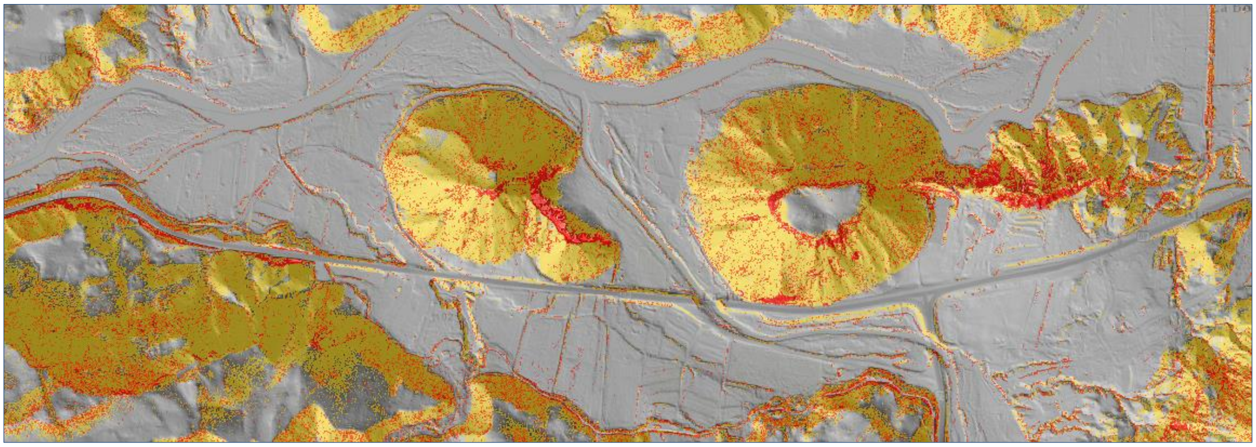

UNM Earth Data Analysis Center

New Mexico State Cooperating Technical Partner, FEMA Region 6

FY16-PM-MAS008

Mapping Activity Statement 006

Automated Landslide Hazard Detection

September 2017

EDAC | EARTH DATA ANALYSIS CENTER

LiDAR Derived Landslide Products
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Figures and Tables

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Table of Abbreviations and Acronyms

3DEP	[USGS] 3D Elevation Program
BLM	Bureau of Land Management
CTP	[FEMA] Cooperating Technical Partner
DEM	Digital Elevation Model
DSM	Digital Surface Model
EDAC	[UNM] Earth Data Analysis Center
FEMA	[U.S.] Federal Emergency Management Agency
ft	foot/feet
GB	gigabyte(s)
GeoTIFF	Geographic Tagged Image File Format
GIS	Geographic Information System
GPSC	Geospatial Product and Service Contracts
GRS80	Geodetic Reference System of 1980 [spheroid]
HUC	Hydrologic Unit Code
img, IMG	ERDAS IMAGINE image file format
LAS	LASer File Format
LiDAR, lidar	light detection and ranging
m	meter(s)
MB	megabyte(s)
NAD83	North American Datum of 1983 [datum]
NAIP	[USDA] National Agriculture Imagery Program
NAVD88	North American Vertical Datum of 1988 [vertical datum]
NDVI	Normalized Difference Vegetation Index
NHD	[USGS] National Hydrologic Dataset
NIR	near infrared [light; reflectance]
NMOSE	New Mexico Office of the State Engineer
NPS	nominal pulse spacing; also, nominal point spacing
QA/QC	Quality Assurance/Quality Control
QL2	Quality Level 2
Red	visible red [light; reflectance]
TB	terabyte(s)
UNM	The University of New Mexico
U.S., US	United States of America
USFS	U.S. Forest Service
USGS	United States Geological Survey
UTM	Universal Transverse Mercator [projection]
WUI	Wildland Urban Interface
XML	Extensible Markup Language

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Introduction

As a part of an on-going contract as a Cooperating Technical Partner (CTP) with FEMA Region 6, Earth Data Analysis Center (EDAC) at the University of New Mexico (UNM) reviewed and processed LiDAR data sets in order to derive maps highlighting areas of landslide risk and the community anchor sites and transportation networks at risk. This particular project covered two different regions of New Mexico, each with their varying degrees of landslide risk – The Santa Fe County area and the Rio Hondo HUC-8 watershed. Both of these areas were covered by LiDAR data meeting the USGS Quality Level 2 (QL2) specification.

The Study Areas

Two areas in New Mexico were chosen for this landslide study, the Santa Fe County and the Rio Hondo HUC-8 Watershed study areas (Figure 1). These study areas have terrains typical of New Mexico composed of mountainous regions as well as cliff-lined mesas and hills and canyons inscribed by streams all of which are landforms which can host features at elevated landslide risk. In both cases, these areas have recently been covered by USGS Quality Level 2 (QL2) LiDAR data with nominal pulse spacing of 0.7- m which was used as the base data set from which the products were derived.

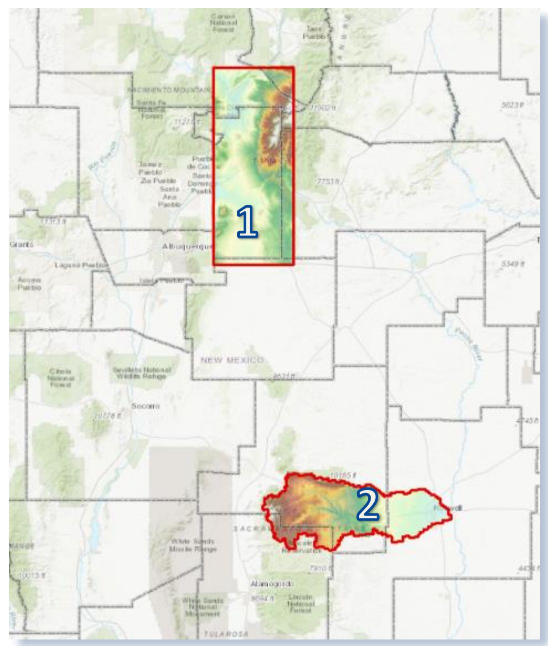

Figure 1 - Santa Fe County (1) and Rio Hondo HUC-8 Watershed (2) study areas.

The Santa Fe County Study Area

This study area had LiDAR acquired for it 2014, largely funded by Santa Fe County and the City of Santa Fe, but also by the USGS and the City of Española. The bounds of the data acquisition go a little beyond the county boundaries to the east, south, and west county boundaries, but due to the additional funding provided by Española, which is in Rio Arriba County to the north, the acquisition polygon includes

Española and its proximal watersheds. All totaled, 3,030 square miles were acquired in 2014.

The study area ranges from about 13,100 feet with the second highest peak in New Mexico, Truchas Peak, down to 5,370 feet along the Rio Grande. Despite this almost 8,000 feet of relief, most of the area is relatively flat with the landslide risk being found along the mesa edges with rock topples and slides along the escarpments and rotational slides along the slumping slopes beneath. On the west side of the study with the Jemez volcanic area and the Ortiz Mountain group, and to the east side, with Sangre de Cristo Mountains, the terrain becomes rougher, the slopes higher angled and with that the full range of landslide risks are possible.

This area includes Santa Fe, in the center of the county, which is the capital of New Mexico and with 68,000 people is the third largest town in the state (Figure2). Most of the population in this study area lives in an area that runs from Santa Fe up along US 84 up to Española in the north, mostly on flat or rolling land subjected to only low slope angle landslide threats. The study area also includes all or part of the tribal lands of 10 pueblos (San Felipe, Santo Domingo, Cochiti, San Ildefonso, Santa Clara, Picuris, Nambe, Ohkay Owingeh, Pojoaque, and Tesuque) who mostly live in the river valleys which are mostly at risk for flooding and mudflows.

Figure 2 - Santa Fe County Study Area with Santa Fe (red star) and Española (blue triangle).

While the Los Alamos National Laboratory is in Los Alamos County the eastern part of the lab is covered by the LiDAR acquisition and whereas most of the lab infrastructure is located safely on top of the mesas the connecting roads go up and down from these mesas and into areas of heightened landslide risk; in addition, the canyon bottoms host an unknown number of radioactive material waste sites which can be subject to flooding and mud flows; this was a concern after the 2000 Cerro Grande and the 2011 Las Conchas wildfires in the Jemez mountains upstream from these sites.

Other federal lands, including the US Forest Service (USFS) and the Bureau of Land Management (BLM) lands, cover about a third of the study area, but these lands have the roughest terrain and as such the greatest landslide risk. Although relatively stable, much of this area is covered with forest which if removed due to wildfire or insect herbivory can cause the landslide threat to increase; this not just a theoretical threat as mentioned above the Jemez

Mountains to the west have had several major wildfires as have the Sangre de Cristo mountains to the east and all the forests in the study area have been subjected to large-scale beetles infestations.

This study area covers a portion of the watershed of New Mexico's largest river and second largest river, the Rio Grande and the Rio Chama, respectively. These rivers act as a major source of drinking water for most of the state's population and a conduit for irrigation water for agriculture. This vital water delivery system can be disrupted from mudflows filling the rivers up with silt and debris which happened after the Las Conchas fire. Likewise, the Santa Fe River and the Nichols Reservoir which it feeds upstream from Santa Fe, provides the city with most of its water and are equally susceptible to a similar type of threat.

Transportation infrastructure includes an interstate, I-25, a number of US and state highways and a major trans-continental railway; the railroad, I-25, and many of the highways travel through a number of chokepoints at heightened landslide risk. In particular, NM State Highway 68 to the north goes through Taos Canyon which has a notable problem with rock slides – in 1998 five died and fourteen were injured when a boulder slammed into a bus along that stretch of the highway.

Rio Hondo HUC-8 Watershed Study Area

The approximately 1,861 square-mile Rio Hondo HUC-8 sub-basin study area was acquired by FEMA in 2015. There is almost 8,500 feet of relief in the watershed. The sub-basin is centered on the Rio Hondo from its source in Sierra Blanca at 12,000 feet, to the west to its outflow into the Pecos River near Roswell in the east at almost 3,500 feet. The study area's terrain is about a third which is highly mountainous with Sierra Blanca in the west and the Capitan Mountains to the north, the center third which is dominated by incised, serpentine canyons, and the eastern third which is the relatively flat Pecos River floodplain.

This area includes the populated areas of Capitan, Ruidoso, Ruidoso Downs, and most of Rowell, New Mexico's fourth largest town (Figure 3); most of the communities are found in the valley floor or in Roswell's case along the Pecos River floodplain, although the communities to the north of Ruidoso are found in the mountainous terrain. Several state and US highways run through this watershed and run through a number of high landslide risk areas.

Nearly a quarter of the study area are covered by the unpopulated USFS and BLM lands as well as parts of the sparsely populated Mescalero Apache tribal lands; but these lands tend to host the forested slopes upstream from these communities and can cause an indirect threat after events such as a wildfire and heavy rainfalls which cause mudflows downstream; such as was the case after the Little Bear Fire in 2012 when a large rain flooded down the denuded slopes above Bonito Lake and caused the lake to fill up with sediment and debris which cut off a major water supply to Alamogordo and Holloman Air Force Base 60 miles away.

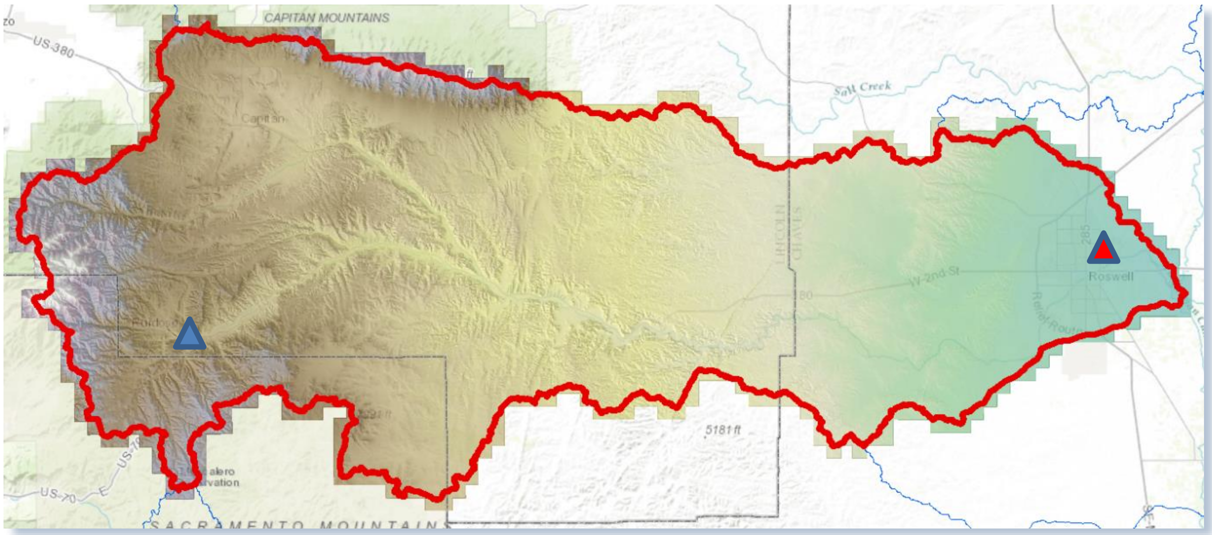

Figure 3 Rio Hondo HUC-8 Watershed Study Area with Ruidoso (blue triangle) and Roswell (red triangle)

Landslide Types

Landslides are generally classified by type of movement – falls, topples, slides, spreads or flows – and then classed as to the size of clastic material that it mostly composed of – rocks, debris, and earth in order of decreasing size (Highland *et al.*, Hungr *et al*.). Landslide risks can occur with all rock and soil types but loosely compacted soils are more susceptible to landslide risks than consolidated rock. Also, the landslide risk increases proportionally with an increase in slope. Landslide risk will increase with the addition of moisture due to increasing of weight on a given slope and decreasing the slide resistance; this can happen naturally under flooding or high rainfall events or by artificial irrigation upslope. Risks can also increase if the vegetation cover is removed which reducing its ability to tie together loosely consolidated material as well as providing a barrier to downslope erosion; this can happen naturally due to insect herbivory or wildfire or through manmade events such forest thinning or clearing. Cutting into an otherwise stable slope can also make areas susceptible to landslides, especially toe slope cutting as that is the key pressure point that the slope is directing its stress on to; this can happen naturally due to stream cutting or through man made disturbances such as road cuts and excavations. In addition, areas subject to shaking or vibrations due to earthquakes or volcanic activity can have their risk increase substantially.

Debris flows, debris avalanches and earth flows tend to happen rapidly and are some of the major types of mass movement that occur typically at lower slope angles (20 – 45 degrees). These are usually on slopes composed of loosely consolidated materials or fine textured soils. These can occur due to a high rainfall event, or in areas that have recently lost their vegetative cover or have had toe slope undercutting. Wet debris flows that occur in channels are often called mud flows. Slower earth flows are typically known as creep.

Rotational slides are large mass movements which occur along a whole line of rupture usually on low angle slopes (20 – 40 degrees). These can be brought on by undercutting of the toe slope. Indicators of areas prone to rotational slides are escarpments or cliff faces on the head slope where the earth mass has begun to slip down and hummocky terrain down slope with fissures and cracks.

Rock topples, rock falls, rock spreads and rock flows are typically rapid movements of anything from individual rocks to mass movements or rocks. These occur on high slopes (45 – 90 degrees) and can be exacerbated by high rainfall events or winter's freeze-thaw action. These are usually found naturally along cliff faces, escarpments, talus slopes, scree falls, or stream cuts or by man-made disturbances of road cuts or excavation.

Methodology

Slope

EDAC created a Degree Slope image from the Bare Earth DEM using the ERDAS Imagine2015 *slope module* to quantify the degree change in slope (rise over run). The *slope* module output unsigned 8-bit images, with values ranging from 0 to 89 degrees and where 0 degrees slope represented flat surfaces and higher numbers represented increasingly steep slopes.

This data was then simplified to represent the major slope breaks for landslide processes noted above with slopes below 20 degrees classified with a value of “0”, slopes between 20 and 45 degrees classified with a value of “1”, and slopes 45 degrees or above classified with a value of “2” (Figure 5). Thus with this reclassified slope map value “1” represents areas at risk for debris flows, debris avalanches, earth flows, and rotational slides and with values of “2” represent areas susceptible to rock topples, rock falls, and rock flows.

Figure 4 - Classified slopes (yellow [value 1] and red [value 2]) along NM68 in Taos Canyon on the left and the same area from Google Street View (June 2016) on the right.

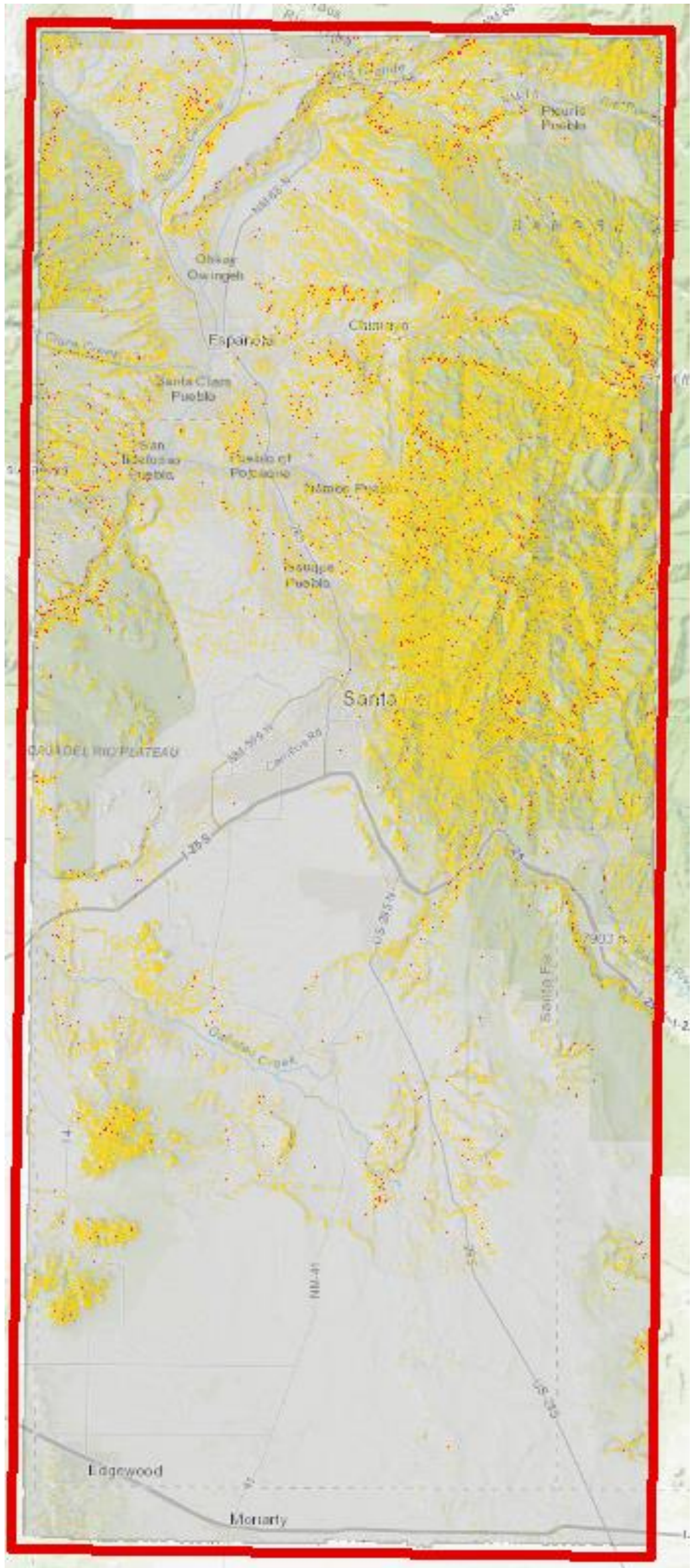

Figure 5- Classified high angle slopes (in yellow [value 1] and red [value2]) in the Santa Fe County study area.

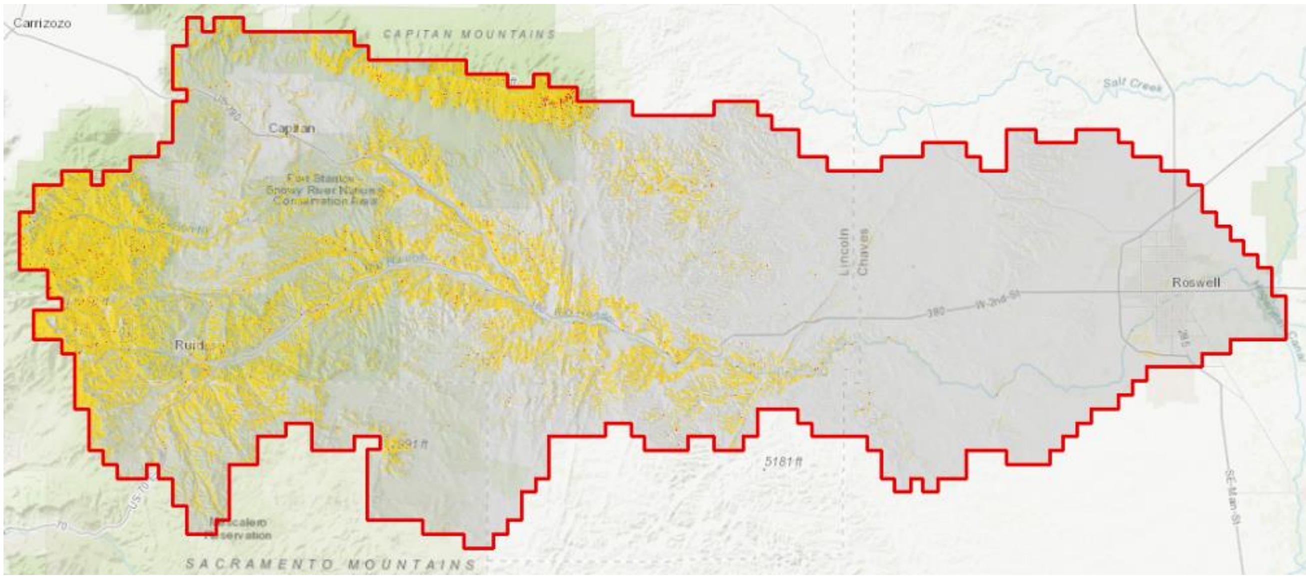

Figure 6 – Classified high angle slopes (in yellow [value 1] and red [value2]) in the Rio Hondo HUC-8 Watershed study area.

Profile Curvature

EDAC created a curvature image for the study areas using ESRI ArcGIS 10.3 *curvature module*. Curvature is a derivative of the slope or the second derivative of the digital elevation map. There are three different types of curvature that can be calculated – profile, planform, and standard. In this case a profile curvature was used. It is calculated parallel to slope and in a profile curvature an increasing negative value shows where the surface is upwardly convex and an increasing positive value shows where the surface is upwardly concave; the closer the value is to a zero value indicates no change of slope. Therefore the higher or lower the value, the more of an inflection there is in the slope with the most extreme values mapping the edges of cliffs, escarpments, excavations, stream cuts, and road cuts.

A floating point image ranging from -100 to 100 was created for both study areas. In surveying the study areas it was found that values above 10 or below -10 best mapped these vertical terrain features. Therefore, a new image was created where all values below -10 and above 10 were classified as value "1" and all other values were classified as "0" (Figure 7).

Figure 7 - An example of the classified curvature (red) in the lower center in Ruidoso on the left and on the right the same cliff edge from Google Street View (June 2015).

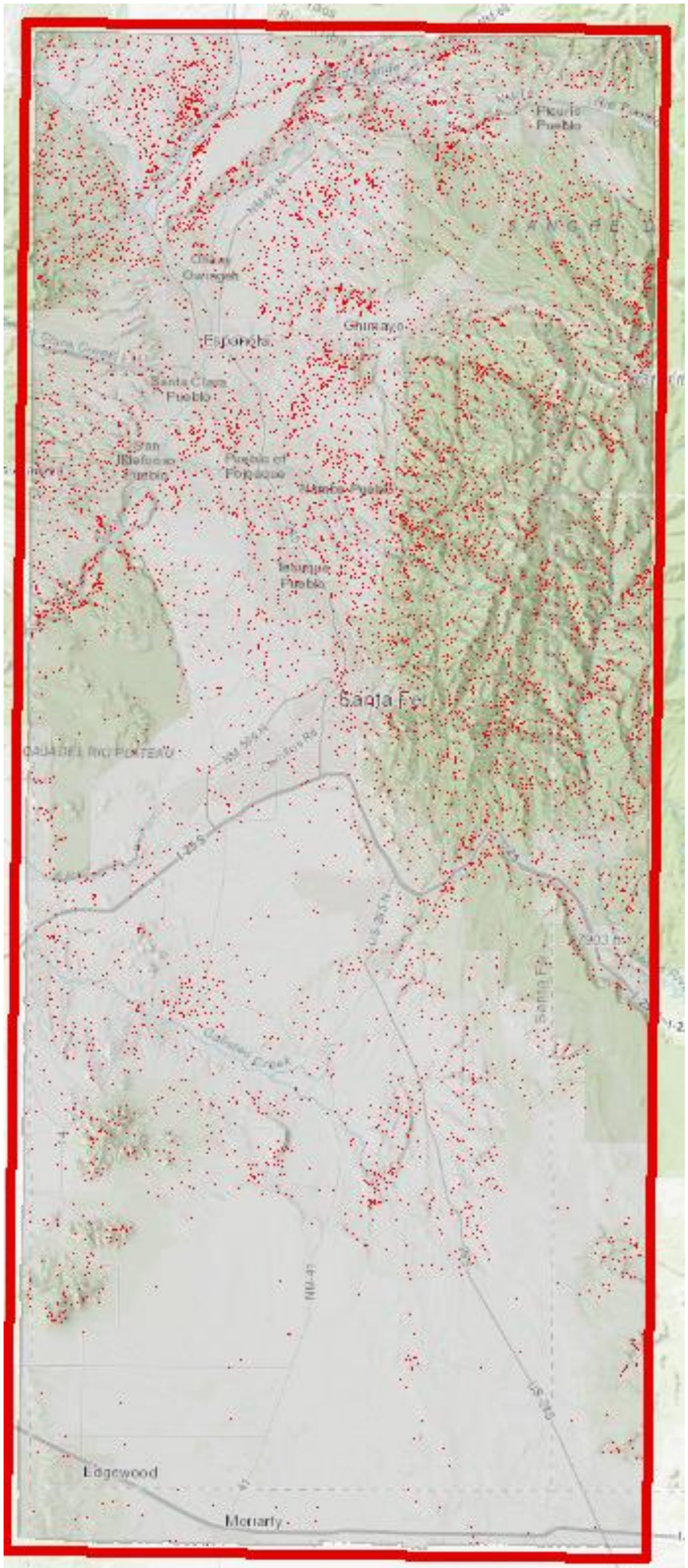

Figure 8 - – Classified curvature values (red) in the Santa Fe County study area.

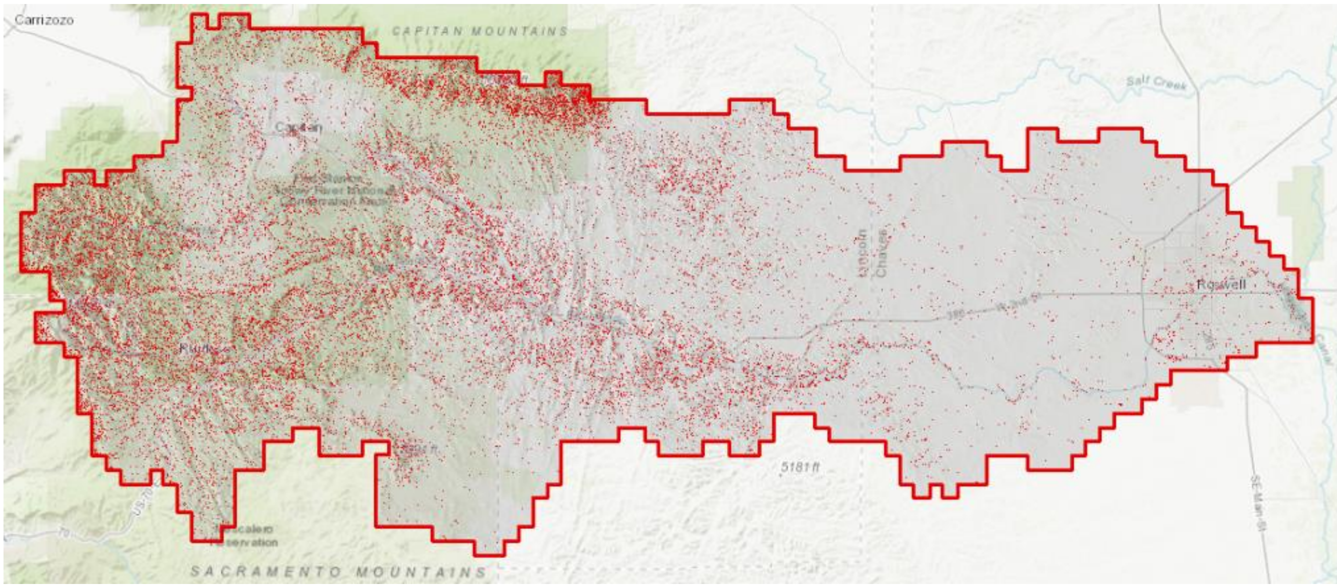

Figure 9 – Classified curvature values (red) in Rio Hondo HUC-8 Watershed (bottom) study area.

Results

The final results of the analysis found that about 6% of the Santa Fe County and 16% Rio Hondo HUC-8 Watershed study areas are covered in terrains susceptible to landslides and other mass movements. As expected, most of the landslide risk areas are outside of the populated areas; the majority of the threats instead are to the transportation infrastructure and indirectly from deforestation of these slopes due to wildfire or insect herbivory which then could lead to mudflows downstream into these communities, important infrastructure, or major streams and rivers.

In 1990, a preliminary landslide map was made for New Mexico based on a 1:500,000 scale map and ground data (Cardinali, *et al*.). This map was overlain on to the results from this project, and as the data is originally from a 1:500,000 scale map, the locations were proximal, but even given that there is good agreement with the locations they had mapped and the areas of landslide risk highlighted in this study as shown in Figure 8 with earth flow slump (green squares), complex slump earth flow (red circles with green crosses), Toreva blocks (green crosses), rock debris/slides (red squares), debris flows/slides/avalanches (green triangles), deep seated landslides (red circles), rock falls/topples (red hexagons).

The NHD HUC-8 flowlines for the Santa Fe County (parts of the Upper Rio Grande, Rio Chama, Rio Grande-Santa Fe, Western Estancia, Pecos Headwaters, and Pintada Arroyo sub-basins) and the Rio Hondo watershed (Rio Hondo) study areas were download form the USGS NHD data site. These were overlain on to the results and all drainages covering potential risk areas or directly downstream were selected – (Figure 12 – Santa Fe County, Figure 13 – Rio Hondo HUC-8 Watershed). These were considered potential mudflow susceptible drainages given the proper conditions (e.g. wildfires, insect herbivory epidemic, timbering operations).

The potential landslide map and the potential mudflow susceptible drainages were then combined the state's Community Anchor Site Assessment (CASA). The CASA datasets contains point locations of known community anchor sites – emergency operations centers, fire stations, government community resources, health centers, higher education facilities, law enforcement facilities, libraries, medical facilities, and K-12 public schools. A manual inspection of each CASA location was conducted to ascertain whether or not it was adjacent to an area of landslide risk.

A new geospatial layer was created highlighting sites that may have a threat due to potential landslide or mudflow. There were some 109 sites identified in the Santa Fe County study area and 41 sites identified in the Rio Hondo HUC-8 watershed study area, Table 1 shows the numbers and types of facilities for each area.

Table 1 Essential Facilities with Potential Landslide or Mudflow Exposure.

Institution	Rio Hondo Watershed	Santa Fe County
Schools K-12	7	37
Library	1	6
Hospital	1	0
Nursing Home	0	1
Urgent Care	0	0
Health Center	2	8
Fire Station	15	21
Law Enforcement	4	8
EOC	2	4
University	1	3
Community College	0	1
Other Post-Secondary	0	0
State Government	2	5
Other Government	5	15
Non-Government	1	0
Total	41	109

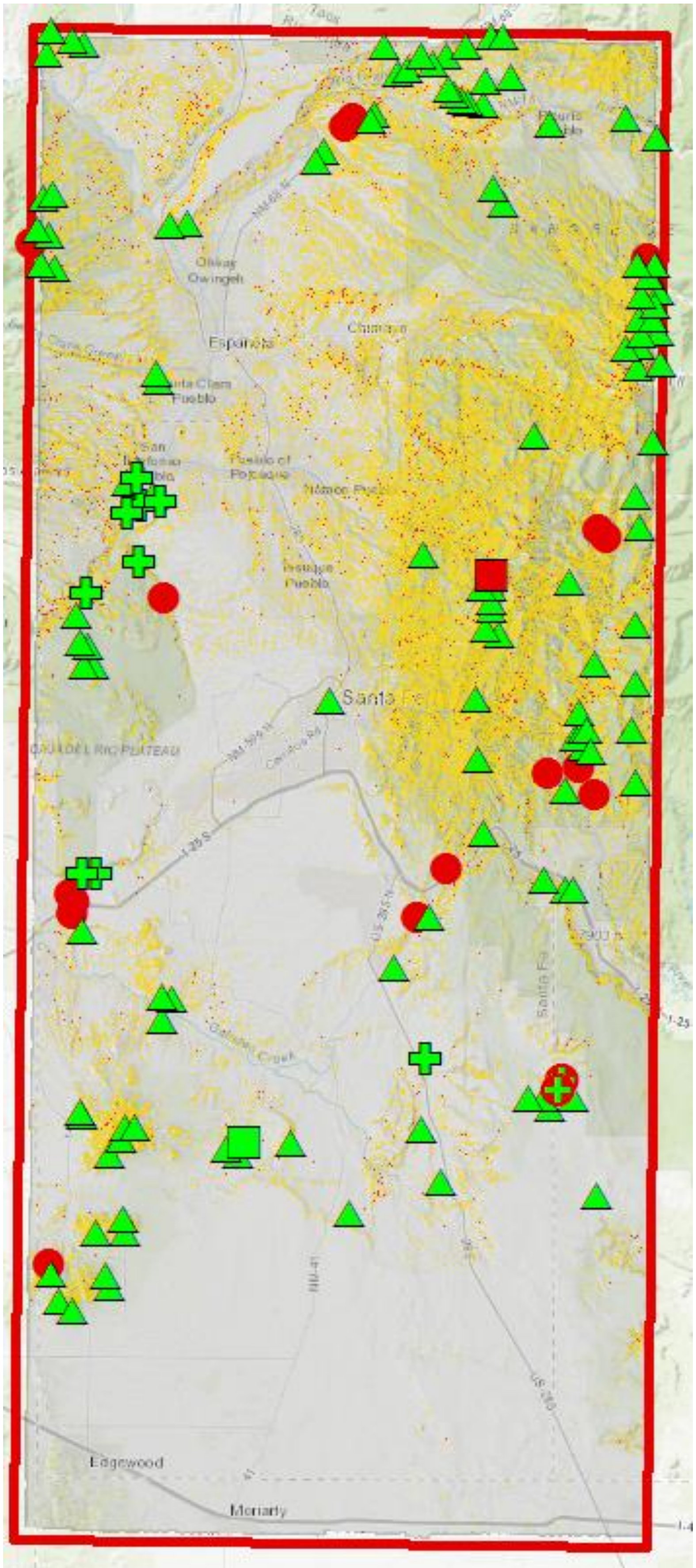

Figure 10 - The preliminary map landslide sites overlain on the classified slope map for the Santa Fe County study area.

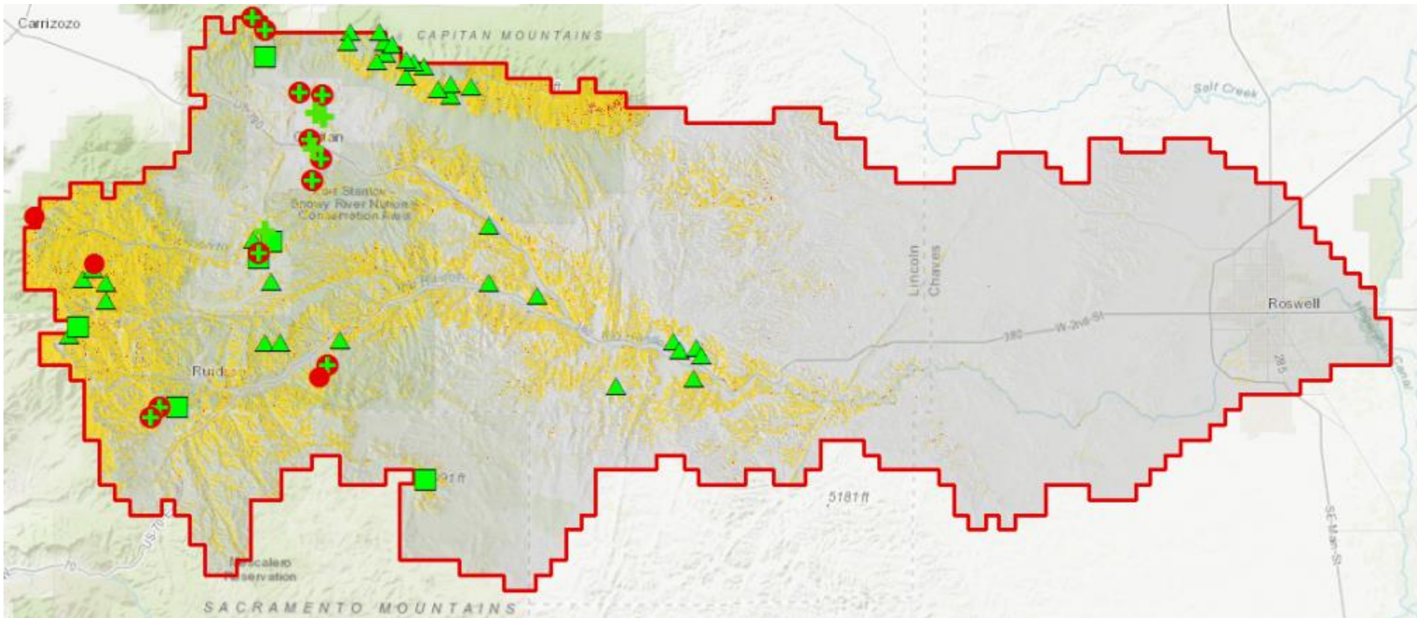

Figure 11 - The preliminary map landslide sites overlain on the classified slope map for Rio Hondo HUC-8 Watersheds study area.

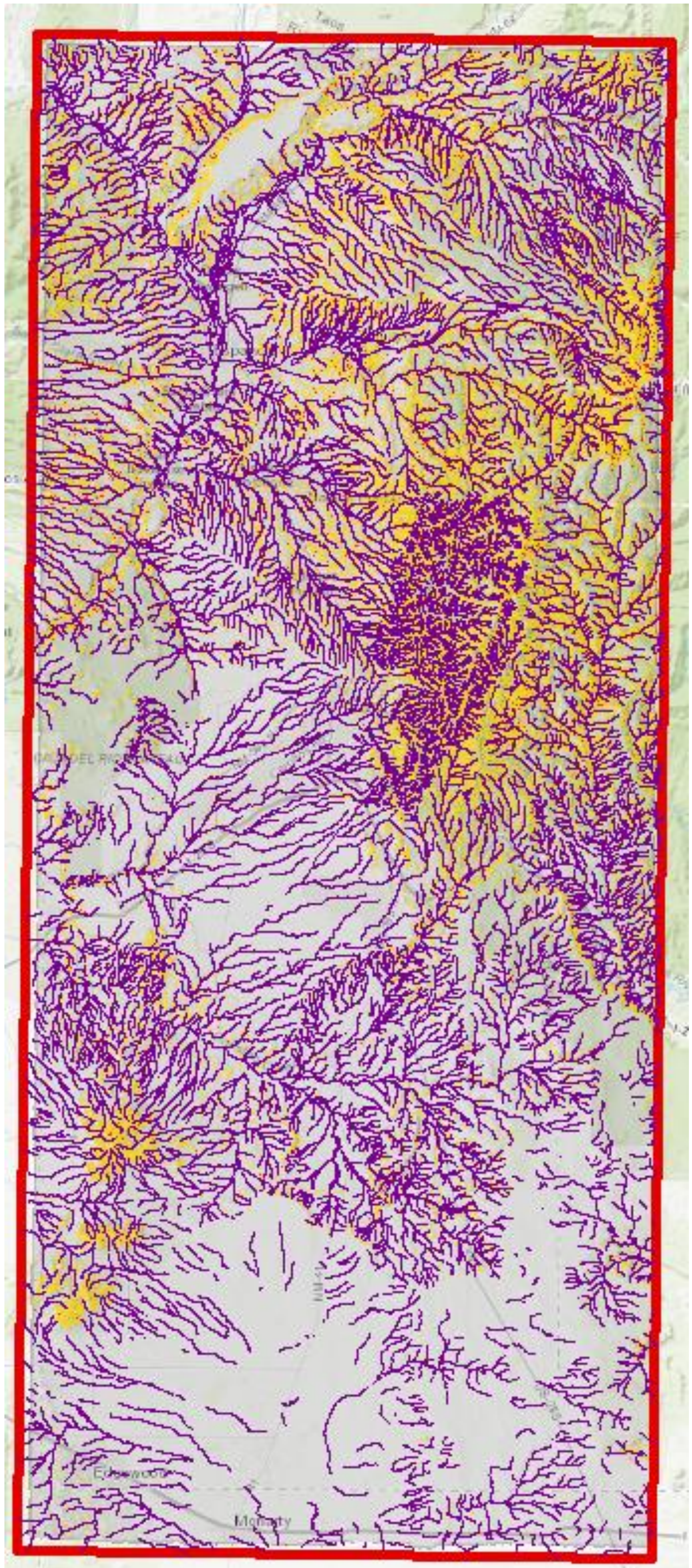

Figure 12 - The mudflow susceptible drainages overlain on the classified slope map for the Santa Fe County study area.

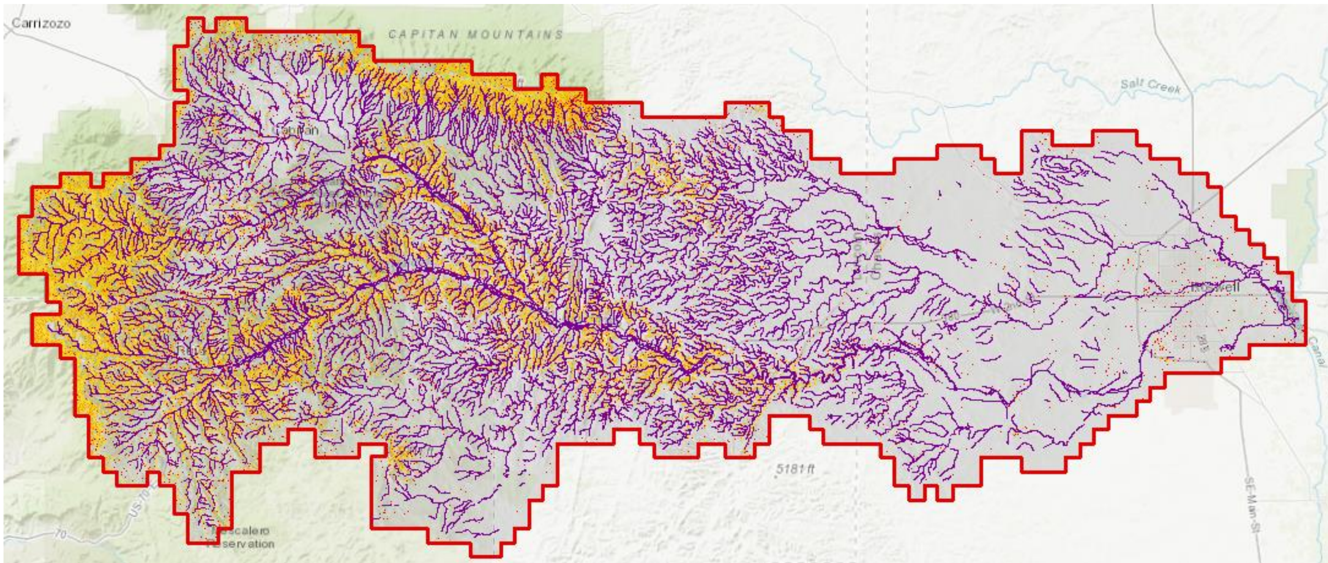

Figure 13 - The mudflow susceptible drainages overlain on the classified slope map for Rio Hondo HUC-8 Watersheds study area.

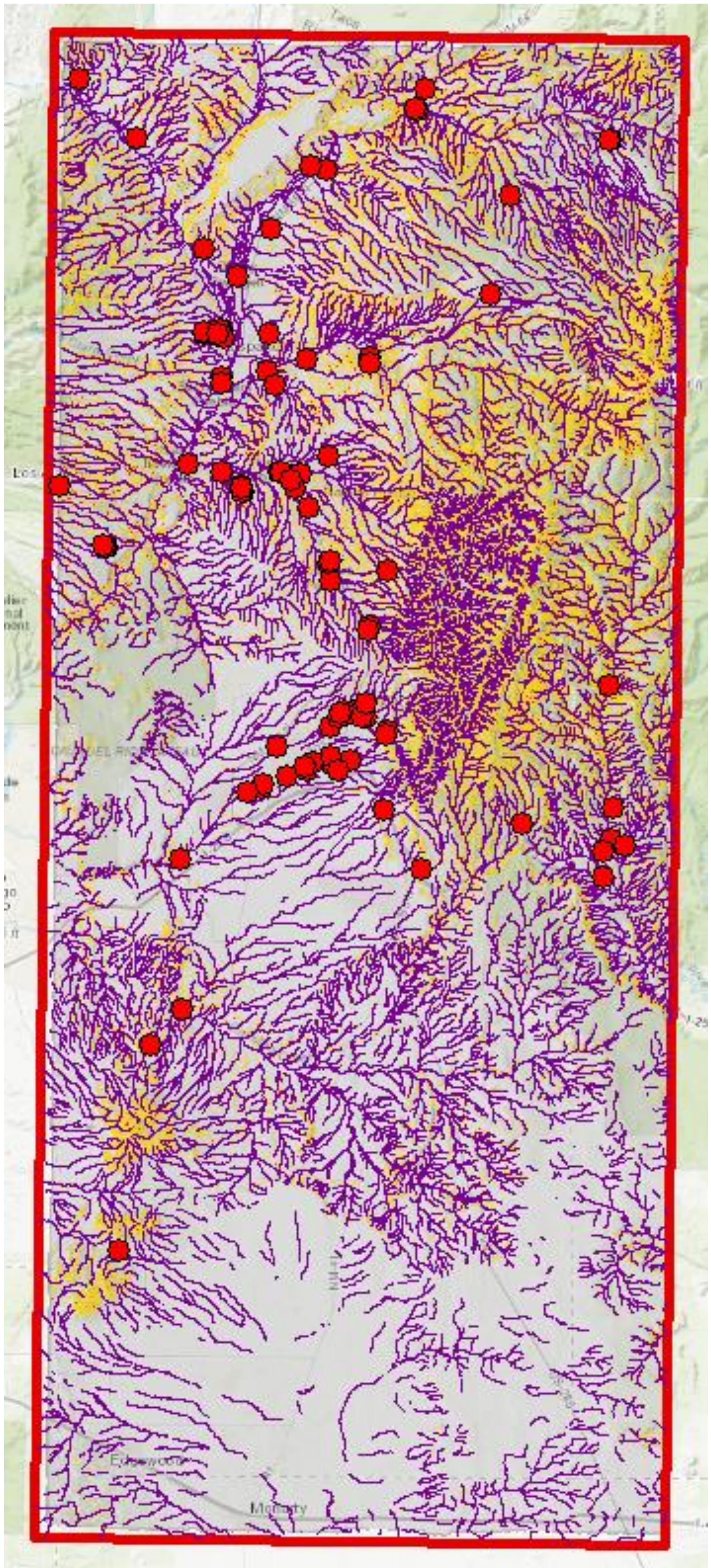

Figure 14 – The community anchor sites (red dots) with the mudflow susceptible drainages overlain on the classified slope map for the Santa Fe County study area.

Figure 15 - The community anchor sites (red dots) with the mudflow susceptible drainages overlain on the classified slope map for the Rio Hondo HUC-8 watershed study area.Figure 16 – The community anchor sites (red dots) with the mudflow susceptible drainages overlain on the classified slope map for the Santa Fe County study area.

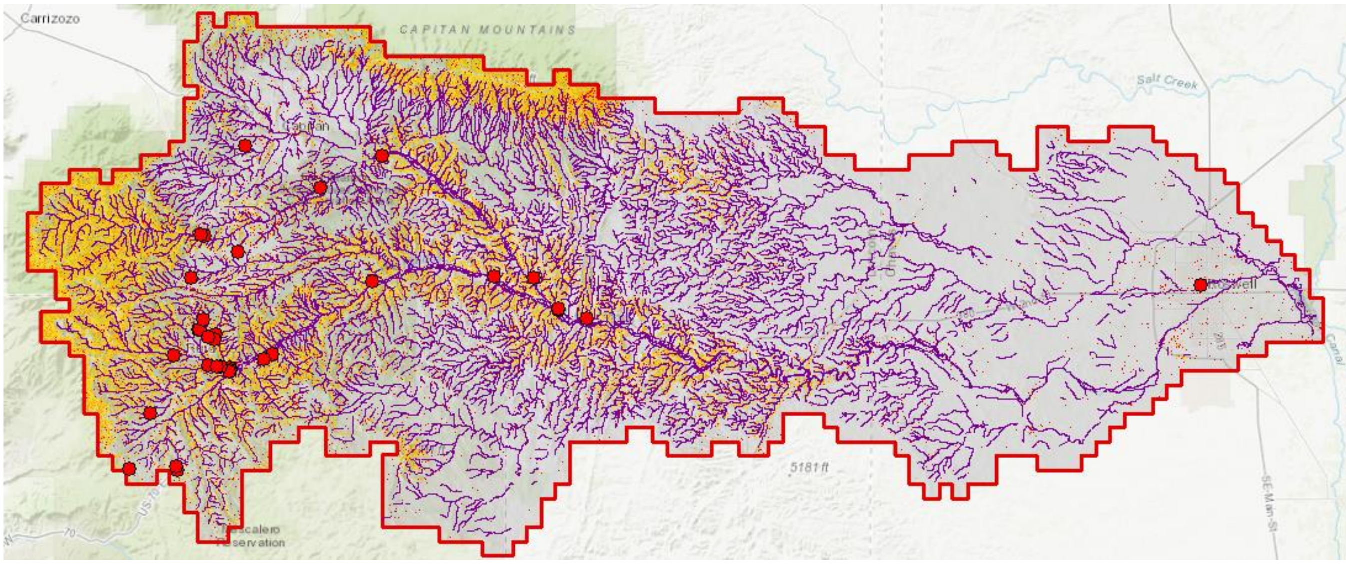

Figure 17 - The community anchor sites (red dots) with the mudflow susceptible drainages overlain on the classified slope map for the Rio Hondo HUC-8 watershed study area.

Figure 18 - The community anchor sites (red dots) with the mudflow susceptible drainages overlain on the classified slope map for the Rio Hondo HUC-8 watershed study area.

Geospatial Landslide Data

The data utilized in this analysis and the datasets generated by this analysis are available on the New Mexico Resource Geographic Information System (RGIS) Clearinghouse (http://rgis.unm.edu/) and NM Flood (http://nmflood.org/ .) This data is either in the format of geodatabases or digital terrain models.

Future Work

This mapping effort is a preliminary effort, albeit at a much finer scale than was done in the 1990 mapping effort (Cardinali *et al*.), this analysis solely utilized a terrain based methodology. Landslide risks vary greatly, not only due to the terrain but also due to the composition of the surface (clay, sand, gravel, and etc…), and depend on whether the surface and subsurface geology is consolidated or unconsolidated. Therefore, to truly identify areas of landslide risk, these terrain based results would need to be combined with detailed mapping of the surface and subsurface geology. The current STATEMAP effort being conducted by the New Mexico Bureau of Geology & Mineral Resources in conjunction with the USGS is mapping this information at a 1:24,000 scale would be extremely useful when combined with these automated results. Although the automated analysis identified potential landslide areas it would need to be combined with both geologic information and field work to produce a detailed landslide risk analysis.

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Hungr, O., S.G. Evans, M.J. Bovis, and J.N. Hutchinson, 2001. A Review of the Classification of Landslides of the Flow Type. Environment & Engineering Geoscience, v. VII, No. 3, pp 221-238.