Quantifying Erosion Susceptibility as a Function of Geomorphic Variables, Trail Type, and Use with Implications for Trail Planning in the City of Boulder Open Space and Mountain Parks, Colorado, USA

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EXECUTIVE SUMMARY

Problem Statement

The City of Boulder Open Space and Mountain Parks (OSMP) in Boulder, Colorado, USA, maintains trail systems on steep hillslopes with regions prone to erosion that impact OSMP managed trails. This research seeks to understand factors influencing hillslope and trail erosion to inform management strategies and specifically consider trails managed as designated primary trails (designated) and those formed and used by humans and wildlife but not currently under management or designated for primary use (undesignated). As such, the results of this study represent research conducted on a small portion of OSMP-managed lands. The designated trails included in the study, while managed and maintained, are *legacy trails*, meaning they were adopted from past travel patterns that occurred before modern trail construction practices were developed. In contrast, newly designated trails are designed using best management practices for sustainability and minimal maintenance. Therefore, the results presented are specific to the trails included in the study and may not apply to other trails managed by OSMP. However, this work informs our understanding of factors influencing hillslope and trail erosion such that recommendations for OSMP current and future trail development and management can be made, and generalization made to inform trail management on hillslopes more broadly.

Summary of Methods

To understand how these hillslopes have evolved and behave, we looked at geomorphic variables (slope, concavity, and topographic position indices), trail designation (designated and undesignated), and high-resolution imagery to determine areas in the OSMP where active erosion and hillslope instability are occurring. We first started at a regional scale looking at process domains and geomorphic variables to see how the overall hillslope evolves. We did this by assessing several geomorphic datasets. In the map series below, we assessed slope, concavity, and topographic position indices. At a regional scale, these process domains provide valuable information on hillslope characteristics. Additionally, these datasets highlight trail properties such as the average slope of the trails, the average concavity (how it moves material), and where most of these trails fall in terms of landform classifications (valleys and ridges). We examined these datasets for both designated and undesignated trails in the OSMP, but notably the vast majority of OSMP trails were not designed with modern best management practices. We found that designated trails have steeper slopes (28.4 degrees), occur more commonly in valleys, and move material by advective processes (movement dominated by water flow and slope). Undesignated trails have lower slopes (24.3 degrees), occur more commonly on top of ridges, and move material by diffusive processes (movement dominated by slope).

Summary of Results

We found that these hillslopes are constantly evolving from drilling, debris flows, earth flows, and slower slow mass movements such as soil creep. Trails that occur in these areas are at risk of erosion and poor trail conditions, regardless of designation status. We also found that designated trails exist in less favorable conditions highlighting more movement on these trails in comparison to undesignated trails. Additionally, we determined that poor trail conditions are likely attributed to lack of design because most trails are legacy trails that were incorporated into the current system. These trails are not sustainable and will likely experience some form of erosion in the future.

Proposed Solutions

Our results indicate clear linkages among geology and hillslope erosional processes, however, the primary factor influencing trail condition appears to be trail placement rather than geomorphology or designation status. To remedy this, we propose the following management strategies:

1) Implement indirect outreach strategies such as new signage at trail heads and trail intersections suggesting visitors to stay on certain trails. Place educational resources at trail heads and intersections to educate visitors on improper trail use and its impact on the landscape.
2) Seasonal closures during wet seasons where trails exhibit active runoff and erosion.
3) Designate undesignated trails that exhibit more favorable conditions and remove trail designations for legacy trails that exhibit poorer conditions.
4) Incorporate sustainable trail designs (e.g., switchbacks, reduction in trail grade) and best management practices where possible.
5) Use datasets developed here to locate favorable conditions for new trails in combination with best management practices.

ABSTRACT

The City of Boulder Open Space and Mountain Parks (OSMP) in Boulder, Colorado, USA, is concerned with the long-term sustainability of their managed trail system that includes legacy trails and newer undesignated routes that have differing levels of observable erosion. Our research objective was to quantify erosion susceptibility of OSMP trails as a function of underlying geology, process domain, and trail type. To this end, we produced lidar-derived physiographic variables (e.g., slope, topographic position index; TPI, curvature) and investigated how they varied by lithology, which we expected to be a primary control. These we in turn summarized by trail type (legacy and undesignated) to infer dominant erosional processes and controls at the regional scale. For zoomed-in areas of interest (AOIs), we investigated active erosion along legacy and undesignated trails using high-resolution imagery and three-dimensional models derived from drone imagery and ground-based lidar.

Consistent with our expectation, different process domains were found as a function of lithology, including hillslope domains exhibiting dominantly soil-mantled, transport-limited diffusive and advective processes, and other domains characterized by production-limited bedrock regions usually forming ridges (e.g., hogbacks and flatirons). Data also revealed that designated legacy trails have less favorable conditions compared to undesignated trails. Legacy trails are steeper (28.4°), within convergent (negative concavities; -0.0153) valleys (negative topographic positions) where water and sediment fluxes are concentrated compared to undesignated trails that occur more often on flatter areas and along ridgetops. Our AOI investigation demonstrates active erosion hot spots on legacy trails, consistent with the regional assessment. This research determined that trail placement and legacy status that lacked intentional design and best management practices are major contributors to poor trail conditions within the

OSMP, although attention should be paid to geomorphic conditions (e.g., active earthflows). To reduce the impact of erosion on the OSMP trail system, management practices such as seasonal closures, redesignation, and the introduction of switchbacks, grade reductions, and indirect management strategies (such as education and outreach) should be introduced. Additionally, any future trails should be developed in areas expected to have low erosion potential and include modern best management practices.

Keywords: trail management, hillslope evolution, physiographic variables, structure from motion, lidar, geomorphic change detection, erosion

INTRODUCTION

The City of Boulder Open Spaces and Mountain Parks (OSMP) maintains roughly 155 miles of designated multi-use trails and 164 miles of undesignated trails throughout the 45,000 acres of open space (Engelman 2018; Leslie 2016) (Figure 1) near Boulder, Colorado, USA. Prior to Covid-19, the OSMP received 6.26 million visitors annually, with most using trails between the spring and fall seasons (Leslie 2016). An updated system tracks visitation since 2020 at select trails, which will allow more detailed analysis of trail use trends in the future for those studied (*OSMP Visitation Data Explorer | City of Boulder*, 2023). The OSMP designates trails as primary routes (designated trails) for recreational use to help minimize the potential impacts on the surrounding landscape, consistent with best practices. However, use of undesignated trails or improperly designed/maintained designated trails can impact the surrounding landscape by affecting vegetation, habits, and erosion rates (Wimpey & Marion, 2011). The condition and impact of legacy designated and undesignated trails that have not incorporated best management practices is currently unknown. Even prior to the onset of the Covid-19 pandemic and increased open-space use, recreational use in open spaces and public lands was projected to increase (Outdoor Foundation n.d.; Schwartz et al., 2018). With so many visitors exploring the OSMP, it is important to understand trail conditions on trails so they can be appropriately managed in the future for sustainable long-term use, while limiting impacts on ecosystems.

In 2013, a high intensity slow-moving storm passed through the Colorado Front Range bringing 450 mm of precipitation (Gochis et al. 2015). The excess precipitation triggered more than 1100 landslides and debris flows within the Colorado Front Range (Anderson et al. 2015). An event of this magnitude was highly unusual for this region (Coe et al. 2014), but such events could increase in the future with climate change. As Colorado experiences changes in precipitation associated with climate change (U.S. Environmental Protection Agency, 2016), the geomorphic system will respond.

Flooding and erosion was widespread throughout northern Colorado as a result of the event, with differential response as a result of factors such as precipitation intensity, landuse and fire history, as well as the underlying lithologic units controlled by the regional geologic history (Gochis et al., 2015; Yochum, 2015). Many shallow landslides were triggered during the event, causing the export of hundreds to thousands of years' worth of weathering products in a few days (Anderson et al., 2015). Landslides occurred preferentially in regions underlain by sedimentary rocks (70% compared to 30% in crystalline rocks; Anderson et al., 2015; Figure 1), suggesting a lithologic control on erosional processes in this instance. The OSMP foothills are comprised primarily of tilted sedimentary formations, some of which were significantly affected by the debris flows triggered in 2013. Within sedimentary strata, differences in erosion style are also apparent, with the predominance of 2013 landslides in weaker shale and limestone units overlying more resistant sandstones. The tilted sedimentary rocks differ in friability resulting in a series of “hogbacks" where strata dip toward the east, overlying granitoid basement rocks (Figure 1). Conversely, resistant “flatirons” experienced fewer landslides, despite steep slopes and higher trail density in these regions.

As a result of the 2013 storm system, shallow landslides now scar the hillslopes along the OSMP Foothills (Figure 2A and Figure 2B). Some of these overlap additional hillslope geomorphic features comprising much of the northern OSMP hillslopes within erodible shale units: mega earthflows active during the last glacial maximum (LGM), which (Figure 3; Foster et al., 2015). In 2015, a smaller earthflow within the LGM-earthflow region became active in response to a lower-magnitude, but longer-duration precipitation event (Anderson et al., 2017) compared to the 2013 event.

The erosional implications of these different styles of landslides on the OSMP trail systems are unknown in terms of trail sustainability (Figure 2C), but clearly highlight the role of the underlying lithology, geomorphology, and hydrology on impacting hillslope erosion and likely trail longevity. Trails that exhibit erosion or an accumulation of sediment are at risk for increasing additional impacts to the surrounding environments and can lead to poorer trail conditions, inhibiting recreational use (Duffy et al., 2006). Likewise, trail development and placement that does not consider that these processes can increase erosion potential where the trail itself is contributing to increasing erosion. Understanding the geomorphic processes occurring allows for improved maintenance and planning techniques, increasing trail sustainability and the recreational benefit of these trails. It could also reduce the potential harmful effects to vegetation, habitat, and soil loss on the surrounding environments (Duffy et al., 2006; Marion and Wimpey 2017).

The contrasting erosional processes that occur across geologic units and under different hydrologic regimes warrants investigating the different process domains on the OSMP trail system, providing a unique opportunity to understand the intersection of geology, geomorphic processes, hydrology, and land use. Although it is known that factors like slope, drainage, substrate, trail design, and use influence trail erosion and sustainaibility ratings exist (Marion & Wimpey, 2017; Olive & Marion, 2009), a comprehensive analsyis of trail sustainability in this geomorphically distinct region has not been done. To this end, our main objective was to provide a recommendation for management regarding trail maintenance or potential closure of certain high-risk trails through three main tasks: (1) Develop a geomorphic process domain map, (2) Quantify active erosion on OSMP trails, including a subsampling of designated legacy and undesignated trails across process domains and geologic units, and (3) Create a statistical model that relates trail erosion and condition to geomorphic (e.g., rock and/or soil type, slope, process domain) variables and trail type, condition, and use.

The results of this study represent research conducted on a small portion of OSMP-managed lands. Since the designated trails included in this study are *legacy trails*, meaning they were adopted from past travel patterns that occurred before modern trail construction and best management practices were developed, the results presented are specific to the trails included in the study and may not apply to other trails managed by OSMP.

METHODS

To understand erosional controls on OSMP hillslopes, we used a nested spatial approach that allowed us to understand processes operating at A) the regional landscape scale, B) Areas of Interest (AOIs; e.g., hundreds of square meters) on different hillslope domains, and C) localized hot spots (e.g., tens of square meters) with active trail erosion observed in the field (Figure 4). Investigating these different scales across the landscape provides different information ranging from understanding overall landscape evolution influencing geomorphic processes to trail-specific factors such as design and local influences. As such, we use methods operating across scales. Landscape-scale geomorphic processes are best characterized by airborne lidar whereas traditionally smaller regions were more difficult to characterize without intensive survey-grade point measurements. Ground-based lidar and photogrammetry can now easily be used to capture scales from square meters to kilometers (Brasington et al., 2012; Westoby et al., 2012) (Iglhaut et al. 2019), effectively covering our AOI and hot spot spatial scales. We therefore used methods tailored to the scales of interest: airborne lidar at the regional scale (A), ground-based lidar and structure from motion (SfM) photogrammetry for the AOIs (B), and SfM and new hand-held ipad-based lidar for hot spots (C) (Figure 5). Repeated measurements over time allowed us to assess geomorphic change and locate erosion and deposition (Wheaton et al., 2010). We compared our dataset (collected 2020) to 2013 lidar and also compared data collected in 2021 to 2020 data, allowing us to assess annual and seven-year.

REGIONAL SCALE METHODS

The regional methods utilized 1) geomorphic process domain maps, 2) cosmogenic nuclide dating, 3) principal component analysis, and 4) scenario planning. Geomorphic process domain maps look at physiographic variables such as slope, topographic position index (TPI), and concavity, showing how material is likely to move throughout the hillslope. To summarize results, we used principal component analysis and scenario planning.

Regional Method 1: To create a geomorphic process domain map of the study area encompassing all AOIs, existing high-resolution lidar data collected in 2013 by the City of Boulder OSMP was used (contact City of Boulder for potential access; collected June 2013 with a Riegle LMS-Q680i). High-resolution lidar data can be useful in determining different types of processes, ranging from slow creep to landslides (Booth et al. 2009; Booth et al. 2013). In addition, these datasets can be used to create digital elevation models (DEMs) which are extremely useful for determining landscape changes. The process domain maps utilized 1-m lidar derived DEMs to create physiographic variables such as slope, TPI, hillshade, and concavity.

Using the ArcGIS Pro geoprocessing toolbox, the slope and hillshade datasets were created from the 2013 DEM using the geoprocessing pre-populated tools. The hillshade allowed visual inspection that highlighted terrain characteristics later characterized quantitatively through landscape attributes. Slope was calculated as steepness in degrees. Slope highlights areas where mass movements are likely to occur based on the steepness of the topography. Similarly, concavity was calculated using the profile curvature geoprocessing tool to determine where concave and convex processes occur. This highlights how material is likely to move over the hillslope. Convex processes are dominated by advective movement meaning movement is dominated by water flow and slope. This movement brings sediment down slope creating a concave hillslope where movement becomes channelized and incises the hillslope (Dietrich and Perron 2006; (Sweeney et al., 2015). Concave processes are dominated by diffusive movement meaning its movement is slope dependent and moves material laterally (Dietrich and Perron 2006). This gives the hillslopes topography a more subtle shape. These processes are competing against one another on the hillslope and give rise to diffusion-dominated ridges and advective-dominated valleys (Dietrich and Perron 2006; Sweeney et al., 2015).

The TPI is a landform classification used to determine roughness indices like valleys and ridges in the study area. The TPI was calculated at different resolutions (5-m, 10-m, 50-m, 100-m) to see if different hillslope attributes were identifiable at the different scales. For this research, the 100-m TPI showed the best hillslope attributes and was the primary classification index. To calculate the TPI, the focal statistic tool was used to determine the mean for each of the resolutions from the 2013 DEM dataset. The mean datasets were then subtracted from the 2013 DEM dataset using the raster calculator tool to determine the TPI for each resolution.

The physiographic datasets were then run through the zonal statistics tool to determine the average slope, concavity, and TPI for both trail designations (legacy and undesignated) and for the underlying lithology in the region. Additional zonal statistics for the regional methods include determining how many trails exist within a certain type of lithology. The generalized geology was produced from Colton (1976) and Kellogg et al. (2008).

Regional Method 2: The second regional method used was cosmogenic nuclide dating on geomorphic regions underlain by different sedimentary units, establishing background erosion rates as a function of lithologic units and process domains (Cockburn and Summerfield 2004). Cosmogenic nuclide dating highlights how hillslopes within different lithologic units are evolving over longer time scales (thousands of years), providing background erosion rates for the hillslopes that set the geologic template on which the trails were built. These rates can tell us which lithologies are more prone to erosion and which are more resistant (Darvill 2013). To plan for uncertainty, a scenario plan incorporates the information gathered from the different scales to create prospective management scenarios and their anticipated outcomes (Peterson et al., 2003). Portions of the OSMP were sampled for cosmogenic nuclides at different locations across coarse- and fine-grained sedimentary rock units (Figure 6A).

We collected in-situ samples from outcrops and sand lenses on the hillslopes that were not too shielded from cosmic rays (Figure 6B) (Gosse and Phillips 2001). Rock outcrops that were composed of softer rock were collected using a chisel and hammer (Figure 6C) (Gosse and Phillips 2001). The more resistant outcrops required the use of a rock drill, which removes sample cores from the outcrop. These samples were then transported to the rock preparation lab at the University of Northern Colorado.

The steps for preparing the samples for nuclide analysis are as follows, first the rock samples were crushed down into sand grains (< 500 mm) and washed prior to starting the chemical process. The rocks first go through a machine called the jaw crusher which gets the samples into small enough pieces to run through the disc mill. The disc mill is the second step in this process and crushes the samples into tinier grain sizes allowing us to sieve out the sand grains. For this analysis, we aimed for 500 grams of 500 microns or smaller sand grains. Once enough sample had been broken down and sieved, the sample was then washed. The sample grains were then placed in a large clean container, water was added to the sample and poured off until the water ran clear. The cleaned sample was then placed inside of the drier until it was fully dry and ready to be packaged for the University of Wyoming to complete the chemical preparation.

The chemical preparation of the samples was conducted at the cosmogenic nuclide laboratory at University of Wyoming. These samples go through a variety of steps to achieve mineral separation and leaching, this ensures the samples are free of impurities. The samples were then shipped off to the PRIME Lab at Purdue University where their cosmogenic nuclide laboratory will finish the remaining chemical preparation and run the accelerator mass spectrometry (AMS) analysis. These results are still pending from the PRIME Lab at Purdue

University and will be provided in an addendum to OSMP with associated interpretations and recommendations by the principal investigators Bywater-Reyes and Romulo.

Regional Method 3: A basic statistical analysis was conducted using a Hedge's G calculator to determine the effect size of our process domain datasets by lithology (Lakens 2013). The effect size tells us how statistically different the data is from one another. Due to limited variability among these datasets, we decided to continue with a principal component analysis (PCA) to further analyze these datasets. A PCA is a statistical procedure that works to minimize large datasets by finding similarities among the data (Jollife & Cadima, 2016). A PCA was conducted in R studio 4.1.2 to understand how the physiographic variables (concavity, TPI-10, TPI-100, slope) and lithology impact trail conditions and erosion susceptibility. For this analysis, we included the 11 lithologies with the most OSMP trails within the region of our AOIs. For this PCA we utilized the mean slope, standard deviation (std) slope, mean concavity, std concavity, mean TPI, and the std TPI for both 10m and 100m resolutions. This data was organized in Excel based on the corresponding lithology and their physiographic characteristics. This spreadsheet was then read into R studio and a PCA was conducted (See Appendix A).

Regional Method 4: A scenario plan was created to showcase potential management recommendations and their intended outcomes. This allows for the City of Boulder to determine various courses of action that could be taken to mitigate erosion in the area. A scenario plan can include a variety of recommendations such as indirect (signage and educational resources) and direct strategies (barriers, trail closures, and redesignations) (Marion & Reid, 2007). Scenario planning is an efficient method to use when looking at evolving landscapes, especially in the mist of climate change, because it allows you to try various scenarios and receive different potential outcomes (Palomo et al., 2011). For this research, five scenarios were identified as potential management recommendations. These management recommendations and techniques combine literature reviewed sustainable trail designs as well as previous studies conducted on undesignated trails in the OSMP (Schwartz et al., 2018).

FINER SCALE AREAS OF INTEREST

Finer-scale areas of interest within our regional setting were identified by their proximity to the 2013 mass wasting events, presence of both designated legacy and undesignated trails occurring in the area, and representing different lithologies we expected to have different geomorphic processes based on the process-domain variables. Based on this information, three AOIs were identified (Figure 7).

The first area of interest is the Wonderland Lake area which is underlain by a mixture of coarser-grained sandstone forming ridges (Dakota) and fine-grained shale (Benton Group) units (Figure 8). Shale is susceptible to weathering and erosion which is why it is critical to understand its impacts on the OSMP trail systems. The Wonderland Lake AOI is an exceptional location to monitor landscape changes and interactions with the trail system because this AOI experienced several styles of mass wasting events in 2013 and 2015 (debris flows and earthflows, respectively; Anderson et al. 2015).

The second area of interest is the Goat Trail area which is underlain by the Dakota, Lykins, and Morrison formations. These formations range in their erosional susceptibility and provide a great location for understanding how different geomorphic variables interact with the underlying lithology (Figure 6) within a region of heavy designated legacy trail use (Goat Trail). This AOI also experienced mass wasting events as a result of the 2013 storm event (debris flows) and contains a more complex terrain and steeper slopes than the Wonderland Lake AOI.

The third area of interest is the East Ridge Trail region which is underlain by coarser-grained, strongly cemented sandstone units including the Lyons and Fountain formations (Figure 6). These formations are more resistant to weathering and provide a good location to understand the lithologic impact on trail conditions in more resistant units. Having areas of interest in different sedimentary units allows us to compare the erosional susceptibilities of each unit and how they influence geomorphic changes in the landscape.

AOI Method 1: To establish a base-station control point to use as a known base location for use in RTK (real-time kinematic) surveys, an Emlid Reach survey-grade GNSS (global navigation satellite system) receiver was set up for at least four hours. The GNSS data was then uploaded to the Canadian Geodetic Survey of Natural Resources Canada (NRCAN) service called the Canadian Spatial Reference System Precise Point Positioning (CSRS- PPP) to achieve a static point with sub- centimeter-level accuracy.

After the base station control point was processed, a roving RTK GNSS unit (Emlid RS2) was used in conjunction with the base unit to collect kinematic points used as ground control for drone surveys within study area polygon that included geomorphic features of interest and a mixture of legacy/undesignated trails. This ensured that our drone imagery was geographically connected to our study sites when the data was post-processed (Westoby et al. 2012; Wolf 2021).

Once the ground control points were placed and surveyed, aerial drone images were acquired. We created flight polygons in Drone Deploy. Pictures were captured with a DJI Mavic II drone with minimum 80 % overlap of photos. Drone Deploy was chosen because it has an option to account for the doming error commonly found in models created from drone imagery and structure from motion (SfM). The doming effect is a systematic error that impacts the DEMs vertical component and can provide errors larger than the usual centimeter level (Sanz-Ablanedo et al. 2020). Generally, each AOI was flown once in fall of 2020 and once in spring of 2021 (see Supporting Information for table of drone data collection flights).

AOI Method 2: Agisoft Metashape, a photogrammetric processing software application, was used to post-process all the aerial imagery taken during data collection. Agisoft Metashape uses structure from motion (SfM) to create a three-dimensional point cloud model from the overlapping aerial images and their corresponding ground control points. As a result of this method, orthorectified aerial images and DEMs for each flight were produced. We followed the workflow developed by UNC, UNVACO, and James Madison University (See Appendix B). Once processed, DEMs were exported to ArcGIS Pro for additional analysis.

AOI Method 3: Drone flights proved challenging, and outright dangerous, because of paragliders, especially in the Wonderland Lake AOI. As such, we chose to use an alternative method (ground-based lidar) in collaboration with UNAVCO to conduct our repeat analysis of this site. A Riegl VZ-2000 scanner was used with Trimble R10 targets. http://tls-1.int.unavco.org/projects/U-055/ DEMs were created in CloudCompare using the protocol outlined in Bywater-Reyes and Pratt-Sitaula (2022).

AOI Method 4: Using the 2013 OSMP DEM and the newly created AOI DEMs, DEMs of difference (DOD) were calculated for each AOI. The DOD quick guide provides detailed methods (see appendix B2). The 2013 OSMP lidar DEM was subtracted from each AOI DEM (2020/2021) using the raster calculator tool. This shows how the landscape has changed over a period of time (James et al. 2012). Because of differences in datums, datasets created here were offset from the 2013 dataset. As such, we selected five points on DODs in areas thought to be stable (e.g. bedrock outcrops), avoiding edges of rasters, as these values are not an accurate representation of the datum shift. The five points were then averaged and DODs shifted accordingly such that DODs could be interpreted as deposition (positive values), no change, or erosion (negative values). Because of artifacts noticed that made absolute values unreasonable, we normalized the ranges of DOD values with the equation: "((DOD dataset – minimum value)/ (maximum value- minimum value)) - 0.5". These values were interpreted from -0.5 (erosion) to 0 (no change) to 0.5 (deposition).

LOCALIZED HOT SPOTS

Spots within our AOIs that exhibited active erosion were chosen for a localized erosion "hot spot" analysis. For this analysis, we used techniques similar to AOI techniques but appropriate for this zoomed in scale. We compared two methods to test the utility for OSMP to use in monitoring trail erosion. First, we used the newest Apple products (iPad Pro, iPhone 12 and 13) that contain lidar-capable cameras from which 3D models can be exported. We tried several applications and preferred Scanner 3D. We also used a hand-held camera (Ricoh GR II) with ground control and compared the 3D models in Cloud Compare to assess accuracy of the iPad lidar. We also conducted a change analysis (DOD) for one site that had repeat data in the Wonderland Lake AOI.

RESULTS

REGIONAL

The process domain map series includes physiographic variables that influence trail conditions: slope, concavity, and TPI-100m at a regional scale (Figure 9). Each map in the series zooms in on an AOI to showcase the dataset. The slope dataset highlights steepness characteristics. At the regional scale, it is easy to distinguish between low slopes and high slopes, however, when zoomed in on the dataset it becomes more complex as the hillslopes have pockets of localized high and low slopes. At a regional view, the concavity dataset is hard to distinguish, however, zoomed-in the dataset becomes clearer showing spots where concave and convex processes are occurring on the hillslopes. Lastly, the TPI-100 dataset classifies landscape characteristics such as valleys and ridges. It also highlights low, middle, and high slopes showing similarities with the slope process domain dataset.

Utilizing the process domain datasets, zonal statistics highlight the average slope, concavity, and TPI-100-m for trail designation and the top 11 lithologies. The two tables below show 1) trail designation (legacy and undesignated) (Table 1) 2) top 11 lithologies and their average process domains (Table 2). The top 11 lithology table includes additional information needed to run the PCA.

The Hedge's G analysis for effective size showed that 2 of the process domains datasets for the lithology were not significantly different from one another. The concavity and TPI-100m datasets showed little variability among the data while the slope dataset showed the most variability. The effect size for the datasets was small effect = 0.2; medium effect= 0.5; large effect 0.8. A large effect size indicates that the data is significantly different. The slope dataset shows the most variability among the process domain datasets, having several lithologies with a large effect size (Table 3). A small effect size suggest that the data is insignificantly different and therefore not important. The other Hedge's G tables for the concavity and the TPI-100m can be found in the appendix (See Appendix C). This analysis allowed for us to complete a more robust statistical analysis with the PCA.

The PCA utilized process domain datasets to determine relationships among physiographic variables and the underlying lithology. The PCA allows interpretation of likelihood and style of erosion. The longer the arrows on the PCA, the more weight that variable has for the lithologies. For instance, the lithologies located near the mean TPI-100m arrow indicates that those lithologies are highly correlated to that physiographic variable (Figure 10). In this case, these lithologies are ridge formers and have similar characteristics.

AREAS OF INTEREST

The number of DOD maps for each of the AOIs differs based on the availability and quality of the data for each site. The metadata for each SfM project is located in Supplemental Document "SfM_Metadata .xlsx". All the AOIs have a map highlighting a 7-to-8-year difference between 2013 and 2020/2021. Due to DOD values below threshold of detection for most sites, the Wonderland Lake AOI and the Goat Trail AOI are the only sites that highlight an annual difference (2020/2021). The East Ridge AOI did not have the needed datasets to complete a yearly analysis. In addition, the Wonderland Lake AOI is the only AOI to have a complete hot spot analysis completed. This was due to the quality of the data and the ability to georeference the images. Although not georeferenced, these images still provide an orthomosaic photo which can be used to determine visual landscape changes (See Appendix D).

Wonderland Lake AOI:

The Wonderland Lake AOI shows substantial regions of change 2020 compared to 2013, consistent with the activation and movement of an earthflow (Figure 11) starting 2015 documented by (Anderson et al., 2017). Notably, several additional areas of recent erosion were identified, one near a bedrock outcrop and knickpoint north of the glider trail (Figure 12). Additional change was detected in 2021 compared to 2020 in the earthflow area (Figure 13). An additional earthflow was discovered in 2021 and baseline data were collected (included in the UNAVCO dataset) such that the site can be monitored for future change. This region is underlain by soft shales (Benton Formation) and older Pleistocene mega earthflows.

East Ridge AOI:

In the East Ridge area, no change was detected near the legacy designated located within the Lykins Formation (a Sandstone). Ground control points were located in the center of the AOI and thus the exterior portions of this datasets have visible doming – as such we only have confidence in the center of this dataset.

Goat Trail AOI:

Goat Trail, a popular legacy trail, traverses the erodible Morrison Formation, with portions going over sandstones of the Morrison and Dakota that form resistant ridges within the mudrock portions of the Morrison. Active erosion and deposition were observed in mudstone sections of the trail and confirmed by the 2020 dataset compared to 2013 (Figure 15). This change becomes even more apparent when comparing to 2021 (Figure 16), with annual changes detected (Figure 17).

LOCALIZED HOT SPOT

When detailed data were collected with two different methods, we found comparable results. Ultimately, hand-held lidar from an IPad Pro yielded useful results compared to georeferenced SfM data from a hand-held camera (Figure 18). The IPad data is much easier to use and render into a 3D model, however, it has more distortion compared to the hand-held SfM. Hand-held SfM data collection requires the same field and post-processing protocol as the aerial UAV data with the difference being only implementation of photo collection with a hand-held camera rather than a drone. The dataset must still be georeferenced with ground control and postprocessed in a software such as Agisoft Metashape. To this end, the handheld IPad lidar protocol may be easier for OSMP to use for hot-spot monitoring. If a local ground control system such as permanent markers were implemented, the data could be georeferenced with limited training and effort.

DISCUSSION

REGIONAL

The process domains showed that the hillslopes in the OSMP are soil-mantled, transport-limited with sediment production exceeding the ability to transport material. This means that the hillslope is constantly trying to achieve equilibrium conditions by moving material by either diffusive or advective processes. These processes give rise to the hillslope's form, highlighting concave diffusive dominated ridges and convex advective dominated valleys (Dietrich and Perron 2006; Sweeney et al., 2015).

Understanding the process domains that are occurring in the area is very important for hillslope stability because it highlights patterns of movement over the hillslope. Furthermore, the TPI-100-m dataset classifies these landform characteristics as valleys, mid-slopes, and ridges further suggesting a complex system of concave and convex processes in the OSMP.

Slope is a large factor when it comes to hillslope stability and can influence hillslope failure and mass wasting events. The steeper the slope the more dangerous a potential failure could be. Eight of the eleven lithologies in the Top 11 lithology table have slopes that are steeper than 30°. Of those eight lithologies, five exceed slopes of 45° or higher, highlighting the increased potential of mass wasting events in those lithologies. Grade, or slope, has been linked to trail erosion magnitude in other studies (Meadema et al., 2020).

Additionally, the composition of the geology plays a role in the likelihood of a mass wasting events. Lithologies such as Pierre Shale, Carlile Shale, Colluvium, Alluvium, and Landslide Deposits are comprised of more erodible material and are more likely to experience hillslope failure given the perfect conditions (saturated soils, slope). Depending on the slope, soil production rate, and the water content of the material, various mass wasting events of different magnitudes can occur such as soil creep, heave, earthflows, debris flows, and rock falls.

Utilizing the process domain datasets to analyze trail conditions, we found that on a regional scale, designated legacy trails have an average slope of 28.5°, an average negative concavity of -0.0153, and an average negative TPI- 100-m of -0.7231. This suggest that legacy trails occur in less favorable conditions (valleys, concave systems, and steeper slopes). The undesignated trails occur in more favorable conditions, with an average slope of 24.3°, an average concavity of 0.0005, and an average TPI-100-m of 3.3899. This indicates that undesignated trails occur more commonly on top of ridges, in lower slopes, and in concave systems. This suggest that legacy trails are more likely to move material based on the local process domains. In addition, undesignated trails can be the result of desire paths which are created by visitors as a path of least resistance to a viewpoint or another trail. The Top 11 table and the PCA further suggest that legacy trails occur in more erodible lithologic units than the undesignated trails. However, from the data and field observations we can say that poor trail conditions are likely attributed to poor trail design rather than from erodibility of the lithologic units. This highlights the need for enhanced management practices on designated legacy trails.

AREAS OF INTEREST

Due to a difference between collection methods and datum errors, we are not able to quantify exact erosion rates. Therefore, we are only able to provide qualitative analyses of erosional features for the AOIs. This is still very helpful for determining areas in the AOIs that exhibit active erosion. While not exact, this data can provide OSMP managers with valuable information on hillslope stability, erosion, and where potential failures could occur.

WONDERLAND LAKE AOI

The Wonderland Lake AOI is an active spot in OSMP where erosion is actively occurring on designated legacy trails. Over a seven-year period we were able to detect landscape changes such as erosion and deposition on the main Wonderland Hill trail near the earthflow. Additionally, we detected change in this area over a year period suggesting that the earthflow is active and can be reactivated under wet conditions. This is concerning as the designated legacy trail (Wonderland Hill) runs right through the active earthflow.

Another erosional feature that has shown landscape changes in this AOI over a seven-year period is a knickpoint. Traditionally tied to river systems, a knickpoint is characterized by a steep or sudden drop in the channels slope. The knickpoint in the Wonderland Lake AOI is in a small hollow just northeast of the earthflow and acts as a channelized area for water flow. The knickpoint is not located near the designated trail, however, if the trail (Wonderland Hill) were to get re-routed due to erosion at the earthflow, then it could pose potential issues for future trail management.

Not included in the DOD analysis is another earthflow just north of the knickpoint. This area shows active movement and potential groundwater seepage. To our knowledge, this earthflow has not previously been described and there may be other earthflows along similar lithologic-hillslope positions. We believe that there is a layer of impermeable rock between the lower Benton formation and the Dakota group which is hindering infiltration in this area. Because of this, the water is seeping from the ground in multiple locations and is saturating the soil. This could be a potential cause for the newly developed earthflow. We were able to capture this earthflow using the iPad Pro but were only able to produce a 3D image, the data is not georeferenced (See Appendix D).

The Hot Spot analysis on the Wonderland Hill trail near the larger southern earthflow shows that there is localized erosion occurring on the trail. Both the iPad and hand-held camera detected the changes over a year period; however, the hand-held camera was able to detect changes on a more accurate level than the iPad. Both monitoring techniques can provide OSMP managers with data to determine localized hot spots without quantifying exact erosion rates. I would suggest that the OSMP utilize the iPad Pro method as it is relatively inexpensive and easy to use.

EAST RIDGE AOI

The East Ridge AOI is unique in comparison to the two other AOIs, because here we did not detect any landscape change over the seven-year period. Areas exhibiting “deposition” are within vegetated areas are thus do no accurately depict the ground and changes thereof. Similarly, “erosion” occurs frequently along the edges of the DEM where the error is higher. Therefore, these values do not accurately depict erosional/depositional features in this AOI. In addition, the East Ridge trail is located in more resistant lithologies such as the Fountain, Lyons, and Lykins formations which likely explains why there is little change in DEMs over a seven-year period.

GOAT TRAIL AOI

The Goat Trail is a steep narrow trail that has multiple spots showing signs of active erosion. Over an eight-year period, we were able to detect landscape changes in 5 spots on the Goat trail. Of those five spots, we were able to see landscape changes on an annual basis for at least one spot which highlights the complexity of erosion on the Goat Trail. If our hot spot data was of quality for this AOI, we would be able to see the active erosion occurring in this spot. Further hot spot analyses on the Goat Trail could provide the OSMP with valuable erosion data.

RECOMMENDATIONS

Using the data from the regional, AOI, and localized hot spots, five scenarios and/or management recommendations were created for the OSMP. This is used in conjunction with consistent monitoring methods such as high-resolution aerial imagery and SfM and hot spot analyses. In addition, working with location organizations like UNAVCO located Boulder, Colorado could provide the OSMP with high-resolution data without having to front cost of obtaining the equipment. The below five scenarios describe how potential management actions result in changes to hillslope stability and erosion. The actions can be combined for synergistic effects. Direct and indirect strategies work best when combined together to influence the public on current management policies (Marion et al. 2016; McAvoy and Dustin 1983). We recommend that OSMP utilize both direct and indirect strategies to address erosional concerns in the open spaces as it would directly reduce hillslope instability in some areas. It is important to note that the trails studied here were legacy or undesignated trails. These suggestions may not be applicable to other trails.

Scenario 1) No Action or "Business as Usual" - This scenario keeps current management techniques and does not adopt any new direct or indirect strategies. If the OSMP were to keep the current management practices without the introduction of new strategies, we would expect that the processes that are occurring would continue to occur, which means that several areas in the OSMP may experience hillslope instability and increased erosion. Particularly at the Wonderland Lake AOI because erosion is actively occurring, and changes are detectable over a 7-year period with some locations having detectable change on an annual basis. We would therefore expect the erosional processes active on these hillslopes to continue and perhaps be exacerbated with extreme weather events.

Scenario 2) Education and Outreach – If OSMP were to adopt indirect strategies such as newly developed educational resources and new signage at the trailheads and trail intersections, there may be some adjustment in trail usage by visitors, though previous research in the Boulder area has shown that educational materials alone are not the best approach and 40% of visitors are not aware that there are undesignated trails in the OSMP system (Schwartz et al., 2018) and other research has shown that even people with pro-environmental attitudes walk off trail (Goh, 2020). It is possible that adopting new signage would reduce some of the impact on the trails exhibiting active erosion but may be negligibly different from Scenario 1 in the absence of more aggressive management options described in Scenario 3 or 4.

Scenario 3) Seasonal Trail Closures - In this scenario, OSMP would seasonally close trails exhibiting active erosion during wet seasons. Trail users walk adjacent to muddy areas, widening trails and exacerbating impacts (Leung & Marion, 1996; Marion & Wimpey, 2017). If OSMP were to temporarily restrict access to particular trails during the wet season, then there would be a decrease in trail erosion and surrounding vegetation loss. Wonderland Hill trail at the Wonderland Lake AOI would be an excellent candidate for the implementation of this scenario. A similar approach is implemented by neighboring Boulder County and Lory State Park (https://bouldercounty.gov/open-space/parks-and-trails/trail-closures/; https://cpw.state.co.us/placestogo/parks/Lory/Pages/Conditions.aspx).

Scenario 4) Switch Trail Designations – In this scenario OSRMP would designate undesignated trails that exhibit sustainable trail characteristics as designated trails and remove trail designation from trails exhibiting active erosion (e.g., Goat Trail, Wonderland Hill). Indirect strategies (signage) would also be used in conjunction with direct strategies (barriers). Redesignating certain undesignated trails in close proximity to current legacy trails and closing the legacy trails would likely reduce active erosion on designated legacy trails and would allow visitors to use desired paths created by other visitors. Cost for this strategy would be minimal, requiring only the communication signage and barriers as opposed to trail design, structure, and maintenance costs needed for some of the other scenarios.

Scenario 5) Incorporate more sustainable trail designs – Sustainable trail design includes switchbacks, reduced trail grade, and following the natural contours of the topography. Incorporating sustainable trails designs would provide long term solutions to trail erosion in several spots in the OSMP, however would require intense construction activity. Additionally, certain trails (e.g., Goat Trail) would not qualify for this scenario as its location and the topography would make it challenging. It has been shown in other studies that sustainable trail design, rather than other approaches (reducing traffic or switching trails), is the most economic and sustainable long-term approach to trail management (Huynh & Koudelka, 2020).

Lessons Learned

In addition to the recommendations related to the research findings, we also include here a list of Lessons Learned regarding future trail erosion studies using similar methods:

1. **Gliding should be suspended during drone flights.** The speed and heights at which gliders fly (i.e., by Wonderland Lake) make it dangerous to also be flying drones for data collection. If gliding activities cannot be suspended for drone flights, we recommend not using drones.
2. **Have a ground crew of at least 4-6 people.** In addition to the Remote Pilot in Charge (RPIC) who operates the drone, an additional 3-5 people were necessary to support the RPIC in always maintaining line-of-sight with the drone, avoid hazards, watch for trail users, and talk to the public when they had questions.
3. **Most people are amenable to waiting 5-10 min.** When flying drones for data collection we sometimes asked people to wait while the drone was directly overhead a trail. Most were curious and asked questions, and were also supportive of both student research and also research related to trail conditions. A few people were not amenable to being stopped for any amount of time and even went off trail, exacerbating off-trail use. Luckily drones can be paused, but frequent pauses make the overall time of impact much longer than necessary. We recommend encouraging a culture of heeding trail closures.

CONCLUSION

The hillslopes that comprise the OSMP are geomorphically active and experience active erosion. Some of these mass wasting events are interacting with designated legacy trails in the OSMP. Consistent monitoring of these hillslopes is needed to ensure long-term sustainability of these trails in addition to implemented best management practices and preferred scenarios such as 3, 5, and 5. At the moment, designated legacy trails included in this study exhibit less favorable conditions for trail sustainability in comparison to undesignated trails. This suggests that legacy trails need more attention in terms of indirect and direct management strategies to ensure sustainability of the trails and the surrounding landscape.

Using our geomorphic process domain datasets, OSMP can identify regions most appropriate for sustainable long-term trail management, including low-slope areas, concave hilltop positions, and resistant lithologies. This approach combined with best management practices such as grade control, switch backs, etc., should provide an appropriate approach going forward. Educating the public and providing outreach resources on trail conditions can improve the open space and mountain parks mission to preserve and protect the natural environment and land resources that characterize OSMP, but cannot be implemented along. In addition, providing volunteer opportunities such as trail restoration events for visitors and Boulder residents can help reduce the physical demand on the OSMP staff and provide a means for the community to connect to the land. The existing Community Connections and Partnerships Workgroup could be engaged to ensure that the community is informed and involved in the decision making around trail management. We especially encourage OSMP to partner with entities such as UNAVCO to implement monitoring of trails and hillslopes suspected of active erosion.

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TABLES

Table 1. Process Domain Data for Designated and Undesignated Trails

Designation	Mean Slope (degrees)	Mean TPI-100m	Mean Concavity
Designated	28.5	-0.7231	-0.0153
Undesignated	24.3	3.3899	0.0005

Table 2. Top 11 Regional Lithologies, Corresponding Trail Lengths, and Process Domain Values

PCA ID #	Geology	Designated Trail Length (m) in Lithology	Undesignated Length (m) in Lithology	Mean Slope (degrees)	Std slope	Mean TPI-100m	Std TPI-100m	Mean Concavity	Std Concavity
5	Qc- Colluivum	246789.57	116902.74	34.69	20.56	-4.511	15.408	-0.00226	0.125545
11	Qpc- Piney-Creek Alluvium	233534.56	105388.68	13.85	15.43	0.014	6.709	-0.00267	0.139929
4	PPF- Fountain	88224.87	23430.17	57.53	14.93	2.004	32.889	0.000213	0.107739
1	Kpl-Low. Member of Pierre Shale	81597.35	30036.08	18.22	13.63	-0.834	6.017	-0.00077	0.113312
9	Kd- Dakota	53351.86	40134.30	45.7	15.51	3.027	19.542	0.000023	0.08541
8	TRPI- Lykins	43693.88	18383.09	48.48	13.06	-3.781	18.172	-0.00131	0.083798
10	Ply- Lyons	40782.63	10270.61	57.93	12.7	6.732	32.096	0.000173	0.08333
2	Kcg- Carlile Shale	32850.83	16105.25	31.75	16.28	-1.808	10.793	-0.0015	0.107853
3	JTRmj- Morrison	31998.90	18533.02	47.92	14.78	7.560	22.852	0.001266	0.086752
6	Ql - Landslide Deposits	26506.66	13187.23	39.36	15.54	-0.365	13.017	-0.00065	0.088082
7	Kn- Niobrara	24765.36	11579.65	27.18	16.72	-0.513	9.831	-0.00125	0.128602

Table 3. Hedge's G – Slope and Lithology												
Top 11		1 kpl	2 kcg	3 j^mj	4 P*f	5 Qc	6 Ql	7 Kn	8 ^PI	9 Kd	10 Ply	11 Qpc
kpl	1	n/a										
kcg	2	0.9145	n/a									
j^mj	3	2.0991	1.0426	n/a								
P*f	4	2.6865	1.6966	0.6446	n/a							
Qc	5	0.8491	0.1471	0.6704	1.2463	n/a						
Ql	6	1.4478	0.48	0.5629	1.2046	0.2373	n/a					
Kn	7	0.6095	0.2774	1.3346	1.2046	0.3717	0.7642	n/a				
^PI	8	2.2654	1.1513	0.0406	0.6227	0.7122	0.6347	1.4799	n/a			
Kd	9	1.8411	0.8873	0.1453	0.6227	0.5787	0.408	1.1754	0.1885	n/a		
Ply	10	3.0218	1.8467	0.7369	0.0281	1.2165	1.3197	2.1965	0.7342	0.8401	n/a	
Qpc	11	0.2871	1.1533	2.2173	0.0282	1.1874	1.6515	0.8587	2.2844	2.0608	2.9263	n/a

FIGURES

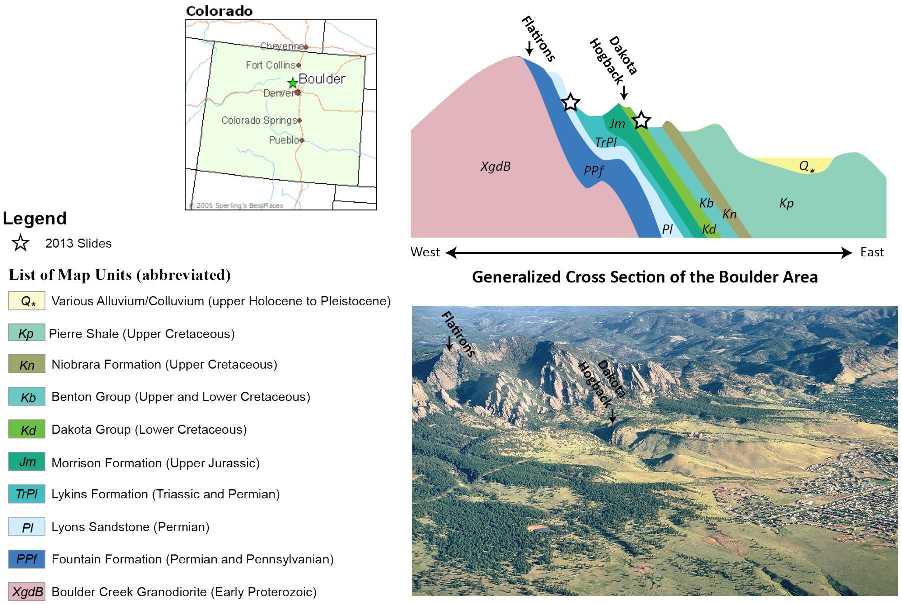
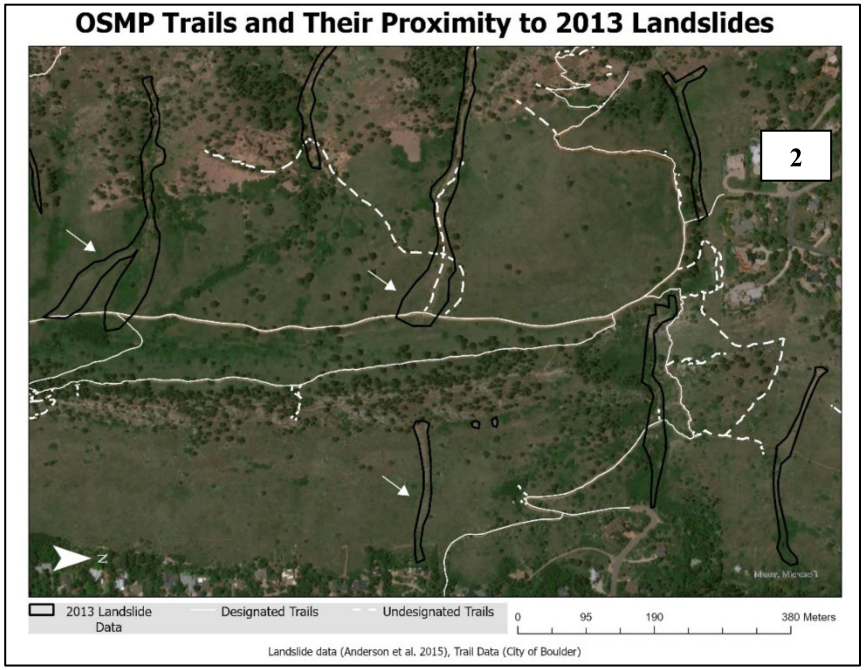


Figure 1. Generalized cross section of the Boulder, CO region showing crystalline rocks (Boulder Creek Granodiorite) in the western region and a sequence of tilted sedimentary units comprising the eastern foothills. 2013 landslides (Boulder Creek Critical Zone Observatory, 2013) occurred most frequently at the contact between a resistant sandstone and weaker overlying shale unit (hogback; after Runnells, 1976). OSMP trails often traverse these hogbacks that experienced LGM earthflows (Qls) and 2013



Landslide data (Anderson et al. 2015), Trail Data (City of Boulder)

Figure 2A. Google Earth imagery from 2013 following the precipitation event that triggered landslides and debris flows throughout the OSMP.

Figure 2B. Google Earth imagery from 2020 showing landslides scars as a result of the 2013 precipitation event

Figure 2C. Map of designated and undesignated trails in the OSMP and their proximity to some of the 2013 landslides. Data provided by Anderson et., al 2015 and the City of Boulder

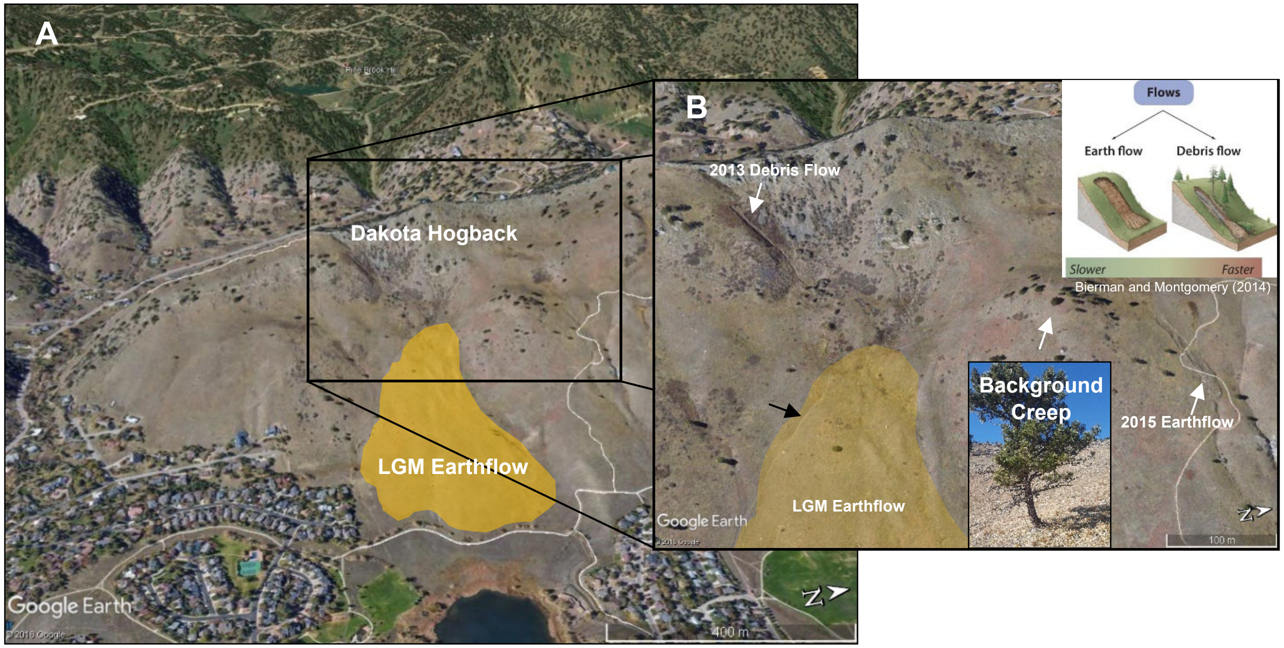


Figure 3. In the Wonderland Lake hillslope (A) a wide variety of erosional processes occur, from instantaneous 2013 debris flows to background soil creep (B). In 2015, a wet year, a slow-moving earthflow became active (Anderson et al., 2017) resulting in rerouting of the Wonderland Hill trail (B; white line). The black arrow (B) points to an undesignated trail traversing this hillslope with complex geomorphic process domains, including mega earthflows associated with the Last Glacial Maximum (LGM) ending approximately (~20,000 years ago; Foster et al., 2015).

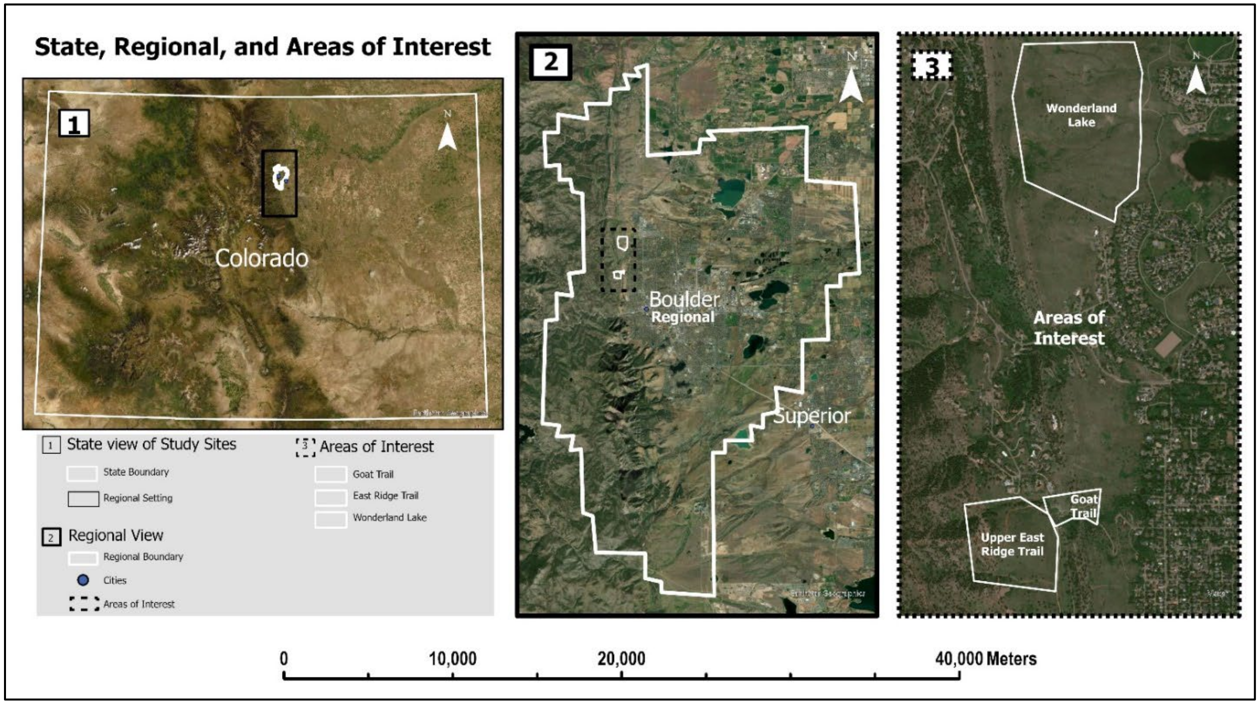
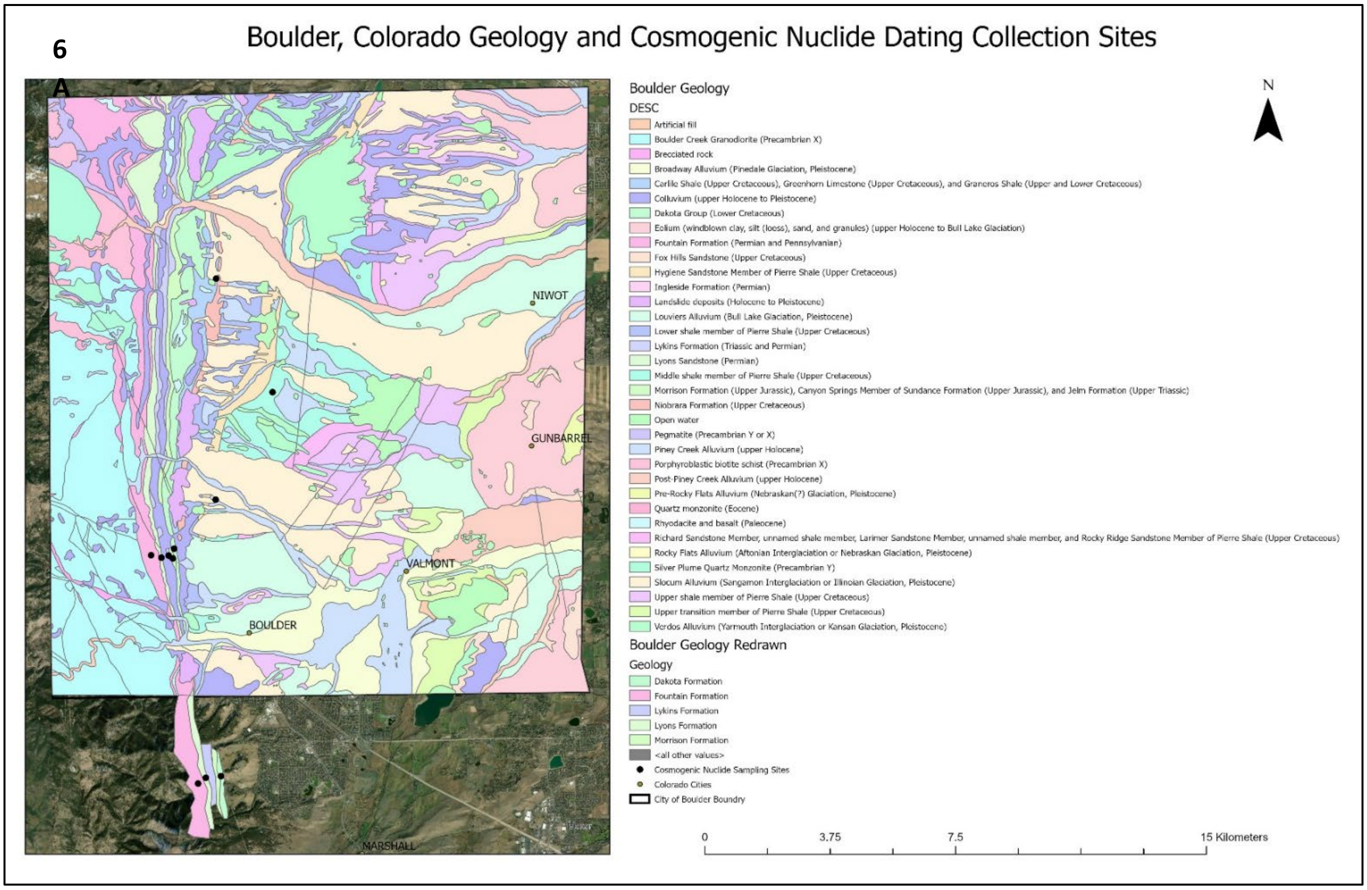


Figure 4. State and regional view highlighting areas of interest in the City of Boulder Open Space and Mountain Parks. The first map showcases the state view of the regional datasets. The second map showcases the regional boundary and the areas of interest. The third map looks at the areas of interest.

Figure 5. Shows designated trails that are exhibiting active erosion in the OSMP. The first and second images are of the East Ridge Trail and the third image shows the Wonderland Hill trail at the Wonderland Lake AOI.


6
A
Boulder, Colorado Geology and Cosmogenic Nuclide Dating Collection Sites
NIWOT
GUNBARREL
VALMONT
BOULDER
MARSHALL
Boulder Geology
DESC
Artificial fill
Boulder Creek Granodiorite (Precambrian X)
Brecciated rock
Broadway Alluvium (Pinedale Glaciation, Pleistocene)
Carlile Shale (Upper Cretaceous), Greenhorn Limestone (Upper Cretaceous), and Graneros Shale (Upper and Lower Cretaceous)
Colluvium (upper Holocene to Pleistocene)
Dakota Group (Lower Cretaceous)
Eolium (windblown clay, silt (loess), sand, and granules) (upper Holocene to Bull Lake Glaciation)
Fountain Formation (Permian and Pennsylvanian)
Fox Hills Sandstone (Upper Cretaceous)
Hygiene Sandstone Member of Pierre Shale (Upper Cretaceous)
Ingleside Formation (Permian)
Landslide deposits (Holocene to Pleistocene)
Louviers Alluvium (Bull Lake Glaciation, Pleistocene)
Lower shale member of Pierre Shale (Upper Cretaceous)
Lykins Formation (Triassic and Permian)
Lyons Sandstone (Permian)
Middle shale member of Pierre Shale (Upper Cretaceous)
Morrison Formation (Upper Jurassic), Canyon Springs Member of Sundance Formation (Upper Jurassic), and Jelm Formation (Upper Triassic)
Niobrara Formation (Upper Cretaceous)
Open water
Pegmatite (Precambrian Y or X)
Piney Creek Alluvium (upper Holocene)
Porphyroblastic biotite schist (Precambrian X)
Post-Piney Creek Alluvium (upper Holocene)
Pre-Rocky Flats Alluvium (Nebraskan(?) Glaciation, Pleistocene)
Quartz monzonite (Eocene)
Rhyodacite and basalt (Paleocene)
Richard Sandstone Member, unnamed shale member, Larimer Sandstone Member, unnamed shale member, and Rocky Ridge Sandstone Member of Pierre Shale (Upper Cretaceous)
Rocky Flats Alluvium (Aftonian Interglaciation or Nebraskan Glaciation, Pleistocene)
Silver Plume Quartz Monzonite (Precambrian Y)
Slocum Alluvium (Sangamon Interglaciation or Illinoian Glaciation, Pleistocene)
Upper shale member of Pierre Shale (Upper Cretaceous)
Upper transition member of Pierre Shale (Upper Cretaceous)
Verdos Alluvium (Yarmouth Interglaciation or Kansan Glaciation, Pleistocene)
Boulder Geology Redrawn
Geology
Dakota Formation
Fountain Formation
Lykins Formation
Lyons Formation
Morrison Formation
<all other values>
Cosmogenic Nuclide Sampling Sites
Colorado Cities
City of Boulder Boundry
N
0
3.75
7.5
15 Kilometers


6B


6C

Figure 6A Cosmogenic nuclide dating sites in the OSMP. The black dots indicate where samples were taken.

Figure 6B Is an in-place outcrop where samples were collected for cosmogenic nuclide dating.

Figure 6C Shows the chisel and hammer method used to collect rock samples for cosmogenic nuclide dating.

Figure 7. Designated and Undesignated Trails in the Areas of Interest. Data provided by OSMP

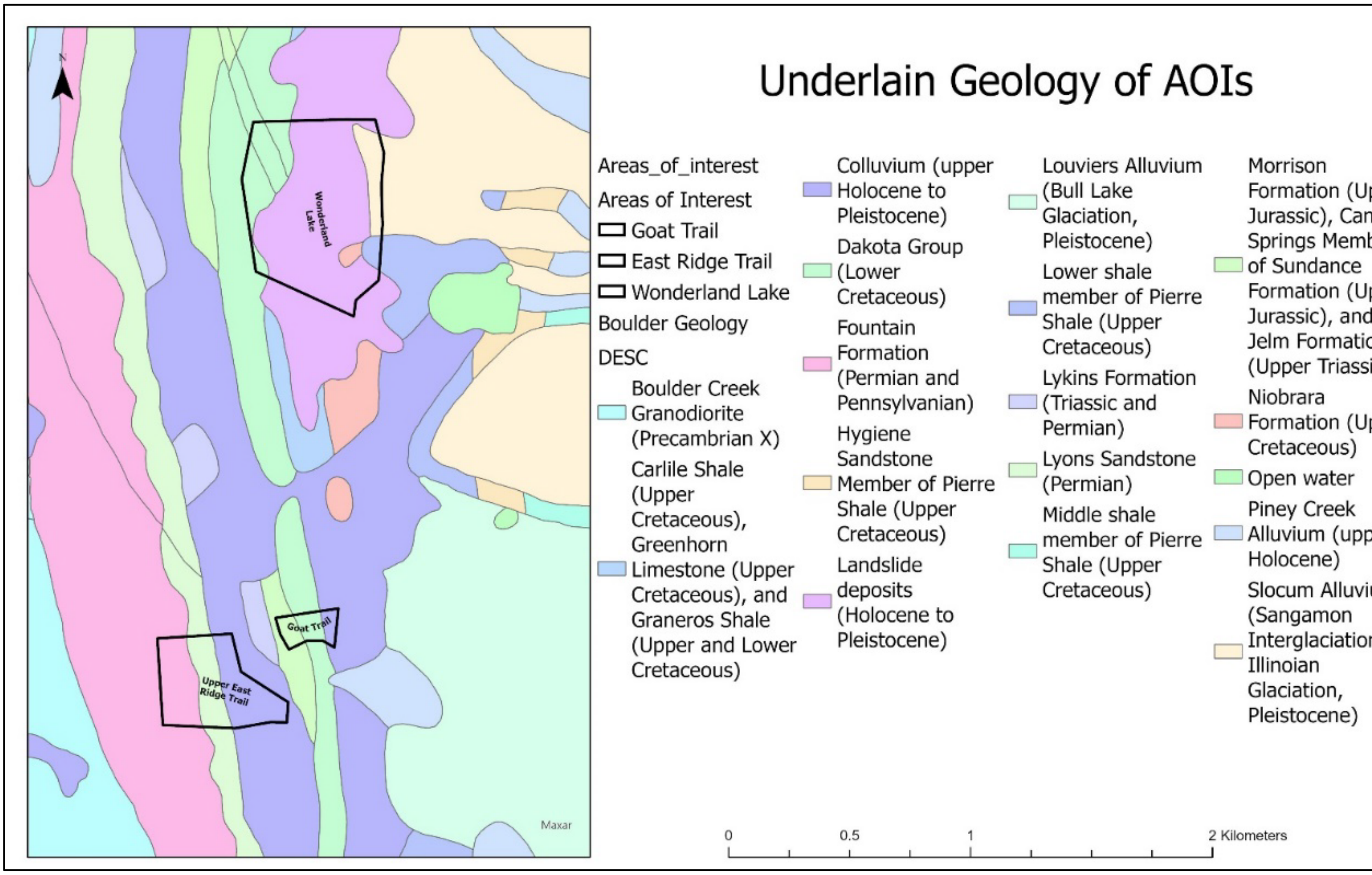


Figure 8. Underlain geology of the AOIs. Geology data is provided by USGS.

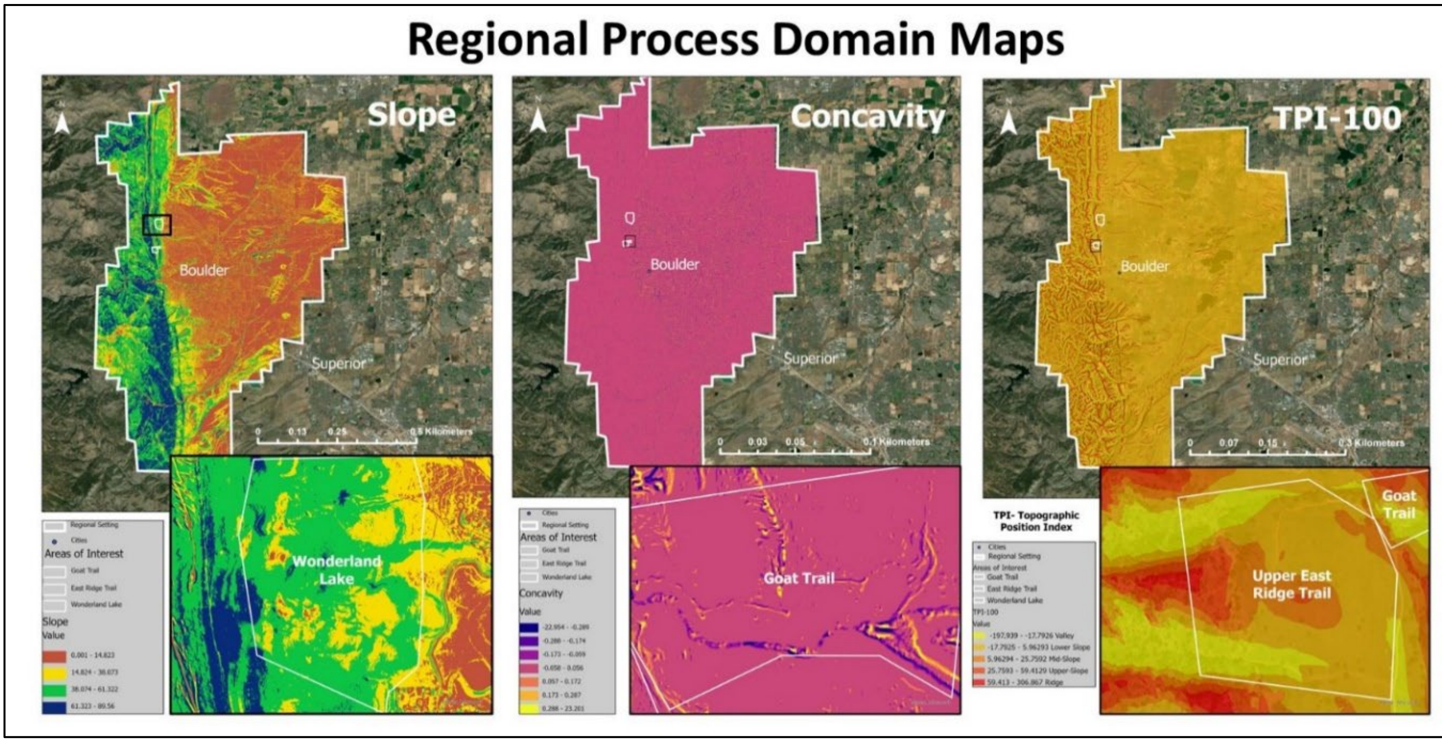
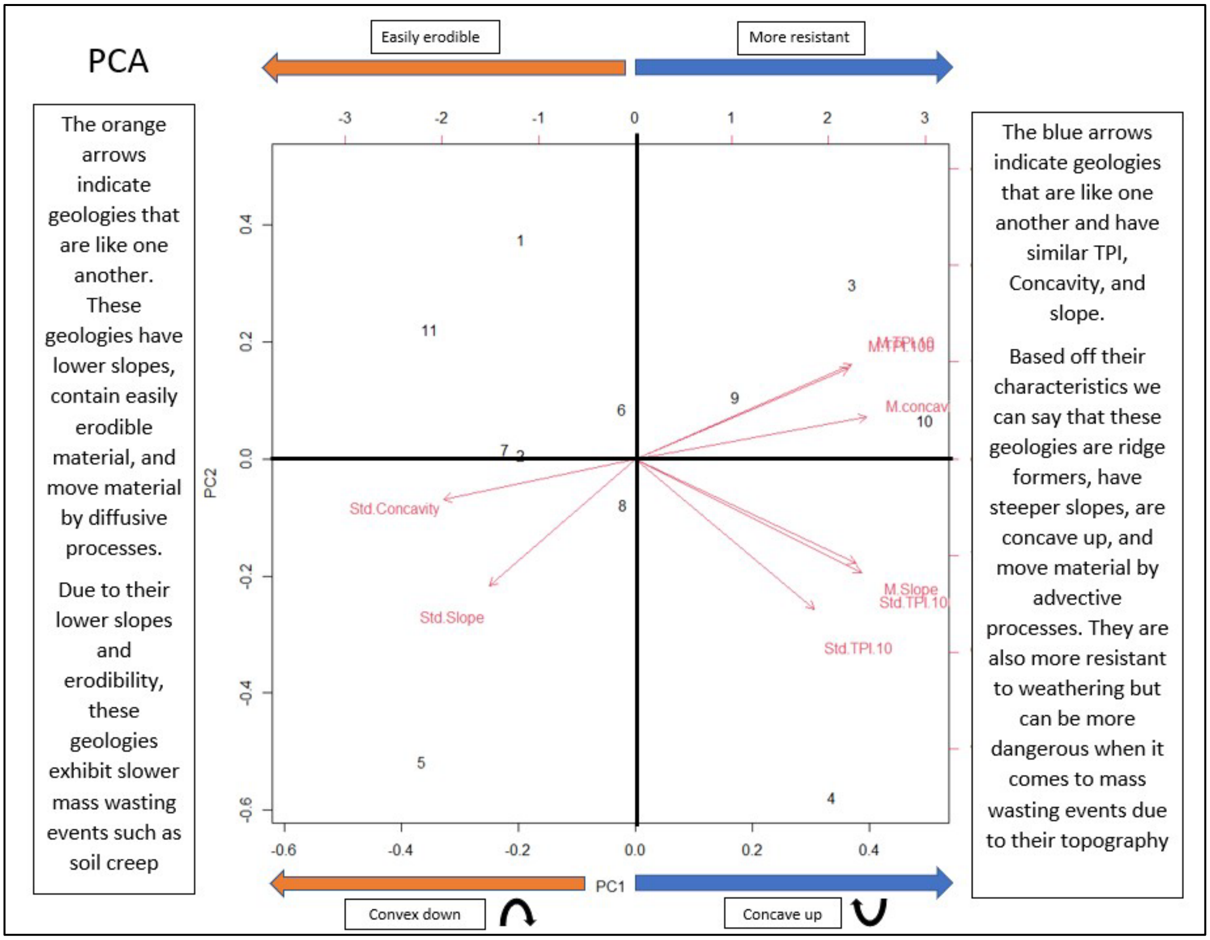


Figure 9. The process domain map series shows the regional view of the slope, concavity, and TPI-100m datasets. These datasets were created from the 2013 OSMP DEM.



The orange arrows indicate geologies that are like one another. These geologies have lower slopes, contain easily erodible material, and move material by diffusive processes.

Due to their lower slopes and erodibility, these geologies exhibit slower mass wasting events such as soil creep

The blue arrows indicate geologies that are like one another and have similar TPI, Concavity, and slope.

Based off their characteristics we can say that these geologies are ridge formers, have steeper slopes, are concave up, and move material by advective processes. They are also more resistant to weathering but can be more dangerous when it comes to mass wasting events due to their topography

Figure 10. PCA numbers and the corresponding lithologies: **1**-Lower Member of Pierre Shale **2**-Carlile Shale **3**-Morrison **4**- Fountain **5**- Colluvium **6**- Landslide Deposits **7**- Niobrara **8**-Lykins **9**-Dakota **10**-Lyons **11**- Piney Creek Alluvium.

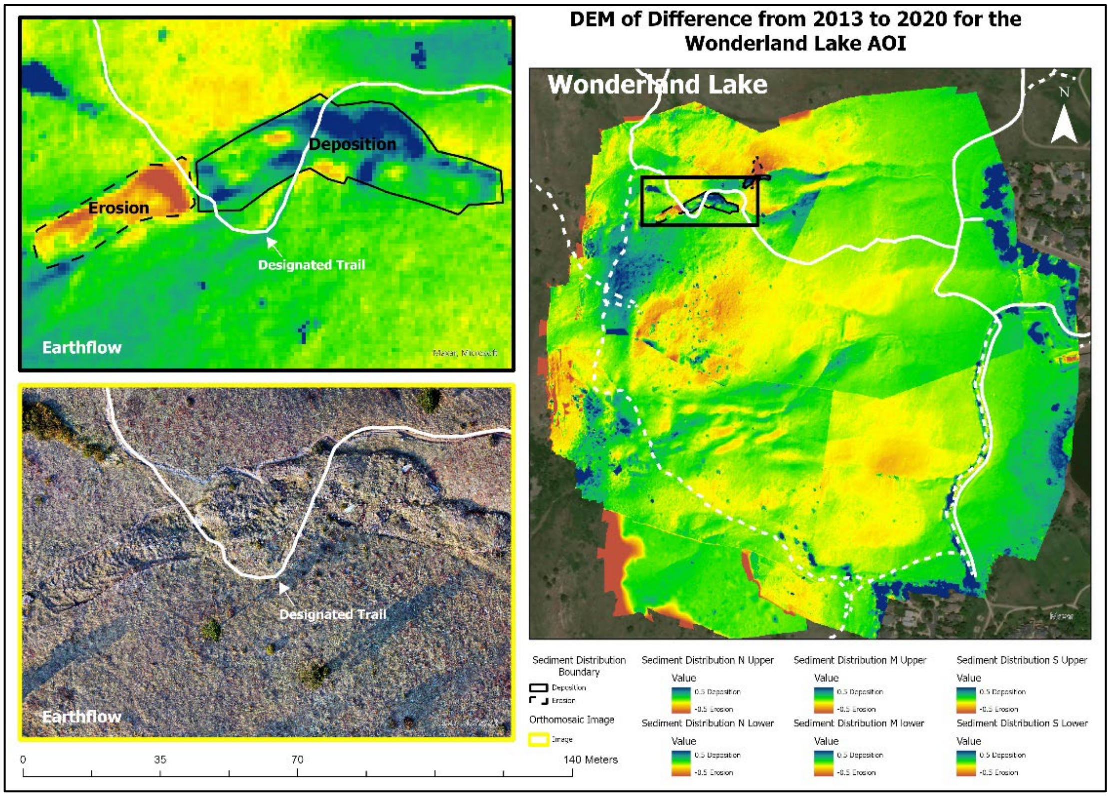


Figure 11. Wonderland Lake AOI DEM of Difference from 2013 to 2020. 2013 OSMP DEM data used for this analysis.

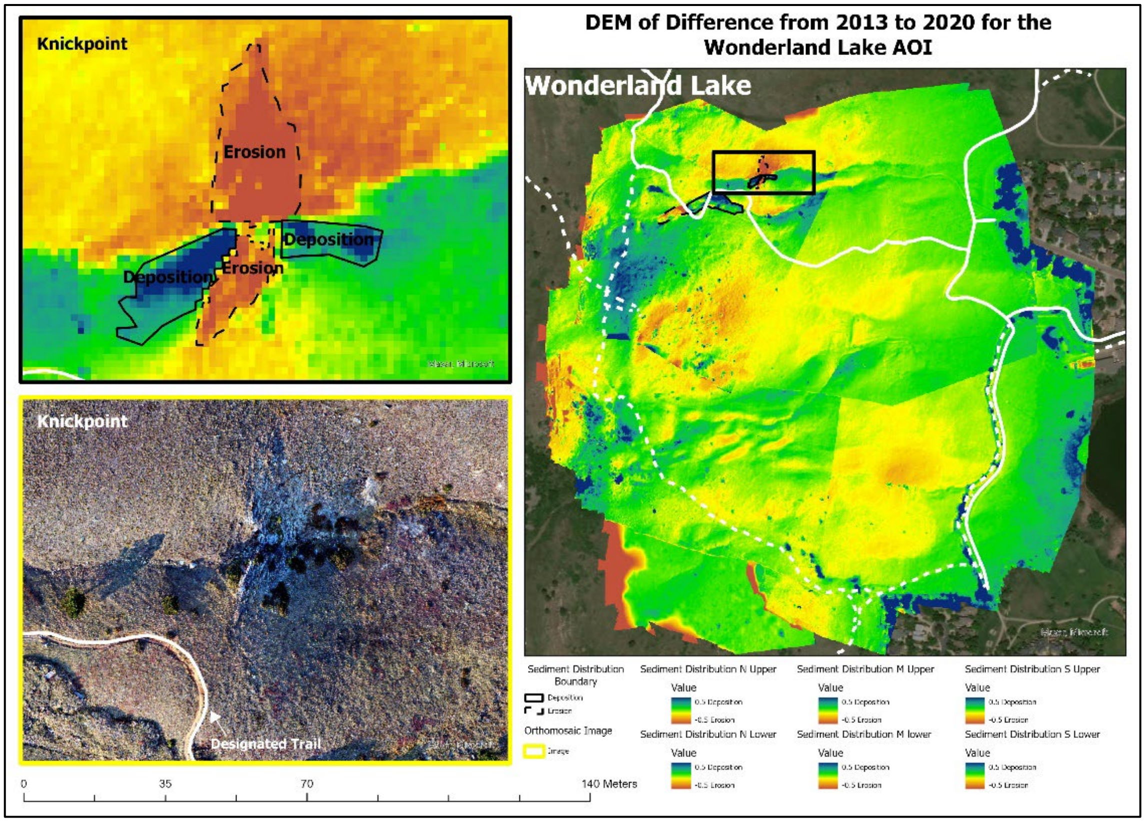


Figure 12. Wonderland Lake AOI DEM of Difference from 2013 to 2020. 2013 OSMP DEM used for this analysis

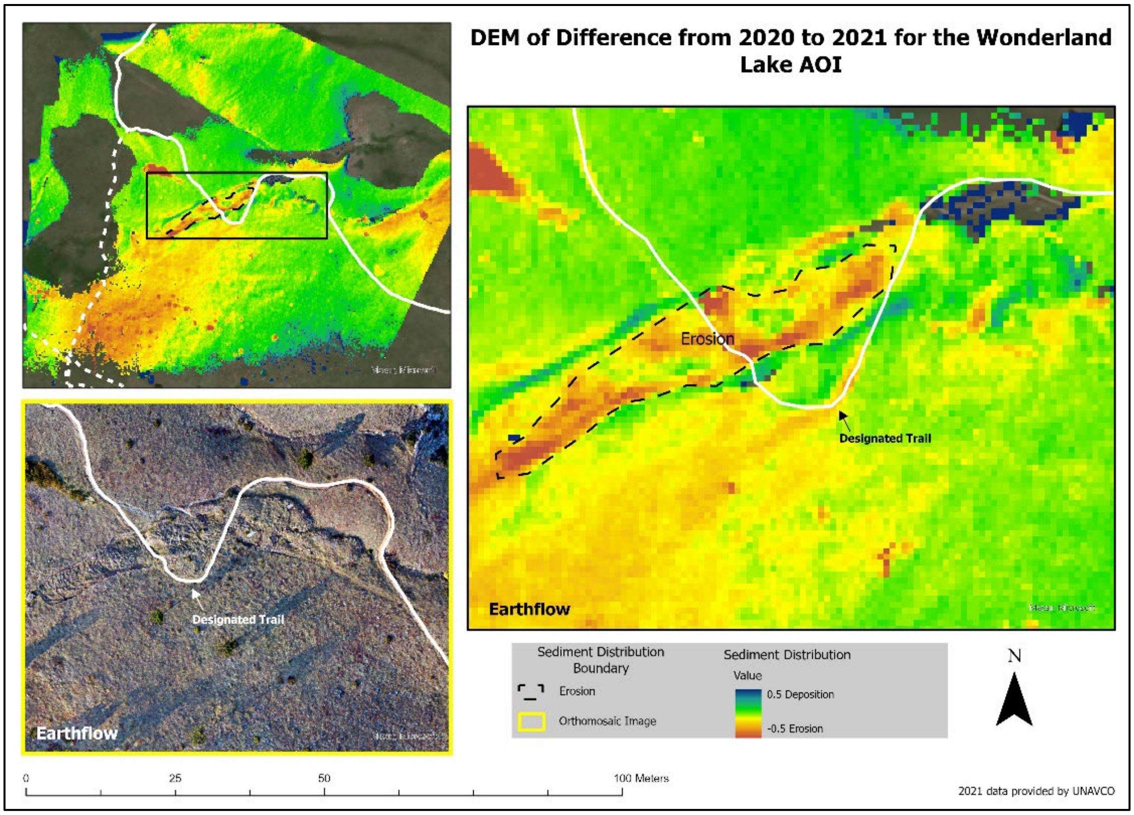


Figure 13. Wonderland Lake AOI DEM of Difference from 2020 to 2021. 2021 Wonderland Lake data provided by UNAVCO.

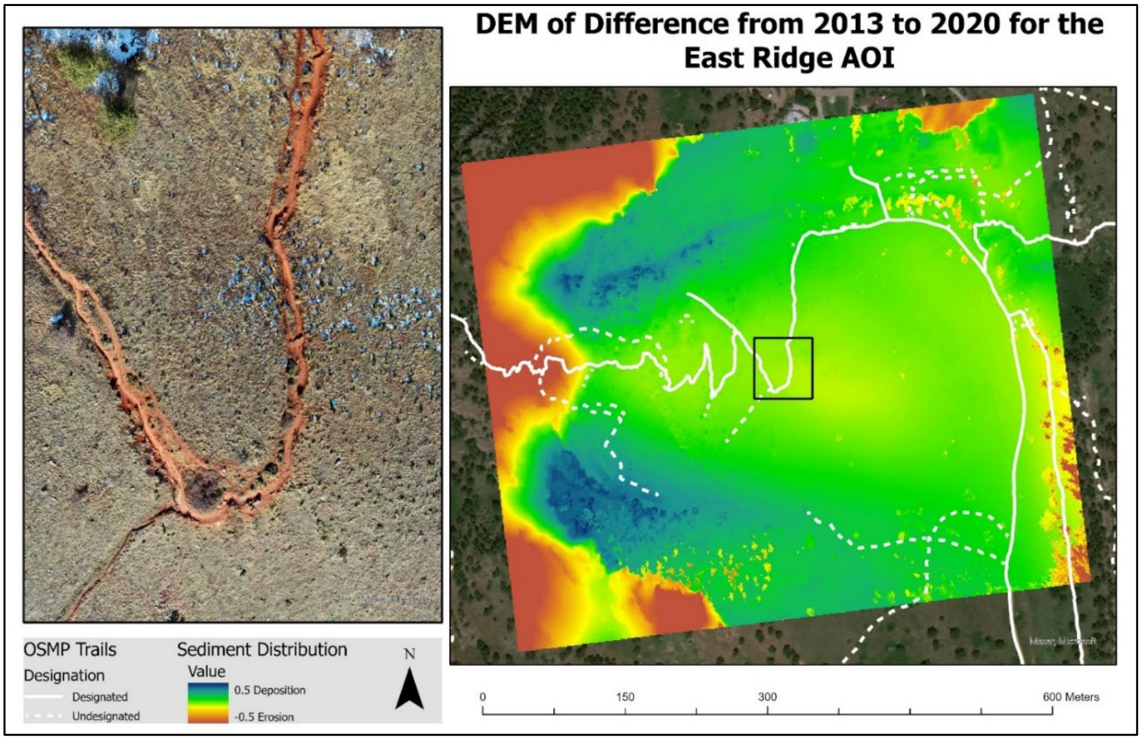


Figure 14. East Ridge DEM of Difference from 2013 to 2020. 2013 OSMP DEM used for analysis

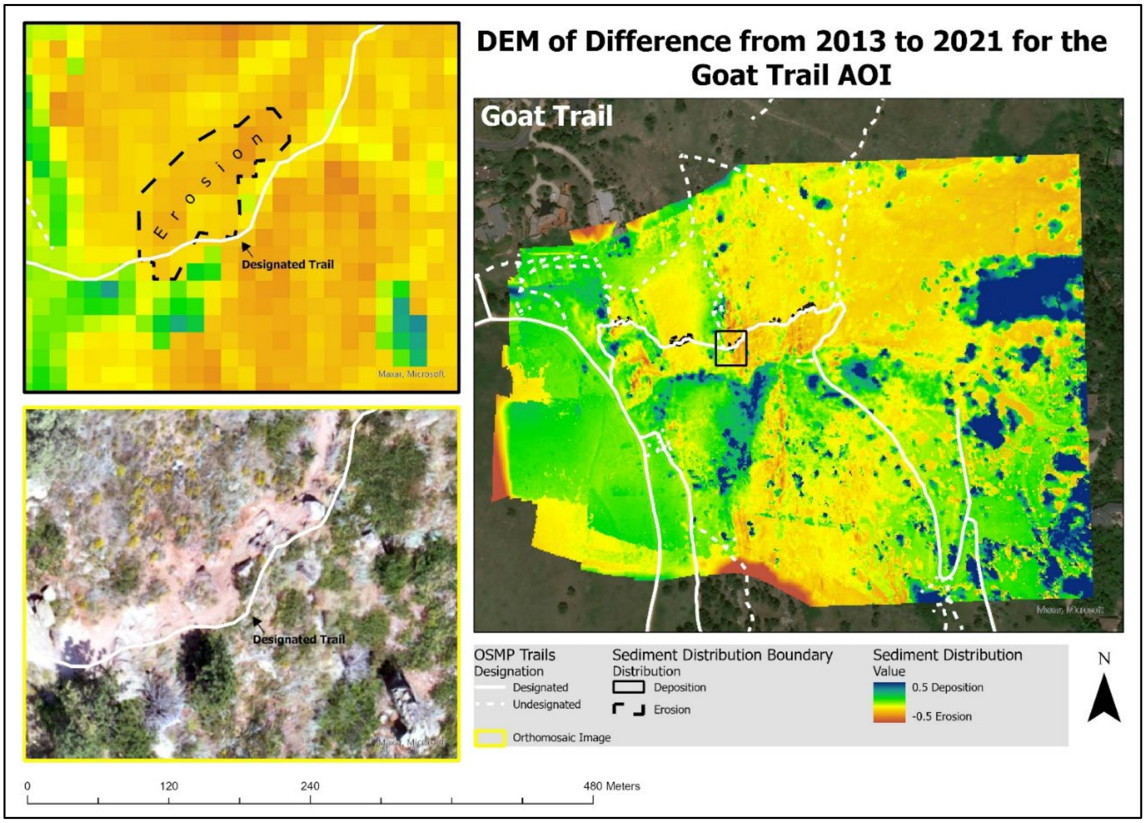


Figure 15. Goat Trail DEM of Difference from 2013 to 2021. 2013 OSMP DEM used for analysis.

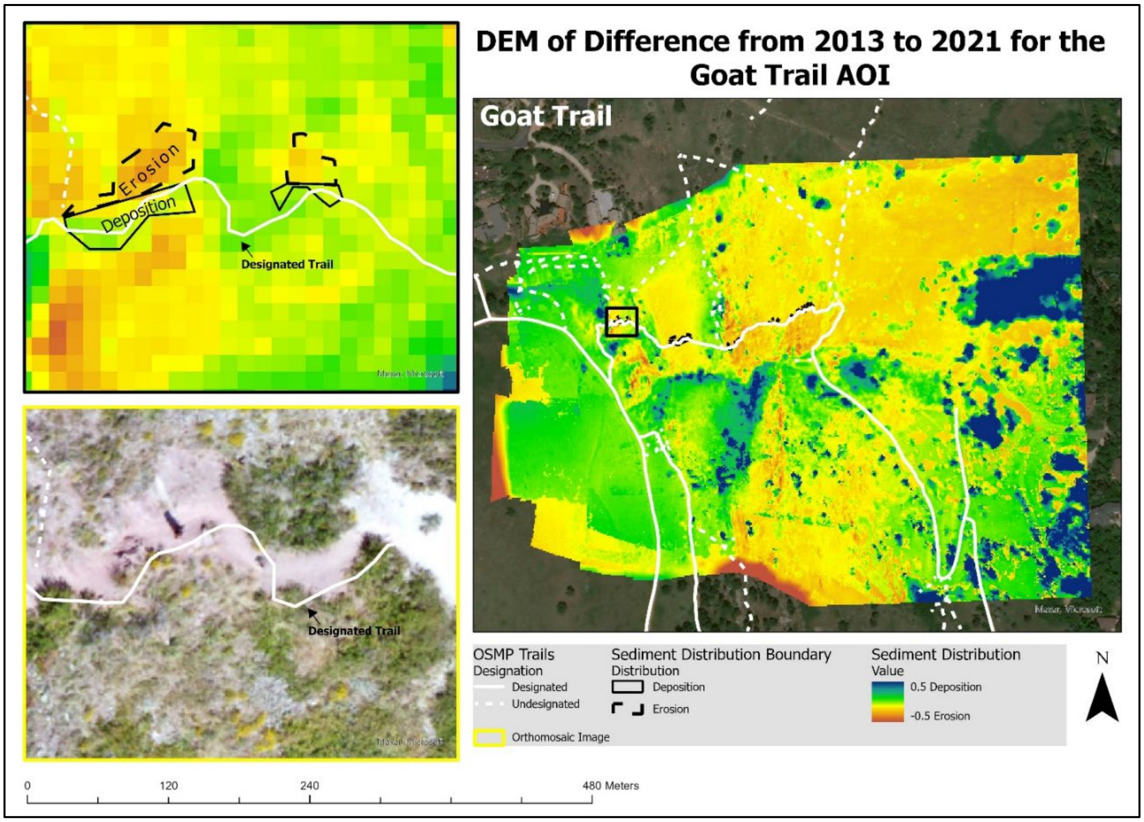


Figure 16. Goat Trail AOI DEM of Difference from 2013 to 2021. 2013 OSMP DEM used for this analysis.

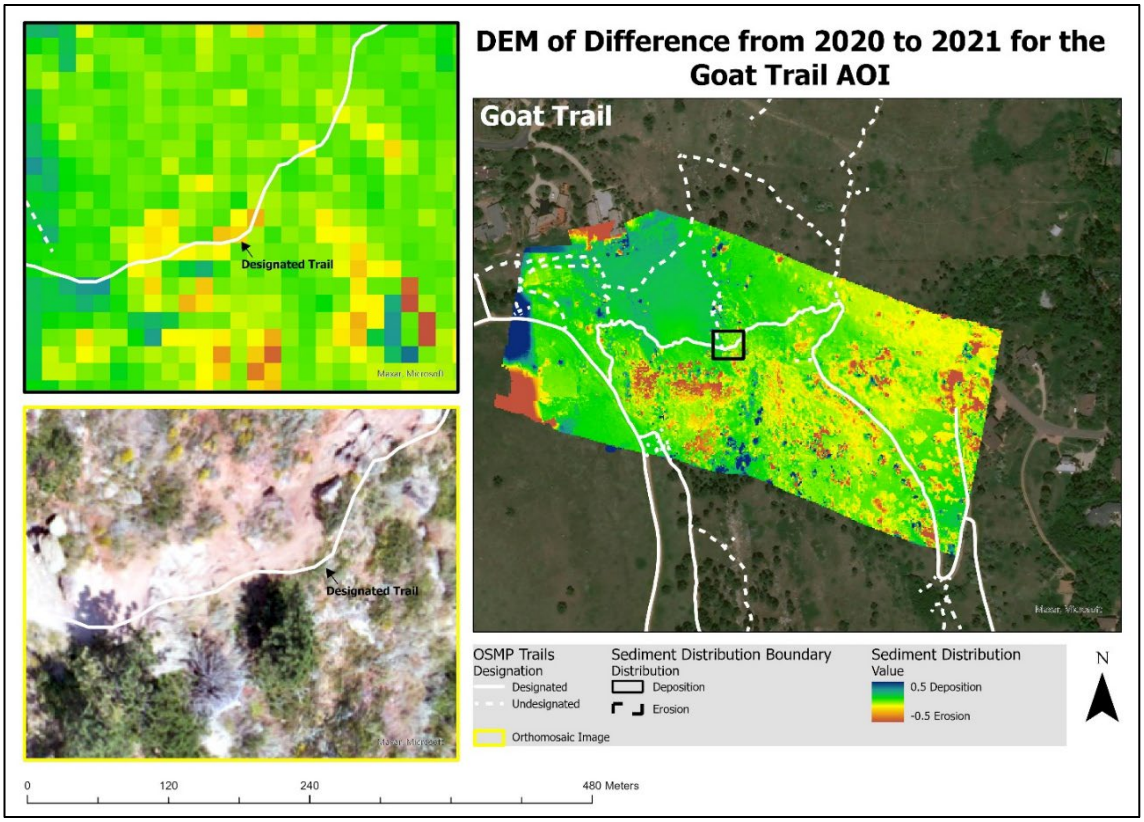
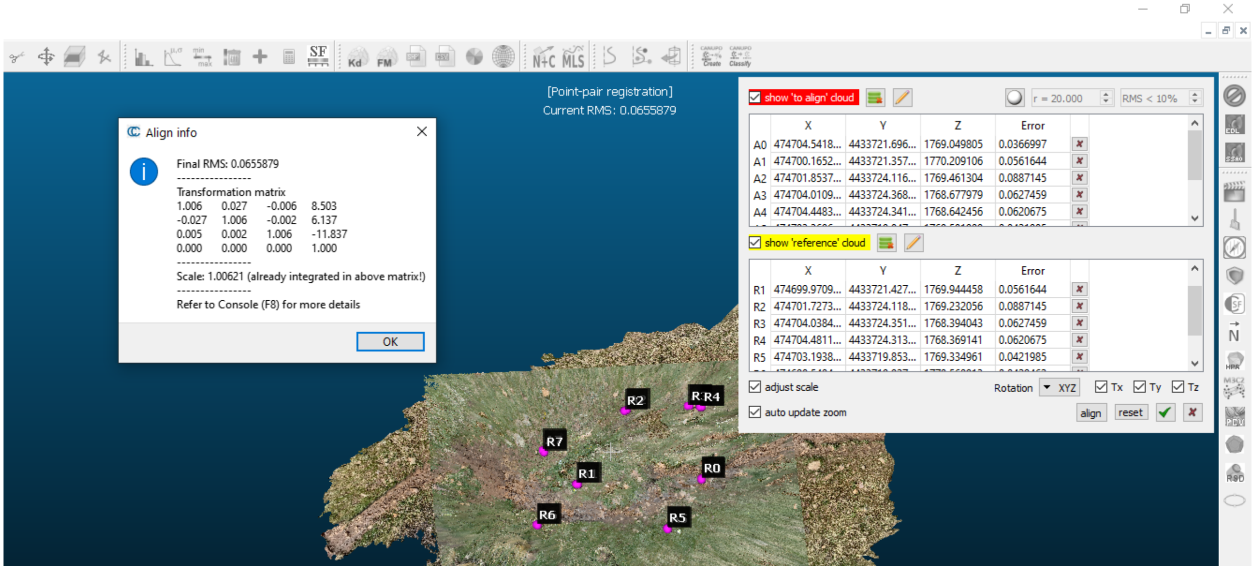


Figure 17. Goat Trail AOI DEM of Difference from 2020 to 2021.



Align info

```
Final RMS: 0.0655879
----------------
Transformation matrix
1.006    0.027    -0.006   8.503
-0.027   1.006    -0.002   6.137
0.005    0.002    1.006    -11.837
0.000    0.000    0.000    1.000
----------------
Scale: 1.00621 (already integrated in above matrix!)
----------------
Refer to Console (F8) for more details
```

☑ show 'to align' cloud

r = 20.000

RMS < 10%

	X	Y	Z	Error
A0	474704.5418...	4433721.696...	1769.049805	0.0366997
A1	474700.1652...	4433721.357...	1770.209106	0.0561644
A2	474701.8537...	4433724.116...	1769.461304	0.0887145
A3	474704.0109...	4433724.368...	1768.677979	0.0627459
A4	474704.4483...	4433724.341...	1768.642456	0.0620675

☑ show 'reference' cloud

	X	Y	Z	Error
R1	474699.9709...	4433721.427...	1769.944458	0.0561644
R2	474701.7273...	4433724.118...	1769.232056	0.0887145
R3	474704.0384...	4433724.351...	1768.394043	0.0627459
R4	474704.4811...	4433724.313...	1768.369141	0.0620675
R5	474703.1938...	4433719.853...	1769.334961	0.0421985

☑ adjust scale

Rotation XYZ ☑ Tx ☑ Ty ☑ Tz

☑ auto update zoom

Figure 18. Comparison of hand-held SfM with hand-held IPad lidar, showing very little error between them (~6 cm).

APPENDIX

APPENDIX A: SOURCE CODE FOR PCA

```
setwd("C:/Users/arame/Documents/Research/R_folder")


GeoPCA <- read.csv("Geo_table_4PCA_short.csv")


View(GeoPCA)


GeoPCA$Mlabel <- as.factor(GeoPCA$Mlabel)


str(GeoPCA)


pca <- prcomp(GeoPCA[-1],retx=TRUE,center=TRUE,scale.=TRUE)


plot(pca)


summary(pca)


print(pca)


biplot(pca, choices = 1:2)
```

APPENDIX B1: AGISOFT METASHAPE QUICKGUIDE

https://drive.google.com/file/d/1qOelMd5cIrIWi-EXVK2Giae06Fpa0_V9/view?usp=sharing

APPENDIX B2: DEM OF DIFFERENCE QUICKGUIDE

https://docs.google.com/document/d/1yXhLywa-51mVKRf_Hp1zEyKfKPyplCNk/edit?usp=sharing&ouid=116031217593818385468&rtpof=true&sd=true

APPENDIX C: HEDGE’S G

Table 4. Hedge's G- TPI-100 (Topographic Position Index)

Top 11		1 kpl	2 kcg	3 j^mj	4 P*f	5 Qc	6 Ql	7 Kn	8 ^PI	9 Kd	10 Ply	11 Qpc
kpl	1	n/a										
kcg	2	0.1168	n/a									
j^mj	3	0.5303	0.5159	n/a								
P*f	4	0.0988	0.1269	0.1785	n/a							
Qc	5	0.2615	0.1825	0.7167	0.2649	n/a						
Ql	6	0.0464	0.1189	0.4379	0.0805	0.2768	n/a					
Kn	7	0.0429	0.1243	0.4243	0.0816	0.2679	0.0122	n/a				
^PI	8	0.2202	0.1278	0.551	0.0816	0.0457	0.2166	0.2059	n/a			
Kd	9	0.2357	0.2732	0.2209	0.036	0.4459	0.1917	0.1955	0.3561	n/a		
Ply	10	0.3174	0.3273	0.0289	0.1447	0.5537	0.2814	0.2633	0.3934	0.1493	n/a	
Qpc	11	0.1281	0.2531	0.7732	0.1027	0.4173	0.0488	0.0759	0.4237	0.2709	0.4881	n/a

Table 5. Hedge's G - Concavity

Top 11		1 kpl	2 kcg	3 j^mj	4 P*f	5 Qc	6 Ql	7 Kn	8 ^PI	9 Kd	10 Ply	11 Qpc
kpl	1	n/a										
kcg	2	0.0066	n/a									
j^mj	3	0.0198	0.0283	n/a								
P*f	4	0.0089	0.0158	0.0101	n/a							
Qc	5	0.0121	0.0062	0.0293	0.0209	n/a						
Ql	6	0.0011	0.0087	0.0219	0.0083	0.0134	n/a					
Kn	7	0.0041	0.0021	0.0239	0.0131	0.008	0.0057	n/a				
^PI	8	0.0055	0.0019	0.0302	0.0148	0.0079	0.0077	0.0007	n/a			
Kd	9	0.0082	0.0165	0.0145	0.0019	0.0199	0.0078	0.0133	0.0157	n/a		
Ply	10	0.0095	0.0178	0.0129	0.0004	0.0201	0.0096	0.0143	0.0177	0.0018	n/a	
Qpc	11	0.0139	0.0086	0.0291	0.0221	0.0031	0.015	0.0103	0.0101	0.0208	0.0213	n/a

APPENDIX D: 3D IMAGES OF THE NEWLY DEVELOPED EARTHFLOW AT THE WONDERLAND LAKE AOI (Not georeferenced)