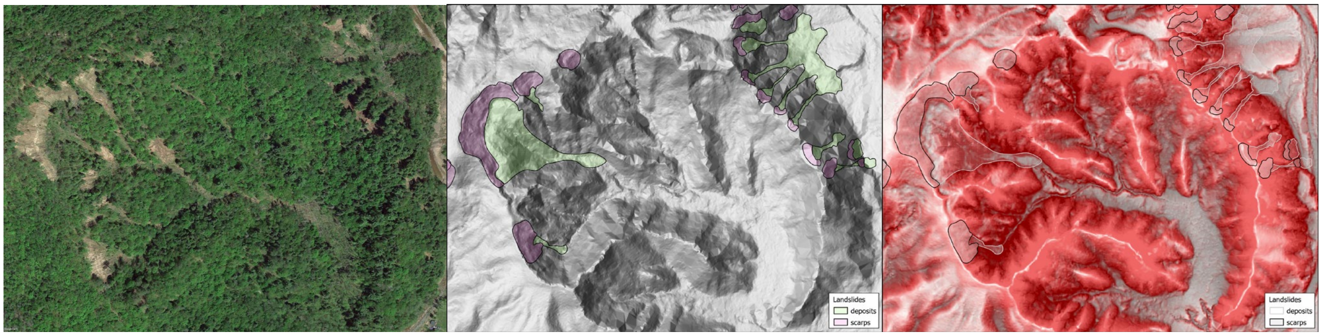


*Figure: Three kinds of data visualizations used for mapping landslide scarps and deposits (left: Google Earth imagery from 2017, middle: multidirectional hillshade, right: red relief). The area shown here is 500 meters across, and is located in the Mission Creek watershed in Fond du Lac, Minnesota.*

Remote mapping occurred at a scale between 1:1500 and 1:4000. Initial mapping occurred at the lower resolution (1:3000 or 1:4000 depending on the area), with high-resolution zoom used to edit vertices on mapped polygons. All mapped areas were reviewed by a team of USGS staff to help ensure standardization between mapping areas. The QA/QC effort took longer than anticipated, which has delayed the final release of the database. Currently, the database is complete and under USGS review.

The database produced from historical and remote mapping was field-checked (Objective 2), and information on slide type, underlying geologic material, and other relevant attributes were added to the database (Objective 2). All of the attribute information including whether the slide was located via historical data and whether or not it was field-checked are included in attributes in the database.

The digital database contains almost 10,000 mapped landslides with attributes across the state of Minnesota. Although not all of the state was covered by this mapping effort, most of the landslide-prone areas were covered. It should be a valuable resource for municipalities, counties, and state and federal agencies charged with protecting infrastructure throughout the state.

**ACTIVITY 2: *Preliminary landslide susceptibility map***

**Budget: $250,913**

**Description:** Identify relationships among landslide process, local topography, geography, geology, and hydrology.

Following the geospatial database assembled in activity 1, slide sites and likely slides sites will be field-checked. The partners responsible for the historical mapping in each region will be in charge of the field data collection for the same regions. While in the field, observations on slope composition, underlying geology, potential perched aquifers, seeps and springs, vegetation cover, and land use will be noted. Field-based interpretation of landslide process domain will be made, where possible.

GIS layers for all potential drivers of landslides will be compiled across all five study regions including, but not limited to, surficial geology, soils, bedrock geology, depth to bedrock, vegetation cover, and land use. These will be added to the lidar topographic database along with topographically-derived parameters including slope, relief, and aspect. In addition, all of the data from landslide sites visited in the field will be compiled in the same GIS framework for use in developing a predictive landslide hazards map.

**Summary Budget Information for Activity 2:** **ENRTF Budget: $250,913**

**Amount Spent: $250,692**
**Balance: $222**

| Outcome | Completion Date |
|---|---|
| 1. Field work to check historical records and GIS analyses | Oct. 2018 |
| 2. Identification of geology and topography at landslide sites | Oct. 2019 |
| 3. Interpretation of landslide process and domain | May 2020 |

**Activity 2 Status as of** *March 5, 2018:*
Field work has begun in the Minnesota River valley, southeastern Minnesota, and Hennepin County. Elsewhere, field crews are being hired on for the summer to do field checking of historical records and mapping of landslide features.

**Activity 2 Status as of** *July 30, 2018***:**
Field work to check historical records and remote mapping is underway in most of the study areas. A field training event was held in June in the Minnesota River valley, and most of the groups involved in this project were able to attend. Different kinds of mass wasting sites were visited to discuss how we should classify different mass failures, what kinds of data need to be collected, and how each feature should be mapped. This phase of the project will intensify for all groups as we complete the landslide inventories from topography mapping.

Progress towards susceptibility mapping is also underway. Project staff completed a review of landslide susceptibility literature. We are focusing initial efforts towards landslide susceptibility work on the rich dataset from the greater Duluth region. In this area, we are characterizing landslide process, topographic change and underlying geologic materials. Our initial efforts include development of data for multiple logistic regression analysis in order to identify predictive variables for landslide occurrence, and also the use of object-based image analysis to characterize landslide activity based on a wide range of remote sensing and observational data.

In our test area in northeastern Minnesota, field observations of landslide occurrences, including GPS location, site photographs, and field notes have been paired with multi-temporal aerial photographs and lidar data to map 60 specific landslide sites in St. Louis River and its tributaries, specifically along the Gill Creek, Steelton Creek, Sargeant Creek, and Mission Creek, in the quadrant WM56. These mapped sites are used to understand the underlying environmental attributes (e.g., slope, aspect, roughness, soil, landcover and landuse, hydrography, precipitation, past landslides, etc.) associated with landslide occurrences in 2012. Next steps are to develop landslide susceptibility workflow using the environmental attributes associated with past observed landslides.

Susceptibility mapping is also underway in the Minnesota River valley, but is limited by the spatial scale, varied magnitude, and frequency of mass wasting events within that study reach. We are using preliminary data to determine potential environmental (e.g. morphologic, geologic, biologic, atmospheric) relationships to the spatial distribution of mass wasting failures. This is being done in order to note any obvious similarities or characteristics driving failures at sites throughout the study reach. It has been discussed to use our nearly completed inventory and geodatabase as a test for predictive susceptibility mapping being developed for the larger group. The diversity and frequency of occurrence of mass wasting failures within this study reach has been surprising (to date, 262 mapped sites with more to come) and has delayed efforts to adequately begin susceptibility mapping without combined efforts of the entire group as a whole.

**Activity 2 Status as of** *January 30, 2019:*
Progress continues on this activity, with field work continuing over the late summer and fall. Our original proposal had field work to check mapping completed by Oct. 2018, with field work to determine underlying

geology and process completed by Oct. 2019. In most places, these two have been combined, with field checking and investigation of underlying geology and process occurring simultaneously. Both should be complete by Oct. 2019.

Work into landslide susceptibility is also in progress in most of the regions across the state. In Hennepin County, a combination of field investigation by Freshwater Society/UMN and compilation of geologic data provided by the Minnesota Geological Survey (MGS) refined the understanding of the geologic units involved in three main types of slides present in Hennepin county: 1) bedrock-dominated slides on near-vertical bluffs, 2) deep-seated slides in glacial sediment, and 3) shallow slides in glacial sediment.

1. Slides not observable on the elevation model because they were located on near-vertical bedrock-dominated slopes along the Mississippi River were field-checked and compared to spring discharge points and bedrock stratigraphy. Monitoring the bluff or infrastructure on the bluff for movement can anticipate and avoid damage. Providing a fall zone for debris is prudent.

2. The largest failures in Hennepin County can be found along the Minnesota River valley but most predate settlement of the area. However, human activity in the area has the potential to reactivate failures. These deep-seated slides along the Minnesota River valley involved glacial units that are not well exposed and required the use of the logs of borings and cross sections created by the MGS for the newly released, revised Hennepin County Geologic Atlas (Lusardi et al., 2018). Springs along stratigraphic contacts in the glacial sequence influence the location of failure by steepening slopes, creating sapping hollows and lubricating failure surfaces. Wise land-use practices such as protecting the slope and careful routing of water can minimize the chances of reactivation.

3. Shallow slides in the interior of the county involve the upper, lower density layer of the uppermost glacial sediments. Textures of soil and parent material involved in shallow slides varied significantly. Geophysical means could be used to identify the density contrast in critical areas. Setbacks from slopes can reduce damages and financial loss while signaling the inherent risk in the landscape.

Different approaches to reducing landslide impact by zoning and planning are being compiled.

In the Minnesota River valley, Larson and Swanson (MSU Mankato) are finalizing their Minnesota River landslide inventory. This complete inventory is fully field-verified and contains >500 mass movements, including slides, rock falls, and rotational failures. Wickert (UMN Twin Cities) has developed a simple theoretical basis for landslide susceptibility based on a Mohr-Coulomb stress balance between the weight of the landslide block, the internal friction of the material, the cohesive strength, and pore-fluid pressure that relates to precipitation events. Wickert has committed to hosting Swanson in his lab in Minneapolis for 1 week to guide her in linking this theoretical framework to her data, with the goal of informing topographic metrics of landslide susceptibility.

**Activity 2 Status as of** *July 30, 2019:*
Progress continues with field checking in all areas. Field mapping and verification is complete in Hennepin County and the upper Minnesota River valley reach. Field verification continues in the 7-county metropolitan area, southeastern Minnesota, northeastern Minnesota, the lower Minnesota River valley, and the Red River valley. Depending on geographic extent, some areas will have more extensive field verification than others which will rely on checking a subset of the field area. We are keeping track of which areas are being visited in the field and which are not.

As landslides continue to occur in our study region, we are documenting them and including them in the inventory. For example, we responded to Highway 61 lane closures in May after southeastern Minnesota experienced several days of low intensity rainfall that saturated soils and weakened slope stability. We found dozens of smaller slides in the Mississippi River corridor between Lake City and just south of Winona. These slides were mapped using GPS locations and documented with photos. Most of these slides were translational slides of debris over a bedrock failure plane, however, there were several rock falls identified. These individual slides would have been too small and too short-lived (road crews quickly clear debris) to be identified from lidar imagery, but most slides were associated with larger sections of oversteepened road cuts, allowing us to identify these actively eroding zones.

In addition to field mapping and verification, progress continues on determining process domains and drivers of different types of mass movements across the state. In Hennepin county, a combination of field investigation and compilation of geologic data provided by the Minnesota Geological Survey (MGS) has refined our understanding of the geologic units involved in four main types of slides present:

1) bedrock-dominated landslides on near-vertical bluffs.
2) deep-seated landslides in glacial sediment.
3) shallow landslides in glacial sediment.
4) slides along the slopes of widening rivers.

These four slide types are also evident in nearby reaches of the Minnesota River, although we see fewer bedrock-dominated landslides on near-vertical bluffs there. This may be an observational issue as field-verification is still on-going in this region. As in other regions, we expect these would be field-identified, rather than observed on LiDAR.

The bedrock-dominated slides were not observable on the high-resolution elevation model because they were located on near-vertical bedrock-dominated slopes along the Mississippi River gorge. These were field-checked and their occurrence compared to spring discharge points and the bedrock units involved. Monitoring the bluff or infrastructure on top of the bluff for movement can help anticipate and avoid damage. Providing space for a fall zone is prudent.

Deep-seated slides along the Minnesota River valley involved glacial units that are not well exposed and required the use of the logs of borings and cross sections created by the MGS for the revised Hennepin County Geologic Atlas (Lusardi et al., 2018). The largest failures in Hennepin County can be found along the Minnesota River valley but most predate settlement of the area. However, human activity in the area has the potential to reactivate failures. Springs along stratigraphic contacts in the glacial sequence influence the location of failure by steepening slopes and creating sapping hollows. Wise land-use practices based on sound geotechnical site investigation and protecting the slope by careful routing of stormwater can reduce the chances of reactivation.

Shallow slides in the interior of the county involve the upper low density layer of the surficial glacial sediment deposits. Textures of soil and parent material involved in shallow slides varied significantly so correlation to a particular soil type is not apparent. Geophysical means could be used to identify the density contrast in the surficial sediment of critical areas. Setbacks from slopes and river banks, both the upper portion and toe of the slope, can reduce damages and financial loss and also signals the inherent risk in the landscape. Cooperation between landowners at the top and bottom of the slope is key to maintaining slope integrity.

In the upper Minnesota River valley reach, we are working on a statistical analysis of mass wasting sites to try and identify key drivers. Utilizing the historic inventory and the associated geodatabase, we are running basic statistical analysis on some of the catalogued “key variables” associated with mass wasting sites. This may give us an idea of the antecedent conditions necessary for different types of failures to occur. With each identified mass wasting event, we catalogued the following attributes in an attribute table within an ArcGIS geodatabase: 1) class-type of failure, 2) type of substrate/geologic material that failed, 3) headscarp height and width, 4) failure depth, 5) aspect of movement-bearing, 6) failure mass area-if observed in LiDAR, 7) estimated date of occurrence or age range, 8) associated damage, 9) photograph of site, 10) slope of landscape where failure occurred. A final report from this study reach is on the horizon. The graduate student associated with this work has defended her thesis and is in the process of final revisions with Dr. Larson. Upon completion of revisions, this student's second chapter will be submitted to the project PI's as our report/analysis of mass wasting in this study area.

In northeastern Minnesota, the bedrock is different than in other parts of the state, and the presence of Lake Superior adds to the mix of process drivers. Hydrologic factors such as channel incision, toe-cutting, lateral migration, sapping, and wave action drive slope instability within the Lake Superior watershed. Observations so far suggest most slope failures are concentrated in thicker glacial sediments along river valleys and the Lake Superior shoreline. Mass wasting events are more common in areas containing glacial-lake deposits that were destabilized in response to the 2012 flood. We observe igneous and sedimentary bedrock-dominated rockfalls on high relief near-vertical bluffs along stream channels and the Lake Superior shoreline. We observe deeper-seated landslides in areas where channels have incised through thicker packages of glacial sediments. Shallow translational slides are common also observed along the contact between the topsoil and subsoil horizons in areas with thick glacial deposits.

In the Red River valley, there is a slightly different framework for mass movements. While more data are necessary, initial observation suggests the mode of landsliding is dependent on the distance from the Lake Agassiz lake plain. The earth movement in the offshore clays appear to be primarily slow-moving slumps and creep. These likely should not be referred to as landslides, but are certainly a type of mass wasting that can threaten (and has threatened) infrastructure. These seem to be most common in areas where development has changed the local environment, through the removal of trees or construction of buildings. Moving east to the nearshore environment the mass movements occur more rapidly and landslides are observed here. The sediments in this environment are more diverse and the landslides are similarly diverse. Moving into the glacial sediments farther east, the landslides are typically the largest we see in this area, similar to those observed in the Minnesota River watershed.

**Activity 2 Status as of** *January 30, 2020:*

Field checking is essentially complete for the entire project, and each area has assembled a map showing extent mapped and extent field checked to help communication data integrity.

The previous status update explains many of the important differences we are finding in the bedrock and surficial geology across the state that helps drive landslides in different ways.

Susceptibility modeling is on-going across the state using the important observations noted in the bedrock and surficial geology. For example, we are working to assess landslide susceptibility in Northeast Minnesota using a logistic regression approach in ArcGIS. Factors currently included in our assessment are slope, aspect, elevation, local relief, drift thickness, soil K-factor, land cover, Quaternary material, bedrock type, and distance to streams. We are currently improving the methodology for our susceptibility assessment. One of the primary obstacles has come from using datasets with different spatial resolutions (i.e. drift thickness, soil k factor, and bedrock type). We plan to implement our susceptibility assessment in three different watersheds to investigate the impact of scale on the effectiveness of our model.

**Activity Status as of July 1, 2020:**

Review of all submitted map data is underway. GIS shapefiles are being refined to accurately delineate landslide area, attributes of slides are being added to tables linked to each slide area, and stylistic differences of mappers in the 5 different areas are being minimized as data are reviewed.

**Activity Status as of January 1, 2021:**

Field work is complete. GIS shapefiles are being refined to accurately delineate landslide areas, attributes of slides are being added to tables linked to each slide area, and stylistic differences of mappers in the 5 different areas are being minimized as data are reviewed. The susceptibility parameters have been identified, although susceptibility modeling in each subregion has to wait until mapped data are QA/QC'd. This is on-going.

**Final Report Summary:**

GIS layers including lidar topography and derivatives (slope, relief, aspect), soils, surficial geology, bedrock geology, depth to bedrock, vegetation cover, and land use were used to extend historic and field mapping of slides as well as in the compilation of attributes. Landslides mapped remotely were field checked where possible. Given the vast area covered, not all mapped slides could be directly field checked. During field checking, observations on slope materials, land cover, and the presence of seeps or springs were made and included in the attribute tables. At some field-checked sites, measurements were made of landslide size and/or slope angle. In most mapped landslides, geometric parameters were mapped from lidar data in ArcGIS.

Each mapped slide has a unique ID number that allows deposits, scarps, and slide property data to remain linked together. Information on how the slides were located (lidar, google earth, historical) and their estimated age or date, if known, are included. The kind of mass movement, whether the slide is shallow or deep-seated, and the geologic material and unit are included. There is room in the attribute table for geometric properties of slides including length, width, depth, headscarp height, area, volume, slope, and aspect. Finally, the attribute table has room to record the mapper's confidence in landslide class and in landslide location. A description field is used for notes. Most mapped landslides do not contain full attribute data due to time constraints. Detailed information on how different attributes were derived will accompany the database when it is released.

Field-checking helped ensure that mapped slide locations were accurate. In northeastern Minnesota, for example, just over 2000 slides were mapped, with 702 field-checked. Field-checking found that 97% of the field-checked slides had been accurately mapped, giving us greater confidence in the overall landslide map.

Field mapping and verification also helped inform our understanding of what drives high landslide susceptibility in different regions of the state. Much of what we have learned about process domains and landslide susceptibility across the state is summarized in the USGS Fact Sheet, and the text below is adapted from that publication as well as summaries of process domains from earlier updates.

In southeastern Minnesota, much of the region was not covered by ice during the last glaciation. Layered Paleozoic sedimentary rocks are covered by colluvium and loess deposits, with some older glacial material in upper portions of tributary valleys that drain to the Mississippi River. The carbonate rocks are prone to dissolution, forming caves, sinkholes, and other karst landforms that convey water to seeps and springs that help destabilize slopes. Landslides and rockfalls occur on steep bluffs adjacent to the Mississippi River and its many tributary valleys. These landslides commonly involve shallow soils, weather rock, and/or bedrock blocks. They occur along roadcuts or rivers where lateral channel migration has steepened adjacent slopes. Small rockfalls occur throughout the year, especially during freeze-thaw conditions in early spring and late fall, and during intense or prolonged rainfall. Landslides and rockfalls often occur where sedimentary layers of variable strength are exposed on slopes. For example, the Cambrian St. Lawrence Formation consists of weaker siltstone and sandstone interbedded with stronger dolostone layers. As the weaker siltstone and sandstone are progressively eroded by rainfall, groundwater sapping, freeze-thaw, bioturbation, and other processes, blocks of the overlying stronger dolostone are undermined, and can fail abruptly.

Farther upstream along the Mississippi River, we find four main kinds of slides present: bedrock-dominated landslides and rockfalls on near-vertical bluffs, deep-seated landslides in glacial sediment, shallow landslides in glacial sediment, and slides along the slopes of widening rivers. These four slide types are also evident in nearby reaches of the Minnesota River in the Twin Cities metropolitan area.

Much like southeastern Minnesota, bedrock-dominated landslides and rockfalls on near-vertical bluffs form in layered Paleozoic strata of variable strength. Many are covered by thick sand deposits from earlier glacial meltwater flow. Springs in the bluffs can weaken bedrock and cause erosion. Monitoring the bluff or infrastructure on top of the bluff for movement can help anticipate and avoid damage. Providing space for a fall zone is prudent.

Deep-seated slides along the Minnesota River valley involve glacial units that are not well exposed and required the use of the logs of borings and cross sections created by the MGS for the revised Hennepin County Geologic Atlas (Lusardi et al., 2018). The largest failures in Hennepin County can be found along the Minnesota River valley but most predate settlement of the area. However, human activity in the area has the potential to reactivate failures. Springs along stratigraphic contacts in the glacial sequence influence the location of failure by steepening slopes and creating sapping hollows. Wise land-use practices based on sound geotechnical site investigation and protecting the slope by careful routing of stormwater can reduce the chances of reactivation.

Shallow slides in the interior of the county involve the upper low-density layer of the surficial glacial sediment deposits. Textures of soil and parent material involved in shallow slides varied significantly so correlation to a particular soil type is not apparent. Geophysical means could be used to identify the density contrast in the surficial sediment of critical areas. Setbacks from slopes and river banks, both the upper portion and toe of the slope, can reduce damages and financial loss and also signals the inherent risk in the landscape. Cooperation between landowners at the top and bottom of the slope is key to maintaining slope integrity.

In these urban areas, human activities impact slopes by concentrating stormwater runoff, steepening slopes adjacent to roads and rail corridors, and loading them with structures, artificial fill, or weakening them with infiltrated water or by removing material. These human activities can increase landslide hazards on natural slopes that were already susceptible to landslides. More broadly, landslides also occur in glacial and artificial fill sediment on short, steep slopes such as lake shorelines and areas of focused runoff in ravines and areas of focused stormwater discharge

In northeastern Minnesota, the bedrock is different than in other parts of the state, and the presence of Lake Superior adds to the mix of process drivers. Hydrologic factors such as channel incision, toe-cutting, lateral migration, sapping, and wave action drive slope instability within the Lake Superior watershed. Landslides and rockfalls are located along the steep shoreline of Lake Superior and in tributaries to the lake. These include the steep streams of the North Shore that incise into bedrock and glacial sediment, and the St. Louis and Nemadji River watersheds, where channels incise into fine-grained, unstable sediment deposited in a former glacial lake. The most common landslides are shallow translational and rotational earth slides, earth flows, and rockfalls.

Clay-rich glacial till and lacustrine clay and silt bury Precambrian bedrock along the shore of Lake Superior and in tributary valleys. Rockfalls occur where streams and roads have exposed bedrock and are common in jointed bedrock, triggered by freeze-thaw processes or undercutting by streams or waves. Landslides in clay-rich glacial sediment northeast of Duluth occur along tributary streams. Increased soil moisture, steepening of slopes by river erosion at their base, and groundwater seepage are contributing factors to landslide occurrence.

Many tributaries along the lower St. Louis and Nemadji Rivers are incising into fine-grained glacial lake and deltaic sediments, creating narrow, steep-sided valleys susceptible to failure. Surface water runoff from heavy precipitation or rapid snowmelt saturates sediment, weakening it, and what may begin as erosion from surface runoff can lead to seepage erosion once there is enough infiltration and relief to drive subsurface flow. This area is particularly susceptible to landslides, which was evident in the 2012 storm event that triggered hundreds of landslides in the lower St. Louis and Nemadji watersheds.

In the Red River valley in northwestern Minnesota, there is a slightly different framework for mass movements. Subtle variations in lake sediment texture affect landslide occurrence from the center of the valley to the east.

Landslides in the main river valley and the downstream reaches of tributaries have steep scarps and hummocky slopes below, indicating multiple failure planes. Earth movement in the offshore clays appears to be primarily slow-moving slumps and creep, a type of mass wasting that can threaten (and has threatened) infrastructure. These can occur in areas where development has changed the local environment, through the removal of trees or construction of buildings. Farther up tributary valleys to the east, sediment deposited in the nearshore environment of the past glacial lake has more sand and gravel, and the landslides have a more distinct, single failure plane. The sediments in this environment are more diverse and the landslides are similarly diverse. Landslides beyond the extent of the former glacial lake occur where rivers have incised into glacial sediment, similar to the Minnesota River valley failures.

**ACTIVITY 3: *Analysis of multitemporal and multi-source lidar to better understand landslide process and extents***

**Budget: $198,729**

**Description:** Process repeat airborne lidar data in regions where available, compare to terrestrial lidar data, create digital database of findings

This last activity will focus on several major objectives. The first focuses on the use of repeat lidar data to quantify landslide impacts, with an emphasis on sediment loading to major rivers. Lidar data map the land surface in high-resolution (meter-scale horizontal resolution with decimeter vertical accuracy) at a single point in time. By using lidar-derived topographic data collected before and after landslides occur, it is possible to quantify how much change occurred between the two scans. This allows us to calculate the volume of sediment that was eroded as a result of that slide event.

The Minnesota DNR collected lidar just prior to and following the dramatic 2012 storms that led to widespread flooding and landsliding. Unfortunately, there are internal processing and georeferencing issues within the existing 3D data that have prevented use of the repeat lidar data for quantitative measurements. Andrew Wickert at the University of Minnesota and Stephen DeLong of the USGS will address these issues using advanced processing methods to correct internal errors and to properly align the pre-and post-event lidar data. The alignment will be verified at select locations where we have repeat terrestrial lidar data collected over the same time period by Karen Gran at the University of Minnesota Duluth.

A similar dataset consisting of repeat airborne lidar data over a longer time period (2005-2012) exists in Blue Earth County. It has been aligned and evaluated by Schaffroth et al. (2015) and can be compared with data collected by Stephanie Day at NDSU. On-going data collection by both Gran and Day in the Duluth-area and the Minnesota River valley will provide erosion rates from landslides along river valleys that can be used to assess the impact of landslides on sediment loading in rivers.

DeLong and Wickert will work on establishing best practices for using lidar data for change detection associated with landslides. The change detection data will be included as another dataset in the geospatial database combining all of the historic and likely landslide sites across the study regions. These data will all be combined to develop a landslide susceptibility and hazard map for the five study regions in the state, which covers most of the area where landslides are a concern. The database, map, and a factsheet on landslides in Minnesota will be QA/QC'd and disseminated through the USGS as official USGS publication, and results of the 2012 Duluth area lidar analysis will be published in a peer-reviewed scientific journal.

| | | |
|---|---|---|
| **Summary Budget Information for Activity 3:** | **ENRTF Budget:** | **$198,729** |
| | **Amount Spent:** | **$193,816** |
| | **Balance:** | **$4,913** |

| Outcome | Completion Date |
|---|---|
| 1. Analyze repeat airborne lidar in the Duluth area | May 2018 |
| 2. Use ongoing terrestrial lidar scans in each region for comparison with airborne lidar | May 2020 |
| 3. Develop best management practices for using lidar for meaningful change detection | June 2020 |
| 4. Create and disseminate preliminary landslide hazard map based on lidar topographic analyses, underlying geology, and empirical evidence from landslide inventory | June 2020 |

**Activity 3 Status as of** *March 5, 2018:*
We have begun analyzing the repeat airborne lidar data in the Duluth area. We expect to have preliminary results by the end of April 2018.

**Activity 3 Status as of** *July 30, 2018***:**
We have acquired the entire raw observational lidar dataset from the original data vendor for the 2011 and 2012 Duluth area lidar that brackets the megastorm of June 2012. We are working with the developer of StripAlign software to improve the processing of the lidar collections in order to minimize the significant internal alignment errors within each dataset. This is being done using Bayesian methods that better interpret the raw trajectory information form the airborne sensor suite. This is complete at a first pass, though we are still assessing the degree of improvement and may refine our work further. This important step will lead to improved change detection across the region. The improved topographic change maps will feed into object-based image analysis (described below) to properly characterize the effects of the 2012 storm and to assist with landslide susceptibility analysis. This portion of the project will lead to development of sophisticated workflows that can be used in response to future landslide events and to existing data elsewhere in the State.

GIS and data integration: We started work using object-based identification of landforms to map zones that are likely influenced by landslides. This work is developing new methods to integrate topographic change analysis with satellite and aerial imagery and topographic metrics to improve understanding of how landscape is affected by extensive landsliding. We are using eCognition software to develop a ruleset for extracting indicators of landscape change as geospatial objects. These objects can be classified in terms of landscape position, type of geomorphic change, effects on vegetation, and other metrics. For example, this analysis will allow us to calculate the volume of sediment stored along valley floors and river bottoms, the amount of erosion occurring on slopes, and the amount of sediment liberated by bank failures caused by stream flooding. This approach to sediment budgeting can help decision makers prioritize mitigation efforts across landscapes.

We anticipate the final change detection data for the Duluth area will be available for these other analyses in the coming months, and the suite of new tools and workflows to be utilized elsewhere in the project for the duration of the work.

**Activity 3 Status as of** *January 30, 2019:*
USGS team members completed the reprocessing of the raw repeat lidar data from northeastern Minnesota. This was performed in collaboration with the BayesMap StripAlign software develper. This method improves on standard techniques for positioning overlapping strips of lidar data collected as the survey aircraft traverses the area by reprocessing the original GPS and flight attitude data. We have verified that the error in lidar flightline overlap has been significantly reduced relative to how the data are currently publically available. In mid-December we began quantifying this improvement and performing new change detection analysis. This work ceased when the federal government shut down, furloughing the USGS researchers.

This work will now resume, subject to future federal shutdowns. We plan to have updated change detection maps prepared for analysis by USGS, UMN, UWS, and UMD research teams in the coming weeks. We will then proceed with comparison to existing terrestrial lidar scans, and to classify areas of topographic change with respect to the type of process that led to the change. This will improve landslide susceptibility maps. The results of the updated change detection will also be reported in a peer-review scientific journal article in the coming months.

As the landslide inventory is being developed, and the entire research team is making progress identifying landslides on the statewide lidar, we are developing a list of landscape features that indicate the most common landslide occurrences in Minnesota. These are helping us develop the conceptual plan for future lidar analyses that can identify landslide hazards across the state. Interesting features include shallow failures of clay-rich glacial sediments in low-slope areas well above the steep valleys in northern Minnesota that will not be captured by typical slope analyses, and a rich array of large ancient landslides found in the tributaries of the Minnesota River.

Analyses of repeat terrestrial lidar will also be proceeding in the Red River valley. Two graduate students at NDSU have been assigned to focus on the work of comparing TLS and repeat aerial lidar data. Work toward this goal will begin in spring or summer.

**Activity 3 Status as of** *July 30, 2019:*
The reprocessed lidar data reported in previous progress reports has been carefully analyzed for quality control. Several issues have been identified and are being addressed. The StripAlign software improved the alignment of individual data strips collected by repeat passes by the survey aircraft. However, the following issues remain, likely due to slight errors in data collection procedures by the vendor: 1) vertical errors in the alignment of the 2011 and 2012 data. These errors are different in different areas of the survey, likely due to errors in survey procedures for each day or each flight of the airborne survey. These errors are up to about half a meter. Our approach to correcting these errors is to identify them automatically by creating a “correction surface” using differences in elevation between 2011 and 2012 in flat areas away from stream valleys and away from elevation differences greater than ~0.5 meter to avoid incorporating actual landscape change into the correction. These data are then interpolated and the correction is applied across the survey area. The second issue is horizontal misalignment up to a few tens of centimeters. We will correct this by identifying areas that share common errors (again the errors are consistent within irregular blocks of data but not consistent across large areas of the survey). These blocks will be aligned using an iterative closest point approach using point cloud data. These corrections will then be applied to the DEM data. This is currently in progress, and is the last step in producing a corrected lidar change map for the 2012 Duluth storm event.

We have made significant progress with the analysis of the maps of landscape change in parallel with creating the final change maps. We have identified object-based imagery analysis (OBIA) as a novel tool for proper segmentation and classification of maps of landscape change. This approach segments maps of landscape change into “objects” having similar characteristics. This initial segmentation is done using the map of elevation changes as well as maps of slope. These segmented map objects are then classified using a wide range of associated data including magnitude of landscape change, slope, aspect, distance to streams, satellite imagery, NDVI (vegetation), roughness, and topographic relief, for example. The output of these analyses are geographic objects (mapped shapes) that are classified according to landscape position, amount of landscape change, type of geomorphic process and a range of other characteristics. This will allow us to calculate volumes of materials derived from a range of landscape altering processes and in a range of landscape positions. We anticipate preparing a manuscript detailing this work in the fall of 2019.

**Activity 3 Status as of** *January 30, 2020:*
Activity 3 data analysis is complete. We have generated a complete analysis of landscape change that occurred in the 2012 extreme precipitation event in the greater Duluth Area. This has involved reprocessing the 2011 and 2012 airborne lidar survey data from the original data strips collected on each pass of the survey aircraft. We used Baysian methods as implemented in BayesMap Strip Align software to reprocess the lidar flightlines using GPS and inertial data provided to us by the original survey vendor. We then had to align some 2011 data with missing GPS data to 2012 data using iterative-closest point methods. Following this we reduced remaining

elevation error by generating correction surfaces using flat, unchanged areas and applied these corrections to adjacent steep terrain. These steps resulted in an updated, error-minimized map of elevation change across the Duluth area at one meter resolution.

These data, owing to their large spatial extent (from the Two Harbors area all the way to southern Carlton County) are not trivial to interpret. As such we performed analysis leading to classification of distinct polygons (areas having similar properties in terms of landscape setting and landscape change) that allow for better understanding of the effects of the 2012 Duluth area rain event on the landscape. These analyses were performed using Object Based Image Analysis in which several data layers (landscape change, slope, stream network geometry, etc) were used to classify the landscape change. In particular, we have classified areas of landscape change by the magnitude of landscape change (erosion and deposition) as well as the characteristics of the landscape that changed. For example, we have classifications for shallow and deep landsliding across several classes of slope (steep, moderate, etc.), we are able to track the effects of landsliding on river channels and their adjacent valley-floor floodplains by characterizing how deposition extents and volumes affects streams in the area. What this allows us to do is then import the magnitude of landscape change in these areas to better understand the volumes of sediment delivered from various parts of the landscape and the fate of that sediment after slopes fail. This includes deposition in local alluvial fans at the base of steep tributaries, deposition along stream valleys, and transient deposition in translated soil and sediment masses on slopes. These methods allow a user to quickly identify areas of landscape where natural resources such as stream habitat is most impacted and to develop indicators for vulnerability of landscape to future similar extreme weather events.

Ongoing work in Task 3 includes manuscript preparation and use of the results of this work to feed into landslide susceptibility analysis (Activity 2).

**Activity Status as of July 1, 2020:**

We generated a complete analysis of landscape change that occurred in the 2012 extreme precipitation event in the greater Duluth Area. This involved reprocessing the 2011 and 2012 airborne lidar survey data from the original data strips collected on each pass of the survey aircraft. We used Bayesian methods as implemented in BayesMap Strip Align software to reprocess the lidar flightlines using GPS and inertial data provided to us by the original survey vendor. We then had to align some 2011 data with missing GPS data to 2012 data using iterative-closest point methods. Following this we reduced remaining elevation error by generating correction surfaces using flat, unchanged areas and applied these corrections to adjacent steep terrain. These steps resulted in an updated, error-minimized map of elevation change across the Duluth area at one meter resolution. The area of coverage was expanded significantly over the past six months to encompass nearly the full area that has repeat lidar coverage in NE Minnesota.

These data, owing to their large spatial extent (from the Two Harbors area all the way to southern Carlton County) are not trivial to interpret. As such we performed analysis leading to classification of distinct polygons (areas having similar properties in terms of landscape setting and landscape change) that allow for better understanding of the effects of the 2012 Duluth area rain event on the landscape. These analyses were performed using Object Based Image Analysis in which several data layers (landscape change, slope, stream network geometry, etc.) were used to classify the landscape change. In particular, we have classified areas of landscape change by the magnitude of landscape change (erosion and deposition) as well as the characteristics of the landscape that changed. For example, we have classifications for shallow and deep landsliding across several classes of slope (steep, moderate, etc.), we are able to track the effects of landsliding on river channels and their adjacent valley-floor floodplains by characterizing how deposition extents and volumes affects streams in the area. What this allows us to do is then import the magnitude of landscape change in these areas to better understand the volumes of sediment delivered from various parts of the landscape and the fate of that sediment after slopes fail. This includes deposition in local alluvial fans at the base of steep tributaries, deposition along stream valleys, and transient deposition in translated soil and sediment masses on slopes.

These methods allow a user to quickly identify areas of landscape where natural resources such as stream habitat is most impacted and to develop indicators for vulnerability of landscape to future similar extreme weather events. Over the past six months the area covered has expanded from a test location in Mission Creek to cover a greater area of NE Minnesota.

Susceptibility mapping has continued as well. In the past six months, a series of susceptibility models were completed for NE Minnesota, investigating the importance of spatial scale and input variables on model predictability. We chose to use a logistic regression approach with multiple parameters including slope, surficial geology, depth to bedrock, and distance to stream; and this approach is being spread to other regions across the state now.

**Activity Status as of January 1, 2021:**

Work proceeded in two main areas during the last six months. The Object Basin Image Analysis of landscape change during the 2012 flood in the Duluth area was completed, and most of this period was on writing up the results of that work in a manuscript. The goal is to have that submitted for publication this spring.

In addition, work continued on the susceptibility modeling across the state. Susceptibility modeling was explored in depth in the NE MN mapping area. M.S. student Emilie Richard defended her thesis in July 2020, which incorporated susceptibility modeling in Jay Cooke State Park, Mission Creek, and the Lake Superior South watershed. One of the goals of her work was to query the scale over which susceptibility modeling should occur and how transferable susceptibility models completed in one area were to an adjacent area. The methods she developed are now being used across the state to develop a series of susceptibility models in each subregion. The susceptibility modeling has to wait until all data in a subregion are QA/QC'd, but that work is nearing completion now.

**Final Report Summary :**

Our work on analyzing repeat lidar data focused on aerial lidar data collected in 2011 and 2012 in the Duluth area, before and after a major storm event in June 2012. The data were poorly aligned, making quantitative analyses of landscape change unreliable. We took a multi-prong approach to analyzing these data by first realigning the original point cloud datasets and then using an Object-Based Image Analysis to both quantify the amount of change associated with different landscape processes (i.e. mass wasting of hillslopes, in-channel deposition, etc.). The result allowed us to quantify both the volumes of change as well as how much erosion and deposition was related to different processes.

Reprocessing the 2011 and 2012 airborne lidar survey data took several steps. We went back to the original data strips collected on each pass of the survey aircraft. We used Bayesian methods as implemented in BayesMap Strip Align software to reprocess the lidar flightlines using GPS and inertial data provided to us by the original survey vendor. We then had to align some 2011 data with missing GPS data to 2012 data using iterative-closest point methods. Following this we reduced remaining elevation error by generating correction surfaces using flat, unchanged areas and applied these corrections to adjacent steep terrain. These steps resulted in an updated, error-minimized map of elevation change across the Duluth area at one meter resolution. These error-minimized data are finalized and will be disseminated in September 2021.

Owing to the large spatial extent (from the Two Harbors area all the way to southern Carlton County), the data are not trivial to interpret. As such we performed analysis leading to classification of distinct polygons (areas having similar properties in terms of landscape setting and landscape change) that allow for better understanding of the effects of the 2012 Duluth area rain event on the landscape. These analyses were performed using Object-Based Image Analysis in which several data layers (landscape change, slope, stream network geometry, etc.) were used to classify the landscape change. In particular, we have classified areas of landscape change by the magnitude of landscape change (erosion and deposition) as well as the characteristics of the landscape that changed. For example, we have classifications for shallow and deep landsliding across several classes of slope (steep, moderate, etc.), we are able to track the effects of landsliding on river channels and their adjacent valley-floor floodplains by characterizing how deposition extents and volumes affects streams in the area. What this allowed us to do is then import the magnitude of landscape change in these areas to better understand the volumes of sediment delivered from various parts of the landscape and the fate of that sediment after slopes fail. This includes deposition in local alluvial fans at the base of steep tributaries, deposition along stream valleys, and transient deposition in translated soil and sediment masses on slopes. These methods allow a user to quickly identify areas of landscape where natural resources such as stream habitat is most impacted and to develop indicators for vulnerability of landscape to future similar extreme weather events.

In addition to quantifying change, the analyses in northeastern Minnesota also provide information on susceptibility to landsliding. The intense mapping effort in the region with repeat lidar allowed us to determine which parameters are statistically associated with high landslide frequencies. We used a logistic regression approach with multiple parameters including slope, surficial geology, depth to bedrock, and distance to stream. The results indicate that slope, distance to stream, and the depth of surficial deposits overlying bedrock are most correlated with high landslide susceptibility. Mapping efforts and the OBIA analyses found that clay-rich glaciolacustrine sediments and glacial till are highly susceptible to erosion and have significant effects on hillslopes and valley floors at the watershed scale. From the OBIA analyses of the repeat lidar, we found that 4,500,000 $m^3$ of sediment was eroded in the area covered by repeat lidar between fall 2011 and fall 2012. Of this, ~2,500,000 $m^3$ was deposited in what may be transient deposits on hillslopes and valley floors, and ~2,000,000 $m^3$ were removed from watersheds and likely deposited downstream in the St. Louis River and Lake Superior.

Comparisons with repeat ground-based lidar in the Amity Creek watershed found that estimates of sediment loading made with ground-based measurements of select bluffs coupled with a field-mapped inventory of bare bluff area likely underestimated the total volume of sediment removed during the flood. All of the work on repeat lidar analyses and OBIA assessments in the Duluth area have been written up for publication in a peer-reviewed journal. The manuscript is currently undergoing internal U.S. Geological Survey review prior to submission. The paper includes detailed information on methods used to correct misalignments of multi-temporal lidar data as well as techniques used for the OBIA analyses. These methods could be used elsewhere in the state as multitemporal lidar data are collected in the future. It provides a way to map and calculate sediment movement through watersheds, including understanding of sediment sources, locations of transient sediment deposits, and sediment delivery to downstream basins (large rivers, reservoirs, estuaries, Great Lakes). This has implications for how state and local agencies may respond to and plan for future extreme rain, flooding, and landslide events.

All of the mapped landslides and their attributes are being released as a spatial database through a U.S. Geological Survey data release. They will be made publicly available to anyone as soon as the internal review is complete. We anticipate final release of the database in September 2021. The database is being ingested into a nationwide landslide inventory that is in preparation by the Landslide Hazards Program of the USGS. To accompany the database, we created a U.S. Geological Survey Fact Sheet on Landslides in Minnesota. The Fact Sheet is undergoing internal review at the U.S. Geological Survey and will be released to the public upon completion of review and copy-editing. Susceptibility modeling is complete for northeastern Minnesota. The methods used have been published in a graduate thesis (Richard, 2020), that is publicly-available online through the University of Minnesota Digital Conservancy (link below in Dissemination).

**V. DISSEMINATION:**

**Description:** We propose to produce a USGS Fact-Sheet on landslides in Minnesota and a USGS Digital Database detailing the distribution of landslide hazards across the five study regions. To get our results into the hands of policy-makers, we plan to give at least two talks over the course of our project on the results of the findings at venues appropriate to reach regional and statewide environmental and land management agency staff (MPCA, MDA, BWSR, SWCDs, DNR, etc.). Results will be disseminated to the scientific community via journal articles detailing our scientific methods, observations, and conclusions in addition to presentations at the regional meeting of the Geological Society of America in 2020 (to be held in Duluth, MN).

**Status as of** *March 5, 2018:*
No results have been disseminated yet. A report has been finished for Hennepin County that was paid for by funds from Hennepin County Emergency Management. It is acting as a template for our efforts.
We plan to have several presentations at the North-Central GSA meeting in Ames, Iowa, in April 2018 that cover repeat airborne lidar analyses and repeat terrestrial lidar analyses.

**Status as of** *July 30, 2018*:
Several presentations were made regarding the project or elements therein. We have listed those presentations below, along with estimated attendance numbers.

8/28/2017, Silver Jackets (a group of Federal agencies located in Minn. involved with disaster mitigation) 15 people, Jennings

3/12/2018, Hennepin County Association of Cities quarterly meeting, 50 people, Jennings

4/10/2018, Hennepin County Watershed Districts, (Minnehaha, Lower Minnesota, Riley-Purgatory-Bluff Creek, Mississippi, 9-mile Creek), 9 people, Jennings

5/25/2018, PAGES Steering Committee field meeting, 10 people, Jennings

4/16-17/2018, Four presentations were given at North-Central Geological Society of America meeting in Ames, IA, ~30 attendees/talk:
Jennings, C., Kurak, E., 2018. Landslide inventory and categorization for Hennepin County, Minnesota.
DeLong, S.B., Wickert, A.D., Gran, K.B., Breckenridge, A.J., DeLong, W.M., Jennings, C., 2018. Characterizing landscape response to an extreme meteorological event in northeastern Minnesota in 2012 using multitemporal lidar.
Gran, K.B., Neitzel, G., Hall, L., Brown, E., 2018. Utilizing repeat terrestrial lidar data to track bluff erosion in and after a major flood event.
Brown, E., Gran, K.B., 2018. Monitoring bluff erosion using terrestrial laser scanning and structure-from-motion photogrammetry on Minnesota’s North Shore streams.

**Status as of** *January 30, 2019*
Several presentations on this effort were given over the past six months:

12/11/18 MnDOT, Oakdale, Joint meeting of the Transportation Infrastructure Research Council and the Environment and Energy Research Council, sponsored by the Center for Transportation Studies, U of M. The topic of the meeting was resilient design. Presentations were recorded, archived and distributed to attendees. 20 people.

12/11/18 Poster presentation at the American Geophysical Union annual meeting in Washington D.C.:
Endres, M.A., McDermott, J.A., Gran, K.B., Orchard, V.L., Kurak, E., DeLong, S.B., DeLong, W.M., Engle, Z.T., Wickert, A.D., Jennings, C.E., VanBerkel, J.T., Mohn, K.E., 2018. Historical Inventory and Lidar-Based Mapping of Landslides in the Minneapolis-St.Paul Metro Area, Minnesota. AGU annual meeting, Washington, D.C.
A copy of the poster is available online at https://agu.confex.com/agu/fm18/meetingapp.cgi/Paper/445931.

11/5/18: The completed Wabasha and Goodhue County work was presented at the Annual Geological Society of America Fall meeting in Indianapolis, IN:

Dean BA, Blumentritt D, DeLong WM, Wickert AD, Gran KB, Jennings CE. 2018. Documenting landslides in the driftless area of southeastern Minnesota. GSA annual meeting, Indianapolis, IN.

Available online at https://gsa.confex.com/gsa/2018AM/webprogram/Paper320339.html

Work in the Minnesota River valley has been highlighted in the Mankato area media and recognized by the community. There is much interest in what comes of this work:

http://www.mankatofreepress.com/news/local_news/slippery-slopes-study-details-mankato-s-landslide-risks/article_d7da35f6-cd8c-11e8-8670-fb0aad30029c.html

and

https://geo.mnsu.edu/geo/Landslides-LCCMR/KEYC12/KEYC12.mp4

(username: landforms password: rock)

and

https://www.claimsjournal.com/news/midwest/2018/11/26/287989.htm

**Status as of** *July 30, 2019*

Three presentations were given over the past six months:

4/22/2019 County Geologic Atlas and Landslide Atlas presentation to staff and public, Ridgedale Public Library, Hennepin County, C. Jennings. 70 people

5/23/2019 MnDOT geotechnical staff, Update on Landslide work in Minnesota River valley, Melissa Kohout and C. Jennings. 9 people

4/5/2019 Swanson, M., Kuehl, K., Bergstrom-Conley, R., Millett, J., Wickert, A., Jennings, C., Bowen, M., Larson, P.H. (2019). Revisiting the post-glacial landscape evolution of the Minnesota River valley: Preliminary Results. Abstracts with Programs: American Association of Geographers annual meeting, Washington D.C.

Work in the Minnesota River valley has been highlighted in the Mankato area media and recognized by the community. Here is one more article that was missed in the last 6-month report:

http://www.startribune.com/study-looks-at-landslides-in-mankato-other-minnesota-areas/501175881/

**Status as of** *January 30, 2020*

Two presentations were given at the Geological Society of America national meeting in Phoenix, AZ, from 9/22/20-9/25/20, in sessions focused on landslide inventories and susceptibility mapping.

Richard E.M., Dahly D.T., Gran K.B., Breckenridge A.J., DeLong S.B., DeLong W.M., Engle Z., Jennings C.E., Wickert A.D., 2019. Landslides in northeast Minnesota: Inventory mapping and susceptibility assessment. Presented at the Geological Society of American annual meeting.

https://gsa.confex.com/gsa/2019AM/webprogram/Paper339758.html

DeLong, Stephen B., Engle, Zachary, Hammer, Morena, DeLong, Whitney M., Gran, Karen B., Richard, Emilie M., Breckenridge, Andy J., Wickert, Andrew D., Jennings, Carrie and Jalobeanu, Andre, 2019. Understanding changing landscapes by improving multitemporal lidar data and exploring object-based image analysis. Presented at the Geological Society of America Annual meeting.

https://gsa.confex.com/gsa/2019AM/meetingapp.cgi/Paper/339825

**Activity Status as of July 1, 2020:**

We have drafted a factsheet for ultimate publication by the USGS. Leads in each area submitted text that was edited for content and plain language considerations. Final formatting, figure creation, and USGS review remain.

Carrie Jennings discussed progress on the project with legislators in one-on-one meetings during the regular session, especially those in impacted districts and members of the LCCMR.

We convened a session called “Flash Floods, Landslides, and Debris Flows in the Midcontinent” at a regional geology meeting (North-Central Section of the Geological Society of America) to present our work. The session was sponsored by the Geological Society of America Quaternary Geology and Geomorphology Division. Talks and posters were presented virtually and recordings are available in the links provided below. A planned field trip to view landslides in the Duluth area had to be canceled because this was converted to a virtual meeting.

JENNINGS, Carrie E., GRAN, Karen B., DELONG, Stephen B., BARTLEY, Julie K., BLUMENTRITT, Dylan, BRECKENRIDGE, Andy J., DAHLY, Derek T., DAY, Stephanie S., ENGLE, Zachary, HAMMER, Morena KURAK, Ethan, LARSON, Phillip H., MCDERMOTT, Jeni A., RICHARD, Emilie M., SWANSON, Melissaand TRIPLETT, Laura D., 2020. A LANDSLIDE INVENTORY FOR MINNESOTA (links to the talk) Geological Society of America Abstracts with Programs. , ISSN 0016-7592 doi: 10.1130/abs/2020NC-348173

DAY, Stephanie S., NIXON Jr., Charles Idell, JENNINGS, Carrie, GRAN, Karen B., DELONG, Stephen B., DELONG, Whitney, STRAND, Megan, MAROLT, Samuel D., HALVORSON, Victoria Elizabeth and SULLIVAN, Micheal 2020. LANDSLIDES IN THE RED RIVER VALLEY, MINNESOTA (links to the talk) Geological Society of America Abstracts with Programs. , ISSN 0016-7592, doi: 10.1130/abs/2020NC-348211

RICHARD, Emilie M.., DAHLY, Derek T., REHWINKEL, Rayann W., GRAN, Karen B., BRECKENRIDGE, Andy J., DELONG, Stephen B., DELONG, Whitney M., ENGLE, Zachary T., JENNINGS, Carrie E. and WICKERT, Andrew D., 2020. LANDSLIDES IN NORTHEAST MINNESOTA: INVENTORY MAPPING AND SUSCEPTIBILITY ASSESSMENT (links to the talk) Geological Society of America Abstracts with Programs. , ISSN 0016-7592
doi: 10.1130/abs/2020NC-348219

DELONG, Stephen B., ENGLE, Zachary T., HAMMER, Morena, RICHARD, Emilie M., GRAN, Karen B., BRECKENRIDGE, Andy J., and JALOBEANU, Andre. REVISITING THE 2012 DULUTH, MN EXTREME PRECIPITATION EVENT: CHARACTERIZING THE EXTENT AND MAGNITUDE OF LANDSLIDES, EROSION, AND SEDIMENTATION USING REPEAT LIDAR AND OBJECT-BASED IMAGE ANALYSIS (links to the talk) Geological Society of America Abstracts with Programs., ISSN 0016-7592 doi: 10.1130/abs/2020NC-348208

ENGLE, Zachary T., DELONG, Stephen B., BARTLEY, Julie K., BLUMENTRITT, Dylan, BRECKENRIDGE, Andy J., DAY, Stephanie S., GRAN, Karen B., JENNINGS, Carrie E., LARSON, Phillip H., MCDERMOTT, Jeni A., TRIPLETT, Laura D., WICKERT, Andrew D. TOWARDS DESIGN OF A LANDSLIDE INVENTORY GEODATABASE FOR MINNESOTA (links to a short talk to accompany poster) Geological Society of America Abstracts with Programs. , ISSN 0016-7592doi: 10.1130/abs/2020NC-348185
https://gsa.confex.com/gsa/2020NC/virtual/eposter.cgi?eposterid=50

Karen Gran and Carrie Jennings communicated with a faculty member Dr. Prajukti (Juk) Bhattacharyya, Professor of Geography, Geology, and Environmental Science, UW-Whitewater on the use of motion sensing instruments and discussed remote mapping approaches with her colleagues and students. Her award-winning project is: Developing Prototype Multimodal Sensors and Wireless Network System for Landslide Monitoring and Early Warning. Project description: Dr. Bhattacharyya recognized that there is no uniform system for landslide monitoring, or an instrument to sense multiple factors leading to landslides, perform risk assessment based on the cumulative effects of different risk factors, or provide early warning via electronic communication for evacuation and mitigation purposes. This project aims to design a prototype for such a multimodal sensing mechanism with a built-in algorithm capable of assessing landslide risk and generating early warnings via electronic communication.

Jennings continues to work with Hennepin County on the final production of their Landslide Atlas and webpage with an online map.

Jennings and DeLong met with USGS Landslide Hazards Stephen Slaughter, Landslide Response Coordinator about the potential for a national landslide hazards susceptibility map incorporating our data.

**Activity Status as of January 1, 2021:**

One presentation was given at a scientific conference during this time period:

DeLong, S.B., Engle, Z.T., Hammer, M., Scott, C.P., Arrowsmith, J.R., 2020, Regional-Scale Landscape Change: Data Preparation and Two Examples Using Object-Based Image Analysis and Windowed Iterative Closest Point Algorithm to Interrogate Results. AGU Fall Meeting, 2020.

Emilie Richard completed and defended her M.S. Thesis at the University of Minnesota Duluth. The public thesis presentation was given in July 2020. The thesis will be available soon on the University of Minnesota Digital Conservancy:
E. Richard, 2020, Landslides in Northeastern Minnesota: Inventory mapping and susceptibility assessment. M.S. Thesis: University of Minnesota Duluth, July 2020, 65 p.

**Final Report Summary:**

The main products of this project are 1) a USGS Fact Sheet on landslides in Minnesota, 2) a USGS Digital Database of landslide locations, and 3) journal articles detailing the scientific methods, observations and conclusions. The timeline for publication of the journal articles is beyond the scope of this grant as peer review can take years. One journal article (DeLong et al., in review, "Regional-scale mapping of landscape response to extreme precipitation using repeat lidar and object-based image analysis") is complete and undergoing internal USGS review before submission. A final report on the 2012 Duluth area landscape change work will be presented at the American Geophysical Union Meeting in December 2021. Both the Fact Sheet and the digital database are complete but need to undergo internal review through the USGS before they can be publicly released. We anticipate release of the digital database within one month, and the Fact Sheet within 3 months. The landslide inventory will be ingested and published as part of a new nationwide USGS landslide inventory within the next 12-24 months.

To disseminate information to stakeholders, we proposed to give at least two talks over the course of the project to regional and statewide environmental and land management agency staff. Over the course of the project, members of the team gave presentations to the Silver Jackets (Federal agencies involved in disaster mitigation), the Hennepin County Association of Cities, Hennepin County watershed districts, the PAGES steering committee, the Transportation Infrastructure Research Council, MnDOT geotechnical staff, the USGS Landslide Hazards landslide response coordinator, the general public, and legislators one-on-one. These presentations and meetings were attended by an estimated 180-200 attendees.

In addition to formal meetings and presentations, our research efforts were highlighted by at least four media articles, mostly focusing on landslides in the Minnesota River valley.

To disseminate information to the scientific community, we proposed both journal articles and presentations at the regional meeting of the Geological Society of America in 2020. That meeting was run virtually in May 2020. Our group ran a session on "Flash Floods, Landslides, and Debris Flows in the Midcontinent" and gave five presentations there. In addition to the five presentations given at the North-Central GSA 2020 meeting, team members gave ten more presentations over the course of this project at scientific meetings.

Two graduate students: Melissa Kohout and Emilie Richard, completed their M.S. degrees over the course of the project. A third graduate student, Zachary Phillips, completed his Ph.D. on a related project in the Red River basin. Although he was not funded by the LCCMR grant, his research contributed to the project.

Here is a full list of publications and presentations that are publicly available to date:

**Graduate Theses:**

Kohout, M., 2019, Mass wasting investigation and assessment in the Midwest: Case study of the Minnesota River valley, New Ulm to St. Peter, Minnesota, USA. M.S. Thesis: Minnesota State University, Mankato, 92 p.

Phillips, Z.R., 2020, Holocene postglacial fluvial processes and landforms in low relief landscapes. PhD dissertation, North Dakota State University, Fargo, ND.

Richard, E., 2020, Landslides in Northeastern Minnesota: Inventory mapping and susceptibility assessment. M.S. Thesis: University of Minnesota Duluth, July 2020, 65 p.

**Presentations available on-line:**

Endres, M.A., McDermott, J.A., Gran, K.B., Orchard, V.L., Kurak, E., DeLong, S.B., DeLong, W.M., Engle, Z.T., Wickert, A.D., Jennings, C.E., VanBerkel, J.T., Mohn, K.E., 2018. Historical Inventory and Lidar-Based Mapping of Landslides in the Minneapolis-St.Paul Metro Area, Minnesota. AGU annual meeting, Washington, D.C.

Day, Stephanie S., Nixon Jr., Charles Idell, Jennings, Carrie, Gran, Karen B., DeLong, Stephen B., DeLong, Whitney, Strand, Megan, Marolt, Samuel D., Halvorson, Victoria Elizabeth and Sullivan, Micheal, 2020. Landslides in the Red River Valley, Minnesota. Geological Society of America Abstracts with Programs. , ISSN 0016-7592, doi: 10.1130/abs/2020NC-348211.

DeLong, Stephen B., Engle, Zachary T., Hammer, Morena, Richard, Emilie M., Gran, Karen B., Breckenridge, Andy J., and Jalobeanu, Andre, 2020. Revisiting the 2012 Duluth, MN Extreme Precipitation Event: Characterizing the Extent and Magnitude of Landslides, Erosion, and Sedimentation using Repeat Lidar and Object-Based Image Analysis. Geological Society of America Abstracts with Programs., ISSN 0016-7592 doi: 10.1130/abs/2020NC-348208.

Jennings, Carrie E., Gran, Karen B., DeLong, Stephen B., Bartley, Julie K., Blumentritt, Dylan, Breckenridge, Andy J., Dahly, Derek T., Day, Stephanie S., Engle, Zachary, Hammer, Morena Kurak, Ethan, Larson, Phillip H., McDermott, Jeni A., Richard, Emilie M., Swanson, Melissa, and Triplett, Laura D., 2020. A Landslide Inventory for Minnesota. Geological Society of America Abstracts with Programs, ISSN 0016-7592 doi: 10.1130/abs/2020NC-348173.

Richard, Emilie M., Dahly, Derek T., Rehwinkel, Rayann W., Gran, Karen B., Breckenridge, Andy J., DeLong, Stephen B., DeLong, Whitney M., Engle, Zachary T., Jennings, Carrie E. and Wickert, Andrew D., 2020. Landslides in Northeast Minnesota: Inventory Mapping and Susceptibility Assessment. Geological Society of America Abstracts with Programs. , ISSN 0016-7592, doi: 10.1130/abs/2020NC-348219.

**Additional abstracts published that are available on-line:**

Richard E.M., Dahly D.T., Gran K.B., Breckenridge A.J., DeLong S.B., DeLong W.M., Engle Z., Jennings C.E., Wickert A.D., 2019. Landslides in northeast Minnesota: Inventory mapping and susceptibility assessment. Presented at the Geological Society of American annual meeting.

DeLong, Stephen B., Engle, Zachary, Hammer, Morena, DeLong, Whitney M., Gran, Karen B., Richard, Emilie M., Breckenridge, Andy J., Wickert, Andrew D., Jennings, Carrie and Jalobeanu, Andre, 2019. Understanding changing landscapes by improving multitemporal lidar data and exploring object-based image analysis. Presented at the Geological Society of America Annual meeting.

Swanson, M., Kuehl, K., Bergstrom-Conley, R., Millett, J., Wickert, A., Jennings, C., Bowen, M., Larson, P.H., 2019. Revisiting the post-glacial landscape evolution of the Minnesota River valley: Preliminary Results. Abstracts with Programs: American Association of Geographers annual meeting, Washington D.C.

Engle, Zachary T., DeLong, Stephen B., Bartley, Julie K., Blumentritt, Dylan, Breckenridge, Andy J., Day, Stephanie S., Gran, Karen B., Jennings, Carrie E., Larson, Phillip H., McDermott, Jeni A., Triplett, Laura D., Wickert, Andrew D. 2020. Towards Design of a Landslide Inventory Geodatabase for Minnesota. Geological Society of America Abstracts with Programs, North-Central Section meeting, ISSN 0016-7592, doi: 10.1130/abs/2020NC-348185.

Dean BA, Blumentritt D, DeLong WM, Wickert AD, Gran KB, Jennings CE. 2018. Documenting landslides in the driftless area of southeastern Minnesota. Geological Society of America annual meeting, Indianapolis, IN.

DeLong, S.B., Engle, Z.T., Hammer, M., Scott, C.P., Arrowsmith, J.R., 2020. Regional-Scale Landscape Change: Data Preparation and Two Examples Using Object-Based Image Analysis and Windowed Iterative Closest Point Algorithm to Interrogate Results. AGU Fall Meeting, 2020.

**VI. PROJECT BUDGET SUMMARY:**

**A. ENRTF Budget Overview:**

**This section now contains the actual expenditures from the grant.**

| Budget Category | $ Amount | Overview Explanation |
|---|---|---|
| Personnel: | $ 174,448 | UMN personnel: Gran ($20,915), Jennings ($34,158), Wickert ($17,630), 2 graduate students and temporary/casual staff ($72,948), 1 post-doctoral research assistant ($19,543), and summer research assistants ($9,253) |
| Professional/Technical/Service Contracts: | $ 318,543 | Collaborations with USGS (DeLong and geologist TBD) ($161,142), Minnesota State University at Mankato (Larson) ($51,964), Gustavus Adolphus College (Triplett) ($18,034), NDSU (Day) ($49,202), UW Superior (Breckenridge) ($6,614), Univ. of St. Thomas (McDermott) ($18,886), and Winona State Univ. (Blumentritt) ($12,700) |
| Equipment/Tools/Supplies: | $ 179 | Field equipment and supplies |
| Printing: | $ 0 | Fact sheet (will be printed by USGS) |
| Travel Expenses in MN: | $ 1,683 | Travel for field work and to attend annual collaboration meetings |
| Other: | $ | |
| **TOTAL ENRTF EXPENDITURES:** | **$ 494,853** | |

**Explanation of Use of Classified Staff:** None used

**Explanation of Capital Expenditures Greater Than $5,000:** None requested

**Total Number of Full-time Equivalents (FTE) Directly Funded with this ENRTF Appropriation:** 2 FTEs

**Total Number of Full-time Equivalents (FTE) Estimated to Be Funded through Contracts with this ENRTF Appropriation:** 5.5 FTEs

**B. Other Funds:**

| Source of Funds | $ Amount Proposed | $ Amount Spent | Use of Other Funds |
|---|---|---|---|
| **Non-state** | | | |
| University of Minnesota | $67,665 | $73,094 | Waived overhead (52% of direct costs) |
| North Dakota State University | $22,902 | $22,141 | Waived overhead (45% of direct costs) |
| University of St. Thomas | $7,760 | $7,743 | Waived overhead (41% of direct costs) |
| Winona State University | $4,520 | $5,080 | Waived overhead (40% of direct costs) |
| U.S. Geological Survey | $10,000 | $90,000 | In-kind salary |
| Minnesota State Univ., Mankato | $6,236 | $6,236 | Waived overhead (12% of direct costs) |
| | | | |
| **State** | $ | $ | |
| **TOTAL OTHER FUNDS:** | **$119,083** | **$204,294** | |

**VII. PROJECT STRATEGY:**

**A. Project Partners:**

The team was assembled because of their scientific and technical competence and their experience in each of the five study areas. Most received degrees from the U of M. The USGS Landslide Hazard Program's limited budget is focused on the Mountain West. One of their experts (DeLong) is based in Mounds View, Minn. and has joined this team. The USGS is a trusted source of geologic information and they will increase the quality and impact of our work including dissemination through USGS publications. All project partners listed here that are collaborating with University of Minnesota and UMD investigators would be funded with ENRTF funds, with additional in-kind support being provided from the University of Minnesota, MNSU, and the USGS.

**Partners receiving ENRTF funding**

1. *USGS Hazards Mission Area, Stephen DeLong and geologist to be named: fix issues with 2011-2012 Duluth lidar; do spatial analyses on statewide lidar; align efforts with USGS Landslide Hazard Program; mentor students, produce USGS publications.*
2. *North Dakota State University, Stephanie Day, Geosciences Department: supervise students mapping and doing historical research; advise grad-level project in terrestrial lidar in Red River valley and Le Sueur basin.*
3. *Minnesota State University, Mankato, Phil Larson, Geography Department and Earth Science Program: Supervise student mapping, hazard assessment and historical work; cover area between New Ulm and St. Peter.*
4. *Gustavus Adolphus College, Laura Triplett, Geology and Environmental Studies: supervise students mapping and doing historical research; cover area from St. Peter to Chaska.*

5. *University of Wiscosin Superior, Andy Breckenridge, Natural Sciences Department & Adjunct, Earth & Environmental Sciences, University of Minnesota Duluth: create metadata for prior work in lower St. Louis watershed; evaluate lidar difference map to be created for this area.*
6. *University of St. Thomas, Jeni McDermott, Geology Department: supervise undergraduates to inventory slope modifications and repairs in the metro area; field area metro to Red Wing.*
7. *Winona State University, Dylan Blumentritt, Geosciences Department: supervise students mapping and doing historical research in SE Minnesota along Mississippi and its tributaries.*

**B. Project Impact and Long-term Strategy:** This work acquires, analyzes, and distributes new data on landslides across the state of Minnesota. We are producing a USGS Fact-Sheet on landslides in Minnesota, a USGS Digital Database detailing the distribution of landslide hazard and journal articles detailing our scientific methods, results, and conclusions. This work has included the development and application of innovative lidar processing techniques, making use of the state's investment in lidar data acquisition. In addition, alignment correction of the repeat aerial lidar in 2011 and 2012 from the Duluth area also improves the quality and utility of that database for other users. Publication of landslide hazard assessments will provide science-based information to support decision-making to help:

- the MPCA implement targeted sediment-reduction strategies
- the DNR manage critical river corridors and avoid home buyouts
- communities manage land use in vulnerable areas
- a wide range of stakeholders plan for emergency response

**C. Funding History:**

| Funding Source and Use of Funds | Funding Timeframe | $ Amount |
|---|---|---|
| Hennepin County and FEMA funds to start the Twin Cities landslide inventory – grant to Jennings | 2015-2016 | $40,000 |
| *MPCA funds to document erosion rates on river bluffs in Minnesota River – grant to NDSU | 2012-2016 | $118,600 |
| *GLRI funds to UMD to assess impact of stream stabilization efforts on river bluff erosion rates in Duluth-area streams | 7/11-9/14 | $60,588 |
| *MN DNR Coastal Zone grant for lidar-based bluff assessment for coastal zone planning | 8/12-12/14 | $34,723 |
| *UMN Water Resources Center funds from USGS to UMD to study erosional hotspots in North Shore streams using high-resolution spatial data | 5/12-2/16 | $39,047 |
| Minnesota State University, Mankato, Funding for 2 graduate students to begin work on impact of landslides + in-kind time and travel for Larson | Current | $32,415 |

*Portions of these grants have provided initial data on sediment loading to rivers from landslides and other bluff failures and on spatial data analyses to map potential slide locations in the MN River basin and the North Shore.

**VIII. REPORTING REQUIREMENTS:**
Three years (7/1/17 – 6/30/20) to allow two full field seasons and three academic years.

- The project is for 4 years, will begin on 07/01/2017, and end on 06/30/2021.
- Periodic project status update reports will be submitted *January 30* and *July 30* of each year.
- A final report and associated products will be submitted between June 30 and August 15, 2021.

**IX. VISUAL COMPONENT or MAP(S): (attached)**

**X. FEE TITLE ACQUISITION/CONSERVATION EASEMENT/RESTORATION REQUIREMENTS: NA**
**Restoration N/A**

**Environment and Natural Resources Trust Fund**
**M.L. 2017 Final Project Budget**

**Project Title:** Landslide Susceptibility, Mapping, and Management Tools
**Legal Citation: M.L. 2017, Chp. 96, Sec. 2, Subd. 03i**
**Project Manager:** *Karen Gran*
**Organization:** *University of Minnesota*
**M.L. 2017 ENRTF Appropriation: $** *500,000*
**Project Length and Completion Date:** *4 Years, June 30, 2021*
**Date of Report: August 16, 2021**

| ENVIRONMENT AND NATURAL RESOURCES TRUST FUND BUDGET | Activity 1 Budget | Amount Spent |
|---|---|---|
| **BUDGET ITEM** | ***Landslide inventory*** | |
| **Personnel (Wages and Benefits)** | $13,765 | $13,754 |
| **Karen Gran ($23,422), UMD**, Co-PI, (75% salary+25% benefits, 4% FTE/yr for 3 years) (summer): Supervise student mapping and historical research, graduate student synthesis project & terrestrial lidar scanning, Superior Basin. | | |
| **Carrie Jennings ($24,671), U of M,** Project Manager, Co-PI, (75% salary+25% benefits, 6% FTE/yr for 3 years) (summer): Coordinate work, reports and budget; field characterization; result dissemination. Metro MN | | |
| **Andrew Wickert ($16,372), U of M**, Geologist, (75% salary+25% benefits, 4%FTE/yr for 3 years) (summer): Supervise statewide LiDAR analyses and alignment of repeat Duluth lidar. | | |
| **Graduate research assistants (2) and Temp and Casual Research Staff ($84,530), UMD and U of M**, (51% salary+49% fringe) GRA1:(27% FTE for 1 year, 7/1/17-6/30/18) GRA2: (50% time for year 1, 19% FTE for year 2, 9/1/18-6/30/20). 1) Assist with synthesis of 5 regional maps; develop process domain model to aid with hazards delineation. 2) Statewide lidar and repeat lidar analyses. | | |
| **Post-doctoral research assistant (1) ($19,500), U of M, Researcher (82% salary, 18% fringe)** (33% FTE/yr for 1 year, 3/15/18-7/15/18). Assist with development of process domain model to aid with hazards delineation. | | |
| **Undergraduate research assistants (1) ($8,364), UMD**, (100% salary, 19% FTE) (summer). Conduct historical research, field mapping & verification; terrestrial lidar collection; Superior basin. | | |
| **Professional/Technical/Service Contracts** | $36,017 | $36,017 |
| **U.S. Geological Survey ($161,142): Stephen DeLong (GS-13), Mounds View, MN, Landslide Hazards Program,** 20% FTE/yr for 3 years; GIS Specialist (GS-7), 33% FTE/yr for 3 years: Properly align 2011-2012 repeat Duluth LiDAR; spatial analyses on statewide LiDAR; align efforts with USGS Landslide Hazard Program; mentor students; assist with QA/QC and data publication and dissemination. | | |

| | | |
|---|---|---|
| **Minnesota State University, Mankato, ($51,964) Phil Larson** 4% FTE/yr for 3 years; undergraduate assistants (20% FTE/yr for 2 yrs); graduate assistant (50% FTE for 1 yr); Mapping, hazard assessment and historical work between New Ulm and St. Peter. | | |
| **North Dakota State University ($50,903), Stephanie Day 2**% FTE/yr for 3 years; Undergraduate assistant (20% FTE/yr for 2 yrs), Graduate assistant (50% FTE/yr for 2 yrs); Terrestrial Lidar rental: Mapping, hazard assessment and historical research in Red River; repeat terrestrial LiDAR analyses in Red River and Le Sueur. | | |
| **Gustavus Adolphus College ($18,034), Laura Triplett** 4% FTE.yr for 3 years; undergraduate assistants 20% FTE/yr for 2 yrs. Mapping and historical research in area from St. Peter to Chaska. | | |
| **University of St. Thomas ($18,922), Jeni McDermott** 4% FTE.yr for 3 years; undergraduate assistants (20% FTE/yr for 2 yrs): Mapping and historical research in Twin Cities. | | |
| **UW Superior ($6614), Andy Breckenridge:** 2% FTE/yr for 3 years. Create metadata for prior work in lower St. Louis watershed; evaluate LiDAR difference map to be created for this area. | | |
| **Winona State University ($12,700), Dylan Blumentritt** 4% FTE/yr for 3 years; undergraduate assistants (20% FTE/yr for 2 years): Mapping and historical research in SE MN. | | |
| **Equipment/Tools/Supplies** | | |
| *Equipment/Tools/Supplies: Field books, shovels, TLS storage cards, sample bags, Munsell charts (1,500)* | | |
| **Printing** | | |
| *Fact Sheet for Landslide Hazards in Minnesota; Poster printing (1000)* | | |
| **Travel expenses in Minnesota** | $575 | $575 |
| *Quarterly meetings (1280 mi/yr); Field work (1063 mi/yr); NC GSA meeting (4,996)* | | |
| **Other** | | |
| | | |
| **COLUMN TOTAL** | **$50,357** | **$50,346** |

**UPDATED THROUGH JUNE 30, 2021**

| Activity 1 Balance | Revised Activity 2 Budget 5/7/21 | Amount Spent | Revised Activity 2 Balance 5/7/21 | Revised Activity 3 budget 5/7/21 | Amount Spent |
|---|---|---|---|---|---|
| | | | | | |
| $11 | $86,291 | $86,161 | $130 | $76,803 | $74,533 |
| | | | | | |
| | | | | | |
| | | | | | |
| | | | | | |
| | | | | | |
| | | | | | |
| $0 | $163,958 | $163,867 | $92 | $120,303 | $118,660 |
| | | | | | |

| | | | | | |
|---|---|---|---|---|---|
| | | | | | |
| | | | | | |
| | | | | | |
| | | | | | |
| | | | | | |
| | | | | | |
| | $179 | $179 | $0 | | |
| | | | | | |
| | | | | $1,000 | $0 |
| | | | | | |
| $0 | $485 | $485 | $0 | $623 | $623 |
| | | | | | |
| | | | | | |
| | | | | | |
| **$11** | **$250,913** | **$250,692** | **$222** | **$198,729** | **$193,816** |

| Revised Activity 3 balance | Revised Budget 4/25/21 | Revised Total Balance |
|---|---|---|
| | | |
| $2,270 | $176,859 | $2,411 |
| | | |
| | | |
| | | |
| | | |
| | | |
| | | |
| $1,643 | $320,278 | $1,735 |
| | | |

| | | |
|---|---|---|
| | | |
| | | |
| | | |
| | | |
| | | |
| | | |
| | $179 | $0 |
| | | |
| $1,000 | $1,000 | $1,000 |
| | | |
| $0 | $1,683 | $0 |
| | | |
| | | |
| | | |
| **$4,913** | **$500,000** | **$5,146** |

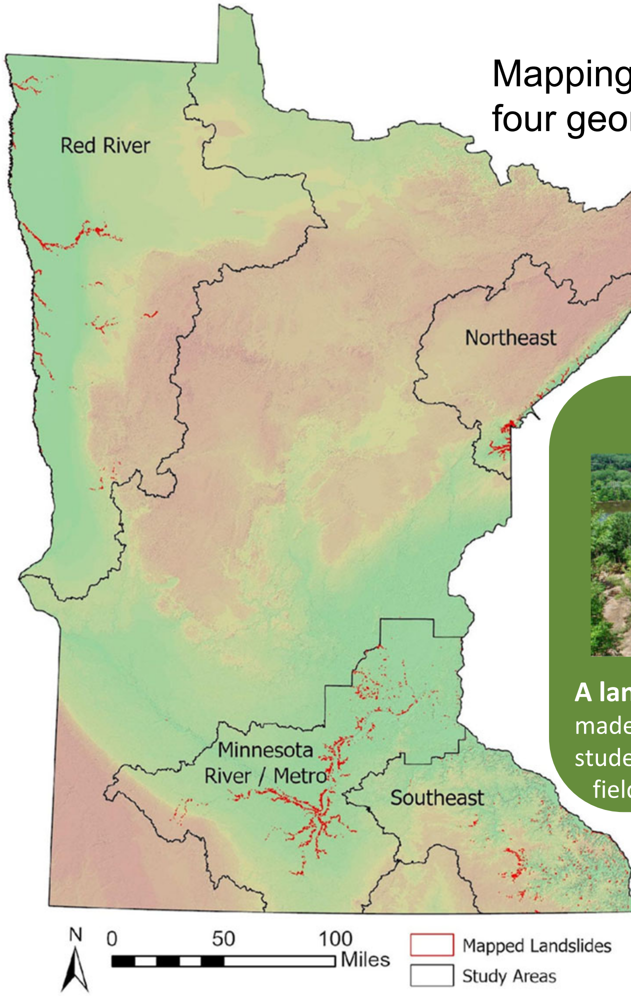
# Costs of Landslides in Minnesota

## Red River


**Landslides in Crookston** have led to compromised house foundations.


**Slow Mass wasting between 2012 and 2015** damaged this fishing spot that only existed over the same time frame in Moorhead.

Mapping efforts focused on four geomorphic regions.




## Northeast


**Flooding in the Summer of 2012** caused landslides leading to significant infrastructure damage in Duluth.

## Metro Area

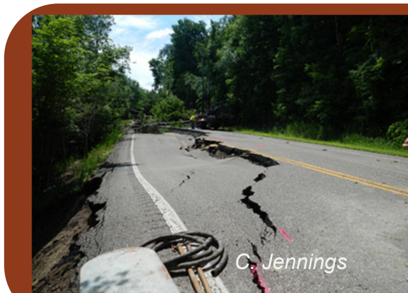

**A landslide in the spring of 2013** made news when two elementary students were killed during a class field trip.


**A landslide in June 2014** caused the West River parkway in Minneapolis to be closed and 20 people at the Fairview Hospital to be temporarily evacuated. The hospital was declared safe, but the hospital steam site sits just 10 feet from the cliff edge.

## Minnesota River

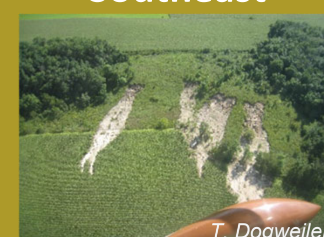


**A massive landslide in the summer of 2014** didn't damage any infrastructure, but contributed to high sediment loads in the Minnesota River watershed.




**Roads damaged in Blakeley** following a major precipitation event that triggered landslides.

## Southeast




**Landslides in southeastern Minnesota** damage fields and rockfalls impact roads.