# INDENTIFYING ACTIVE LANDSLIDES

## REPEAT LiDAR COVERAGES ALLOW REMOTE SENSING OF SLOPE MOVEMENT

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### LANDSLIDE IDENTIFICATION: PAST, PRESENT, AND FUTURE

Before any building foundation or road base is constructed on any grade, before any fiber optic, electric, oil, gas, water, or sewer line can be laid, engineers must first consider slope stability. Despite its reputation as a relatively flat plains state, even North Dakota's more gentle slopes are often comprised of weak, clay-rich sediments that cause costly impacts to infrastructure where they fail. The North Dakota Geological Survey (NDGS) documents the settings in which these slope failures have occurred across the state through its landslide mapping program. Recent Geo News articles have documented the progress of the program, including the dramatic advances in landslide identification via LiDAR (Light Detection and Ranging) and digital aerial photography over the nearly 20 years NDGS geologists have been mapping them (Murphy, 2017; Moxness, 2019; 2022). To date, the NDGS maintains an inventory of over 45,000 slope failures within North Dakota, a number that will continue to grow as older maps are updated using the latest digital imagery.

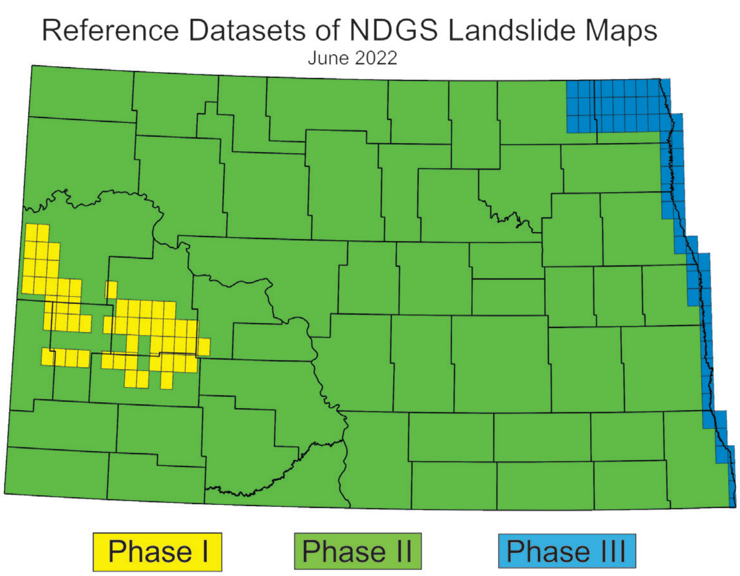



**FIGURE 1.**
NDGS landslide maps available as of June 2022 based on the reference dataset used. Phase I: 1950's and 60's black-and-white aerial photographs viewed in stereopairs and early digital imagery, Phase II: historical aerial photographs, modern NAIP digital aerial imagery, and LiDAR hillshade models: Phase III: the existing landslide maps, supplemented with 2021 aerial imagery and differential elevation models produced from a second LiDAR collect.

The NDGS maps landslides at 1:24,000 scale in standard 7.5-minute quadrangles (an area just under 6 by 9 miles). Shapefiles or maps (landslide areas plotted on a USGS topographic base) for all 1,464 North Dakota quadrangles can be downloaded at https://www.dmr.nd.gov/ndgs/landslides/. These maps utilized the best reference imagery available at the time they were completed, and as a result newer maps are more comprehensive than older maps. Internally, the NDGS marks "phases" of the program based on the reference dataset(s) used (fig. 1). About 300 maps were published under the first phase of landslide mapping between 2003 and 2017, where landslide delineation was primarily done via stereo projection of black-and-white 1:20,000-scale aerial photographs from the 1950s and '60s. The resolution of digital aerial and satellite imagery increased several-fold during this period and played a more prominent role as a reference in later phase I maps. Phase II work began as LiDAR coverage became available over western North Dakota (where most early mapping was occurring) in 2017. The bare earth hillshade models produced from LiDAR imagery allow for terrain visualization without vegetation, which led to a significant increase in the number of landslides identified (Moxness, 2019; 2022; Maike, 2021). By 2021, the rest of the state was mapped using phase II methods (fig. 2) and most of the phase I maps have since been updated.

Inventory maps do not attempt to characterize landslide susceptibility directly; rather, by documenting where slopes have failed, these areas and those nearby (similar in slope angle or geologic unit) can be avoided or more rigorously geotechnically assessed. That said, it is apparent that many mapped landslide areas are currently active (and thus pose a high risk to nearby infrastructure), while many others are relatively stable (lower risk). Visually identifying slope movement after landslide “events” is easy, especially when 4,790 cubic yards of material is deposited directly onto a busy roadway on a Sunday afternoon (Moxness, 2020), but it is the slower moving, seemingly stable slopes that cause most of the damage because they are not avoided. We know that many of the massive rotational slumps across the state likely occurred at the end of the last ice age (over 10,000 years ago). Ice sheets diverted massive amounts of water across the landscape, which cut steep slopes through weak bedrock from the Little Missouri Badlands to the Sheyenne Valley to the Pembina Gorge. The conditions which caused these slumps to form have long passed. Did most of the displacement in these bedrock masses occur in a short time at the end of the ice age, or have they continued to incrementally slip downhill for millennia? The reality may be somewhere in between, but either way the answer cannot be observed by visually comparing photographs of differing resolutions across a few decades. High accuracy elevation data across multi-year timescales is needed to recognize more subtle movement on slopes, and the latest repeat LiDAR data from eastern North Dakota allows us to begin the next phase of landslide mapping.

**FIGURE 2.**
Phase II landslide mapping along the Sheyenne River Valley using 1:20,000-scale 1959 aerial photographs viewed through a stereoscope (bottom), a Barnes County surface geology map (left screen), LiDAR DEM (center screen), and aerial imagery on Google Earth (right screen).

## LiDAR AND ITS NEW COVERAGES IN NORTH DAKOTA

LiDAR is a remote sensing technology utilized in many STEM fields. It has a wide range of applications from cell phone cameras to autonomous car technology, but in natural resource fields it is most commonly used for terrain modeling (Maike, 2016). Geologists utilize this detailed model in landslide identification, surface geologic mapping, paleontology surveying, flood mapping, and erosion modeling (Maike, 2021). For terrain modeling, LiDAR is collected over large areas and used to create a three-dimensional image of Earth’s surface. To briefly explain this technology, a plane carrying high-precision GPS equipment flies at low altitude, and light waves from the LiDAR are emitted to the surface and travel back to the sensor (fig. 3). The time it takes the light to travel is known as the two-way travel time. From this, a precise X,Y,Z (latitude, longitude, elevation) grid of millions of points is acquired for a dataset. This type of grid is known as a three-dimensional point cloud, represented as a .LAS file. For North Dakota, on average, the point clouds

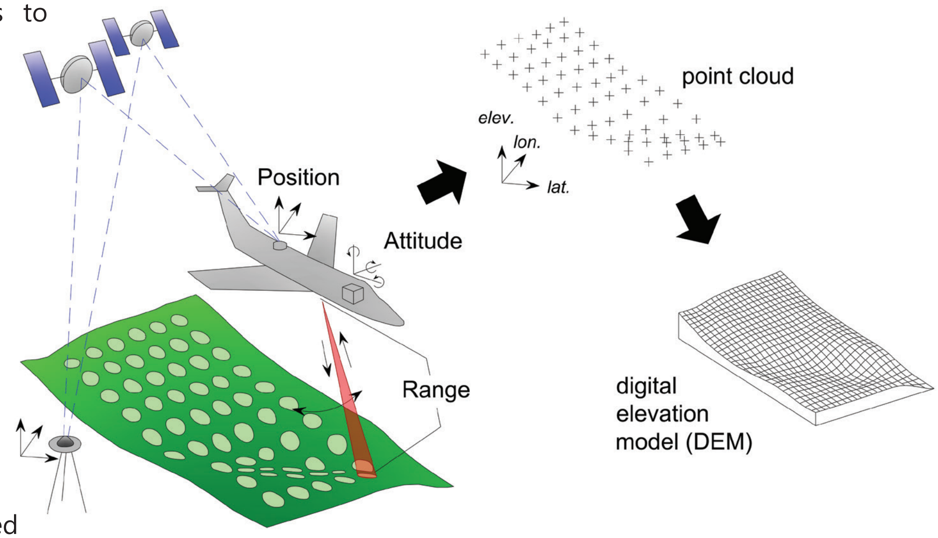



**FIGURE 3.**
A General representation of airborne LiDAR being acquired and processed. Adapted from https://historicmappingcongress.files.wordpress.com/2012/06/lidar.jpg (Date retrieved July 7, 2016).

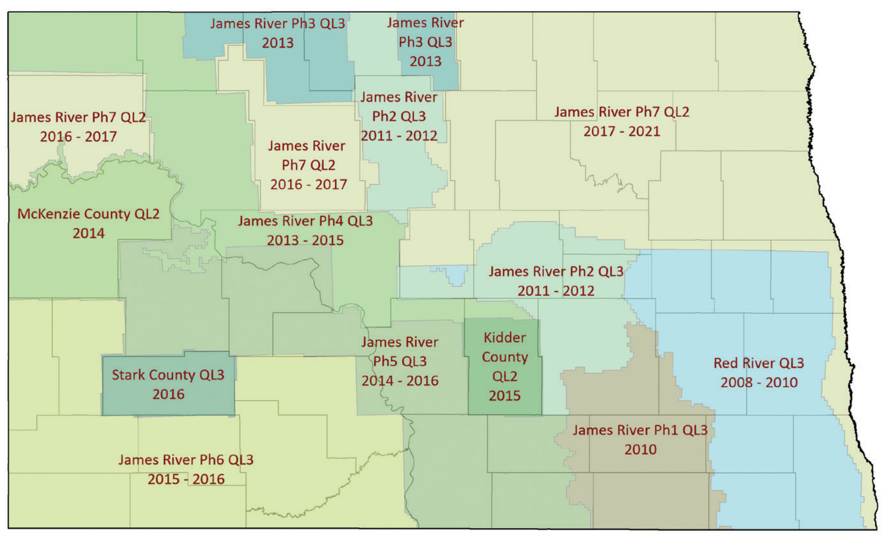



**FIGURE 4.**
The locations, dates, and quality levels of LiDAR within the State of North Dakota. This data is managed by the North Dakota Department of Water Resources.

typically have an average horizontal spacing of approximately one meter between points. From this dense array of points the elevation between them can be interpolated as pixels, resulting in a model of Earth's surface known as a DEM (Digital Elevation Model). Software can filter out trees, vegetation, buildings, etc, which results in a smooth "bare-earth" model.

The primary sources of funding to collect the LiDAR data within the state of North Dakota (fig. 4) are at the Federal, State and County Level, such as: US Fish and Wildlife Service, Natural Resources Conservation Service, Federal Emergency Management Agency, US Army Corps of Engineers, North Dakota Department of Water Resources, McKenzie County, and the International Water Institute. The stewardship of this

**TABLE 1.**
The different levels of LiDAR quality and associated metrics. Adapted from https://www.usgs.gov/3d-elevation-program/topographic-data-quality-levels-qls (Date retrieved May 26, 2022).

| QUALITY LEVEL | DATA SOURCE | VERTICAL ACCURACY RMSEz (cm) | NOMINAL PULSE SPACING (NPS) meters | NOMINAL PULSE SPACING (NPD) points per square meter | DIGITAL ELEVATION MODEL (DEM) cell size (meters) |
|---|---|---|---|---|---|
| **QL0** | **Lidar** | **5 cm** | **<= 0.35 m** | **>= 8 pts/square meter** | **0.5 m** |
| **QL1** | **Lidar** | **10 cm** | **<= 0.35 m** | **>= 8 pts/square meter** | **0.5 m** |
| **QL2** | **Lidar** | **10 cm** | **<= 0.71 m** | **>= 2 pts/square meter** | **1 m** |
| QL3 | Lidar | 20 cm | <= 0.35 m | >= 0.5 pts/square meter | 2m |
| QL4 | Imagery | 139 cm | N/A | N/A | 5 m |
| QL5 | IfSAR | 185 cm | N/A | N/A | 5 m |

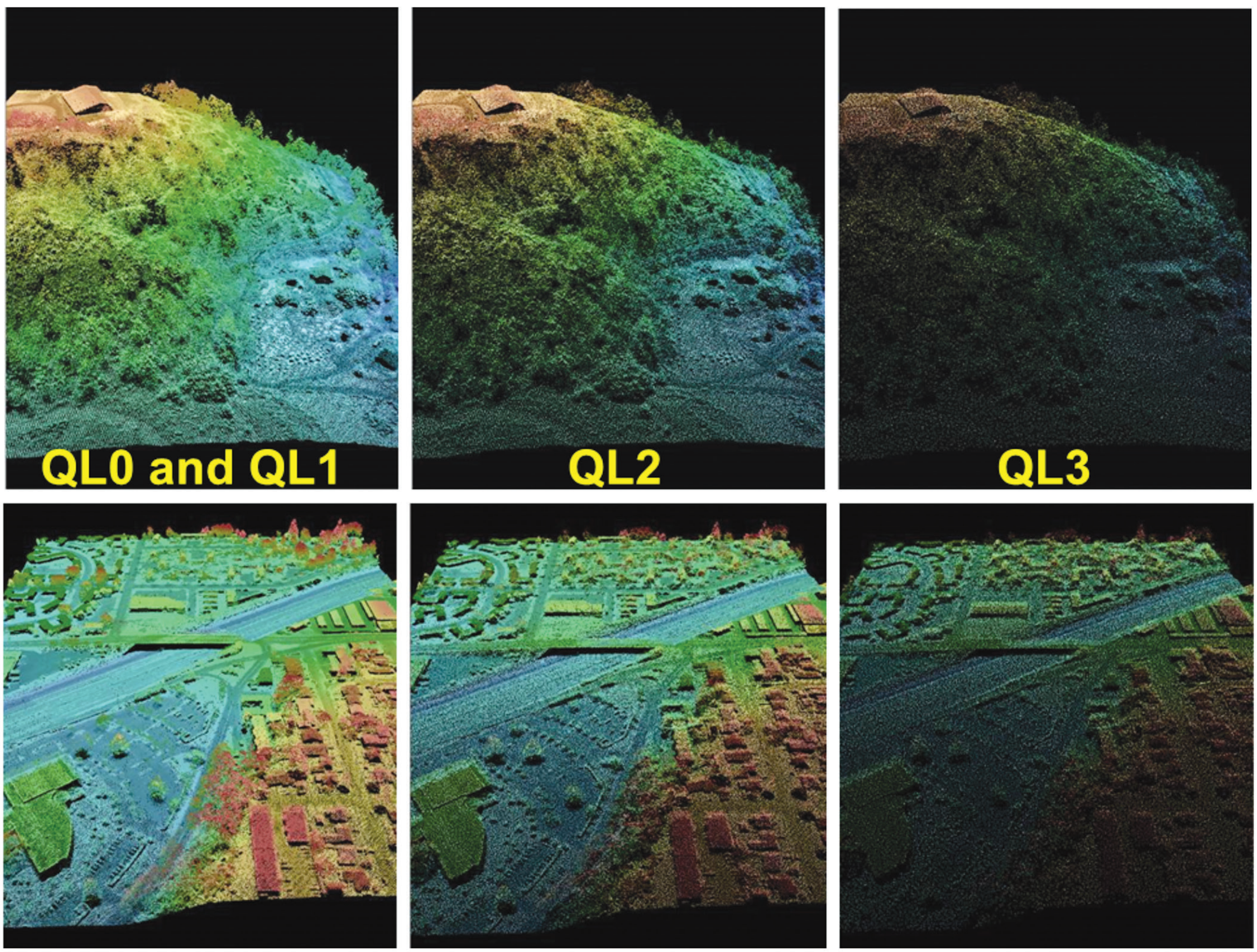



**FIGURE 5.**
A visual representation of LiDAR point cloud quality levels. This gives insight into how a more dense point cloud results in a higher quality image. https://www.usgs.gov/media/images/figure-1-3d-view-lidar-point-clouds-demonstrating-qls (Date retrieved May 26, 2022).

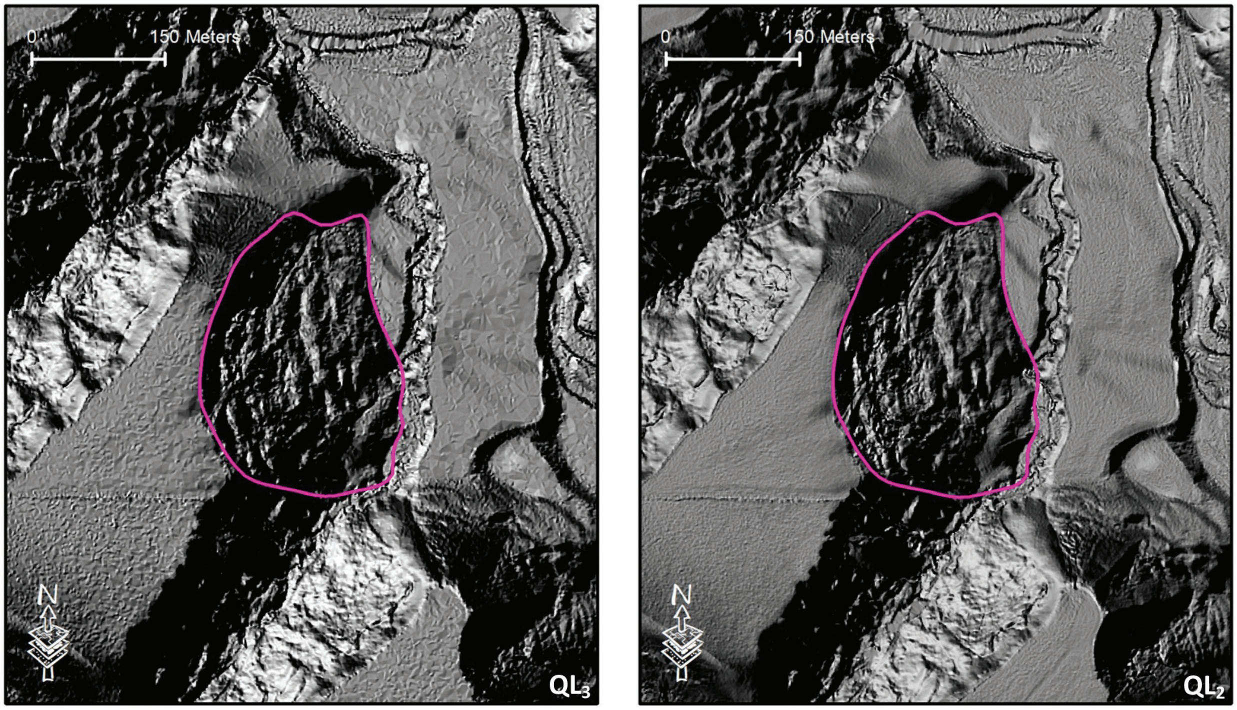



**FIGURE 6.** A landslide (outlined in pink) overlain on QL3 (left) and QL2 (right) hillshades in the Pembina Gorge. The QL3 data was collected in the 2008/2009 time frame and the QL2 data was collected in 2018.

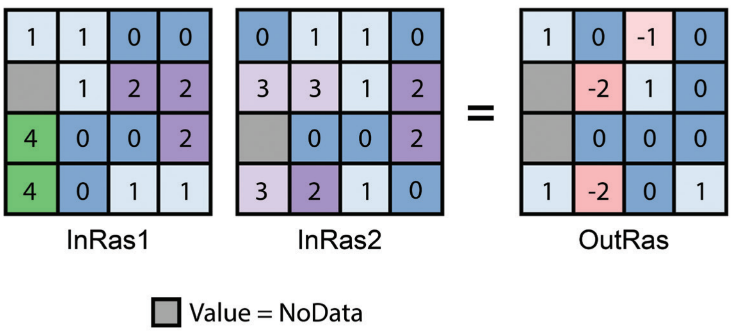



**FIGURE 7.**
The graphic represents the second raster being subtracted from the first raster. This process allows elevation change to be detected. https://pro.arcgis.com/en/pro-app/2.8/tool-reference/spatial-analyst/minus.htm (Date retrieved June 1, 2022).

data is handled by the North Dakota Departments of Water Resources and can be found at (https://lidar.swc.nd.gov). The Department of Water Resources has organized tiles through the state where data can be downloaded such as: ASCII grids, DEM images, Intensity Hybrid images, and .LAS files. The NDGS found that it would be downloading and using the entirety of the data for its use in landslide mapping, surface mapping, and other functions at 1:24,000 and 1:100,000, the scales commonly used in standard quadrangle maps. The NDGS provides these 1:24,000 and 1:100,000 maps as PDFs, DEMs, and hillshades available at www.dmr.nd.gov/ndgs/lidar/.

There are different quality levels used to determine the grade of LiDAR data, as defined by the USGS 3D Elevation Program (3DEP). The State of North Dakota in its entirety has had LiDAR collected at QL3 quality level (fig. 4). Some 10 years after the first QL3 was collected, QL2 data has now been collected, primarily in NE North Dakota, the Red River corridor, and

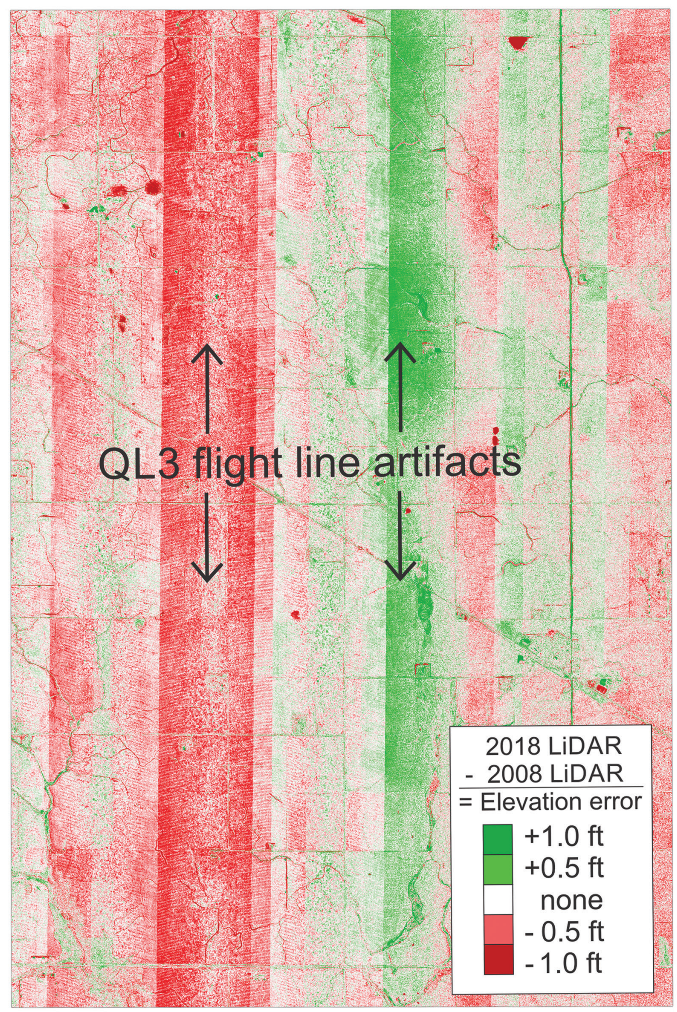



**FIGURE 8.**
Raw differential elevation raster of the Osnabrock quadrangle, a flat, stable area, illustrating the different vertical precision between 2008 QL3 LiDAR and 2018 QL2 LiDAR. Artifacts from the older flight lines are visible but are typically within +/- 1 foot.

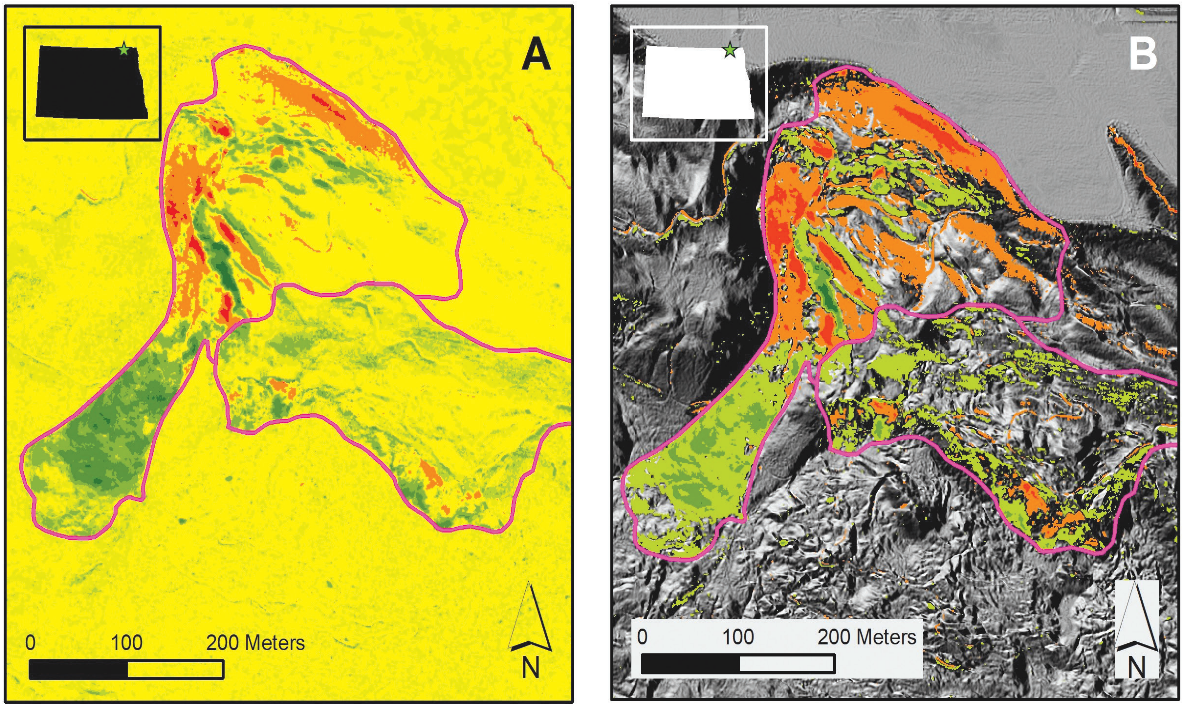
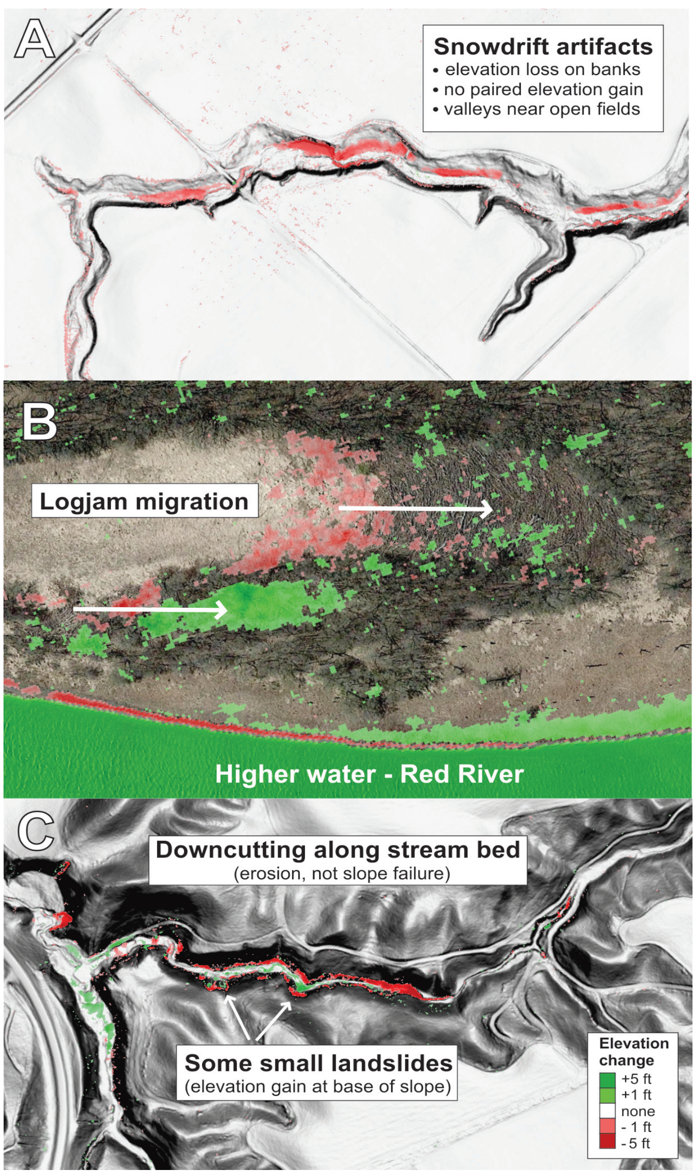



**FIGURE 9.**
(A) on the left displays two landslides (identified by pink polygons) located in the Pembina Gorge region of North Dakota. (A) shows the result of how the difference calculation appears unfiltered. The yellow color is interpreted to be "noise." (B) on the right displays how the difference calculation is presented after the noise is filtered out from the data. This data is then overlain on 2018 QL2 LIDAR data. In both maps (A) and (B) shades of red/orange are negative z-values (collapse), whereas, green areas are positive z-values (deposition/accretion).




McKenzie County. The different characteristics of quality levels are displayed in Table 1 and visually from the USGS in Figure 5. A large portion of the rest of the State of North Dakota is scheduled to have LiDAR QL2 available in the coming years. QL3 data, although "lower" quality, was a massive step from older elevation datasets and greatly expedited the NDGS landslide mapping program.

The addition of a QL2 dataset has provided a slight increase in quality, allowing imagery to become a bit more refined. Figure 6 displays a comparison of a landslide overlain on a hillshade model produced from QL2 and QL3 data. This landslide is located in the heavily collapsed shale bedrock of the Pembina Gorge. The comparison of the two quality levels shows that while QL2 data has a denser point cloud, resulting in a smoother DEM, QL3 hillshades are very comparable when viewed at the scale used by the NDGS landslide mapping program (1:24,000). For slope investigations at this scale, the primary advantage of the new LiDAR is not its higher quality but its existence as a second comparative dataset.

## PHASE III LANDSLIDE MAPPING

The availability of two LiDAR datasets, collected years apart, gives insight into land displacement that occurred during this window of time. The Minus tool (Spatial

**FIGURE 10.**
Elevation changes that could be confused for landslides. (A) Snowdrifts may be captured by LiDAR flown early in the season, typically along the north or west wall of draws near open fields. (B) Dense logjams along the Red River south of Pembina are not filtered out on bare-earth LiDAR, and show downstream movement from seasonal flooding. (C) Fluvial incision from downcutting streams near the heads of draws.

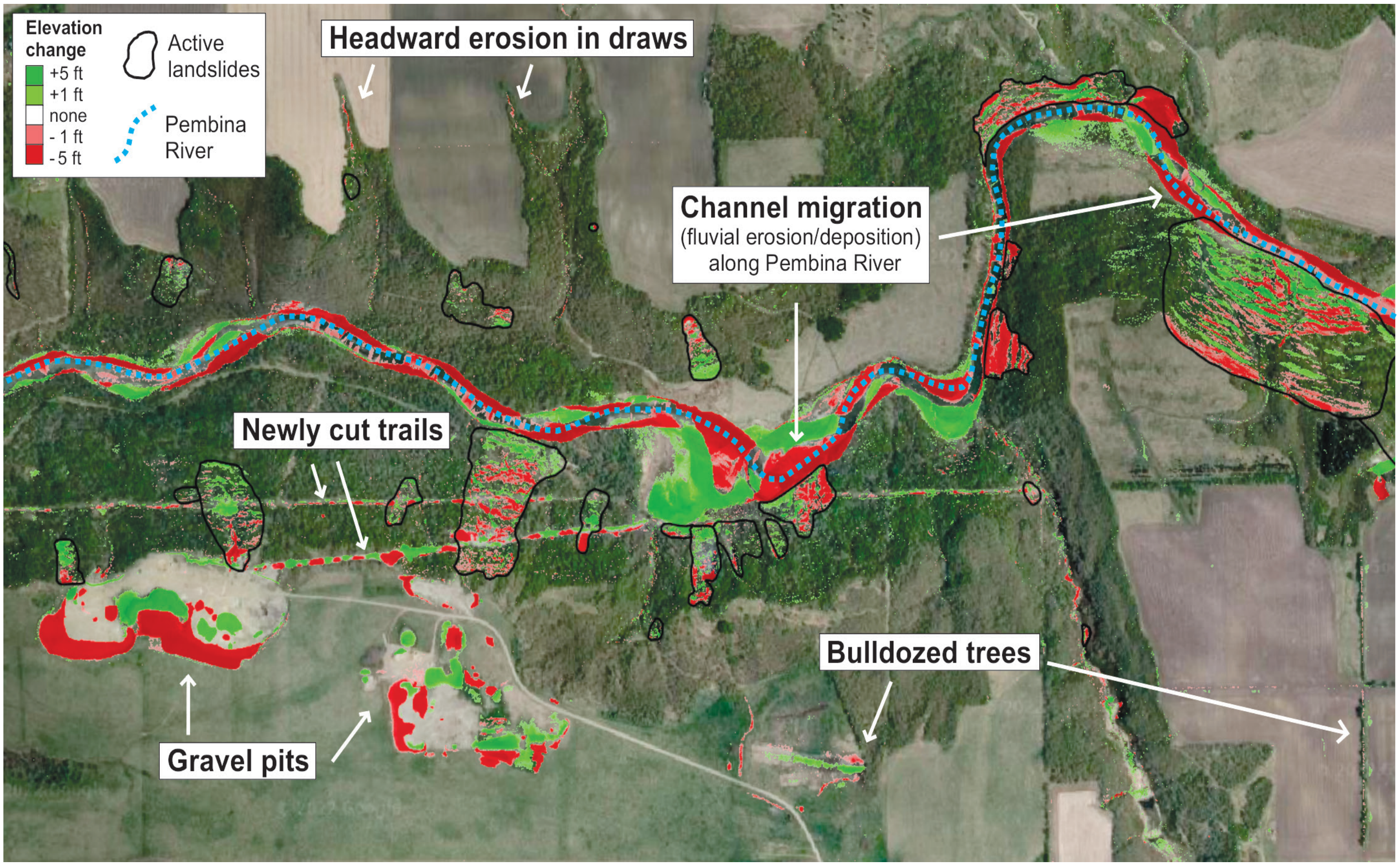



**FIGURE 11.**
Differential elevation raster overlaid on aerial imagery of the Pembina River southwest of Walhalla, ND. Elevation changes (between 2008 and 2018) caused by landslides and many other sources are apparent.

Analyst) in ArcGIS, allows for the difference between two elevation rasters to be calculated, resulting in an output of X (latitude), Y (longitude), and Z (vertical displacement) (fig. 7). All geospatial data has some amount of error, however, and there is a degree of noise in the resulting differential elevation raster. Nearly all of this "disagreement" between the two datasets is within one vertical foot (in the positive or negative direction), which is mostly artifacts between flight lines within the older, lower quality LiDAR dataset (fig. 8). There is also the aforementioned normal imprecision during data acquisition and post-processing. Much of this noise can be removed. NDGS geologists filter out any displacement from -1 to +1 feet by increasing the transparency of this interval on the differential elevation raster when looking for landslide movement (fig. 9).

Once the noise is removed, the resulting dataset shows areas where the ground has moved up or down over one foot between the two LiDAR collects, which in eastern North Dakota is about 10 years. Geologists can overlay this raster on the phase II landslide dataset and identify which have been active or delineate lobes of movement within individual slides. Not all of the signal changes over one foot can be attributed to landslides, however. Geologists map while referencing multiple years of aerial photographs and hillshade models to avoid mapping non-landslide features common on slopes (fig. 10). Snowdrifts, logjams, ponding water, human earthwork, and stream erosion (which can undermine a slope but is not mapped in isolation) all produce changes that appear on the differential elevation raster, oftentimes in between or overprinting signal from actual landslides (fig. 11).

One of the first areas to receive a second LiDAR collect is also one of the most landslide prone: the Pembina Gorge in eastern Cavalier County. Phase II mapping in 2019 showed that nearly every slope in the gorge had failed, including everything from massive rotational slumps to highly fluidized earthflows. In the Vang quadrangle alone, 1,709 landslides were mapped, including 604 active areas between 2008 and 2018 (Maike and others, 2021). NDGS geologists take special note of landslide activity in close proximity to infrastructure, and thus were paying close attention when the integrity of dams in the area, more specifically, the Bourbanis Dam, was the subject of much regional media reporting on May 3, 2022. Given that virtually all slopes along the Pembina Escarpment and within the gorge have failed, some of these dams may have been built onto landslide material when they were constructed between 1955 and 1961, and active landslides had recently been mapped above the southwest end of Bourbanis Dam (fig. 12). As more information became

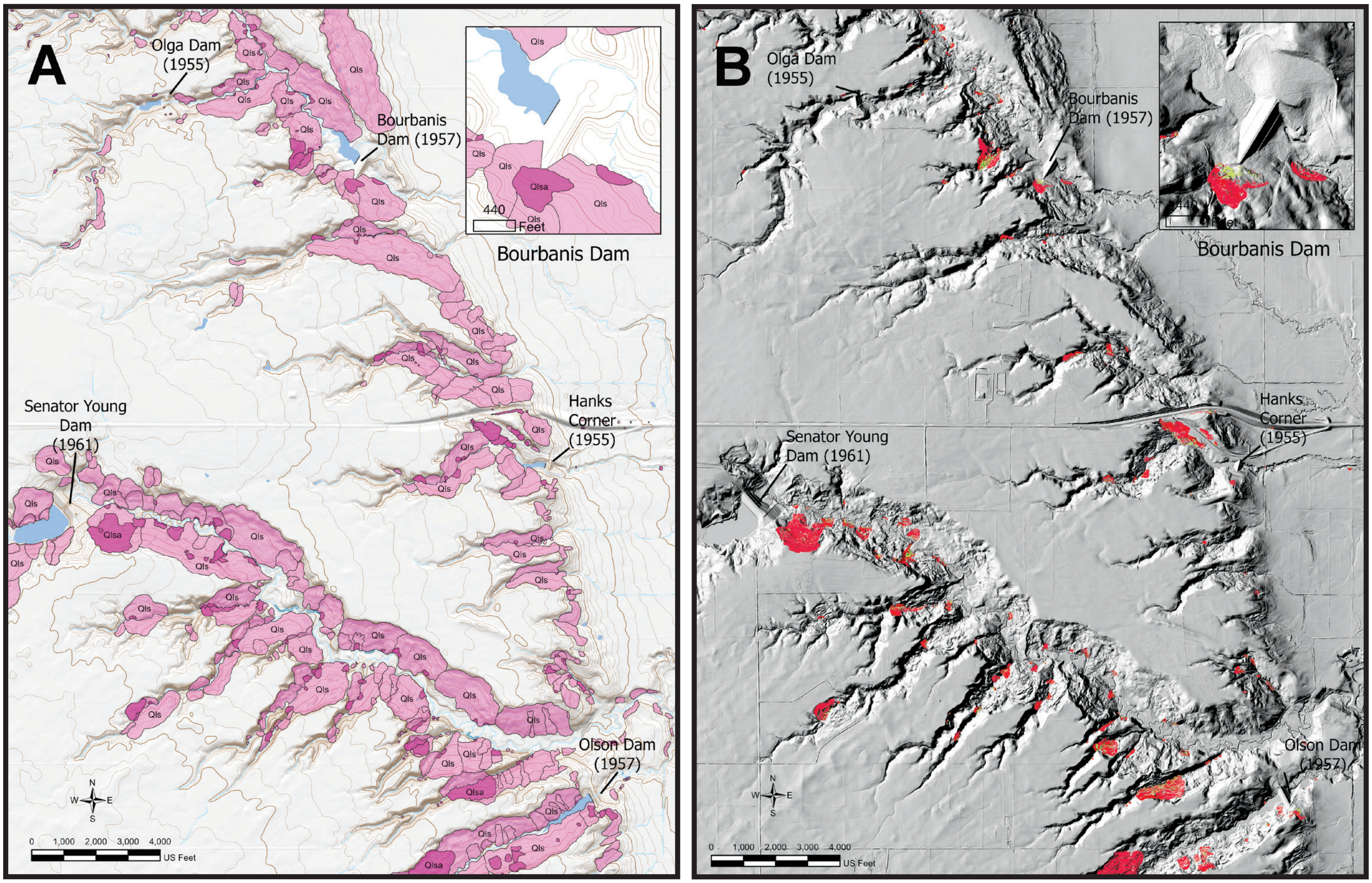



**FIGURE 12.**
Proximity of landslides to dams in northeast North Dakota. Located in the Pembina Gorge region, Map A (left) displays mapped landslide polygons (Qls-lighter pink) and active landslides (Qlsa-darker pink) overlain on a topographic shaded relief base layer. Qlsa are areas where movement occurred between 2008/2009 and 2018, shown on Map B (right) as areas of elevation loss (red) and elevation gain (green) are overlain on a QL2-quality hillshade.

available later that day, it became clear landslides posed no direct role or imminent threat in the emergency. Erosion from heavy spring precipitation threatened the integrity of the spillway. The National Guard delivered sandbags via UH-60 Black Hawk helicopters and prevented further downcutting. The dams in the Pembina Gorge are a good application for contextualizing landslide activity around important infrastructure with phase III landslide mapping. You wouldn't need a differential elevation raster to notice a catastrophic slope failure, but most impactful slides are the subtle shifts of vegetated slopes, quietly undermining anything constructed within their boundaries. Although current methods don't allow for the detection of the most subtle shifts (moving less than one foot vertically), the future may hold increasingly precise LiDAR coverages for North Dakota, which will in turn provide increasingly detailed data on landslide activity. The intersection of geology, lasers, and a window of few years' time has provided an entirely new dataset with which NDGS geologists can characterize the state's most hazardous slopes.

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