Cesare, Inc.
Geotechnical Engineers & Construction Materials Consultants

October 10, 2017

Ms. Nicole Wobus
Boulder County Land Use Department
2045 13th Street
Boulder, CO 80302

Subject: Addendum No. 1
Geologic Hazard Study
Boulder County, Colorado
Project No. 16.3097

Dear Ms. Wobus:

Cesare, Inc. (Cesare) is issuing this addendum to the geologic hazard study report issued on March 31, 2017. This addendum presents updates to Plates 7 and 9 of the original report. Plates 7 and 9 from the original report should be removed and replaced with Plates 7 and 9 contained herein. This addendum also presents new data, with an explanation for methods, intended use, and limitations of each map provided within this addendum. Geographic information system (GIS) data for this project has been delivered to the Boulder County GIS team.

After further consideration, it has been determined that depicting the landslide susceptibility in terms of slope units (Plate 7 of original report) is overly generalized in representing mass movement potential across Boulder County. The initial intent for depicting the landslide susceptibility in terms of slope units was to minimize the level of interpretation required by the end user and also to convey the down-gradient impacts of the source zones delineated in the original landslide susceptibility map.

Cesare and TerraCognito GIS Services, Inc. (TerraCognito) have been working together to produce a set of geologic hazard susceptibility maps and associated GIS datasets which are data driven, statistically robust, and utilize the best available LiDAR, GIS, and remote sensing information. There are different techniques and modeling approaches available to produce landslide susceptibility maps which are chosen based on available information or the scale of the project area. Landslide susceptibility maps typically capture multiple types of mass movements and require some level of interpretation from the reader. Mass movements were divided into three general groups typically found in Boulder County in order to minimize additional interpretation by the end user and so that specific modeling approaches could be applied for each group. The groups considered for this study include landslides, debris flows, and rockfalls (Table 1, Figure 1).

In addition to modeling areas prone to slope failure (initiation zones), the down-gradient impact areas (runout zones) for debris flows and rockfalls were modeled. (The initiation zone plus the runout zone is referred to as the *process area.*) Delineating process areas for debris flows and rockfalls is critical for the quick and effective evaluation of potential hazards in a planning and site review context. On the other hand, modeling process areas for landslides requires site-specific geological and geotechnical information, and is beyond the scope of this project. Furthermore, process areas for landslides typically have aerial extents too small to be reasonably represented on a regional scale map.

The following map plates are attached to this addendum and should replace those included in the original Cesare report:

Plate 7 Landslide Susceptibility Map
Plate 9 Boulder County Geologic Hazards Map

The following map plates are attached to this addendum and are in addition to those included in the original Cesare report:

Plate 10 Rockfall Susceptibility Map
Plate 11 Debris Flow Susceptibility Map

1. LANDSLIDE SUSCEPTIBILITY MAP

Boulder County can be divided into four major physiographic regions, including alpine/subalpine, montane, foothills, and piedmont zones. Each of these physiographic regions can be characterized by distinctly different geomorphology, geology, elevation, and relief. Each zone can also be characterized by typical slope failure mechanisms common to those regions. Table 1 lists the general characteristics for each physiographic zone in Boulder County (exceptions exist due to the variability of geologic and geomorphic conditions).

TABLE 1. General Characteristics for Physiographic Zones in Boulder County

Physiographic Zone	Alpine/Subalpine	Montane	Foothills	Piedmont
Elevation Range	8,500 to 14,000+	7,000 to 8,500	5,000 to 7,000	4,000 to 5,000
Relief	High	Moderate	High	Low
Geology	Igneous, metamorphic, glacial moraine	Igneous, metamorphic, glacial moraine, colluvial deposits	Sedimentary, colluvial deposits	Sedimentary, alluvial and colluvial deposits
Geologic Structure	Folded, faulted, fractured	Folded, faulted, fractured, eroded	Stratified, steeply-tilted	Stratified, moderately to gently-tilted
Geomorphology	Glacial, periglacial	Fluvial, structural, deeply incised canyons	Fluvial, structural	Gently-sloping to flat-topped mesas separated by low-lying river and stream valleys, alluvial, fluvial
Typical Slope Failure Types	Rockfall, rock glacier, debris flow	Rockfall, shallow soil slip, debris flow	Rockfall, shallow soil slip, debris flow, block slide, landslide	Landslide

The term *landslide* can be used to describe any outward or downward movement of earth, rock, or debris. For this study, the term *landslide* refers to slope movements with a distinct zone of weakness separating the slide mass from relatively stable material below, and also a relatively large initiation zone, the potential for both shallow and deep slip planes, as well as multiple types of movement (e.g., slide, slump, slip, or flow). *Landslides* are differentiated from faster moving, gravity driven debris flows (hyper-concentrated) and rockfalls, which typically occur on short time scales and have longer process areas. The causes for rockfalls are unpredictable but commonly related to water and temperature (freeze-thaw cycles, precipitation). Landslide triggers are also complex and variable and can be related to a variety of contributing factors. Figure 1 illustrates the types of landslides modeled for this study.

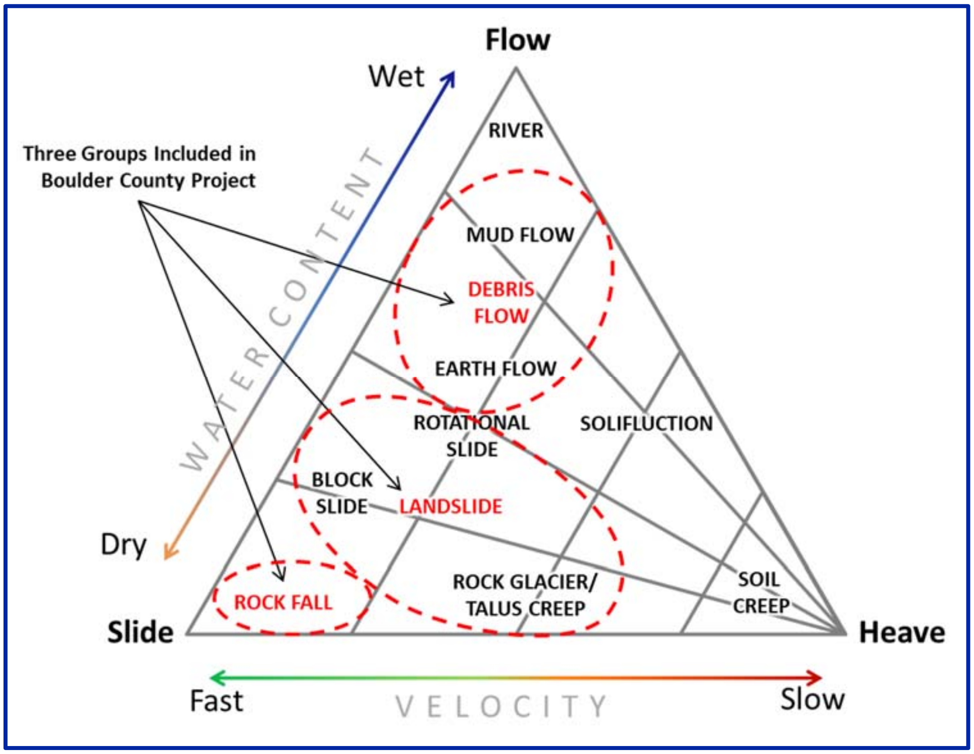

FIGURE 1. Gravity Driven Processes Typology[1]

In general, debris flows can occur in all regions of Boulder County. The Montane and Alpine/Subalpine regions are typically characterized by rockfall and debris flow events as the dominant slope failure mechanism, with relatively few mapped deep-seated landslides. Rockfalls can occur anywhere with rock outcrops and relief. Rock glaciers are typically present above timberline (elevation 11,000 to 12,000) in the Alpine/Subalpine zone and rock talus creeps exist at lower elevations; both of which consist of large accumulations of rock fragments on moderately- to steeply-sloping terrain. Landslides are predominantly found in the Foothills and Piedmont regions, with some in the Alpine/Subalpine and Montane regions where poorly sorted glacial till has been deposited on steep valley walls, creating the potential for slope instability.

The "Landslide Susceptibility Map" produced for this study was developed by analyzing the landslide inventory and multiple predisposing factors using the Modified Information Value (MIV)

[1] Carson, M.A, and Kirby, M.J., 1972, Hillslope Form and Process: Cambridge University Press, Science, 475 pages.

model[2]. This method is data-driven and objectively quantifies the predictive power of each predisposing factor by analyzing its prevalence within each landslide class compared to the occurrence within the entire study area. The MIV formula is as follows:

$$\mathrm{I}(H, x_i) = log_2\left(\frac{S_i/N_i}{S/N}\right) + 1$$

Where:

I(H, x_i) =	the information value of landslide subgroup **H** of a predisposing factor **x_i** (e.g., to what degree predisposing factor 20 to 30° slopes [**x_i**] determines landslide susceptibility for landslides [**H**])
S_i =	the area of landslides in subclass **i** (e.g., area within landslide polygons consisting of 20 to 30° slopes)
N_i =	the total area of subclass **i** (e.g., area within Boulder County containing 20 to 30° slopes)
S =	the total landslide area in the study area (e.g., area of all landslides within Boulder County)
N =	the total area of the study area (total area of Boulder County)

The total information value **I_{total}** for each pixel is computed by summing the information values for each predisposing factor with the following equation:

$$\mathrm{I}_{\mathrm{total}} = \sum_{\mathrm{i}=1}^{\mathrm{n}} \mathrm{I}(\mathrm{H}, \mathrm{x_i})$$

The "Landslide Susceptibility Map" (Plate 7) depicts areas in Boulder County with susceptibility for slope movement based on a set of predisposing factors, documented slope failures, and mapped landslide extents. Cesare verified the extents of published landslides and mapped new landslide features using a high resolution digital terrain model created for this study in conjunction with ortho-imagery, and geologic and topographic maps. The MIV method was used to analyze the Cesare landslide inventory along with a set of predisposing factors related to slope instability (Table 2). Predisposing factors considered for this analysis included slope angle, terrain ruggedness index, slope height, topography-bedding intersection angle, geology, topographic wetness index, and root strength index:

1. **Slope Angle** – A LiDAR-derived digital elevation model (DEM) was used to determine slope angle of the ground surface across Boulder County. Slope angles were divided into subclasses of 0° to 5°, 5° to 10°, 10° to 20°, 20° to 30°, and >30°, and were ranked according to general tendency toward slope instability.

[2] Wang, Q., Wang, D., Huang, Y., Wang, Z., Zhang, L., Guo, Q., Chen, W., Chen, W., and Sang, M., 2015, Landslide Susceptibility Mapping Based on Selected Optimal Combination of Landslide Predisposing Factors in a Large Catchment: Sustainability, pages 16653-16669.

2. **Terrain Ruggedness Index (TRI)** – A measure of ground surface roughness derived from LiDAR DEM and ranked from smoothest to roughest based on the natural breaks of the data distribution (Jenks natural breaks classification method; a data clustering method designed to determine the best arrangement of values into different classes). Surface roughness plays a role in slope failure with respect to surface strength characteristics and surface water absorption.
3. **Slope Height** – Computed using a high resolution LiDAR DEM by analyzing relative slope position. This is a direct measure of relief which provides the potential energy for slope failure in gravity-driven processes.
4. **Topography Bedding Intersection Angle (TOBIA)** – The geometric relationship between the ground surface and the bedrock structure of the underlying geologic formations[3]. Bedrock bedding and foliation orientations were collected from published geologic maps and were compared to surface slope angle and direction vector to quantify and map areas that are in-phase vs. out-of-phase with the underlying bedrock structure. This provides a relative measure of slope stability, where in-phase slopes tend to be less stable than out-of-phase slopes.
5. **Geology** – Mapped geologic units were ranked in terms of relative stability or landslide-prone characteristics based on information from published literature and Cesare's experience in the project area and with similar conditions (e.g., 1=very low, 5=very high susceptibility). Published literature was reviewed for information specific to Boulder County and the geologic units exposed in the region.
6. **Topographic Wetness Index (TWI)** – Computed using the LiDAR DEM for Boulder County and weighted with average annual precipitation. TWI is commonly used to quantify and map topographic control on hydrological processes[4]. With respect to landslide susceptibility, TWI indicates areas where surface flow accumulation may contribute to slope instability.
7. **Tree Root Strength Index** – Computed from LiDAR-derived tree height and tree density, root strength captures the slope stabilizing effect of tree roots as a function of tree height and tree density[5]. This index provides a more robust alternative to using aspect (slope azimuth) as an indicator of vegetation and slope stability.

[3] Meentemeyer, R.K., and Moody, A., 2000, Automated mapping of conformity between topographic and geological surfaces: Computers & Geosciences, pages 815-829.

[4] Boehner, J., Koethe, R. Conrad, O., Gross, J., Ringeler, A., Selige, T., 2002, Soil Regionalisation by Means of Terrain Analysis and Process Parameterisation. In: Micheli, E., Nachtergaele, F., Montanarella, L. [Ed.]: Soil Classification 2001. European Soil Bureau, Research Report No. 7, EUR 20398 EN, Luxembourg, pages 213-222.

[5] Iwahashi, J, Okatani, T., Nakano, T, Koarai, M., and Otoi, K, 2014, Landslide Susceptibility Analysis by Terrain and Vegetation Attributes Derived from Pre-event LiDAR data: a case study of granitic mountain slopes in Hofu, Japan: Conference Paper in: INTERPRAEVENT 2014 in the Pacific Rim.

TABLE 2. Predisposing Factor Classes and Modified Information Values

Group	Factor	Classes (x_i)	Modified Information Value: Rock Glaciers/ Talus Creep	Modified Information Value: Other Landslides
Topography	Slope Angle	0° to 5°	0.28	0.30
		5° to 10°	1.29	1.75
		10° to 20°	1.91	2.29
		20° to 30°	2.48	1.93
		> 30°	3.47	1.32
	Terrain Ruggedness Index	0 to 1	0.00	0.02
		1 to 2	0.13	0.27
		2 to 4	0.91	1.43
		4 to 16	2.29	2.14
		> 16	3.50	1.15
	Slope Height (ft)	0 to 57	3.96	3.52
		57 to 184	3.91	3.56
		184 to 382	3.07	2.41
		382 to 707	2.20	1.11
		707 to 1995	2.04	0.00
Geology	Topography-Bedding Intersection Angle	Anaclinal slopes	0.66	0.43
		Orthoclinal slopes	1.02	0.78
		Underdip slopes	0.78	1.40
		Dip slopes	2.16	2.22
		Overdip slopes	3.88	2.30
	Geology	Igneous, Metamorphic	1.29	0.43
		Hard Sedimentary, Alluvium, Quaternary Deposits	0.01	0.34
		Sedimentary, Schist, Glacial, Quaternary Deposits	2.57	0.39
		Sedimentary, Alluvium, Colluvium, Quaternary Deposits	0.16	3.01
		Shale, Claystone, Siltstone, Landslide, Talus, Debris Flow	3.56	4.50
Hydrology	Topographic Wetness Index (precipitation weighted)	0 to 0.18	0.25	0.06
		0.18 to 0.36	1.56	0.62
		0.36 to 0.59	2.83	1.80
		0.59 to 0.85	1.56	2.29
		0.85 to 1.00	1.44	1.05
Land Cover	Tree Root Strength Index	0 to 30	2.57	1.98
		30 to 194	0.97	1.38
		194 to 358	0.53	0.81
		358 to 522	0.57	0.61
		> 522	0.75	0.65

The landslide inventory was categorized into two subgroups based on general slope movement type (rotational/translational vs. rock glacier/talus creep), and the MIV method was applied separately to each subgroup. The results were combined into a "Landslide Susceptibility Map" (Plate 7) ranking Boulder County into zones of low (0% to 50%), moderate (50% to 70%), and high (70% to 100%) susceptibility.

2. BOULDER COUNTY GEOLOGIC HAZARDS MAP

The "Boulder County Geologic Hazards Map" (Plate 9) is a compilation of the geologic hazard datasets compiled from existing publications or newly created by Cesare and TerraCognito using LiDAR, GIS, and remote sensing data. Plate 9 of the original report should be replaced with the updated version provided in this addendum. The map depicts multiple geologic hazards, including landslide susceptibility, debris flow susceptibility, rockfall susceptibility, areas potentially underlain by steeply dipping, heaving bedrock, swelling soils and bedrock[6], and the extent of undermined areas in the Boulder-Weld Coal Field[7]. For landslide susceptibility, the zones with 70% to 100% susceptibility are considered the critical zones, shown in blue on the "Boulder County Geologic Hazards Map". The debris flow and rockfall susceptibility zones shown in brown and yellow, respectively, on Plate 9, include both the source and runout zones for those geologic hazards. Refer to Plates 10 and 11 for a differentiation between the source and runout zones.

3. ROCKFALL SUSCEPTIBILITY MAP

Logistic regression (LR) analysis was used to model rockfall source zones using training points selected from high resolution ortho-imagery and a set of predictor variables (elevation, slope, topographic wetness index, topographic position index, terrain ruggedness index, convergence, tree density, ortho-imagery color values, and profile curvature). LR is a robust, data-driven regression model that objectively quantifies the predictive power of each independent variable and returns the probability of an event or phenomenon. In this case, the phenomenon is exposed rock outcrops (rockfall sources zones), which are used as inputs in the Gravitational Process Path (GPP) model developed by Wichmann[8] in order to delineate the runout and accumulation zones. The GPP model uses both spatial and numerical parameters to determine process paths. The modeled runout zones were compared with boulder field and talus extents on recent ortho-imagery, in order to validate GPP input variable settings and results. Refer to Plate 10 of this addendum for the "Rockfall Susceptibility Map" depicting both initiation (shown in red) and runout (shown in orange) zones for Boulder County.

4. DEBRIS FLOW SUSCEPTIBILITY MAP

The debris flow susceptibility for Boulder County was determined by applying LR analysis to the 841 shallow landslide and debris flow scarps mapped by the USGS after the September 2013 rain event, and nine predictor variables (terrain ruggedness index, precipitation (September 2013 rain event), ortho-imagery color values, presence of soil cover, slope angle, root strength index, topographic position index, topography bedding intersection angle, and convergence). LR is a robust, data-driven regression model that objectively quantifies the predictive power of each independent variable and returns the probability of an event or phenomenon. In this case, the phenomenon is debris flow initiation susceptibility. Areas with high susceptibility (70% to 100% probability) of debris flow initiation were used as inputs for the GPP model. The results of this modeling approach are depicted on Plate 11, which shows debris flow susceptibility for Boulder County, including both initiation (shown in red) and runout (shown in orange) zones.

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[6] Hart, S.S., 1974, Potentially Swelling Soil and Rock in the Front Range Urban Corridor, Colorado: Colorado Geological Survey, Environmental Geology 7.

[7] Roberts, S.B., Hynes, J.L., and Woodward, C.L., 2001, Maps Showing the Extent of Mining, Locations of Mine Shafts, Adits, Air Shafts, and Bedrock Faults, and Thickness of Overburden Above Abandoned Coal Mines in the Boulder-Weld Coal Field, Boulder, Weld, and Adams Counties, Colorado: United States Geological Survey, Geologic Investigations Series I-2735.

[8] Wichmann, V., 2017, The Gravitational Process Path (GPP) model (v1.0) – a GIS-based simulation framework for gravitational processes: Geoscientific Model Development, Discussions, 27 pages.

The "Debris Flow Susceptibility Map" differs from previously available debris flow mapping of Boulder County in several ways. The map produced for this study is based on a sub-meter scale digital terrain model which allows for a more detailed delineation of susceptible areas. The "Debris Flow Susceptibility Map" is based on a LR analysis of actual scarps mapped after the September 2013 rain event, and is thus a data-driven depiction of debris flow susceptibility. The GPP model used for this study is a GIS-based modeling tool with the capacity to be configured for different gravitational processes, including rockfall, debris flow, and snow avalanche. The modeled runout zones were calibrated to and compared with corresponding 2013 debris flow events via ortho-imagery to validate GPP input variable settings and results.

5. INTENDED USE

The intended use of the "Landslide, Rockfall, and Debris Flow Susceptibility Maps" and the compiled "Boulder County Geologic Hazards Map" is to support land use decisions and site review processes, and to determine appropriate site-specific geologic hazard and geotechnical studies. Proposed development within or near areas identified to be susceptible to geologic hazards would warrant further evaluation by a qualified professional geologist or licensed geotechnical engineer, and should be studied on a site-specific basis. These maps were generated through a high level, regional analysis and were not field checked. Hazard potential may exist outside the extents of the susceptibility zones depicted on these maps.

6. LIMITATIONS AND OTHER CONSIDERATIONS

Limitations exist for the maps produced for this study. This study was a regional analysis of geologic hazard susceptibility for Boulder County. Models are limited by the resolution and countywide coverage of input data such as geology, geologic structure, precipitation, and LiDAR. Some of the model inputs for complex landslides and rockfall were determined using available LiDAR and remote sensing data, and were not field verified. The model outputs for complex landslides, rockfall, and debris flows were not field verified. Field work to verify the model results should be considered for future studies. The landslide inventory was based on available published mapping, imagery, and analysis of high resolution LiDAR DEM, and did not include field verification. Additional landslides may exist outside the extents of those included in the Cesare landslide inventory.

The susceptibility maps produced for this study do not assign a level of risk and do not replace site specific geologic hazard studies. There is no guarantee that the areas within susceptibility zones will be impacted by the geologic hazard identified. Some slopes may remain stable if left in their natural state and are not subjected to development or adverse conditions (e.g., high intensity, long duration rainfall, seismic shaking, or wildfire). The use of caution and an informed, proactive approach to development in and around areas identified as having susceptibility to certain geologic hazards is advised. The maps produced for this study represent the susceptibility at the time the study was completed and are based on the assumptions inherent in the methods previously explained. Geologic hazard susceptibility maps should be updated as new or higher resolution data becomes available, or natural causes such as wildfires modify the slope character and potentially the slope stability of areas within Boulder County. Geologic hazard inventories which track the location and extents of events such as landslides, rockfalls, and debris flows should also be maintained and updated.

If you have any questions or comments regarding this information, please feel free to contact our office.

Sincerely,
CESARE, INC.

Julia M. Frazier, P.G.
Senior Geologist

JMF/ksm

Attachments

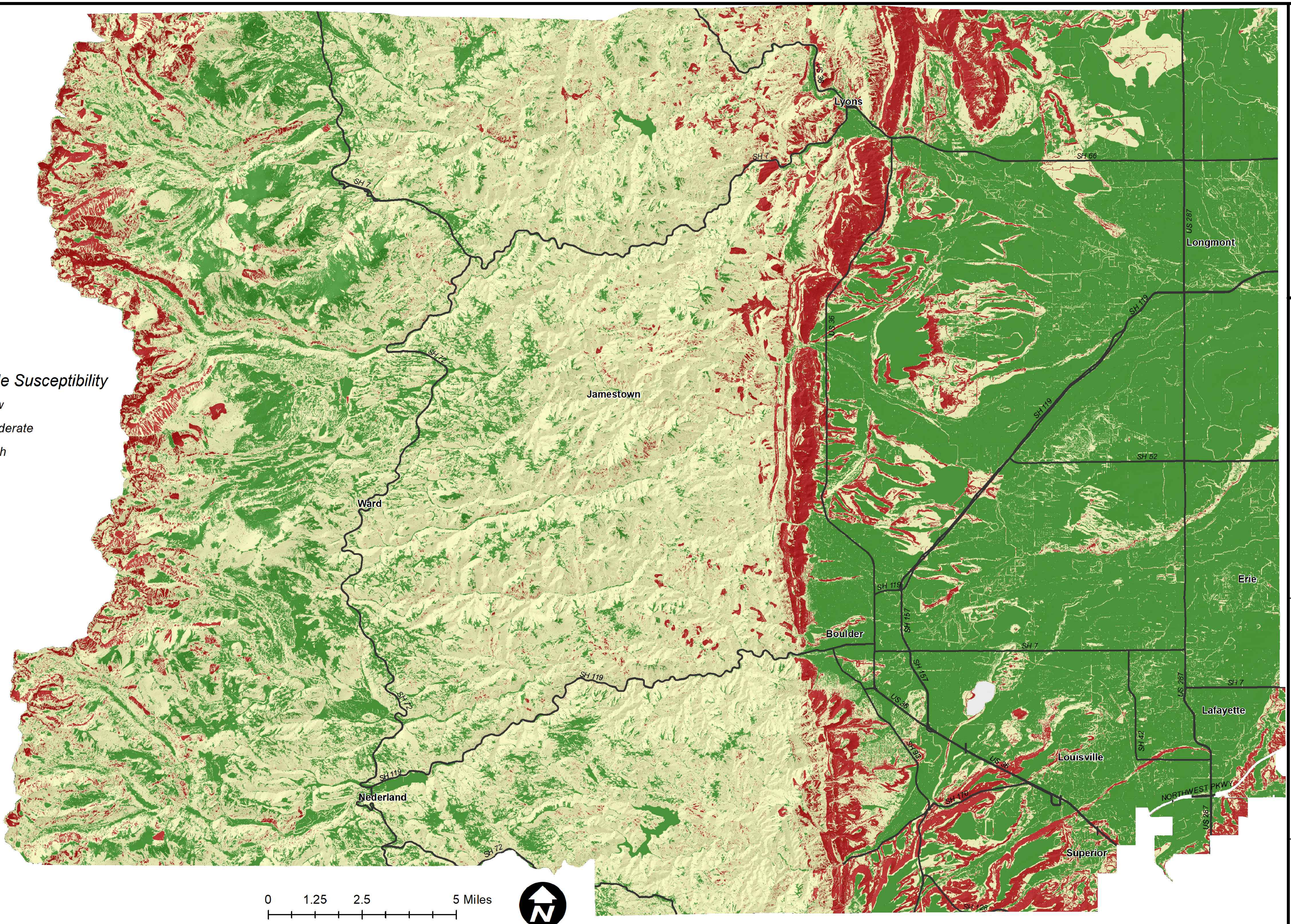

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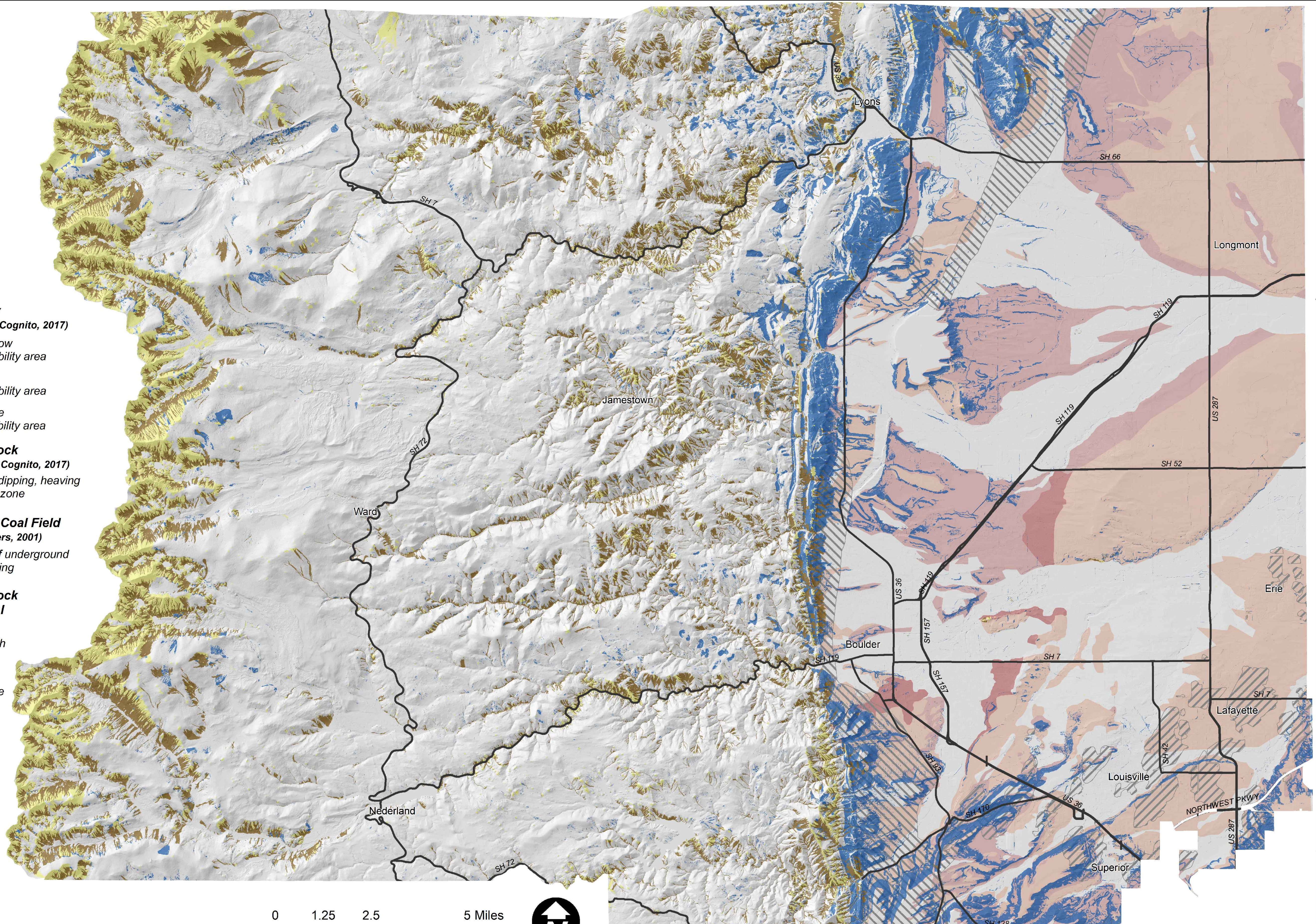
PLATE 7
Landslide Susceptibility Map

PROJECT NO:	16.3097		
PROJECT NAME:	Boulder County Geologic Hazard Study		
DRAWN BY:	JMF	CHECKED BY:	DRD
DWG DATE:	03.31.17	REV. DATE:	10.10.17



Slope Stability
(Cesare and TerraCognito, 2017)

- Debris flow susceptibility area
- Rockfall susceptibility area
- Landslide susceptibility area

Heaving Bedrock
(Cesare and TerraCognito, 2017)

- Steeply dipping, heaving bedrock zone

Boulder-Weld Coal Field
(Roberts and others, 2001)

- Extent of underground coal mining

Soil and Bedrock Swell Potential
(Hart, 1974)

- Very High
- High
- Moderate

0 1.25 2.5 5 Miles

N

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PLATE 9
Boulder County Geologic Hazards Map

PROJECT NO:	16.3097
PROJECT NAME:	Boulder County Geologic Hazard Study
DRAWN BY:	JMF
CHECKED BY:	DRD
DWG DATE:	03.31.17
REV. DATE:	10.10.17

W:\2016\Frederick Projects\16.3000\16.3097.G Boulder County Geotechnical-Geohazard Services\ACAD\Final Plates - Addendum No. 1\PLATE 10 Rockfall Susceptibility Map.dwg 10/10/2017 3:17 PM

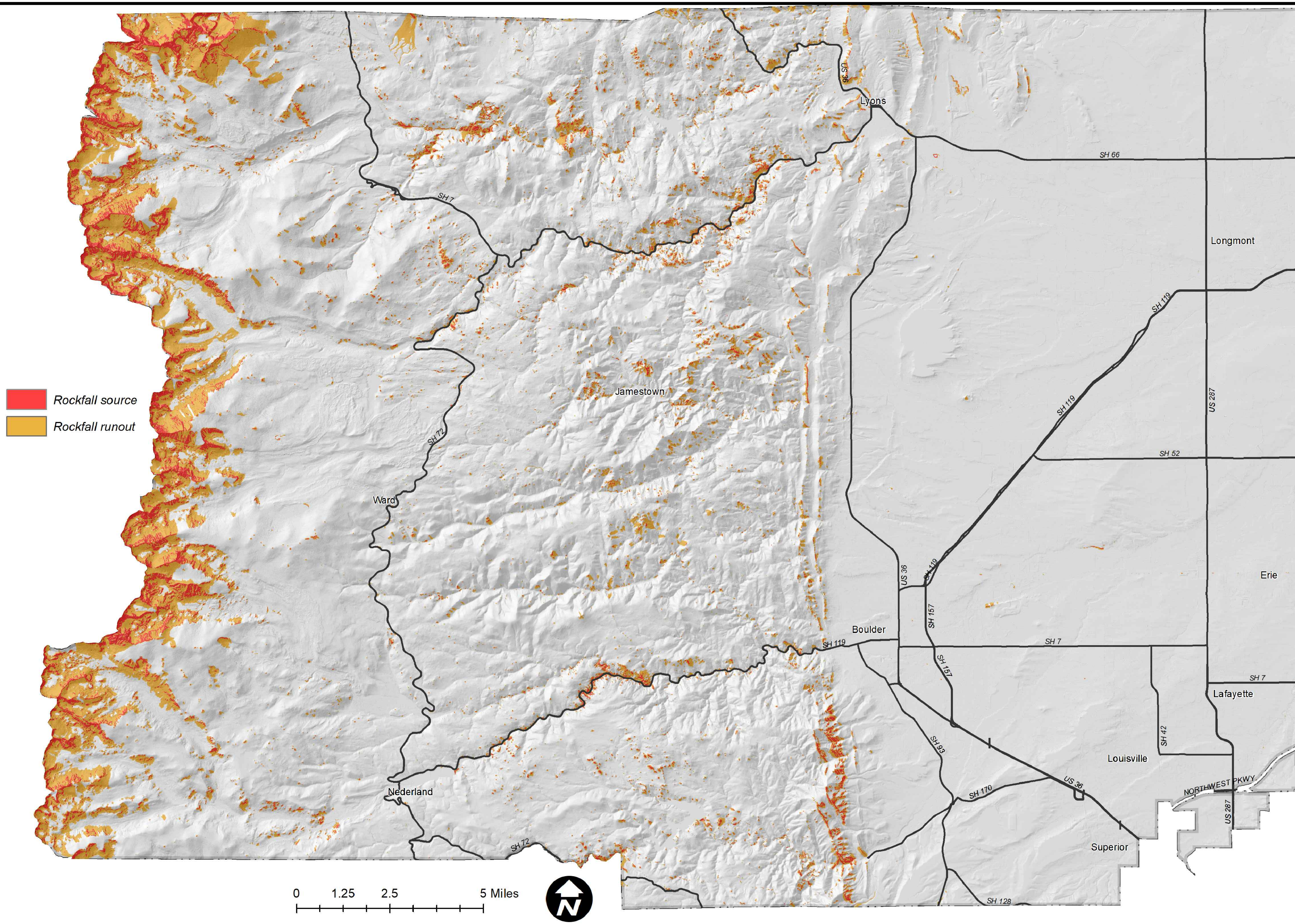

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PLATE 10
Rockfall Susceptibility Map

PROJECT NO:	16.3097
PROJECT NAME:	Boulder County Geologic Hazard Study
DRAWN BY:	JMF
CHECKED BY:	DRD
DWG DATE:	03.31.17
REV. DATE:	10.10.17

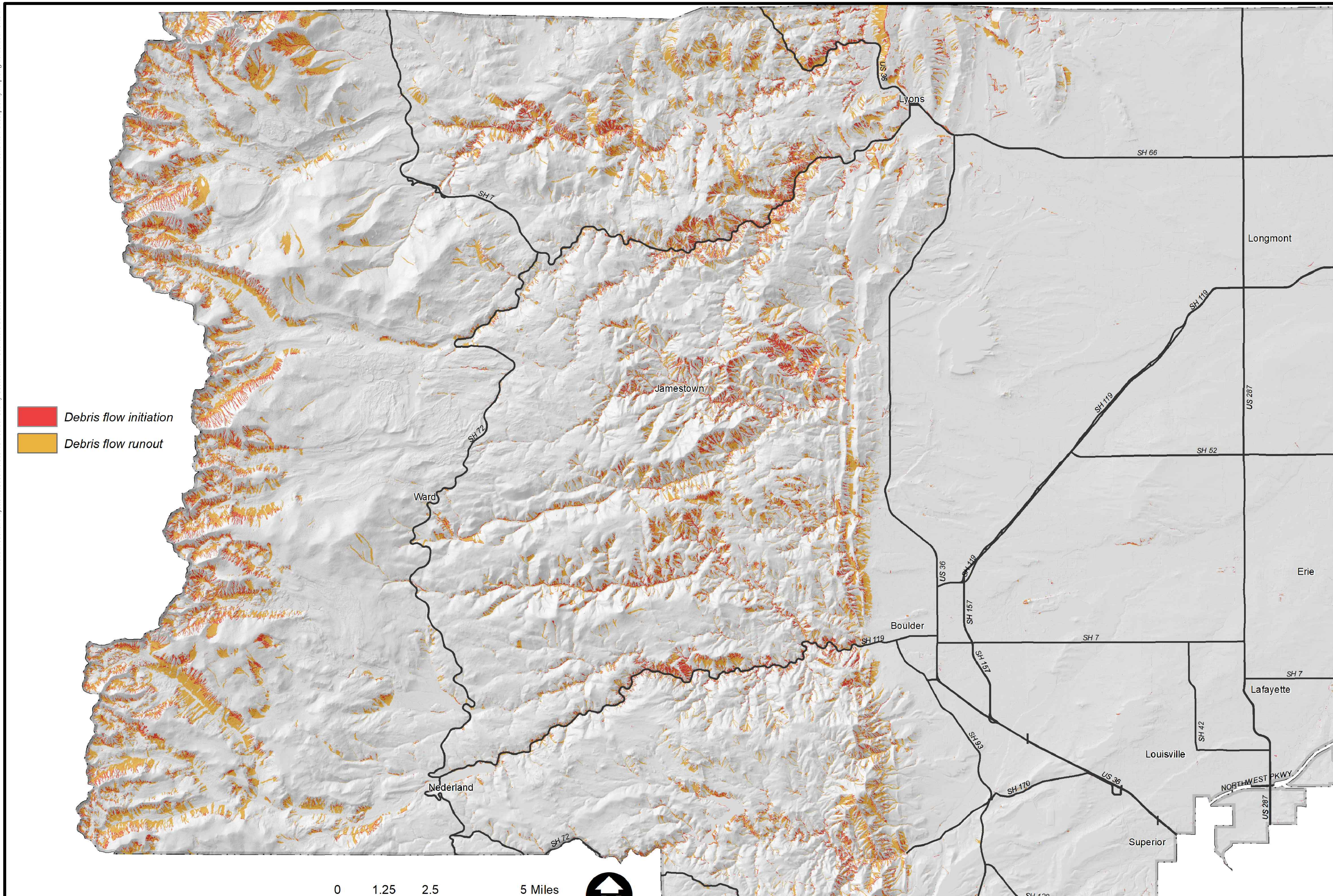

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PLATE 11
Debris Flow Susceptibility Map

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PROJECT NAME:	Boulder County Geologic Hazard Study		
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