SSCI 583 Spatial Analysis: Final Project
Trail Slope Study – Henry Coe State Park, California

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Abstract

Using both a 1/3 arc-second and a 1/9 arc-second 3DEP DEM, a slope model for a portion of the hiking trial network of Henry Coe State Park was constructed. Trail segments are categorized as to difficulty using a variation of the IMBA Trail Difficulty Rating criteria. The outputs from the two different DEM resolutions are compared. The analysis shows the DEMs did not have a significant impact on the trail rating distribution. Segmentation choices did manifest MAUP issues.

Motivation

Hiking and backpacking are common outdoor activities for many Americans (Bowker 2012, Cordell et all 2008). An obvious prerequisite for a hike is choosing a route given the time and desired level of effort. For the experienced hiker, reading topographic maps to assess distance and terrain difficulty is an essential part of that experience. An experienced eye can examine the contour lines on a topographic map and intuitively envision the terrain and estimate the effort required for various route choices. Such assessments are often beyond the abilities of less experienced individuals. This study presents an approach to answering the question of trail difficulty and to quantify, to some degree, factors that can be used in choosing a route for a hike.

From a spatial analysis perspective, the concept of "difficulty" is an interesting question. What is easy for an experienced hiker is potentially quite difficult for one less capable. How do you quantify such a subjective question? Distance is one obvious factor. The longer any route, all other factors held constant, the more difficult the journey. Slope needs to be considered. It goes without saying that steeper slopes require more effort than level surfaces. Other considerations are ground cover and soil composition. Heavy brush and unconsolidated soils are more difficult to navigate than open grasslands and level rock surfaces. Climate, season, and the immediate weather present yet another element to be considered, though more transitory. Last, but not least, the abilities of the individuals examining the question set a relative scale that can vary not only person-to-person, but day-to-day depending on mood, health, and circumstances.

In practice, it is a combination of all these factors that influence the difficulty of a route through a terrain. This study chooses to explore just one of the spatial factors involved: trail slope. As an additional factor, output from Tobler's hiking function (Tobler 1993) will be calculated as a suggested surrogate for effort.

Project Scope

1. Analyze the trail network in the study area. Determine the following information for each of the major trail segments:
    - Slope
    - Classification using a rating system based on slope
    - Using Tobler's Hiking Function (Tobler 1993), estimate time required to complete the segment
    - Slope and time will be bi-directional

2. Analyze using a 1/3 arc-second U.S. Geological Survey 3D Elevation Program (USGS 3DEP) digital elevation model (DEM) and then compare it to an analysis using a 1/9 arc-second 3DEP DEM.

3. Analyze the significance of the differences, if any, and discuss results.
    - Slope generated from the two DEMs
    - Trail rating impacts

Study Area

Henry Coe State Park (here after simply Coe) covers approximately 87,000 acres (35,000ha) of wildlands in northern California (Figure 1). The park is a large, irregular polygon with several private parcels within the overall park boundaries, creating "holes" of ownership. There are over 340 miles (400km) of trails in the park (Figure 2). Elevations range from 710 feet to 3560 feet (215m to 1085m). Typical routes entail ascents and descents of several hundred to several thousand feet of elevation change (Pine Ridge Association 2017). More information about the park can be viewed on the California Parks and Recreation website (https://www.parks.ca.gov/?page_id=561).

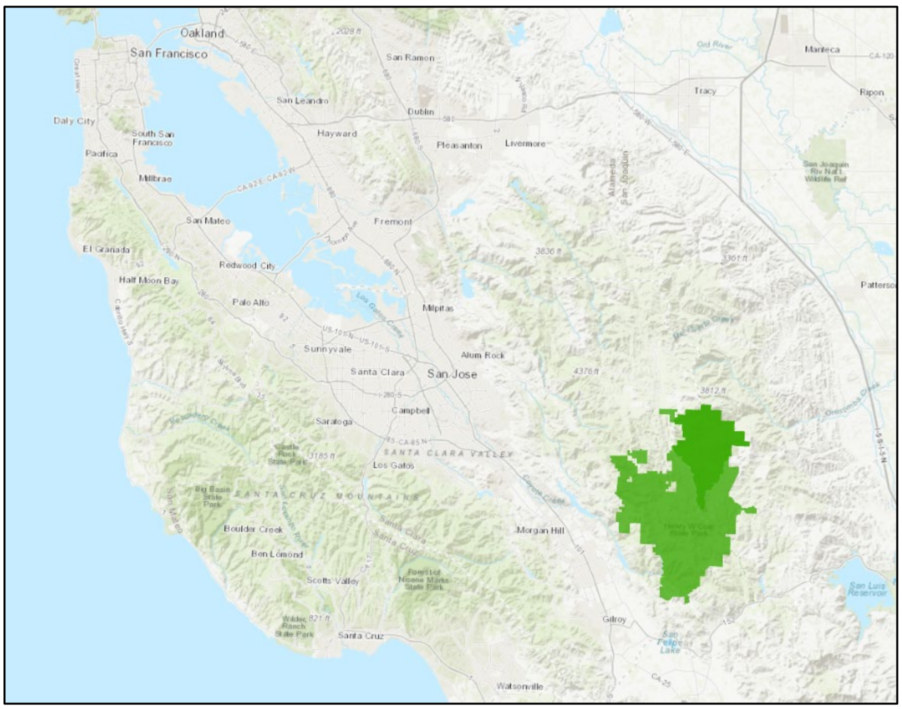

Figure 1:Location of Henry Coe State Park

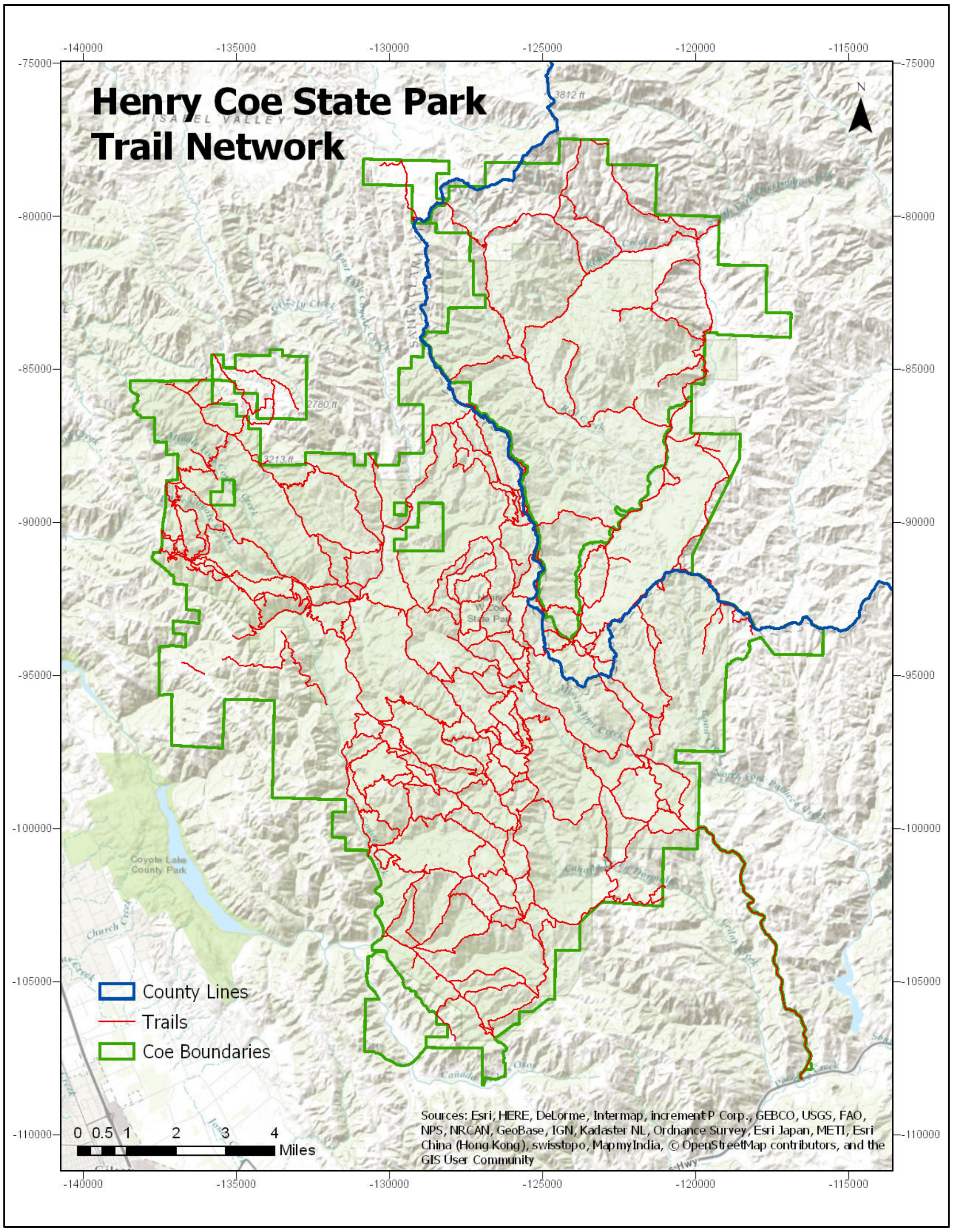

Figure 2: Overview of Coe boundaries and trail network

Given the large size of the park and the extensive trail network, the study area is limited to a portion of the overall area. This allows a reasonable demonstration of the analysis without an overwhelming amount of data processing. The area encompasses a wide variety of terrain and a significant trail set for the study.

The extent of the study area is illustrated in Figure 3 and Figure 4. The area is approximately 8 miles (12.5km) east-west and 7 miles (11km) north-south, encompassing the lower third of the park. The trail network in this area is approximately 100 miles (162km). Trail elevations range from 760 feet to 2620 feet (230m to 800m).

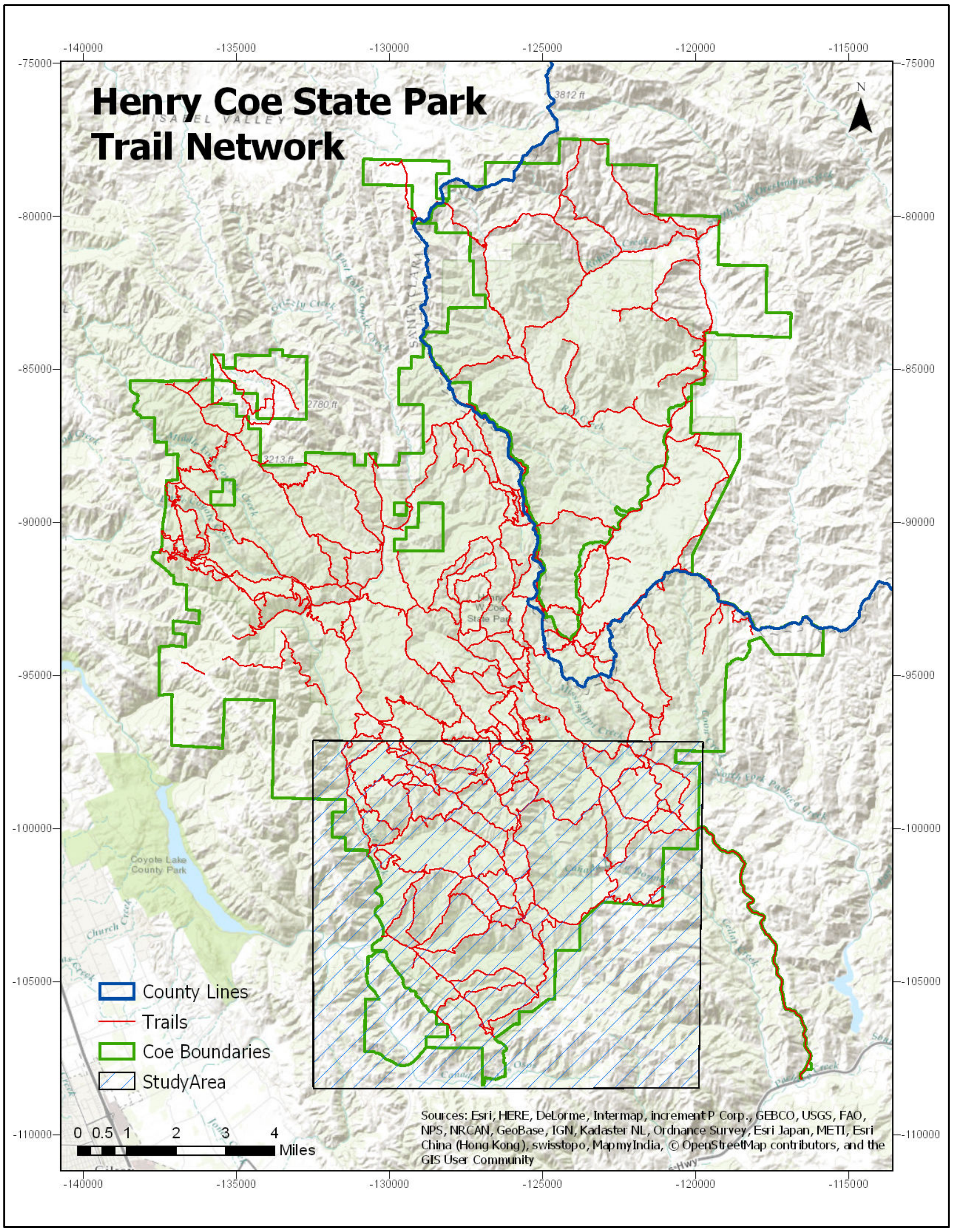

Figure 3: Study area highlighted with hashed area

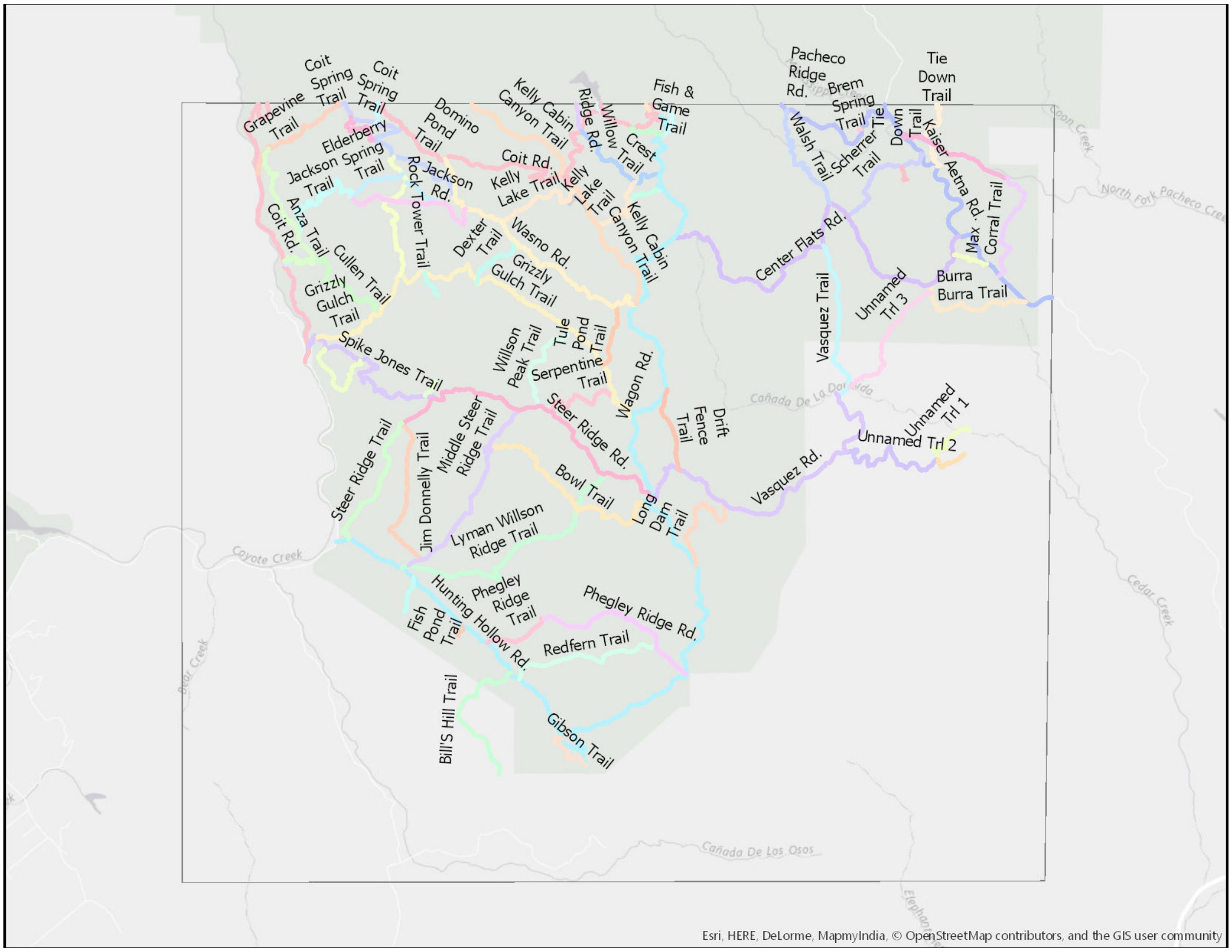

Figure 4: Study area detail

Data Review

Broadly, three datasets are used for this study.

1) Vector data of the trail network, park boundary, and county boundaries.
2) DEM raster data
    a. 1/3 arc-second DEM (~9m)
    b. 1/9 arc-second DEM (~3m)
3) Rating system

Following is a review of the source datasets for the vector, raster data, and a discussion regarding the rating system.

Vector Data

The vector data was obtained from the California State Parks GIS website (https://www.parks.ca.gov/?page_id=862). File formats available included a GDB geodatabase file and an ArcMap MXD file. The GDB and MXD files included layers for the state park boundaries, buildings, entry points, and other infrastructure. The files were packaged together in the downloaded ZIP file and contained identical content. Oddly, the trail network was a separate shape file, also included in the download package.

The information from the GDB file was used. The "Opbdys" and "County_15" layers were imported into the ArcGIS Pro project created for this analysis. These layers included the needed boundary information. The shape file "CalStParks_Trails" was also imported. A summary of the metadata is presented in Table 1.

Table 1: Vector layer metadata

	Source data layer	CalStParks_Trails	Opbdys	County_15
	Short Description	Trail networks	Park boundaries	County boundaries - 2015
	Data Type	Shapefile - Polylines	Feature class - Polygons	Feature class - Polygons
	Records	10693	433	58
	Attribute Fields	3	6	5
	PCS	NAD 1983 California Teale Albers	NAD 1983 California Teale Albers	NAD 1983 California Teale Albers
	GCS	GCS North American 1983	GCS North American 1983	GCS North American 1983
	Horizonatal Unit	Meter	Meter	Meter
	Vertical Unit	Meter	No Z value	No Z value
Extent	Top	441,269.437000 m	449,530.510000 m	450,023.161800 m
	Bottom	-589,445.210000 m	-604,454.502500 m	-604,495.794300 m
	Left	-354,161.556000 m	-354,248.760000 m	-373,987.932700 m
	Right	505,263.362600 m	505,738.372400 m	540,082.750000 m

The attribute data for the vector datasets is provided in Table 2. The attributes for the trail shape file are simple. It contains the trail name, a calculated length (separate from the system generated attribute), and surface type. The surface type was not used for this study. The boundary data is more elaborate, but little of this information was needed for the analysis. The park and county boundary polygons were the only data used.

Table 2: Vector data attributes

CalStParks_Trails	
Field Name	Data Type
ROUTENAME	Text(65)
Shape_Leng	Double
Surface	Text(15)

Opbdys	
Field Name	Data Type
ENTITYID	Long
GISACRES	Double
SUBTYPE	Short
UNITCODE	Long
UNITNAME	Text(60)
UNITNUM	Text(4)

County_15	
Field Name	Data Type
COUNTY_NAME	Text(40)
COUNTY_ABBREV	Text(3)
COUNTY_NUM	Short
COUNTY_CODE	Text(2)
COUNTY_FIPS	Text(3)

The trail network at Coe is extensive. An extract was taken from the statewide dataset of just the Coe trail network. The attribute data for this extract indicates ~344 miles (~554 km) of trails in the Coe network. As indicted in the record count in Table 3, those miles are spread across 832 trail segments. However, these segments are not distinct trails in and of themselves. There are numerous sub-meter trail segments recorded. Some are mere centimeters long. Cleanup of these artifacts was performed before the analysis was executed.

Table 3: Coe park extent data

	Extracted data layer	CoeTrails
	Short Description	Trail networks - Coe only
	Data Type	Shapefile - Polylines
	Records	832
	Fields	3
	PCS	NAD 1983 California Teale Albers
	GCS	GCS North American 1983
	Horizonatal Unit	Meter
	Vertical Unit	Meter
Extent	Top	-77,488.639800 m
	Bottom	-108,190.008200 m
	Left	-137,497.720000 m
	Right	-116,233.797000 m

As a point of clarification, the trail network is conceptually considered a hierarchy. The trail network is comprised of trails; the trails are comprised of segments. The term “trail segments” indicates section of a trail between trail junctions. The trail segments are analyzed for the factors in the scope for the project (i.e. the slope, difficulty rating, time).

Overall, the trail network is well documented and appears as distinct lines. There often is a risk of some inherent ambiguity given lines between nodes of a plot do not always follow the natural curves of a trail on terrain. A scan of the trail network overlaid on satellite imagery of the park showed no major resolution issues in this regard. The trail polylines map closely to the imagery once the projections were aligned.

Raster Data

Four raster files were acquired from the USGS 3DEP website (https://nationalmap.gov/3DEP/3dep_prodserv.html).

1) grdn38w122_13.zip
2) ned19_n37x25_w121x50_ca_santaclaraco_2006.zip
3) ned19_n37x25_w121x75_ca_santaclaraco_2006.zip
4) ned19_n37x50_w121x50_ca_santaclaraco_2006.zip

The 3DEP raster files are generated from lidar data acquisitions. The coordinates in the file names represent the northwest corner of each raster. Item #1 is the 1/3 arc-second raster (hence the "…_13" in the name) and the other three are the 1/9 arc-second rasters ("ned19…") that were available for the Coe area. Each ZIP file contains the raster imagery as well as a set of ancillary and metadata files.

Some pre-processing was done on the datasets.

- The three 1/9 arc-second datasets were combined in ArcGIS Pro to a mosaic dataset.

- The mosaic and the 1/3 arc-second data were projected to the NAD 1983 California Teale Albers coordinate system to match the vector data. New data layers were created.

- Symbology was generated for the two datasets.

Overviews of the extent of the unprocessed raster data are shown in Figure 5 and Figure 6. Local views of the pre-processed datasets are provided in Figure 7 and Figure 8. (Be aware that the symbology range values are not synchronized in these overviews.) The extent of the source datasets exceeds the boundaries of Coe in most cases, but the 1/9 arc-second data does not cover the northeast sector of the park. The 1/9 arc-second data was only available for Santa Clara County. The missing area is the part of Coe that is within Stanislaus County. The study area is well enclosed within both datasets, however.

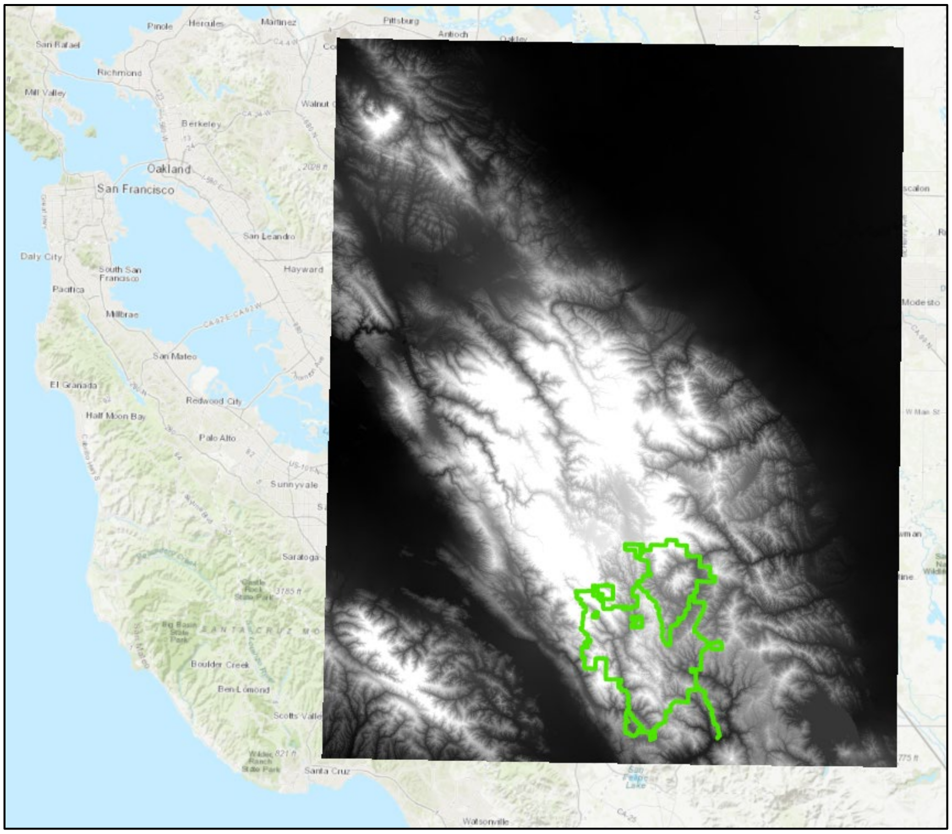

Figure 5: Extent of 1/3 arc-second raster data

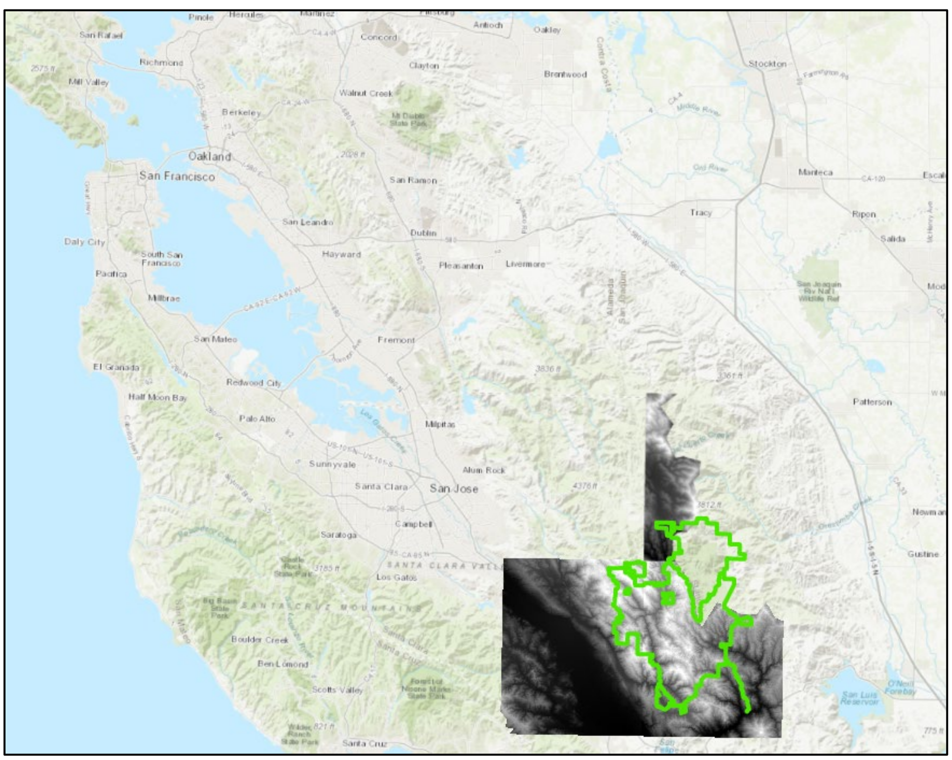

Figure 6: Extent of 1/9 arc-second raster data

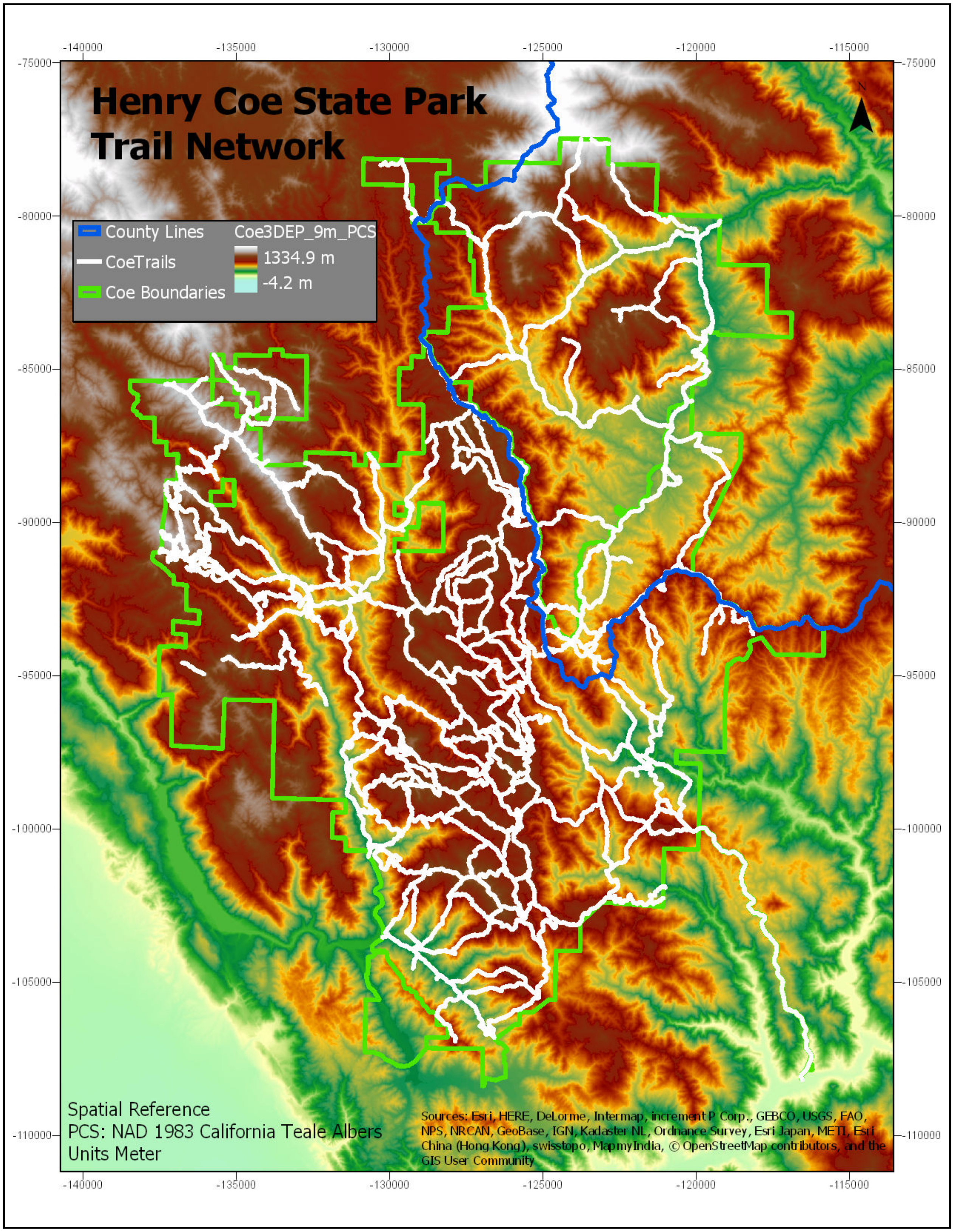

Figure 7: Local view of 1/3 arc-second dataset

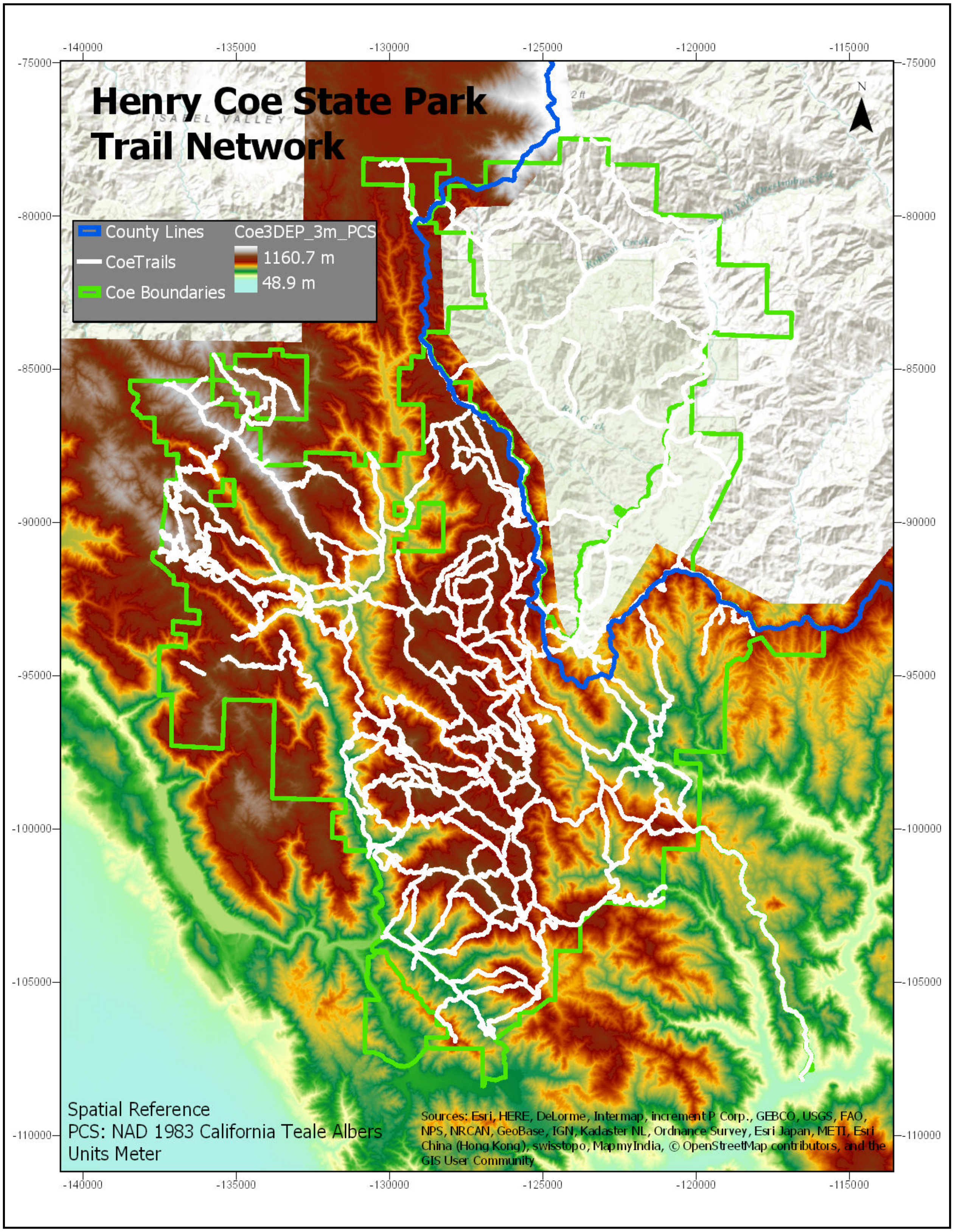

Figure 8: Local view of 1/9 arc-second dataset

Summary information about the raster datasets follows. Table 4 provides raster information on the source data. Table 5 provides a refresh of the information once the datasets were projected.

Table 4: Source raster metadata

	Source data layer(s)	grdn38w122_13	ned19_n37x25_w121x50_ca_santaclaraco_2006 ned19_n37x25_w121x75_ca_santaclaraco_2006 ned19_n37x50_w121x50_ca_santaclaraco_2006 Mosaic Dataset: Coe3DEP_3m
	Short Description	3DEP 1/3 arc-sec	3DEP 1/9 arc-sec
	Data Type	Lidar	Lidar
	Cells	10812x10812	16212x16212 (mosaic)
	Cell Size	1/3 arc second	1/9 arc second
	PCS	Not projected	Not projected
	GCS	GCS North American 1983	GCS North American 1983
	Horizonatal Unit	N/A	N/A
	Vertical Unit	Meter	Meter
Extent	Top	38.000556 dd	37.500185 dd
	Bottom	36.999444 dd	36.999815 dd
	Left	-122.000556 dd	-121.750185 dd
	Right	-120.999444 dd	-121.249815 dd

Table 5: Projected raster metadata

	Source data layer	Coe3DEP_9m_PCS	Coe3DEP_3m_PCS
	Short Description	3DEP 1/3 arc-sec (projected)	3DEP 1/9 arc-sec (projected)
	Data Type	Lidar	Lidar
	Cells	9671x12089	14524x18097
	Cell Size	9.3m	3.1m
	PCS	NAD 1983 California Teale Albers	NAD 1983 California Teale Albers
	GCS	GCS North American 1983	GCS North American 1983
	Horizonatal Unit	Meter	Meter
	Vertical Unit	Meter	Meter
Extent	Top	93.413145 m	-55,955.725776 m
	Bottom	-112,581.075505 m	-112,271.756407 m
	Left	-177,778.476470 m	-155,531.373537 m
	Right	-87,640.749633 m	-110,334.156933 m

All data meets or exceeds the "USGS National Geospatial Program" standards and the "USGS lidar Base Specifications" (https://nationalmap.gov/3DEP/3dep_prodstandards.html). The baseline statistics for the datasets (Table 6) seem well aligned with the general topography of the area. No serious outliers in minimum or maximum elevations are noticeable. The -4.243 meter minimum is appropriate given the bay lands in the area. The 1335.687 meter maximum aligns with the local peaks. The mean and standard deviation are of little probative value given the variety of terrain in the area.

Table 6: Raster data statistics

Dataset - downloads	Min	Max	Mean	SD
grdn38w122_13	-4.243	1335.687	261.468	269.818
ned19_n37x25_w121x50_ca_santaclaraco_2006	58.811	859.410	453.372	150.802
ned19_n37x25_w121x75_ca_santaclaraco_2006	48.911	982.155	299.128	227.453
ned19_n37x50_w121x50_ca_santaclaraco_2006	467.146	1160.811	773.642	142.146
Dataset - processed	**Min**	**Max**	**Mean**	**SD**
Mosaic Dataset: Coe3DEP_3m	60.375	857.846	450.285	148.971
Coe3DEP_3m_PCS	48.929	1160.709	417.934	243.594
Coe3DEP_9m_PCS	-4.238	1334.911	261.867	269.858

Pre-processing with the hydrology toolset was considered to eliminate pits, dams, and local outliers. This was omitted for the study. It was assumed the comparison of the 1/3 arc-second and 1/9 arc-second data would highlight any local anomalies. No significant outliers were discovered in the DEM layers.

Rating System

Determining proper slope intervals for a difficulty rating system is somewhat arbitrary. For a hiking trail, what may be difficult for one person may be trivial for another person in better physical condition. Conversely, that same trail may be impossible for a third person with lesser physical capabilities.

Several rating systems were considered for this study. A simple system adopted by the Sierra Club uses a three-factor code (https://www.sierraclub.org/loma-prieta/gls-hike-ratings). Criteria centers around trip length, elevation, and terrain. A common rating system used in the ski industry is the color-coded trail symbol approach (Ryan 2015, Wikipedia "Piste"). The color and symbol shape designate the difficulty of the trails in the ski resort network, with slope and trail width being the main criteria. A modification of the sky resort system was adopted by the International Mountain Biking Association (IMBA), with added elaborations for terrain features and a more precise definition of slope characteristics (Table 7).

Table 7: IMBA Trail Difficulty Ratings

Trail Difficulty Rating System

	Easiest White Circle	Easy Green Circle	More Difficult Blue Square	Very Difficult Black Diamond	Extremely Difficult Dbl. Black Diamond
Trail Width	72" or more	36" or more	24" or more	12" or more	6" or more
Tread Surface	Hardened or surfaced	Firm and stable	Mostly stable with some variability	Widely variable	Widely variable and unpredictable
Average Trail Grade	Less than 5%	5% or less	10% or less	15% or less	20% or more
Maximum Trail Grade	Max 10%	Max 15%	Max 15% or greater	Max 15% or greater	Max 15% or greater
Natural Obstacles and Technical Trail Features (TTF)	None	Unavoidable obstacles 2" tall or less Avoidable obstacles may be present Unavoidable bridges 36" or wider	Unavoidable obstacles 8" tall or less Avoidable obstacles may be present Unavoidable bridges 24" or wider TTF's 2' high or less, width of deck is greater than 1/2 the height	Unavoidable obstacles 15" tall or less Avoidable obstacles may be present May include loose rocks Unavoidable bridges 24" or wider TTF's 4' high or less, width of deck is less than 1/2 the height Short sections may exceed criteria	Unavoidable obstacles 15" tall or greater Avoidable obstacles may be present May include loose rocks Unavoidable bridges 24" or narrower TTF's 4' high or greater, width of deck is unpredictable Many sections may exceed criteria

While geared toward a different mode of travel, the IMBA levels reasonably apply to hiking. An adaptation of the IMBA standard was used for this study (Table 8). Pace would be different, but effort is comparable between the two activities. The IMBA "Average Trail Grade" was used to set the trail grade classifications. Opportunities exist to add the other criteria for future studies, as well as for fine tuning the criteria from field study and feedback.

Table 8: Trail Classifications

Slope	Rating
<=5%	Easy - Green
<=10%	Moderate - Blue
<=15%	Difficult - Black
>15%	Extremely Difficult - Double Black

Literature Review

The key element of this study is evaluating the slope in the trails of the study area using two different DEMs, then comparing the results. Most of the literature surveyed focused on least-cost or least-effort path determinations, with slope and effort being inputs. Slope specific studies tended to focus on soil erosion issues not pertinent to this study. From the survey, two articles had relevance to the project.

Chiou *et al* (2010) tackled the question of least-effort paths in a study of a trail network in Taiwan. There were two aspects of this study of interest: evaluation of slope over a trail segments; time and effort evaluations of those segments.

To evaluate the slope, the following process was used by the authors.

- Divide the trail network into 1 meter segments.
- Interpolate the elevation at each of the endpoints of the segments.
- Calculate the slope between adjacent endpoints and assign that to the segment.

The calculated slope then becomes a factor in subsequent time cost and effort cost equations in their study. Data appears to have been stored in ancillary tables, with records for each segment. This was to facilitate later path cost combinations. For the time factor, they used Naismith's Rule, a generalization developed in the 1800's by the Scottish mountaineer William Naismith (Naismith 1892). Lastly, they used studies of effort to factor in a third element in their analysis. Least effort paths for the trail network were then derived from this base information.

A study by Wimpey and Marion (2011) analyzed use-trails, comparing their characteristics against formal trails in the study area, and then assessing their impacts on the park resources. Again, the focus relative to this project is the authors' calculation of the slope of the informal trails in the study area. The authors use a TIN (triangular irregular network) for the slope information and a set of external macros to extract the information and apply it to the trail features. Coincidently, they also divide the trails into 1-meter segments. In this case, point features are created from the endpoints and the slope information added as an attribute to the point feature.

Elements from both these studies were explored in experimental sessions in preparation for the project analysis. As will be seen in the methodologies that were eventually applied in this project, the use of the macros for data extraction and the external tools for segmentation is no longer needed. The ArcGIS products provide the functionality in the toolsets. A TIN was generated and explored, but given the project scope and the ArcGIS Pro application capabilities, it was determined the direct use of the DEMs was sufficient.

Methodology

Broadly, two sets of data outputs are desired for the analysis: slope for trail segments and for 3 meter increments of the same trail segments. The trail segments use trial junctions to segregate the trail network into units typically used by hikers when planning a route. One moves from trail junction to trail junction. The slope and time attributes generated for these segments, however, are averages of the underlying terrain. Given the lengths of the segments vary, these averages can cover a broad set of terrain features.

The 3 meter increments echo the approaches taken by prior studies (Chiou et al 2010, Wimpey and Marion 2011). Breaking the trails into small segments provides more granularity for the analysis and allows for smaller terrain variations to manifest in the data. The 3 meter length was a compromise, selected to provide additional granularity, but to limit data redundancy. Given the 3 meter cell size of the 3M DEM, a shorter segment choice would have resulted in substantial data redundancy. Multiple segments would have fallen into the same raster cell. There is still some redundancy within the 3M DEM data as segments can randomly fit within a cell depending on their orientation. This redundancy is also a factor in the 9m DEM analysis as the segments often fall within the same cell given the greater sizing. There was some risk of a plateau effect in the data, but this was not evident in the subsequent data analysis.

Data on slope and time are generated using both a 3m DEM and a 9m DEM. Results of the trail ratings, slope characteristics, and timing are then compared across the four combinations. Figure 9 provides the general work flow. Details of each component follow.

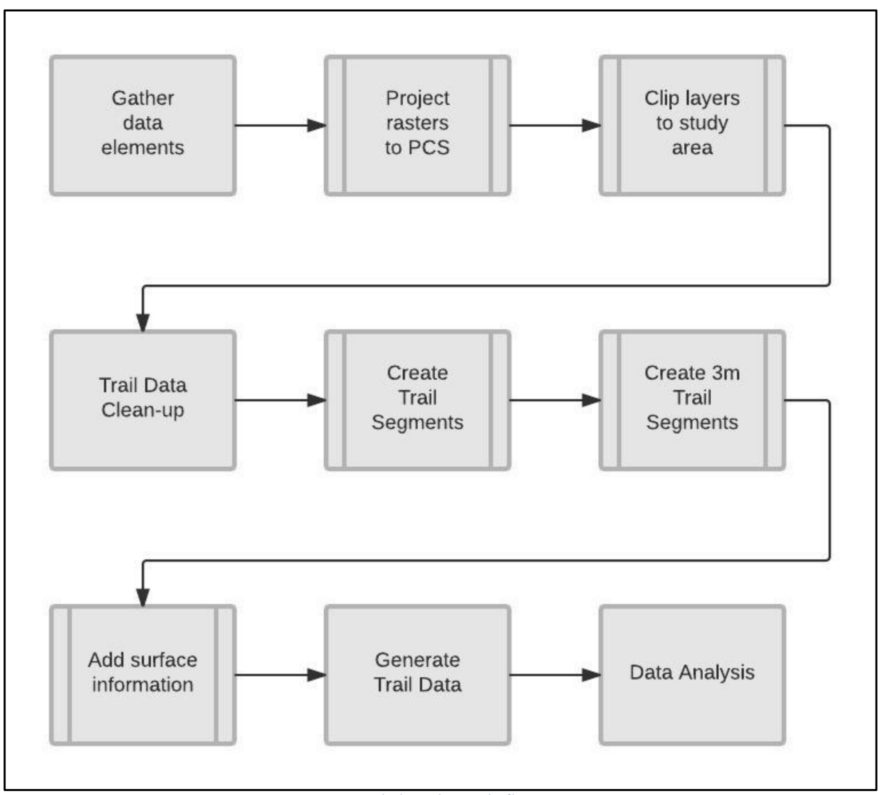

Figure 9: High level work flow

Gather Data Elements
The data gathering is outlined in the data review provided above. The various data files are assembled within an ArcGIS Pro 2.0 project.

Project Rasters To PCS
The vector data as provided is in the NAD 1983 California Teale Albers projected coordinate system (PCS). The raster data is projected to the same PCS.

Clip Layers To Study Area
To limit the data to just the study area, thereby reducing processing requirements, a series of clips are done on the datasets (Figure 10).

- The trail feature layer is clipped to the study area using a manually created polygon as the Clip Feature. This area was described previously.

- This same polygon with a 200m buffer was used to create a second polygon. The buffer polygon is then used to clip the raster layers. This is done to avoid edge effects in the data analysis. A smaller buffer would have sufficed given the slope tools used later, but 200m does not add to the processing requirements and insures there will be no issues.

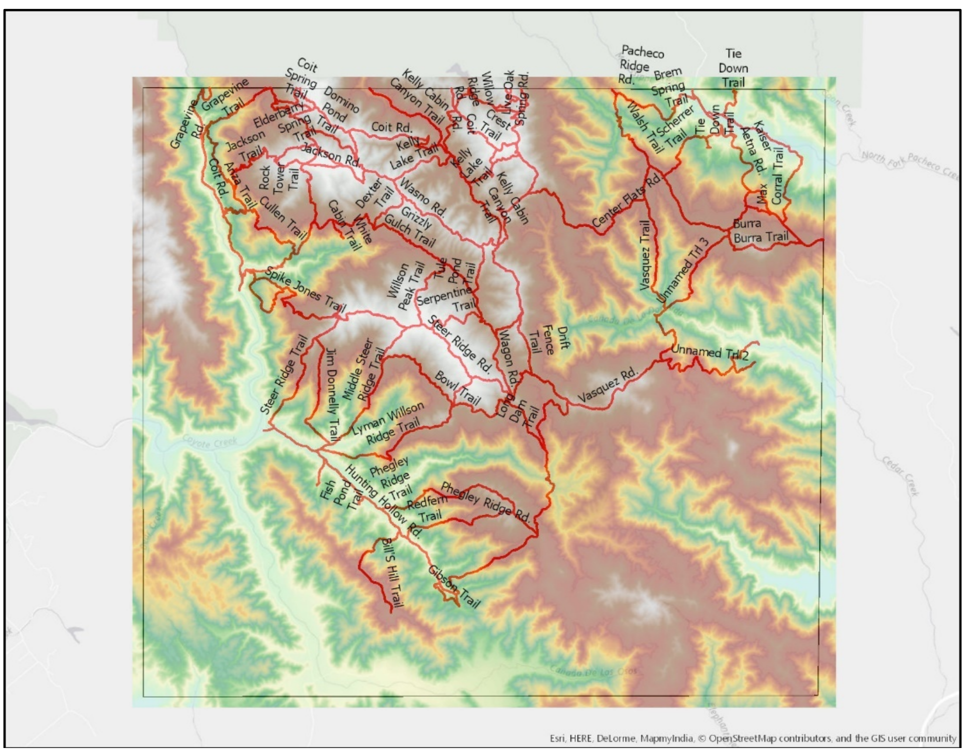

Figure 10: Data clipped to study area. The 3m DEM extends 200m beyond the study area polygon.

Trail Data Clean-up
The next major task in the process was cleanup of the trail network data. Trails in the original

vector layer were broken into 279 random segments. Some trail names were not consistent.

- Corrections were made to align the naming across segments of the same trail. The following trail name discrepancies were edited directly in the attribute table (ROUTENAME attribute). The original name is listed first and the correction second in the listing below.
    - Blue Tank Spring Rd. > Blue Tank Spring Trail
    - Crest Rd. > Crest Trail
    - Grapevine Trl > Grapevine Trail
    - Grapevine Rd. > Grapevine Trail
    - Grizzly Gulch Rd. > Grizzly Gulch Trail
    - Kelly Cabin Canyon Trl > Kelly Cabin Canyon Trail
    - Rock Tower Trl > Rock Tower Trail
    - Unnamed Trl (4 dispersed segments) > Unnamed Trail 1, 2 (two segments), and 3

- Selecting segments using the ROUTENAME attribute, the Edit > Modify Features > Merge tool was used to merge the various trail pieces into singular polylines. Each new polyline was one full trail.

- The clean-up resulted in 68 trails in the study area. A Trail_ID attribute was added to the layer. A number (1 to 68) was assigned to each of the trails. The ID numbers have no significance other than as an identifier that could be used in subsequent processing and in the analysis.

<u>Create Trail Segments</u>
The now singular trail lines were broken into segments to be used in the analysis. The break points were trail junctions and end points. A new layer was created to contain this data.

- The Feature To Line tool was used to break the trail lines into segments. The tool breaks existing lines that touch or cross. This processing resulted in 183 trial segments. The segment lengths ranged from 9.9m to 3324.0m, with a mean of 874.6m.

- A Segment_ID attribute was added to the data layer. The ID was set using the Object_ID as a sequencing key. This provided a means to associate the order of the segments within the overall trail. The Trail_ID can be used to assemble the segments and the Segment_ID retains their spatial order.

<u>Create 3m Trail Segments</u>
Another data layer was created consisting of 3 meter long segments.

- The trail segments layer created above was used as input for the Generate Points Along Lines tool. The point placement was set at 3 meters with end points included. A new output layer was created, containing 53,634 points.

- This new point layer was then used as input to the Split Line At Point tool. The input feature was the trail segments layer. The search radius parameter was set to 0.5 meters. A value of some kind was needed in this field to ensure that all the points in the dataset would be considered. (A blank entry results in only one break in the line.) The output layer contained the trails broken into 3 meter segments.

- 53,496 line segments were generated. Segment lengths were generally 3m, but given the trail segments were not always evenly divisible by 3 meters some short segments were present in the data.

- A Split_ID field was added to the layer, with the attribute being populated with the ObjectID to provide a sequence number for the segments.

<u>Add Surface Information</u>
The Add Surface Information tool was used to generate additional data for each of the layers created. Average slope, mean z value, and surface length were selected from the available options. The average slope was the only valued used, the others being generated for possible reference if needed.

The tool interpolates slope from measurements along the line, using a rook's pattern of four nearest cells. The tool uses vertices for internal segmenting of the input line features. Per the ArcGIS documentation, "Average slope is obtained by weighing each slope by its 3D length, then determining the average. This results in longer segments having greater influence on the resulting value over shorter segments." For the short 3 meter segments this is a non-issue. For the trail segment data, the weighted averaging of the slope provided a characterization of the surface that was subsequently evaluated against the 3 meter segment data in the analysis.

- Parameters used for the Add Surface Information tool
  - Input Features: The Trails_Segments and Trails_3mSegments layers
  - Input Surface: both the 3m DEM and the 9m DEM were used
  - Output property: Mean Z, Surface Length, and Average Slope (min and max for slope and elevation ignored)
  - Method: Bilinear (only option available for a DEM)
  - Sampling distance: blank
  - Z Factor: 1 (data is in meters)
  - Noise filtering: blank (all segment lengths considered)

- The tool adds fields to the layers for the indicated output properties. The tool was first run with the 3m DEM. The field names then were then changed, appending "_3m" to each new field name. Then the tool was rerun using the 9m DEM and the generated fields changed with "_9m". This provided a consolidated data table for the analysis.

Resulting fields:

- Z_Mean_3m
- Z_Mean_9m
- Avg_Slope_3m
- Avg_Slope_9m
- SLength_3m
- SLength_9m

The Z_Mean and SLength data was not needed for this analysis, but generated for potential future use.

<u>Generate Trail Data</u>

Eight calculated fields were added to the attribute tables. Alternatively, these fields could have been calculated in the subsequent Excel analysis. Centralizing the data in the geodatabase allowed for easier retrieval if needed later.

- Minutes_3m_POS
- Minutes_9m_POS
- Minutes_3m_NEG
- Minutes_3m_NEG
- SlopeDelta
- Z_Delta
- TimeDelta_POS
- TimeDelta_NEG

The four “Minutes_xxx” fields were calculated using Equation 1, with the pace elements coming from either Equation 2 for positive slope (POS fields) or Equation 3 for negative slope (NEG fields). The Avg_Slope_xx fields were used for the slope in Equation 2 and Equation 3. An example of the form of the full equation used in ArcGIS Pro is shown in Equation 4.

$$t = L * p \div 60 \tag{1}$$

Minutes Calculation

t = time in minutes

L = Length of segment in meters

p = pace at seconds per meter

$$p = 0.6 * e^{3.5*\left|\frac{S}{100}+0.05\right|} \tag{2}$$

$$p = 0.6 * e^{3.5*\left|\frac{-S}{100}+0.05\right|} \tag{3}$$

Tobler’s Hiking Function for pace

p = pace at seconds per meter

S = slope expressed as a percent of grade

(!SLength_9m! * (0.6 * math.exp(3.5 * math.fabs((!Avg_Slope_9m! / 100) + 0.05)))) / 60 (4)

ArcGIS Pro form of the minutes calculation

Analysis

The attribute data from each of the layers was exported from ArcGIS Pro and then imported into Microsoft Excel 2016 for further analysis. Summary statistics were compiled and compared across the datasets. In addition, maps were generated to display the slope characteristics of each of the trail segments.

The first data considered was simple count data of the ratings using the two DEMs and the different trail segment approaches. For the trail segments, very little variation was seen between the 3m DEM and the 9m DEM results (Table 9). The 9m DEM seemed to have a bias toward the lower end of the rating scale compared to the 3m DEM, but the shift was only 8 trail segments out of the total of 183 segments. Figure 11 shows the 3m DEM results and Figure 12 the 9m DEM results. The 8 segments that changed ratings are marked with red arrows in Figure 12.

Table 9: Ratings of Trail Segments

	Trail Segments					
	3 meter DEM		9 meter DEM		Delta (3m - 9m)	
	Count	Percent	Count	Percent	Count	Percent
Green	13	7.1%	16	8.7%	3	1.6%
Blue	58	31.7%	63	34.4%	5	2.7%
Black	62	33.9%	58	31.7%	-4	-2.2%
Double	50	27.3%	46	25.1%	-4	-2.2%

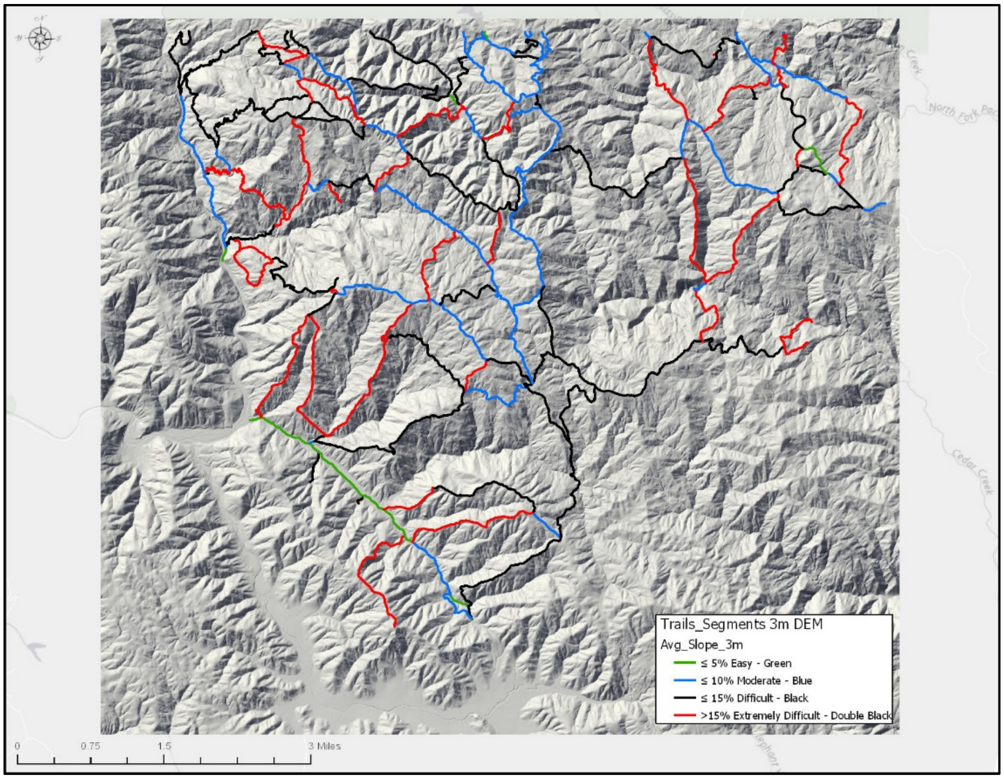

Figure 11: Trail Segments, Slope From 3m DEM.

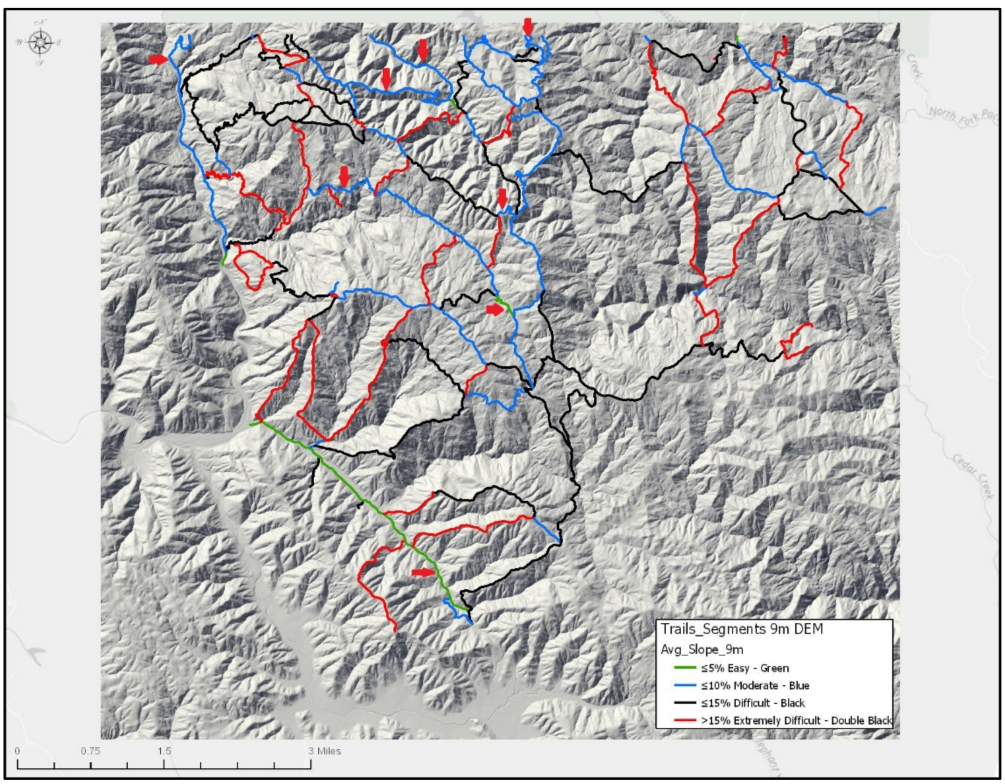

Figure 12: Trail Segments, Slope From 9m DEM. Red arrows mark rating changes from 3m DEM.

A comparison of the results from the 3 meter segmentation yielded a different mix of ratings, but again, not a significant difference between the 3m DEM and the 9m DEM (Table 10). As with the trail segmentation, there was a slight bias toward the lower ratings for the 9m DEM, with a shift of 379 segments from the highest rating into the three lowest. However, overall this was only 0.7% of the total segment population. (A complete listing of the segment rating mix by trail segment is provided in Appendix A. The rating mix by trail is provided in Appendix B.)

Figure 13 and Figure 14 illustrate the results of applying the ratings to the 3 meter segments. The segments shifts are not highlighted given the quantity and the granularity of the segment rating changes. A visual scan between the two maps indicates that the segment shifts are broadly scattered across the trail network and do not appear to correlate to the broader segment shifts seen in the trail segmentation. Figure 15 provides a close-up of a portion of the trail segment showing the segmentation effect.

Table 10: Ratings with 3 Meter Segmentation

	3 Meter Segments					
	3 meter DEM		9 meter DEM		Delta (3m - 9m)	
	Count	Percent	Count	Percent	Count	Percent
Green	13072	24.4%	13334	24.9%	262	0.5%
Blue	11981	22.4%	12041	22.5%	60	0.1%
Black	9913	18.5%	9970	18.6%	57	0.1%
Double	18530	34.6%	18151	33.9%	-379	-0.7%

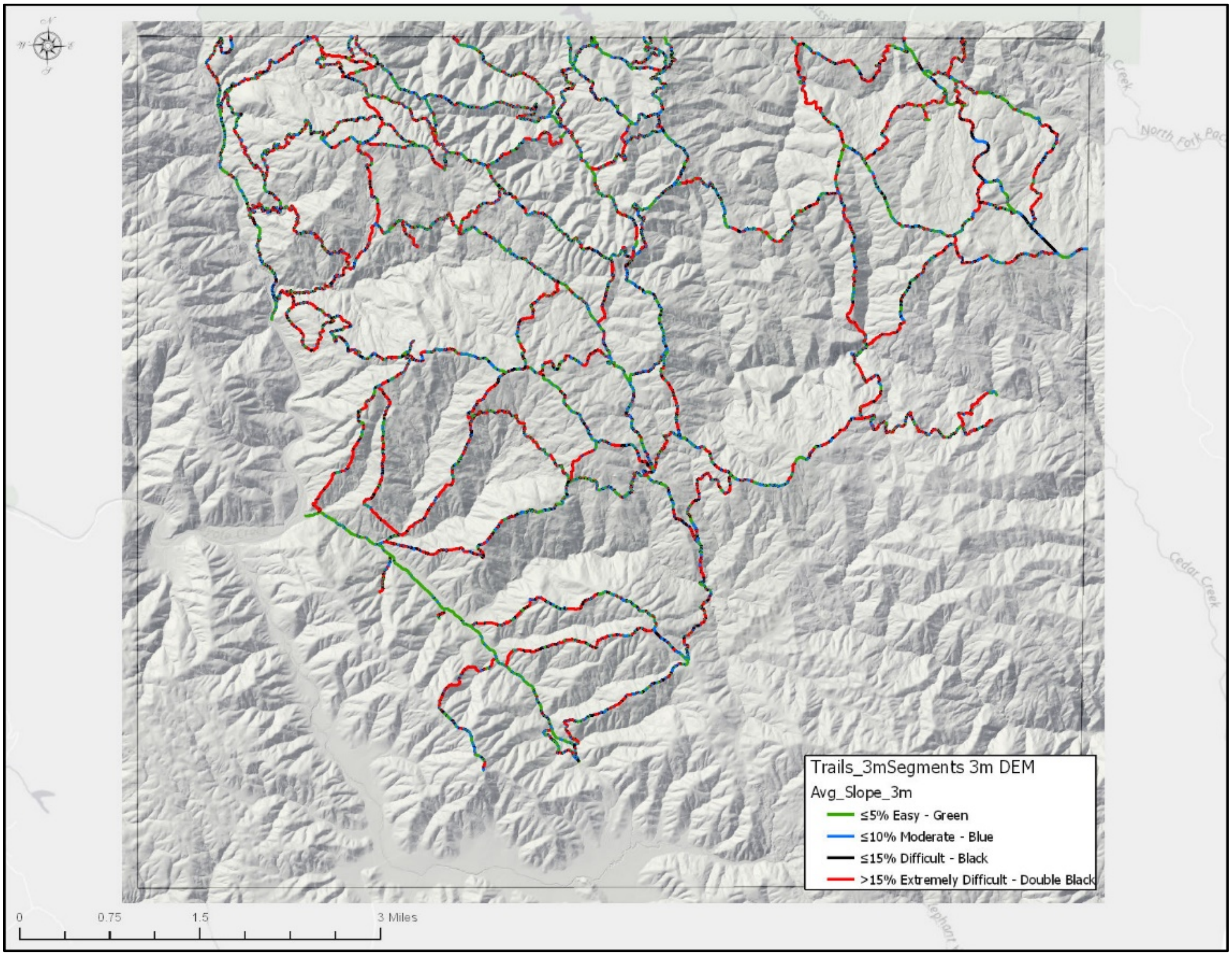

Figure 13: 3 Meter Segments, Slope From 3m DEM.

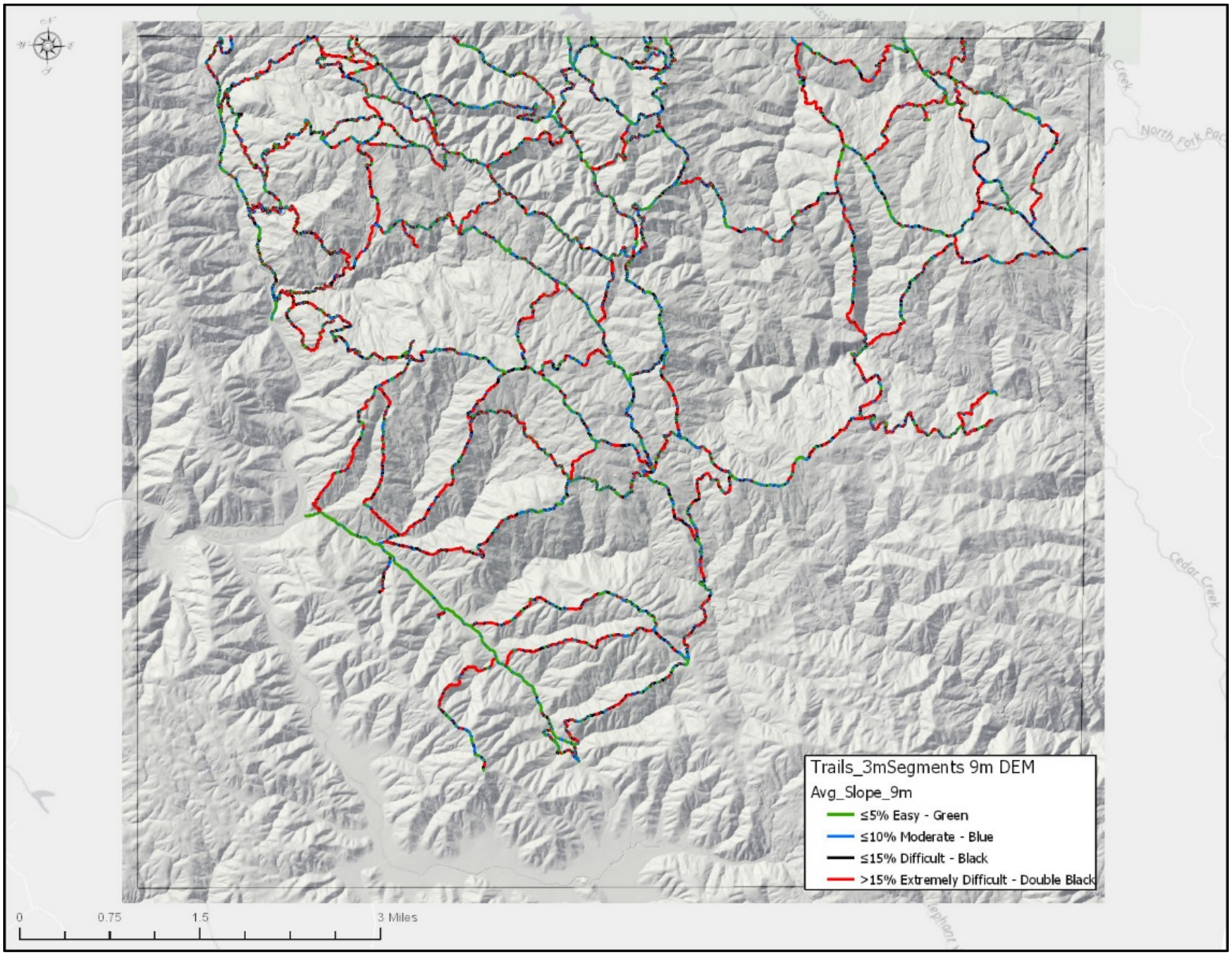

Figure 14: 3 Meter Segments, Slope From 9m DEM.

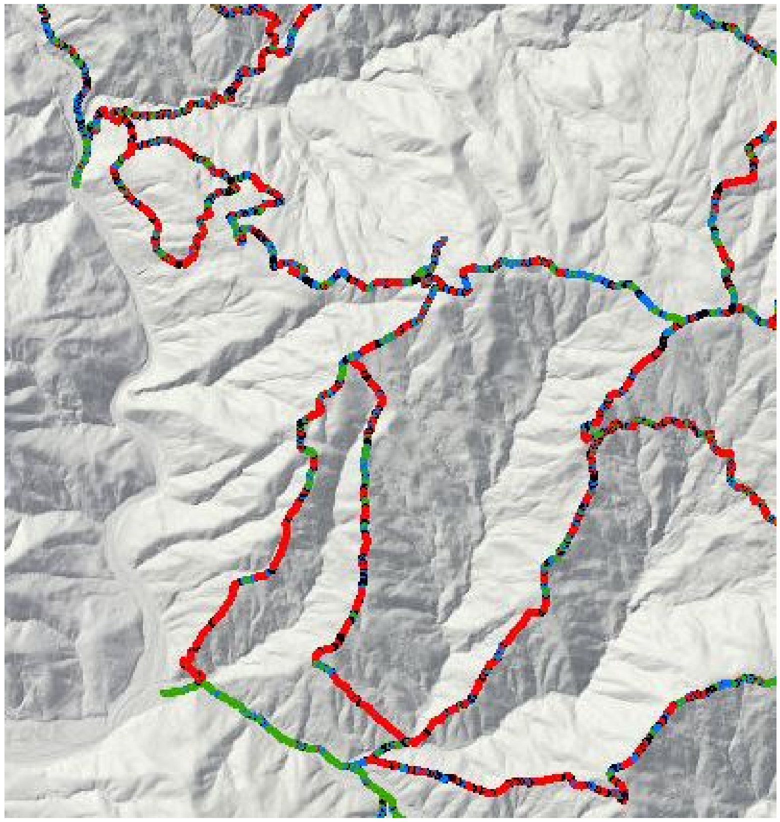

Figure 15: Close up of 3 meter segmentation

Scatter plots were generated for the slope deltas for the trail segmentation (Figure 16) and for the 3 meter segmentation (Figure 18) approaches. These deltas represent the differences between the average slopes reported for each segment for the two DEMs. Overall deltas and the R^2 between the 3m DEM and 9m DEM slopes were minimal, reinforcing the observations from the ratings above. There was one major outlier in the trail segment data. This proved to be an odd trail segment (Figure 17) that was missed in the trail segment clean-up.

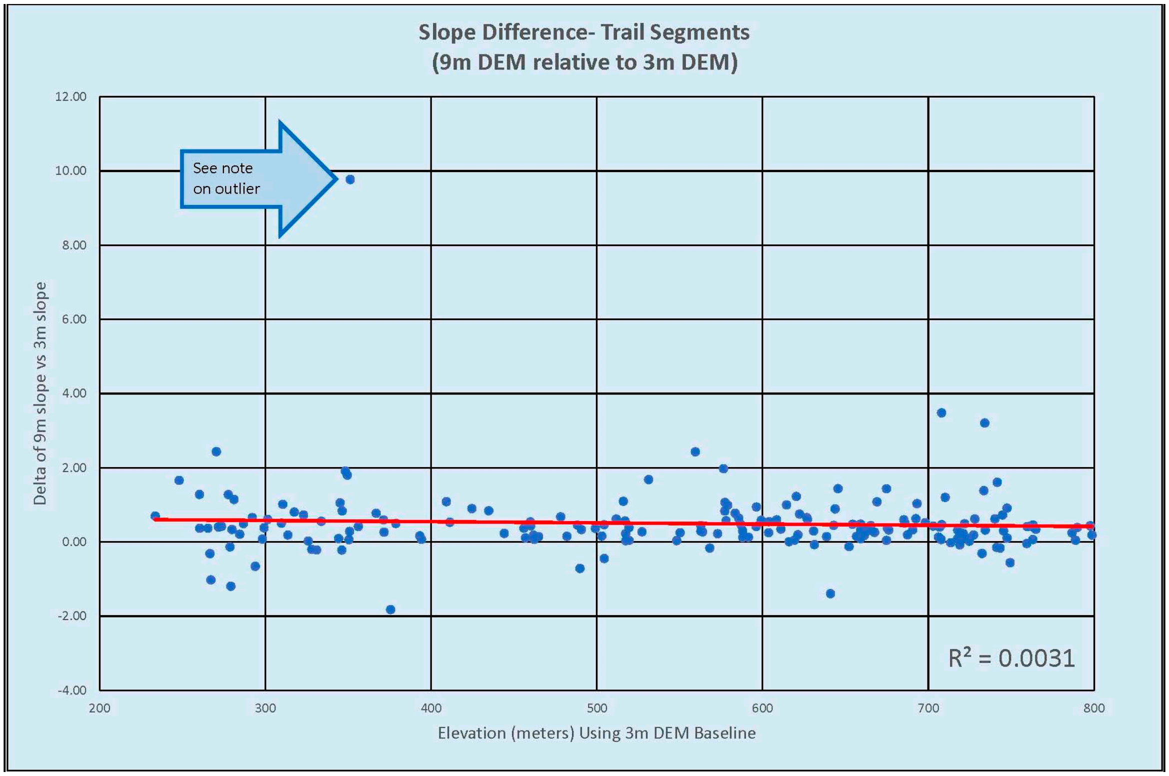

Figure 16: Scatter chart of slope delta - trail segments.

Figure 17: Trail segment anomaly.

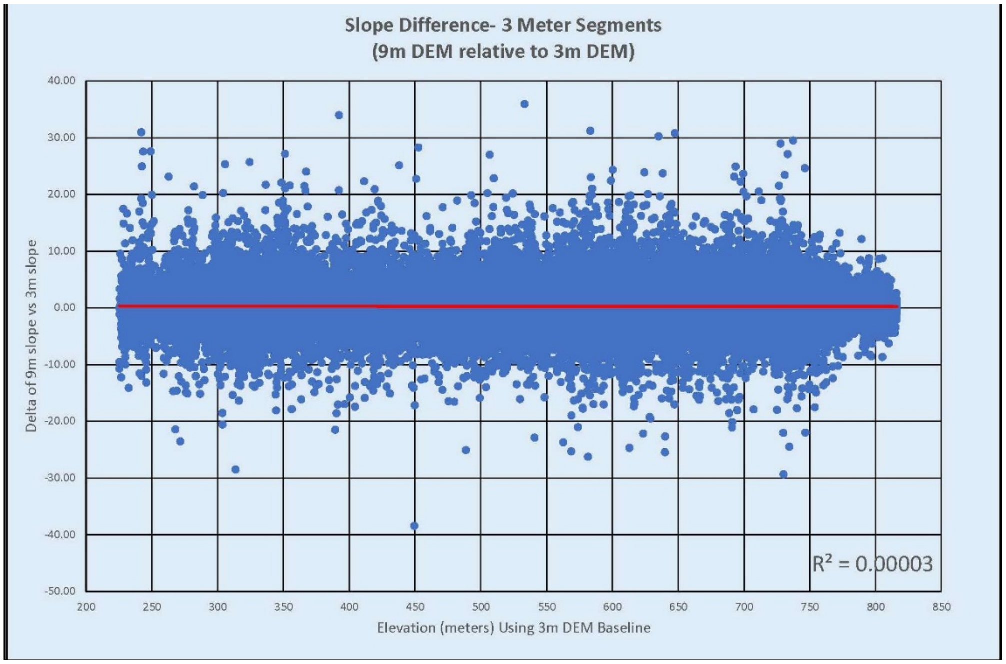

Figure 18: Scatter chart of slope delta – 3 meter segments.

Shifting focus, the next view of the data was comparing the segmentation approach within a single DEM. While the comparisons between DEMs did not yield any significant differences, changes in the segmentation approach did yield significant differences within a specific DEM. Table 11 highlights the changes within the slope rating distribution when the segmentation moves from the broad trail segment approach to the more granular 3 meter approach.

Table 11: Comparison of segmentation within each DEM.

	3m DEM	
Segments>	Trail	3m
Green	7.1%	24.4%
Blue	31.7%	22.4%
Black	33.9%	18.5%
Double	27.3%	34.6%

	9m DEM	
Segments>	Trail	3m
Green	8.7%	24.9%
Blue	34.4%	22.5%
Black	31.7%	18.6%
Double	25.1%	33.9%

To explore this further, additional segmentation approaches were generated at 5 meter and 15 meter increments. 5 meters was chosen as it is just larger than the ~4.2m diagonal of the 3m DEM. Likewise, 15 meters is slightly larger than the 12.7m diagonal of the 9m DEM. Results for the 3m DEM are shown in Table 12 and results from the 9m DEM are shown in Table 13.

Table 12: Additional segmentation approaches with 3m DEM.

	3m DEM			
Segments>	Trail	3m	5m	15m
Green	7.1%	24.4%	23.6%	19.7%
Blue	31.7%	22.4%	23.1%	26.1%
Black	33.9%	18.5%	18.9%	20.1%
Double	27.3%	34.6%	34.3%	34.0%

Table 13: Additional segmentation approaches with 9m DEM.

	9m DEM			
Segments>	Trail	3m	5m	15m
Green	8.7%	24.9%	24.6%	21.8%
Blue	34.4%	22.5%	22.9%	25.9%
Black	31.7%	18.6%	18.7%	19.5%
Double	25.1%	33.9%	33.8%	32.8%

The results between the 3m, 5m, and 15m segmentations are relatively consistent when contrasted with the broad trail segment approach. All three represent fairly concise intervals from a hiking perspective.

The next question explored was what differences, if any, in the trail segment ratings would manifest using the aggregate data from the different segmentation approaches. In other words, if one were to add up all the pieces within the 3m, 5m, and 15m segmentation and reassemble the trail segments, would there be a different view of the trail slope? The Add Surface Information tool analyzes slope and elevation data along the length of the line to generate its weighted averages, using the lengths between vertices for the weighting. The lengths are, by the nature of the trail data, random. Would the fixed distance segments show a different rating mix?

The trail segments were reassembled using the 3m, 5m, and 15m splits to create three new layers of trail segments. The mean slope of each reassembled trail segment was calculated by taking the mean of the smaller segments it was comprised of. The results are presented in Table 14 and Table 15.

Table 14: Reassembled trail segments - 3mDEM

	Orginal	3m DEM - Reassembled		
Segments>	Trail	3m	5m	15m
Green	7.1%	6.6%	7.1%	6.6%
Blue	31.7%	32.2%	30.6%	32.2%
Black	33.9%	33.9%	35.0%	33.9%
Double	27.3%	27.3%	27.3%	27.3%

Table 15: Reassembled trail segments - 9mDEM

	Orginal	9m DEM - Reassembled		
Segments>	Trail	3m	5m	15m
Green	8.7%	8.7%	8.2%	7.1%
Blue	34.4%	33.9%	34.4%	35.5%
Black	31.7%	31.7%	31.7%	31.7%
Double	25.1%	25.7%	25.7%	25.7%

Discussion and Conclusions

The expectation going into the project was there would be marked differences in the trail profiles generated by the two DEMs given their different granularity and the diverse terrain of the study area. Interestingly, the differences were minimal in that regard. Instead, the segmentation size was shown to be the more impactful factor for the slope analysis. Essentially, a manifestation of the modifiable areal unit problem (MAUP) presented itself. Tying the small segments back together into the random trail segments lengths confirmed this as the aggregate numbers realigned with the original trail segment data.

What would be the best approach for practical application to hikers exploring the region? Use the random trail segments for the ratings or the more granular approach of the 3m/5m/15m segments? The broad ratings of the trail segments are helpful, but mask significant detail in areas that have a high degree of terrain variation such as this study area. The irregularities are smoothed over. The small segmentation provides this detail, but lacks an easily comprehended overview of the trail segments.

The smaller segmentation pieces are significant and need to be considered. A look at examples from the summary data (Appendix A) illustrate this. Figure 19 and Figure 20 assemble rating data for two segments. The slope average for the overall trail segment is provided in the outside columns and is color coded for rating. The inner columns provide the count and percentage distribution of the 3 meter segments within that same trail segment.

Trail segment 166 (Figure 19) is rated as Difficult/Black given its overall average slope of ~14%. Looking at the mix of segmentation data gives a different impression of the trail profile. While ~19% of the trail is indeed at the Difficult level, over 42% of the trail is Extremely Difficult. While mathematically correct, the number of small segments in the Easy and Moderate ratings draw down the overall rating of the trail segment, masking the steeper sections.

3m DEM				9m DEM			
Avg Slope	Trail Name/Segment #/Ratings	Count	% of Count	Trail Name/Segment #/Ratings	Count	% of Count	Avg Slope
	Grapevine Trail						
14.5	166						14.1
	1-Easy/Green	76	14.4%	1-Easy/Green	76	14.4%	
	2-Moderate/Blue	125	23.8%	2-Moderate/Blue	125	23.8%	
	3-Difficult/Black	102	19.4%	3-Difficult/Black	102	19.4%	
	4-Extremely Difficult/Red	223	42.4%	4-Extremely Difficult/Red	223	42.4%	
	166 Total	526		166 Total	526		

Figure 19: Sample data - Segment 166

Trail segment 67 (Figure 20) has a similar issue. Overall its slope is 6%-7%, yielding a Moderate rating. However, nearly half the trail is actually at the Easy level. The smaller number of Difficult and Extremely difficult sections pull the rating up slightly.

3m DEM				9m DEM			
Avg Slope	Trail Name/Segment #/Ratings	Count	% of Count	Trail Name/Segment #/Ratings	Count	% of Count	Avg Slope
	Grizzly Gulch Trail						
7.0	67						6.5
	1-Easy/Green	129	48.5%	1-Easy/Green	129	48.5%	
	2-Moderate/Blue	72	27.1%	2-Moderate/Blue	72	27.1%	
	3-Difficult/Black	32	12.0%	3-Difficult/Black	32	12.0%	
	4-Extremely Difficult/Red	33	12.4%	4-Extremely Difficult/Red	33	12.4%	
	67 Total	266		67 Total	266		

Figure 20: Sample data - Segment 67

From a practical application perspective, the recommendation is to use some variation of the fixed length segmentation approach rather than the trial segment approach. The choice of segment length is subjective and would require experimentation to see which length provides the needed balance of capturing terrain variations versus readability of the resulting map.

Regarding Tobler's Hiking Function (1993), the formula was used to generate timing information on each of the trail segments per the original project scope. However, this data was not explored in the analysis. The data is useful from a hiker perspective as it provides timing for the segments. It did not add any value to the overall analysis of the slope/trail relationships. Given it is a derivative of the slope values evaluated, it was redundant.

Illustration of the Tobler data for hiking purposes could take a couple different forms. Tabular information could easily be provided for each trail segment (Table 16).

Table 16: Tobler data sample

Trail and segments	Minutes Uphill	Minutes Downhill
Anza Trail		
89	24.30	17.29
98	8.79	6.53
138	36.55	26.48
Anza Trail Total	**69.64**	**50.31**
Grizzly Gulch Trail		
50	8.74	6.88
59	9.07	6.68
67	12.48	9.53
68	19.61	14.07
69	0.26	0.18
70	6.23	4.41
78	28.94	21.60
80	20.31	14.35
82	8.50	6.31
83	19.90	14.60
Grizzly Gulch Trail Total	**134.03**	**98.61**

As suggested by a classmate, providing the information as a map overlay along with contour lines would be a visually appealing approach (Figure 21).

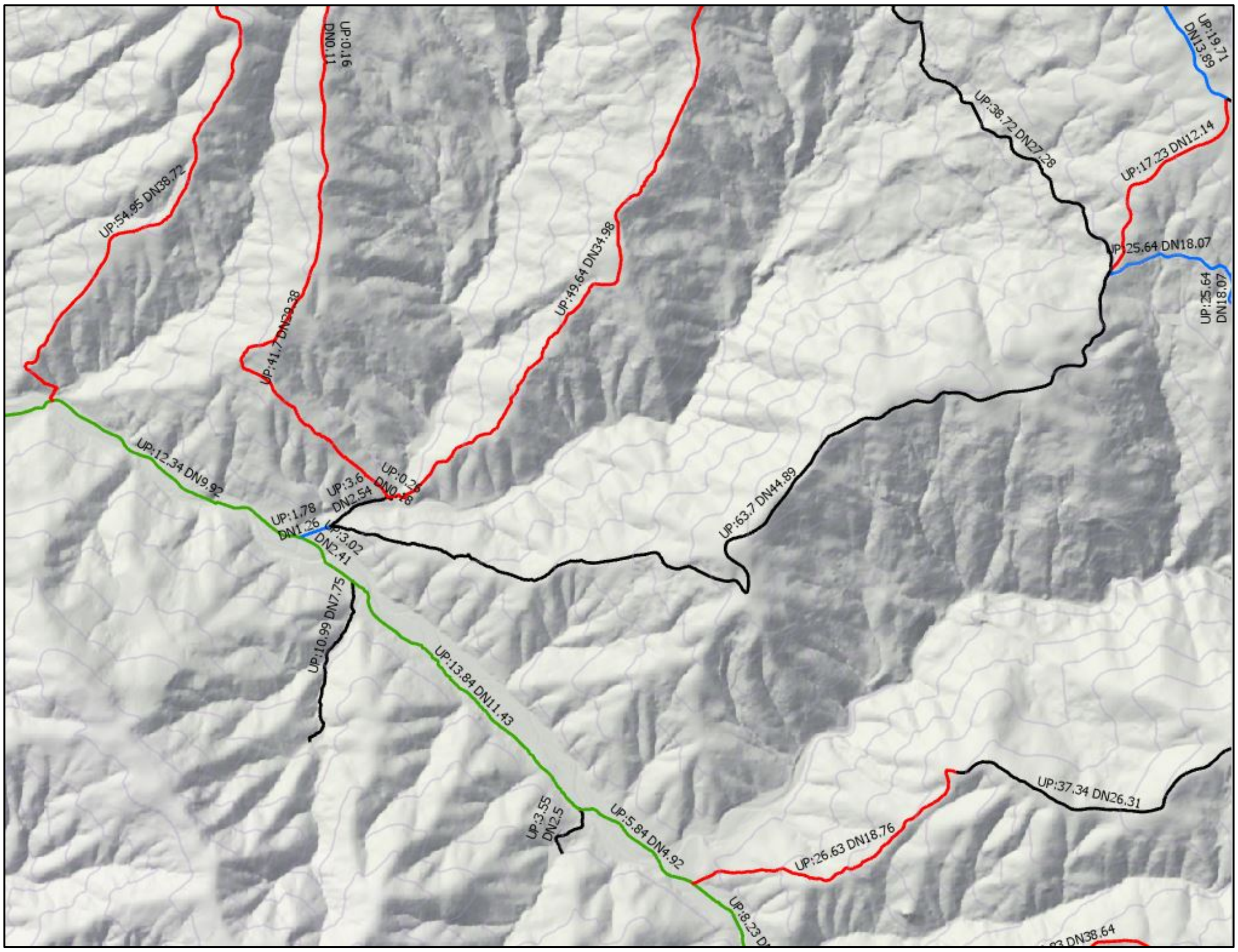

Figure 21: Timing information mock-up

The data could also be incorporated into information pop-ups in interactive maps. Assuming a production map would have naming and rating information, placing the timing and perhaps distance information in the pop-up would provide cleaner cartography.

The study was successful in generating useful hiking information on slope ratings and timing of the various trail segments in the study area. The question of suitable segmentation length is debatable, but an approach for gathering and presenting that information was devised. Regarding the DEMs resolution, differences between the 3m and 9m were not significant in this context. Only availability of the resolutions would constrain the choice as either would provide adequate results for a slope study for hiking purposes as we have seen here.

Further Study

Several areas of further study are suggested given the insights provided by this initial study.

- Factor in a 30M DEM to give a broader perspective on the DEM impact.

  The 30m DEM is a common scale used historically for slope analysis and contour generation. The early planning for this project considered using a 30m DEM with a 10m DEM, but the direction shifted when the lidar data was found. Repeating some of the analysis would potentially quantify quality gains from the finer resolution scans.

- Explore the segmentation issue further.

  What is the "right" segmentation value? Is there a particular segmentation length that provides the ideal balance between detail and practical application? Better yet, explore ways of localizing the segment lengths to the ideal given the variation in the immediate terrain. In concept, this is similar to the geographically weighted regression (GWR) methods used for regression analysis.

  One possible approach is to reclassify the 3m segments using the "nearest neighbors" concept. Look at the 2, 4, or 6 nearest line segments (1 on either side, 2 on either side, or 3 on either side of each segment). Take the mode of ratings and apply that to the segment. Using mode would aggregate the 3m segments into like terrain units, eliminating isolated "chicklet" segments in the trail segment profiles. The granularity would vary as needed across the trail network, avoiding the overall smoothing of using the full trail segments. It would also provide some smoothing of the rigid, fixed length segments.

- Least-effort paths using the Tobler data as discussed.

  The function would be a natural friction surface variable for a least-cost path analysis of the trails. Combined with an application front end, it would be an interesting tool to provide to a user community. The user could select destinations and be provided a suggested route, along with details on timing and trail profiles.

- Consider more elaborate factors in the rating system.

  The IMBA rating system includes other attributes of the trail system in its levels. It also has a more complex incorporation of scope, covering not only the average slope, but maximums as well. The slope maximums for the line segments could be incorporated into a better mix of criteria for the line segments.

References

Bowker, James M. 2012. *Outdoor recreation participation in the United States -- projections to 2060: a technical document supporting the Forest Service 2010 RPA assessment*. Asheville, NC: U.S. Dept. of Agriculture, Forest Service, Southern Research Station.

Chiou, Chyi-Rong, Wei-Lun Tsai, and Yu-Fai Leung. 2010. "A GIS-Dynamic Segmentation Approach to Planning Travel Routes on Forest Trail Networks in Central Taiwan." *Landscape and Urban Planning* 97 (4): 221-228. doi:10.1016/j.landurbplan.2010.06.004. http://www.sciencedirect.com.libproxy2.usc.edu/science/article/pii/S0169204610001301.

Cordell, H. Ken, Carter J. Betz, And Gary T. Green. 2008. "Nature-based Outdoor Recreation Trends and Wilderness." *International Journal of Wilderness* 14, no. 2 (2008).

IMBA (International Mountain Bicycling Association). "TRAIL DIFFICULTY RATINGS AND SIGNS." Website accessed November 3, 2017. https://www.imba.com/resources/maps/trail-difficulty-ratings.

Mitchell, Andy. 2012. *The ESRI Guide to GIS analysis. 3, 3*. Redlands, Calif: ESRI.

Naismith, W. W. 1892. "Excursions. Cruach Ardran, Stobinian, and Ben More". *Scottish Mountaineering Club Journal*. Scottish Mountaineering Club. 2 (3): 136. http://gdl.cdlr.strath.ac.uk/smcj/smcj009/smcj0090603.htm.

Pine Ridge Association. 2017. "Henry W. Coe State Park." Accessed 28-Aug-2017. http://coepark.net/pineridgeassociation/.

Ryan, Michael. 2015. "SKI SLOPE RATING SYMBOLS: WHAT THEY MEAN AND WHAT THEY REALLY MEAN." *Outdoor Tech*. February 4, 2015. Accessed November 3, 2017. https://news.outdoortechnology.com/2015/02/04/ski-slope-rating-symbols-mean-really-mean/.

Sierra Club. "GLS Hike Ratings." Website accessed November 3, 2017. https://www.sierraclub.org/loma-prieta/gls-hike-ratings.

Tobler, Waldo R. 1993. *Three presentations on geographical analysis and modeling: non-isotropic geographic modeling, speculations on the geometry of geography and, global spatial analysis*. Santa Barbara, CA: National Center for Geographic Information and Analysis.

Wikipedia contributors. "Piste." *Wikipedia, The Free Encyclopedia*. Accessed November 3, 2017. https://en.wikipedia.org/w/index.php?title=Piste&oldid=785832003.

Wimpey, Jeremy and Jeffrey L. Marion. 2011. "A Spatial Exploration of Informal Trail Networks within Great Falls Park, VA." *Journal of Environmental Management* 92 (3):

1012-1022. doi://doi-org.libproxy1.usc.edu/10.1016/j.jenvman.2010.11.015. http://www.sciencedirect.com.libproxy1.usc.edu/science/article/pii/S0301479710004184.

Zeiler, Michael, and Jonathan Murphy. 2010. *Modeling our world: the ESRI guide to geodatabase design*. Redlands, California: ESRI Press.

Datasets

California State Park System Map. Accessed 28-Aug-2017. https://www.parks.ca.gov/?page_id=862.

USGS 3DEP (USGS 3D Elevation Program). Accessed 1-Sept-2017. https://nationalmap.gov/3DEP/3dep_prodserv.html.

Appendix A and B provided in separate documentation

Appendix A: 3 METER TRAIL SPLIT – RATING BREAKDOWN BY TRAIL SEGMENT

Appendix B: 3 METER TRAIL SPLIT – RATING BREAKDOWN BY TRAIL