The Effects of DEM Resolution on Visibility

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Abstract

Viewshed analysis is commonly used to analyze the visibility or lack of visibility in terrain data. This study identifies how the resolution of bare-Earth DEMs (digital elevation model) effects the visibility and invisibility of varying terrains during a viewshed analysis by looking at changes in visible and invisible areas based on three DEM resolutions (1m, 10m, and 30m). Results are displayed using terrain mapping techniques and profiles to show how small changes in elevation can alter the visible area.

This study uses a stratified sampling strategy, first classifying terrains across the conterminous United States into three categories: flat, hilly, and mountainous. Three sample sites were selected from different regions. Potential sites within each terrain type must contain good quality DEMs at all three resolutions and continually cover a minimal sample area measuring 30x30 km. This allows enough space for four evenly-spaced observation points to have a viewshed radius of 5 km without any overlap. The observer points used in this study are not designed to be the ideal locations (best view), but are rather at random elevations, despite a regular horizontal spacing.

Key findings in this study show the benefits of using multiple resolutions to check and confirm the accuracy of data. Across all nine sites, there was an 81.6% consistency between the 1m, 10m, and 30m DEMs (Figure 18). Also, no obvious landform type patterns were observed, however some patterns that influenced the observer's sight were noted. The observer height varied across the DEM resolutions, and these changes to the observer or the nearby area in the line-of-sight greatly affected what was visible to the observer. It also found that effects around the observer or where the observer

stands impact the line-of-sight profiles and the overall visibility of the observer. Choosing the placement of the observer point to be optimal at all resolutions could help improve the accuracy among various DEM resolutions.

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Introduction

Miller commented that, “Terrain visibility has had an enormous impact on military history and has determined the outcomes of battles….” In order to make the best-informed battle decisions, being at the highest place on the battlefield offered troops the ability to gain an understanding of where their sight advantages were before computers existed and viewshed analysis was performed digitally. (Miller, 56, 2011). While knowing the landscape may alter the outcome of a battle, it is imperative that the analysis can accurately evaluate the landscape.

The purpose of this paper was to study how a DEM’s resolution changed the amount of visibility across different landforms. When considering what resolution to use, this study sought to use line-of-sight analysis of DEMs across a spectrum of resolution using viewshed analysis. One might anticipate mountains to produce the greatest amount of change in visibility, but can a higher resolution reduce the amount of area visible, or what is invisible? If a 1m DEM shows a valley or little nooks that the 10m DEM does not detect, this may indicate it is the best imagery for viewsheds in mountainous areas. If there is not a large difference, however, then why invest in a higher resolution than is actually needed?

First, a square representing the study area was created in ArcMap and projected into the area’s appropriate UTM zone. Then, a feature class containing four evenly-spaced points was created for each study area. Once the DEMs were visually inspected for errors and preprocessed in ArcMap, the appropriate DEM was added and an automated viewshed tool used the line-of-sight analysis, creating individual viewsheds for each point on the grid.

The visibility of each observer was captured in area of visibility. The study could then determine how many resolutions overlapped over the entire area. Also, line-of-sight profiles were used for comparison, allowing the DEMs to be compared at 1m, 10m, and 30m across various types of terrains in the continental United States (ex: mountains and plains).

Using viewsheds to determine variations in visible area and the reasons for these changes, this study hoped to produce results to determine if DEM resolution changed the viewsheds across different landscapes and determine if the highest resolution DEM is always a consumer's best choice for the most accurate results. An additional objective was to determine if certain land types would always require higher quality resolution than others and if some land types could be as accurate with lower quality DEMs.

Literature Review

One challenge for this study was to determine how many landforms would accurately reflect the contiguous United States. Too many landforms would greatly increase the scope of the study, while too few would leave gaps, lacking enough variety to capture the diverse landscapes. In addition to how the landforms appear on a map, differences of landforms in DEMs were also considered.

One approach to determining important landforms is the use of physical regions. The U.S. Geographical Survey divided the United States into eight regions: the Laurentian Uplands, Atlantic Plains, Appalachian Highlands, Interior Plains, Interior Highlands, Rocky Mountain System, Intermontane Plateaus, and Pacific Mountain System (Thelin and Pike, 1991). Combining the different regions would create five landform categories:

highlands, mountains, the Intermontane Plateaus, plains, and uplands, and samples could be collected from the eight regions (Figure 1).

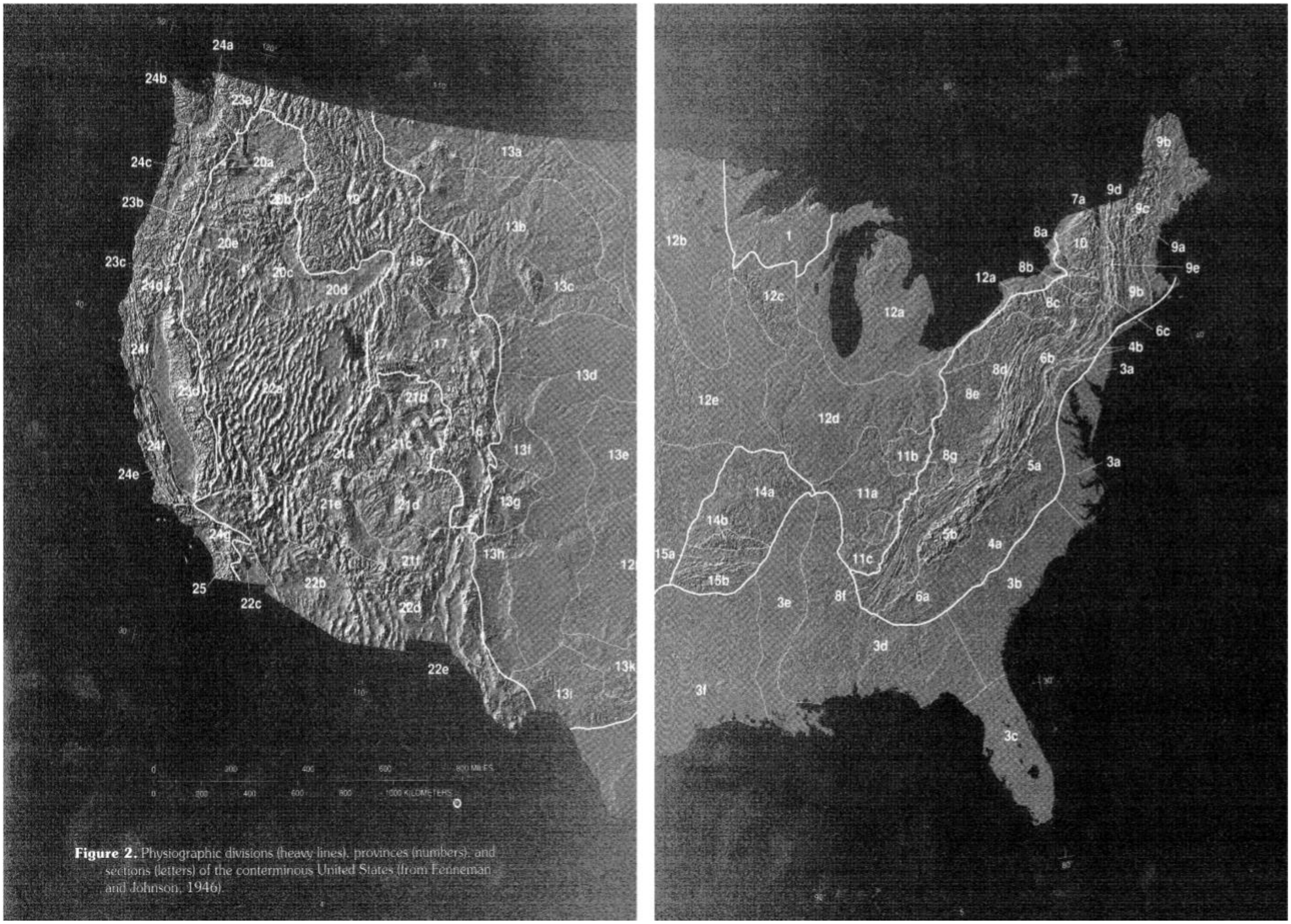

Figure 2. Physiographic divisions (heavy lines), provinces (numbers), and sections (letters) of the conterminous United States (from Fenneman and Johnson, 1946).

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EXPLANATION

LAURENTIAN UPLAND
1. Superior Upland

ATLANTIC PLAIN
2. Continental Shelf (not on map)
3. Coastal Plain
   a. Embayed section
   b. Sea Island section
   c. Floridian section
   d. East Gulf Coastal Plain
   e. Mississippi Alluvial Plain
   f. West Gulf Coastal Plain

APPALACHIAN HIGHLANDS
4. Piedmont province
   a. Piedmont Upland
   b. Piedmont Lowlands
5. Blue Ridge province
   a. Northern section
   b. Southern section
6. Valley and Ridge province
   a. Tennessee section
   b. Middle section
   c. Hudson Valley
7. St. Lawrence Valley
   a. Champlain section
   b. Northern section (not on map)
8. Appalachian Plateaus
   a. Mohawk section
   b. Catskill section
   c. Southern New York section
   d. Allegheny Mountain section
   e. Kanawha section
   f. Cumberland Plateau section
   g. Cumberland Mountain section
9. New England Province
   a. Seaboard Lowland section
   b. New England Upland section
   c. White Mountain section
   d. Green Mountain section
   e. Taçonic section
10. Adirondack province

INTERIOR PLAINS
11. Interior Low Plateaus
   a. Highland Rim section
   b. Lexington Plain
   c. Nashville Basin
12. Central Lowland
   a. Eastern Lake section
   b. Western Lake section
   c. Wisconsin Driftless section
   d. Till Plains
   e. Dissected Till Plains
   f. Osage Plains
13. Great Plains province
   a. Missouri Plateau, glaciated
   b. Missouri Plateau, unglaciated
   c. Black Hills
   d. High Plains
   e. Plains Border
   f. Colorado Piedmont
   g. Raton section
   h. Pecos Valley
   i. Edwards Plateau
   k. Central Texas section

INTERIOR HIGHLANDS
14. Ozark Plateaus
   a. Springfield-Salem plateaus
   b. Boston "Mountains"
15. Ouachita province
   a. Arkansas Valley
   b. Ouachita Mountains

ROCKY MOUNTAIN SYSTEM
16. Southern Rocky Mountains
17. Wyoming Basin
18. Middle Rocky Mountains
19. Northern Rocky Mountains

INTERMONTANE PLATEAUS
20. Columbia Plateau
   a. Walla Walla Plateau
   b. Blue Mountain section
   c. Payette section
   d. Snake River Plain
   e. Harney section
21. Colorado Plateaus
   a. High Plateaus of Utah
   b. Uinta Basin
   c. Canyon Lands
   d. Navajo section
   e. Grand Canyon section
   f. Datil section
22. Basin and Range province
   a. Great Basin
   b. Sonoran Desert
   c. Salton Trough
   d. Mexican Highland
   e. Sacramento section

PACIFIC MOUNTAIN SYSTEM
23. Cascade-Sierra Mountains
   a. Northern Cascade Mountains
   b. Middle Cascade Mountains
   c. Southern Cascade Mountains
   d. Sierra Nevada
24. Pacific Border province
   a. Puget Trough
   b. Olympic Mountains
   c. Oregon Coast Range
   d. Klamath Mountains
   e. California Trough
   f. California Coast Ranges
   g. Los Angeles Ranges
25. Lower Californian province

Figure 1: USGS, 1991. The USGS groups the United States into eight physical regions with subcategories.

Another approach is to consider what landform types are visible on a small-scale map and how they would be grouped. Edwin H. Hammond created a small-scale map of the United States that would more accurately reflect the variety of terrains, while also being easily read visually; this means that he did not include too many categories, which would be difficult to test, and that the groupings were more general than regional or local studies. The eight groupings he chose were: Nearly flat plains, rolling and irregular plains, plains with widely spaced hills or mountains, partially dissected tablelands, hills, low mountains, high mountains, and ice caps. These groupings can be reduced to: plains, mountains, hills, and tablelands; ice caps would be removed because Alaska is not included in the study. Definitions appear in Figure 2 and Figure 3 shows Hammond's map of North America (Hammond, 1954). While this approach seems simpler because there are only four groups, other samples would have to be used to satisfy the seven subcategories.

Approximate definitions of the groupings or terrain types shown on the maps are as follows:

I. *Nearly flat plains.* Lands of low relief and a very high percentage of near-level land. Profile not critical.

II. *Rolling and irregular plains.* Lands of rather low relief and a high percentage of near-level land. No high steep slopes. Profile otherwise not critical.

III. *Plains with widely-spaced hills or mountains.* Lands of moderate to high relief, but with a high percentage of near-level land. Much of the level land is relatively low-lying.

IV. *Partially dissected tablelands.* Lands of moderate to high relief, but with a high percentage of near-level land. Much of the level land is relatively high-lying.

V. *Hills.* Lands of moderate relief, but with a low percentage of near-level land. Profile not critical.

VI. *Low mountains.* Lands of high relief, with a low percentage of near-level land. Profile not critical.

VII. *High mountains.* Lands of very high relief, with a low percentage of near-level land. Profile not critical.

In addition to these seven classes based upon relief, flatness and profile, an eighth class is recognized, based upon the distinctive character of the surface material:

VIII. *Ice caps.* Extensive fields of permanent ice.

This type of terrain is fairly extensive in occurrence and clearly does not fit adequately into the other classes.

Figure 2: Hammond, 1954 also uses eight groupings, however he looks at breaking down the land more by elevation changes.

Figure 3: Hammond, 1954 breaks mountains, plains, and hills into several groups. Ice caps exist outside of the region of this study.

Since Hammond's work was published in 1954, another method has built off his approach. The Dikau method, as revised by MacMillian and Shary (2008), condensed Hammond's eight landforms into five groups: plains, hills and mountains, plains with hills or mountains, open hills and mountains, and tableland and uses twenty-four subclasses (Figure 4 and Figure 5) (MacMillan and Shary, 2008). The subclasses, however, are too specific for this study.

TABLE 4 Classification criteria of the Dikau et al. (1991) method

Distribution of gentle slopes	Local relief	Profile type
(A) More than 80% of the area is gently sloping	(1) 0–30 m	(a) More than 75% of gentle slope is lowland
(B) 50–80% of the area is gently sloping	(2) 30–91 m	(b) 50–75% of gentle slope is lowland
(C) 20–50% of the area is gently sloping	(3) 91–152 m	(c) 50–75% of gentle slope is upland
(D) Less than 20% of the area is gently sloping	(4) 152–305 m (5) 305–915 m (6) >915 m	(d) More than 75% gentle slope is upland

Figure 4: MacMillan and Shary, 2008. Dikau adds slope into Hammond's method.

TABLE 5 Classes and subclasses of the Dikau method (Bayramin, 2000)

Landform type	Landform class	Landform subclass code
Plains (PLA)	Flat or nearly flat	A1a, A1b, A1c, A1d
	Smooth plains with some local relief	A2a, A2b, A2c, A2d
	Irregular plains with low relief	B1a, B1b, B1c, B1d
	Irregular plains with moderate relief	B2a, B2b, B2c, B2d
Tablelands (TAB)	Table lands with moderate relief	A3c, A3d, B3c, B3d
	Table lands with considerable relief	A4c, A4d, B4c, B4d
	Table lands with high relief	A5c, A5d, B5c, B5d
	Table lands with very high relief	A6c, A6d, B6c, B6d
Plains with Hills or Mountains (PHM)	Plains with hills	A3a, A3b, B3a, B3b
	Plains with high hills	A4a, A4b, B4a, B4b
	Plains with low mountains	A5a, A5b, B5a, B5b
	Plains with high mountains	A6a, A6b, B6a, B6b
Open Hills and Mountains (OPM)	Open very low hills	C1a, C1b, C1c, C1d
	Open low hills	C2a, C2b, C2c, C2d
	Open moderate hills	C3a, C3b, C3c, C3d
	Open high hills	C4a, C4b, C4c, C4d
	Open low mountains	C5a, C5b, C5c, C5d
	Open high mountains	C6a, C6b, C6c, C6d
Hills and Mountains (HMO)	Very low hills	D1a, D1b, D1c, D1d
	Low hills	D2a, D2b, D2c, D2d
	Moderate hills	D3a, D3b, D3c, D3d
	High hills	D4a, D4b, D4c, D4d
	Low mountains	D5a, D5b, D5c, D5d
	High mountains	D6a, D6b, D6c, D6d

Figure 5: MacMillan and Shary, 2008 Dikau attempts to simplify Hammond's eight categories into five, however the subcategories now group a larger variety of landforms/elevation combinations.

Especially because Hammond's approach is dated, factors like technology advancements needed to be considered. So, to determine the better approach, the affects that landscape could have on DEMs was investigated. Ultimately, one of the biggest factors considered was that elevation fluctuations reduce the accuracy of a DEM (Miller, 2011), and for this reason Hammond's approach will likely give a better reflection of DEM resolution differences across the contiguous United States for this project.

Miller performed a study in Wytheville, Virginia to compare DEMs created through photogrammetric processes to DSMs resulting from LiDAR using a viewshed analysis algorithm. The DEMs (1m, 5m, 10m, 20m, 30m, and 40m) and DSMs (.5m, 1m, 2m, 5m, and 10m) were compared at several resolutions, as well, to determine if some resolutions were more suited to viewshed analysis than others. He used observer points and then a created a second set of points of what the observers would be attempting to view. The results from the viewshed were compared to field study results as a method to verify the results (Miller, 2011).

The results, as shown in Figure 6 and Figure 7, reflect that as resolution decreases, so will a viewshed's accuracy. Miller noted that .5m, 1m, and 2m DSMs showed very similar results (they varied two to three percent in all categories), while results for 5m and 10m varied more. He suggested that .5m, 1m, and 2m DSMs were very similar and that the differences could not be confirmed as significant because they were so close together. The DEMs results, overall, were lower than the LiDAR DSMs and tended to vary more, not creating any sort of pattern. DSMs were also more likely to mark areas that were visible as not visible (often because of vegetation), while DEMs over-reported visible areas that were not actually visible. In his study, Miller used various degrees of visibility, and concluded that DEMs will be most accurate if assuming any point being observed is visible (Miller, 2011). Because this study will not be field-checking elevation points, based on Miller's results, the accuracy of the viewshed created cannot be verified.

Degrees of field visibility considered:		*All visibility levels*		*Partially, mostly, and fully visibile*		*Mostly and fully visible*		*Only fully visible*	
	Surface Resolution	% Correct	% Incorrect	% Correct	% Incorrect	% Correct	% Incorrect	% Correct	% Incorrect
	LIDAR 0.5m	61.9	38.1	67.1	32.9	71.0	29.0	71.0	29.0
LIDAR DSMs	LIDAR 1m	62.6	37.4	68.4	31.6	71.0	29.0	71.0	29.0
	LIDAR 2m	60.6	39.4	65.8	34.2	68.4	31.6	71.0	29.0
	LIDAR 5m	62.6	37.4	69.0	31.0	67.7	32.3	67.7	32.3
	LIDAR 10m	59.4	40.6	64.5	35.5	64.5	35.5	63.2	36.8

Figure 6: Miller, 2011. The results of the DSMs show fully visible as having the best percentage of correct results, however incorrectness did not vary between mostly and fully visible. Results generally improved as visibility improved (correctness increased, and incorrect mistakes decreased).

Degrees of field visibility considered:		*All visibility levels*		*Partially, mostly, and fully visibile*		*Mostly and fully visible*		*Only fully visible*	
	Surface Resolution	*% Correct*	*% Incorrect*	*% Correct*	*% Incorrect*	*% Correct*	*% Incorrect*	*% Correct*	*% Incorrect*
	DEM 1m	53.5	46.5	52.9	47.1	48.4	51.6	41.9	58.1
	DEM 5m	54.8	45.2	52.9	47.1	48.4	51.6	41.9	58.1
DEMs	DEM 10m	50.3	49.7	52.9	47.1	49.7	50.3	41.3	58.7
	DEM 20m	51.6	48.4	51.6	48.4	45.2	54.8	40.0	60.0
	DEM 30m	50.3	49.7	51.6	48.4	45.2	54.8	40.0	60.0
	DEM 40m	52.9	47.1	52.9	47.1	46.5	53.5	41.3	58.7

Figure 7: Miller, 2011. The DEMs tested started off lower the DSMs and decreased as visibility increased. Correctness or incorrectness did not seem to be affected by resolution.

Miller's study shows the importance of accuracy in viewshed analysis, but factors impacting a DEMs accuracy might also affect the number of landforms that should be used in this study. Factors like height can reduce the accuracy of DEMs. It is expected that as the slope and elevation of a DEM increase, there will be more differences between resolutions than on flatter areas. Therefore, in more hilly or mountainous areas, one should expect some viewshed accuracy to be lost (Miller, 2011 and Thompson, Bell, and Butler, 2001). When considering LiDAR, one should also pay attention to the spacing of points; more closely spaced points will more accurately reflect the terrain (Miller, 24-26, 2011); this is also true for DEMs. The way elevation data was measured, how precisely the elevation was measured, and where the elevation data came from also plays an important role in its accuracy (Thompson, Bell, and Butler, 2001).

The study done by Thompson selected a site in Dalton, Minnesota and collected 10m and 30m USGS DEMs and created four of their own, so the 10m and 30m had vertical precision of .1 and 1.0. They confirmed findings of previous studies that horizontal resolution affects a DEM’s slope; they refer to this as smoothing. As the resolution decreases (from 10m to 30m) the size of every cell is increased and therefore small details disappear. This can make slopes flatter or steeper than they really are. The vertical precision created sharper changes in steepness when changed from .01 to 1.0, though this changes in relation to horizontal resolution. Their study found the biggest variations were along dips in the landscape (ex: valleys and riverbanks) (Thompson, Bell, and Butler, 2001).

This study extended on existing research by diving deeper into the differences between different DEM resolutions comparing the types of terrain selected for this study. Studies found for the literature review either tested one landform type or a mix of several as one sample. Resolutions compared two types of landforms or several close together but across many terrain features (Miller, 2011). This study broke apart the landforms and tested them separately against a broader range of DEM resolutions, and the findings offer recommendations based on the patterns across resolution quality and landforms. By grouping this way, this study gained insights into how DEM resolutions effect what is visible or not in a viewshed, as well as if landform types shaped these outcomes.

Methods

To perform this study, only bare earth DEMs were used. This was intended to prevent noise caused by human-made obstructions and vegetation. 1 meter, 10 meter, and 30 meter data from USGS was used, and it was decided to limit study locations to only parts of the continental United States; islands, Hawaii, and Alaska were excluded. The five groups used in the modified Dikau method were further condensed into three groups in this study (flat, hilly, and mountainous), and three sites were collected for each type, resulting in nine study sites. The exact location for each site depended on the availability of 1m DEMs continuous over a 30 x 30 meter area from USGS and its landform type.

The areas with 1m DEM availability were compared to an adapted map (Figure 8) downloaded from USGS (https://water.usgs.gov/GIS/metadata/usgswrd/XML/na70_landfrm.xml, 1970). Using ArcMap, the subclasses had to be linked back to which of Dikau's five classes they belonged to by adding another field and searching for all the subcategories that fit into the broader groupings.

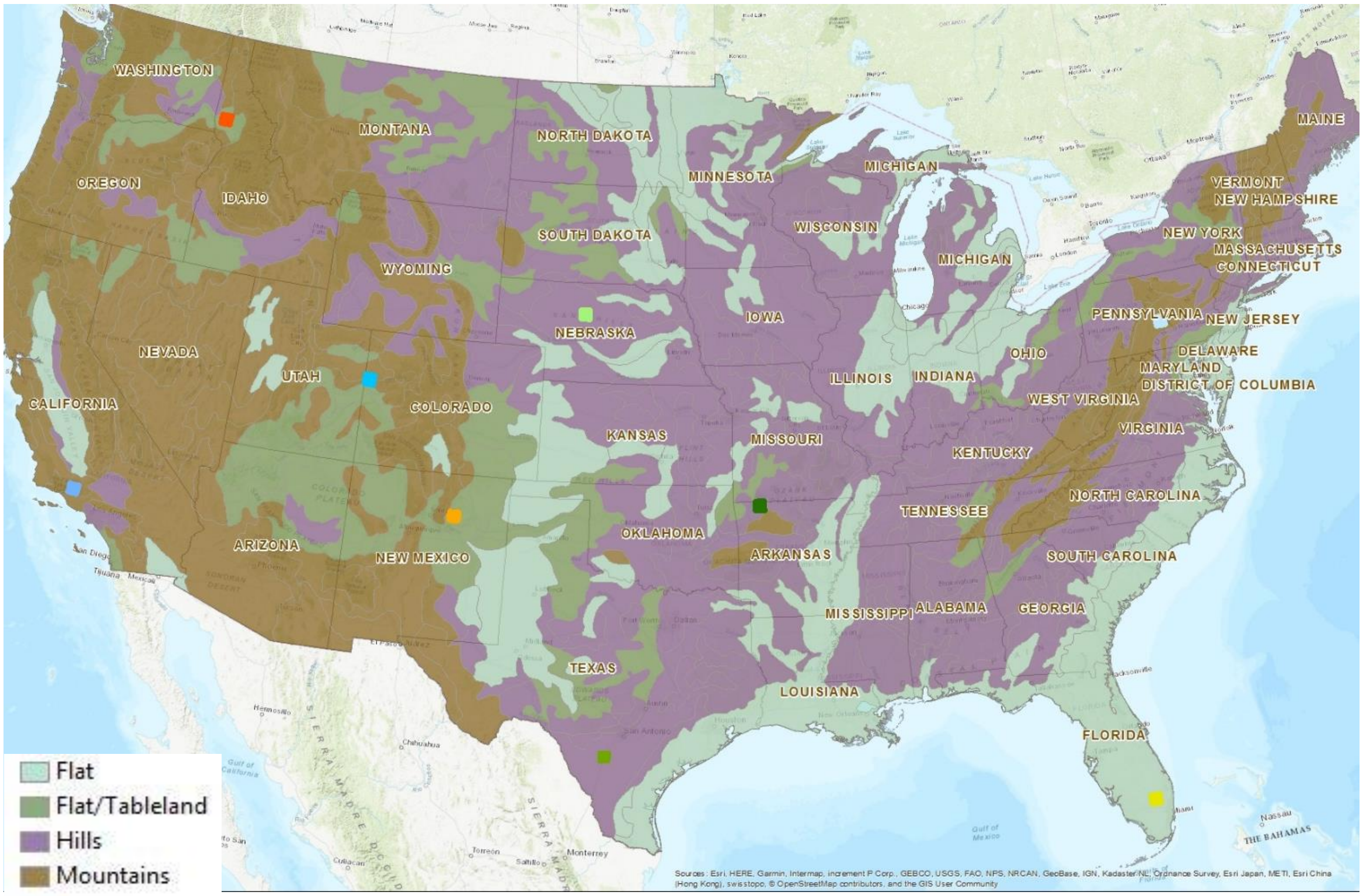


Figure 8: The modified map of landform types across the United States and the 9 sites that were selected for this study. The landform subclass code, as shown in Figure 5, had to be manually grouped into their general landform type. The general landform types were also taken from Figure 5 and were created manually by adding a field and sorting them using Select By Attribute in ArcMap. (USGS, 1970).

Using the map created in ArcMap, sites that fit the correct landform type and had 1m DEM on the USGS National Viewer were investigated to select a site that was the appropriate size. Once all nine sites were selected and downloaded, then, the workflow for this project could be carried out (Figure 9). 1m DEM data had to be available for at least a 30km by 30km continuous area to be considered.

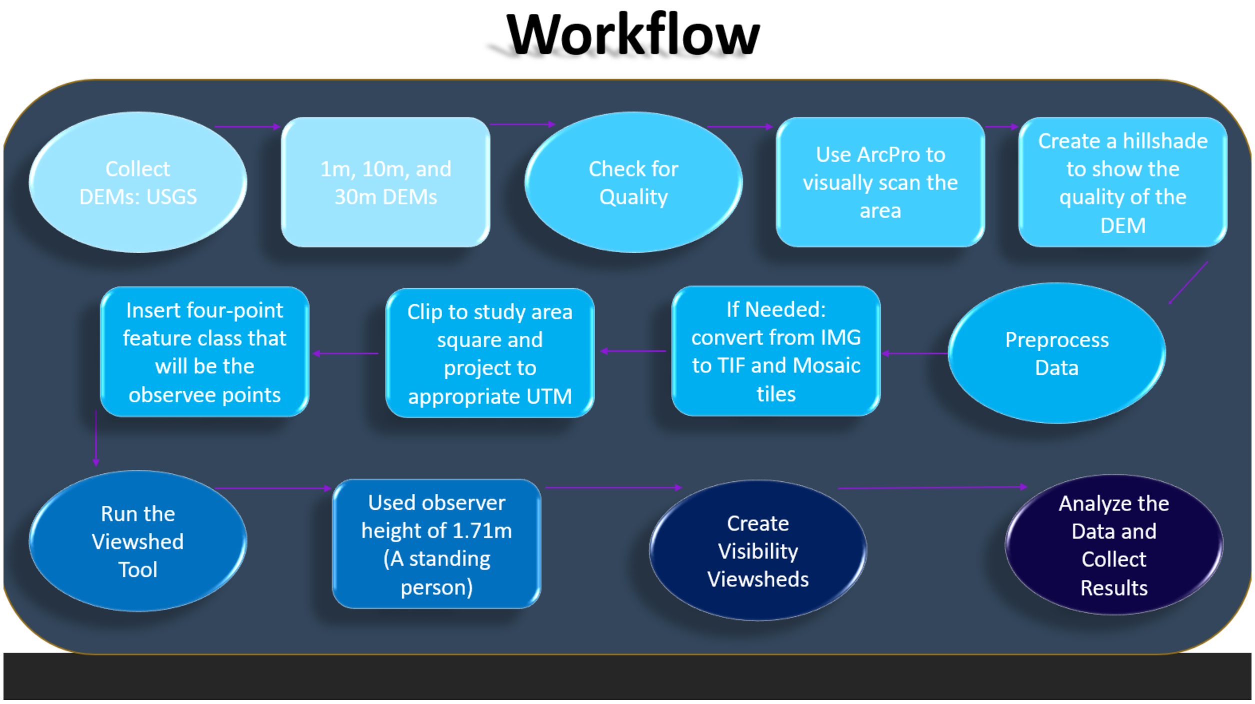


Figure 9: The General Workflow.

For higher resolution DEMs, especially 1m, several titles needed to be downloaded, visually checked for holes and errors in the data, and preprocessed before the viewshed could be run. A hillshade also provided some upfront information about the study area. Once the data was downloaded and unzipped, it needed to be converted from IMG to TIF in ArcMap. Next, the tiles could be mosaiced together and projected to the site's correct UTM zone. Finally, each area was clipped to the 30km by 30km study square.

Once the data was collected and preprocessed, one more input was required for the viewshed analysis tool in ArcMap. The tool requires observer points to be input (Note: the observer height used was 1.71m). To determine where to place each point, the study used stratified sampling for the points, using the Create Fishnet tool. A fishnet with labeled points was created with two rows and two columns. The labeled points layer generated became the four observer points. The fishnet evenly-spaced the points so that a 5km circle could be buffered around each point without overlapping another buffer or going outside of the study box. The four observer points and each DEM for each study area was then run through the viewshed analysis tool (Figure 10).

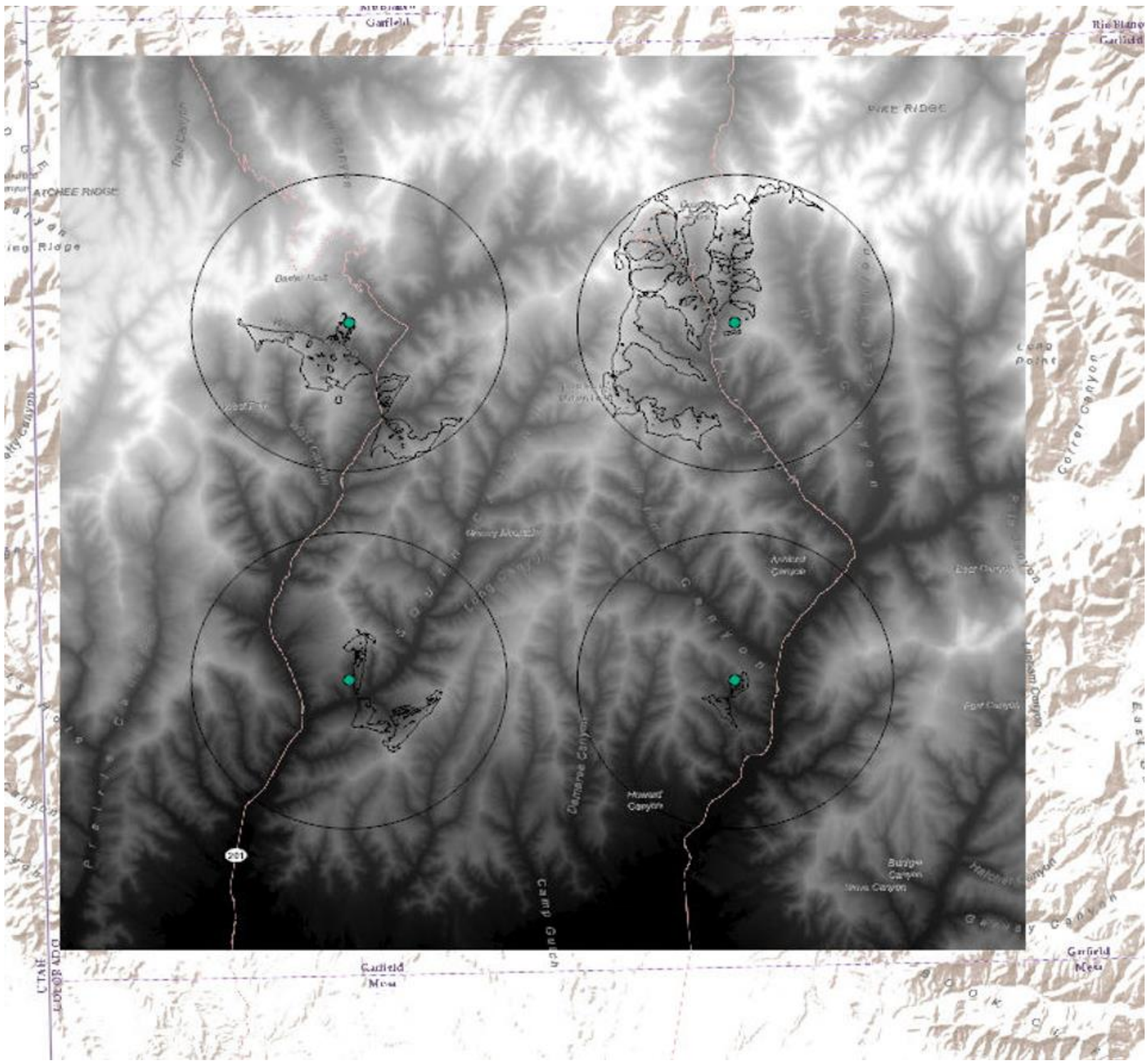


Figure 10: The stratified sampling points used to generate the viewsheds with the 5km max-sight distance.

Two additional processes were run on the created viewsheds. All analysis and numbers were generated from the viewsheds, a line-of-sight analysis, and/or a map of where DEMs were visible (plus how many).

First, the visibility comparison maps were created (Figure 11). This was performed using the geoprocessing tool union. All three resolutions are unioned together and then a new field is added. A calculation is performed to add all the ones (visible cells) in each row. This calculation determines how many resolutions (1, 2, or 3) are visible in each cell of the viewshed. Then, using the symbology, the field was color-coded by the sum.

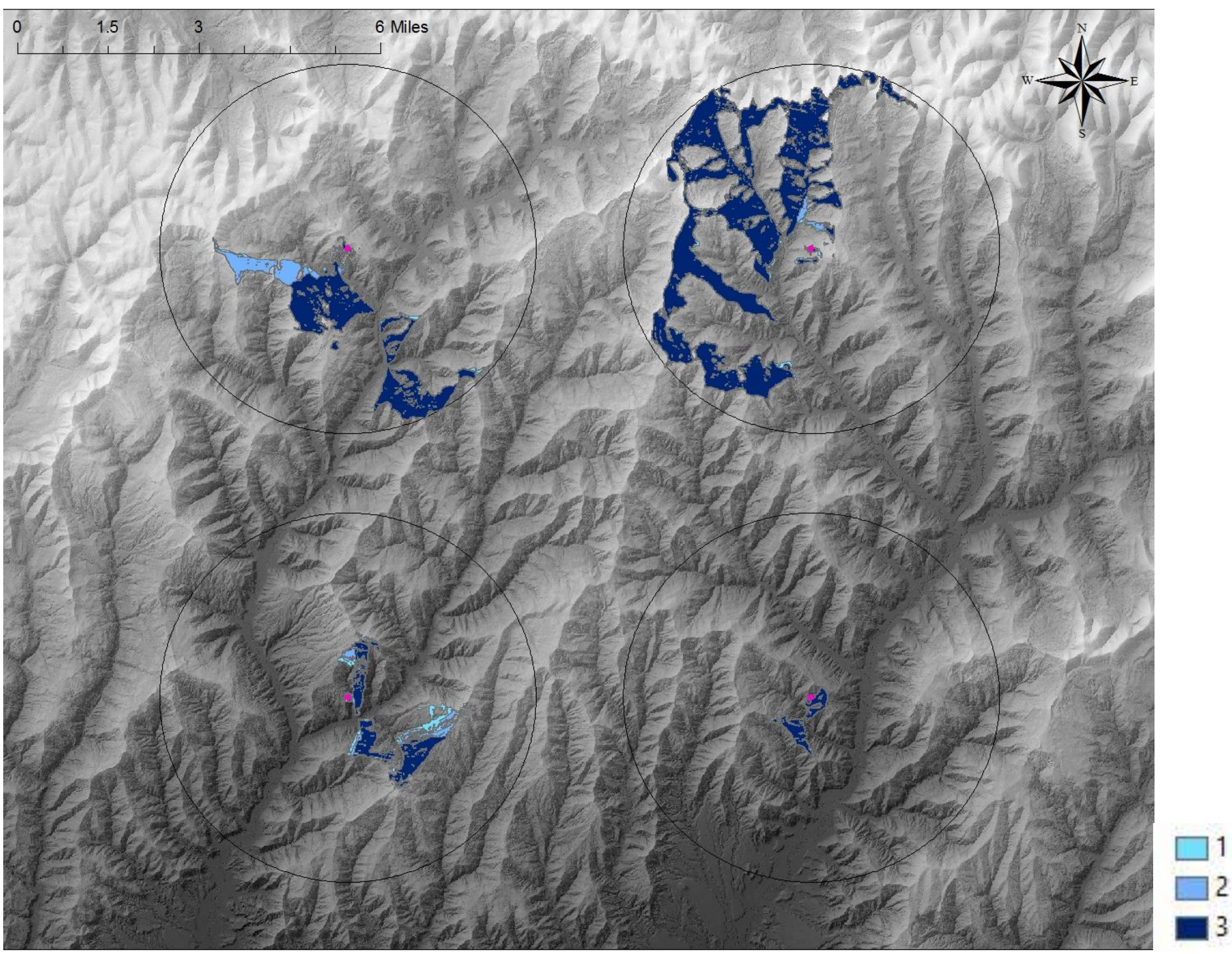


Figure 11: The output of the visibility comparison map for Colorado.

Based on the results, areas that did not agree could be examined, and lines-of-sight were drawn through selected areas containing variation (Figure 12). To create the lines-of-sight, the observer points, the 5km max sight distance (with the fill removed so it is just an outline), and the visibility map were used to determine the placement.

For each site, one new feature class must be created. Then, the desired line-of-sight can be drawn (one end snaps to the observer point and the other to the edge of the 5km max sight distance). Each line can be individually selected and exported with its specific name. The specific lines must individually be run through the Generate Points Along Line Tool. Regardless of resolution, the point spacing was set to 1m (the finest resolution). Once each line was converted to points, the Extract Multiple Values to Points was used to combine the elevation values of all three DEMs. The final step was to Intersect each point with the original viewshed generated. Now, each line can be colored according to visible (1) or non-visible (0). The profiles can be graphed by opening the attribute table and selecting graph (Figure 13).

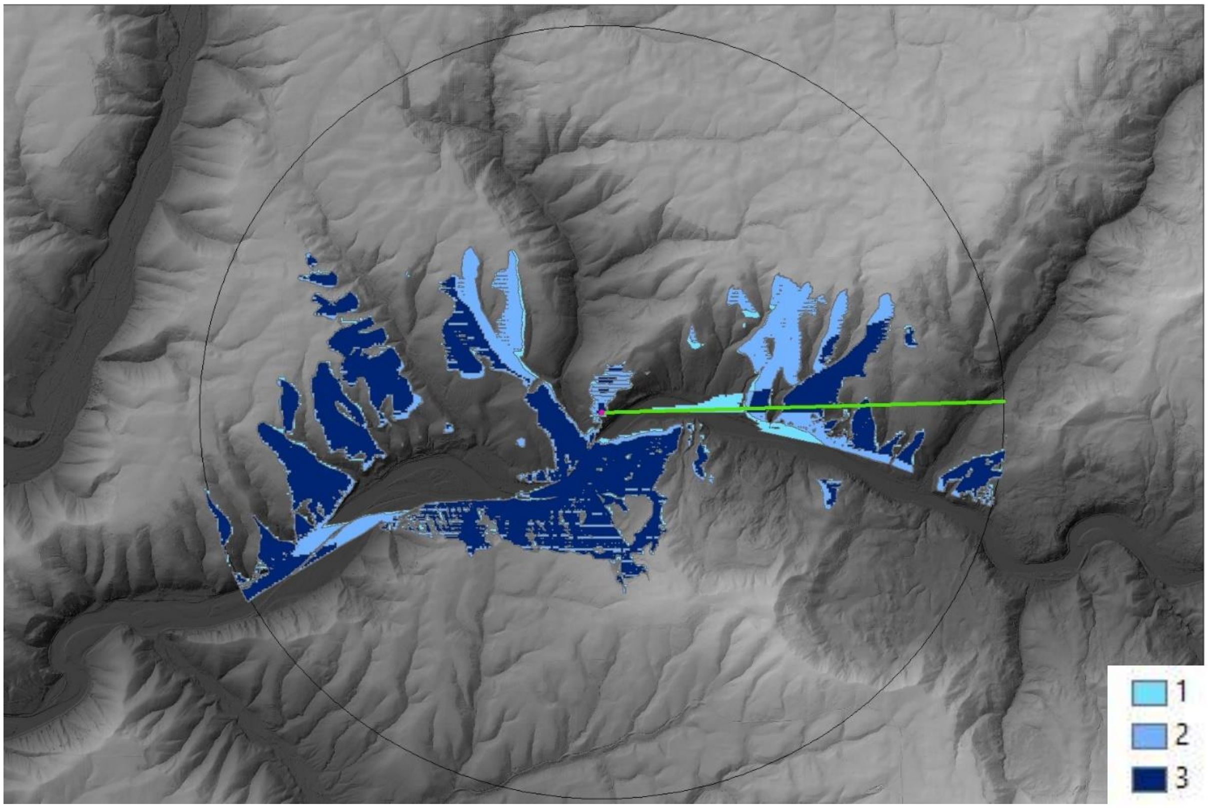


Figure 12: An example of a viewshed that was analyzed using line-of-sight along the green line.

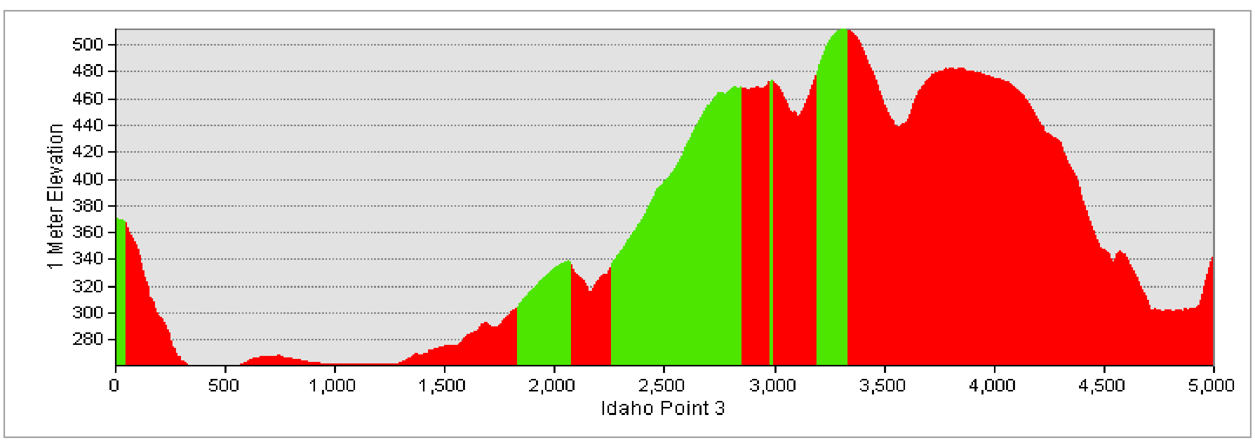


Figure 13: Figure 12's line-of-sight profile. A profile is drawn for the 1m, 10m, and 30m DEMs.

Results and Discussion

For this study, a viewshed analysis and line-of-sight analysis were run for all nine sites. Additionally, to better understand the resulting profiles, the Observer Point DEM elevation was collected (and 1.71meters was added as the standing observer) for every line-of-sight created (Annex A2-I2). For each of the nine sites, a slope analysis of the slope variation at each site (Figure 14), an elevation analysis that compared the range of elevations at each site (Figure 15), the percent change between DEM resolutions (Annex 16), and a visible area versus non-visible comparison (Annex A3-I3) and the number of layers visible (Figure 17-18 and Table 1 show the overview of all nine sites and Annex A1-I1 for individual comparisons). All numbers and images used to determine the results can be found in the Annexes at the end of this paper.

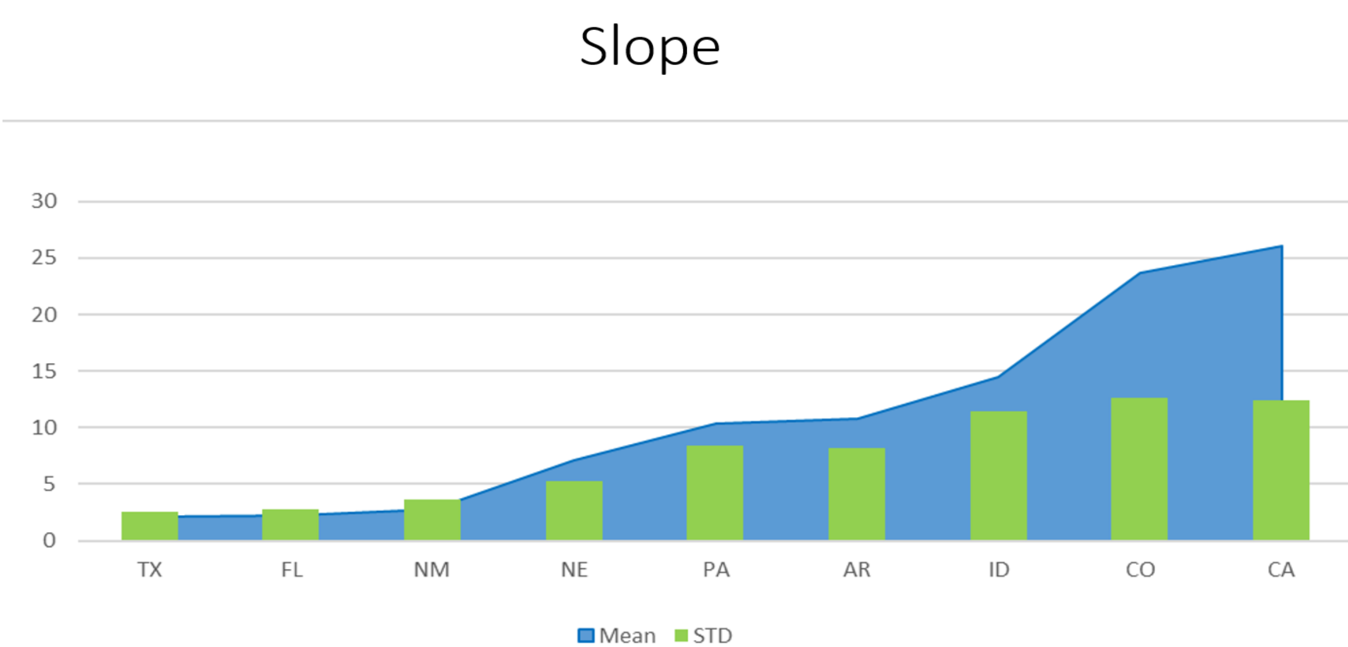


Figure 14: The slope map shows the mean range of slope values at each of the nine sites, as well as its standard deviation.

The slope analysis created (Figure 14) showed that the landform classification (flat, hilly, or mountainous) did not always show the site in order of increasing slope. For example, Texas was irregular plains, which was considered small hills, but the range of slopes resembled Florida (grouped as flat), which was the flattest of all sites.

Additionally, the sites were compared by elevation (Figure 15) to so the role of elevation could be examined. Florida is shown as having the least amount of change (correctly showing the tendencies of being flat land), while NM also does not have a lot of range but has high elevation (capturing tableland). We see the greatest amount of change in the three types of mountains (PA, CO, and CA).

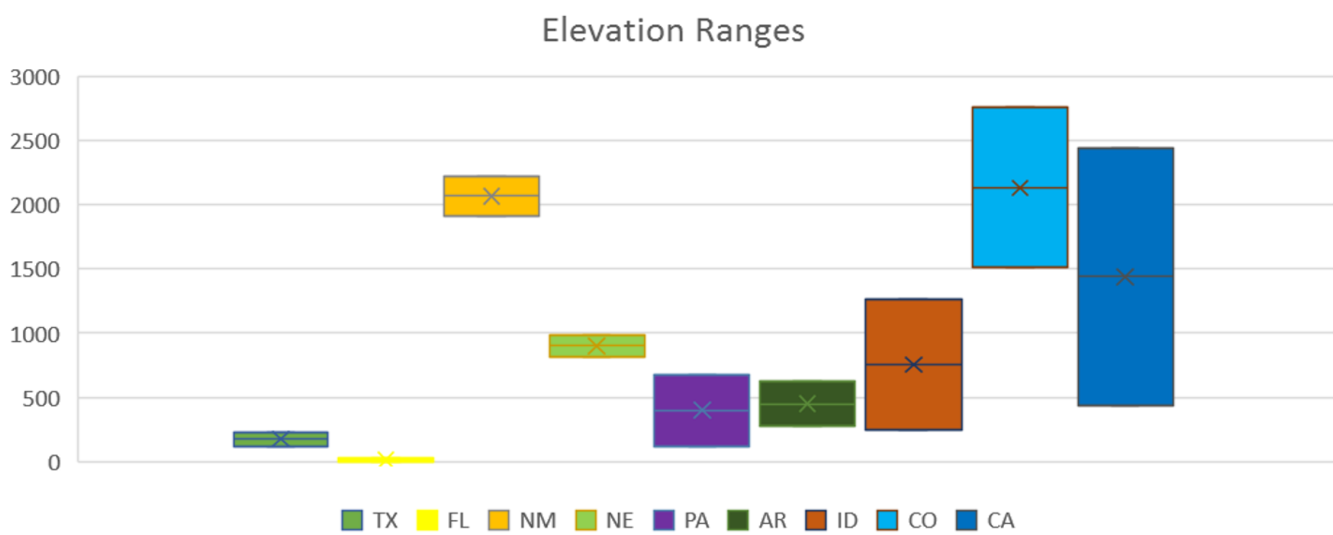


Figure 15: The elevation map shows the ranges of elevations for each study site. The study selected site of varying elevations to see if it affected multi-resolution viewsheds.

Across all nine sites, there was an 81.6% consistency between the 1m, 10m, and 30m DEMs (Figure 17). Six of the nine sites had more visibility at the 30m than the 1m—the 10m was highest at one of the six sites and the 1 m was the highest at the other five. Meanwhile, the other three showed more at the 1m than the 30m, and two showed the most visible area at the 10m (Figure 17-18). When comparing the three graphs in Annex A3 more closely, AR (Hilly) and ID (Flat) decrease in visibility as the resolution becomes coarser (1m to 10m or 10m to 30m). NE (Hilly) decreases in 2 of 3 graphs. CO (Mountain) and NM (Flat) decrease in only 1 of 3 graphs (Figure 16). The general conclusion for how visibility changes across the three resolutions is that typically, the 30m is showing more area than other resolutions, but the accuracy of visible areas that are not identified at the other two resolutions are questionable.

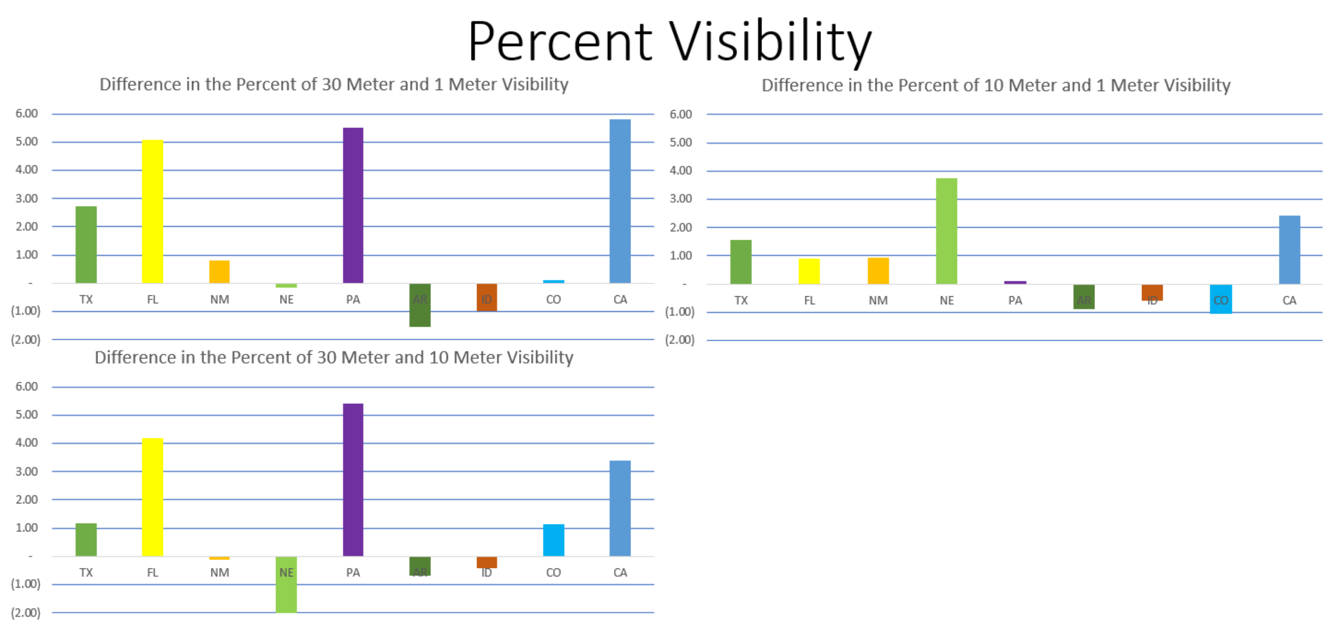


Figure 16: The percent visibility maps compared the percent differences between 30m and 1m, 30m and 10m, and 10m and 1m visibility changes. It breaks down changes happening between resolutions as opposed to the overall trends.

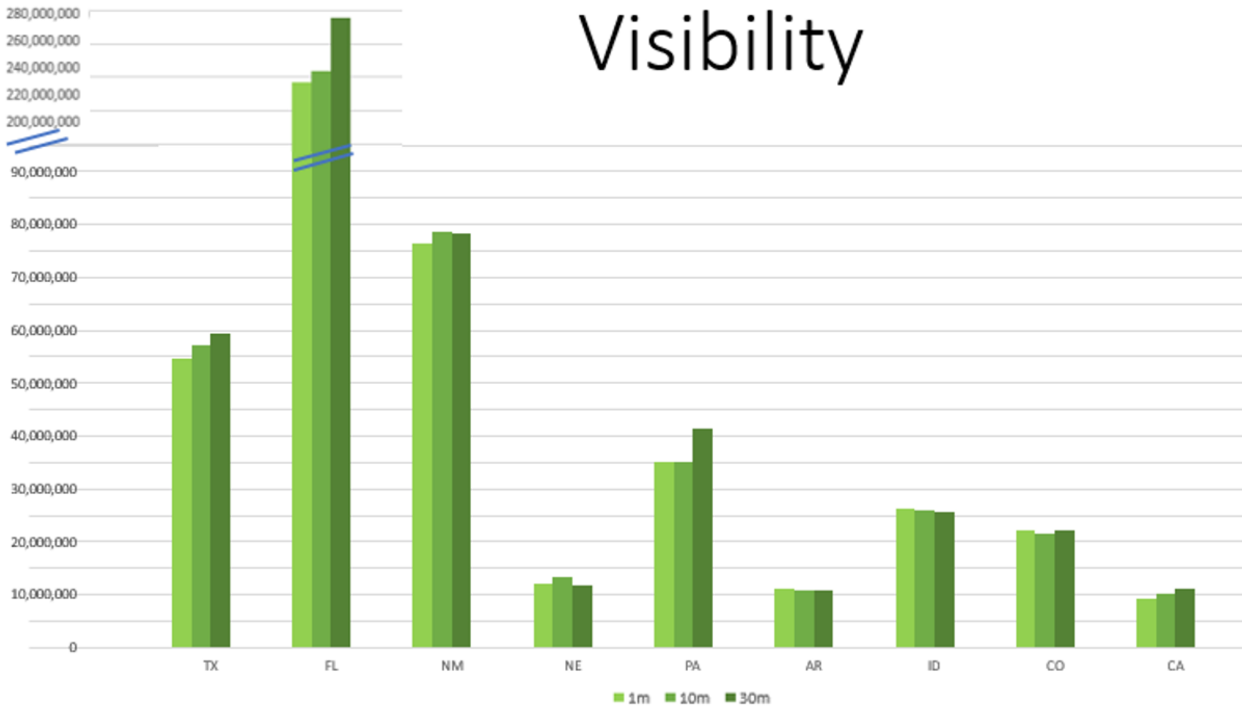


Figure 17: The visibility is measured using the total area visible at each of the nine sites. This is done by adding the visible viewshed areas at each of the four points for each resolution.

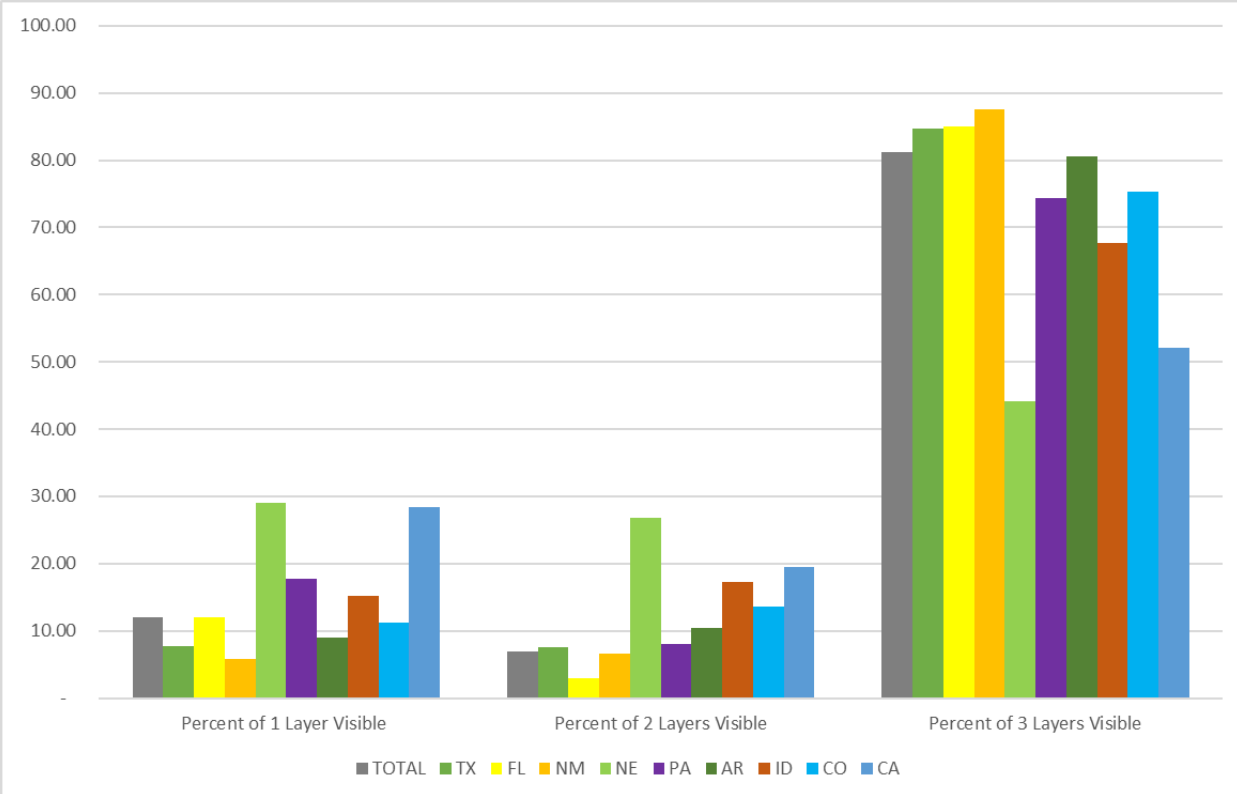


Figure 18: The percentage of each site visible only one resolution versus two or all three resolutions are broken out for each of the nine sites.

	AREA: Number of 1 Overlaps	Percent of 1 Layer Visible	AREA: Number of 2 Overlaps	Percent of 2 Layers Visible	AREA: Number of 3 Overlaps	Percent of 3 Layers Visible	SUM of ALL
AR	1,086,168.91	9.01	1,266,438.26	10.50	9,705,813.50	80.49	12,058,420.67
CA	3,253,305.34	28.37	2,232,430.43	19.47	5,979,896.59	52.15	11,465,632.36
CO	2,777,079.72	11.17	3,366,234.33	13.54	18,717,923.30	75.29	24,861,237.35
ID	4,653,635.93	15.15	5,288,046.72	17.21	20,785,188.30	67.64	30,726,870.95
FL	33,355,760.23	12.05	8,094,441.73	2.92	235,421,397.34	85.03	276,871,599.30
PA	7,689,661.83	17.68	3,482,629.11	8.01	32,333,141.88	74.32	43,505,432.82
NE	5,013,070.61	28.98	4,640,657.24	26.83	7,643,490.15	44.19	17,297,218.00
NM	4,836,716.71	5.83	5,459,190.04	6.58	72,651,383.83	87.59	82,947,290.58
TX	5,014,018.91	7.73	4,874,678.07	7.51	54,998,630.08	84.76	64,887,327.05
TOTAL	67,679,418.18	11.99	38,704,745.92	6.85	458,236,864.99	81.16	564,621,029.09

Table 1: The total areas displayed in the bar graph in Figure 18.

The second question pertained to whether any patterns emerged based on the landform groupings. While no obvious patterns were observed, some patterns that influenced the observer's sight were noted. First, several observer point elevations changed several meters between DEMs. The most drastic change captured was CA in the SE observer point, which changed roughly 12m between the 1m and 30m DEMS and 13m between the 10m and 30m. These changes to the observer or the nearby area in the line-of-sight greatly affected what was visible to the observer. One instance occurs in PA's SE observer point, when at 1m the observer's view is obstructed almost instantly because of elevation differences in the DEMs near the observer.

Some DEMs also had artifacts that did not become apparent until the line-of-sight was run. CA's SE observer point had two line-of-sights because ANNEX B2 reveals that the 10m profile results are unexplainable and likely caused by and error in the source data. Florida was also difficult to decipher because of the relatively small changes in elevation across all three viewsheds that were used in line-of-sights; the accuracy of the results cannot be determined.

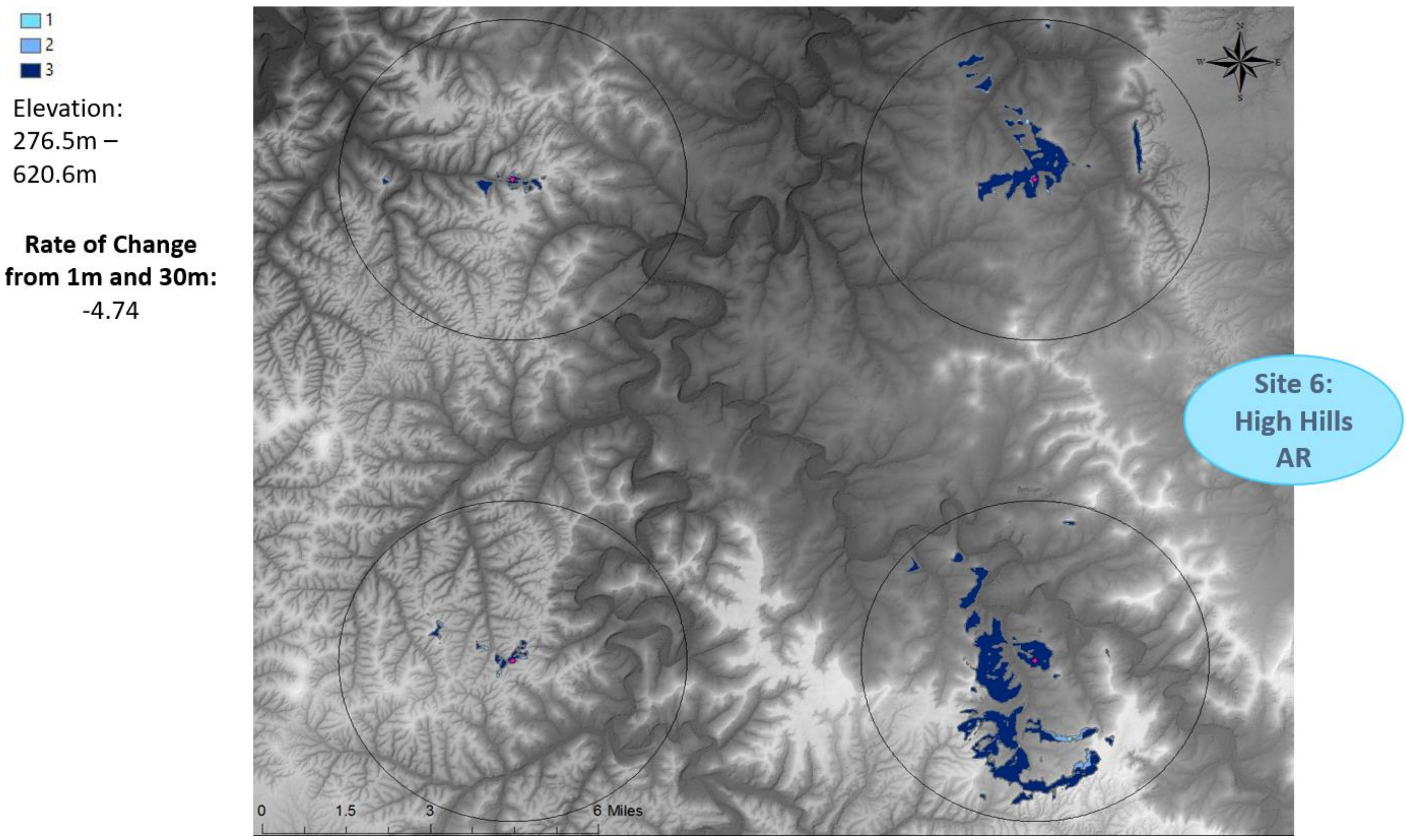
Conclusion

Overall, the stability of each site's visible results could be assessed by comparing the amount of agreement in the three DEM resolutions. The amount of consistency between all three DEMs about visible (or invisible areas) can also help with other studies. This method is recommended in any multi-scaled studies looking to increase the accuracy of their results.

Another recommendation for future studies is to analyze the site at all DEM resolutions to be used and place the observer in a location where the height are more consistent to improve the accuracy of the viewshed and profile results. Starting at a high point is also recommended to minimize effects of change around the observer. This study found that the elevation where the observer is standing and the area near the observer are more important than the actual landform being studied, elevations of the site, or the site's slope. By placing the observer high and on a consistent surface across all the DEM scales being used, many artifacts and inconsistencies can be removed prior to creating the viewsheds or line-of-sights.

ANNEX A: Each of the nine sites was analyzed in three different ways.

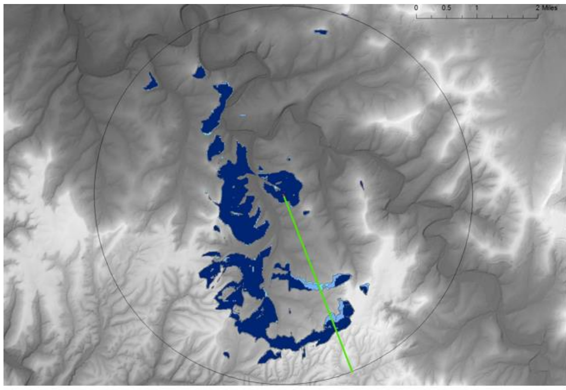
A1: This is an overview of the Arkansas site that shows the terrain, the observer point as a pink point, and the visible area at various DEM resolutions in blue. Light blue (1) means that the area is only visible at one of the three resolutions. Medium blue (2) means two resolutions match. Finally, the darkest blue shows where all three resolutions agree.

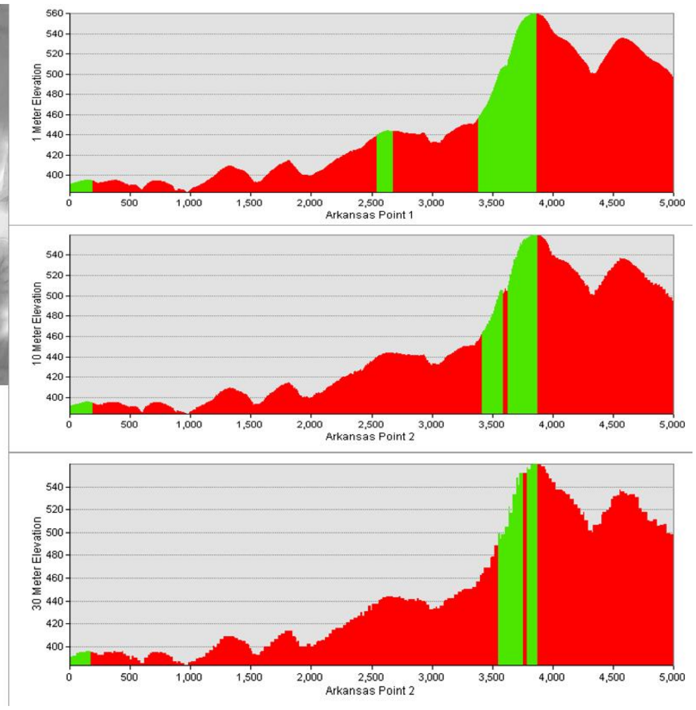


A2: A. The visibility map for the southeast observation point, as well as the observer heights and line-of-sight results for each resolution. B. shows the individual visibility for Arkansas broken down by point (starting with Point 1 in the SW, Point 2, in the SE, Point 3 in the NW and finally Point 4 in the NE) and the percentage visible at 1, 2, or 3 resolutions.

Observer Height at Start

A.





Observer Height at Start Point

Pt1 1m	442.086
Pt 1 10m	437.592
Pt 1 30m	440.871

1 2 3 Elevation: 276.5m – 620.6m

B.

AREA: Number of 1 Overlaps	Percent of 1 Layer Visible	AREA: Number of 2 Overlaps	Percent of 2 Layers Visible	AREA: Number of 3 Overlaps	Percent of 3 Layers Visible	SUM of ALL
97,720.57	21.27	104,591.98	22.77	257,019.45	55.96	459,332.00
579,033.36	7.54	746,634.55	9.72	6,354,642.42	82.74	7,680,310.33
112,136.52	19.73	136,802.60	24.07	319,512.85	56.21	568,451.97
297,278.47	8.87	278,409.12	8.31	2,774,638.78	82.82	3,350,326.37
1,086,168.91	9.01	1,266,438.26	10.50	9,705,813.50	80.49	12,058,420.67

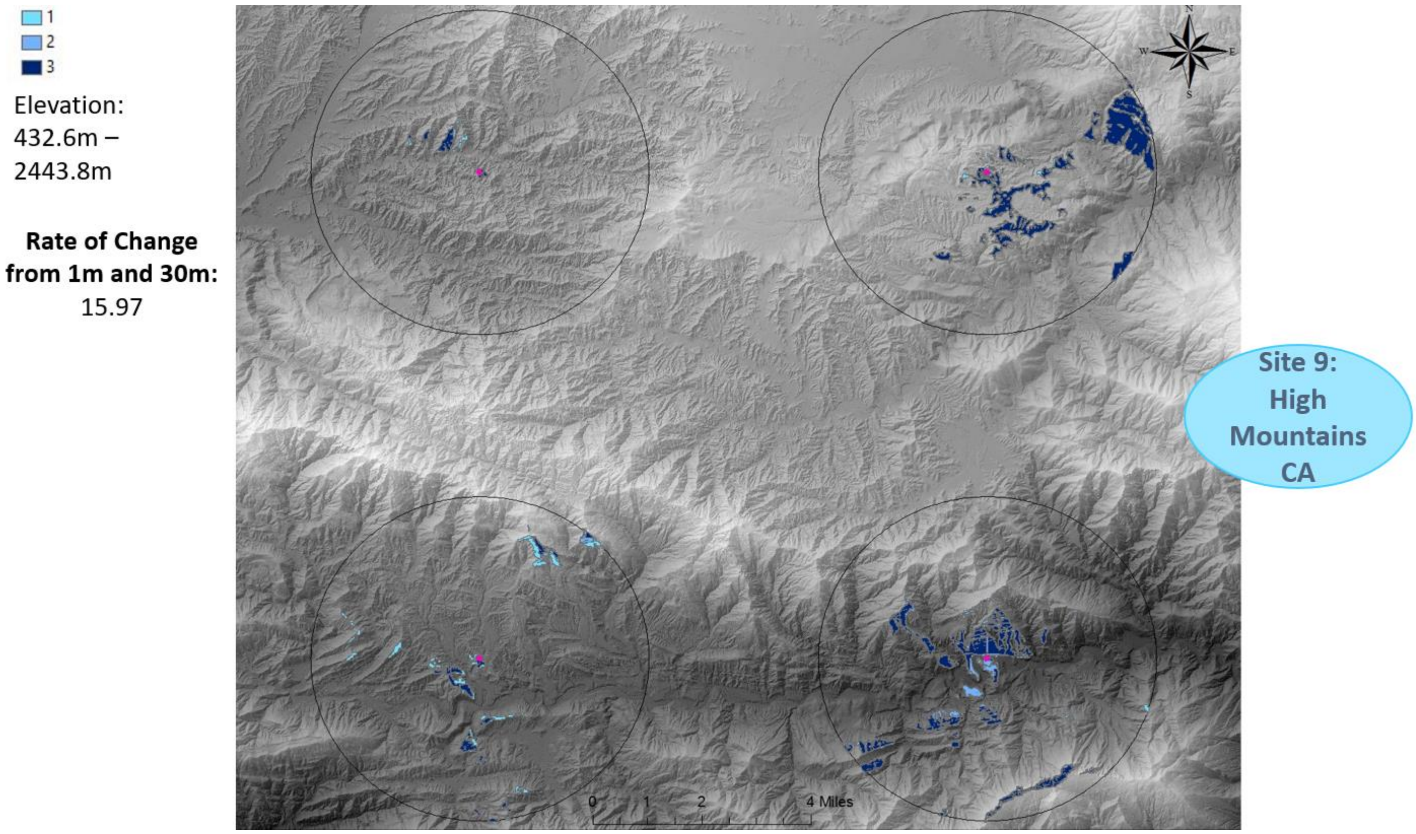
A3: Summary of how much the visibility changed between resolutions. The area that is not visible is also shown as a comparison.

Visible Area By Viewshed					
	Pt1	Pt2	Pt3	Pt4	Totals
1M	424,124.00	7,206,903.00	502,466.00	3,042,844.00	11,176,337.00
1m-10m % Change	-26.58	-1.59	-22.76	0.27	
10M	335,072.04	7,094,408.52	409,312.65	3,051,177.20	10,889,970.41
10m-30m % Change	-5.12	-3.80	5.36	1.06	
30M	318,766.84	6,834,918.21	432,501.62	3,083,991.85	10,670,178.52
TOTALS	Pt1	Pt2	Pt3	Pt4	
SUM	1,077,962.89	21,136,229.73	1,344,280.27	9,178,013.05	
AVE	359,320.96	7,045,409.91	448,093.42	3,059,337.68	

Area Not Visible By Viewshed					
	Pt1	Pt2	Pt3	Pt4	Totals
1M	79,375,186.00	72,592,407.00	79,296,914.00	76,756,536.00	308,021,043.00
1m-10m % Change	0.11	0.15	0.12	-0.01	
10M	79,461,969.18	72,702,632.71	79,389,621.15	76,747,756.60	308,301,979.64
10m-30m % Change	0.01	0.36	-0.04	-0.05	
30M	79,469,657.48	72,962,016.88	79,355,149.01	76,712,169.54	308,498,992.91
TOTALS	Pt1	Pt2	Pt3	Pt4	
SUM	238,306,812.67	218,257,056.59	238,041,684.16	230,216,462.14	
AVE	79,435,604.22	72,752,352.20	79,347,228.05	76,738,820.71	

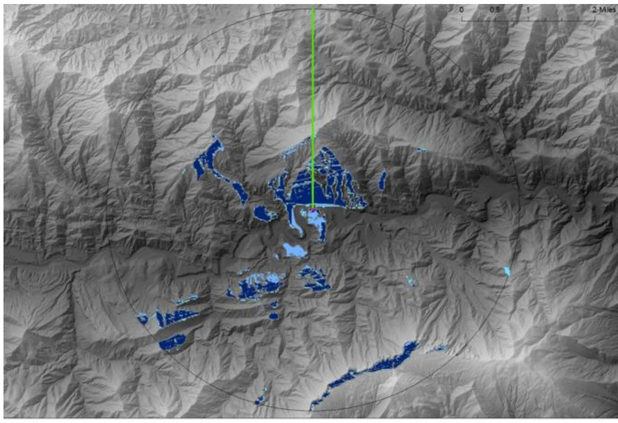
ANNEX B: Each of the nine sites was analyzed in three different ways.

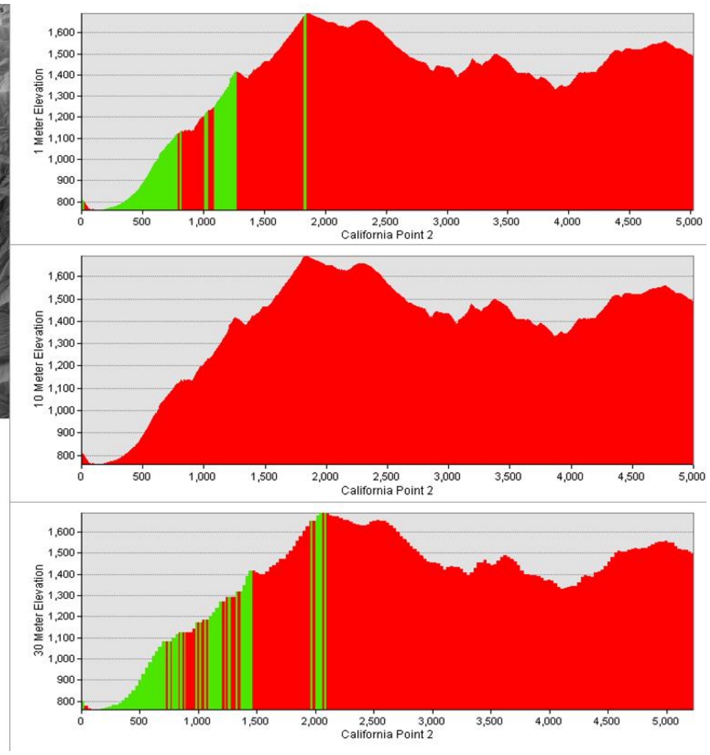
B1: This is an overview of the California site that shows the terrain, the observer point as a pink point, and the visible area at various DEM resolutions in blue. Light blue (1) means that the area is only visible at one of the three resolutions. Medium blue (2) means two resolutions match. Finally, the darkest blue shows where all three resolutions agree.



B2: A. and B. The visibility map for the southeast observation point, as well as the observer heights and line-of-sight results for each resolution. C. shows the individual visibility for California broken down by point (starting with Point 1 in the SW, Point 2, in the SE, Point 3 in the NW and finally Point 4 in the NE) and the percentage visible at 1, 2, or 3 resolutions.

A.

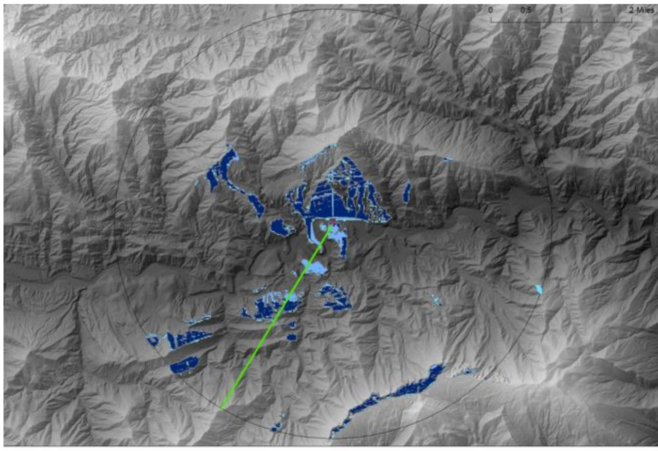


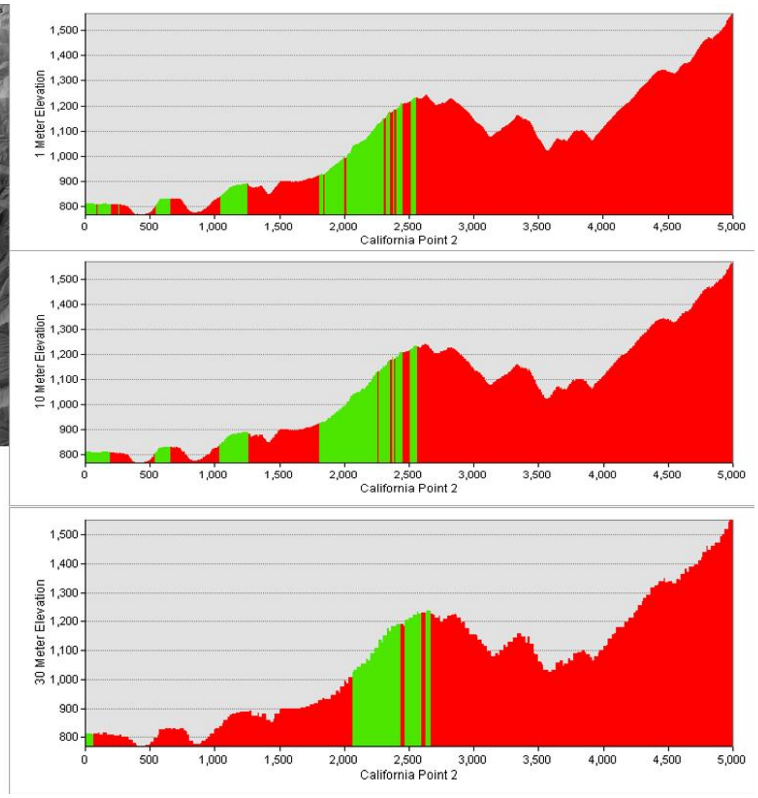


Observer Height at Start Point	
Pt 2 1m	812.705
Pt 2 10m	813.806
Pt 2 30m	800.635

1 Elevation:
2 432.6m –
3 2443.8m

B.





Observer Height at Start Point

Pt 2 1m	812.705
Pt 2 10m	813.806
Pt 2 30m	800.635

1 Elevation:
2 432.6m –
3 2443.8m

C.

AREA: Number of 1 Overlaps	Percent of 1 Layer Visible	AREA: Number of 2 Overlaps	Percent of 2 Layers Visible	AREA: Number of 3 Overlaps	Percent of 3 Layers Visible	SUM of ALL
1,139,423.44	52.89	325,843.84	15.12	689,195.09	31.99	2,154,462.37
1,069,663.83	28.86	1,318,265.01	35.57	1,318,265.01	35.57	3,706,193.85
221,054.84	39.45	99,366.30	17.73	239,946.76	42.82	560,367.90
823,163.23	16.32	488,955.28	9.69	3,732,489.74	73.99	5,044,608.25
3,253,305.34	28.37	2,232,430.43	19.47	5,979,896.59	52.15	11,465,632.36

B3: Summary of how much the visibility changed between resolutions. The area that is not visible is also shown as a comparison.

Visible Area By Viewshed

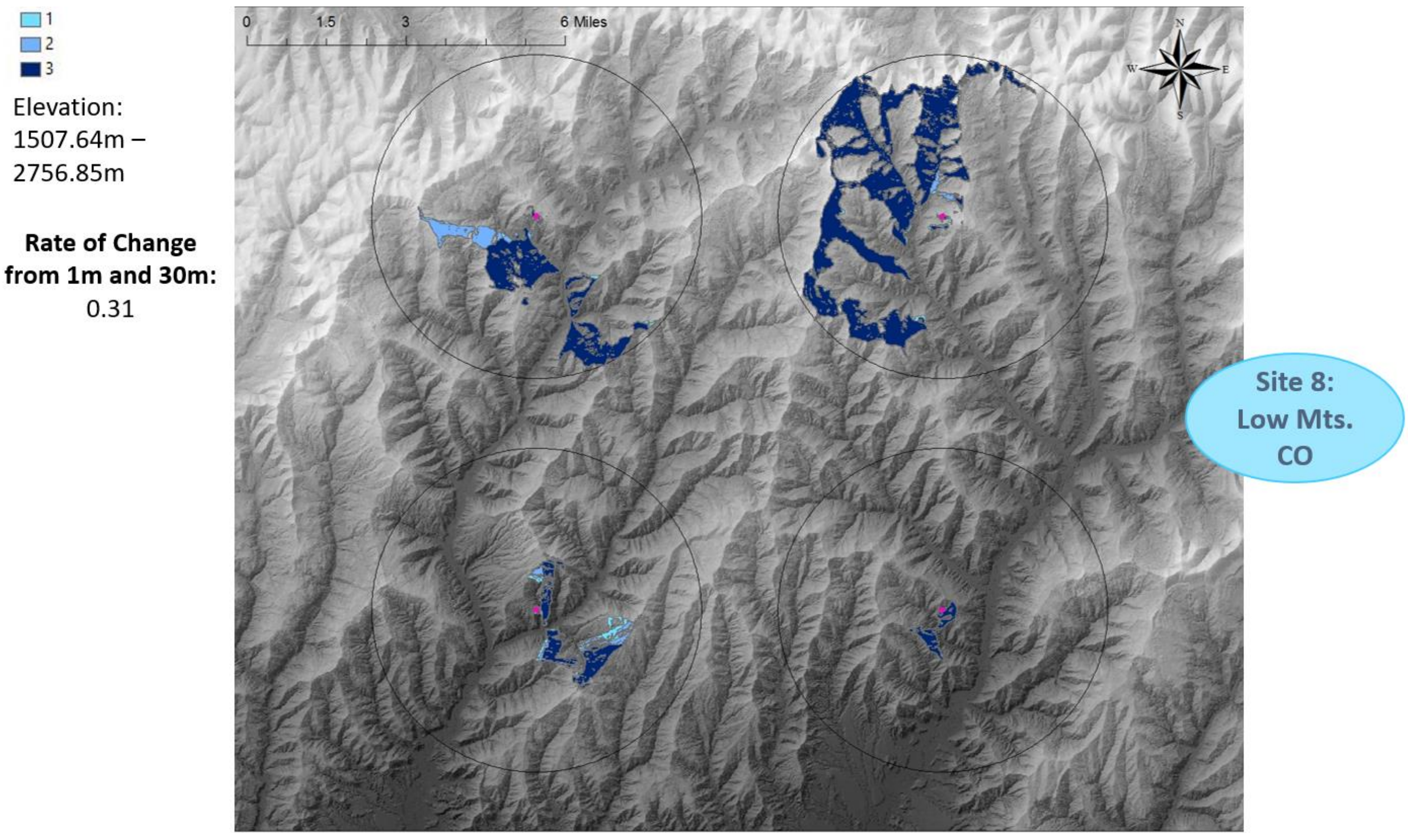
	Pt1	Pt2	Pt3	Pt4	Totals
1M	812,803.00	4,190,003.00	260,667.00	4,139,223.00	9,402,696.00
1m-10m % Change	34.88	5.42	26.39	-0.53	
10M	1,248,232.13	4,429,896.54	354,096.11	4,117,496.36	10,149,721.15
10m-30m % Change	30.56	-7.39	32.54	13.17	
30M	1,797,661.26	4,125,107.73	524,864.60	4,741,823.64	11,189,457.24
TOTALS	Pt1	Pt2	Pt3	Pt4	
SUM	3,858,696.39	12,745,007.27	1,139,627.71	12,998,543.01	
AVE	1,286,232.13	4,248,335.76	379,875.90	4,332,847.67	

Area Not Visible By Viewshed

	Pt1	Pt2	Pt3	Pt4	Totals
1M	78,986,699.00	75,609,499.00	79,538,835.00	75,660,279.00	309,795,312.00
1m-10m % Change	-0.55	-0.32	-0.12	0.03	
10M	78,552,038.93	75,370,374.52	79,446,174.95	75,682,774.70	309,051,363.09
10m-30m % Change	-0.69	0.42	-0.20	-0.82	
30M	78,014,562.32	75,687,115.85	79,287,358.98	75,070,399.95	308,059,437.11
TOTALS	Pt1	Pt2	Pt3	Pt4	
SUM	235,553,300.25	226,666,989.37	238,272,368.93	226,413,453.64	
AVE	78,517,766.75	75,555,663.12	79,424,122.98	75,471,151.21	

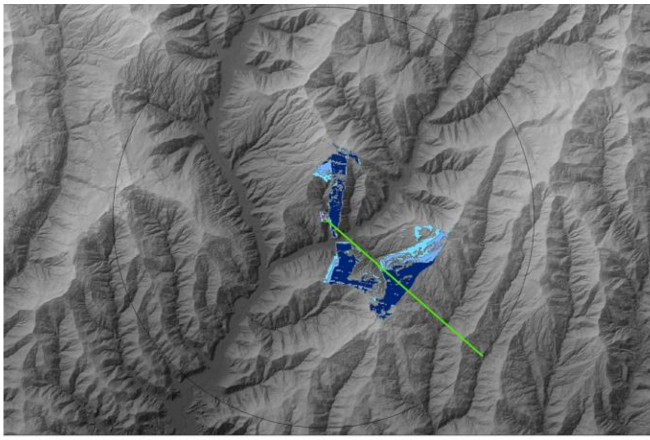
ANNEX C: Each of the nine sites was analyzed in three different ways.

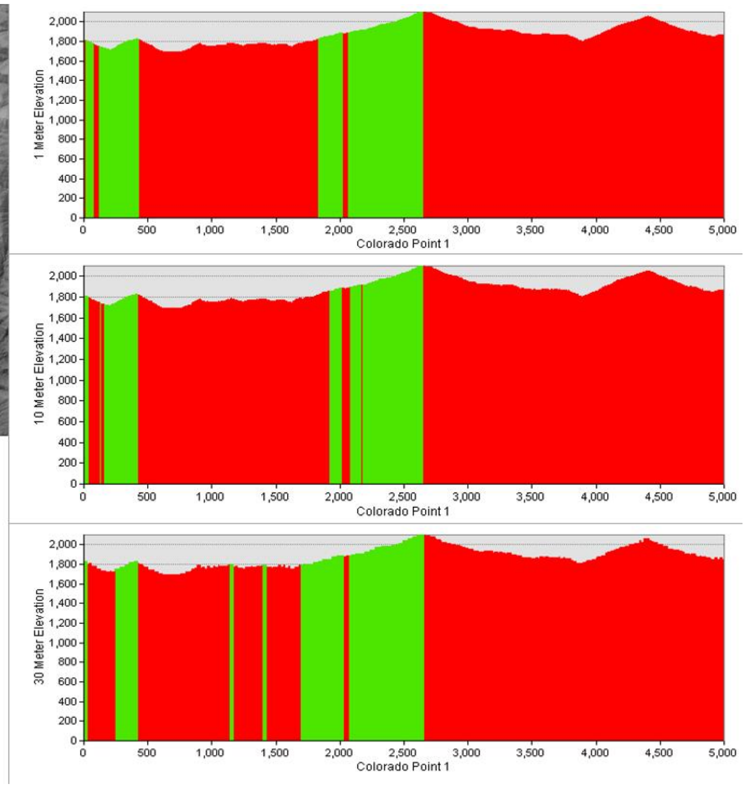
C:1 This is an overview of the Colorado site that shows the terrain, the observer point as a pink point, and the visible area at various DEM resolutions in blue. Light blue (1) means that the area is only visible at one of the three resolutions. Medium blue (2) means two resolutions match. Finally, the darkest blue shows where all three resolutions agree.



C2: A., B., and C. The visibility map for the southwest, northwest, and northeast observation points, as well as the observer heights and line-of-sight results for each resolution. D. shows the individual visibility for Colorado broken down by point (starting with Point 1 in the SW, Point 2, in the SE, Point 3 in the NW and finally Point 4 in the NE) and the percentage visible at 1, 2, or 3 resolutions.

A.



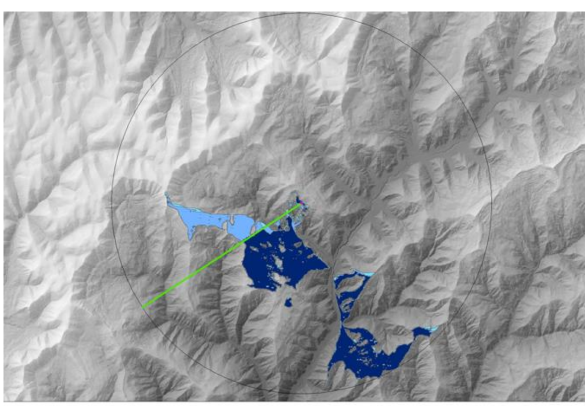


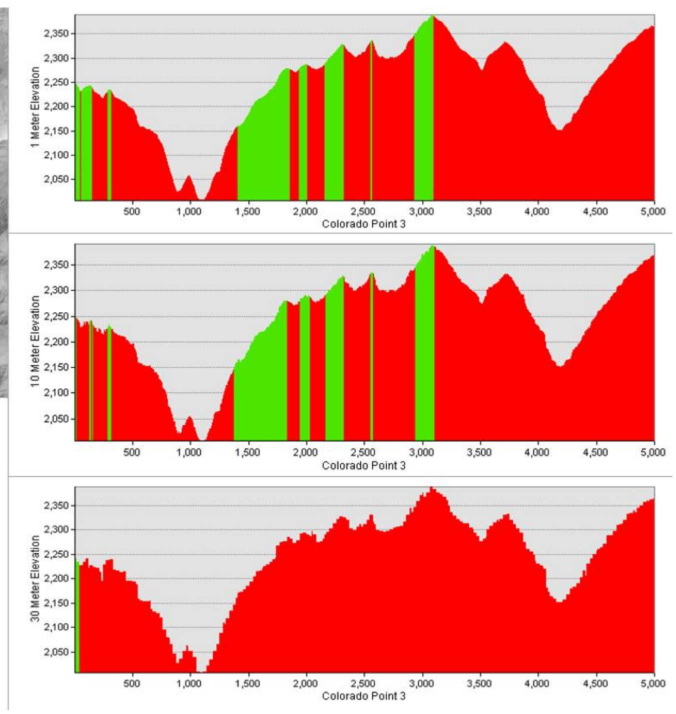
Observer Height at Start Point

Pt1 1m	1824.37
Pt 1 10m	1811.7
Pt 1 30m	1830.05

1 Elevation:
2 1507.64m –
3 2756.85m

B.



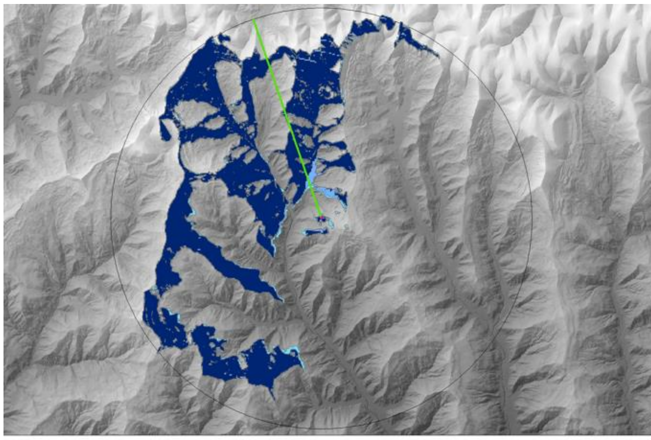


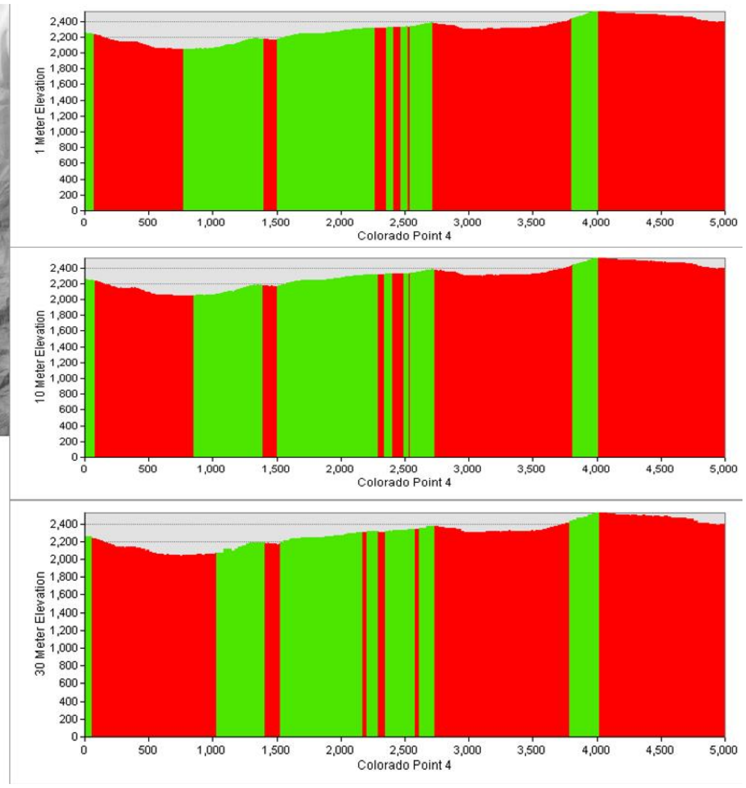
Observer Height at Start Point

Pt3 1m	2255.68
Pt 3 10m	2253.75
Pt 3 30m	2259.16

1 Elevation:
2 1507.64m –
3 2756.85m

C.





Observer Height at Start Point

Pt 4 1m	2253.29
Pt 4 10m	2253.35
Pt 4 30m	2252.76

1 Elevation:
2 1507.64m –
3 2756.85m

D.

AREA: Number of 1 Overlaps	Percent of 1 Layer Visible	AREA: Number of 2 Overlaps	Percent of 2 Layers Visible	AREA: Number of 3 Overlaps	Percent of 3 Layers Visible	SUM of ALL
766,822.84	24.90	680,568.69	22.10	1,632,747.93	53.01	3,080,139.46
93,275.88	12.96	82,085.35	11.40	544,581.07	75.64	719,942.31
559,760.20	9.26	1,350,879.56	22.36	4,131,346.04	68.38	6,041,985.80
1,357,220.80	9.04	1,252,700.72	8.34	12,409,248.26	82.62	15,019,169.78
2,777,079.72	11.17	3,366,234.33	13.54	18,717,923.30	75.29	24,861,237.35

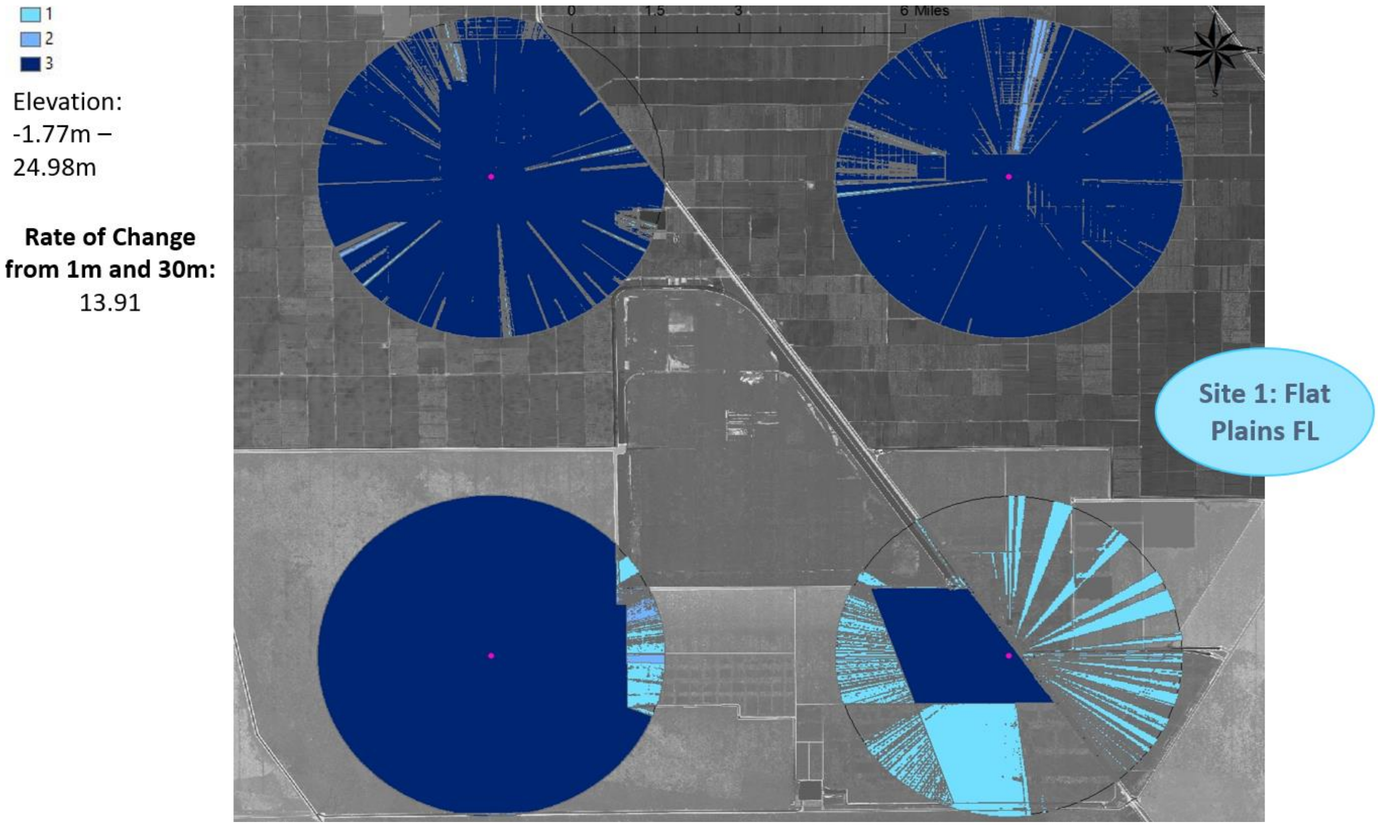
C3: Summary of how much the visibility changed between resolutions. The area that is not visible is also shown as a comparison.

Visible Area By Viewshed					
	Pt1	Pt2	Pt3	Pt4	Totals
1M	2,361,090.00	598,549.00	5,603,209.00	13,529,506.00	22,092,354.00
1m-10m % Change	-28.07	5.07	-4.11	0.17	
10M	1,843,588.68	630,525.18	5,381,998.16	13,552,900.63	21,409,012.65
10m-30m % Change	34.66	4.77	-15.24	3.25	
30M	2,821,525.09	662,115.83	4,670,350.26	14,007,960.40	22,161,951.57
TOTALS	Pt1	Pt2	Pt3	Pt4	
SUM	7,026,203.77	1,891,190.01	15,655,557.42	41,090,367.02	
AVE	2,342,067.92	630,396.67	5,218,519.14	13,696,789.01	

Area Not Visible By Viewshed					
	Pt1	Pt2	Pt3	Pt4	Totals
1M	77,438,166.00	79,200,706.00	74,196,133.00	66,269,812.00	297,104,817.00
1m-10m % Change	0.69	-0.02	0.32	-0.01	
10M	77,972,572.82	79,185,636.31	74,434,163.34	66,263,260.87	297,855,633.35
10m-30m % Change	-1.28	-0.04	0.94	-0.70	
30M	76,990,859.27	79,150,268.53	75,141,261.50	65,803,651.36	297,086,040.66
TOTALS	Pt1	Pt2	Pt3	Pt4	
SUM	232,401,598.09	237,536,610.84	223,771,557.84	198,336,724.24	
AVE	77,467,199.36	79,178,870.28	74,590,519.28	66,112,241.41	

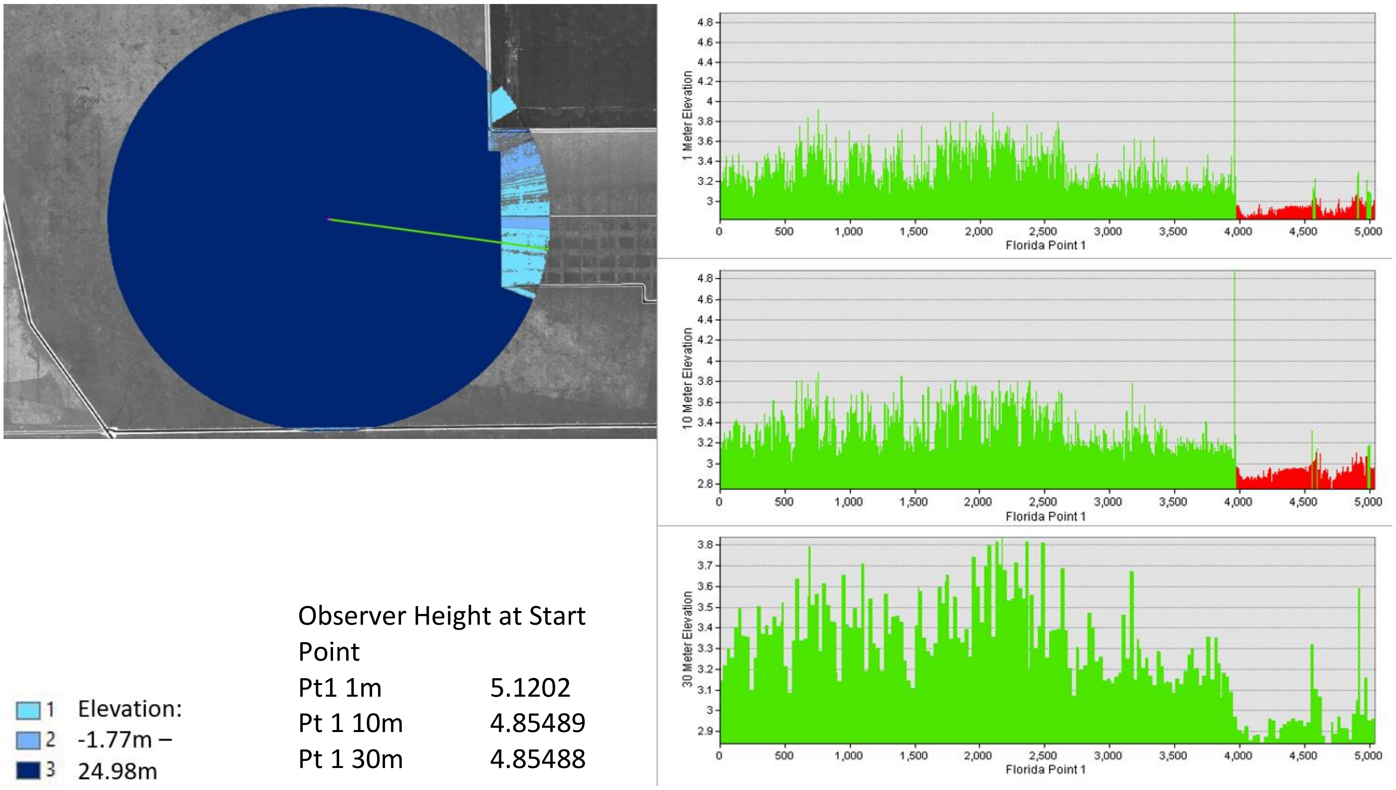
ANNEX D: Each of the nine sites was analyzed in three different ways.

D1: This is an overview of the Florida site that shows the terrain, the observer point as a pink point, and the visible area at various DEM resolutions in blue. Light blue (1) means that the area is only visible at one of the three resolutions. Medium blue (2) means two resolutions match. Finally, the darkest blue shows where all three resolutions agree.

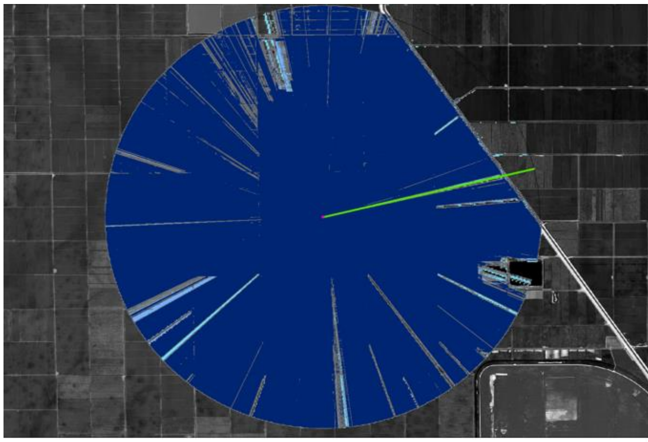


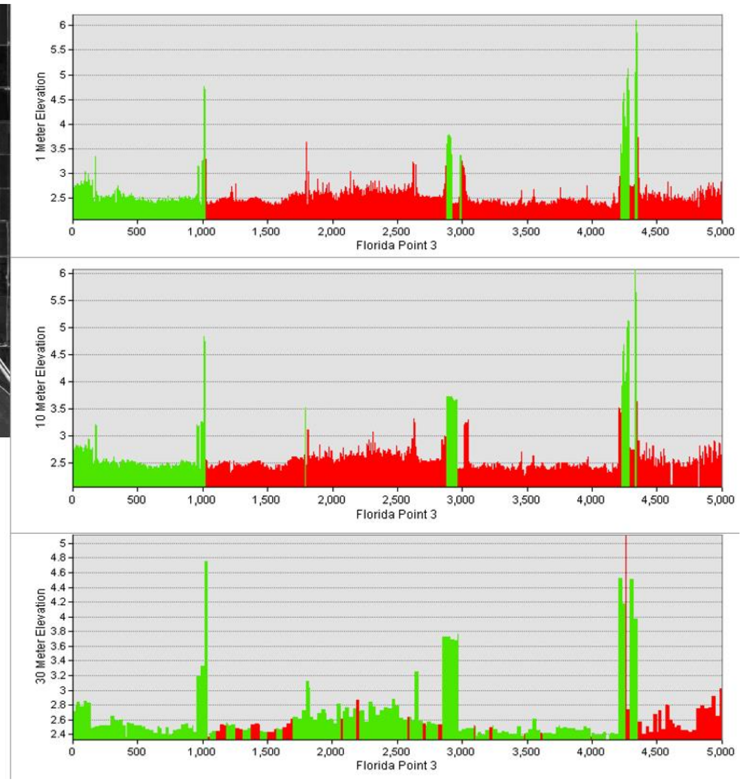
D2: A., B., and C. The visibility map for the southwest, northwest, and northeast observation points, as well as the observer heights and line-of-sight results for each resolution. D. shows the individual visibility for Florida broken down by point (starting with Point 1 in the SW, Point 2, in the SE, Point 3 in the NW and finally Point 4 in the NE) and the percentage visible at 1, 2, or 3 resolutions.

A.


1 Meter Elevation
Florida Point 1
10 Meter Elevation
Florida Point 1
30 Meter Elevation
Florida Point 1
Observer Height at Start Point
Pt1 1m 5.1202
Pt 1 10m 4.85489
Pt 1 30m 4.85488
1
2
3
Elevation:
-1.77m –
24.98m

B.



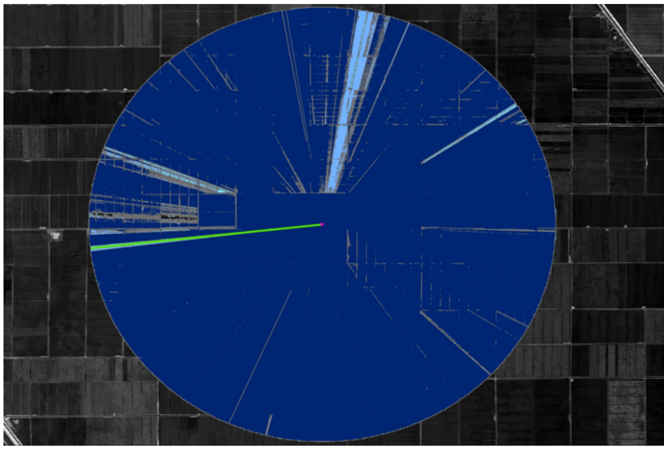


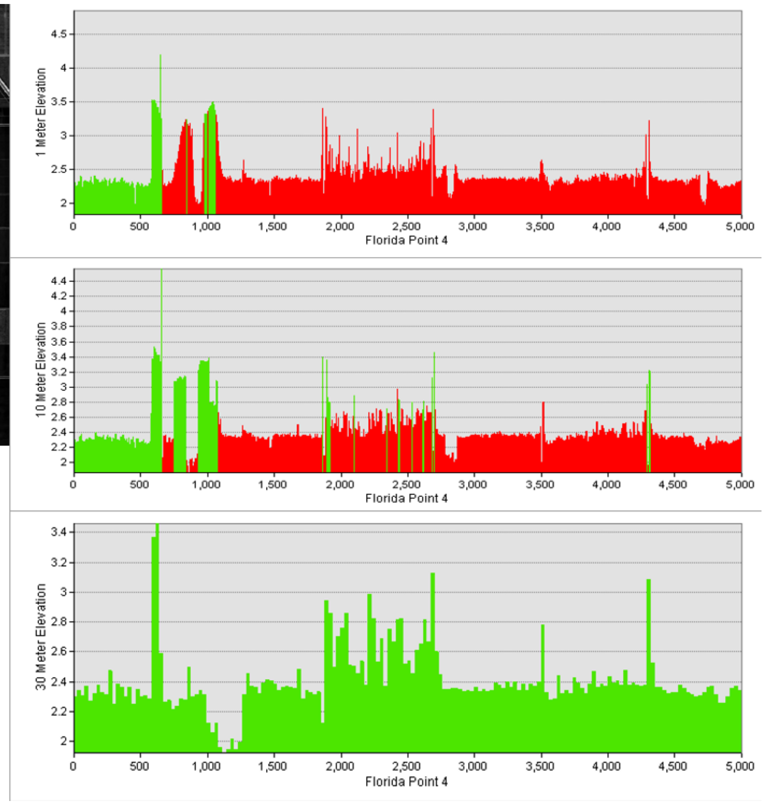
Observer Height at Start Point

Pt3 1m	4.4368
Pt 3 10m	4.40051
Pt 3 30m	4.42325

1 2 3 Elevation: -1.77m – 24.98m

C.





Observer Height at Start Point

Pt 4 1m	4.01993
Pt 4 10m	4.03878
Pt 4 30m	4.0116

1 Elevation:
2 -1.77m –
3 24.98m

D.

AREA: Number of 1 Overlaps	Percent of 1 Layer Visible	AREA: Number of 2 Overlaps	Percent of 2 Layers Visible	AREA: Number of 3 Overlaps	Percent of 3 Layers Visible	SUM of ALL
2,949,412.67	3.71	1484028.90	1.87	75,055,230.46	94.42	79,488,672.03
28,073,772.83	65.59	1637041.48	3.82	13,092,649.61	30.59	42,803,463.92
1,510,463.48	2.02	2145213.41	2.87	71,079,405.27	95.11	74,735,082.16
822,111.25	1.03	2828157.94	3.54	76,194,112.01	95.43	79,844,381.20
33,355,760.23	12.05	8,094,441.73	2.92	235,421,397.34	85.03	276,871,599.30

D3: Summary of how much the visibility changed between resolutions. The area that is not visible is also shown as a comparison.

Visible Area By Viewshed

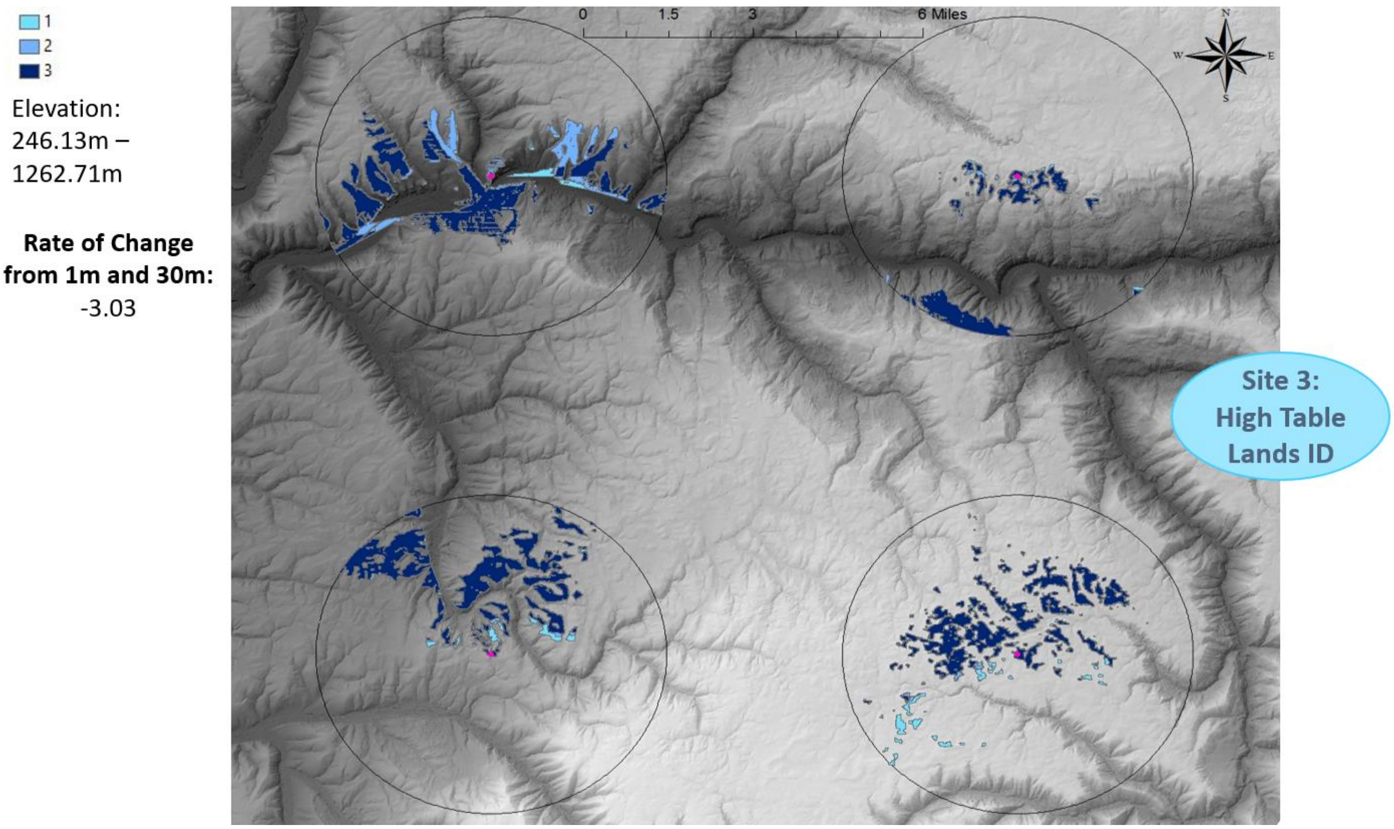
	Pt1	Pt2	Pt3	Pt4	Totals
1M	75,229,977.00	13,611,001.00	71,636,540.00	76,477,635.00	236,955,153.00
1m-10m % Change	1.68	8.78	2.20	3.12	
10M	76,516,940.10	14,920,470.18	73,246,239.14	78,939,106.11	243,622,755.54
10m-30m % Change	3.55	64.55	1.23	0.89	
30M	79,336,244.74	42,094,333.44	74,156,326.96	79,644,022.04	275,230,927.18
TOTALS	Pt1	Pt2	Pt3	Pt4	
SUM	231,083,161.84	70,625,804.62	219,039,106.10	235,060,763.16	
AVE	77,027,720.61	23,541,934.87	73,013,035.37	78,353,587.72	

Area Not Visible By Viewshed

	Pt1	Pt2	Pt3	Pt4	Totals
1M	4,569,439.00	66,188,415.00	8,162,876.00	3,321,781.00	82,242,511.00
1m-10m % Change	-39.04	-2.01	-24.49	-284.65	
10M	3,286,428.70	64,882,231.39	6,557,129.67	863,595.45	75,589,385.21
10m-30m % Change	-616.52	-72.09	-16.27	-469.11	
30M	458,665.34	37,701,433.96	5,639,440.44	151,745.36	43,951,285.09
TOTALS	Pt1	Pt2	Pt3	Pt4	
SUM	8,314,533.04	168,772,080.35	20,359,446.10	4,337,121.81	
AVE	2,771,511.01	56,257,360.12	6,786,482.03	1,445,707.27	

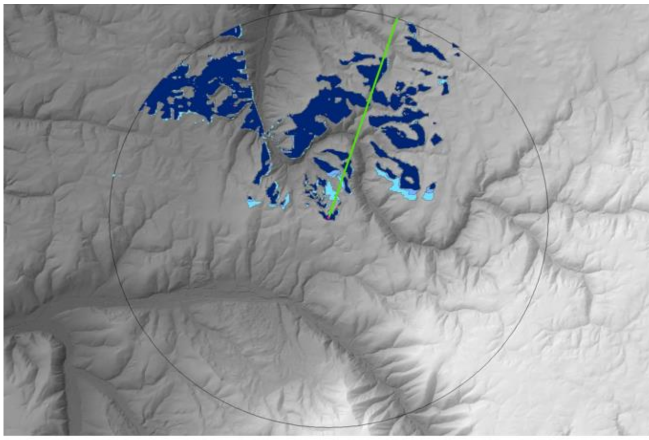
ANNEX E: Each of the nine sites was analyzed in three different ways.

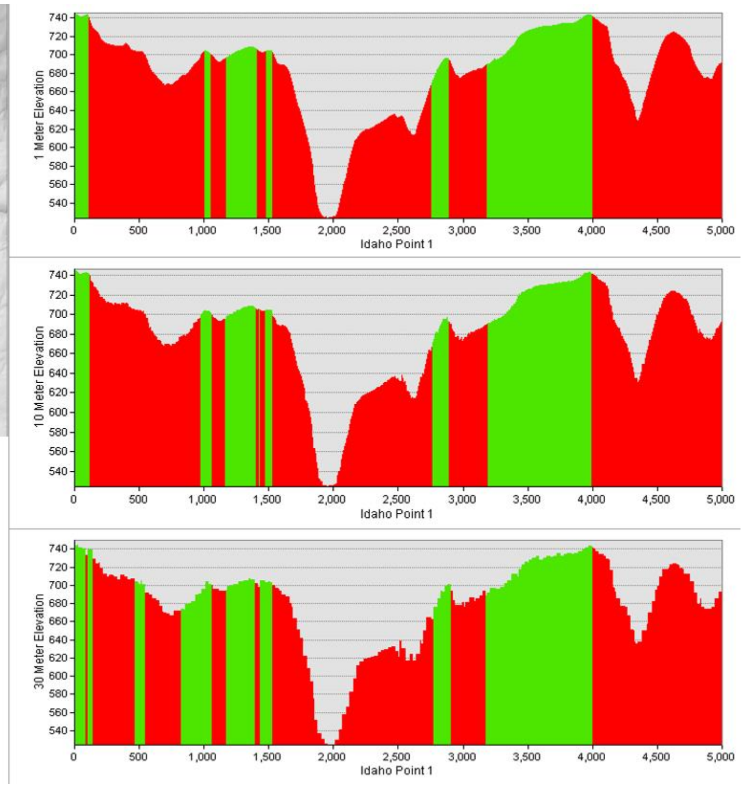
E1: This is an overview of the Idaho site that shows the terrain, the observer point as a pink point, and the visible area at various DEM resolutions in blue. Light blue (1) means that the area is only visible at one of the three resolutions. Medium blue (2) means two resolutions match. Finally, the darkest blue shows where all three resolutions agree.



E2: A., B., and C. The visibility map for the southwest, southeast, and northwest observation points, as well as the observer heights and line-of-sight results for each resolution. D. shows the individual visibility for Idaho broken down by point (starting with Point 1 in the SW, Point 2, in the SE, Point 3 in the NW and finally Point 4 in the NE) and the percentage visible at 1, 2, or 3 resolutions.

A.



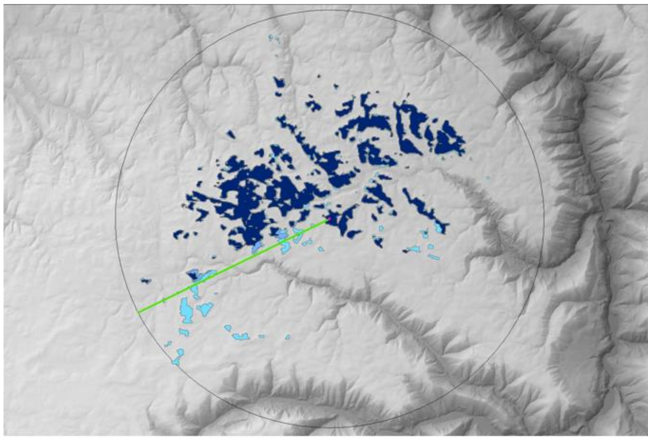


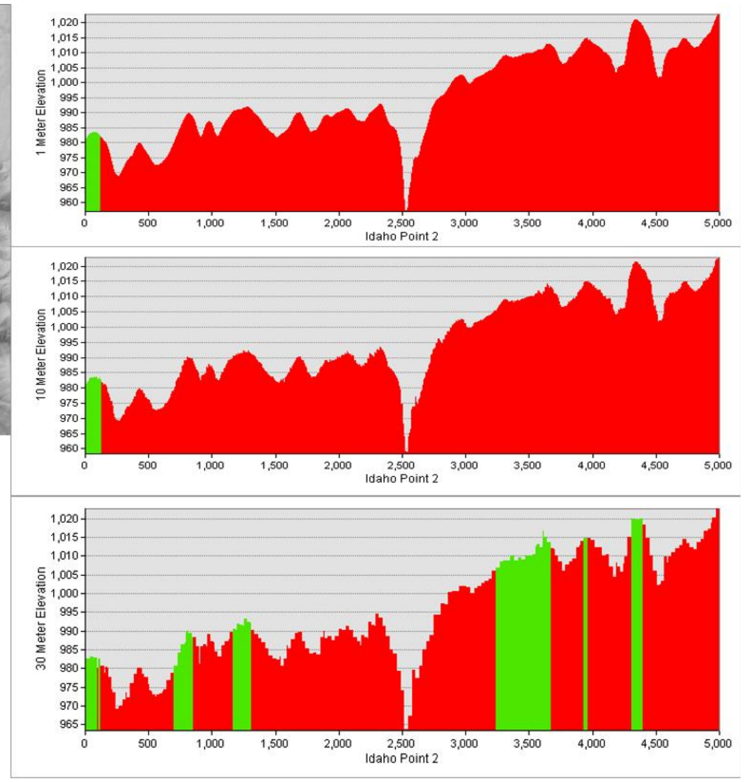
Observer Height at Start Point

Pt1 1m	746.851
Pt 1 10m	748.118
Pt 1 30m	751.338

1 Elevation:
2 246.13m –
3 1262.71m

B.



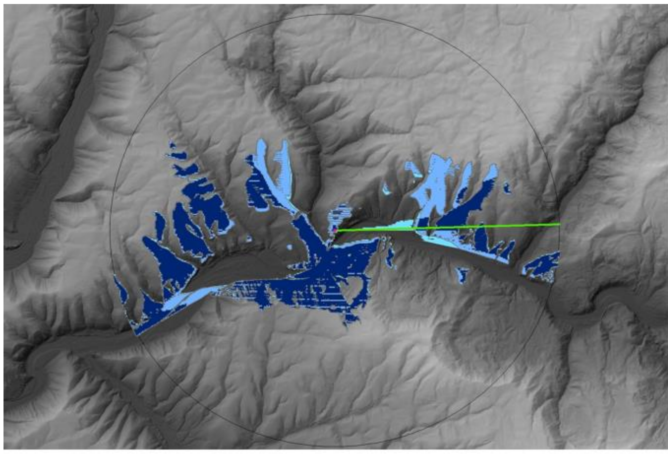


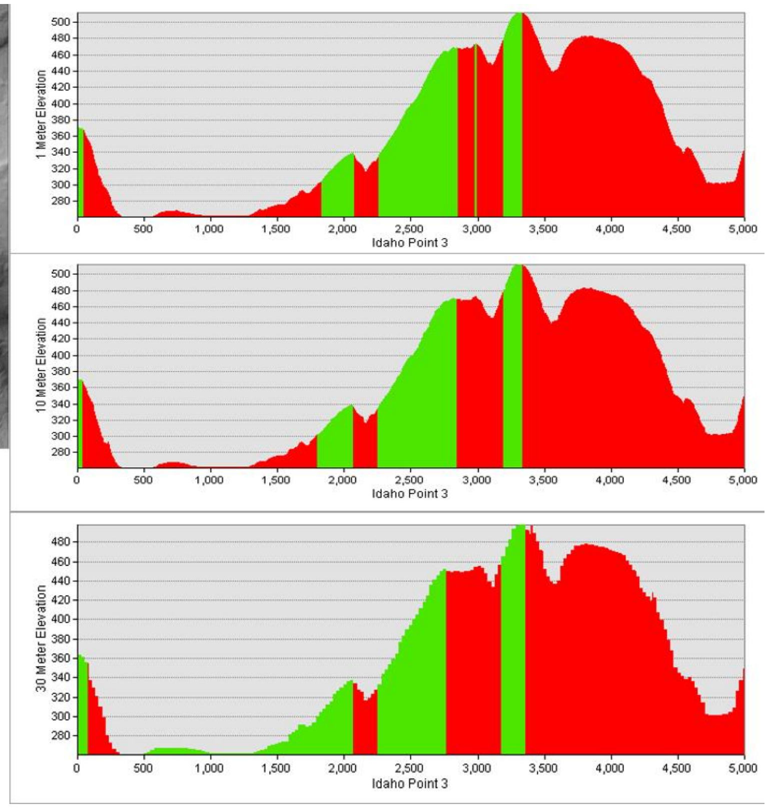
Observer Height at Start Point

Pt 2 1m	982.505
Pt 2 10m	982.42
Pt 2 30m	982.877

1 2 3 Elevation: 246.13m – 1262.71m

C.





Observer Height at Start Point

Pt3 1m	370.79
Pt 3 10m	369.811
Pt 3 30m	363.396

1 Elevation:
2 246.13m –
3 1262.71m

D.

AREA: Number of 1 Overlaps	Percent of 1 Layer Visible	AREA: Number of 2 Overlaps	Percent of 2 Layers Visible	AREA: Number of 3 Overlaps	Percent of 3 Layers Visible	SUM of ALL
1,255,630.16	15.13	718595.45	8.66	6,325,068.23	76.21	8,299,293.84
1,617,928.91	21.68	615395.90	8.24	5,230,889.19	70.08	7,464,214.00
1,365,241.03	11.84	3481478.20	30.19	6,685,556.44	57.97	11,532,275.67
414,835.82	12.09	472577.18	13.77	2,543,674.45	74.14	3,431,087.45
4,653,635.93	15.15	5,288,046.72	17.21	20,785,188.30	67.64	30,726,870.95

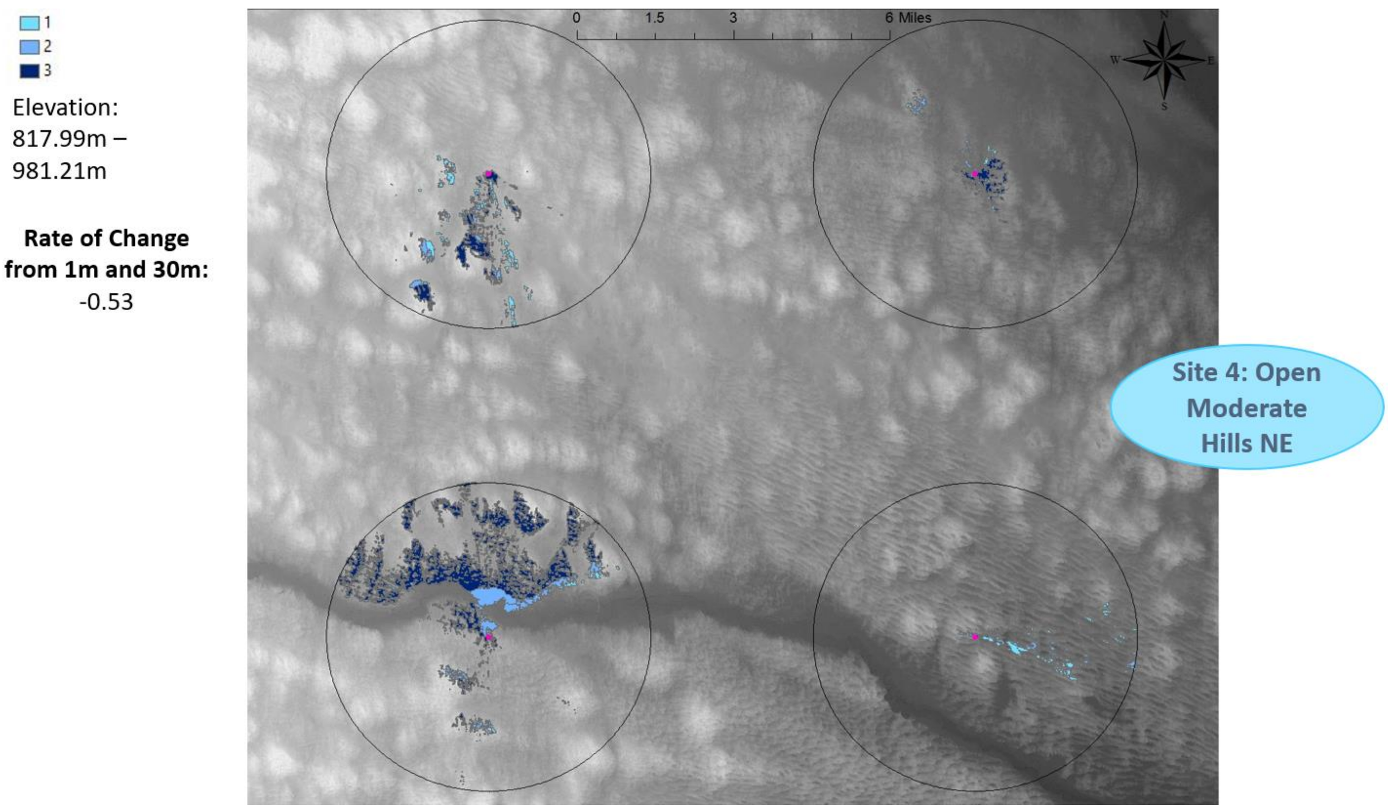
E3: Summary of how much the visibility changed between resolutions. The area that is not visible is also shown as a comparison.

Visible Area By Viewshed					
	Pt1	Pt2	Pt3	Pt4	Totals
1M	6,839,847.00	5,763,490.00	10,611,520.00	3,054,159.00	26,269,016.00
1m-10m % Change	2.49	-1.21	-4.98	-1.72	
10M	7,014,267.83	5,694,564.33	10,108,614.73	3,002,558.83	25,820,005.72
10m-30m % Change	10.23	19.61	-31.88	-2.33	
30M	7,813,910.95	7,083,333.92	7,664,732.05	2,934,295.72	25,496,272.64
TOTALS	Pt1	Pt2	Pt3	Pt4	
SUM	21,668,025.78	18,541,388.25	28,384,866.78	8,991,013.55	
AVE	7,222,675.26	6,180,462.75	9,461,622.26	2,997,004.52	

Area Not Visible By Viewshed					
	Pt1	Pt2	Pt3	Pt4	Totals
1M	72,959,569.00	74,035,926.00	69,187,896.00	76,745,257.00	292,928,648.00
1m-10m % Change	-0.23	0.10	0.73	0.07	
10M	72,788,974.97	74,108,678.48	69,695,146.65	76,801,202.55	293,394,002.65
10m-30m % Change	-1.11	-1.91	3.38	0.08	
30M	71,986,811.78	72,717,388.82	72,135,990.69	76,866,427.02	293,706,618.30
TOTALS	Pt1	Pt2	Pt3	Pt4	
SUM	217,735,355.76	220,861,993.29	211,019,033.34	230,412,886.57	
AVE	72,578,451.92	73,620,664.43	70,339,677.78	76,804,295.52	

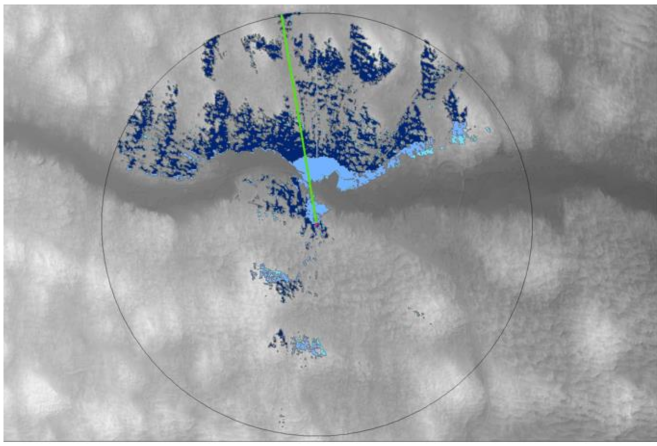
ANNEX F: Each of the nine sites was analyzed in three different ways.

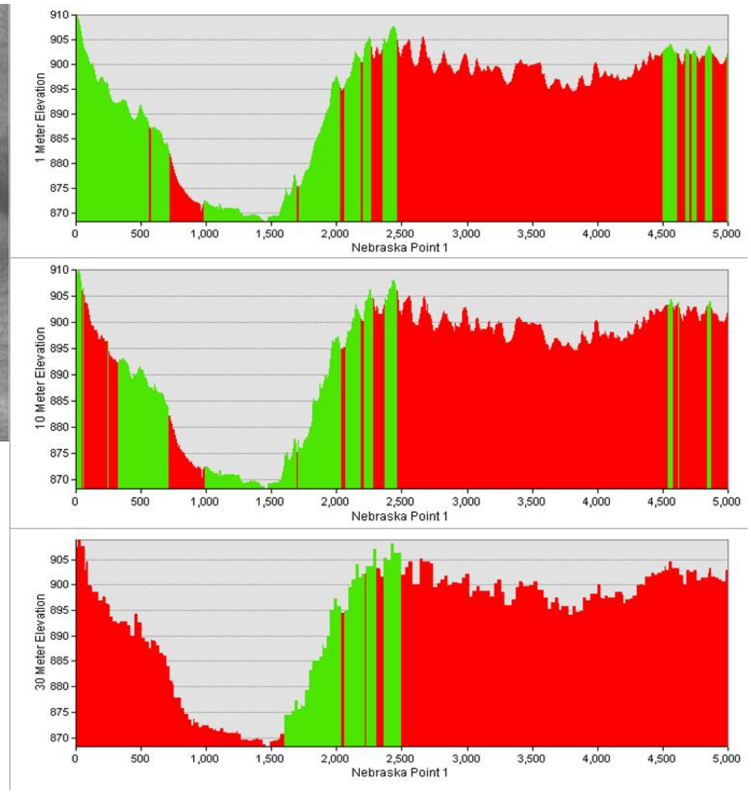
F1: This is an overview of the Nebraska site that shows the terrain, the observer point as a pink point, and the visible area at various DEM resolutions in blue. Light blue (1) means that the area is only visible at one of the three resolutions. Medium blue (2) means two resolutions match. Finally, the darkest blue shows where all three resolutions agree.



F2: A., B., and C. The visibility map for the southwest, southeast, and northwest observation points, as well as the observer heights and line-of-sight results for each resolution. D. shows the individual visibility for Nebraska broken down by point (starting with Point 1 in the SW, Point 2, in the SE, Point 3 in the NW and finally Point 4 in the NE) and the percentage visible at 1, 2, or 3 resolutions.

A.

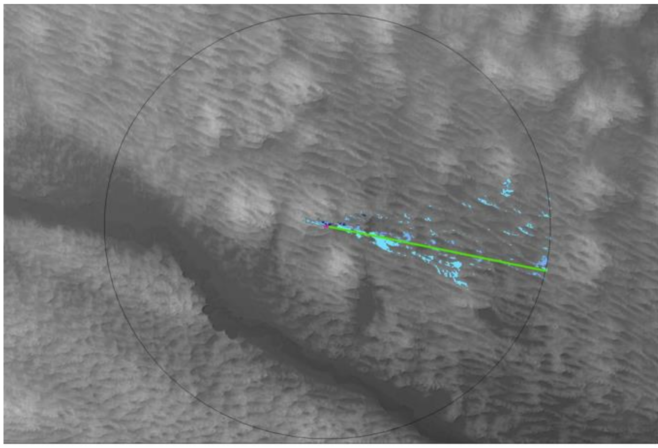


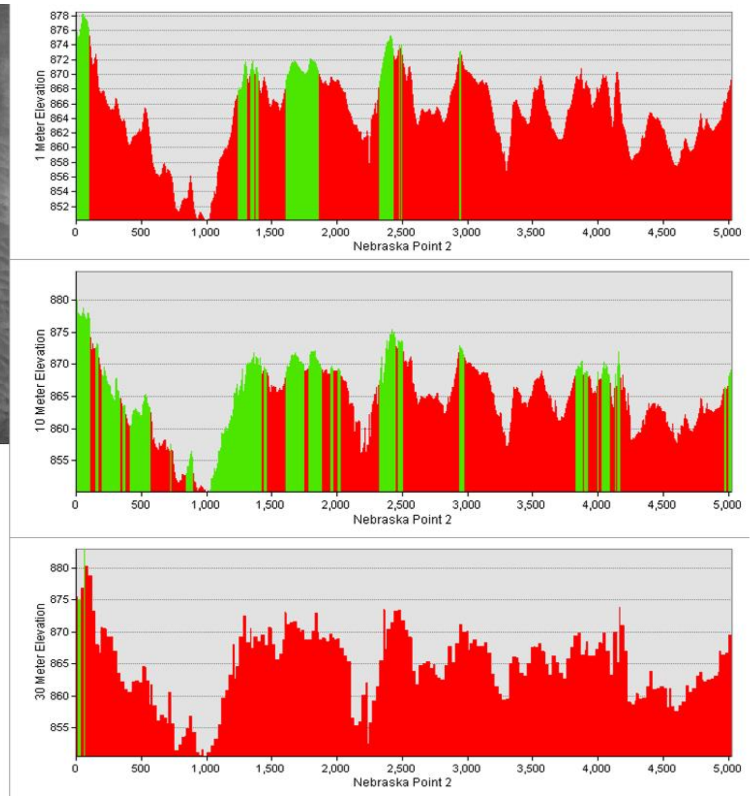


Observer Height at Start Point	
Pt1 1m	911.609
Pt 1 10m	911.241
Pt 1 30m	909.026

1 Elevation:
2 817.99m –
3 981.21m

B.



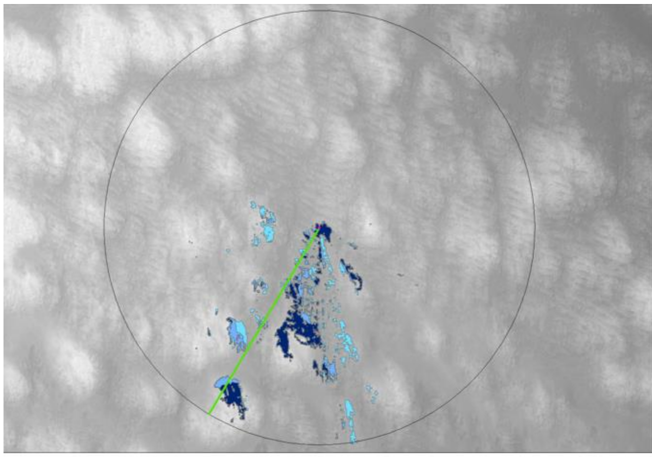


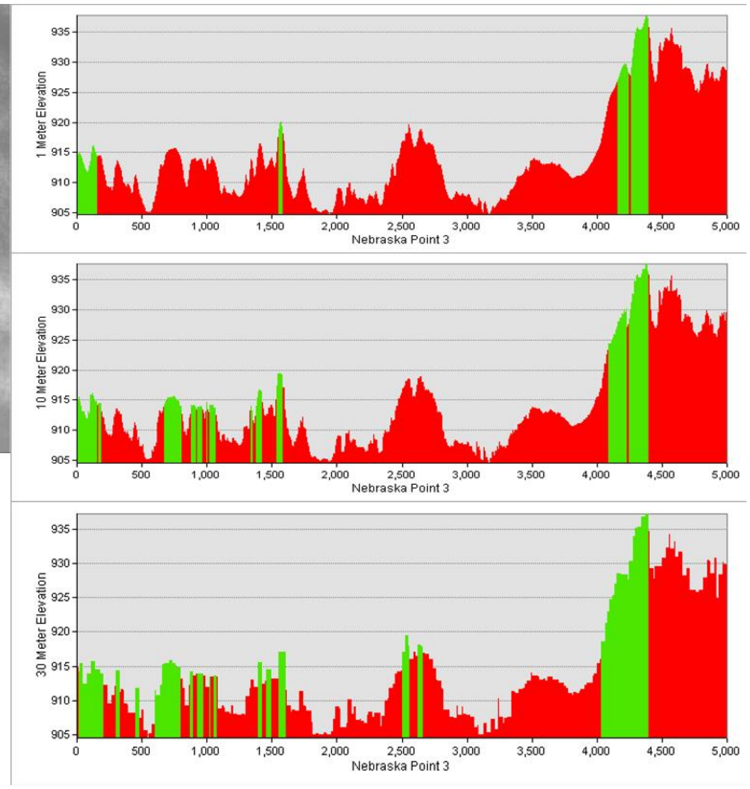
Observer Height at Start Point

Pt 2 1m	878.396
Pt 2 10m	880.241
Pt 2 30m	877.209

1 Elevation:
2 817.99m –
3 981.21m

C.





Observer Height at Start Point

Pt3 1m	915.432
Pt 3 10m	916.663
Pt 3 30m	916.536

1 2 3 Elevation: 817.99m – 981.21m

D.

AREA: Number of 1 Overlaps	Percent of 1 Layer Visible	AREA: Number of 2 Overlaps	Percent of 2 Layers Visible	AREA: Number of 3 Overlaps	Percent of 3 Layers Visible	SUM of ALL
2,382,712.51	20.10	3,325,804.50	28.06	6,145,549.16	51.84	11,854,066.16
870,218.41	74.28	272,874.83	23.29	28,444.20	2.43	1,171,537.44
1,310,489.76	44.12	714,393.93	24.05	945,271.21	31.83	2,970,154.90
449,649.92	34.55	327,583.98	25.17	524,225.59	40.28	1,301,459.49
5,013,070.61	28.98	4,640,657.24	26.83	7,643,490.15	44.19	17,297,218.00

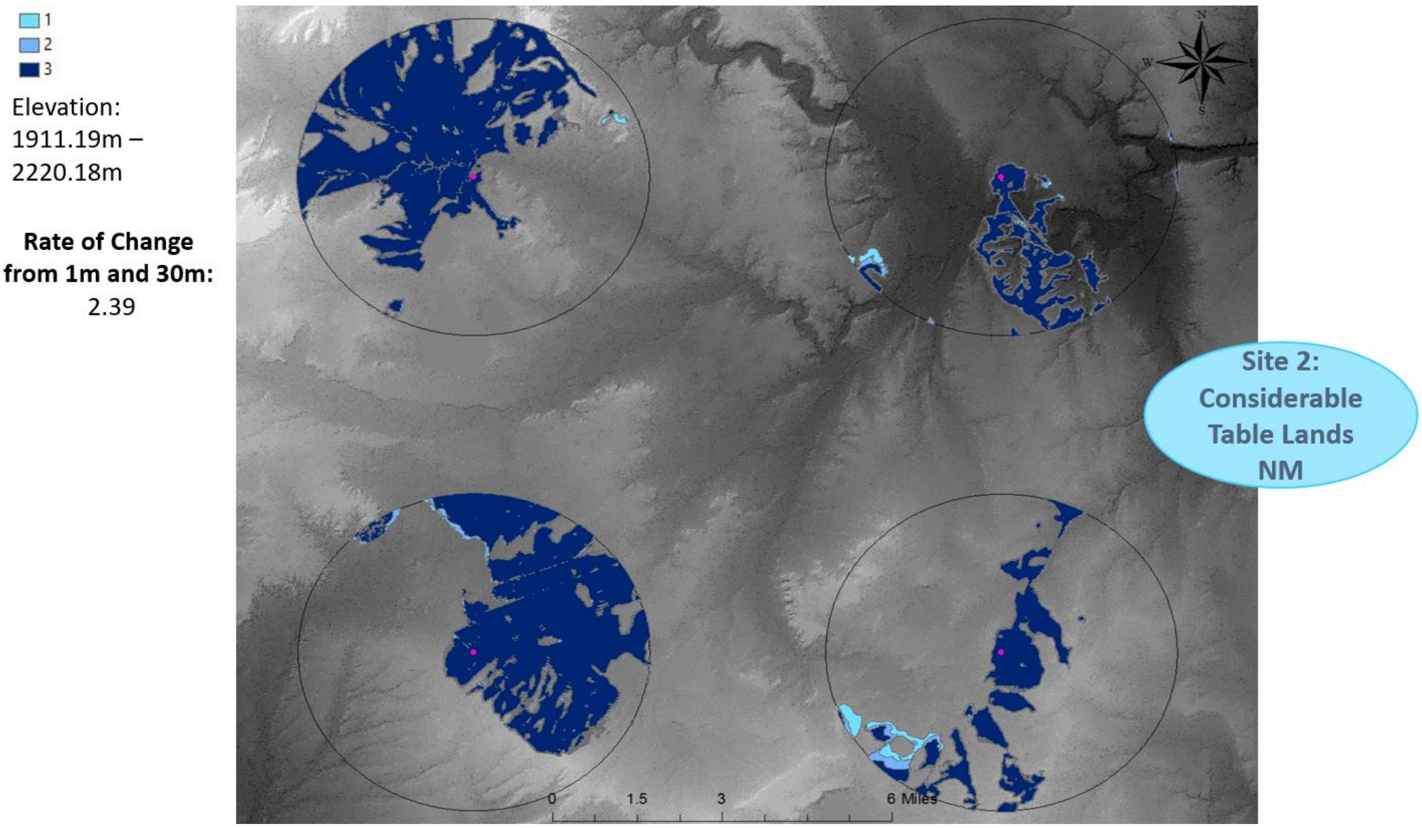
F3: Summary of how much the visibility changed between resolutions. The area that is not visible is also shown as a comparison.

Visible Area By Viewshed					
	Pt1	Pt2	Pt3	Pt4	Totals
1M	9,757,263.00	299,936.00	1,081,498.00	826,001.00	11,964,698.00
1m-10m % Change	-2.40	73.80	39.00	9.45	
10M	9,528,446.68	1,144,744.40	1,772,916.43	912,177.82	13,358,285.32
10m-30m % Change	-16.41	-1921.79	34.84	2.89	
30M	8,185,259.30	56,620.28	2,720,676.82	939,315.85	11,901,872.25
TOTALS	Pt1	Pt2	Pt3	Pt4	
SUM	27,470,968.98	1,501,300.67	5,575,091.25	2,677,494.67	
AVE	9,156,989.66	500,433.56	1,858,363.75	892,498.22	

Area Not Visible By Viewshed					
	Pt1	Pt2	Pt3	Pt4	Totals
1M	70,042,047.00	79,499,374.00	78,717,882.00	78,973,379.00	307,232,682.00
1m-10m % Change	0.33	-1.07	-0.88	-0.10	
10M	70,275,160.96	78,658,863.24	78,030,691.21	78,891,429.82	305,856,145.23
10m-30m % Change	1.88	1.37	-1.22	-0.03	
30M	71,623,922.48	79,752,561.50	77,088,504.95	78,869,865.93	307,334,854.86
TOTALS	Pt1	Pt2	Pt3	Pt4	
SUM	211,941,130.44	237,910,798.74	233,837,078.17	236,734,674.75	
AVE	70,647,043.48	79,303,599.58	77,945,692.72	78,911,558.25	

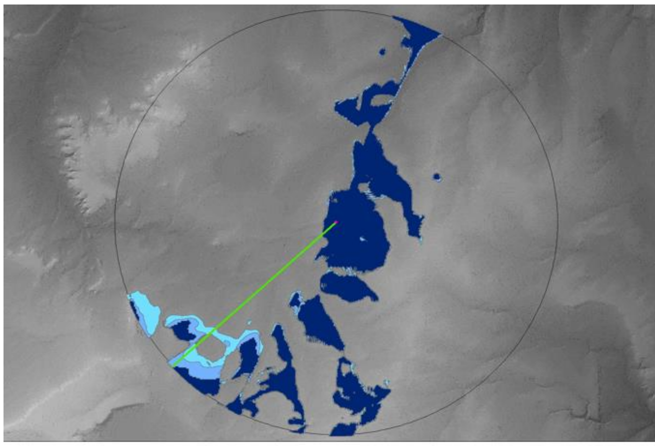
ANNEX G: Each of the nine sites was analyzed in three different ways.

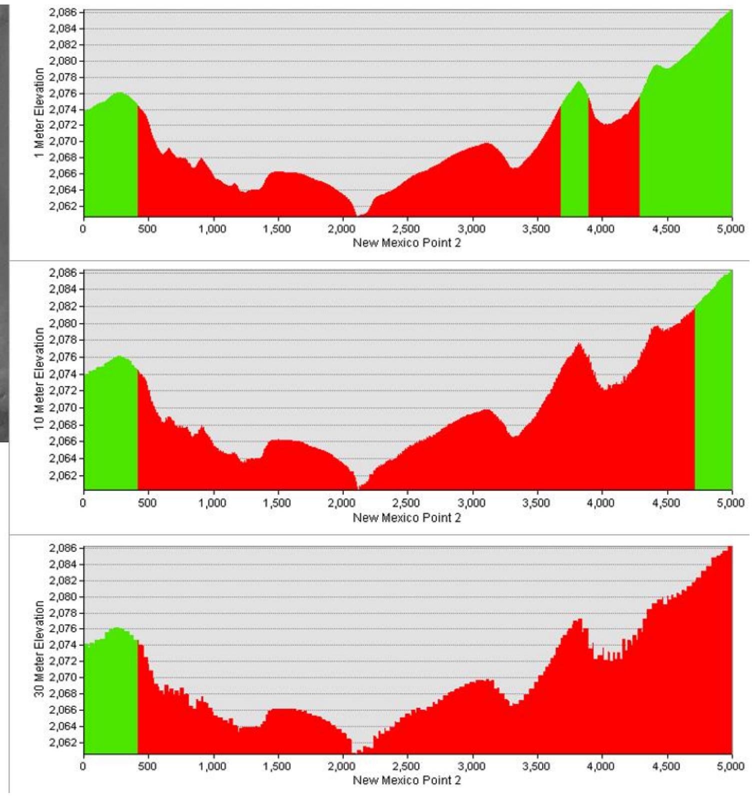
G1: This is an overview of the New Mexico site that shows the terrain, the observer point as a pink point, and the visible area at various DEM resolutions in blue. Light blue (1) means that the area is only visible at one of the three resolutions. Medium blue (2) means two resolutions match. Finally, the darkest blue shows where all three resolutions agree.



G2: A. The visibility map for the southeast observation point, as well as the observer heights and line-of-sight results for each resolution. B. shows the individual visibility for New Mexico broken down by point (starting with Point 1 in the SW, Point 2, in the SE, Point 3 in the NW and finally Point 4 in the NE) and the percentage visible at 1, 2, or 3 resolutions.

A.





Observer Height at Start Point

Pt 2 1m	2075.36
Pt 2 10m	2075.142
Pt 2 30m	2075.15

1 Elevation:
2 1911.19m –
3 2220.18m

B.

AREA: Number of 1 Overlaps	Percent of 1 Layer Visible	AREA: Number of 2 Overlaps	Percent of 2 Layers Visible	AREA: Number of 3 Overlaps	Percent of 3 Layers Visible	SUM of ALL
1,080,695.84	3.51	1,843,401.88	5.98	27,878,322.27	90.51	30,802,419.99
1,630,192.74	13.26	1,477,917.07	12.02	9,189,627.46	74.73	12,297,737.27
1,221,097.94	3.77	1,426,073.09	4.40	29,741,545.24	91.83	32,388,716.28
904,730.18	12.13	711,797.99	9.54	5,841,888.86	78.33	7,458,417.03
4,836,716.71	5.83	5,459,190.04	6.58	72,651,383.83	87.59	82,947,290.58

G3: Summary of how much the visibility changed between resolutions. The area that is not visible is also shown as a comparison.

Visible Area By Viewshed

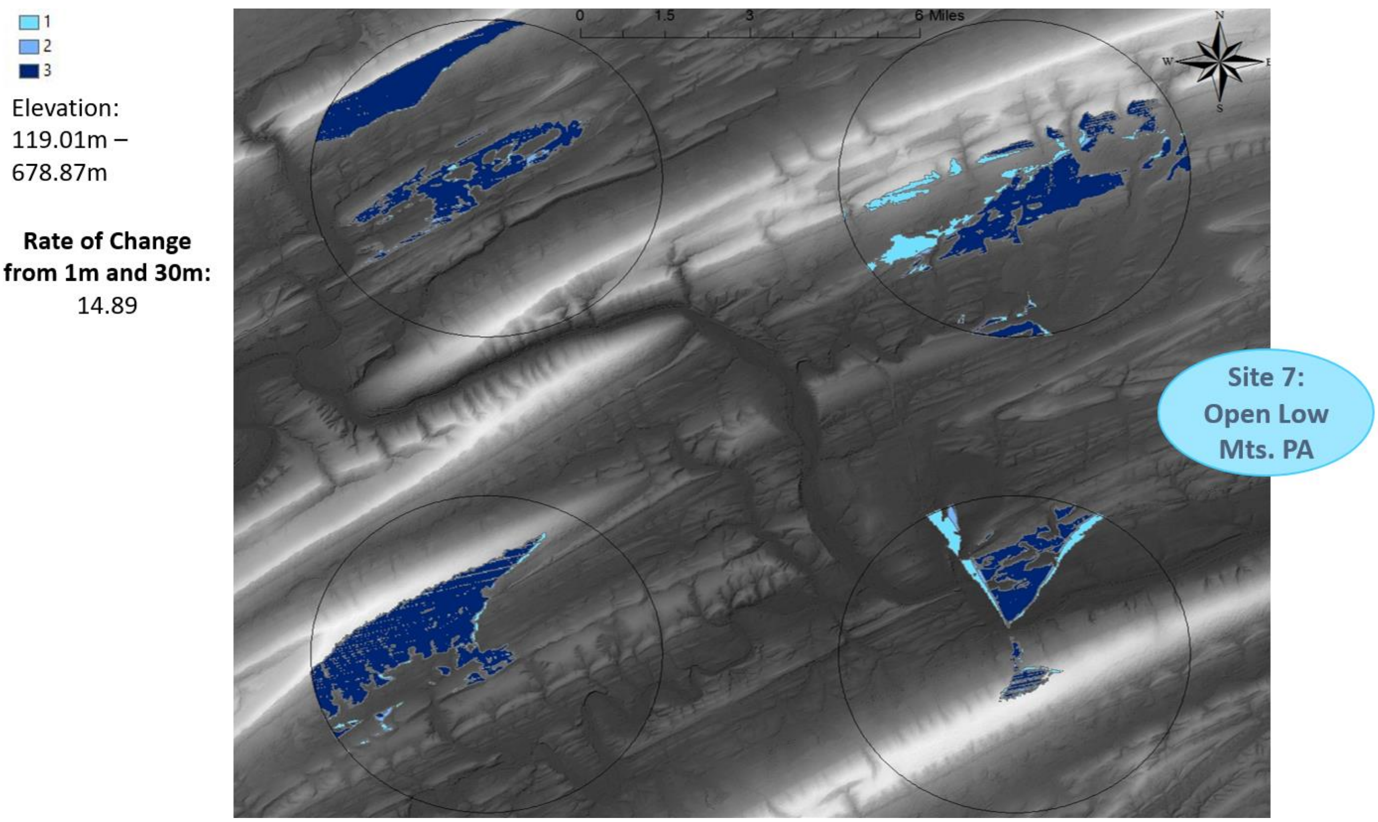
	Pt1	Pt2	Pt3	Pt4	Totals
1M	28,354,235.00	11,390,465.00	30,362,144.00	6,447,050.00	76,553,894.00
1m-10m % Change	5.30	-4.56	3.65	-1.15	
10M	29,942,378.26	10,893,505.69	31,513,809.88	6,373,516.90	78,723,210.72
10m-30m % Change	0.54	-10.36	-0.29	9.38	
30M	30,105,853.14	9,870,938.57	31,421,926.02	7,033,425.85	78,432,143.58
TOTALS	Pt1	Pt2	Pt3	Pt4	
SUM	88,402,466.40	32,154,909.26	93,297,879.90	19,853,992.75	
AVE	29,467,488.80	10,718,303.09	31,099,293.30	6,617,997.58	

Area Not Visible By Viewshed

	Pt1	Pt2	Pt3	Pt4	Totals
1M	51,445,181.00	68,408,951.00	49,437,272.00	73,352,366.00	242,643,770.00
1m-10m % Change	-3.18	0.72	-2.38	0.10	
10M	49,859,313.74	68,908,186.31	48,287,882.12	73,428,175.10	240,483,557.27
10m-30m % Change	-0.32	1.47	0.20	-0.90	
30M	49,698,800.05	69,933,714.62	48,382,727.16	72,771,227.33	240,786,469.16
TOTALS	Pt1	Pt2	Pt3	Pt4	
SUM	151,003,294.78	207,250,851.93	146,107,881.29	219,551,768.44	
AVE	50,334,431.59	69,083,617.31	48,702,627.10	73,183,922.81	

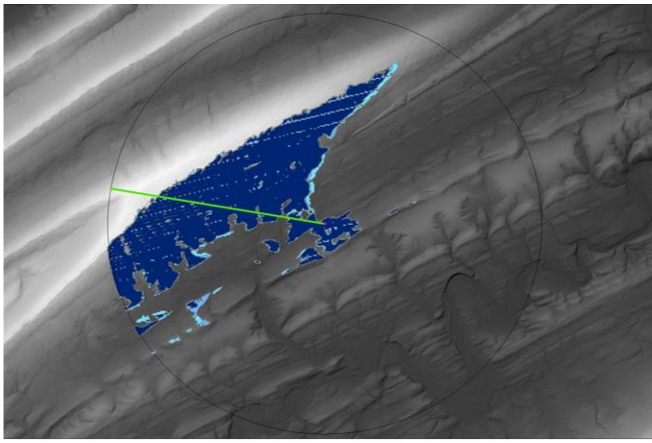
ANNEX H: Each of the nine sites was analyzed in three different ways.

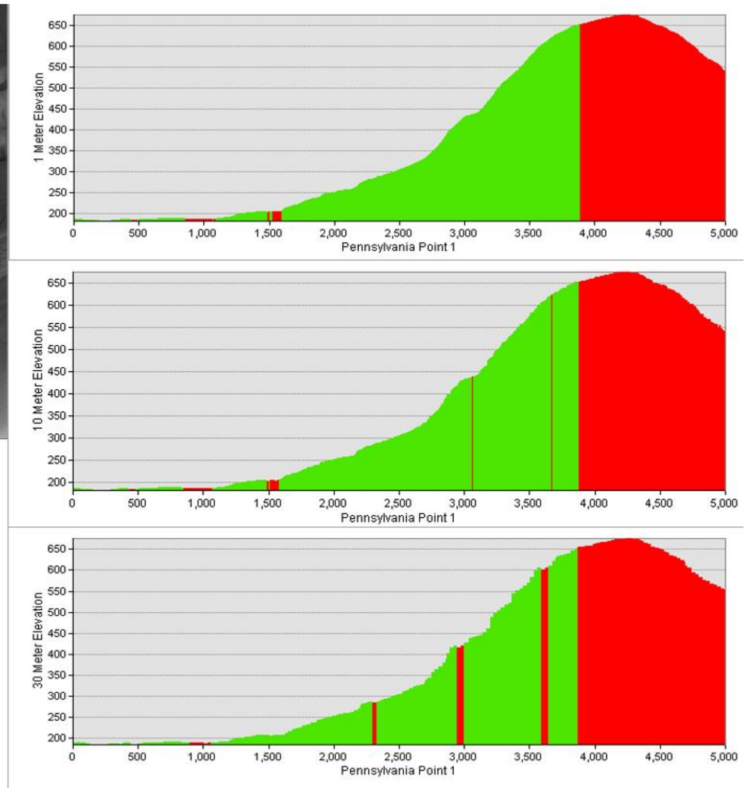
H1: This is an overview of the Pennsylvania site that shows the terrain, the observer point as a pink point, and the visible area at various DEM resolutions in blue. Light blue (1) means that the area is only visible at one of the three resolutions. Medium blue (2) means two resolutions match. Finally, the darkest blue shows where all three resolutions agree.



H2: A., B., C., and D. The visibility map for all of the observation points, as well as the observer heights and line-of-sight results for each resolution. E. shows the individual visibility for Pennsylvania broken down by point (starting with Point 1 in the SW, Point 2, in the SE, Point 3 in the NW and finally Point 4 in the NE) and the percentage visible at 1, 2, or 3 resolutions.

A.





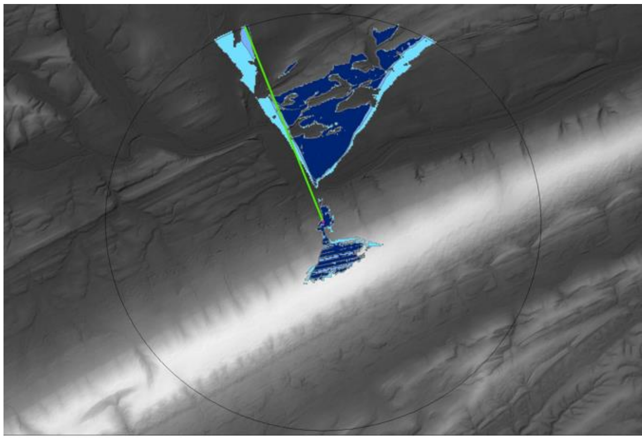
Observer Height at Start Point

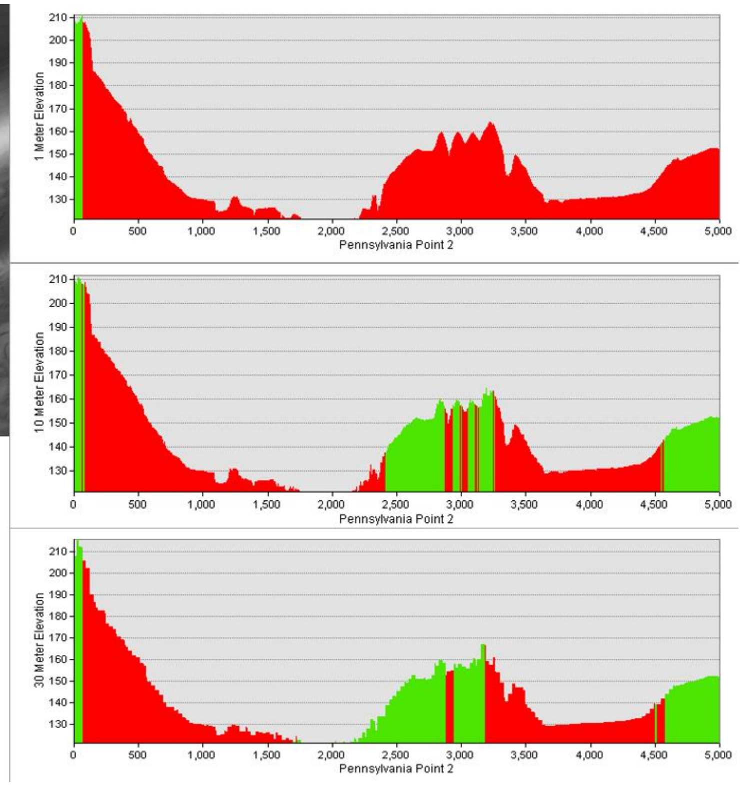
Pt1 1m	189.553
Pt 1 10m	189.302
Pt 1 30m	189.847

1
2
3

Elevation:
119.01m –
678.87m

B.



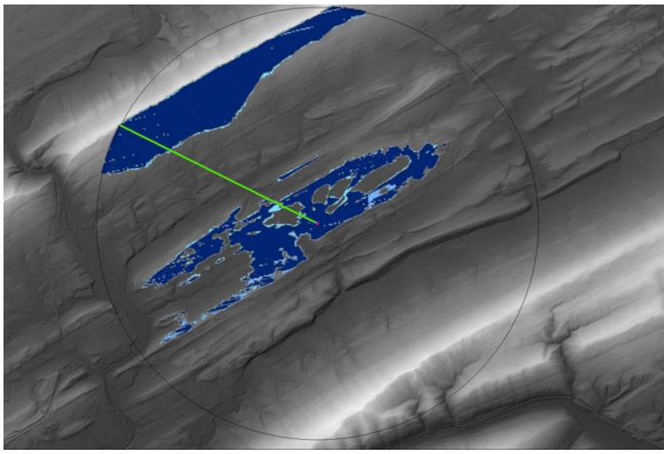


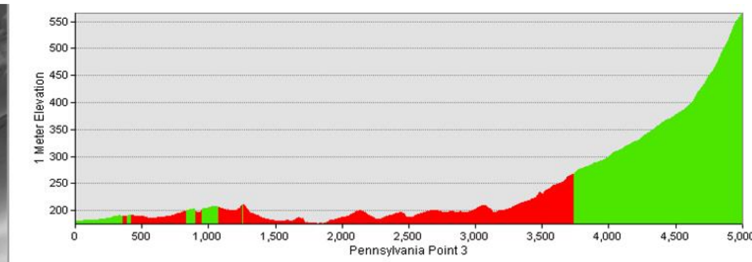
Observer Height at Start Point

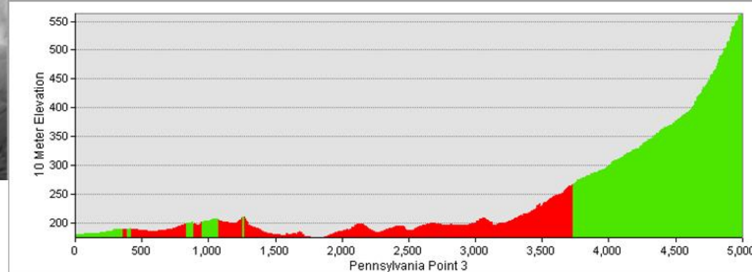
Pt 2 1m	211.406
Pt 2 10m	211.944
Pt 2 30m	213.638

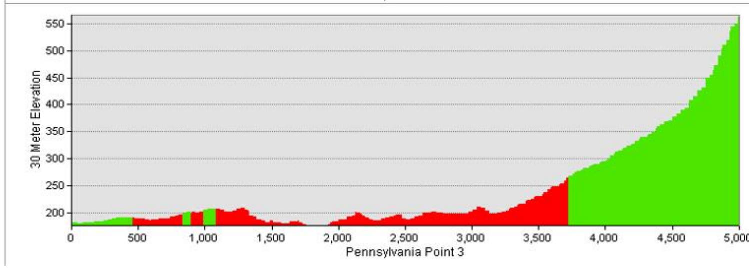
1 Elevation:
2 119.01m –
3 678.87m

C.





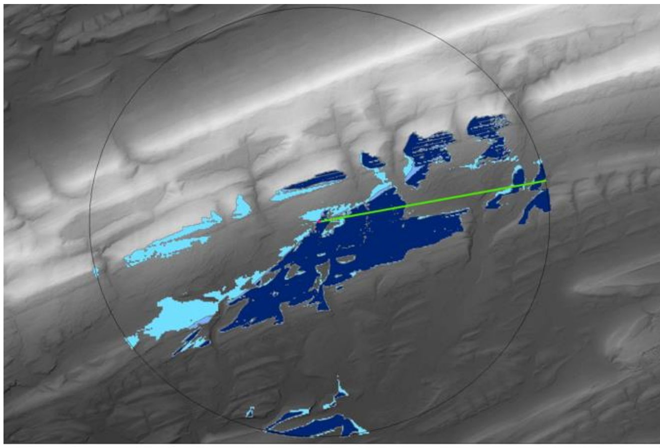


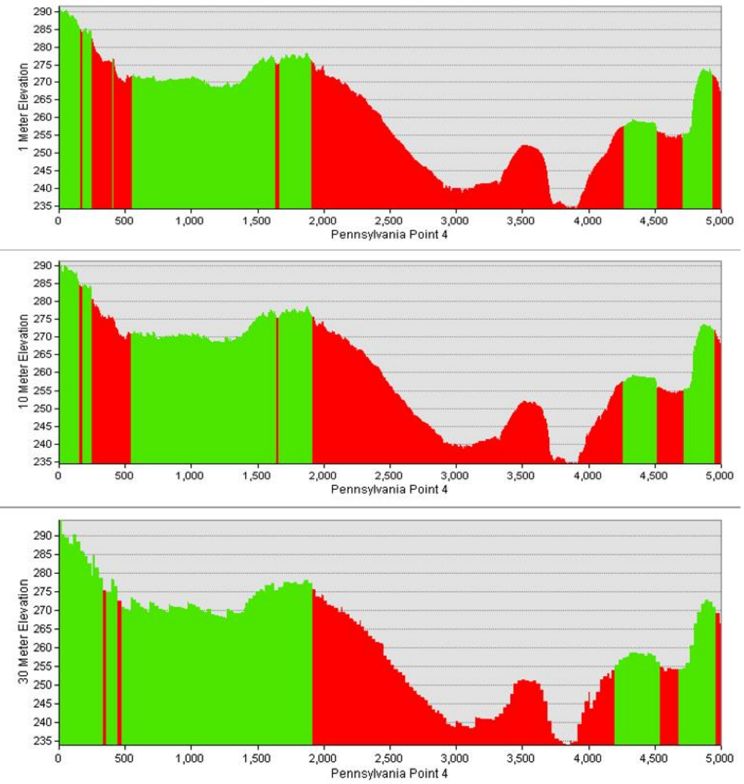


Observer Height at Start Point	
Pt3 1m	182.98
Pt 3 10m	182.603
Pt 3 30m	183.352

1 Elevation:
2 119.01m –
3 678.87m

D.





Observer Height at Start Point

Pt 4 1m	293.282
Pt 4 10m	293.076
Pt 4 30m	295.897

1 Elevation:
2 119.01m –
3 678.87m

E.

AREA: Number of 1 Overlaps	Percent of 1 Layer Visible	AREA: Number of 2 Overlaps	Percent of 2 Layers Visible	AREA: Number of 3 Overlaps	Percent of 3 Layers Visible	SUM of ALL
999,670.56	8.02	908,966.47	7.29	10,552,085.08	84.68	12,460,722.11
1,876,304.82	29.67	757,021.20	11.97	3,691,304.17	58.36	6,324,630.18
1,041,574.50	8.51	921,309.78	7.53	10,274,514.57	83.96	12,237,398.85
3,772,111.96	30.22	895,331.66	7.17	7,815,238.05	62.61	12,482,681.67
7,689,661.83	17.68	3,482,629.11	8.01	32,333,141.88	74.32	43,505,432.82

H3: Summary of how much the visibility changed between resolutions. The area that is not visible is also shown as a comparison.

Visible Area By Viewshed

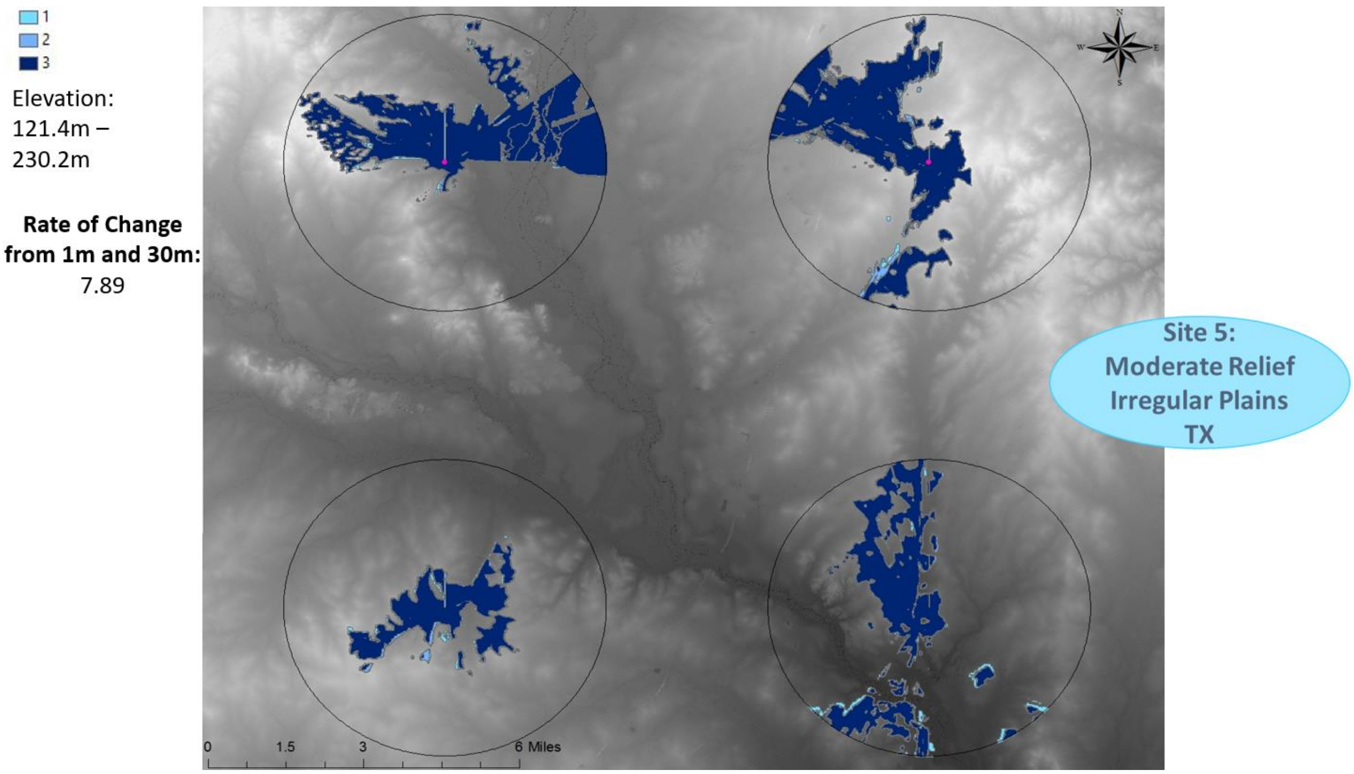
	Pt1	Pt2	Pt3	Pt4	Totals
1M	11,348,534.00	4,050,311.00	11,123,754.00	8,607,246.00	35,129,845.00
1m-10m % Change	0.45	7.48	-0.26	-2.79	
10M	11,400,237.02	4,377,824.99	11,094,688.14	8,373,543.00	35,246,293.15
10m-30m % Change	5.22	27.47	3.43	28.58	
30M	12,027,700.38	6,036,123.71	11,489,295.66	11,725,087.74	41,278,207.48
TOTALS	Pt1	Pt2	Pt3	Pt4	
SUM	34,776,471.40	14,464,259.70	33,707,737.80	28,705,876.74	
AVE	11,592,157.13	4,821,419.90	11,235,912.60	9,568,625.58	

Area Not Visible By Viewshed

	Pt1	Pt2	Pt3	Pt4	Totals
1M	68,450,790.00	75,749,013.00	68,675,570.00	71,192,078.00	284,067,451.00
1m-10m % Change	-0.07	-0.43	0.05	0.33	
10M	68,403,472.76	75,425,884.79	68,709,363.42	71,430,508.56	283,969,229.53
10m-30m % Change	-0.47	-2.25	-0.58	-5.39	
30M	68,080,163.57	73,769,127.60	68,315,187.60	67,776,782.88	277,941,261.66
TOTALS	Pt1	Pt2	Pt3	Pt4	
SUM	204,934,426.34	224,944,025.39	205,700,121.02	210,399,369.44	
AVE	68,311,475.45	74,981,341.80	68,566,707.01	70,133,123.15	

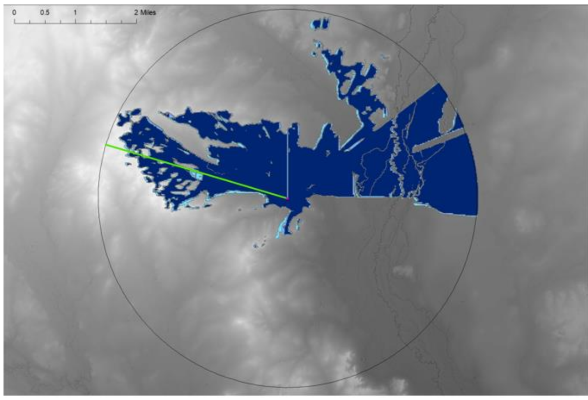
ANNEX I: Each of the nine sites was analyzed in three different ways.

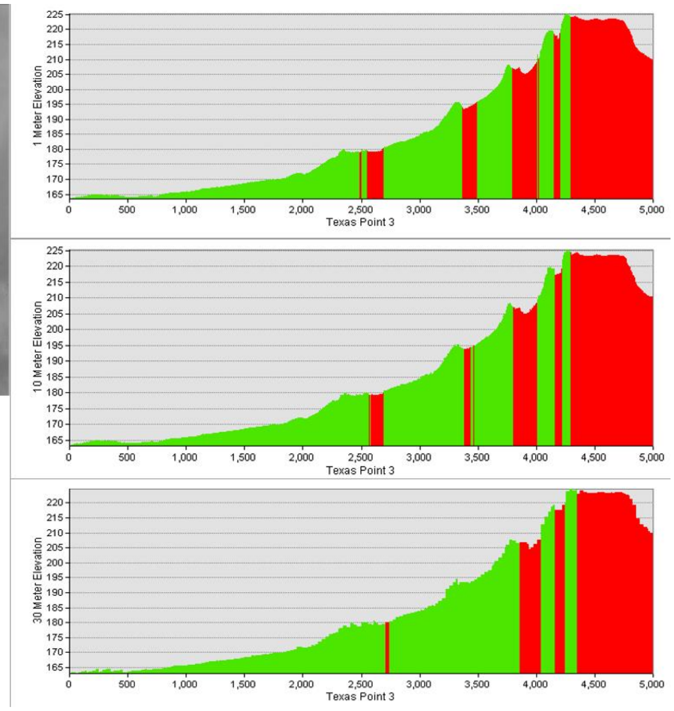
I1: This is an overview of the Texas site that shows the terrain, the observer point as a pink point, and the visible area at various DEM resolutions in blue. Light blue (1) means that the area is only visible at one of the three resolutions. Medium blue (2) means two resolutions match. Finally, the darkest blue shows where all three resolutions agree.



I2: A. and B. The visibility map for the northwest and northeast observation points, as well as the observer heights and line-of-sight results for each resolution. C. shows the individual visibility for Texas broken down by point (starting with Point 1 in the SW, Point 2, in the SE, Point 3 in the NW and finally Point 4 in the NE) and the percentage visible at 1, 2, or 3 resolutions.

A.

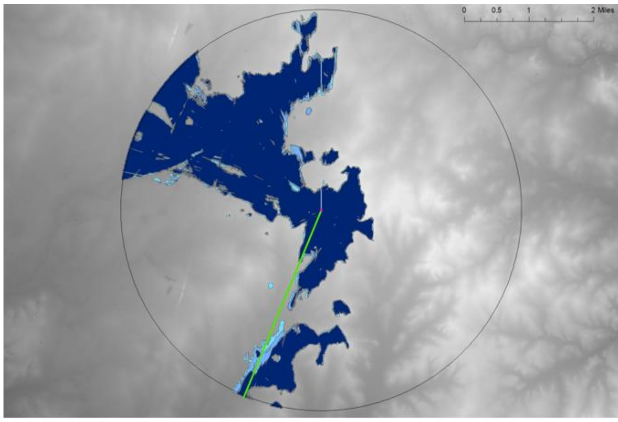


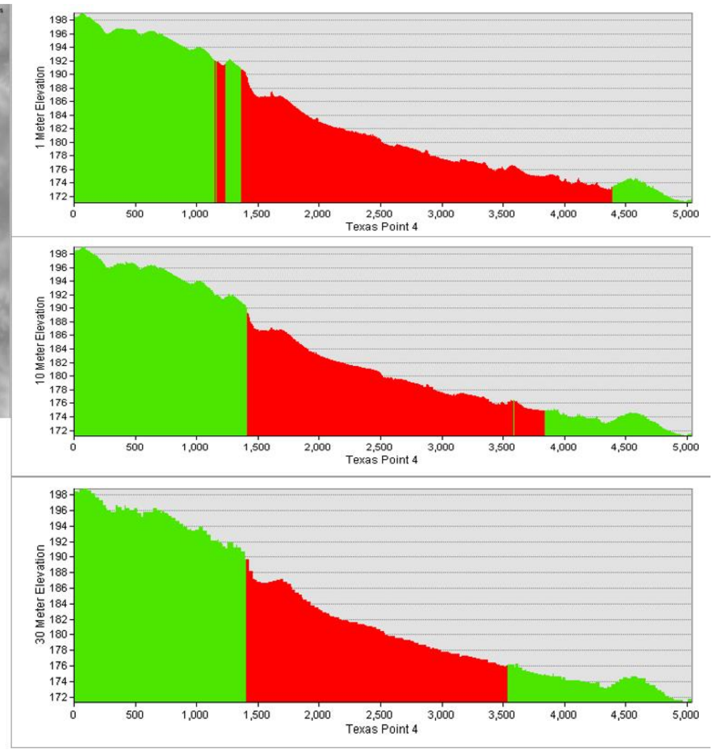


Observer Height at Start Point	
Pt3 1m	165.209
Pt 3 10m	165.08
Pt 3 30m	164.749

1 Elevation:
2 121.4m –
3 230.2m

B.





Observer Height at Start Point

Pt 4 1m	200.076
Pt 4 10m	200.113
Pt 4 30m	200.164

1 Elevation:
2 121.4m –
3 230.2m

C.

AREA: Number of 1 Overlaps	Percent of 1 Layer Visible	AREA: Number of 2 Overlaps	Percent of 2 Layers Visible	AREA: Number of 3 Overlaps	Percent of 3 Layers Visible	SUM of ALL
807,288.91	9.63	874,273.99	10.43	6,701,976.88	79.94	8,383,539.78
1,666,869.44	11.29	1,088,432.83	7.37	12,010,219.32	81.34	14,765,521.58
1,443,727.11	6.29	1,406,934.19	6.13	20,089,148.52	87.57	22,939,809.82
1,096,133.44	5.83	1,505,037.07	8.01	16,197,285.36	86.16	18,798,455.87
5,014,018.91	7.73	4,874,678.07	7.51	54,998,630.08	84.76	64,887,327.05

I3: Summary of how much the visibility changed between resolutions. The area that is not visible is also shown as a comparison.

Visible Area By Viewshed

	Pt1	Pt2	Pt3	Pt4	Totals
1M	7,422,609.00	12,477,649.00	18,194,675.00	16,521,773.00	54,616,706.00
1m-10m % Change	2.49	5.31	2.21	7.69	
10M	7,612,202.85	13,177,510.23	18,606,514.04	17,897,548.14	57,293,775.25
10m-30m % Change	0.19	7.33	2.95	2.09	
30M	7,626,955.71	14,219,233.81	19,171,868.11	18,278,742.50	59,296,800.12
TOTALS	Pt1	Pt2	Pt3	Pt4	
SUM	22,661,767.55	39,874,393.04	55,973,057.15	52,698,063.63	
AVE	7,553,922.52	13,291,464.35	18,657,685.72	17,566,021.21	

Area Not Visible By Viewshed

	Pt1	Pt2	Pt3	Pt4	Totals
1M	72,376,701.00	67,321,661.00	61,604,705.00	63,277,607.00	264,580,674.00
1m-10m % Change	-0.29	-1.08	-0.71	-2.26	
10M	72,164,915.83	66,599,608.45	61,170,604.64	61,879,570.54	261,814,699.46
10m-30m % Change	0.02	-1.54	-0.88	-0.57	
30M	72,182,243.52	65,589,965.41	60,637,331.11	61,530,456.73	259,939,996.77
TOTALS	Pt1	Pt2	Pt3	Pt4	
SUM	216,723,860.35	199,511,234.86	183,412,640.75	186,687,634.27	
AVE	72,241,286.78	66,503,744.95	61,137,546.92	62,229,211.42	

References:

Dikau, R., 1989. The Application of a Digital Relief Model to Landform Analysis in Geomorphology. *Three Dimensional Applications in Geographical Information Systems*, pp. 51-77.

Hammond, Edwin H. (1954). Small-Scale Continental Landform Maps. *Annals of the Association of American Geographers,* 44(1), 3-42. https://www.jstor.org/stable/2561113

MacMillan, R. A. and Shary, P.A. (2008). Chapter 9 Landforms and Landform Elements in Geomorphometry. Developments in Soil Science, 33, 227-254. https://doi.org/10.1016/S0166-2481(08)00009-3

Miller, Matthew L. (2011). Analysis of Viewshed Accuracy with Variable Resolution LiDAR Digital Surface Models, and Photogrammetrically-Derived Digital Elevation Models. *Virginia Polytechnic Institute and State University.* https://pdfs.semanticscholar.org/d6c8/67904dfff3a50b3e709640fee0e052f766b5.pdf

Thelin, Gail P. and Pike, Richard J. (1991). Landforms of the Conterminous United States—A Digital Shaded-Relief Portrayal. *U.S. Department of the Interior U.S. Geological Survey.* https://pubs.usgs.gov/imap/i2206/i2206_pamphlet.pdf

Thompson, James, Bell, Jay, and Butler, Charles (2001). Digital elevation model resolution: effects on terrain attribute calculation and quantitative soil-landscape modeling. Geoderma, 100(1-2), 67-89. DOI: 10.1016/S0016-7061(00)00081-1

USGS (1970). Classes of land-surface form in the United States. U.S. Geological Survey. https://water.usgs.gov/GIS/metadata/usgswrd/XML/na70_landfrm.xml