Possible Climbing Places in the Yosemite Valley, determined using LiDAR

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ABSTRACT

Yosemite Valley glacially carved canyon hosts unique vertical geologic resources, like granitic domes, monoliths, spires, and cliffs. El Capitan (1000m tall), Yosemite Falls or Half Dome attract climbers and tourists from all over the world, Camp 4 is regarded as the birthplace of modern rock climbing. There have been numerous studies in the area, regarding rock fall hazards, landslides, and there is a map of the approximate climbing areas, but there were no public maps of the climbing walls. A map of the climbing walls would be useful for climbers to better understand the climbing environment and visualize the routes vicinity.

This project is an attempt to delineate the Yosemite climbing walls by creating a high resolution Digital Terrain Model (0.5m), from light detection and ranging data (LiDAR) captured using Airborne scanning. The resolution is a crucial factor in the analysis, lower resolution data would result in smaller walls lengths and less steep slopes, because the values would be interpolated. From the 3D model, we derive raster image files and extract the climbing walls: outline the morphologic characteristics of the ground surface (slope), identify the areas with steep slope above 75° and create a cluster of similar zones using raster image generalization algorithms. Also, we determine the wall length using a flow direction algorithm to obtain the main flow lines that cross a wall, and calculating the difference in elevation for each. With the slope and length data, we classify the climbing walls by steepness and length, for example from yellow to red (> 45° and > 100m difference in elevation, > 75° and > 900m difference in elevation). There is an extra suitability analysis in which we overlay subjective criteria (distance to roads, rivers, springs, parking) to find out the best climbing place.

There are still many methods to refine the analysis results and define the climbing walls or to obtain the wall length, correlated with on-site analysis. The project does not analyze the climbing walls in detail, because there is a lack of data from the 'shadow' effect that occurs when data is being collected from above the cliffs and overhangs (LiDAR data from the ground, or high resolution photos would be more useful for this kind of analysis). However, the overall result gives a better overview on the existing climbing areas and highlights possible new climbing areas, proving that LiDAR is a valuable resource that can be used with success to examine the surface morphology.

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INTRODUCTION

Yosemite Valley

Yosemite National Park is located within the heart of the Sierra Nevada, the largest fault-block mountain range in the United States. Trending northwest–southeast for more than 480 km (300 mi), the Sierra Nevada traverses half the length of California. Comprised of granitic rocks that formed approximately 100 million years ago, the massive block forms an asymmetrical mountain range with a gentle western slope and an eastern edge that rises abruptly from adjacent desert basins, forming a nearly vertical wall of rock.

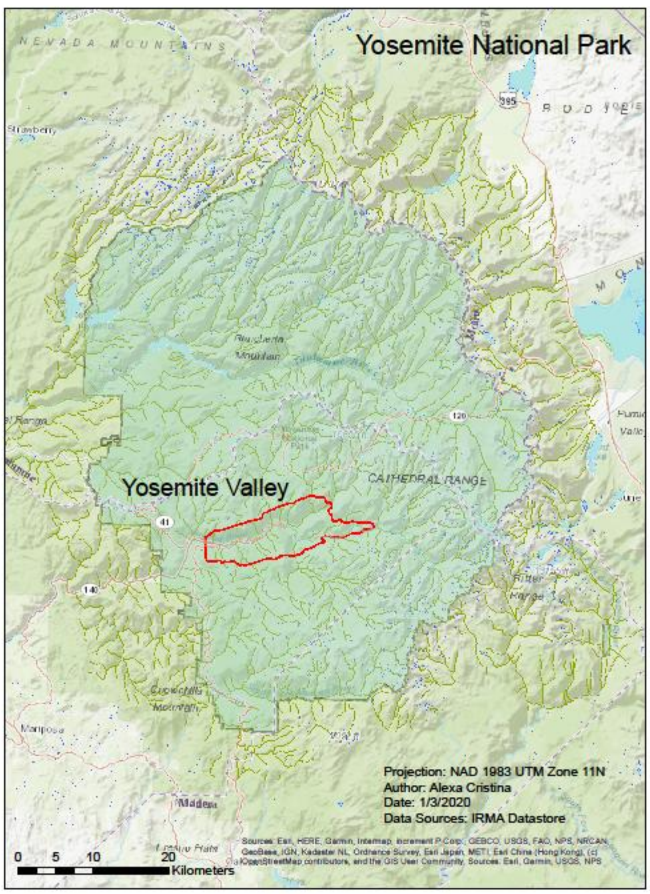


Figure 1. Yosemite National Park

Yosemite Valley is a ~1-km-deep, glacially carved canyon in the Sierra Nevada mountains of California that hosts some of the largest granitic rock faces in the world, as shown in Figure 1. El Capitan is a ~1-km-tall, vertical southeast face, that making it the tallest single face in North America, Yosemite Falls is the tallest waterfall in United States, Camp 4 is regarded as the birthplace of modern rock climbing. (Geologic resources inventory report, 2012)

Here, Quaternary glaciation, river erosion, and ongoing rockfall have produced a steep-sided valley with over 1 km of local relief.

The vertical northwest cliff face of Half Dome is 680 m tall, and continuous exposure from the top of Half Dome to Tenaya Creek covers 1340 vertical meters at an average angle of 51°. This entire section is sculpted in one pluton, the Half Dome Granodiorite (Calkins, 1985). El Capitan exposes a 1-km vertical section of plutonic rocks (Calkins, 1985; Peck, 2002) in a massive cliff that is locally overhanging but is typically steeper than 75°.

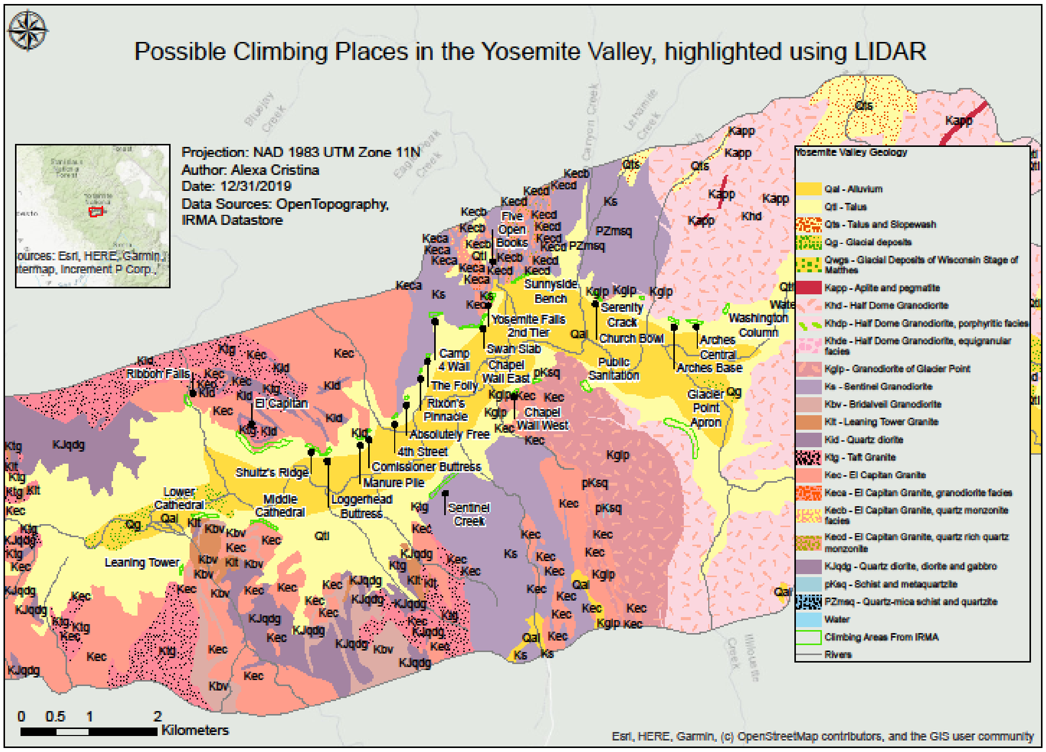


Figure 2. Yosemite Valley Geologic Units

Of the three main categories of rock (igneous, sedimentary, and metamorphic), igneous rocks are most common at Yosemite National Park, including the granitic salt-and-pepper-colored rocks that form such features as Half Dome, El Capitan, and the cliffs of Yosemite Valley. The park's granitic rocks can be classified more specifically as granite, granodiorite, and tonalite, as shown in Figure 2.

LiDAR and Climbing Walls

The primary purpose of this study is to illustrate and describe how to identify the climbing walls in Yosemite Valley using **light detection and ranging (LiDAR) point clouds**, and determine the best places for climbing using specific criteria.

LiDAR is a remote sensing technique that uses visible or near-infrared laser energy to measure the distance between a sensor and an object. LiDAR sensors are versatile and (often) mobile; they help autonomous cars avoid obstacles and make detailed topographic measurements from space. (PDAL Contributors, 2018).

There have been other studies involving LiDAR in the area, with the focus on rock falls, geology and landslides, for example:

- Plutonism in three dimensions: Field and geochemical relations on the southeast face of El Capitan, Yosemite National Park, California
- Use of LiDAR in landslide investigations: A review
- Assessing rockfall susceptibility in steep and overhanging slopes using three-dimensional analysis of failure mechanisms

Rockfall monitoring and research is ongoing in Yosemite National Park. In 2008, the park partnered with Los Angeles–based xRez Studio to create the Yosemite Panoramic Imaging Project, which enables imagery-based rockfall monitoring in Yosemite Valley (National Park Service 2009b). The project created a 3.8-gigapixel photographic map of Yosemite Valley by combining gigapixel panoramic photography with LiDAR-based digital terrain modeling and 3-D computer rendering to capture Yosemite Valley in a single image. The image allows resource managers to examine the cliffs in detail without climbing them. (Geologic resources inventory report, 2012)

Photographs taken by climbers on the southeast face presented the means to study vertical changes in rock texture. Using the Exelis ENVI image processing package, mineral types were classified using simple quantitative thresholds in pixel value for 78 photographs taken over much of the extent of the El Capitan Granite. (Putnam et al. 2015)

Airborne and terrestrial LiDAR, high-resolution photography, and acoustic data were used to help analyze the initiation, dynamics, and talus deposition of the complex rockfall occurring at Ahwiyah Point on March 28, 2009 (Zimmer et al. 2012). LiDAR data accurately determined the volume and dimensions of the detached block, the orientation of fractures bounding the block, the size and dip of the ramp, the vertical ballistic distance, the mid-cliff distance, and the volume of material dislodged from the mid-cliff impact.

In our study, 3D point clouds are processed into a DTM (Digital terrain Model), then a set of conditions is applied to a slope raster image in order to derive possible climbing walls, as shown in Figure 3. A digital elevation model (DEM) is a 3D CG representation of a terrain's surface – commonly of a planet (e.g. Earth), moon, or asteroid – created from a terrain's elevation data.

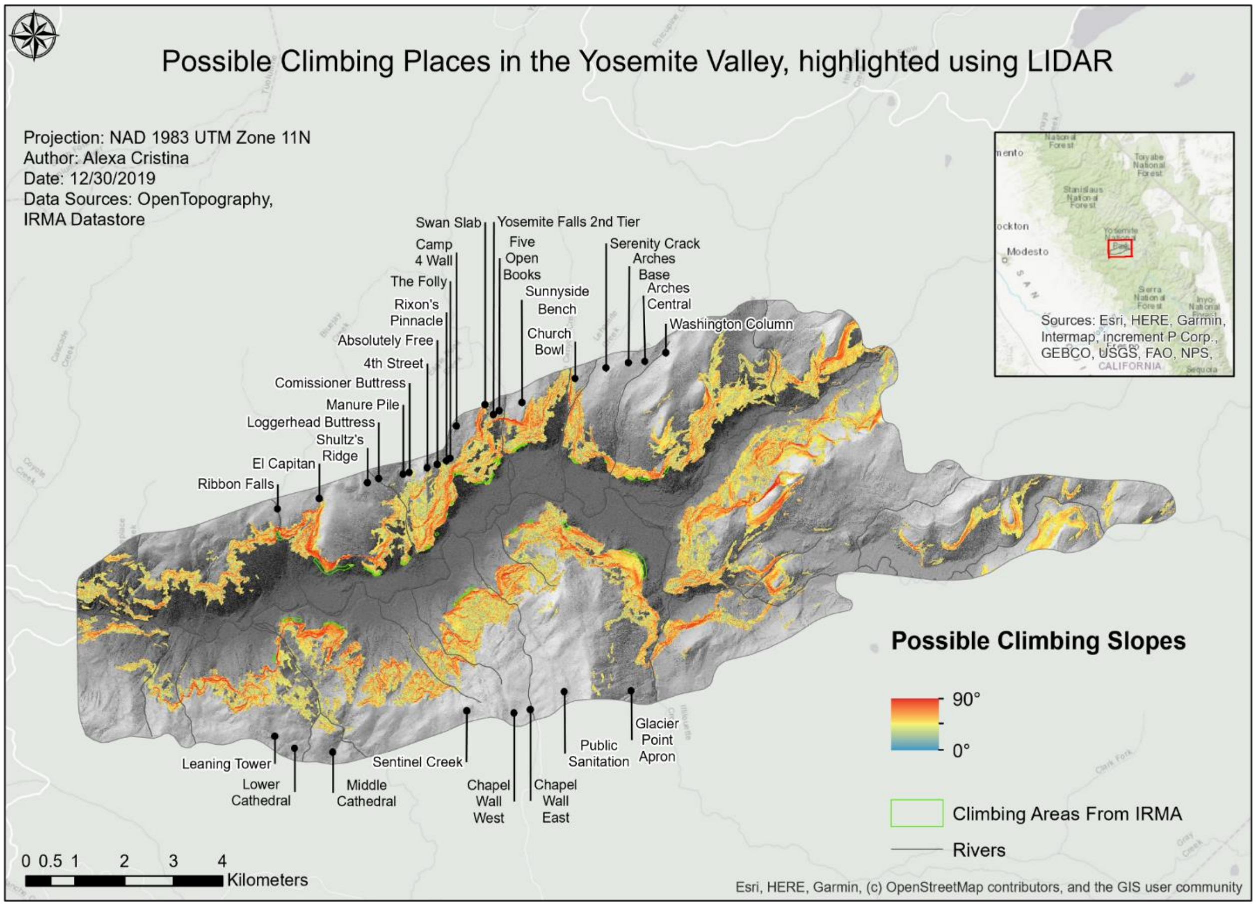


Figure 3. Possible Climbing Slopes in Yosemite Valley, highlighted using data collected by airborne LiDAR scanners

DEMs are used often in geographic information systems, and are the most common basis for digitally produced relief maps. While a digital surface model (DSM) may be useful for landscape modeling, city modeling and visualization applications, a digital terrain model (DTM) is often required for flood or drainage modeling, land-use studies, geological applications, and other applications, and in planetary science.

Rock Climbing Related Features and Climbing Zones List

Rock climbers flock to Yosemite National Park to explore the vertical wilderness created by the granitic domes, monoliths, spires, and cliffs.

At 1,000 m (3,300 ft) high, the nearly vertical *El Capitan* is one of the most popular and challenging climbs in the world (Glazner and Stock 2010), as shown in Figure 4 and Figure 5. El Capitan is opposite Bridalveil Fall.

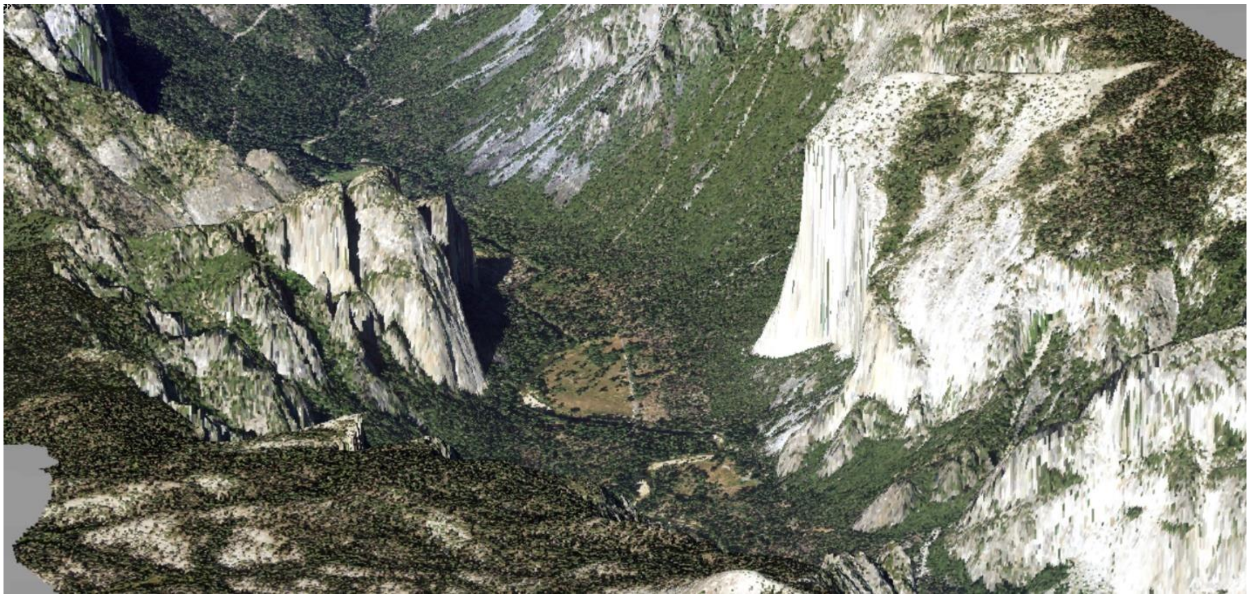


Figure 4. Cathedral Rocks and el Capitan ArcScene 3D

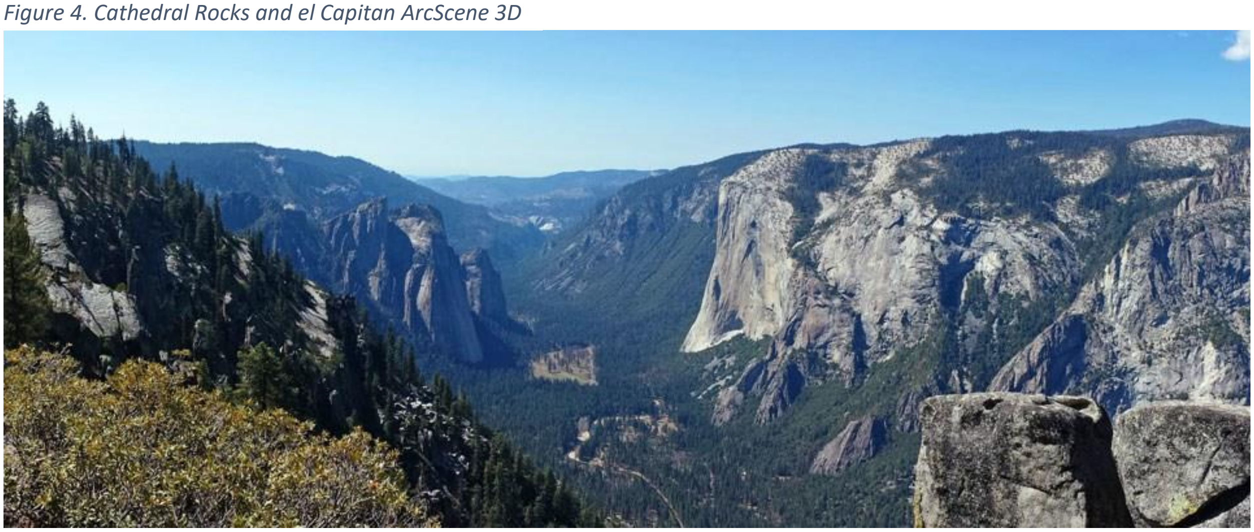


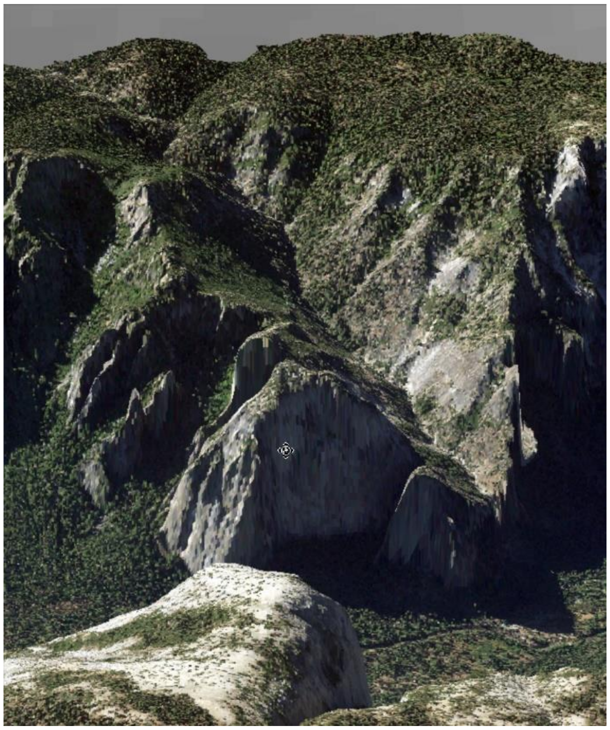
Figure 5. Cathedral Rocks and el Capitan nps.gov/yose/planyourvisit/formations.htm

Cathedral Rocks and *Spires* form the eastern side of the canyon through which Bridalveil Creek flows, as shown in Figure 6 and Figure 7.

The *Three Brothers* are located just east of El Capitan. It is made up of Eagle Peak (the uppermost "brother"), and Middle and Lower Brothers.

Sentinel Rock, like a sentry, overlooks Yosemite Valley, along the opposite side of the Valley From Yosemite Falls.

Glacier Point is most famous for the view you can see from it, but the Glacier Point cliff itself is quite impressive. (Rock Formations in Yosemite Valley, 2012)



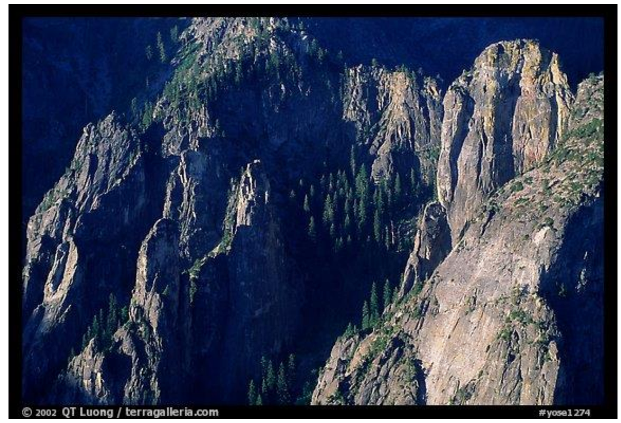


Figure 7. Cathedral Rocks seen from top of El Capitan, terragalleria.com by QT Luong

Figure 6. Cathedral Rocks seen from above El Capitan, ArcScene 3D

Half Dome rises 1,443 m (4,733 ft) from the valley floor, being the most recognized symbol of Yosemite, as shown in Figure 8 and Figure 9. (Geologic resources inventory report, 2012)

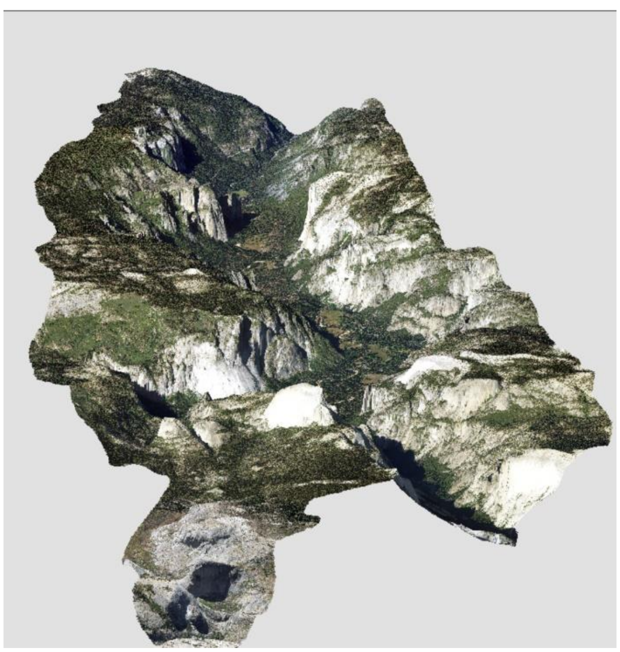


Figure 8. Yosemite Valley ArcScene 3D view from The Dome

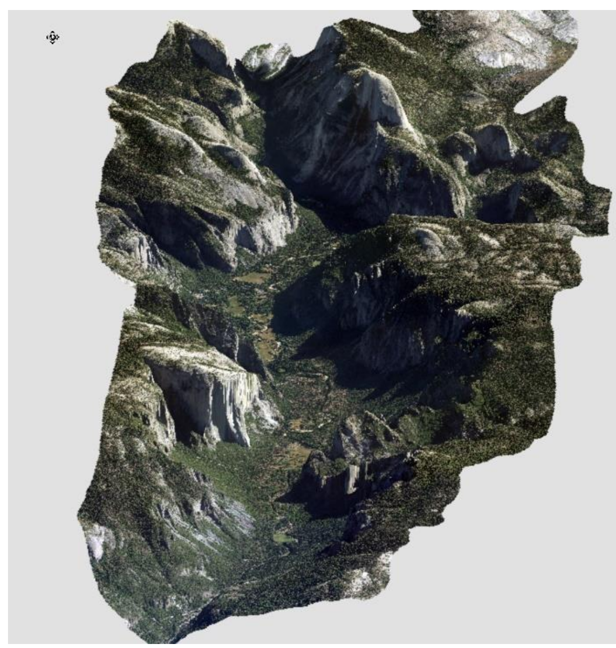


Figure 9. Yosemite Valley ArcScene 3D view from El Capitan

Table 1 shows the existing list of climbing areas in Yosemite Valley, clipped from a layer for all Yosemite National Park, taken from IRMA datastore. Added latitude and longitude.

The layer represents the staging or base areas at some popular climbing spots in Yosemite Valley. These polygons represent the rough human impact areas due to climbing activites at those crags. Many more climbing staging areas than these exist both within Yosemite Valley and elsewhere throughout the park.

Table 1. Climbing areas list for Yosemite National Park, filtered for Yosemite Valley, taken from IRMA Datastore

OI[	OB.	ID	NAME	Shape_Leng	Shape_Area	Lat	Lon
0	1	1	Ribbon Falls	460.083704	11183.39	37.73455806	-119.6481881
1	2	2	El Capitan	2020.60093	60082.885	37.7291523	-119.6356163
2	3	3	Shultz's Ridge	496.751213	7104.6844	37.72900848	-119.6271404
3	4	4	Loggerhead Buttress	477.416263	5926.3763	37.7283677	-119.6248642
4	5	5	Manure Pile	338.687917	4113.6615	37.73043537	-119.6191883
5	6	6	Comissioner Buttress	160.50218	1830.527	37.73137869	-119.6177708
6	7	7	4th Street	282.98854	3783.0993	37.73333668	-119.6135447
7	8	8	Absolutely Free	195.421176	2546.5109	37.73575651	-119.6116199
8	9	9	Rixon's Pinnacle	165.827432	1353.1618	37.73931039	-119.6094555
9	10	10	The Folly	156.945793	1609.1083	37.74137512	-119.6082849
10	11	11	Camp 4 Wall	460.443216	7743.5957	37.74667842	-119.6073737
11	12	12	Swan Slab	1056.08786	13607.318	37.74555864	-119.6006414
12	13	13	Five Open Books	337.447942	3728.1068	37.7490719	-119.5977179
13	14	14	Yosemite Falls 2nd Tier	291.357249	3372.1707	37.74926671	-119.5985185
14	15	15	Sunnyside Bench	751.699255	7519.717	37.75168965	-119.5931959
15	16	16	Church Bowl	383.788294	4309.8176	37.74956142	-119.5803116
16	17	17	Serenity Crack	172.541456	2052.9134	37.74959316	-119.5729988
17	18	18	Arches Base	392.285149	6071.2447	37.74676083	-119.5675683
18	19	19	Arches Central	532.757736	7653.0027	37.74666379	-119.5640411
19	20	20	Washington Column	343.606754	5697.2831	37.74838037	-119.5588985
20	21	21	Glacier Point Apron	1734.16791	59107.841	37.73211108	-119.5651531
21	22	22	Public Sanitation	495.660348	13637.378	37.73789492	-119.5818593
22	23	23	Chapel Wall East	311.120322	4932.8621	37.73849798	-119.5901485
23	24	24	Chapel Wall West	356.268811	4260.8325	37.73676799	-119.593745
24	25	25	Sentinel Creek	1232.15338	22601.835	37.7247397	-119.605202
25	26	26	Middle Cathedral	980.444979	16592.435	37.71899101	-119.6348385
26	27	27	Lower Cathedral	896.586985	19214.05	37.71974128	-119.6447216
27	28	28	Leaning Tower	320.300569	4106.6273	37.71269902	-119.6484384

The following smaller-scale geologic features render these seemingly insurmountable, sheer structures climbable (Glazner and Stock 2010): splitter cracks, flakes, dihedrals, dikes, chickenheads, megacrysts, slabs, boulders.

Splitter cracks

Splitter cracks are long cracks in granite faces that maintain remarkably uniform widths. The cracks form primarily due to. Using a technique appropriately called jamming, climbers jam their hands and feet into the cracks. Classic splitter climbs in Yosemite include “The Grack” below Glacier Point, shown in Figure 10 and Figure 11, “Reed’s Pinnacle Direct” above the Big Oak Flat Road, and “Sons of Yesterday” near Royal Arches beneath North Dome, shown in Figure 12 and Figure 13. (Glazner and Stock 2010)

Figure 10. Glacier Point Apron ArcScene 3D

Figure 11. Glacier Point Apron thecrag.com

Figure 12. North Dome

Figure 13. North Dome supertopo.com by holdenhh

Flakes

Exfoliation also produces flakes, slabs of rock that remain temporarily attached to the cliff and may spall off at any time. Using a technique called laybacking, climbers grasp the edge of a flake, place their feet high on the cliff, lean out, and climb hand over hand up the flake. Examples of flake climbs in Yosemite include “Wheat Thin” on Cookie Cliff and “Hermaphrodite Flake” on Stately Pleasure Dome above Tenaya Lake. “Boot Flake” and “Texas Flake” are two impressively large flakes on the Nose Route of El Capitan, shown in Figure 14 and Figure 15 (Glazner and Stock 2010).

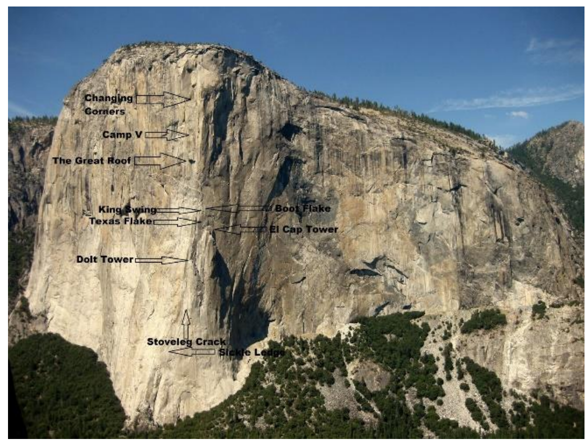


Figure 15. The Nose vividrea1ity.blogspot.com

Figure 14. The Nose ArcScene 3D

Dihedrals

When a slab of rock falls, a dihedral angle forms where the two adjacent walls on the fresh surface meet, which climbers call an open book.

The exfoliation joint that was behind the slab before it fell is usually exposed at the corner of a dihedral, and climbers ascend along the crack by bridging (placing one hand and one foot on each face), jamming, or laybacking.

Popular dihedral climbing routes are found at “Five Open Books,” west of Lower Yosemite Fall, shown in Figure 16 and Figure 17, and “Great White Book” adjacent to Tenaya Lake (Glazner and Stock 2010).

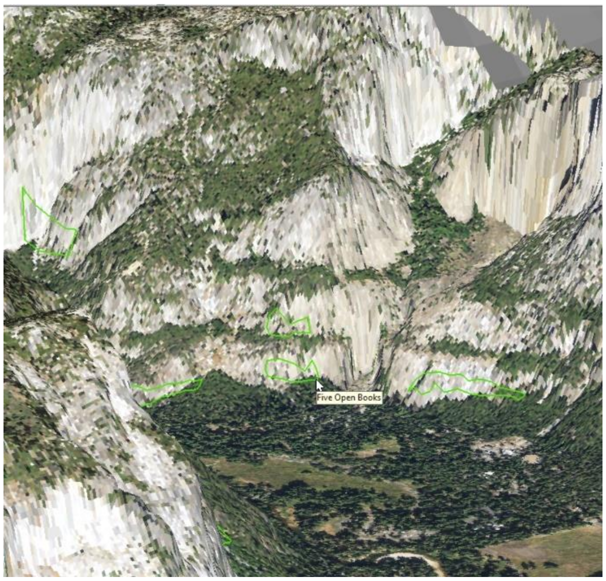


Figure 17. Five Open Books mountainproject.com by M. Morley

Figure 16. Five Open Books ArcScene 3D

Dikes

Igneous dikes, common in Yosemite's granitic rocks, form linear bands that are roughly 0.3 thick. On the east face of El Capitan, dikes of dark, fine-grained diorite cut across El Capitan Granite. Dikes and irregular masses of diorite also intrude Taft Granite. Because they are more resistant to weathering and erosion, dikes often protrude from the surrounding granite. Dike climbing can be dangerous because these features are not associated with cracks. Climbers' only protection is provided by drilling bolts into the rock, which is permitted in Yosemite National Park if done by hand. Examples of dike climbs in Yosemite include "Snake Dike" on the southwest face of Half Dome, shown in Figure 18 and Figure 19 (Glazner and Stock 2010).

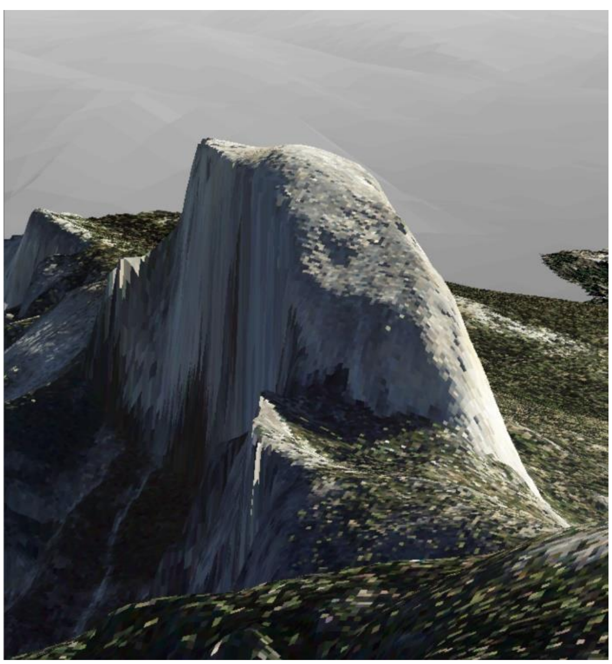


Figure 19. Southwest Half Dome halfaya.org

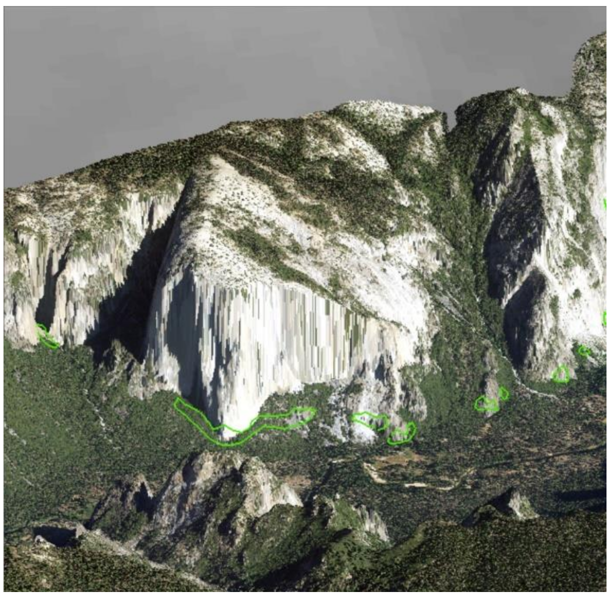
Figure 18. Southwest Half Dome ArcScene 3D

Chickenheads

Like dikes, enclaves in the El Capitan Granite are often more resistant to erosion and weathering and protrude from the surrounding rock.

Climbers use these dark blobs, referred to as chickenheads, as handholds and footholds.

Chickenhead climbs in Yosemite can be found along the western exposures of the El Capitan Granite, shown in Figure 20 and Figure 21, and include “Sloth Wall,” “Boneheads,” and “Fun Terminal” in Merced Gorge (Glazner and Stock 2010).



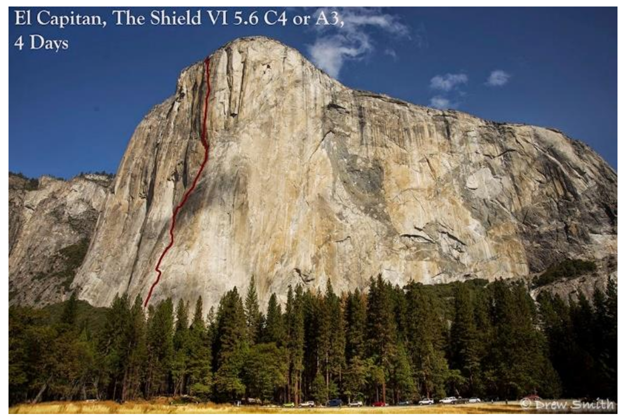


Figure 21. Chickenhead Ledge, The Shield, El Capitan drewsplan.blogspot.com

Figure 20. Chickenhead Ledge, The Shield, El Capitan ArcScene 3D

Slabs

The expansive, sloping slab of rock below Glacier Point, known as the Glacier Point Apron, is a popular slab climbing location in Yosemite National Park.

When the glacier retreated from Yosemite Valley following the end of the Tioga glaciation, it left behind this smooth, low-angled slab of rock, which forms the lower portion of the characteristic, glacially-carved U-shaped profile. In slab climbing, climbers rely on their body weight (and sticky rubber soles on climbing shoes) to keep them anchored to the rock. Because cracks are rare in slabs, climbers use bolts as in dike climbing.

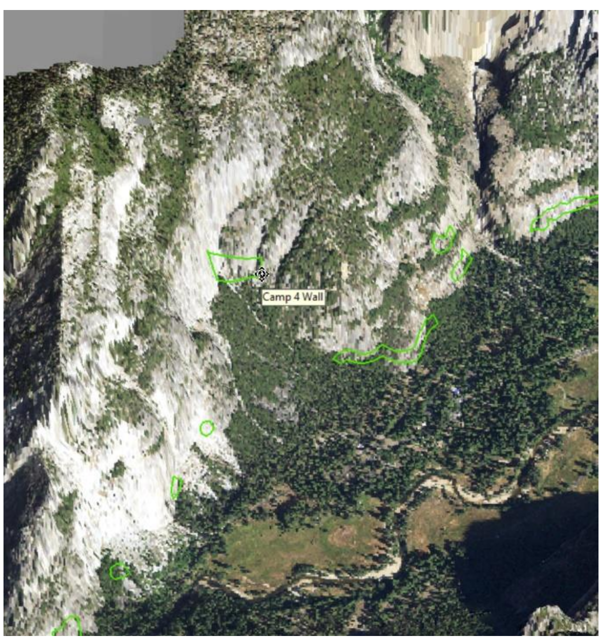
Unique climbing challenges can also be found on the other aprons in Yosemite National Park. Popular slab climbs on the Glacier Point Apron include “Marginal,” “Goodrich Pinnacle”, shown in Figure 22 and Figure 23, and “The Cow” (Glazner and Stock 2010).

Figure 23. Goodrich Pinnacle, Glacier Point Apron gearlooptopo.com

Figure 22. Goodrich Pinnacle, Glacier Point Apron ArcScene 3D

Boulders

Rockfalls in Yosemite National Park provide an excellent opportunity to pursue the sport of bouldering, the freeclimbing of boulders, rather than cliff faces, without the use of ropes or other gear. Large boulders, some the size of small buildings, have come to rest on the valley floor after travelling long distances from cliff bases during a rockfall.Perhaps the most famous bouldering route in the world is on the Columbia Boulder in the middle of Camp 4, shown in Figure 24 and Figure 25 (Glazner and Stock 2010).



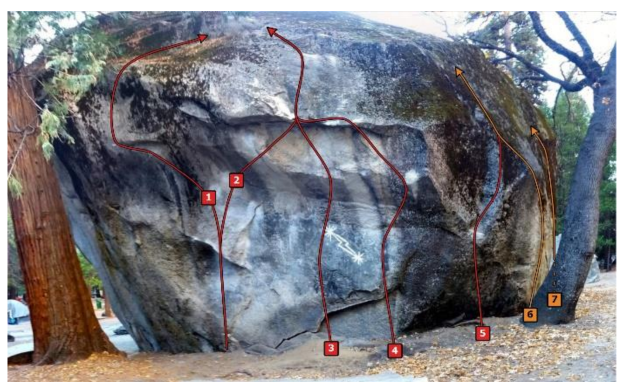


Figure 25. Big Columbia Boulder, Camp 4 thecrag.com

Figure 24. Big Columbia Boulder, Camp 4 ArcScene 3D

■ METHODS

Data acquisition and preprocess

Data for the Yosemite Park from **IRMA datastore** was downloaded, merged and used in this analysis.

1. Roads - https://irma.nps.gov/DataStore/Reference/Profile/2180725
2. Trails - https://irma.nps.gov/DataStore/Reference/Profile/2170447
3. Parking - https://irma.nps.gov/DataStore/Reference/Profile/2260366
4. Geology - https://irma.nps.gov/DataStore/Reference/Profile/1047771
5. Hydrology - https://irma.nps.gov/DataStore/Reference/Profile/2170437
6. Rock fall hazard line - https://irma.nps.gov/DataStore/Reference/Profile/2188906
7. Points of Interest - https://irma.nps.gov/DataStore/Reference/Profile/2225064

NAIP data from USDA-FPAC-BC Aerial Photography Field office that covers the region of interest, was used to analyze the intermediary results and better understand the region.

1. https://earthexplorer.usgs.gov/metadata/15920/2770976/
2. https://earthexplorer.usgs.gov/metadata/15920/2770977/
3. https://earthexplorer.usgs.gov/metadata/15920/2770980/
4. https://earthexplorer.usgs.gov/metadata/15920/2770981/
5. https://earthexplorer.usgs.gov/metadata/15920/2771006/
6. https://earthexplorer.usgs.gov/metadata/15920/2771007/
7. https://earthexplorer.usgs.gov/metadata/15920/2771010/
8. https://earthexplorer.usgs.gov/metadata/15920/2771011/
9. https://earthexplorer.usgs.gov/metadata/15920/2770985/
10. https://earthexplorer.usgs.gov/metadata/15920/2771015/

SRTM 1-ARC resolution data from **EarthExplorer** - Metadata - SRTM_V2 - SRTM1N37W120V2:

https://earthexplorer.usgs.gov/metadata/4960/SRTM1N37W120V2/

OpenTopography point cloud dataset named 'Yosemite National Park, CA: Rockfall Studies' (2010), located in the grounds of the Yosemite National Park, specifically the Half Dome and the Yosemite Valley, 'Yosemite, CA: El Portal, Mariposa Grove, Yosemite Canyon & Tuolumne Meadows' (2006) and 'Airborne Laser Mapping of Yosemite National Park, CA, 2007' to cover El Capitan and a portion of Little Yosemite Valley:

1. Yosemite National Park, CA: Rockfall Studies. Distributed by OpenTopography. https://doi.org/10.5069/G9D798B8. Accessed: 2019-12-10
2. Yosemite, CA: El Portal, Mariposa Grove, Yosemite Canyon & Tuolumne Meadows. Distributed by OpenTopography. https://doi.org/10.5069/G9GQ6VP3. Accessed: 2019-12-10
3. Airborne Laser Mapping of Yosemite National Park, CA, 2007. Distributed by OpenTopography. https://doi.org/10.5069/G9W66HPH. Accessed: 2019-12-10

Mapping

Mapping was conducted using the above data sets and different techniques.

Using ESRI's ArcMap 3.7 and PDAL, a process to identify the climbing walls was developed, based on 4 free point clouds datasets from the Yosemite Valley, from OpenTopography. Spatial Analyst extension is needed.

ArcGIS is a geographic information system (GIS) for users/organizations to create, manage, share, and analyze spatial data. It consists of server components, mobile and desktop applications, and developer tools.

PDAL is Point Data Abstraction Library. It is a C/C++ open source library and applications for translating and processing point cloud data. It is not limited to LiDAR data, although the focus and impetus for many of the tools in the library have their origins in LiDAR.

The coordinate system for the project was taken from the LiDAR files:

- Horizontal: UTM Zone 11N NAD83 (CORS) [EPSG: 26911]
- Vertical: NAVD88 (GEOID 03) [EPSG: 5703]

One file was in WGS84N and had to be reprojected in PDAL during merge.

Preliminary step

The working environment was prepared, and an area of interest was manually digitized:

- Created a File Geodatabase named scratch.gdb, to keep track of all the files and store all the intermediate results, and set geoprocessing workspace to this geodatabase.
- Created a new polygon file, drew the area of interest.
- Created Models that do specific tasks in order to separate functionality.

Extract shapefiles for Yosemite Valley

File geodatabase or shapefile data were downloaded from IRMA Data Store, merged and used in this analysis.

Clipped the data for Yosemite Park to an area of interest in the Yosemite Valley:

- Downloaded the data.
- Created a new file geodatabase named park_data.gdb, and imported specific data to it, for example roads, rivers, springs, trails.
- Created a new file geodatabase named valley_data.gdb, iterated through park_data.gdb, clipped the files using an AOI layer, and saved the results.

Create a mosaic of aerial images

Used NAIP data from USDA-FPAC-BC Aerial Photography Field office that covers the region of interest, to analyze the intermediary results and better understand the region.

Mosaic data from https://earthexplorer.usgs.gov:

Downloaded the files and mosaicked:

- Created a file geodatabase named AerialCollection
- Created Mosaic Dataset
- Added the raster files to Mosaic

Create base raster files

There are three point cloud files of las type for Yosemite Valley on OpenTopography. In order to conduct this study in the area, the files were downloaded, merged and transformed into raster files that could be easier analyzed using Spatial Analyst tools or 3D tools. One file was too large, it was splitted in two for download, resulting four files for processing.

Downloaded the files, merged all las files into a single file, then the tiles into a LAS dataset:

- Used PDAL to merge the four files, reproject to the same coordinate system, create tiles, then extracted ground and denoised the tiles using a batch command.
- Imported all resulting ground tiles to a new LAS dataset, explored in Figure 26.

Generated the primary raster files:

- Created Raster from the LAS dataset, using LAS To Raster. Because the average point density was around 0.5, this value was used as base cell resolution for all the derived products.
- Created Slope in degrees, shown in Figure 27 and Figure 28.

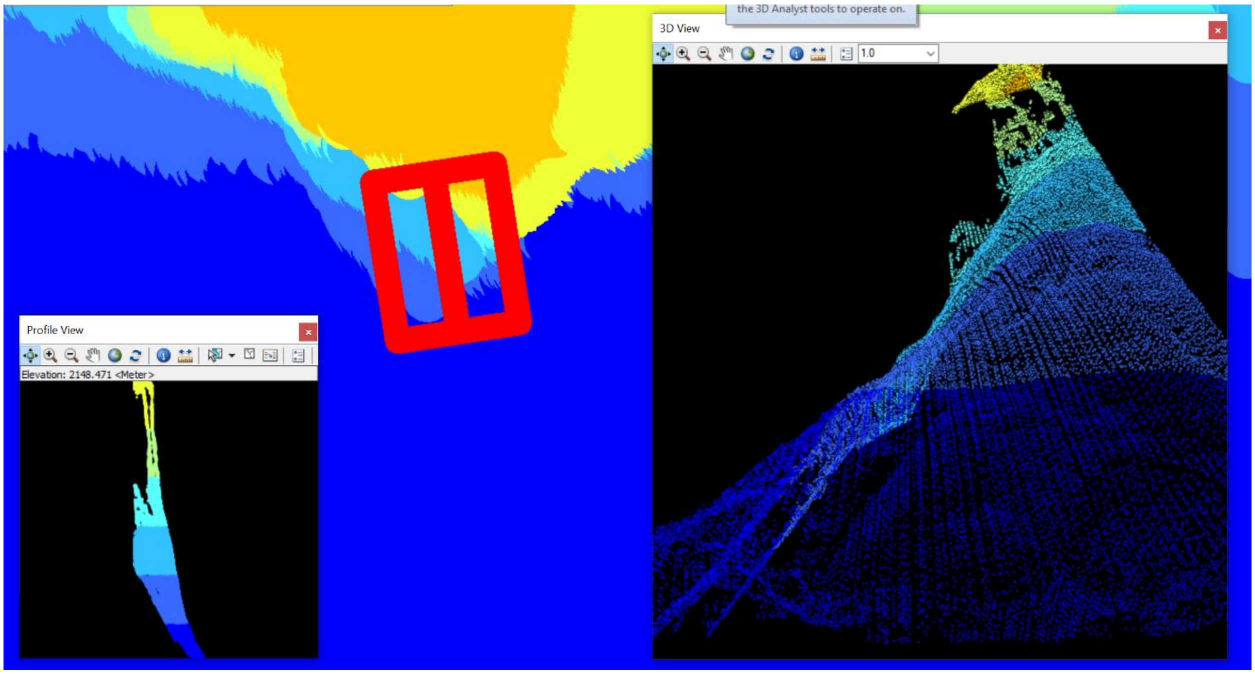


Figure 26. LAS Dataset Profile View and 3D View - El Capitan

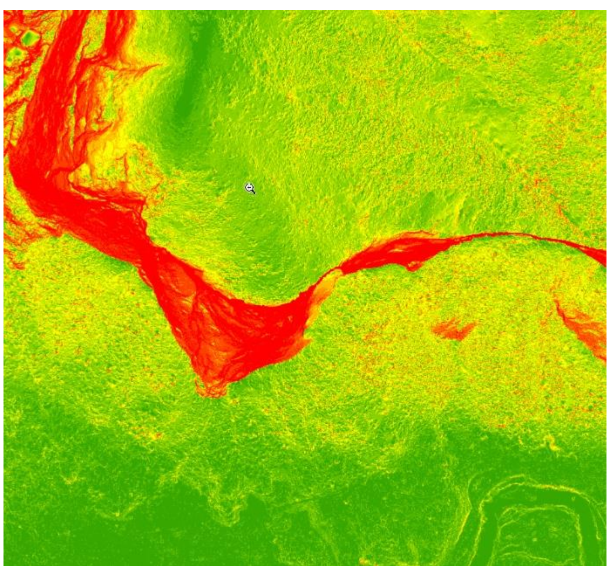


Figure 27. Slope - El Capitan

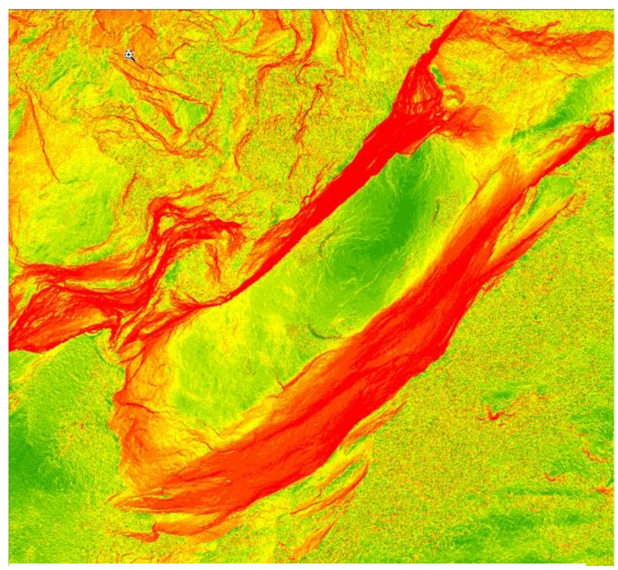


Figure 28. Slope – The Dome

Extract Climbing Walls

This section focuses on a set of threshold operations on the primary raster files, to determine areas where is very likelihood of long and steep walls, seen in Figure 29, 30, 31, 32, 33, 34. The main declivity should be above 75°, but the intention is to include the intercalated smaller zones on the walls, too.

This was achieved using generalization algorithms to create a mask for the zones that include faces with high declivity. Also, there was an operation to extract the approximate difference in altitude for the walls, that was achieved using sections of streams that cross the walls.

Went through a set of operations to extract the possible climbing faces:

A. Selected the areas that are usually considered steep slopes, extracted only faces above 45° using Con.

Figure 29. Aerial Image El Capitan

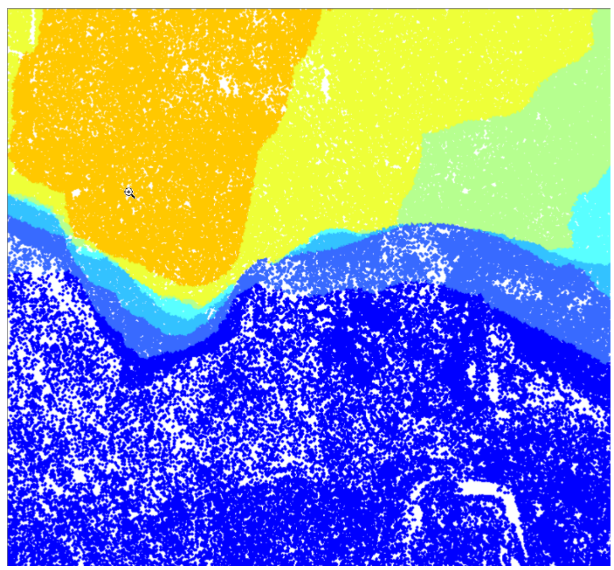


Figure 30. LAS Dataset Elevation

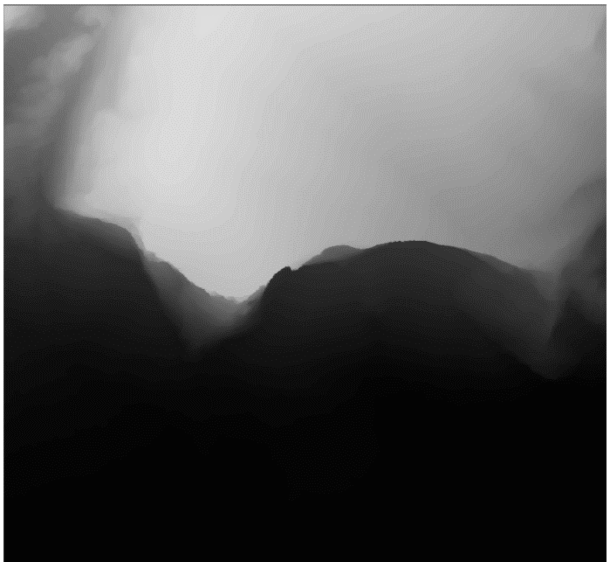


Figure 31. Elevation raster

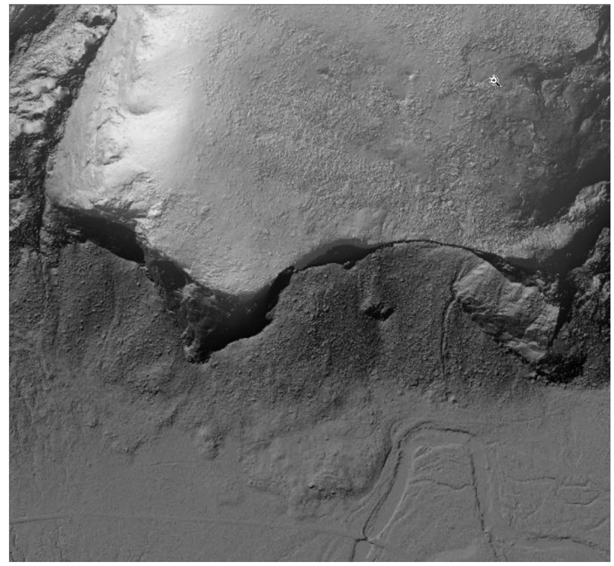


Figure 32. Hillshade

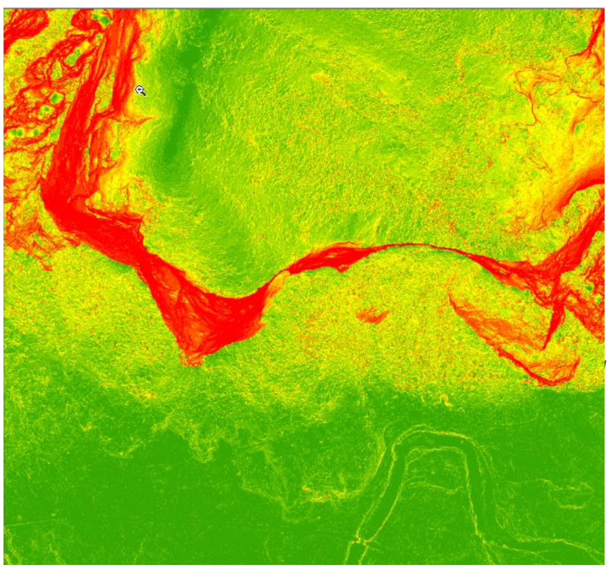


Figure 33. Slope

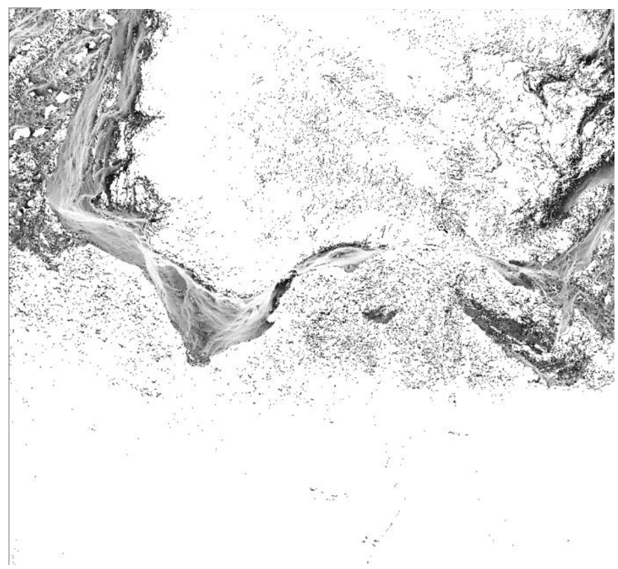


Figure 34. Slope above 45°

B. Generalized the extracted data for slope, in order to get a cluster of similar slope and aspect.

- Did a Boundary Clean and a Majority Filter to generalize the results.
- Boundary Clean sorting technique 'ASCEND'
- Created a mask from the previous result, then refined it through a smoothing process.
- Removed data smaller than 1000 sqm, then use this mask to extract data from the slope raster, as shown in Figure 35 and Figure 36.
- Used Region Group tool

Figure 35. Slope generalized buffer

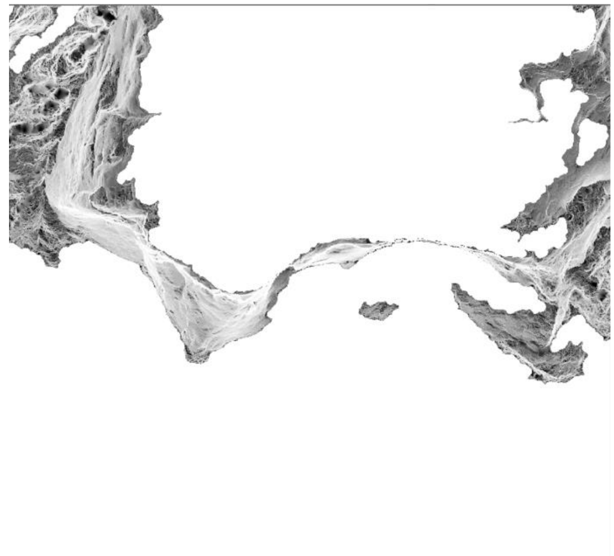


Figure 36. Slope extracted by buffer mask

C. Extracted portions of streams that intersected with the walls, to approximate the difference in elevation.

- Created the stream network from the Elevation raster resulted earlier, using Flow Accumulation, Stream Order, Stream Links, Stream to Feature, as shown in Figure 37.
- Intersected the Streams raster with a raster buffer following the resulting Slope raster, then with the Elevation raster using summary statistics, and got the elevation range per stream, as shown in Figure 38.

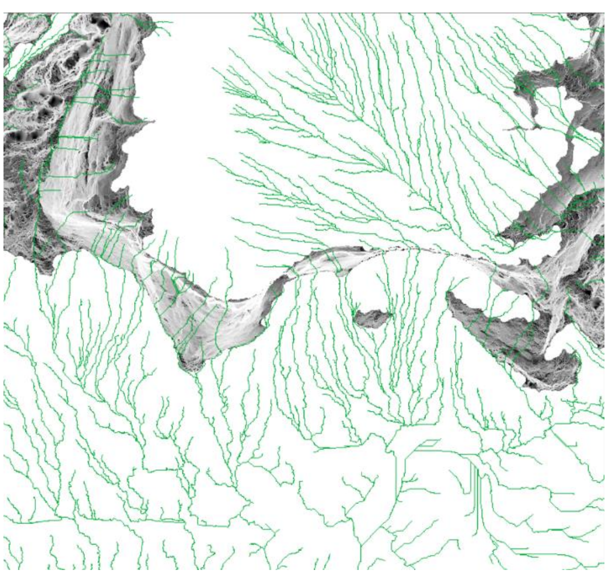


Figure 37. Flow direction

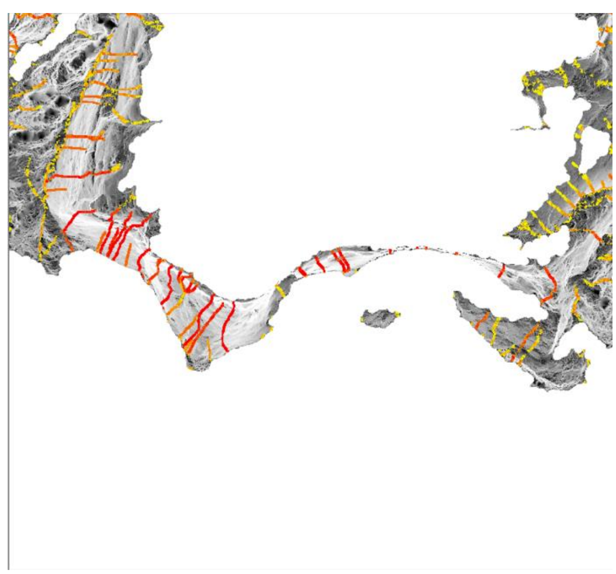


Figure 38. Lines updated with elevation ranges

Get the best Yosemite Valley Climbing Places

Deriving datasets, such as slope, is the first step when building a suitability model. Each cell in the study area will need to have a value for each input criteria. There is the need to combine the derived datasets in order to create a suitability map, which will identify the potential locations for the climbing routes.

To combine the datasets, they first need to be set to a common measurement scale, such as 1 to 10.

Using the Weighted Overlay tool, the values of each dataset can be weighted and combined.

Two main resulting raster files were derived using the results from the previous operations.

Possible Climbing Walls Markers raster

One raster represents zones that combine steep slopes with elevation ranges from 100 to more than 900 m, and answers the question ‘Where are the possible climbing walls in Yosemitte Valley’.

Reclassified the slope output, slicing the values into equal intervals. Assigned a value of 10 to the most suitable range of slopes and 1 to the least suitable range of and linearly rank the values in between.

Used Weighted Overlay on slope and streams raster:

- Percentages of influence:

1. Reclassed slope: 60%
2. Reclassed stream raster: 40%

A scale of 1 to 10 was used when reclassifying datasets, so before adding input raster files to the Weighted Overlay tool, we have set the evaluation scale from 1 to 10 by 1. The results should include slopes greater than **45** degrees, even if all other conditions are ideal. Made values from 1 to 5 restricted, since these values represent slopes from 0 to 45. Then we extract the pixels with a value greater than 0 using Con.

Best Climbing Walls Markers raster

The other raster is an attempt to combine specific suitability factors, that would answer questions like 'Where is the longest climbing route in less than 500 m from the main road, and no more than 100 m from a trail'. The decision to go to one climbing place or another can be influenced by many factors.

Distances to roads, streams, springs, parking, and the overlap with specific geologic areas were taken into account.

Created Euclidean Distance Raster files:

A. Using data from step II, created Euclidean Distance raster files for roads, streams, climbing areas, parking lots, springs, trails.

Reclassified the Raster files:

B. The values in the datasets derived in previous steps were all floating-point, continuous datasets, categorized into ranges, and they had to be reclassified so that each range of values was assigned one discrete integer value. Reclassified each derived dataset to a common measurement scale, giving each range a discrete integer value between 1 and 10. Higher values would be given to attributes within each dataset that were more suitable for locating the climbing route.

  - Slope: reclassified the slope output, slicing the values into equal intervals. Assigned a value of 10 to the most suitable range of slopes (those with the lowest angle of slope) and 1 to the least suitable range of slopes (those with the steepest angle of slope) and linearly rank the values in between.
  - Geology: reclassified the raster, keeping the granite and granodiorite related values.

C. Used Weighted Overlay on previous results, as shown in Figure 38:

  - The reclassified datasets and geology were ready to be combined to find the most suitable locations. The values have all been reclassified to a common measurement scale (more suitable cells have higher values). The geology dataset was still in its original form because we could weigh the cell values for this dataset as part of the weighted overlay process. All the inputs could be weighted assigning each a percentage of influence. The higher the percentage, the more influence a particular input will have in the suitability model.

- Percentages of influence:
  1. Reclassed slope: 50%
  2. Reclassed distance to roads: 5%
  3. Reclassed distance to trails: 10%
  4. Reclassed distance to rivers: 5%
  5. Reclassed distance to springs: 2%
  6. Reclassed distance to parking: 1%
  7. Reclassed distance to climbing areas: 10%
  8. Reclassed distance from clipped streams: 15%
  9. Geology: 2%

D. A scale of 1 to 10 was used when reclassifying datasets, so before adding input raster files to the Weighted Overlay tool, we have set the evaluation scale from 1 to 10 by 1.

E. The results should include slopes greater than **55** degrees, even if all other conditions are ideal. Made values from 1 to 6 restricted, since these values represent slopes from 0 to 55.

On the resulting layer, each pixel has a value that indicates how suitable that location is for a new route. Pixels with the value of 10 are most suitable, and pixels with the value of 0 are not suitable. Therefore, the optimal site location for a new route has the value of 10, as shown in Figure 40.

We extract the pixels with a value of 10 using Con, group them using Region Group with a value of eight, convert to polygon, dissolve, buffer, then we use Mean Center to get the centroids for the resulting polygons.

Figure 39. Weighted Overlay

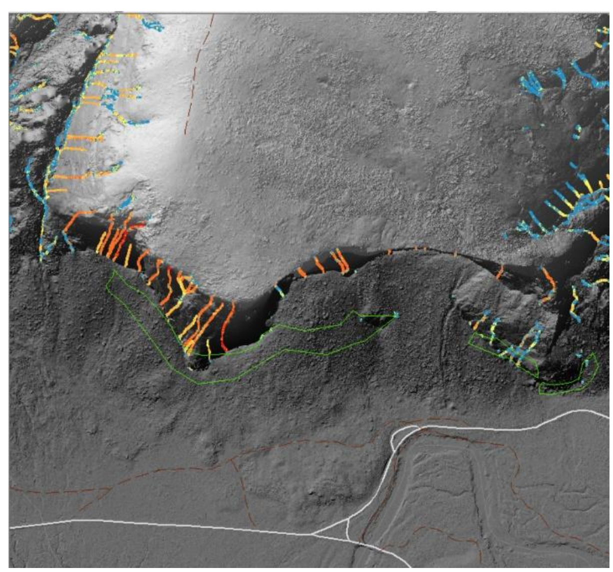


Figure 40. Best Places By Criteria

■ RESULTS

The computed possible climbing area spreads over approximately 47 Km².

By examining the distribution of slope degrees in the Possible Climbing Slopes resulting cluster, we came to the conclusion that most of the area is represented by slopes between 40 and 50 degrees (22.66%), as shown in Figure 41, 42, 43 and Table 2.

The zones representing the steepest slopes (above 80 degrees) represent 3.47% of the total area, 1.7 Km².

A. Possible Climbing Slopes Map

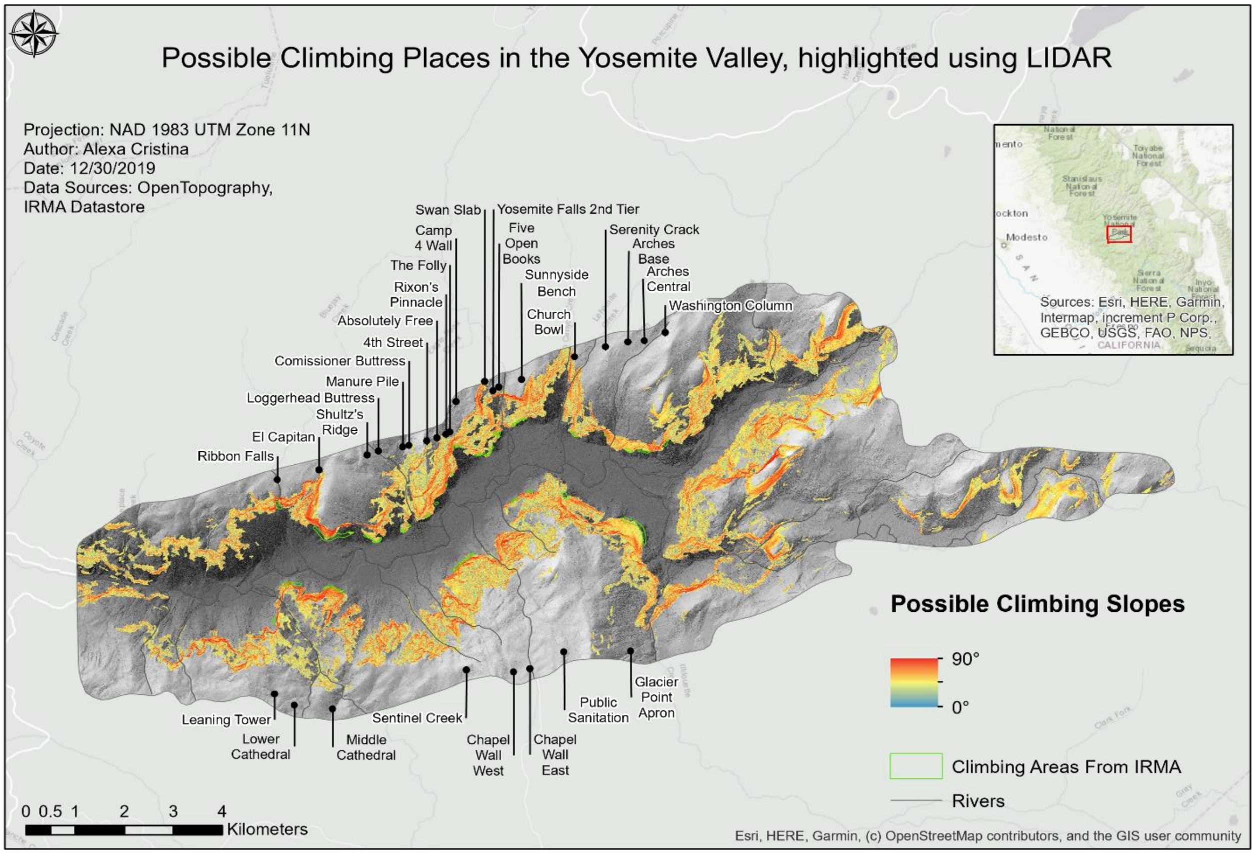


Figure 41. Possible Climbing Slopes Map

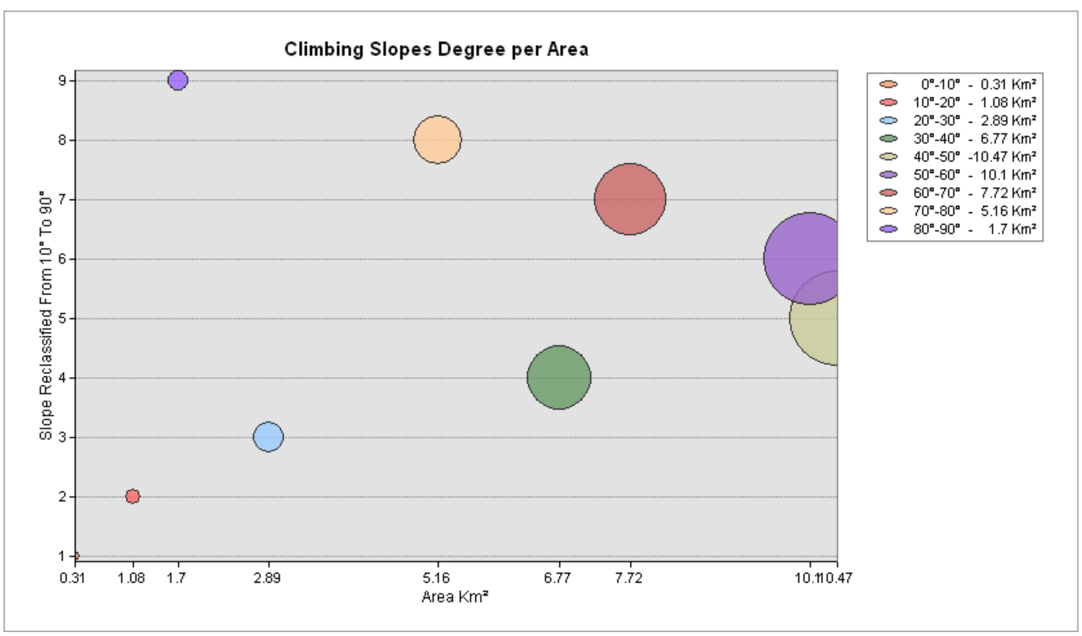


Figure 42. Possible Climbing Slopes Reclassified – Area

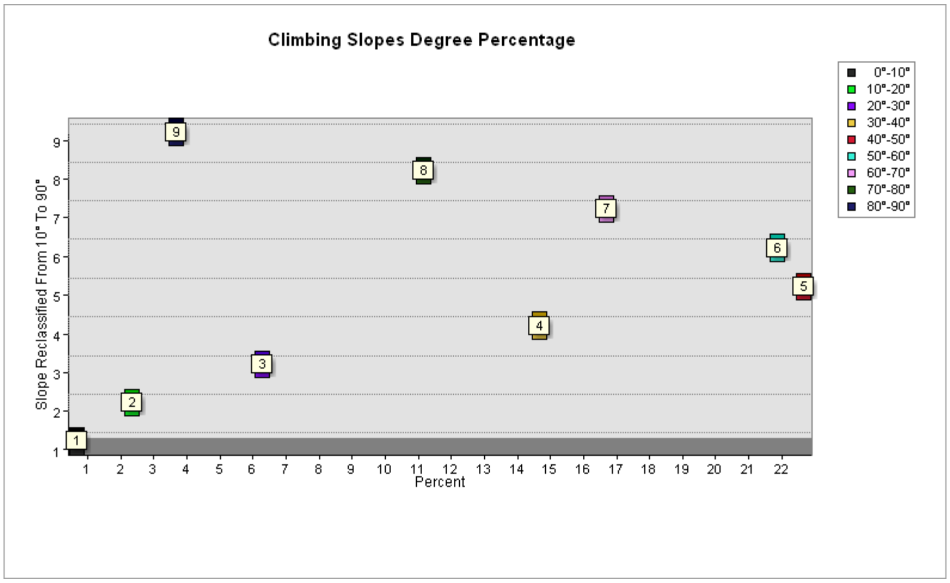


Figure 43. Possible Climbing Slopes Reclassified – Percentage

Table 2. Possible Climbing Slopes – Pixel Count and Area

OID	OBJECTID	Value	Count	Area	Area_sqkn	Percent
0	1	1	618655	309327.5	0.309328	0.67
1	2	2	2157228	1078614	1.078614	2.33
2	3	3	5782803	2891402	2.891402	6.26
3	4	4	13541884	6770942	6.770942	14.66
4	5	5	20939354	10469677	10.46968	22.66
5	6	6	20203787	10101894	10.10189	21.87
6	7	7	15441583	7720792	7.720792	16.71
7	8	8	10312329	5156165	5.156165	11.16
8	9	9	3390972	1695486	1.695486	3.67

When we have narrowed down the results and obtained the Possible Climbing Walls markers raster, we got a total area of almost 3 Km², and the pixels with greater probability for climbing walls summed almost 4755.5 m², as shown in Figure 44, 45 and Table 3. When we added extra criteria like distance to roads, we got 1557 m² for the best climbing walls and the resulting pixels were concentrated in the same area, as shown in Figure 46, 47 and Table 4.

Not surprisingly, the best climbing wall marker turned out to be on El Capitan, the almost 1km length of the wall and the above 75° steepness have had a big weight in the final overlay model. The coordinates of the point are 37.730285, -119.637618 decimal degrees.

B. Possible Climbing Walls Markers Map

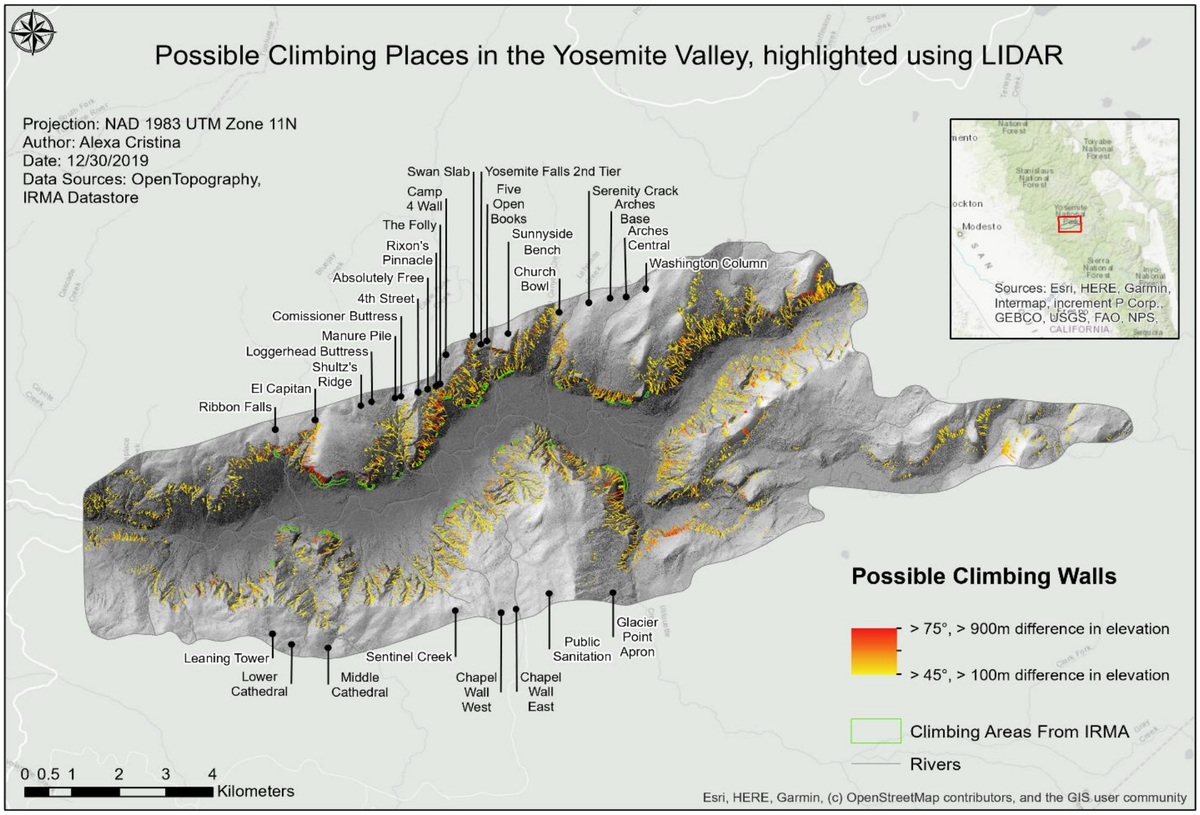


Figure 44. Possible Climbing Walls Markers Map

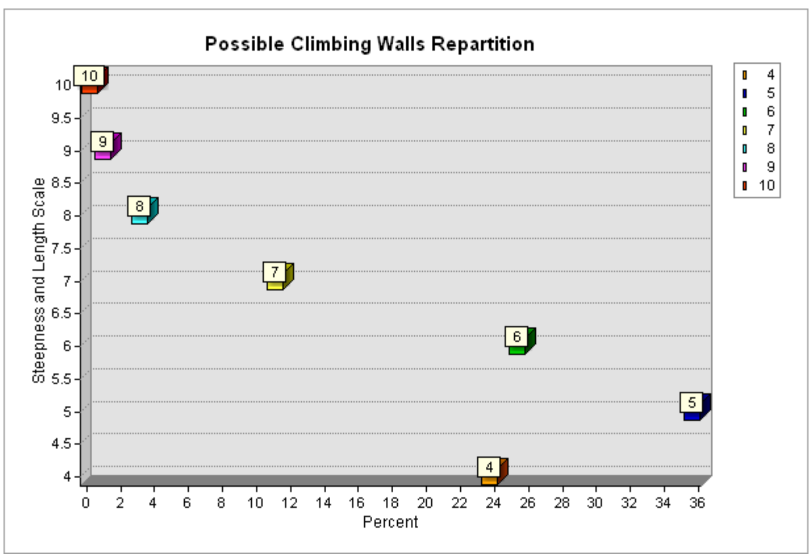


Figure 45. Possible Climbing Walls Repartition – Percentage

Table 3. Possible Climbing Walls – Pixels Count and Area

OID	OBJECTID	Value	Count	Area	Area_sqkn	Percent
0	1	4	1264302	632151	0.632151	23.71
1	2	5	1898826	949413	0.949413	35.61
2	3	6	1349235	674617.5	0.674618	25.31
3	4	7	589747	294873.5	0.294874	11.06
4	5	8	168073	84036.5	0.084037	3.15
5	6	9	51954	25977	0.025977	0.97
6	7	10	9511	4755.5	0.004756	0.18

C. Weighted Overlay Best Climbing Walls Map

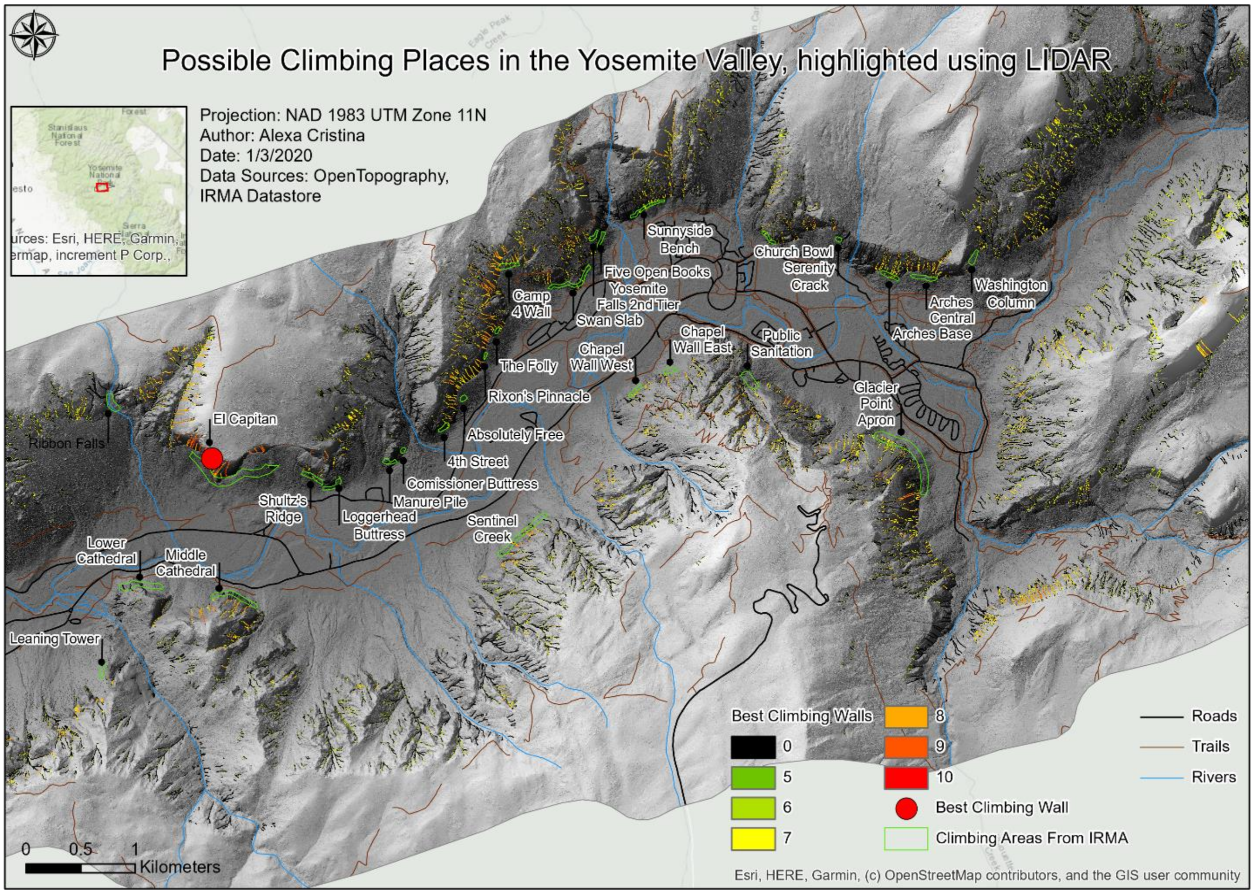


Figure 46. Weighted Overlay Best Climbing Walls Map

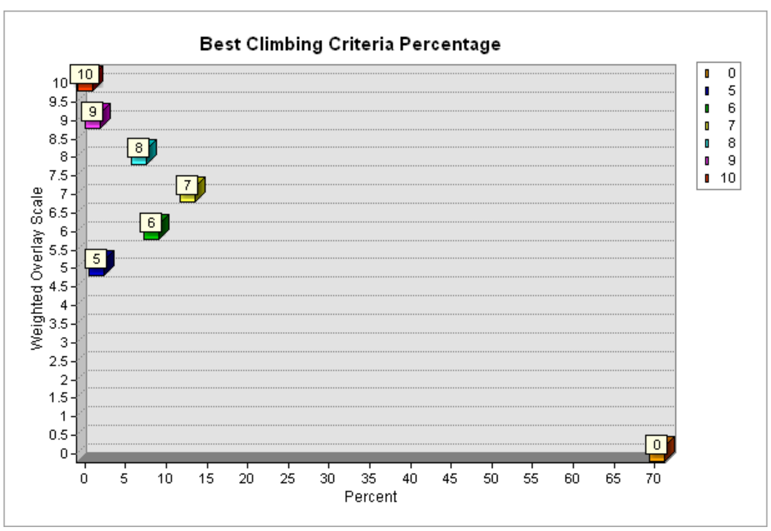


Figure 47. Best Climbing Walls Repartition – Scatter Plot

Table 4. Best Climbing Walls Repartition – Pixel Count and Area

OID	OBJECTID	Value	Count	Area	Area_sqkr	Percent
0	1	0	6954245	3477123	3.477123	70.26
1	2	5	136966	68483	0.068483	1.38
2	3	6	808111	404055.5	0.404056	8.16
3	4	7	1253403	626701.5	0.626702	12.66
4	5	8	651142	325571	0.325571	6.58
5	6	9	90789	45394.5	0.045395	0.92
6	7	10	3114	1557	0.001557	0.03

DISCUSSION

The project results depend much both on the quality of the acquired data, and the whole approach taken during the raster processing.

The data had an average point spacing of about 0.5 meters, so there is enough accuracy for conducting a slope analysis, but data quality depends on the **extraction** of the ground points.

Not all LiDAR data was classified, so in order to get more data I have used PDAL to extract the ground points. The **Simple Morphological Filter (SMRF)**, that classifies ground points based on the approach outlined in [Pingel2013], was chosen. Maybe another method would work better, and this should be tested. For example, The **Progressive Morphological Filter (PMF),** a method of segmenting ground and non-ground returns, an implementation of the method described in [Zhang2003].

I could have used ArcGIS 'Classify LAS Ground' to classify ground points, but PDAL seemed to consume less memory for batch processing.

The data from OpenTopography was from different years and partially **overlapped**. I know LAS Tiles in ArcGIS solves the overlapping issue, but I still have to research how PDAL behaves when tiling merged point clouds.

This study aims to delineate Yosemite's Climbing walls, but with its scope is not to map the walls in detail, because this cannot be accomplished using **Airborne LiDAR scanning (ALS)** only. Usually a project for mapping walls is being driven using airborne LiDAR in conjunction with **Terrestrial LiDAR Scanning (TLS)** or **Mobile LiDAR scanning (MLS)**, because on steep walls there usually are overhangs, that cause a 'shadow' error when the airplane collects the points, that results in zones with no data.

In order to approximate the **walls length**, the approach was to derive streamlines, cut them when they intersect the possible climbing zones buffer, then get the attributes from the Elevation raster file and compute the range for elevation. So, the final length taken into account is the difference in altitude, rather than the combined slopes length. There are other approaches better than the one in this paper, for example using cost path, that would assess a more accurate wall length, and testing them is a subject for further studies.

Another point to take into account is that not all climbing walls are being crossed by pseudo-streams, there are completely isolated rocks where the streams go around, that would not show up in the final results because we combine the climbing zone filter with the length filter. Also, the boulders will not be taken into account, being too small.

Above all, this is not a climbing guide and should not be followed by climbers who want to discover new routes or explore new walls, this is only a starting point for further scientific analysis regarding delineation of climbing walls using LiDAR from airborne scanners.

Still, the method used in this study would give enough insight to delineate the approximative location of the climbing walls.

■ CONCLUSIONS

Even if there are still many ways to improve this project results, what we have achieved until now demonstrates that LiDAR is a great resource for examining the surface morphology.

The precision of the results depends both on the quality of the acquired data and on the sequence of algorithms used during the processing of the raster files. The primary input for Digital Terrain Model generation was a set of point clouds with ground classifications. High resolution data was used to preserve the steepness of the walls as much as possible, the walls length was approximated using flow direction algorithms, and the results were refined through multiple raster generalization and clustering techniques in order to delineate regions that should resemble more to what climbing walls are in reality.

The takeaway from this study is a better understanding of the existing climbing environment and the delineation of possible new climbing areas.

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APPENDIX

D. TABLES

OID	OBJECTID	Value	Count	Area	Area_sqkr	Percent
0	1	1	618655	309327.5	0.309328	0.67
1	2	2	2157228	1078614	1.078614	2.33
2	3	3	5782803	2891402	2.891402	6.26
3	4	4	13541884	6770942	6.770942	14.66
4	5	5	20939354	10469677	10.46968	22.66
5	6	6	20203787	10101894	10.10189	21.87
6	7	7	15441583	7720792	7.720792	16.71
7	8	8	10312329	5156165	5.156165	11.16
8	9	9	3390972	1695486	1.695486	3.67

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2	3	6	1349235	674617.5	0.674618	25.31
3	4	7	589747	294873.5	0.294874	11.06
4	5	8	168073	84036.5	0.084037	3.15
5	6	9	51954	25977	0.025977	0.97
6	7	10	9511	4755.5	0.004756	0.18

OID	OBJECTID	Value	Count	Area	Area_sqkr	Percent
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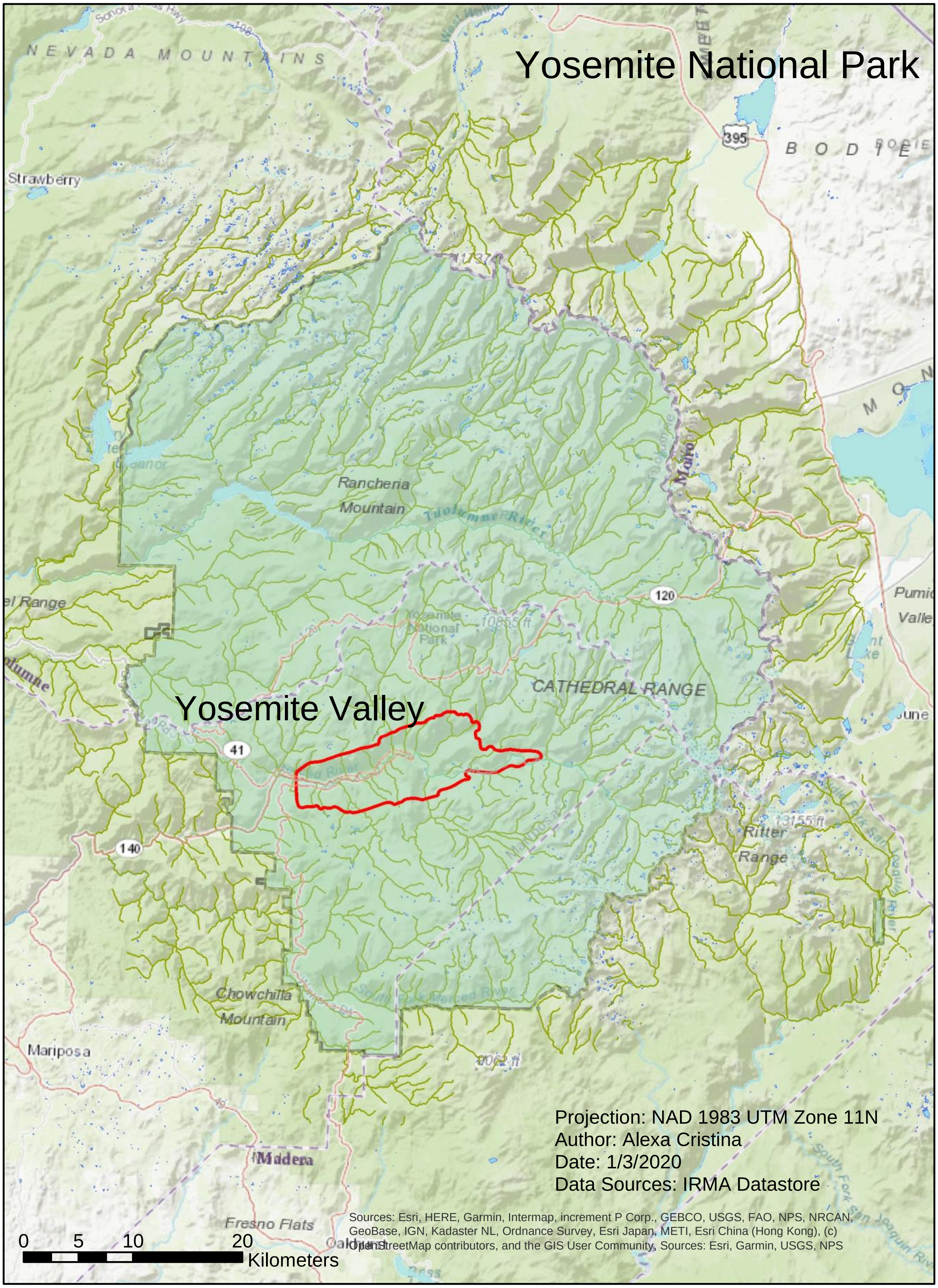
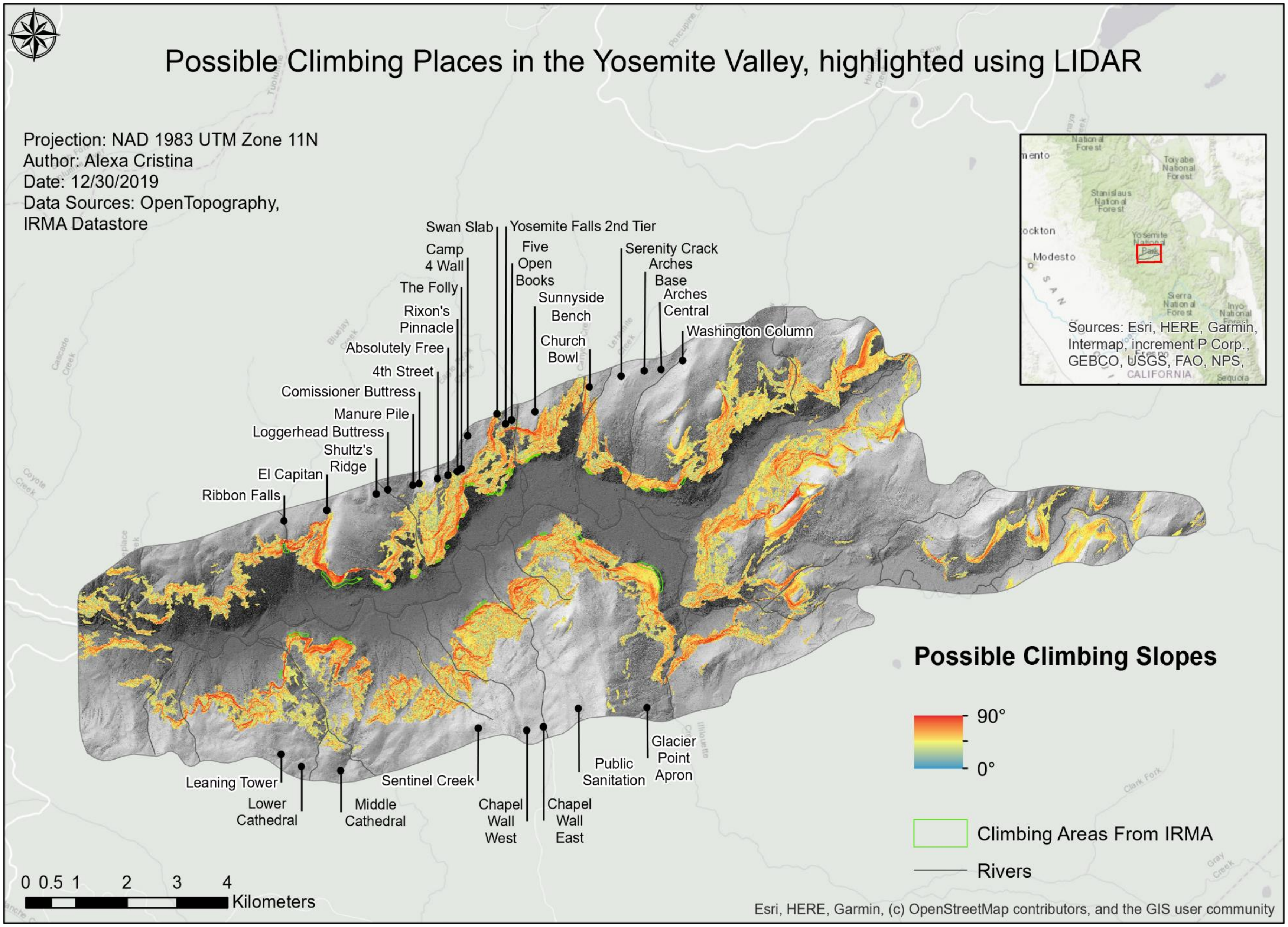
1	2	5	136966	68483	0.068483	1.38
2	3	6	808111	404055.5	0.404056	8.16
3	4	7	1253403	626701.5	0.626702	12.66
4	5	8	651142	325571	0.325571	6.58
5	6	9	90789	45394.5	0.045395	0.92
6	7	10	3114	1557	0.001557	0.03

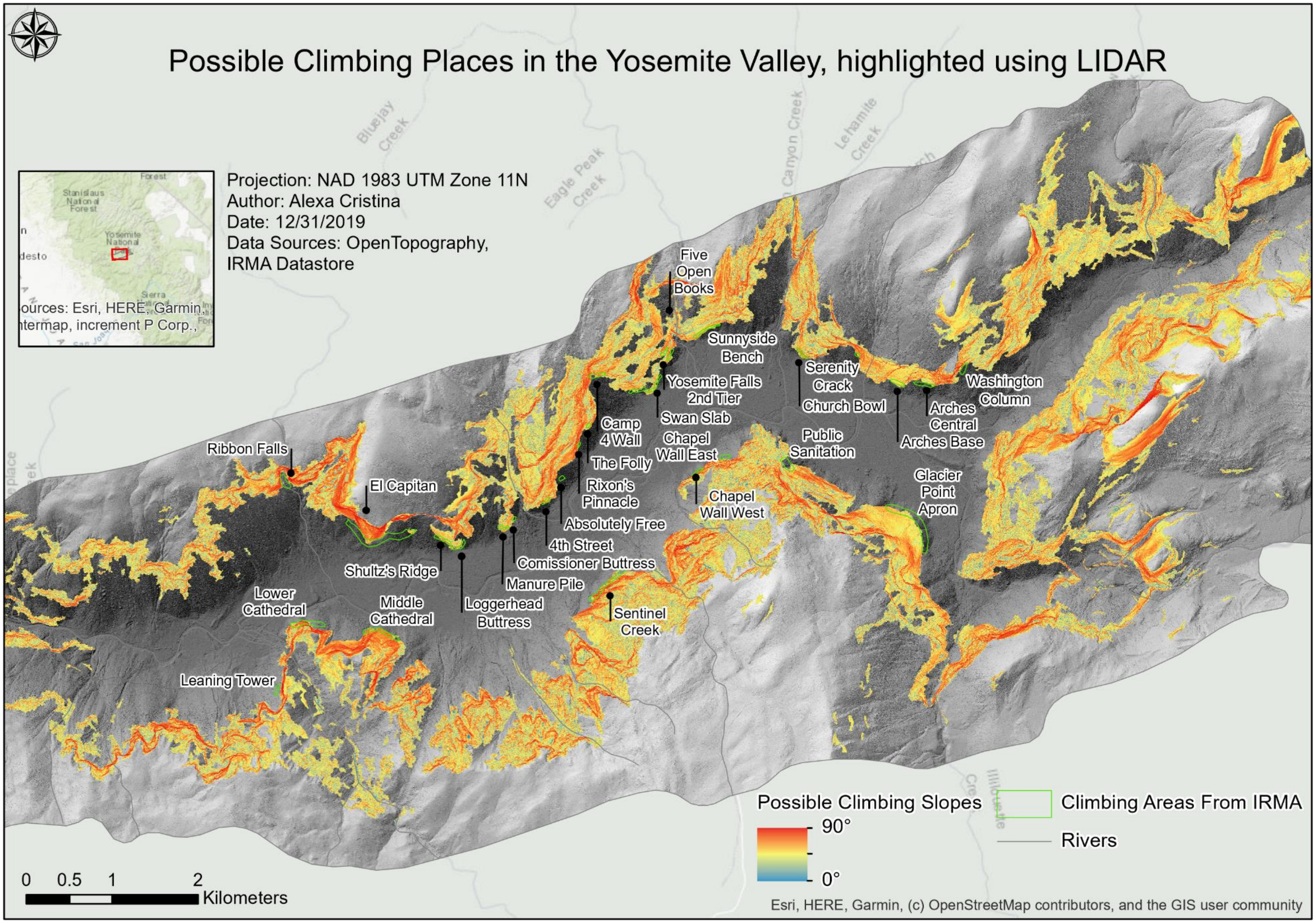
OII	OB.	ID	NAME	Shape_Leng	Shape_Area	Lat	Lon
0	1	1	Ribbon Falls	460.083704	11183.39	37.73455806	-119.6481881
1	2	2	El Capitan	2020.60093	60082.885	37.7291523	-119.6356163
2	3	3	Shultz's Ridge	496.751213	7104.6844	37.72900848	-119.6271404
3	4	4	Loggerhead Buttress	477.416263	5926.3763	37.7283677	-119.6248642
4	5	5	Manure Pile	338.687917	4113.6615	37.73043537	-119.6191883
5	6	6	Comissioner Buttress	160.50218	1830.527	37.73137869	-119.6177708
6	7	7	4th Street	282.98854	3783.0993	37.73333668	-119.6135447
7	8	8	Absolutely Free	195.421176	2546.5109	37.73575651	-119.6116199
8	9	9	Rixon's Pinnacle	165.827432	1353.1618	37.73931039	-119.6094555
9	10	10	The Folly	156.945793	1609.1083	37.74137512	-119.6082849
10	11	11	Camp 4 Wall	460.443216	7743.5957	37.74667842	-119.6073737
11	12	12	Swan Slab	1056.08786	13607.318	37.74555864	-119.6006414
12	13	13	Five Open Books	337.447942	3728.1068	37.7490719	-119.5977179
13	14	14	Yosemite Falls 2nd Tier	291.357249	3372.1707	37.74926671	-119.5985185
14	15	15	Sunnyside Bench	751.699255	7519.717	37.75168965	-119.5931959
15	16	16	Church Bowl	383.788294	4309.8176	37.74956142	-119.5803116
16	17	17	Serenity Crack	172.541456	2052.9134	37.74959316	-119.5729988
17	18	18	Arches Base	392.285149	6071.2447	37.74676083	-119.5675683
18	19	19	Arches Central	532.757736	7653.0027	37.74666379	-119.5640411
19	20	20	Washington Column	343.606754	5697.2831	37.74838037	-119.5588985
20	21	21	Glacier Point Apron	1734.16791	59107.841	37.73211108	-119.5651531
21	22	22	Public Sanitation	495.660348	13637.378	37.73789492	-119.5818593
22	23	23	Chapel Wall East	311.120322	4932.8621	37.73849798	-119.5901485
23	24	24	Chapel Wall West	356.268811	4260.8325	37.73676799	-119.593745
24	25	25	Sentinel Creek	1232.15338	22601.835	37.7247397	-119.605202
25	26	26	Middle Cathedral	980.444979	16592.435	37.71899101	-119.6348385
26	27	27	Lower Cathedral	896.586985	19214.05	37.71974128	-119.6447216
27	28	28	Leaning Tower	320.300569	4106.6273	37.71269902	-119.6484384

E. MAPS



Yosemite National Park
Yosemite Valley
NEVADA MOUNTAINS
BODIE
Strawberry
Rancheria Mountain
Tuolumne River
CATHEDRAL RANGE
Ritter Range
Chowchilla Mountain
Mariposa
Madera
Fresno Flats
395
120
41
140
Projection: NAD 1983 UTM Zone 11N
Author: Alexa Cristina
Date: 1/3/2020
Data Sources: IRMA Datastore
Sources: Esri, HERE, Garmin, Intermap, increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, Esri Japan, METI, Esri China (Hong Kong), (c) OpenStreetMap contributors, and the GIS User Community, Sources: Esri, Garmin, USGS, NPS
0 5 10 20
Kilometers


Possible Climbing Places in the Yosemite Valley, highlighted using LIDAR
Projection: NAD 1983 UTM Zone 11N
Author: Alexa Cristina
Date: 12/30/2019
Data Sources: OpenTopography,
IRMA Datastore
Swan Slab
Yosemite Falls 2nd Tier
Camp 4 Wall
Five Open Books
The Folly
Sunnyside Bench
Rixon's Pinnacle
Serenity Crack
Arches
Base Arches
Central
Washington Column
Church Bowl
Absolutely Free
4th Street
Comissioner Buttress
Manure Pile
Loggerhead Buttress
Shultz's Ridge
El Capitan
Ribbon Falls
Leaning Tower
Lower Cathedral
Middle Cathedral
Sentinel Creek
Chapel Wall West
Chapel Wall East
Public Sanitation
Glacier Point Apron
Possible Climbing Slopes
90°
0°
Climbing Areas From IRMA
Rivers
0 0.5 1 2 3 4
Kilometers
Sources: Esri, HERE, Garmin, Intermap, increment P Corp., GEBCO, USGS, FAO, NPS,
Esri, HERE, Garmin, (c) OpenStreetMap contributors, and the GIS user community


Possible Climbing Places in the Yosemite Valley, highlighted using LIDAR
Projection: NAD 1983 UTM Zone 11N
Author: Alexa Cristina
Date: 12/31/2019
Data Sources: OpenTopography,
IRMA Datastore
Bluejay Creek
Eagle Peak Creek
Lehamite Creek
Ribbon Falls
El Capitan
Five Open Books
Sunnyside Bench
Yosemite Falls 2nd Tier
Swan Slab
Camp 4 Wall
The Folly
Rixon's Pinnacle
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Lower Cathedral
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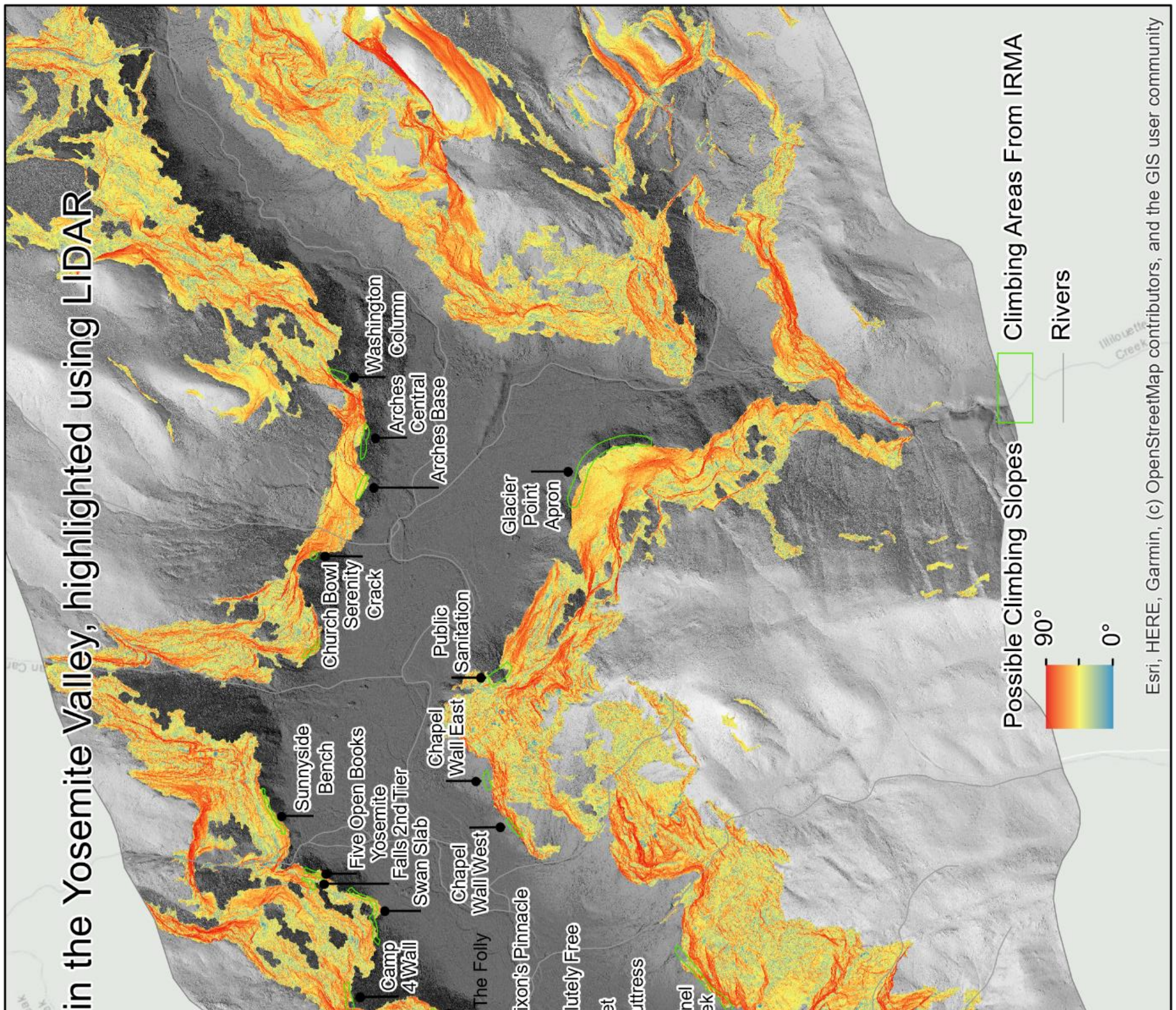
Leaning Tower
Chapel Wall East
Chapel Wall West
Sentinel Creek
Serenity Crack
Church Bowl
Public Sanitation
Arches Central
Arches Base
Washington Column
Glacier Point Apron
Possible Climbing Slopes
90°
0°
Climbing Areas From IRMA
Rivers
0 0.5 1 2 Kilometers
Esri, HERE, Garmin, (c) OpenStreetMap contributors, and the GIS user community


Possible Climbing Places in the Yosemite Valley, highlighted using LIDAR
Projection: NAD 1983 UTM Zone 11N
Author: Alexa Cristina
Date: 12/31/2019
Data Sources: OpenTopography,
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Ribbon Falls
El Capitan
Leaning Tower
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Middle cathedral
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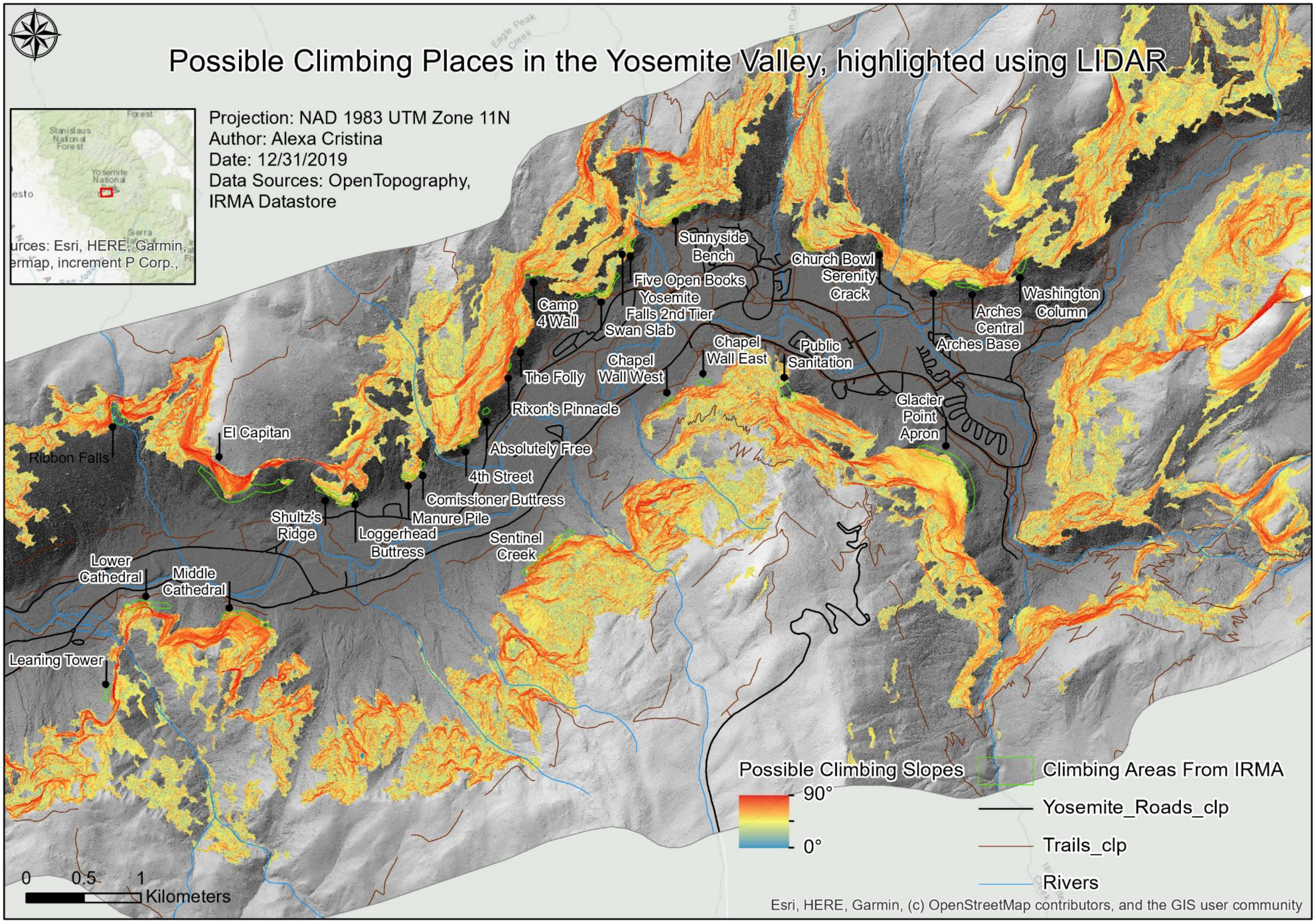
Sunnyside Bench
Public Sanitation
Church Bowl
Serenity Crack
Arches Base
Arches Central
Washington Column
Glacier Point Apron
Possible Climbing Slopes
90°
0°
Climbing Areas From IRMA
Rivers
0
0.5
1
Kilometers
Esri, HERE, Garmin, (c) OpenStreetMap contributors, and the GIS user community


Possible Climbing Places in the Yosemite Valley, highlighted using LIDAR
Projection: NAD 1983 UTM Zone 11N
Author: Alexa Cristina
Date: 12/31/2019
Data Sources: OpenTopography,
IRMA Datastore
Ribbon Falls
El Capitan
Shultz's Ridge
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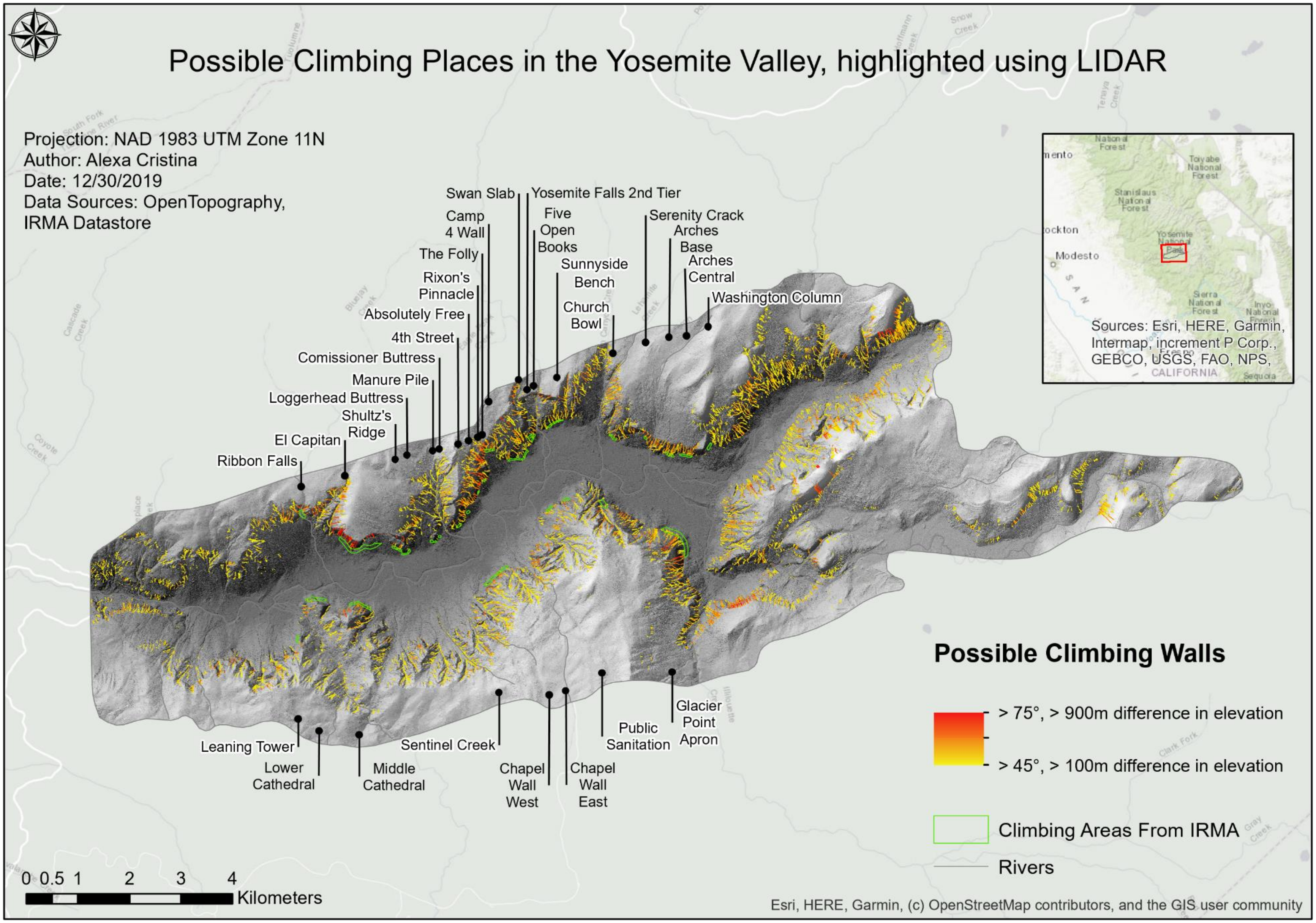
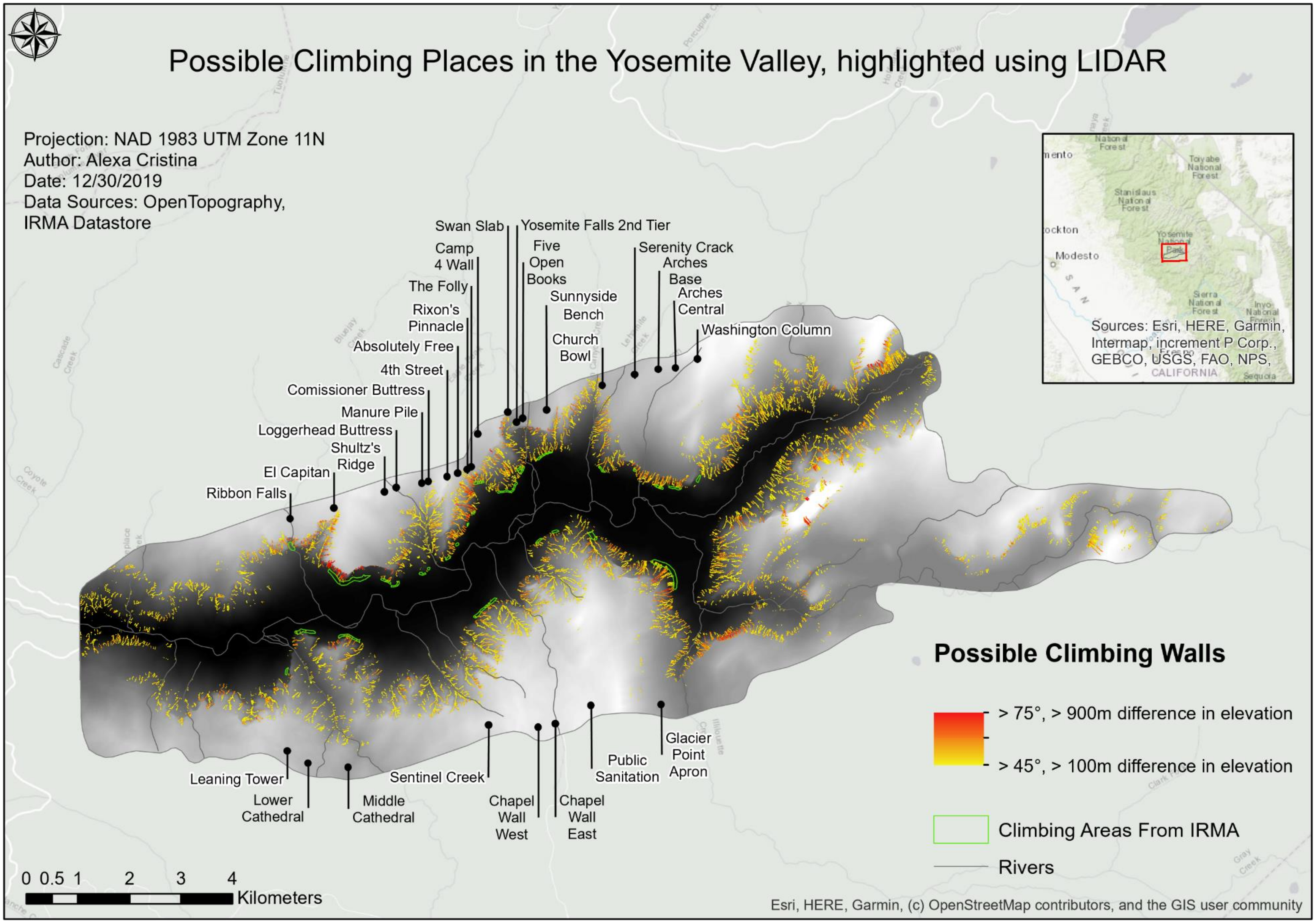
Glacier Point Apron
Arches Base
Arches Central
Washington Column
Sentinel Creek
Lower Cathedral
Middle Cathedral
Leaning Tower
Possible Climbing Slopes
90°
0°
Climbing Areas From IRMA
Yosemite_Roads_clp
Trails_clp
Rivers
0
0.5
1
Kilometers
Esri, HERE, Garmin, (c) OpenStreetMap contributors, and the GIS user community



Possible Climbing Places in the Yosemite Valley, highlighted using LIDAR
Projection: NAD 1983 UTM Zone 11N
Author: Alexa Cristina
Date: 12/30/2019
Data Sources: OpenTopography, IRMA Datastore
Swan Slab
Yosemite Falls 2nd Tier
Camp 4 Wall
Five Open Books
The Folly
Sunnyside Bench
Rixon's Pinnacle
Absolutely Free
4th Street
Church Bowl
Serenity Crack
Arches Base
Arches Central
Washington Column
Comissioner Buttress
Manure Pile
Loggerhead Buttress
Shultz's Ridge
El Capitan
Ribbon Falls
Leaning Tower
Lower Cathedral
Middle Cathedral
Sentinel Creek
Chapel Wall West
Chapel Wall East
Public Sanitation
Glacier Point Apron
Sources: Esri, HERE, Garmin, Intermap, increment P Corp., GEBCO, USGS, FAO, NPS,
Possible Climbing Walls
> 75°, > 900m difference in elevation
> 45°, > 100m difference in elevation
Climbing Areas From IRMA
Rivers
0 0.5 1 2 3 4 Kilometers
Esri, HERE, Garmin, (c) OpenStreetMap contributors, and the GIS user community


Possible Climbing Places in the Yosemite Valley, highlighted using LIDAR
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Author: Alexa Cristina
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IRMA Datastore
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Yosemite Falls 2nd Tier
Camp 4 Wall
Five Open Books
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Sentinel Creek
Chapel Wall West
Chapel Wall East
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Sources: Esri, HERE, Garmin, Intermap, increment P Corp., GEBCO, USGS, FAO, NPS,
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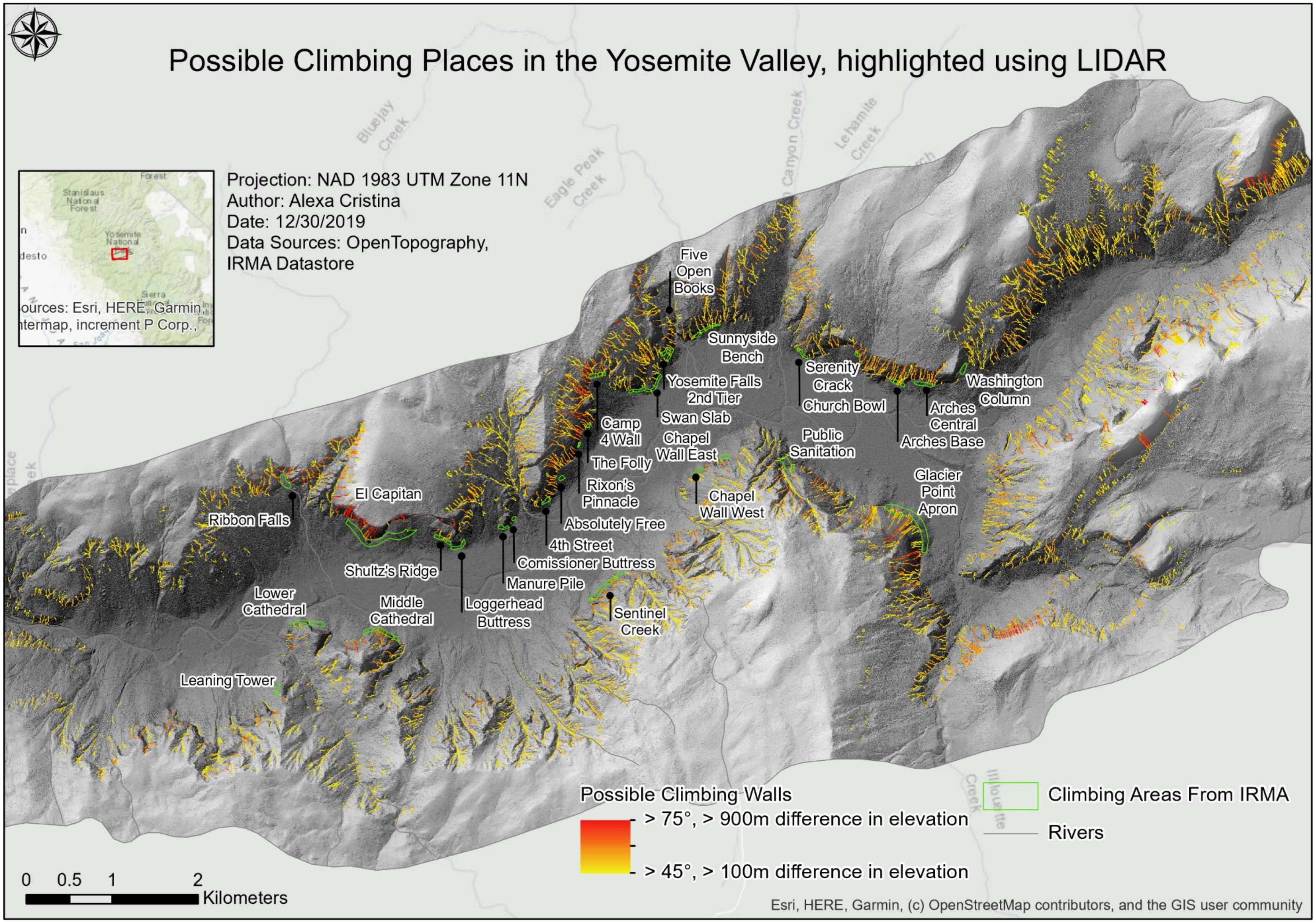
Climbing Areas From IRMA
Rivers
0 0.5 1 2 3 4
Kilometers
Esri, HERE, Garmin, (c) OpenStreetMap contributors, and the GIS user community


Possible Climbing Places in the Yosemite Valley, highlighted using LIDAR
Projection: NAD 1983 UTM Zone 11N
Author: Alexa Cristina
Date: 12/30/2019
Data Sources: OpenTopography,
IRMA Datastore
Ribbon Falls
El Capitan
Shultz's Ridge
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Church Bowl
Public Sanitation
Arches Central
Arches Base
Washington Column
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Bluejay Creek
Eagle Peak Creek
Lehamite Creek
Illilouette Creek
Possible Climbing Walls
> 75°, > 900m difference in elevation
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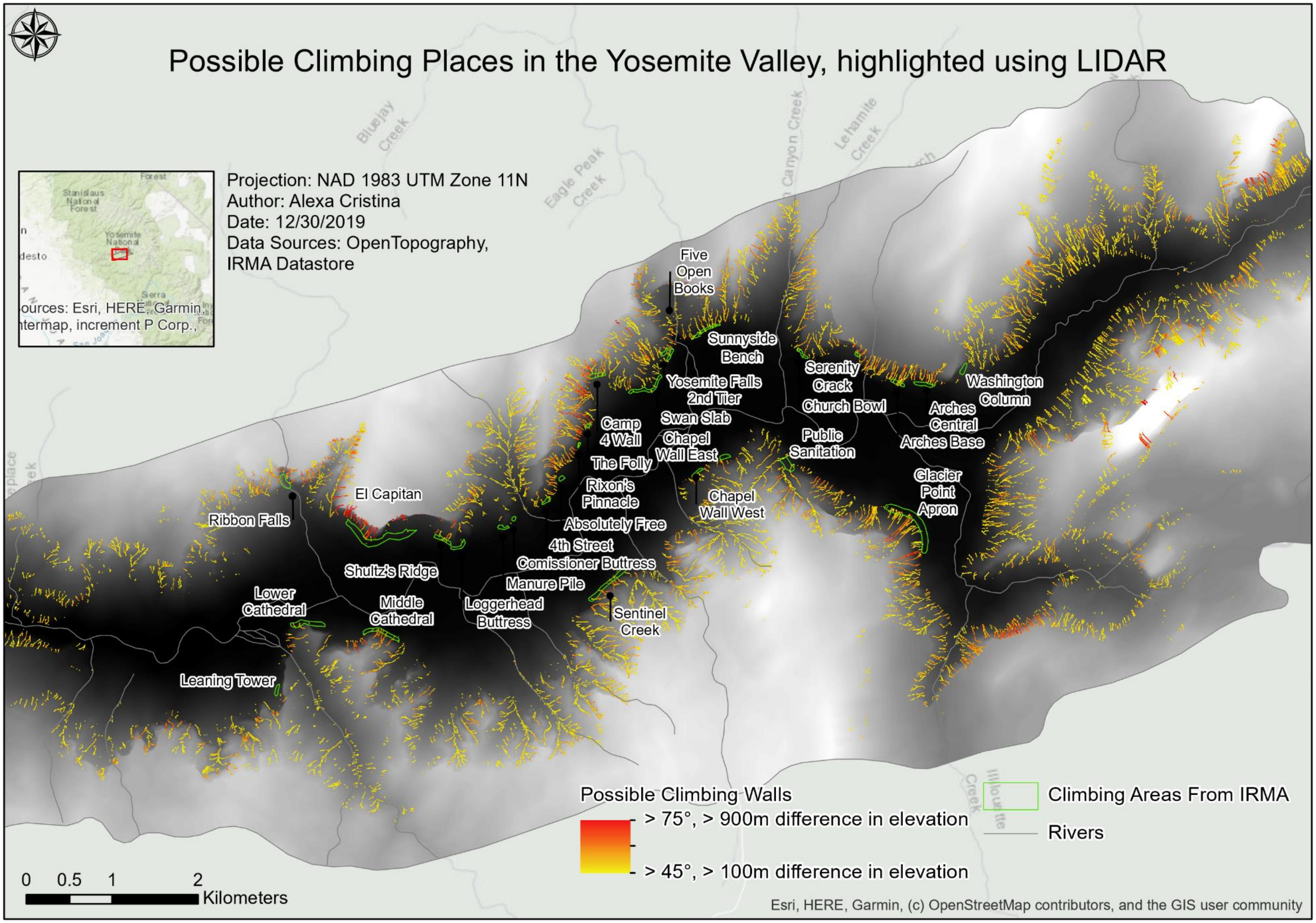
Climbing Areas From IRMA
Rivers
0 0.5 1 2 Kilometers
Esri, HERE, Garmin, (c) OpenStreetMap contributors, and the GIS user community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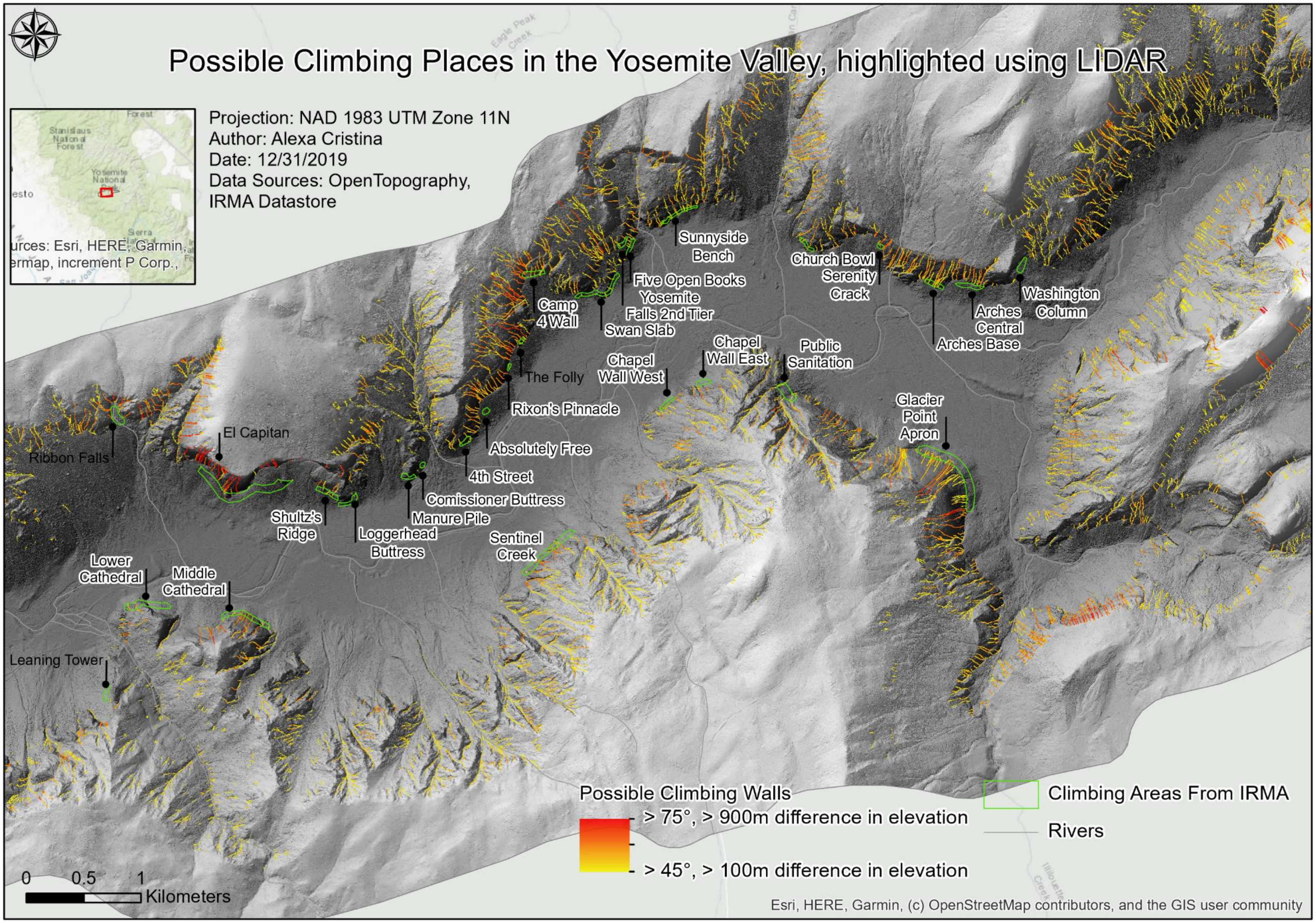
> 45°, > 100m difference in elevation
Climbing Areas From IRMA
Rivers
0 0.5 1 2 Kilometers
Esri, HERE, Garmin, (c) OpenStreetMap contributors, and the GIS user community



Possible Climbing Places in the Yosemite Valley, highlighted using LIDAR
Projection: NAD 1983 UTM Zone 11N
Author: Alexa Cristina
Date: 12/31/2019
Data Sources: OpenTopography,
IRMA Datastore
Stanislaus National Forest
Yosemite National Park
urces: Esri, HERE, Garmin,
ermap, increment P Corp.,
Ribbon Falls
El Capitan
Lower Cathedral
Middle Cathedral
Leaning Tower
Shultz's Ridge
Loggerhead Buttress
Manure Pile
Comissioner Buttress
4th Street
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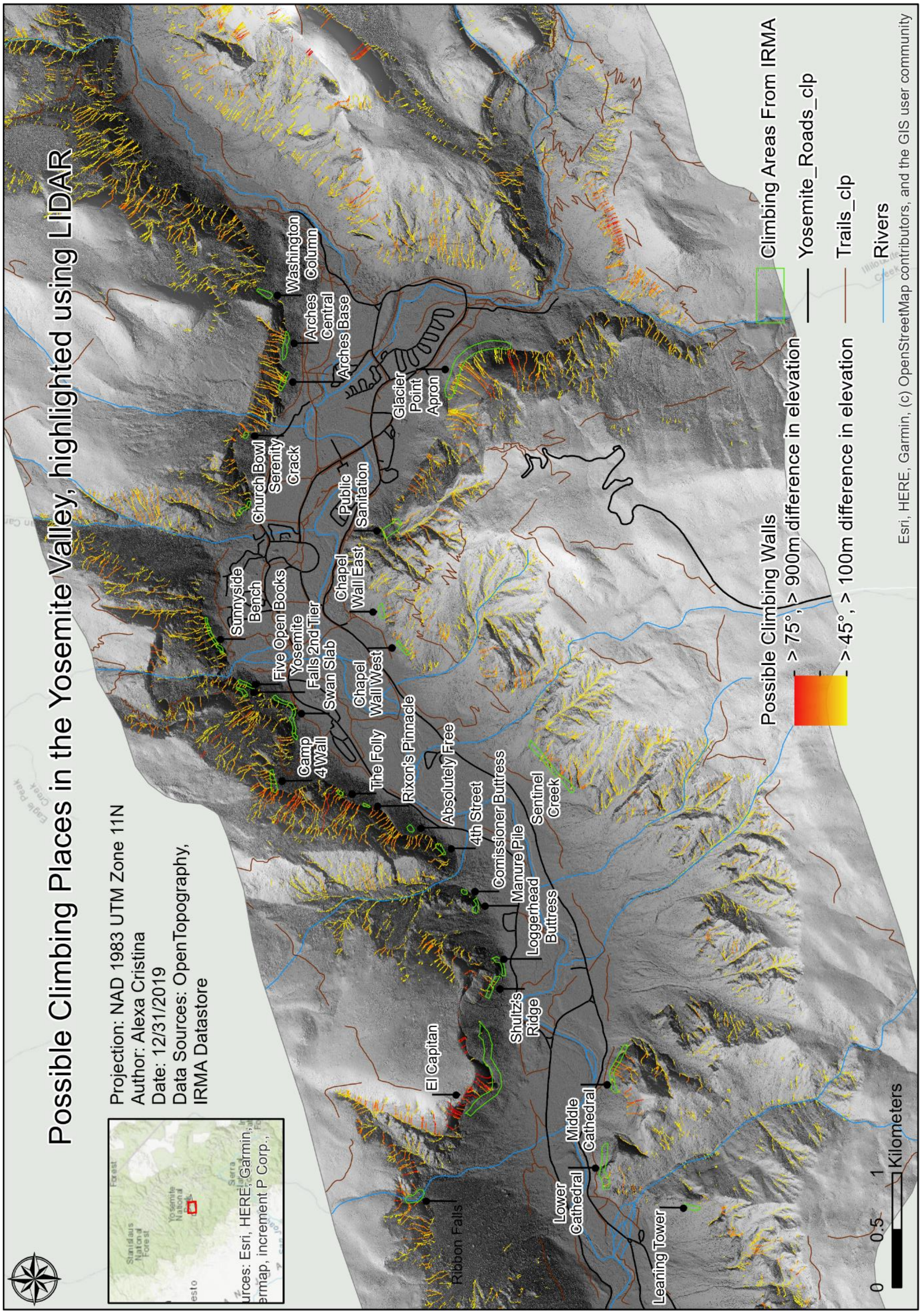
Church Bowl
Serenity Crack
Arches Base
Arches Central
Washington Column
Glacier Point Apron
Possible Climbing Walls
> 75°, > 900m difference in elevation
> 45°, > 100m difference in elevation
Climbing Areas From IRMA
Rivers
0 0.5 1 Kilometers
Esri, HERE, Garmin, (c) OpenStreetMap contributors, and the GIS user community


Possible Climbing Places in the Yosemite Valley, highlighted using LIDAR
Projection: NAD 1983 UTM Zone 11N
Author: Alexa Cristina
Date: 12/31/2019
Data Sources: OpenTopography, IRMA Datastore
Ribbon Falls
El Capitan
Lower Cathedral
Middle Cathedral
Leaning Tower
Shultz's Ridge
Loggerhead Buttress
Manure Pile
Comissioner Buttress
4th Street
Absolutely Free
Rixon's Pinnacle
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Camp 4 Wall
Swan Slab
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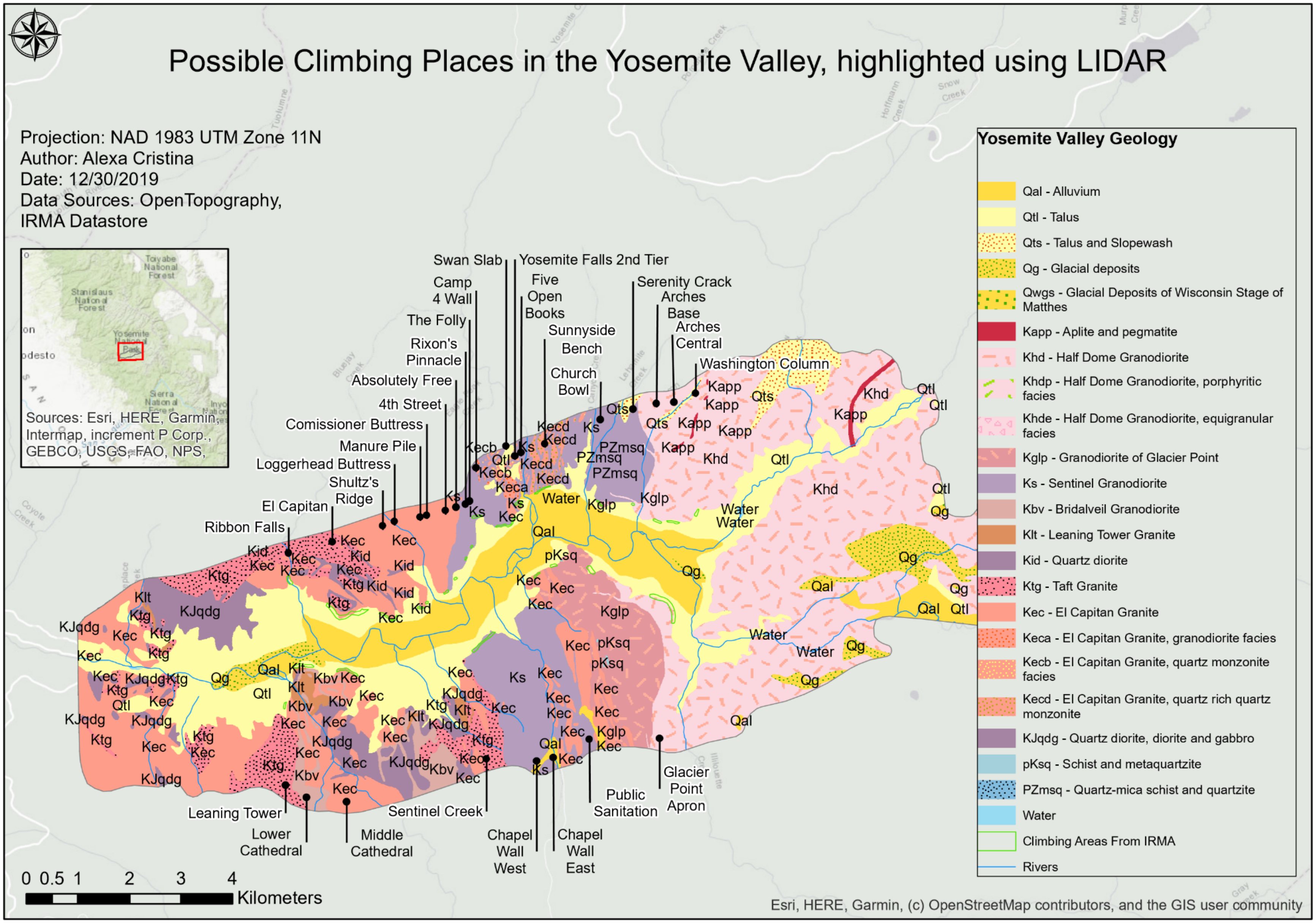
Chapel Wall East
Sentinel Creek
Public Sanitation
Church Bowl
Serenity Crack
Glacier Point Apron
Arches Base
Arches Central
Washington Column
Possible Climbing Walls
> 75°, > 900m difference in elevation
> 45°, > 100m difference in elevation
Climbing Areas From IRMA
Yosemite_Roads_clp
Trails_clp
Rivers
0 0.5 1 Kilometers
Esri, HERE, Garmin, (c) OpenStreetMap contributors, and the GIS user community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Date: 12/30/2019
Data Sources: OpenTopography,
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Sources: Esri, HERE, Garmin, Intermap, increment P Corp., GEBCO, USGS, FAO, NPS,
Swan Slab
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Arches
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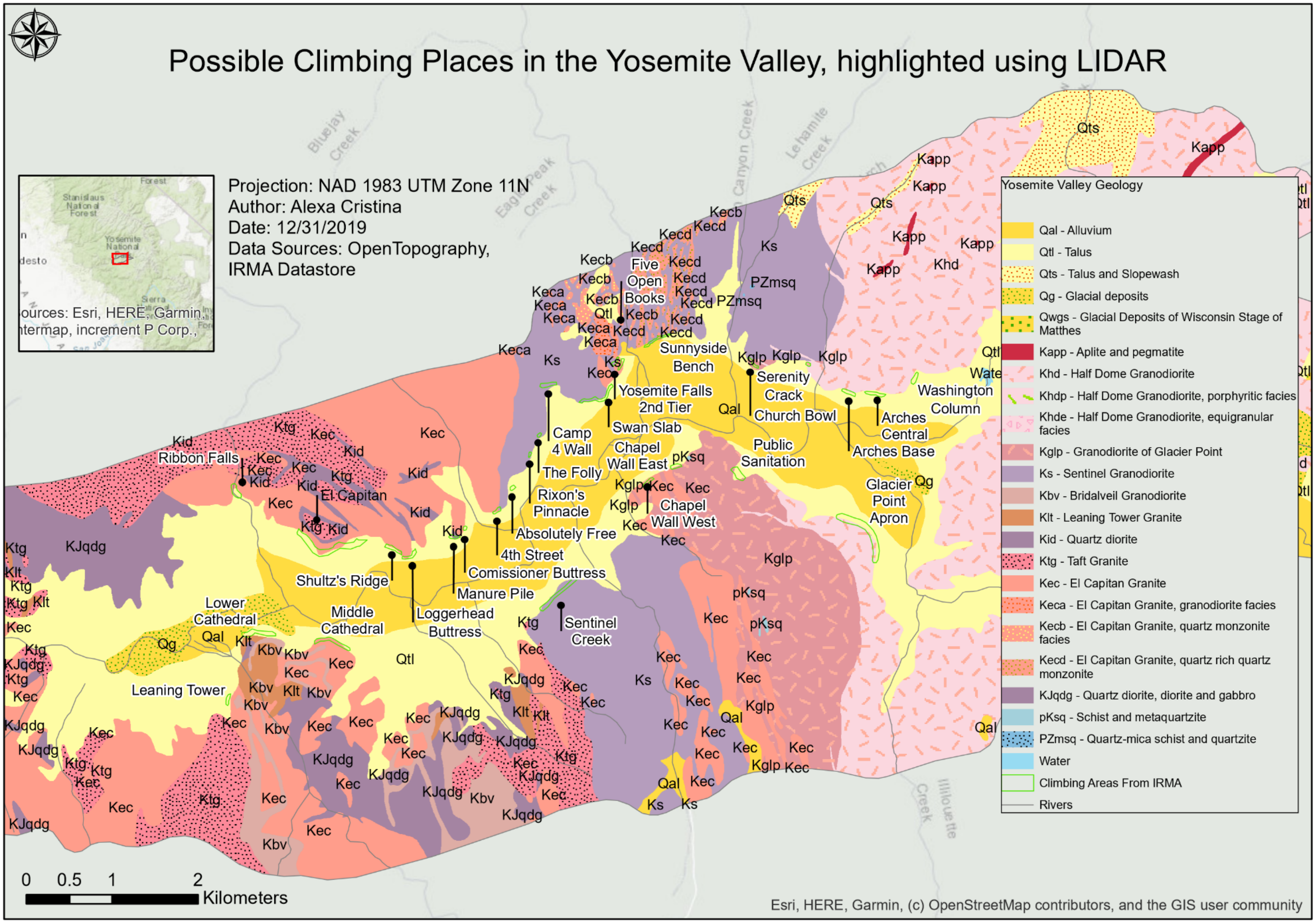
Glacier Point Apron
Public Sanitation
Chapel Wall East
Chapel Wall West
Sentinel Creek
Middle Cathedral
Lower Cathedral
Leaning Tower
Yosemite Valley Geology
Qal - Alluvium
Qtl - Talus
Qts - Talus and Slopewash
Qg - Glacial deposits
Qwgs - Glacial Deposits of Wisconsin Stage of Matthes
Kapp - Aplite and pegmatite
Khd - Half Dome Granodiorite
Khdp - Half Dome Granodiorite, porphyritic facies
Khde - Half Dome Granodiorite, equigranular facies
Kglp - Granodiorite of Glacier Point
Ks - Sentinel Granodiorite
Kbv - Bridalveil Granodiorite
Klt - Leaning Tower Granite
Kid - Quartz diorite
Ktg - Taft Granite
Kec - El Capitan Granite
Keca - El Capitan Granite, granodiorite facies
Kecb - El Capitan Granite, quartz monzonite facies
Kecd - El Capitan Granite, quartz rich quartz monzonite
KJqdg - Quartz diorite, diorite and gabbro
pKsq - Schist and metaquartzite
PZmsq - Quartz-mica schist and quartzite
Water
Climbing Areas From IRMA
Rivers
0 0.5 1 2 3 4
Kilometers
Esri, HERE, Garmin, (c) OpenStreetMap contributors, and the GIS user community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Projection: NAD 1983 UTM Zone 11N
Author: Alexa Cristina
Date: 12/31/2019
Data Sources: OpenTopography, IRMA Datastore
Yosemite Valley Geology
Qal - Alluvium
Qtl - Talus
Qts - Talus and Slopewash
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Kglp - Granodiorite of Glacier Point
Ks - Sentinel Granodiorite
Kbv - Bridalveil Granodiorite
Klt - Leaning Tower Granite
Kid - Quartz diorite
Ktg - Taft Granite
Kec - El Capitan Granite
Keca - El Capitan Granite, granodiorite facies
Kecb - El Capitan Granite, quartz monzonite facies
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pKsq - Schist and metaquartzite
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Water
Climbing Areas From IRMA
Rivers
Ribbon Falls
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Lower Cathedral
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Loggerhead Buttress
Manure Pile
Comissioner Buttress
4th Street
Absolutely Free
Rixon's Pinnacle
The Folly
Camp 4 Wall
Swan Slab
Chapel Wall East
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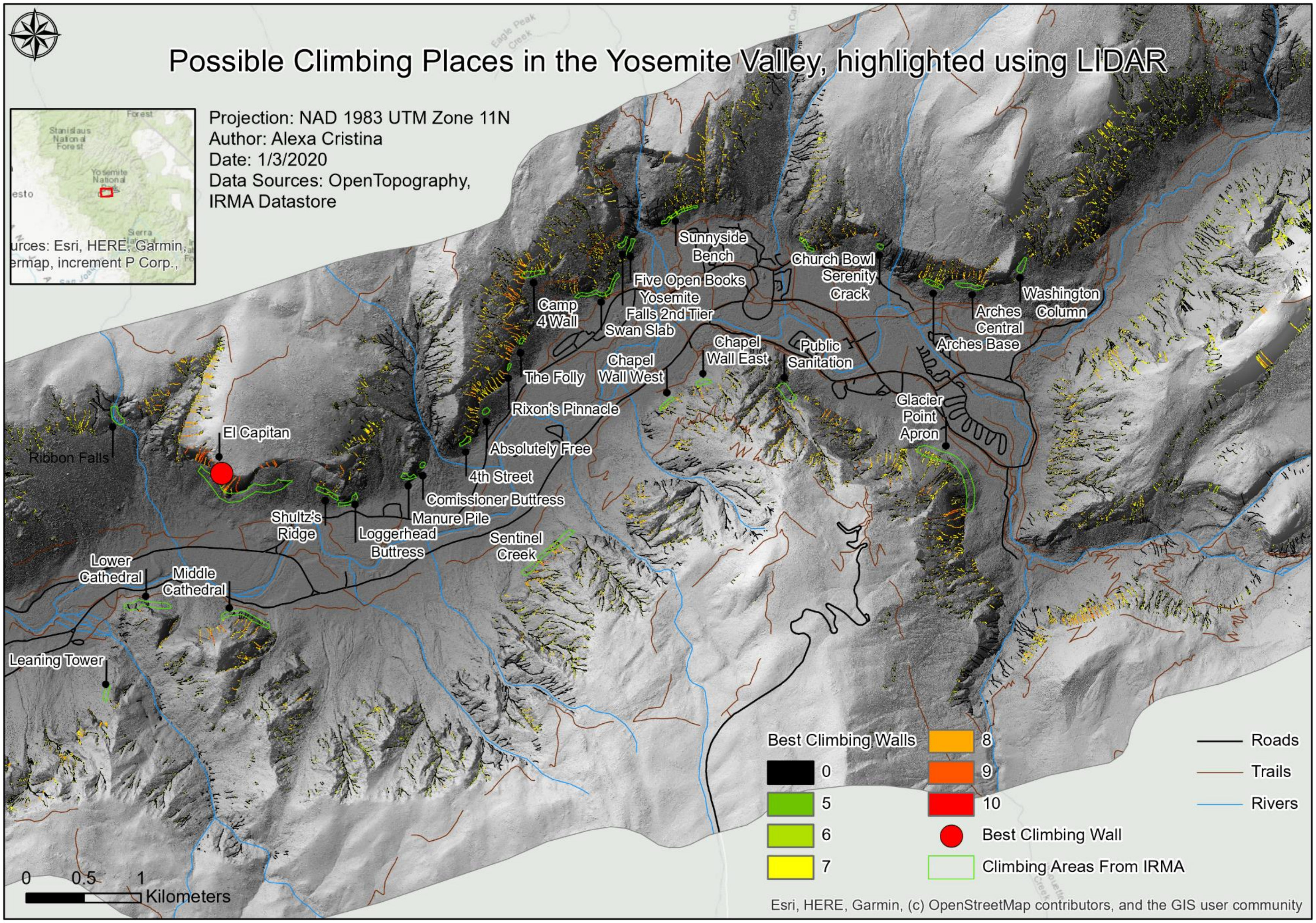
Sentinel Creek
Five Open Books
Yosemite Falls 2nd Tier
Sunnyside Bench
Serenity Crack
Church Bowl
Public Sanitation
Arches Central
Arches Base
Washington Column
Glacier Point Apron
Bluejay Creek
Eagle Peak Creek
Indian Canyon Creek
Lehamite Creek
Illilouette Creek
0 0.5 1 2 Kilometers
Esri, HERE, Garmin, (c) OpenStreetMap contributors, and the GIS user community


Possible Climbing Places in the Yosemite Valley, highlighted using LIDAR
Projection: NAD 1983 UTM Zone 11N
Author: Alexa Cristina
Date: 1/3/2020
Data Sources: OpenTopography,
IRMA Datastore
Ribbon Falls
El Capitan
Lower Cathedral
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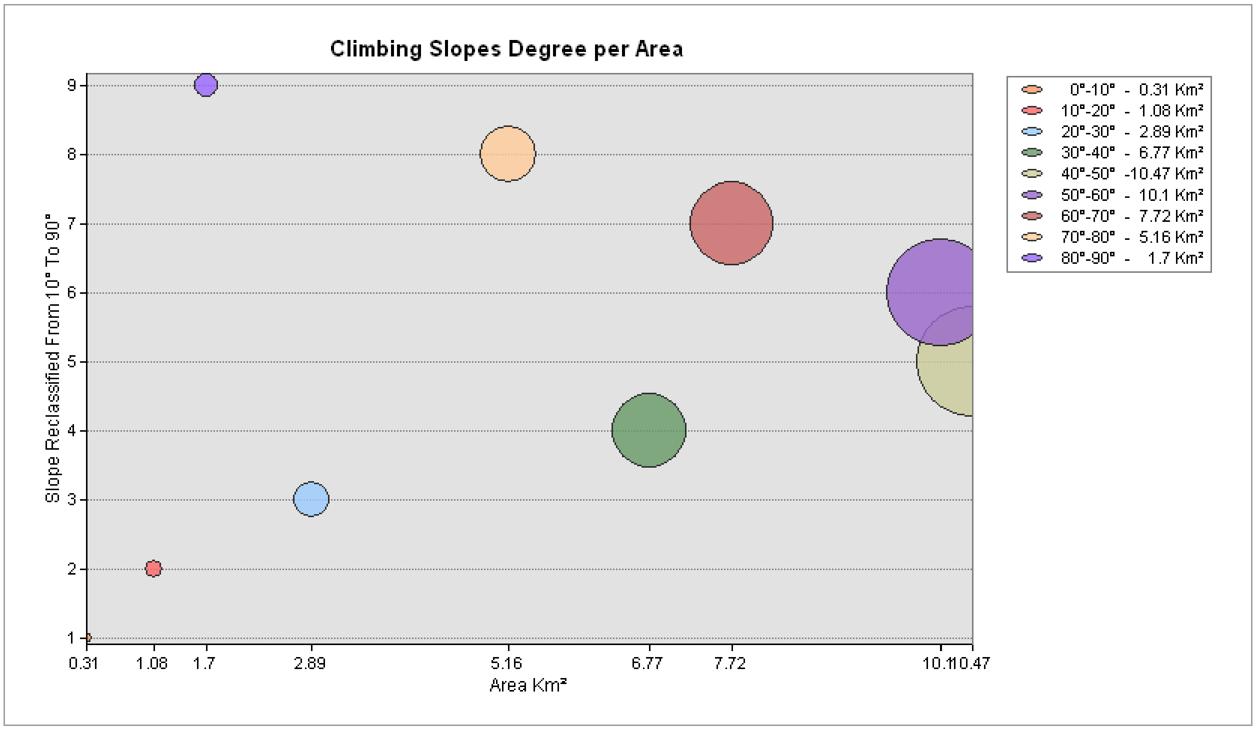
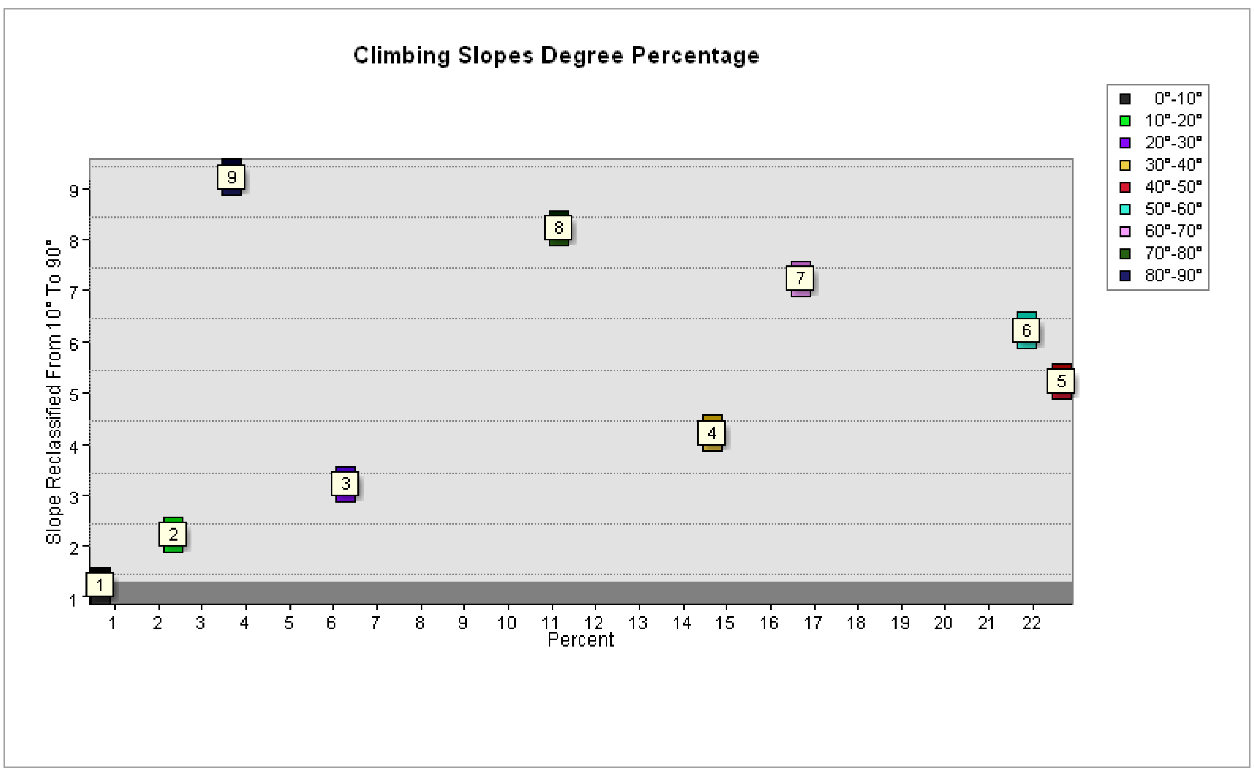
Chapel Wall West
Chapel Wall East
Public Sanitation
Church Bowl
Serenity Crack
Arches Base
Arches Central
Washington Column
Glacier Point Apron
Best Climbing Walls
0
5
6
7
8
9
10
Best Climbing Wall
Climbing Areas From IRMA
Roads
Trails
Rivers
0
0.5
1
Kilometers
Esri, HERE, Garmin, (c) OpenStreetMap contributors, and the GIS user community

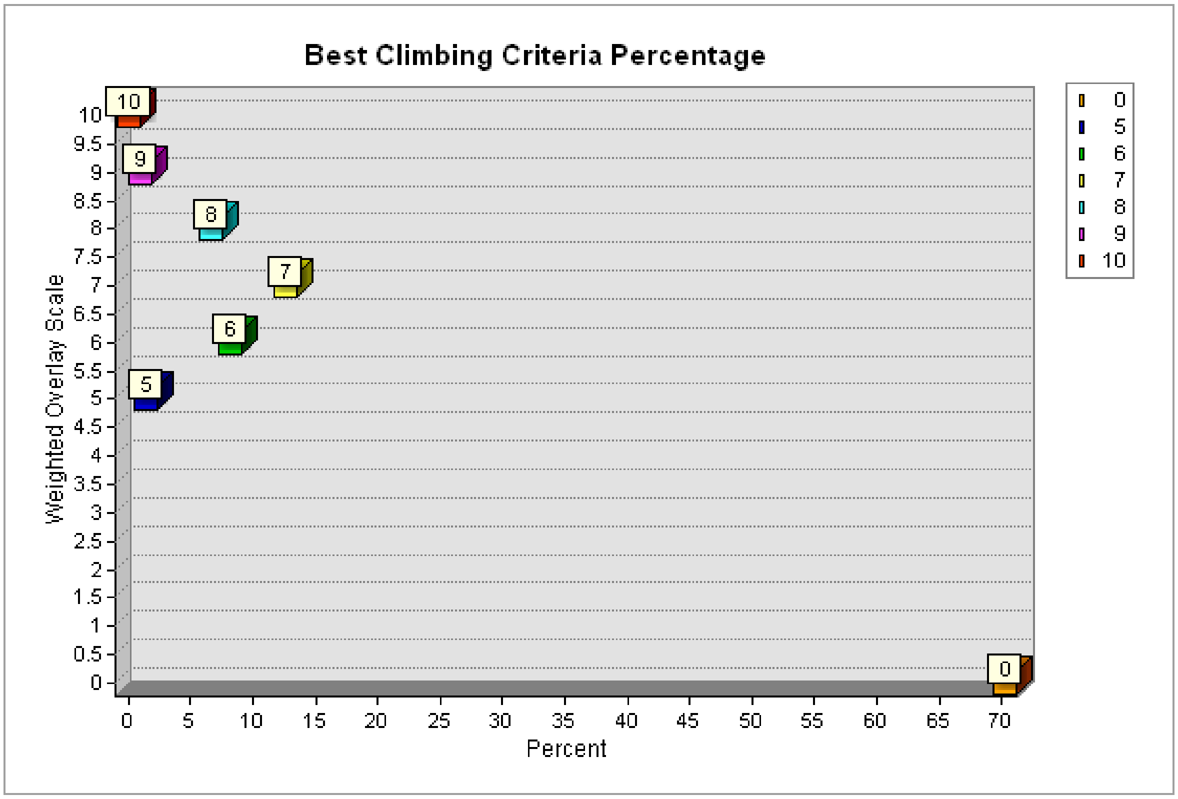
F. GRAPHS

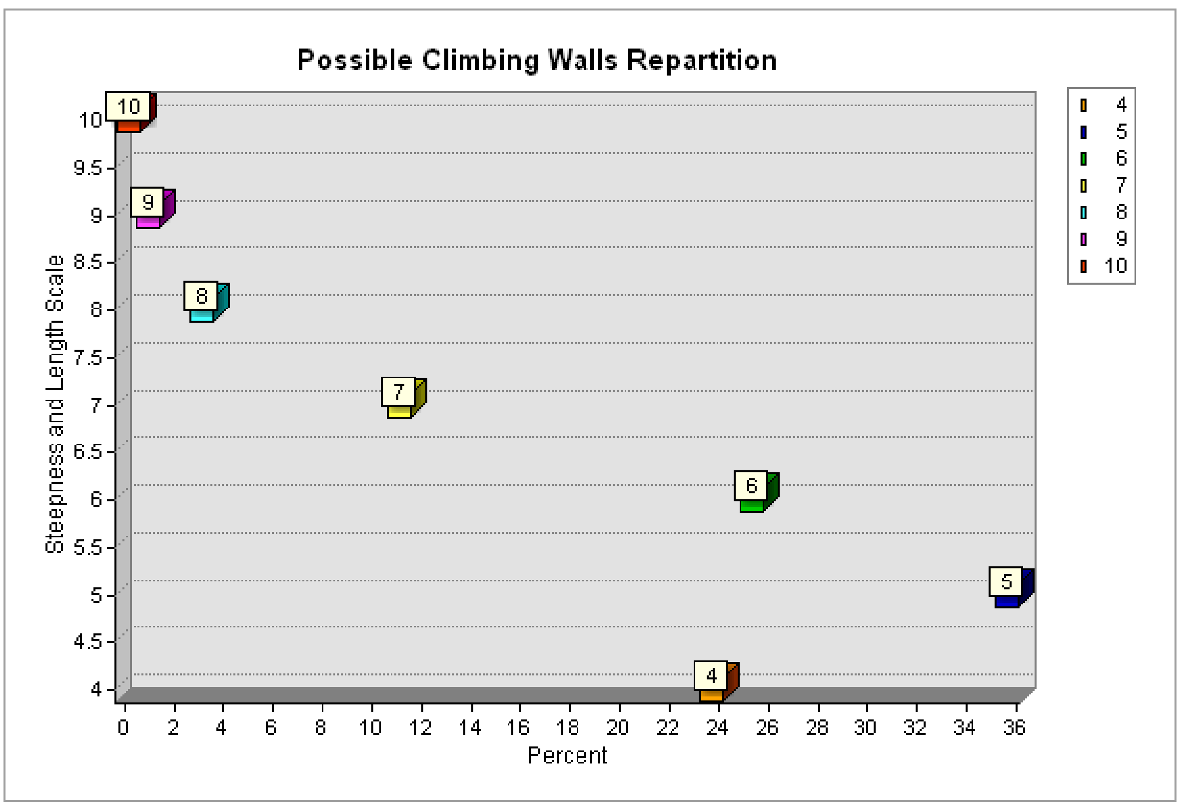


Climbing Slopes Degree per Area
Slope Reclassified From 10° To 90°
Area Km²
0.31
1.08
1.7
2.89
5.16
6.77
7.72
10.110.47
0°-10° - 0.31 Km²
10°-20° - 1.08 Km²
20°-30° - 2.89 Km²
30°-40° - 6.77 Km²
40°-50° -10.47 Km²
50°-60° - 10.1 Km²
60°-70° - 7.72 Km²
70°-80° - 5.16 Km²
80°-90° - 1.7 Km²



Climbing Slopes Degree Percentage
Slope Reclassified From 10° To 90°
Percent
0°-10°
10°-20°
20°-30°
30°-40°
40°-50°
50°-60°
60°-70°
70°-80°
80°-90°


Best Climbing Criteria Percentage
Weighted Overlay Scale
Percent
0
5
6
7
8
9
10


Possible Climbing Walls Repartition
Steepness and Length Scale
Percent
4
5
6
7
8
9
10

G. ARCSCENE 3D MODELS