Topographic Change Detection using Pre- and Post-Flood LiDAR Data from Boulder, Colorado

Term Project

GEOG 603: Remote Sensing Basics and Beyond

Maja Kucharczyk

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Abstract

A major flood occurred in Boulder, Colorado in September 2013. Light detection and ranging (LiDAR) data, obtained two months before and one month after the flood, was converted into pre- and post-flood digital terrain models (DTMs), which were differenced into a DTM of a difference (DOD). The DOD was used to calculate stream channel erosion and deposition volume. The post-flood DTM was used to calculate the slope aspect of possible debris flows. The noise and limitations of the data were examined.

1. Introduction

1.1 Background

Floods are catastrophic events that can result in human fatalities and billions of dollars in damage. Between September 9 and 16, 2013, Boulder, Colorado experienced heavy and persistent rainfall exceeding 450 millimeters that resulted in flash floods, landslides, and debris flows (Gochis et al., 2015). The flood was a 1,000-year precipitation event (Goulden & Kampe, 2014). As a result, eight people died and infrastructure damage exceeded two billion dollars (Gochis et al., 2015).

1.2 Past Studies

According to Coe et al. (2014), over 1,138 debris flows occurred in the greater Boulder region as a result of the flood. The debris flows occurred when heavy rainfall liquefied and rapidly moved masses of soil downslope. Out of the 1,138 debris flows Coe et al. (2014) measured in the field and later digitized using satellite imagery, 78 percent (%) initiated on south-facing slopes. The authors believe one contributing factor to the trend could be that south-facing slopes lack thick tree cover and contain abundant rock outcrops. The geospatial data for the 1,138 debris flows observed in the field by Coe et al. (2014) could not be located. Luckily, the Colorado Geological Survey produced a geospatial dataset

of debris flow locations shortly after the flood in December, 2013 (Morgan, Fitzgerald, & Morgan, 2013). This geospatial dataset was also digitized using pre- and post-flood satellite imagery.

Conveniently, the National Ecological Observatory Network (NEON) of Boulder, Colorado, collected airborne light detection and ranging (LiDAR) data over Boulder approximately two months before the flood occurred and one month after the flood (Goulden & Kampe, 2014). The timing of the data collection introduces an opportunity for temporal analysis of topographic change due to the flood. Specifically, the pre- and post-flood LiDAR datasets can be differenced in order to locate evidence of flood-induced sediment transport in the form of stream channel erosion and deposition. The slope aspect of debris flow locations can also be analyzed.

1.3 Objectives

For this term project, there are three main objectives:

1) Use the pre- and post-flood LiDAR data to produce pre- and post-flood digital terrain models (DTMs), followed by a DTM of difference (DOD)

2) Use the DOD to locate areas of sediment erosion and deposition along a stream channel and calculate erosion and deposition volume

3) Use the post-flood DTM to determine the slope aspects of the satellite imagery-derived debris flow locations by Morgan, Fitzgerald, & Morgan (2014) and compare the results to those obtained by Coe et al. (2014)

2. Methodology

2.1 Study Area

Figure 1 shows the approximate location of Boulder, Colorado, United States. Boulder is situated in the foothills and plains east of the Rocky Mountains, approximately 45 kilometers northwest of Denver. Similar to Calgary, Boulder is susceptible to flooding due to its proximity to the Rocky Mountains.

2.2 Data

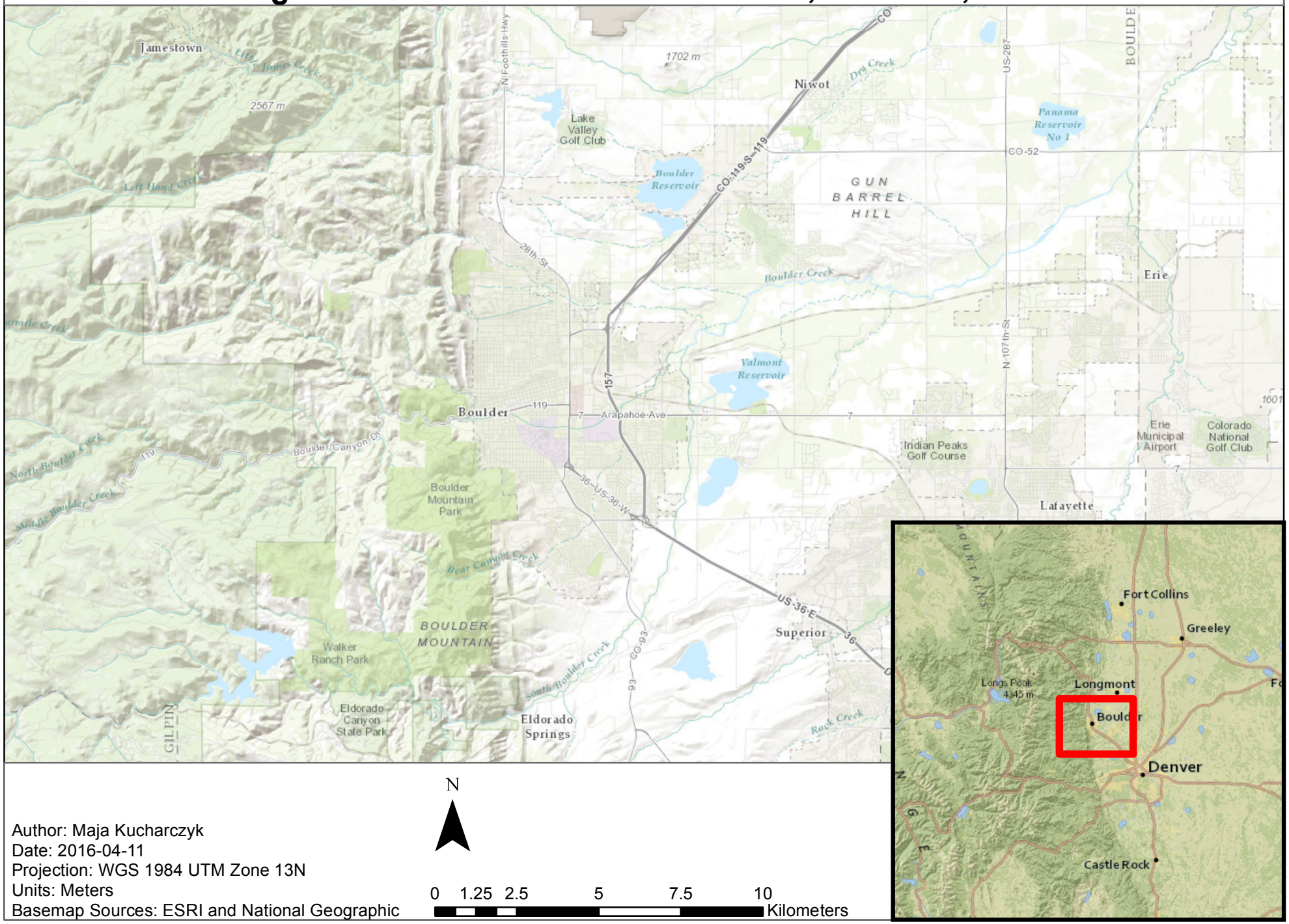
2.2.1 LiDAR Data Overview

NEON collected piloted airborne LiDAR data on June 26 and 27, 2013, approximately two months prior to the flood, and again on October 8, 2013, approximately one month after the flood (NEON, 2016). The boundaries of the pre- and post-flood flights are shown in Figure 2. Table 1 summarizes the characteristics of the pre- and post-flood LiDAR datasets. The two datasets obtained a similar footprint using the same aircraft, LiDAR sensor, and similar flight altitudes. The datasets resulted in similar total point counts, average point density, and average point spacing.

Table 1. NEON LiDAR data acquisition parameters. Modified from (Goulden & Kampe, 2014).

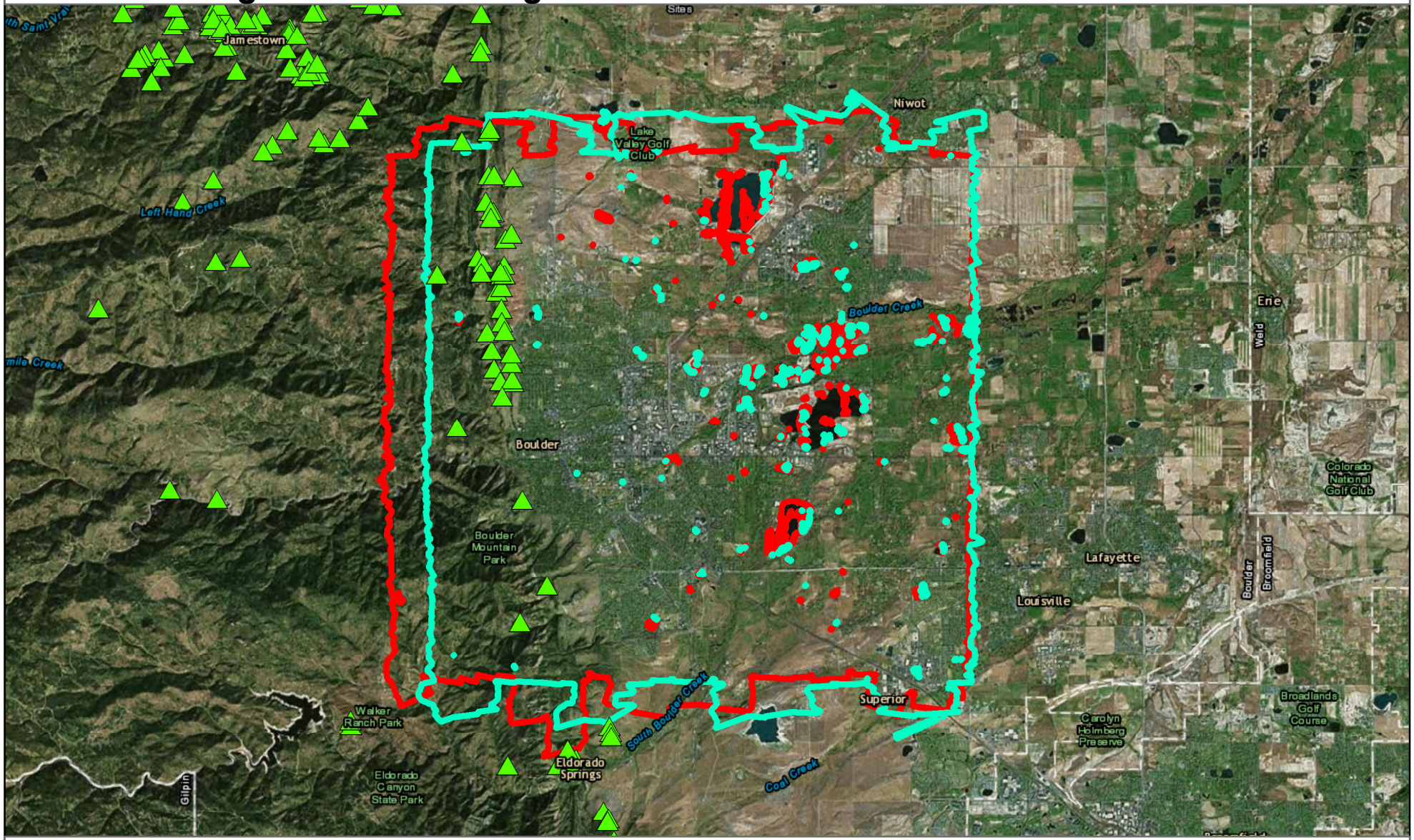
Parameter	**Pre-flood survey**	**Post-flood survey**
Date	June 26-27, 2013	October 8, 2013
Aircraft	Twin Otter	Twin Otter
LiDAR sensor	Optech Gemini (serial #11SEN287)	Optech Gemini (serial #11SEN287)
Mean flight altitude	1500 meters above ground level	1800 meters above ground level
Pulse repetition frequency	70 kHz	70 kHz
Scan frequency	33 Hz	33 Hz
Beam divergence (1/e)	0.8 mRad	0.8 mRad
Half scan angle	18°	18°
Point observations acquired	703,000,000+	729,000,000+
Avg. point density	3.0 pts/m^2	2.88 pts/m^2
Avg. point spacing	0.58 m	0.59 m

Figure 1. General Location of Boulder, Colorado, USA



Author: Maja Kucharczyk
Date: 2016-04-11
Projection: WGS 1984 UTM Zone 13N
Units: Meters
Basemap Sources: ESRI and National Geographic

Figure 2. LiDAR Flight Boundaries and Possible Debris Flows



Author: Maja Kucharczyk
Date: 2016-04-11
Projection: WGS 1984 UTM Zone 13N
Units: Meters
Basemap Sources: ESRI
Flight Boundaries: NEON (2016)
Debris Flows: Morgan, Fitzgerald, & Morgan (2014)

Legend

- Pre-flood LiDAR Flight Boundary
- Post-flood LiDAR Flight Boundary
- Possible Debris Flow Location

N

0 1.25 2.5 5 7.5 10 Kilometers

Since NEON is a publicly funded scientific research organization, the airborne data is available to the public and was obtained by request through NEON (2016). The data was delivered to the user in the form of a classified point cloud; points were classified as either ground, building, vegetation, or unclassified (NEON, 2016).

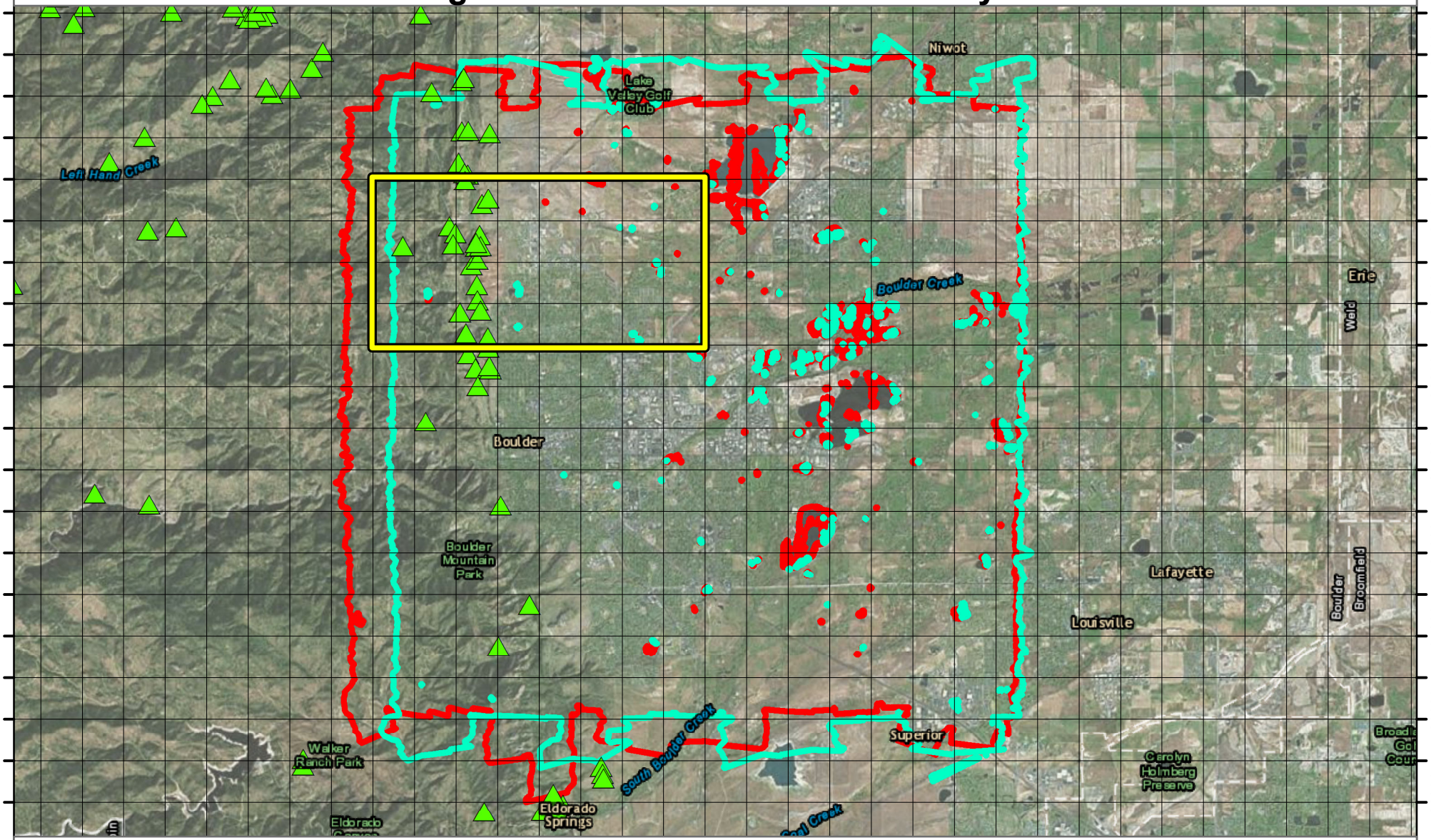
2.2.2 Debris Flow Locations

The Colorado Geological Survey used pre- and post-flood satellite imagery with spatial resolutions of 2.5-5 meters (SPOT 5), 0.46 meters (Digital Globe Worldview-2), and 1 meter (USDA NAIP) to identify possible debris flow locations. The authors produced a point shapefile of the locations, as shown in Figure 1. This shapefile was acquired by download through Morgan, Fitzgerald, & Morgan (2014).

2.2.3 Area of Interest Selection

Due to the file size of the LiDAR datasets (over 700 million data points each), an area of interest (AOI) was delineated based on potential debris flow abundance and stream channel presence. The AOI is shown in Figure 3. The LiDAR datasets are composed of one-square-kilometer (1 km^2) tiles whose boundaries are defined by the WGS 1984 UTM Zone 13N coordinate system grid. The AOI includes 32 tiles, or 32 km^2 of area.

Figure 3. Area of Interest Boundary



Author: Maja Kucharczyk
Date: 2016-04-11
Projection: WGS 1984 UTM Zone 13N
Units: Meters
Basemap Sources: ESRI
Flight Boundaries: NEON (2016)
Debris Flows: Morgan, Fitzgerald, & Morgan (2014)

Area of Interest
Pre-flood LiDAR Flight Boundary
Post-flood LiDAR Flight Boundary
Possible Debris Flow Location

N

0 1 2 4 6 8 Kilometers

2.3 Objective 1: Use the LiDAR data to produce pre- and post-flood digital terrain models (DTMs), followed by a DTM of difference (DOD)

2.3.1 LiDAR Point Cloud Processing

2.3.1.1 Extraction of Compressed Files

The pre- and post-flood LiDAR datasets were delivered to the user in 1-km^2 tiles in a compressed format, ".laz" or "LAZ". The LAZ files were be extracted by an ESRI ArcGIS Extension tool, LAStools, which was downloaded from RapidLasso (2016). The 32 files from each dataset were input into the "laszip" tool of the extension, and were extracted to uncompressed LAS 1.3 files. LAS 1.3 is the standard LiDAR data format as defined by the American Society for Photogrammetry and Remote Sensing (ASPRS, 2010).

2.3.1.2 Creating LAS Datasets

Using ArcCatalog (ArcGIS 10.3), a project geodatabase was created (**Boulder_2013_Flood_LiDAR.gdb**). With 32 LAS tiles for each dataset (pre- and post-flood), a LAS Dataset was created for each dataset to help organize the files. In ArcCatalog, a LAS Dataset was created for the pre-flood data using the Create LAS Dataset tool. The input files consisted of all of the pre-flood LAS files. The output LAS dataset was specified (**preflood_las_dataset.lasd**). By viewing the LAS dataset properties, the user was able to determine the range of average point spacing of all 32 LAS files (0.5-0.7m). The process was repeated for the post-flood LAS files. The output was specified (**postflood_las_dataset.lasd**), and the range of average point spacing was obtained (0.5-0.6m).

2.3.1.3 Creating Mosaic Datasets and Exporting DTMs

In order to export the point clouds of each LAS Dataset to a DTM, a Mosaic Dataset had to be created for each LAS Dataset. Using ArcCatalog, a new pre-flood Mosaic Dataset

(**Preflood_LAS_Mosaic**) was added to the project geodatabase. The projected coordinate system was set to match the LAS files (WGS 1984 UTM Zone 13N). The Add Rasters To Mosaic Dataset tool was used to add the LAS Dataset to the Mosaic Dataset. Under "Raster Type", "LAS Dataset" was specified. The pre-flood LAS Dataset (**preflood_las_dataset.lasd**) was added as an input. A screen capture of the dialog box is available in Appendix A (Figure A.1).

A yellow warning icon then appeared next to "Raster Type", signifying that the "Raster Type Properties" dialog had to be opened and parameters had to be specified. The "Raster Type Properties" icon (second button to the right of "Raster Type") was selected. To ensure that only points classified as "ground" would be included in the DTM, the user specified "ground" for "Class Types". The output pixel size was specified as 1 meter, because the LAS datasets had a maximum average point spacing less than 1 meter. The "Cell Aggregation Type" was specified as "mean", meaning that if multiple points were in one pixel, then the elevation value of the pixel would equal the mean elevation of the points within. "Void Filling" was set to "Linear (Triangulation)", meaning that if a pixel did not contain any points, then the void area would be triangulated and linear interpolation would be used to estimate an elevation value for that pixel. A screen capture of the dialog box is included in Appendix A (Figure A.2).

The same process was repeated for the post-flood dataset. A new Mosaic Dataset (**Postflood_LAS_Mosaic**) was added to the project geodatabase, and the post-flood LAS Dataset (**postflood_las_dataset.lasd**) was added as an input. To obtain the final pre- and post-flood DTMs, both Mosaic Datasets were exported as Raster Datasets (**Preflood_DTM**, **Postflood_DTM**) to the geodatabase with a Pixel Type of 32-Bit Float.

2.3.2 Creating a DOD

Using ArcCatalog, the Minus tool was used to difference the two DTMs to create a DOD. The post-flood DTM was used as the DTM to subtract values *from* in order for positive DOD values to

represent areas of positive change (sediment deposition), and negative DOD values to represent areas of negative change (sediment erosion). The output raster dataset was specified (**Flood_DOD**). A screen capture of the dialog box is available in Appendix A (Figure A.3).

The DOD contained noise along its western boundary. To remove the noise, the Raster Clip tool was used to clip the DOD at 472,750m on the western boundary. The output raster dataset was specified (**Flood_DOD_Clip**). To obtain statistics of the clipped DOD, the DOD was exported to a TIFF file (**DOD_for_Hist.tif**) and opened in PCI Geomatica Focus. Statistics and histograms were produced of the clipped DOD.

2.4 Objective 2: Use the DOD to locate areas of sediment erosion and deposition along a stream channel and calculate erosion and deposition volume

2.4.1 Symbolize the DOD

Using ArcMap, the DOD was symbolized with a two-ended color gradient, showing areas of negative change (erosion) as red and areas of positive change (deposition) as blue. The DOD was used to identify areas along a stream channel that have experienced relatively high amounts of erosion and deposition.

2.4.2 Select Areas of Erosion and Deposition

Two parts along a stream channel (one showing major erosion, and one showing major deposition) were chosen. A polygon feature class was digitized around the area of erosion (**Vol_Poly_1**) and the area of deposition (**Vol_Poly_2**). Using the Raster Clip tool, the pre- and post-flood DTMs were clipped using the two polygon feature classes representing major erosion and deposition along the

stream channel. Four output raster datasets were produced (**Preflood_DTM_Erosion, Postflood_DTM_Erosion, Preflood_DTM_Deposition, Postflood_DTM_Deposition**).

2.4.3 Calculate Erosion and Deposition Volume Along a Stream Channel

Using the Cut Fill tool in ArcMap, the erosion-area pre- and post-flood DTMs were input. Volumetric change was calculated for each pixel of the output raster dataset (**Erosion_Volume**). Then, the deposition-area pre- and post-flood DTMs were input. Volumetric change was calculated for each pixel of the output raster dataset (**Deposition_Volume**).

2.5 Objective 3: Use the post-flood DTM to determine the slope aspects of the satellite imagery-derived debris flows locations by Morgan, Fitzgerald, & Morgan (2014) and compare the results to those obtained by Coe et al. (2014)

2.5.1 Calculate the Aspect of the Post-flood DTM

The debris flow feature class (**Debris_Flows**) from Morgan, Fitzgerald, & Morgan (2014) was mapped on top of the post-flood DTM. The post-flood DTM was used as opposed to the pre-flood DTM, because it is more representative of the topography at the time the debris flows existed. Nineteen out of 330 total debris flows were within the post-flood DTM boundaries.

In ArcMap, the Aspect tool was used to calculate the aspect of every pixel in the post-flood DTM. The post-flood DTM raster dataset was input into the Aspect tool, and the output raster dataset was specified (**Postflood_Aspect**).

2.5.2 Extract the Aspects at the Debris Flow Locations

In ArcMap, the Extract Values to Points tool was used to extract the aspect at each of the nineteen debris flow locations. The debris flow locations were the input point features, and the aspect raster dataset was the input raster. The output feature class was specified (**Debris_Flows_Aspects**). The aspect describes the downslope direction of the maximum rate of change (i.e. the direction of the steepest slope). A value of 0 degrees would be due north, a value of 90 degrees would be due east, a value of 180 degrees would be due south, and a value of 270 degrees would be due west. A value of -1 indicates a flat area with no downslope direction (ESRI, 2016).

3. Results and Discussion

3.1 Objective 1: Use the LiDAR data to produce pre- and post-flood digital terrain models (DTMs), followed by a DTM of difference (DOD)

3.1.1 DTMs

The 1-meter spatial resolution pre- and post-flood DTMs are shown in Figures 4 and 5, respectively. The lowest elevation of the pre-flood DTM (1579.17m) corresponds well with that of the post-flood DTM (1579.44m). The highest elevation of the pre-flood DTM (2126.78m) is lower than that of the post-flood DTM (2135.29m), which can be attributed to the post-flood DTM extending further west and covering more mountainous terrain than the pre-flood DTM.

3.1.2 DOD

The DOD is shown in Figure 6. The maximum positive elevation change (89.73m) and the maximum negative elevation change (-71.99m) are unrealistic values and appear to be noise. The two-color gradient of blue for positive values and red for negative values shows red and blue noise along the western boundary of the DOD. A preliminary inspection of this noise would suggest that one of the DTMs did not cover that area, and therefore, the large voids were filled via interpolation. However, interpolation would not result in these large values, and both datasets covered the areas of noise.

To remove the noise, the DOD was clipped along its western boundary (Figure 7). The resulting maximum positive elevation change (16.09m) and maximum negative elevation change (-13.9m) were more realistic values than those of the original DOD. However, noise remained in the clipped DOD. Particularly, the urban area in the center of the clipped DOD had many high negative and positive values. Zooming into an urban area, the user was able to see evidence of point classification errors (Figure 8). Points on and around buildings were inconsistently classified between the pre- and post-flood LiDAR datasets, resulting in large elevation differences in urban areas.

Figure 4. Pre-flood DTM

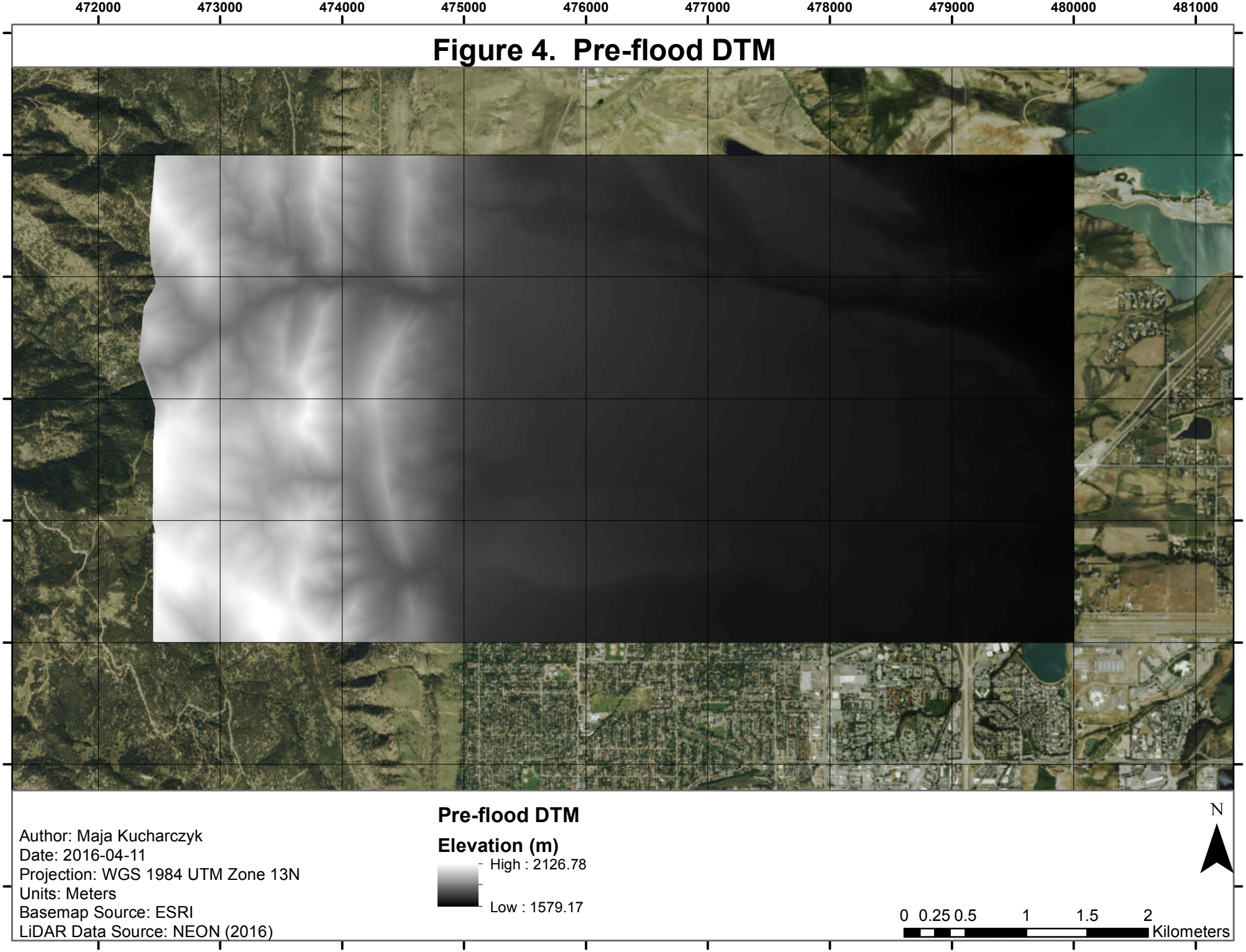
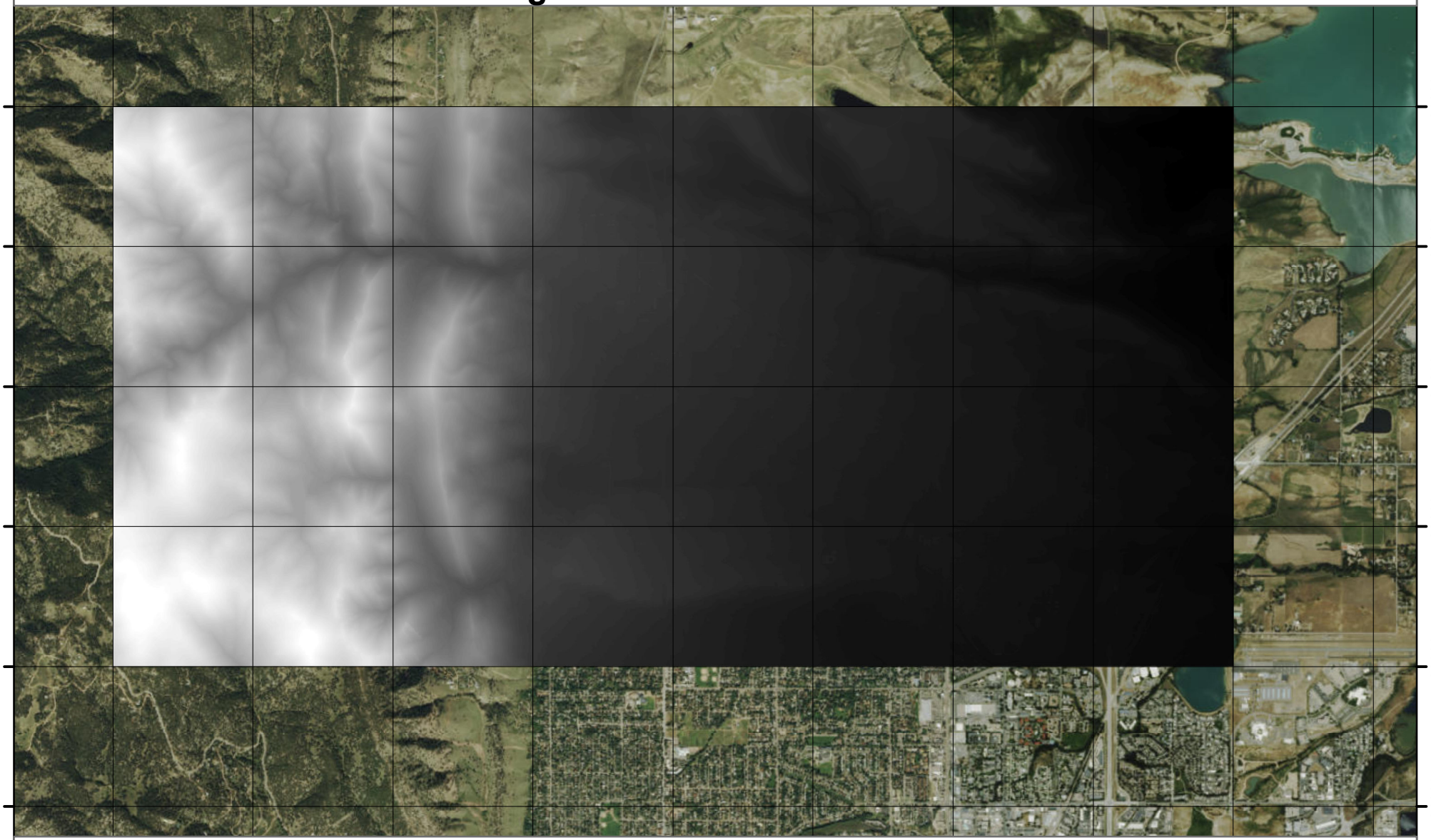


Figure 5. Post-flood DTM



Author: Maja Kucharczyk
Date: 2016-04-11
Projection: WGS 1984 UTM Zone 13N
Units: Meters
Basemap Source: ESRI
LiDAR Data Source: NEON (2016)

Post-flood DTM

Elevation (m)

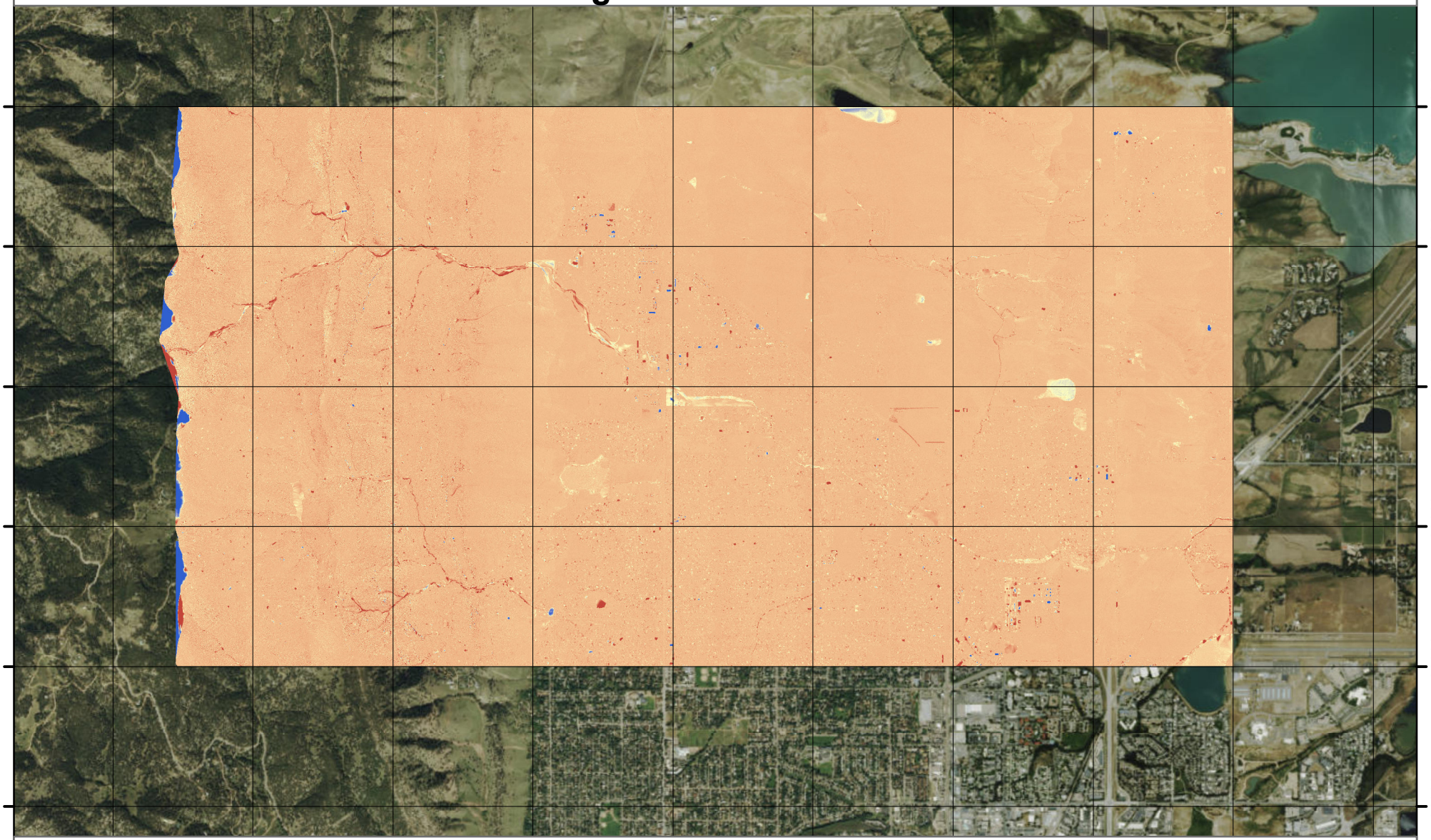
High : 2135.29

Low : 1579.44

N

0 0.25 0.5 1 1.5 2 Kilometers

Figure 6. DOD



Author: Maja Kucharczyk
Date: 2016-04-11
Projection: WGS 1984 UTM Zone 13N
Units: Meters
Basemap Source: ESRI
LiDAR Data Source: NEON (2016)

DOD

Elevation Change (m)

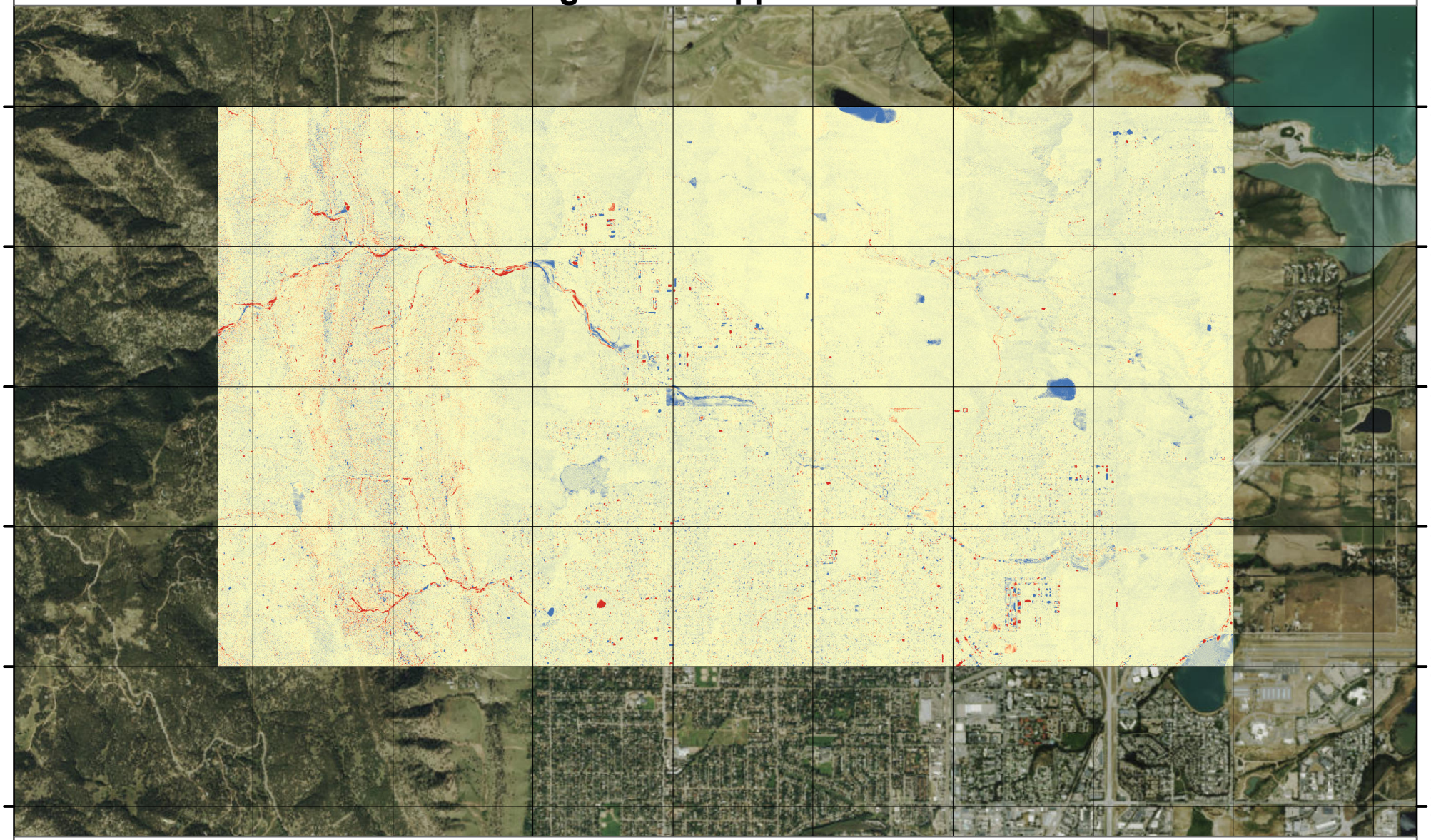
High : 89.7299

Low : -71.9888

N

0 0.25 0.5 1 1.5 2 Kilometers

Figure 7. Clipped DOD



DOD (Clipped)

Elevation Change (m)

High : 16.0934

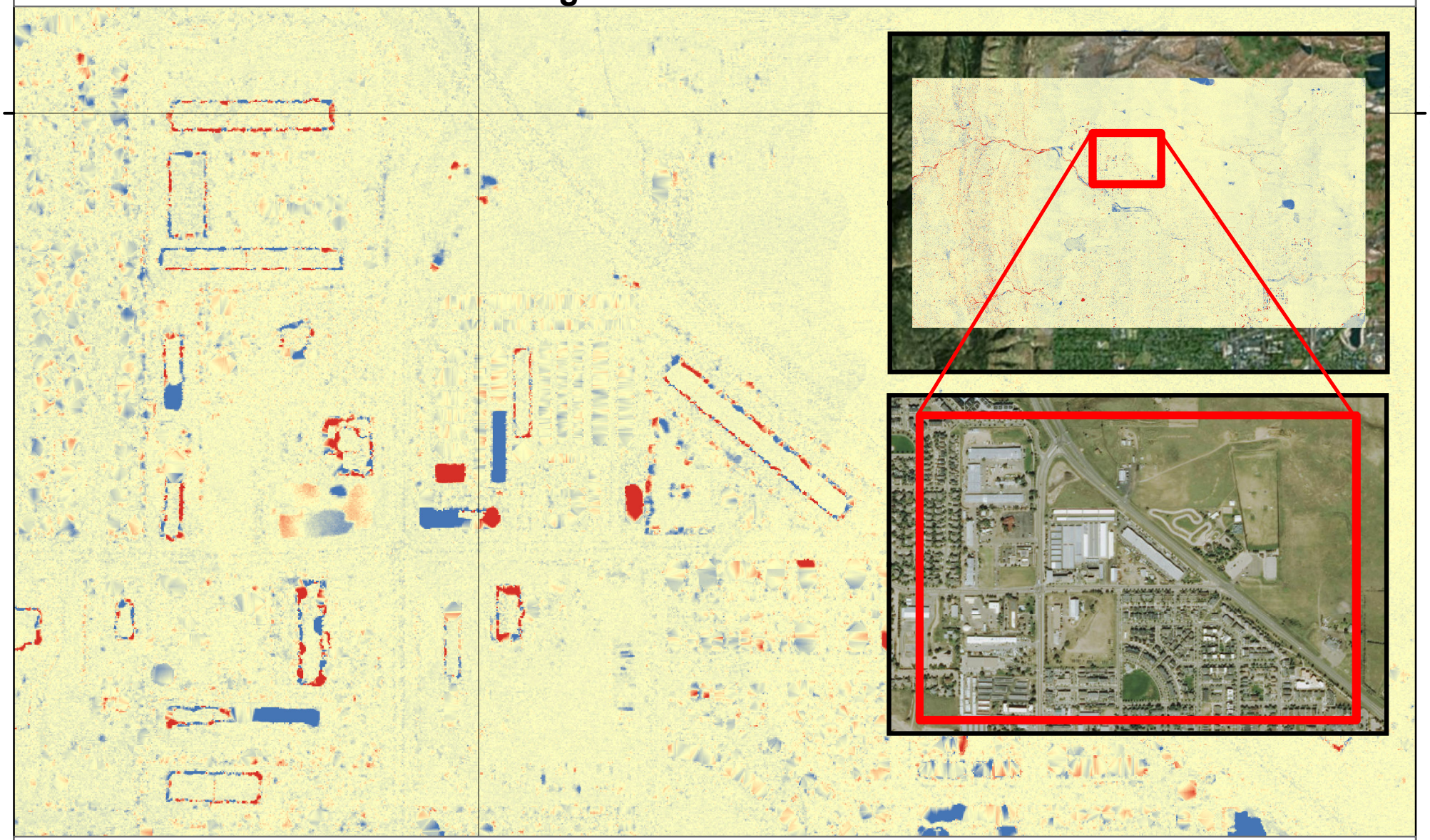
Low : -13.9014

Author: Maja Kucharczyk
Date: 2016-04-11
Projection: WGS 1984 UTM Zone 13N
Units: Meters
Basemap Source: ESRI
LiDAR Data Source: NEON (2016)

N

0 0.25 0.5 1 1.5 2 Kilometers

Figure 8. Urban Noise



Author: Maja Kucharczyk
Date: 2016-04-11
Projection: WGS 1984 UTM Zone 13N
Units: Meters
Basemap Source: ESRI
LiDAR Data Source: NEON (2016)

DOD (Clipped)

Elevation Change (m)

High : 16.0934

Low : -13.9014

N

0 50 100 200 300 Meters

To investigate the noise in the clipped DOD, summary statistics were calculated using PCI Geomatica Focus (Table 2). A histogram of the entire clipped DOD is shown in Figure 9. The data appears to be normally distributed. A standard deviation of 0.26123m of normally distributed data indicates that approximately 68% of the values (elevation change) are within 0.13m (half the standard deviation) from either side of the mean. Furthermore, 95% of the values (elevation change) are within 0.26m (one standard deviation) from either side of the mean. Finally, 99.7% of the values (elevation change) are within 0.39m (1.5 standard deviations) from either side of the mean. These percentages would be accurate for a perfect normal distribution; however, since the clipped DOD has an approximate normal distribution, it can be assumed that 99% of the values (elevation change) are between -1m and +1m. Therefore, any values outside of this range can be discarded as noise. The histogram of clipped DOD values ranging from -1 to 1 are shown in Figure 10.

Table 2. Summary statistics of the clipped DOD. Modified from PCI Geomatica Focus.

Total number of pixels	28,999,996
Minimum Value	-13.9014
Maximum Value	16.0934
Mean Value	0.0158945
Mode Value	0
Median Value	0.0198992
Standard Deviation	0.26123

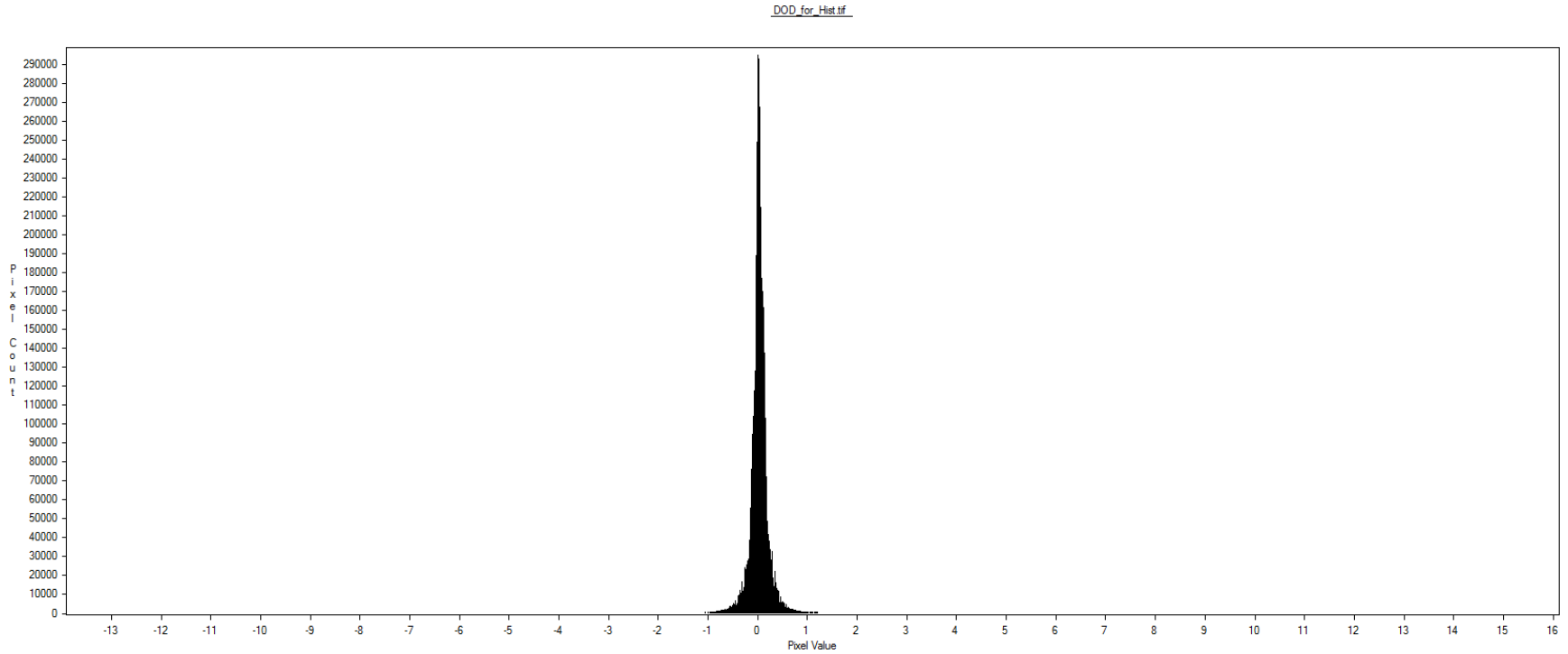


Figure 9. Histogram of the clipped DOD, representing the entire range of values (-13.9014-16.0934m). Copied from PCI Geomatica Focus.

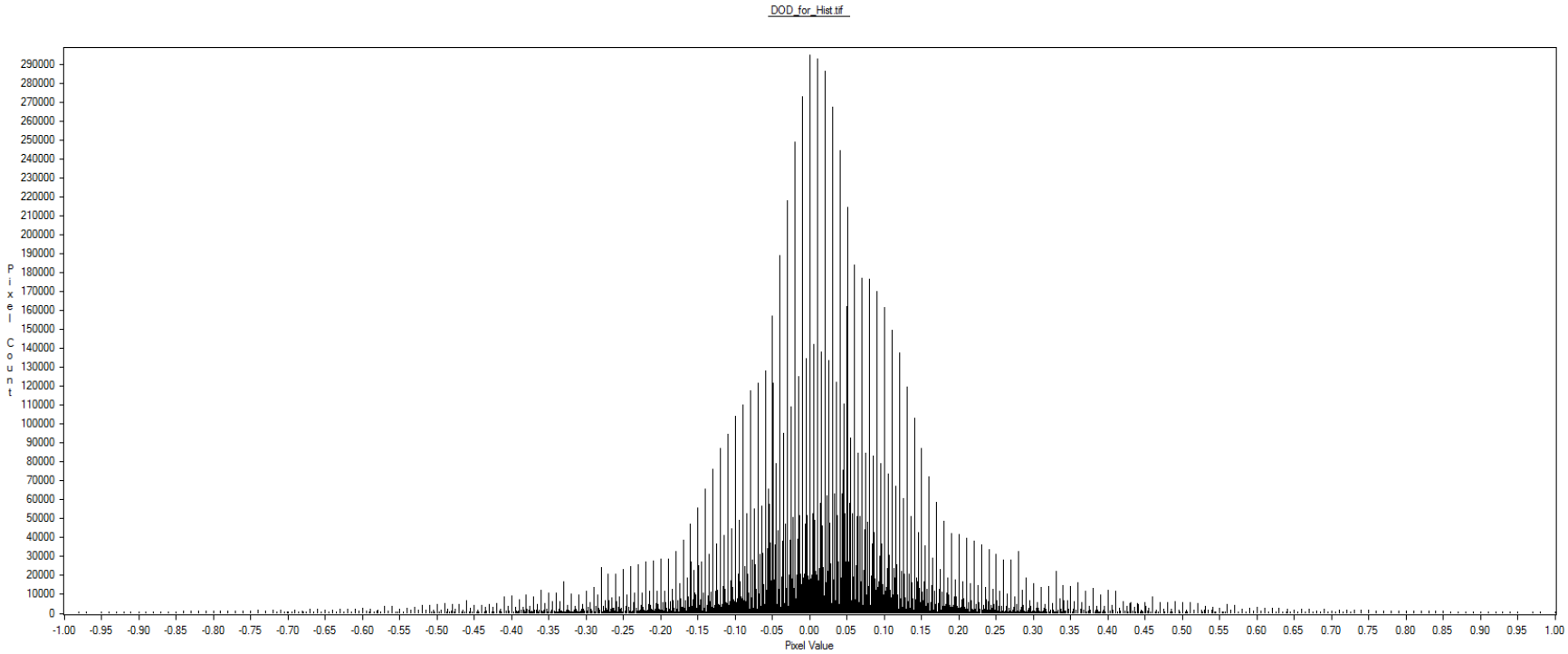


Figure 10. Histogram of the clipped DOD, with a smaller range of values (-1 to 1m). Copied from PCI Geomatica Focus.

A newly symbolized DOD, showing a range of values from -1m to 1m, is shown in Figure 11. With a smaller range of displayed elevation change values, fluvial elevation changes are highlighted with deeper blue and red colors. Stream channels are apparent in the northwest portion of the DOD.

3.2 Objective 2: Use the DOD to locate areas of sediment erosion and deposition along a stream channel and calculate erosion and deposition volume

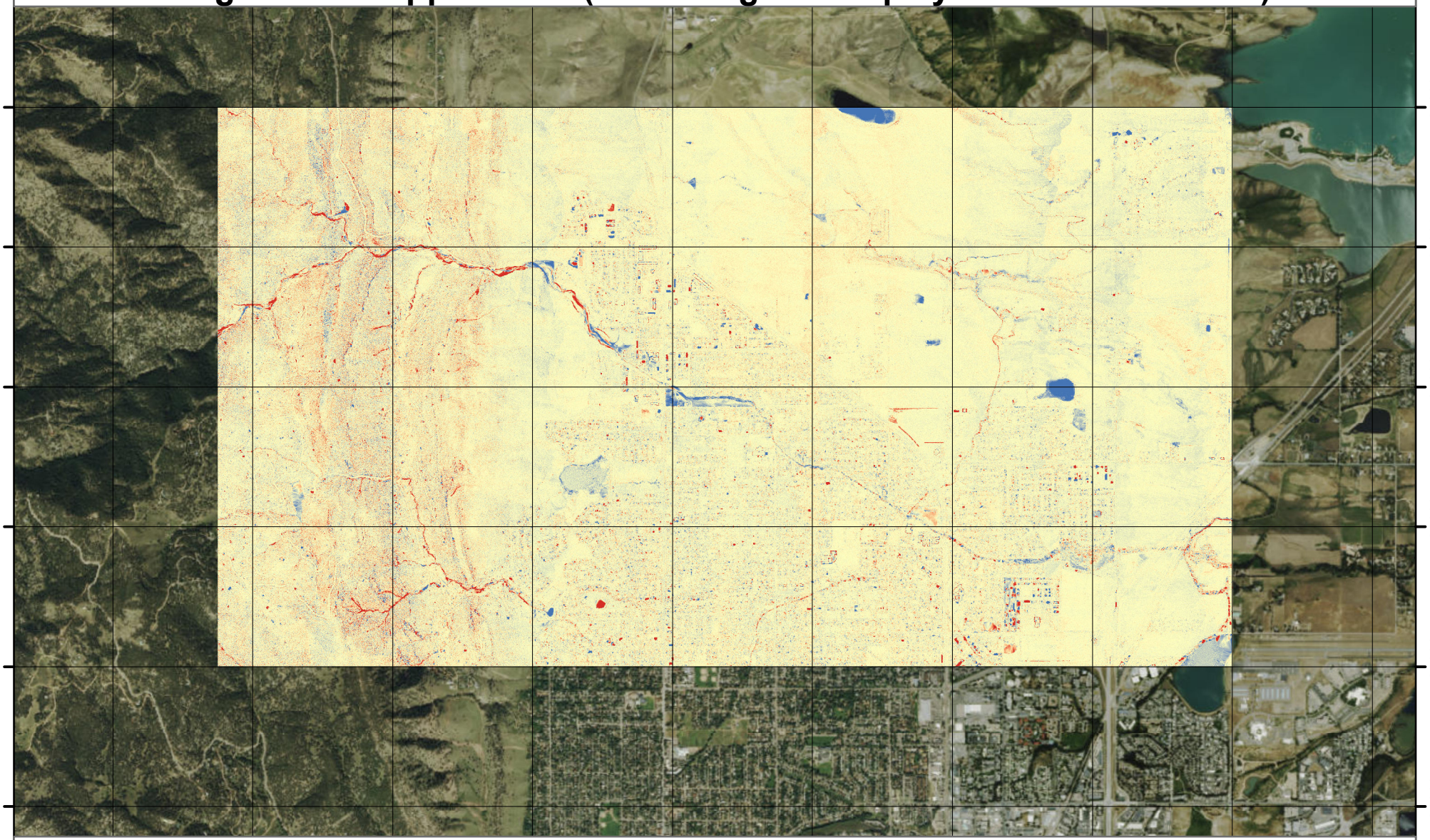
3.2.1 Select Areas of Erosion and Deposition

The selected stream channel is shown in Figure 12. A major area of erosion along the stream channel was bounded by the red polygon. A major area of deposition along the stream channel was bounded by the blue polygon.

3.2.2 Calculate Erosion and Deposition Volume Along a Stream Channel

The volume polygons and output rasters are shown in Figure 13. For the erosion polygon, the total eroded volume was 10,774 cubic meters (m^3), while the total deposited volume was 980 m^3. For the deposition polygon, the total eroded volume was 808 m^3, while the total deposited volume was 10,215 m^3.

Figure 11. Clipped DOD (New Range of Displayed Values: -1 to 1m)



Author: Maja Kucharczyk
Date: 2016-04-11
Projection: WGS 1984 UTM Zone 13N
Units: Meters
Basemap Source: ESRI
LiDAR Data Source: NEON (2016)

DOD (Clipped)

Elevation Change (m)

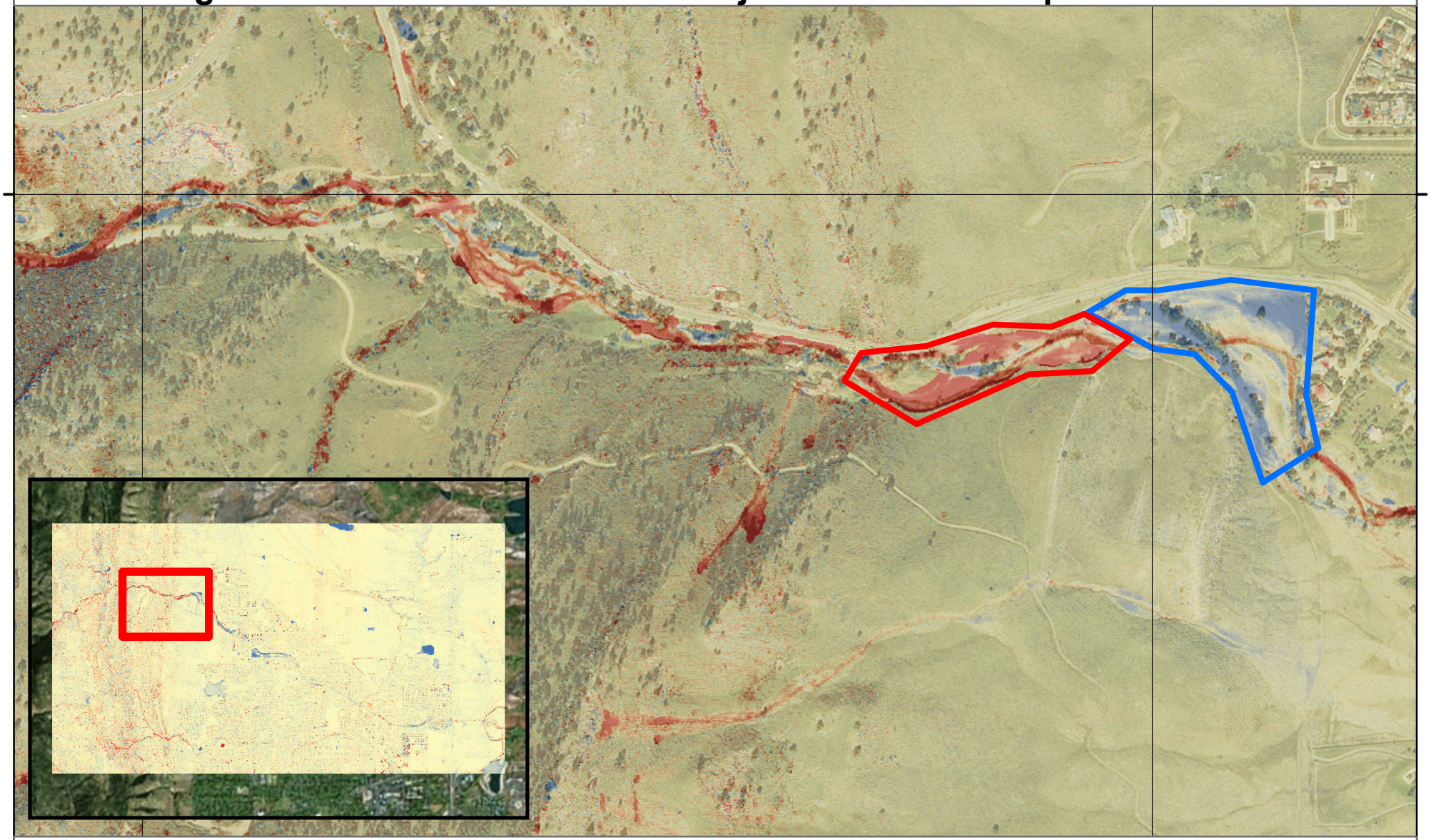
High : 1

Low : -1

N

0 0.25 0.5 1 1.5 2 Kilometers

Figure 12. Stream Channel with Major Erosion and Deposition Areas



Author: Maja Kucharczyk
Date: 2016-04-11
Projection: WGS 1984 UTM Zone 13N
Units: Meters
Basemap Source: ESRI
LiDAR Data Source: NEON (2016)

DOD (Clipped)

Elevation Change (m)

High : 1

Low : -1

Erosion Volume Polygon

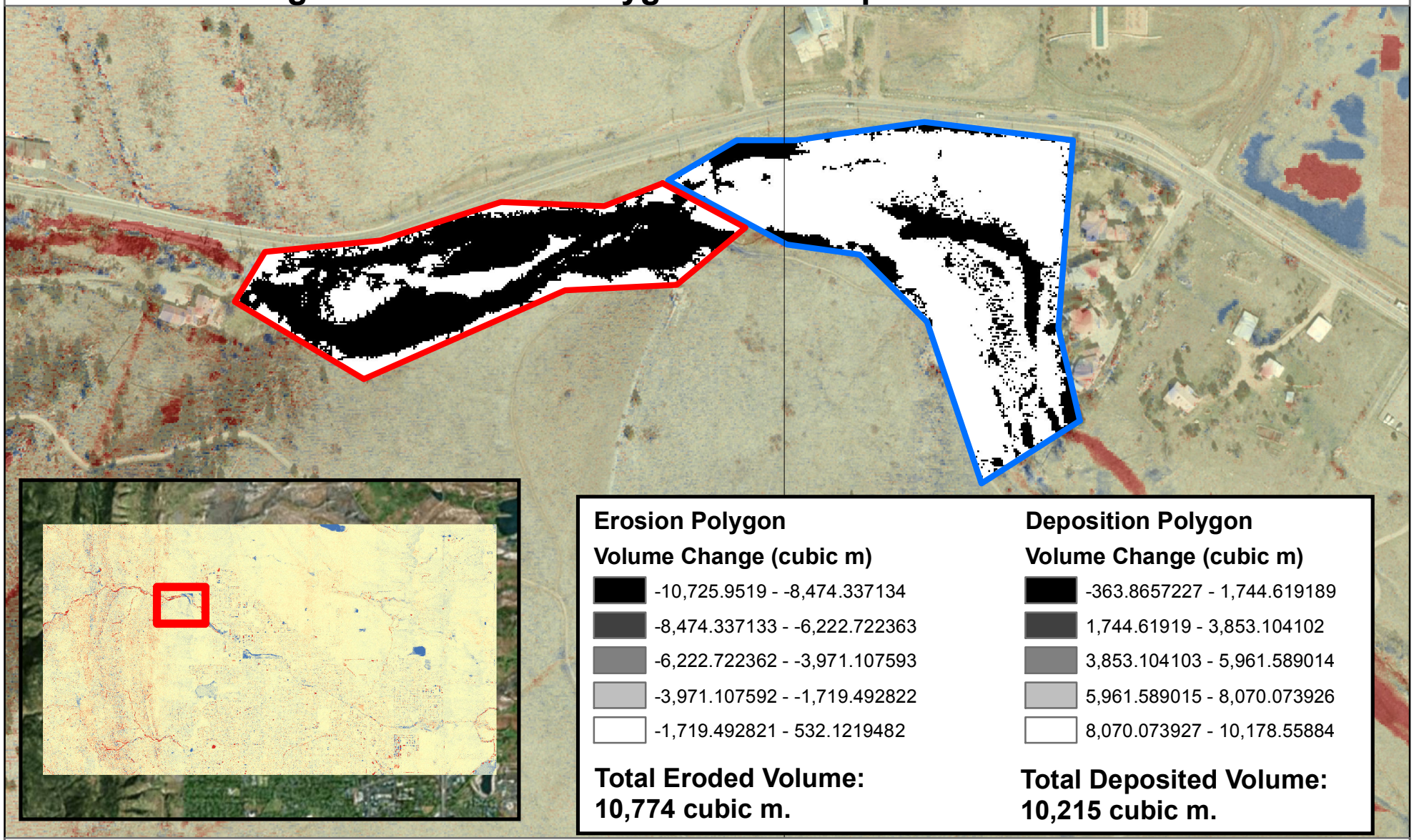
Deposition Volume Polygon

N

0 50 100 200

Meters

Figure 13. Volume Polygons and Output Volume Rasters



Author: Maja Kucharczyk
Date: 2016-04-11
Projection: WGS 1984 UTM Zone 13N
Units: Meters
Basemap Source: ESRI
LiDAR Data Source: NEON (2016)

DOD (Clipped)

Elevation Change (m)

High : 1

Low : -1

Erosion Volume Polygon

Deposition Volume Polygon

N

0 25 50 100

Meters

3.3 Objective 3: Use the post-flood DTM to determine the slope aspects of the satellite imagery-derived debris flows locations by Morgan, Fitzgerald, & Morgan (2014) and compare the results to those obtained by Coe et al. (2014)

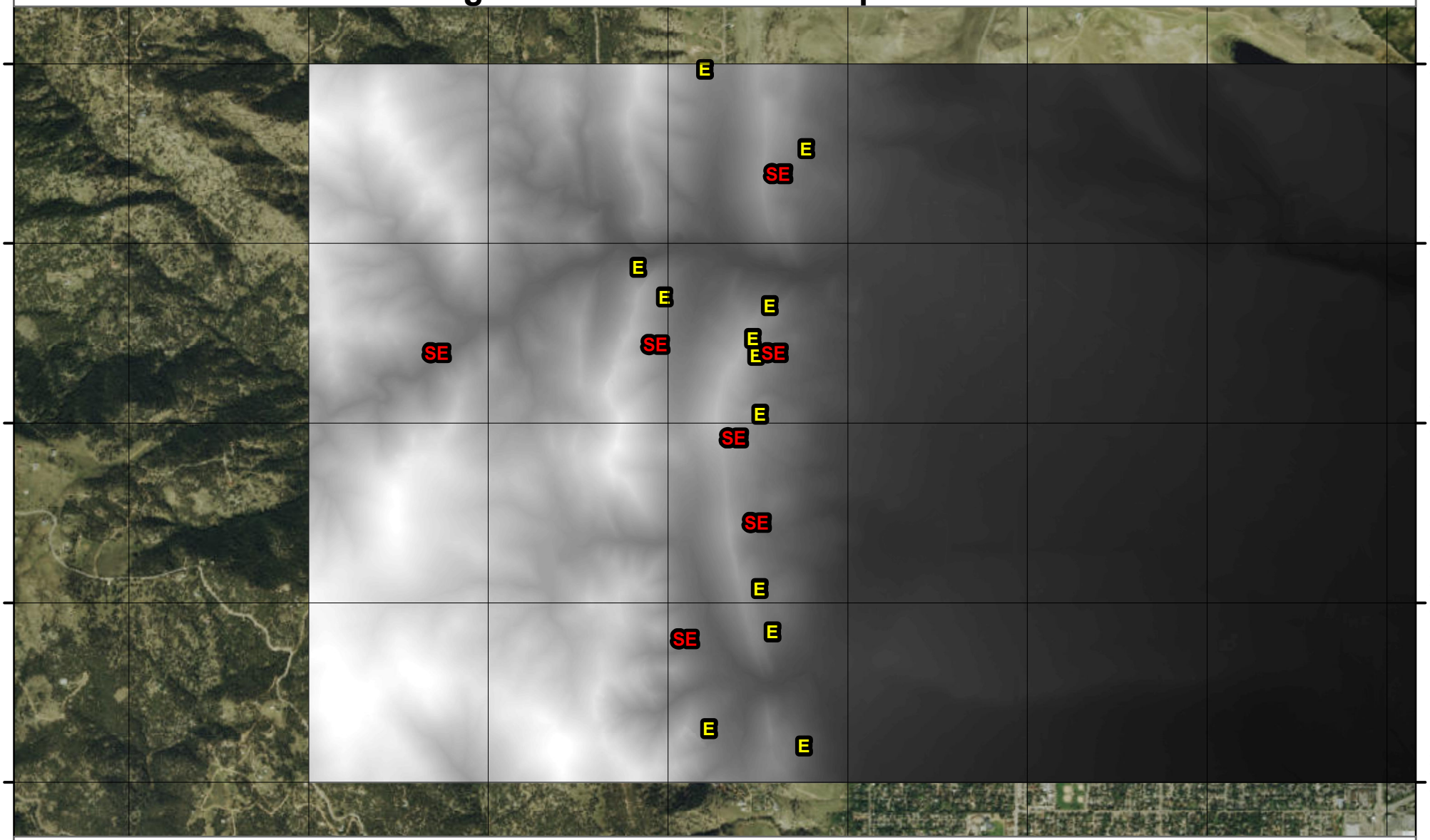
3.3.1 Calculate the Aspect of the Possible Debris Flow Locations

Figure 14 shows the 19 debris flow locations within the post-flood DTM. Table 3 summarizes the aspects of the debris flows. Twelve out of nineteen debris flows have aspects in the east direction, and seven out of nineteen debris flows have aspects in the southeast direction. Coe et al. (2014) reported 78 percent (%) of the 1,138 debris flows they surveyed in the Boulder and greater Boulder region initiated on south-facing slopes. The aspects of the debris flows mapped by Morgan, Fitzgerald, & Morgan (2014) within the post-flood DTM were primarily on east and southeast slopes, which makes sense given the movement of floodwater east down the Rocky Mountains.

Table 3. Debris flow aspects.

Debris Flow Location	Aspect (degrees counterclockwise from north)	Aspect Classification
1	66.57	East
2	80.05	
3	84.92	
4	85.94	
5	86.99	
6	87.27	
7	89.17	
8	89.35	
9	92.46	
10	94.24	
11	94.75	
12	95.14	
13	117.38	Southeast
14	119.32	
15	124.42	
16	125.19	
17	132.42	
18	148.69	
19	154.03	

Figure 14. Debris Flow Aspects



Author: Maja Kucharczyk
Date: 2016-04-11
Projection: WGS 1984 UTM Zone 13N
Units: Meters
Basemap Source: ESRI
LiDAR Data Source: NEON (2016)
Debris Flows: Morgan, Fitzgerald, & Morgan (2014)

Post-flood DTM

Elevation (m)

High : 2135.29

Low : 1579.44

Debris Flow Location and Aspect

E East 67- 95 degrees

SE Southeast 117-154 degrees

N

0 0.25 0.5 1 1.5 2 Kilometers

3.6 Limitations

Temporal change detection studies face challenges regarding their inability to conclusively determine that a detected change is attributed to the phenomenon being studied. For this project, any elevation change detected cannot be assumed to be caused by the flood. There are numerous sources for elevation changes to appear on the DOD.

Sensor and post-processing errors can be disguised as physical elevation change. As was shown in Figure 8, points can be incorrectly classified during the LiDAR point cloud processing stage. Also, the pre-and post-flood LiDAR data acquisitions occurred two months before and one month after the flood, respectively. It is not possible to distinguish natural processes from flood processes when viewing topographic change. Also, during the time between the flood occurring and the post-flood LiDAR data acquisition, some of the damage may have been repaired and thus the true extent of the flood damage has not been depicted.

4. Conclusion

The Boulder, Colorado flood of September 2013 resulted in fatalities and billions of dollars in damage. The environmental impacts of the flood have been surveyed and recorded. Using LiDAR data collected over Boulder before and after the flood, topographic change detection has been performed by differencing the elevation datasets. Erosional and depositional volume along stream channels was calculated, and slope aspect of possible debris flow locations was determined. These methods can be applied for damage remediation, in terms of prioritizing areas that have undergone the most topographic change.

5. References

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Appendix A

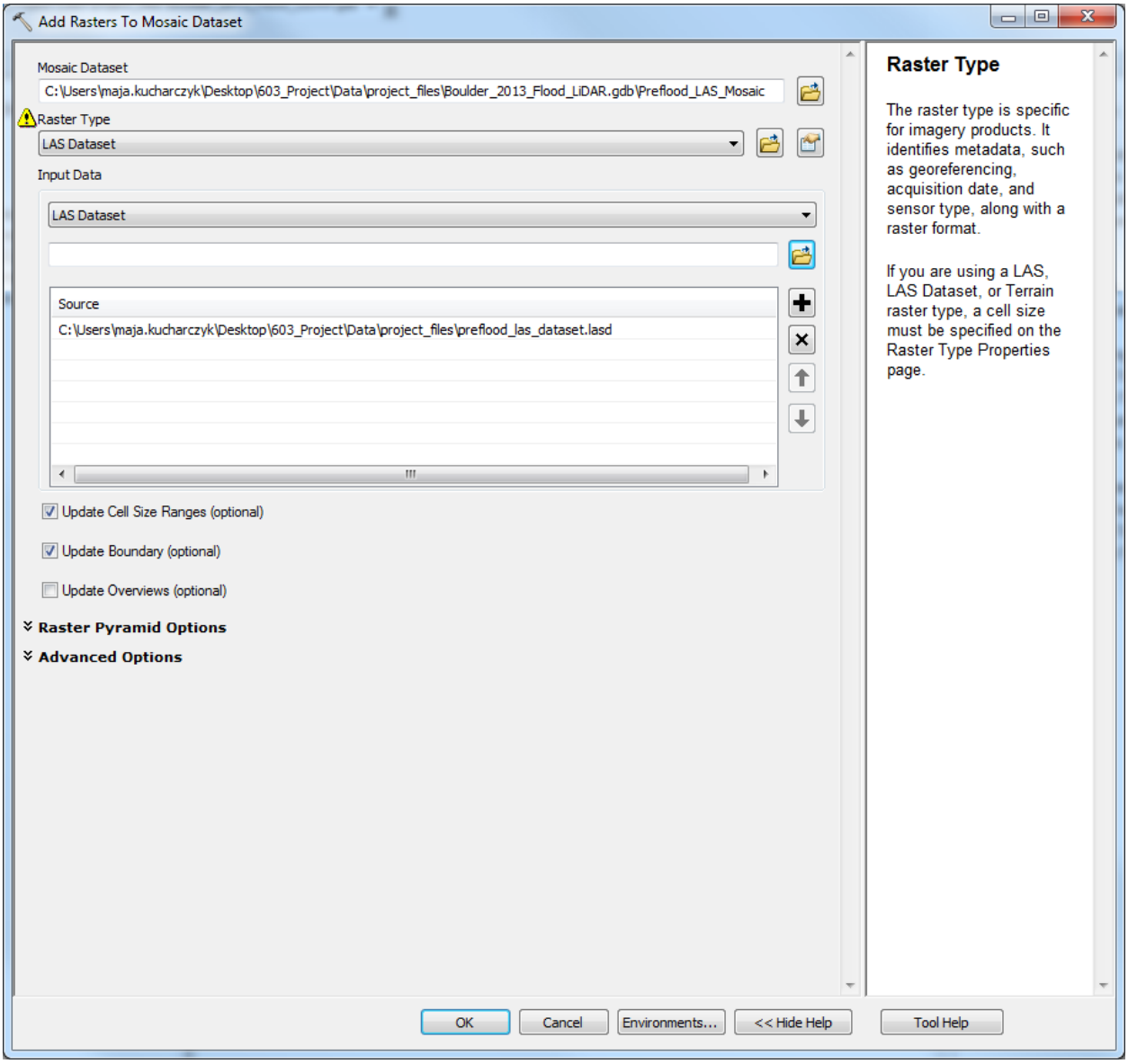

Figure A.1. Add Rasters To Mosaic Dataset tool being used to add the pre-flood LAS Dataset to the pre-flood Mosaic Dataset.

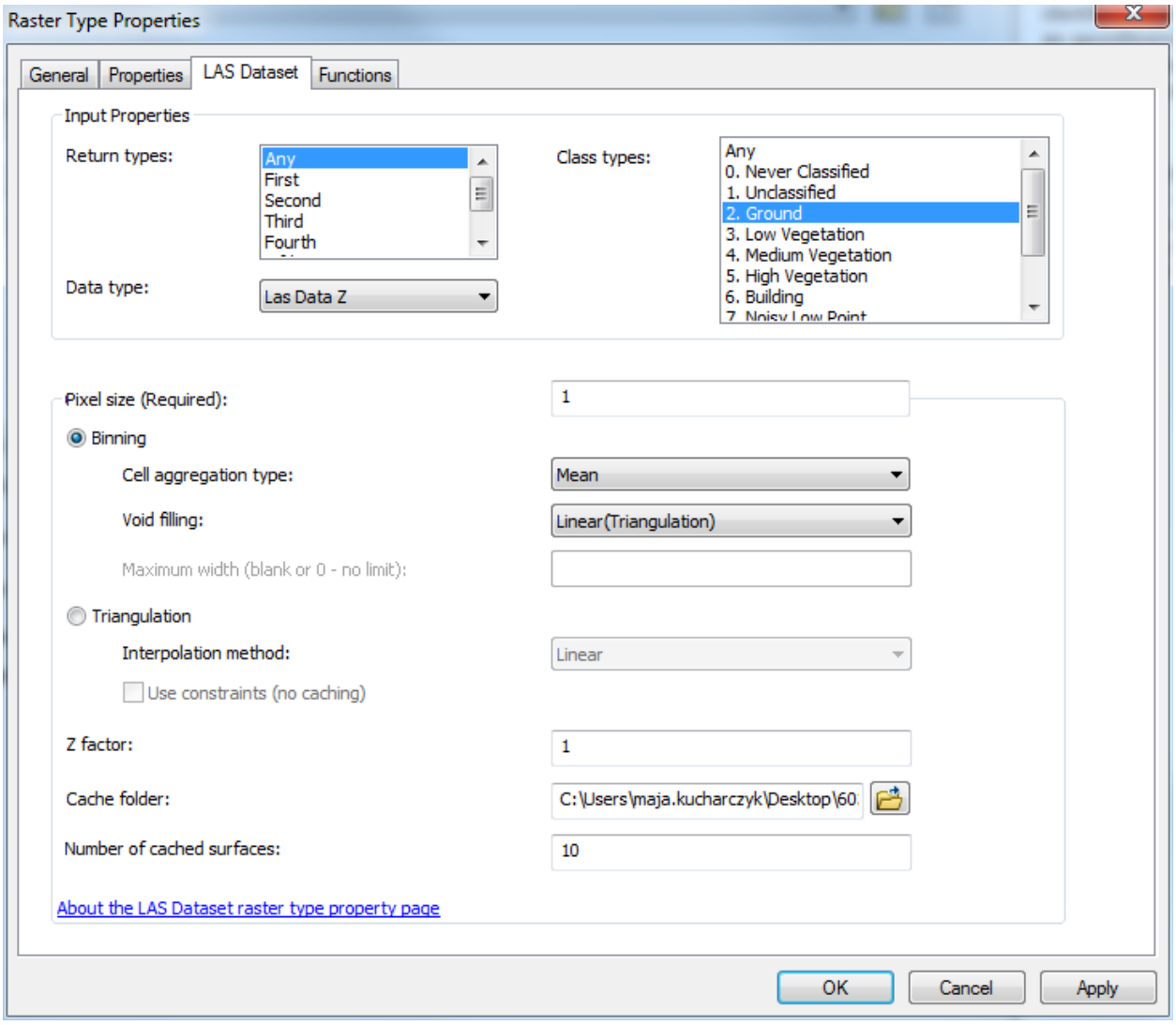

Figure A.2. Raster Type Properties being used to specify the output pre-flood DTM parameters.

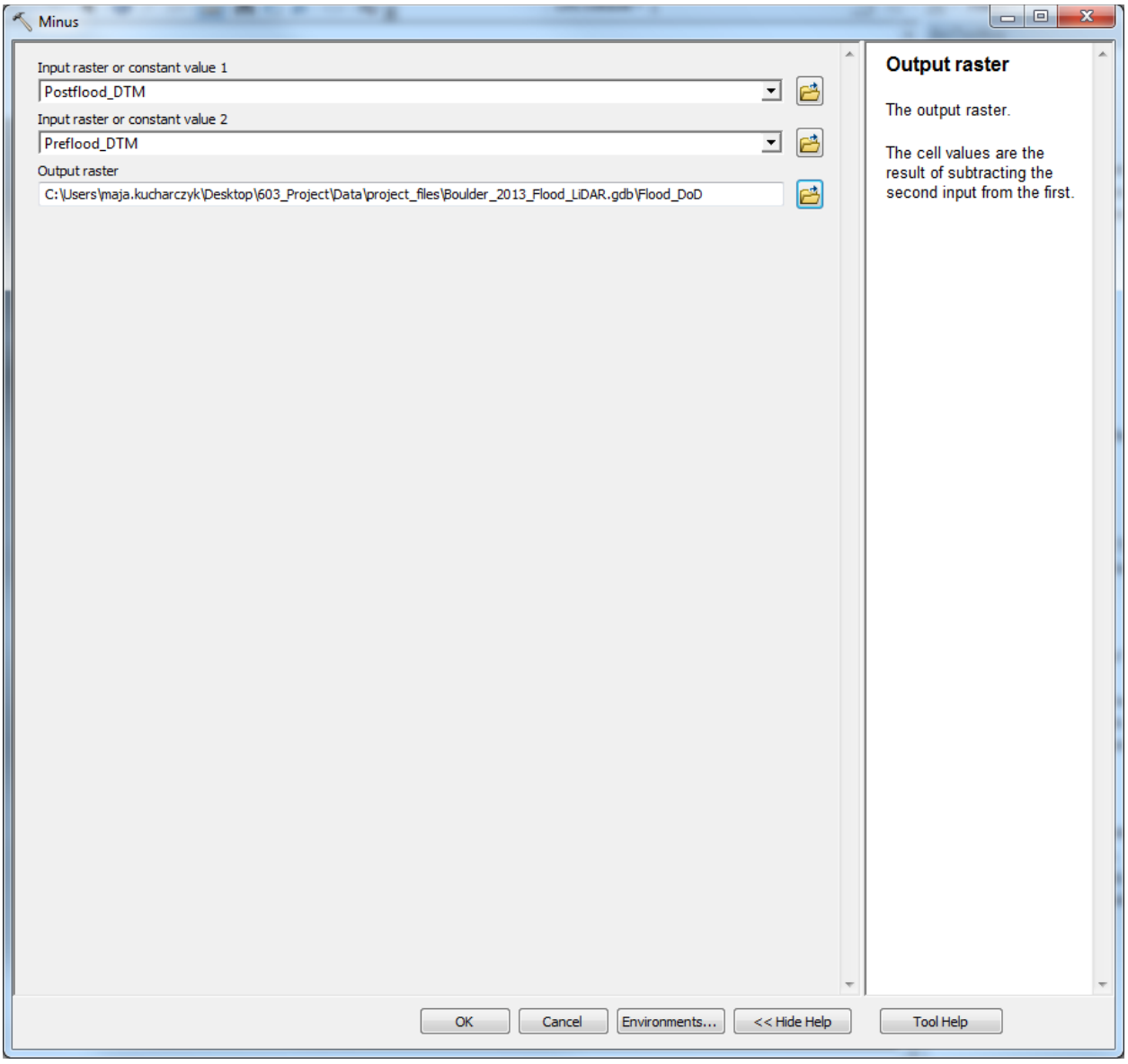

Figure A.3. Minus tool being used to subtract the pre-flood DTM from the post-flood DTM in order to output a DOD.