COLORADO GEOLOGICAL SURVEY

Open-file Report OF-19-06
Landslide Inventory and Susceptibility Map of Boulder County, Colorado

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14 June 2019

Intersection of Hwy 128 and Hwy 93, Boulder County, Colorado, May 2019. Photo Credit: Kassandra Lindsey

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ACKNOWLEDGEMENTS

A special thanks is due to the following individuals for their contributions to the mapping efforts: Ralph Shroba (USGS Emeritus) for undertaking an external review of the map and text, Matt Morgan and Karen Berry with the Colorado Geological Survey (CGS) for an internal review of the materials associated with the publication, and Larry Scott with the CGS for assembling the map plate.

INTRODUCTION

The CGS provides geologic hazard susceptibility maps to state and local governments for use in planning processes and mitigation plans. The Landslide Inventory and Susceptibility Map of Boulder County is part of a statewide effort to develop inventory and susceptibility maps for landslide-prone areas in Colorado. Substantial growth and development is taking place in the city of Boulder and the nearby towns in the county, especially near mesas and major drainages. This study seeks to evaluate and map known and previously unmapped landslide deposits with the aid of new high-resolution light detection and ranging (lidar) data and identify landslide susceptible zones based on slope derived from a 10-m DEM and geology from geologic maps at various scales.

A landslide is the failure and downslope movement of soil or rock due to the force of gravity exceeding the internal strength of the material. A distinct failure or rupture surface commonly forms below the failed mass on the surface where the weaker material moves downslope relative to the stronger, underlying material. Landslides can occur suddenly and move rapidly or can be slow moving. All landslides have the potential to inflict a significant amount of damage to structures. The type of material (for example rock, soil, or a mix) and failure movement mechanism (for example slide, flow, and fall) that provides nomenclature for the type of landslide (Varnes, 1978; Cruden and Varnes, 1996). In this study rockfalls, debris flows, and very slow-moving slumps and soil creep were not mapped.

Topography, geology, and hydrology greatly influence the potential for a failure to occur. In areas of very steep slopes and/or steeply dipping bedrock, the driving force caused by the steepness of topography and/or bedding can exceed the internal strength of the material. Water content of the material can also greatly influence the likelihood of a slope failure. It is very common for initiations to occur during or shortly after significant precipitation. An increase in pore pressure may weaken material, promote instability, and cause it to move downslope. In general, mitigation can be applied to unstable material to detour or slow landslide movement; however, landslide-prone areas should be examined and evaluated by a professional engineer before construction.

The landslide deposits identified in this study are chiefly rotational or translational slides. Landslide deposits consist of varying sizes and types of materials. These deposits may have very distinct morphology, depending on the age and materials that comprise the deposit. They are commonly recognized by a headscarp at the top, indicating where the landslide mass failed and moved away from material farther upslope. The toe or base of landslide deposits are usually compressed and mounded where material has moved downslope and over the ground surface. The main body of the deposit is typically hummocky and may have contained enough water to cause it to flow. On older, eroded landslide deposits, these features become more subdued and can be difficult to identify without examining exposures of the landslide deposits. Older landslide deposits are easier to identify with the aid of lidar imagery.

GEOLOGIC SETTING

Bedrock hogbacks run roughly north-south along the western side of Highways 93 and 36. The hogbacks are predominantly composed of Mesozoic and Paleozoic sedimentary rocks that have been uplifted by faulting during the Laramide orogeny. Landslides usually occur within the Morrison Formation and the Dakota Group where the resistant parts of the unit slip along bedding of the planes of weaker, underlying rocks.

Another geologic setting associated with landslide failures in the county are the slopes along South Boulder Creek and Coal Creek that cut through Eldorado Springs and the Rocky Flats area, respectively. In these areas, rocks of the Laramie Formation and Pierre Shale underlie gravelly terrace and pediment deposits. Landslides are common near the contact of the gravelly deposits and the underlying bedrock units where groundwater seeps outlet at the bedrock-gravel contact.

At high elevations in the western part of the county, there are many landslide deposits derived from glacial till. In general, glacial deposits in this area are underlain by Precambrian crystalline bedrock or volcanic rocks of Cretaceous and Tertiary age.

There are some landslides mapped in areas of competent, crystalline bedrock of Precambrian age. The cause of these landslides are not well known, they are poorly documented, and access for field inspection is difficult.

There are landslide deposits not associated with topographic or geologic features mentioned above. The majority of them are localized failures in the alluvium along stream channels in developed areas. Others occur at the contact between the crystalline bedrock in the foothills and the Fountain Formation.

The major bedrock units in Boulder County are a briefly described in Table 1. They are arranged from youngest at the top to oldest at the bottom.

Age and Rock Unit	**Brief Description**
Cretaceous Arapahoe Formation	Sandstone, siltstone, claystone, thin pebble beds, and conglomerate with sedimentary, igneous and metamorphic clasts.
Cretaceous Laramie Formation	Micaceous siltstone, silty claystone, lignitic claystone, sandstone, and conglomerate with sedimentary clasts.
Cretaceous Fox Hills Sandstone	Micaceous sandstone, shale, massive to thinly bedded sandstone, and claystone.
Cretaceous Pierre Shale	Three members composed of sandstones, silty sandstones, sandy shale, limestone, and shale.
Cretaceous Niobrara Formation	Two members composed of calcareous shale and limestone.
Cretaceous Benton Group	Siltstone, calcareous shale, and limestone.
Cretaceous Carlile Shale	Sandy limestone, shale, silty limestone, and calcareous shale.
Cretaceous Greenhorn Limestone	Limestone, calcareous shale, and calcarenite.
Cretaceous Graneros Shale	Clayey shale and siltstone.
Cretaceous Mowry Shale	Shale.
Cretaceous Dakota Group	Two formations composed of sandstone, siltstone, claystone, and conglomerate.
Jurassic Morrison Formation	Siltstone, sandstone, claystone, and limestone.
Jurassic Ralston Creek Formation	Siltstone, sandstone, limestone, and shale.
Jurassic Canyon Springs Sandstone Member of the Sundance Formation	Sandstone and siltstone.
Triassic Red Draw Member of the Jelm Formation	Fine-grained, crossbedded, calcareous sandstone.
Triassic and Permian Lykins Formation	Four members of silty sandstone, siltstone, limestone, sandy limestone.
Permian Lyons Sandstone	Conglomerate and sandstone.
Pennsylvanian Ingleside Formation	Limestone and sandstone.
Pennsylvanian Fountain Formation	Pebbly sandstone and conglomerate.

Table 1. *Major rock units in Boulder County and used as a part of this study. Unit Descriptions were obtained from the Denver West 1:100,000 and Estes Park 1:100,000 maps.*

METHODS

The landslide inventory was developed using a slope map created from a 1-m resolution lidar DEM underlain by the 1-m DEM. Elevation contours at various intervals derived from the lidar data were also used to aid in identifying and mapping landslide deposits. The datasets were examined at 1:24,000-, 1:10,000-, and 1:5,000-scales to identify deposits of various sizes and various degrees of post-depositional erosion and surface modification. Geomorphic features like headscarps and hummocky topography were used to delineate the landslide deposits; however, headscarps and other landslide features were not mapped separately. Aerial photography, and high-resolution stereo-imagery were also examined using ArcGIS software.

Each landslide deposit was assessed on the basis of their morphologic features and assigned a confidence level using a system developed by Burns and Madin (2009). Well-expressed landslide deposits (easily identified head scarp, hummocky topography, etc.) were assigned a high confidence whereas deposits with poorly expressed surface morphology were assigned a low confidence. As many mapped landslide deposits as possible were field verified.

Landslide susceptibility maps were developed using criteria modified from Wills and others (2011), Ponti and others (2008), and Wilson and Keefer (1985) (Table 2). Slope maps derived from 10-m DEMs and published 1:100,000-scale geologic maps were used to develop the landslide susceptibility maps. A coverage map of geologic maps used for Boulder County landslide susceptibility are shown in Figure 1.

Slope Class	Group A	Group B	Group C
1 (0-5°)	0	0	0
2 (5-10°)	0	V	VII
3 (10-15°)	0	VII	VIII
4 (15-20°)	0	VIII	IX
5 (20-30°)	VI	IX	X
6 (30-40°)	VII	IX	X
7 (>40°)	VIII	IX	X

Table 2. Susceptibility developed for Boulder County by the Colorado Geological Survey.

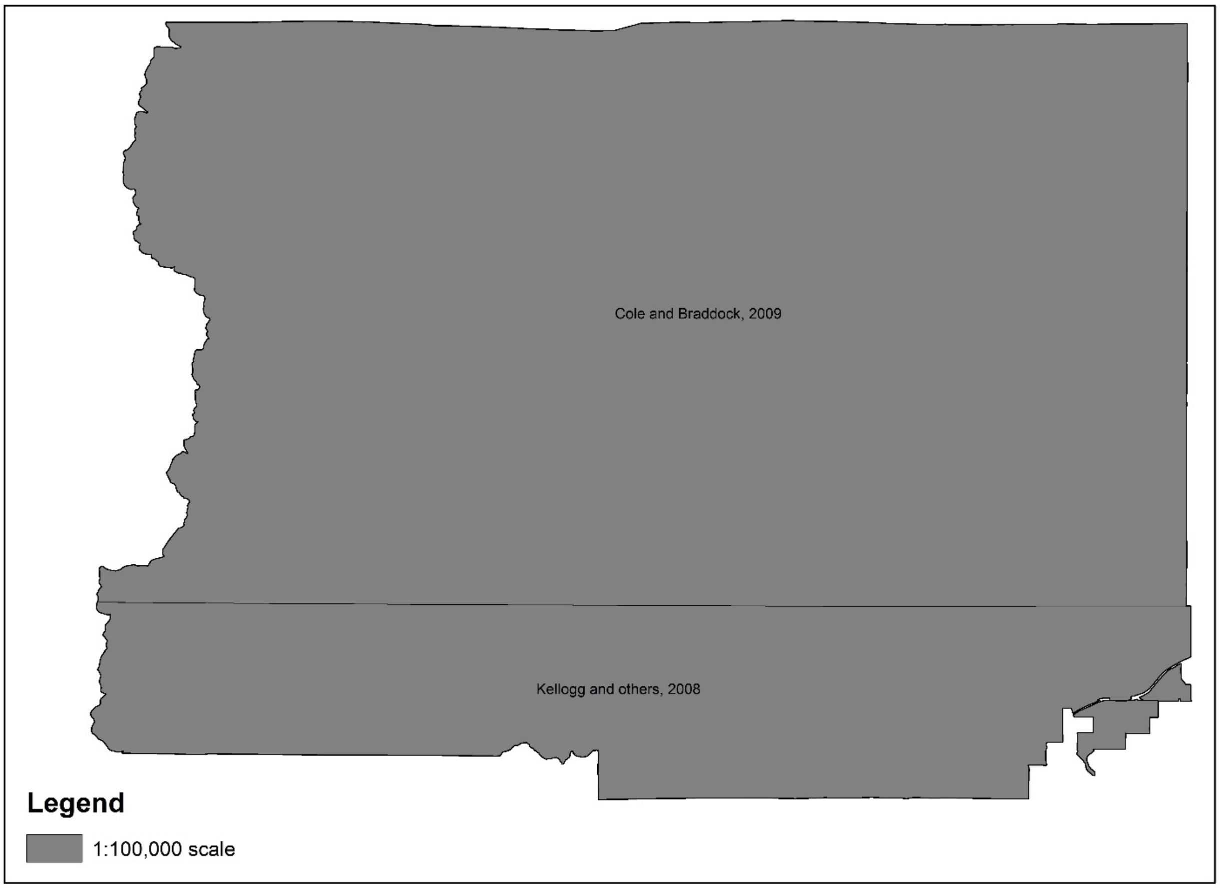

Figure 1: Geologic maps and scales used to develop landslide susceptibility for Boulder County.

The slope map was divided into seven slope classes and each mapped geologic rock unit assigned to one of three relative rock strength groups (Table 3). Competent sandstones and other similar rocks were assigned to Group A as the highest rock strength group, friable sandstones or sandstone units that have many or relatively thick interbedded siltstones, claystones, and/or shales were assigned to Group B as the moderate rock strength group, and rocks that are predominantly or entirely composed of siltstones, claystones, and/or shales were assigned to Group C as the lowest rocks strength group. Units with multiple members were treated as a single rock unit. Surficial deposits in gently sloping terrain were assigned to Group A. All other surficial deposits were assigned to the groups that were assigned to the bedrock units directly adjacent to or beneath them. When surficial units were in contact with multiple bedrock units of different rock-strength groups, they were assigned to the strength group of the lowest strength bedrock unit. This was done by selecting surficial deposits by their proximity to bedrock deposits in ArcGIS.

Group A (High Strength)	Group B (Moderate Strength)	Group C (Low Strength)
Fountain Formation Lykins Formation Lyons Sandstone	Arapahoe Formation Dakota Group Arapahoe Formations Fox Hills Sandstone Ingleside Formation Pierre Shale (incl. Hygiene Sandstone, Larimer Sandstone, Richard Sandstone, Rocky Ridge Sandstone, and Upper Transition members	Benton Group and Mowry Shale, undivided Carlile Shale, Greenhorn Limestone, and Graneros Shale undivided Laramie Formation Morrison, Ralston Creek, Lykins Formation, Canyon Springs Sandstone Member of Sundance Formation, and Jelm Formation, undivided Niobrara Limestone Pierre Shale (incl. Lower, Middle, and Upper shale members)

Table 3: Relative rock strength groups and the units assigned to each group.

Intersections between the different slope groups and rock strength groups were assigned a level of susceptibility from 0-10, where 0-5 is considered low susceptibility, 6-7 is moderate, and 8-10 is high.
Modifications were made to the model of Wills and others (2011) including adjusting the slope classes and which susceptibility designations (V, VI, VII, VIII, IX, X) were associated with which geologic groups and slope classes. This was done because the original model by Wills and others (2011) over-estimated the susceptibility of landslides in Group A and underestimated the susceptibility of landslides in Group B and Group C. The Pierre Shale, in particular, can fail at very low slope and dip angles, sometimes locally as low at 10°.
Areas such as slopes of lawns, artificial fill along roads, and modified urban drainages were overestimated in the susceptibility raster (Figure 2a). In order to remove this overestimation in the raster, it was converted to a point file and the points corresponding to the overestimated cells were removed manually and converted back to a raster (Figure 2b). Following this manual clean-up, the raster was processed using the focal statistics tool in ArcGIS with the neighborhood setting set to a 3x3 cell, the statistic type set to median, and the ignore no data in calculations box checked. The resulting raster was then processed by the majority filter tool with the number of neighbors to use set to 8.0 and replacement threshold set to 0.5. The raster was then processed through the majority filter again using the same settings (Figure 2c). This final raster was then converted to smoothed polygons using tool developed by the (Figure 2d). Due to the ignore no data setting in the focal statistics tool, the susceptibility estimations moved out into major areas without susceptibility and therefore needed to be clipped back so as to not over represent susceptibility where there is none.
Landslide susceptibility for Precambrian crystalline bedrock in the foothills region was not evaluated in this study. Rockfall is the dominant process in that region of Boulder County, because the rocks are predominantly very competent granite, gneiss, schist, and related rocks. The landslide susceptibility represents the areas that are likely to generate rockfall instead of a rotational or translational slide. However, mapped landslide deposits formed from Precambrian bedrock are shown on the map. Methods for identifying susceptibility will continue to be developed and evaluated. If a more suitable method for identifying landslide susceptibility in this area is developed, an update will be made to this report.

MAP USE AND LIMITATIONS

This map is intended to be used at 1:24,000 scale. The coverage shows areas that have mapped landslide deposits and areas that are susceptible to the development of landslides. Due to the nature of the geologic maps used and the limitations of the model, areas that are more susceptible to rockfall or debris flow may be included in the coverage of the susceptibility map. The map is not intended to give site-specific information as to the precise area and level of risk. No levels of risk are assigned. It should be used as a tool to evaluate where slope stability issues exist or may occur. Susceptibility does not imply that landslides will occur in susceptible areas. It indicates that landslides have occurred in similar areas and that combination of the geology and slope of the area may be favorable for landslides to form in the future.

Proper evaluation by a qualified geotechnical engineer or engineering geologist should be made on a site-specific basis prior to future development or alteration to the ground surface that many impact slope stability. Disclosure of potential landslides should be made to any prospective land buyers.

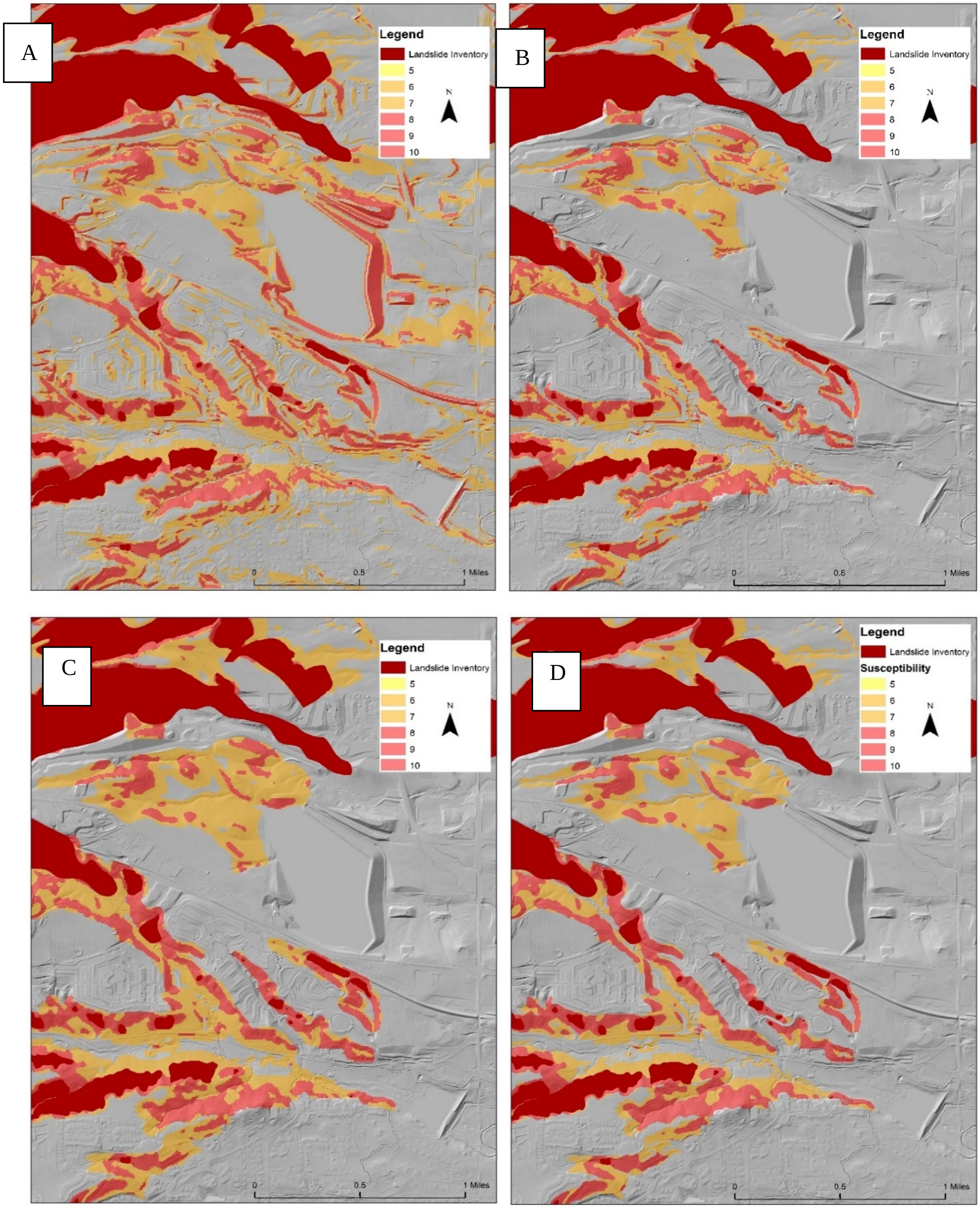

Figure 2. a) Susceptibility raster before any overestimation was removed. b) Susceptibility raster after overestimated cells were manually removed by converting the raster to a point file, deleting the necessary points, and converting the point file back to a raster. c) Susceptibility raster after being processed through the

focal statistics tool and the majority filter tool twice. d) Susceptibility shapefiles with smoothed susceptibility polygons and the landslide inventory overlain.

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