DEVELOPING A HYDROLOGICALLY VALID COMPOSITE DEM FROM LIDAR AND USGS NED ELEVATION DATA

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Abstract

Not all basin-scale watershed modeling efforts have the luxury of a full coverage, high-resolution Digital Elevation Model (DEM) which may be critical to a successful project, especially in rural-urban interface areas. This study explores an alternative to limiting a project to either full coverage of a watershed with coarse resolution DEMs, or partial modeling with high-resolution DEMs, when neither option alone may deliver meaningful or acceptable results. This paper proposes a third option: that of developing a composite DEM from both coarse-resolution (10 meters in this case) U.S. Geological Survey (USGS) National Elevation Dataset (NED) grids and high-resolution (3 ft in this case) LiDARbased elevation data, with a method to "overlap and feather" the boundary between the two, where disparities and discontinuities in elevation may hamper hydrological modeling efforts, without some adjustment. While the results may not be topographically exact, the goal was to enable hydrologic connectivity within the Mike-SHE modeling software for a 123.5 sq mi area of the Rio de Flag watershed in Northern Arizona, using the new composite DEM gridded elevation values as input. Even with a fairly large watershed (123.5 sq mi or 319.9 km^2) and differences between the two elevation datasets (LiDAR – NED) ranging between -186 to +70 feet across the 3000 ft. wide overlap zone, the proposed method achieved significant initial results. Further improvements to the method are detailed in the final section of this report.

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Stormwater Management Section
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December 6, 2016

RE: Letter of Significant Contribution

To Whom It May Concern,

Pam Bergman was our GIS intern in the Stormwater Section of the Utilities Division at the City of Flagstaff from February 2015 to July 2016. During that time, Pam was instrumental in facilitating the successful completion of our watershed hydrology modeling project. She was tasked with researching, obtaining and developing numerous GIS data layers as input to the MIKE-SHE hydrologic model. These layers included:

- A soil type map layer covering the entire Rio de Flag watershed composited from USFS and NRCS data sets, linked with soil descriptions from the source agencies and physical properties, as well as published infiltration values retrieved from the online literature;
- A manually edited updated rural and urban vegetation map for the watershed using aerial imagery as an editing guide;
- A complex, composite map of impervious surfaces based on 2009 and 2013 aerial imagery analysis, building footprint maps and street maps;
- A revised watershed study area boundary based on high resolution contours from LiDAR, with manual editing of NHD HUC boundaries;
- An enhanced stream network map to match LiDAR contours;
- A series of NEXRAD instantaneous precipitation layers for selected storm events which she researched, retrieved and packaged from the NOAA / NEXRAD web site;
- A stormwater infrastructure layer developed from selected culverts and pipe networks, with extensive quality control on existing GIS data including invert elevations, dimensions, materials, as well as manual alignment of GIS stormwater structure with the updated GIS stream networks, together with extensive research into previous survey data to obtain engineering data, and preparation of a reference worksheet for the surveying effort by CDE.

Pam also played a critical role in the analysis and correction of the watershed DEM layer to minimize elevation discontinuities between USGS and LiDAR datasets which were preventing the model from running, and could have caused the project to fail. This work was time sensitive, done under pressure, and she gladly put in extra hours to meet deadlines and deliver outstanding work product.

Pam is able to take direction and constructive criticism, but also to work independently. She can quickly grasp the essence of a problem and design intelligent solutions. During her time on this critical project Pam repeatedly demonstrated excellent analytical, learning, presentation and communication skills.

Sincerely,

James A. Janecek

James A. Janecek, PE, CFM
Stormwater Section Project Manager

1. Introduction

In 2014, the City of Flagstaff, AZ, was funded by a Federal Emergency Management Administration (FEMA) grant to conduct the first effort at a sophisticated stormwater runoff model for the City's Rio de Flag watershed (123.5 sq mi or 319.9 km^2). The model was to be "physically based" using the Mike-SHE and Mike-11 software modules from the Danish Hydrologic Institute (DHI) together with multiple GIS input data layers. These layers included a digital elevation model (DEM), a realistic stream channel network, soil horizons with infiltration characteristics, vegetation types, canopy cover, and gridded, instantaneous precipitation data for selected storm events (source: NOAA NEXRAD). The effort to create, collect and composite these layers began in spring 2015. Although problems were encountered, all GIS input layers were finalized by late 2015, and the first hydrological model was successfully delivered to the City by Integrated Hydro Systems, LLC in spring 2016.

2. Problem Description

The principal problem encountered during the project was the delivery of a seamless, hydrologically connected DEM composited from both high-resolution LiDAR data (which the City had purchased in 2013), and older, coarse-resolution data from the USGS NED. The City LiDAR data covered only the urban / developed areas of the watershed within the city limits. This coverage amounted to roughly two-thirds of the 123.5 sq mi Rio de Flag watershed that was of interest to the modeling effort. The City could not afford and did not have time to purchase a LiDAR survey of the remainder of the watershed, so a composite DEM had to be used for full coverage.

Originally, it was thought that the DEM already in the City's GIS library could be used, but serious elevation anomalies at the "seam" between the LiDAR and NED datasets made it unsuitable for hydrological modeling purposes. Major anomalies included many instances of sharp increases in elevation producing the artifact of a "wall" blocking both channelized and overland flow in the watershed model, preventing the Mike-SHE software from functioning properly. Other anomalies included sharp decreases in elevation, or "waterfalls", which although they might not cause the modeling software to crash, could impact calculations of stream velocity, overland flow and peak flow arrival times. Appendix A illustrates the initial analytical process and the resulting transect and stream channel profiles, with the observed anomalies.

The decision was made to construct a new DEM, and to attempt to correct elevation anomalies that might cause Mike-SHE modeling problems. Literature on processing anomalies in, and correction methods for, both LiDAR and NED-based elevation data, as well as mosaicking DEMs of differing spatial resolutions, was researched for a possible solution.

3. Review of the Literature

A search of the literature revealed several articles regarding processing "artifacts" in USGS NED DEMs (Russell, Kumler and Ochis 1995; Guth 1999; Gallant 2011), the most useful of these being from Russell and Ochis (1998), which analyzed the "quilting pattern" anomalies specifically found in our Level I NED gridded dataset:

Figure 1. This image displays the "quilted pattern" that characterizes many Level I DEMs: i.e., a noisy pattern within the quilt patches with frequent elevation discontinuities at the patch edges. From Russell and Ochis (1998).

The literature contained numerous articles on the potential inaccuracies of LiDAR-based elevation data, especially Hodgson and Bresnahan (2004), while Barber and Shortridge (2005), and French (2003) focused on problems that may be encountered when using LiDAR specifically for hydrological modeling. Because the City was limited to relying on the already-classified ground elevation points provided by the LiDAR vendor (identified below), any further correction of LiDAR elevation errors, beyond what was done by the vendor, was out of scope for this pilot project.

The literature also contained several articles about the benefits of using high-resolution LiDAR data in watershed modeling, especially Liu, Petersen and Zhang (2005), and the ESRI online references contained much useful information about correct processing of LiDAR data into DEMS using ArcGIS 3D Analyst tools. The review found several articles regarding the difficulty of integrating terrestrial and bathymetric LiDAR data, especially Quadros, Collier and Fraser (2008). However, there was surprisingly little information about how to successfully “stitch” two disparate terrestrial elevation datasets into a single, seamless DEM, and even less guidance as how to “smooth” any differences in elevation at the seam line. Indeed, from the conclusions of a recent Australian article (Pourali et al, 2014), it would seem the only viable solution would be to limit the scope of one’s study to the area covered by the LiDAR data. This was not an option in the case of the City’s modeling effort, since the region of interest for modeling purposes exceeded the limits of the LiDAR coverage by roughly one-third (46 sq mi), as discussed above.

One article in the literature stood out for its effort to acknowledge the thorniness of the problem, and to suggest a path toward solution (Gallant and Austin, 2009). In this article, the authors described their effort to identify and characterize the elevation anomalies occurring at the interface between high-resolution terrestrial and bathymetric elevation datasets. Although the authors did not provide a complete solution for resolving the elevation differences, their central recommendations to 1) overlap the two elevation datasets, 2) obtain the elevation differences at each overlapping cell, and 3) somehow “smooth” the elevation profiles across this boundary zone (rather than butting the datasets together), were adopted as a starting point for our own efforts.

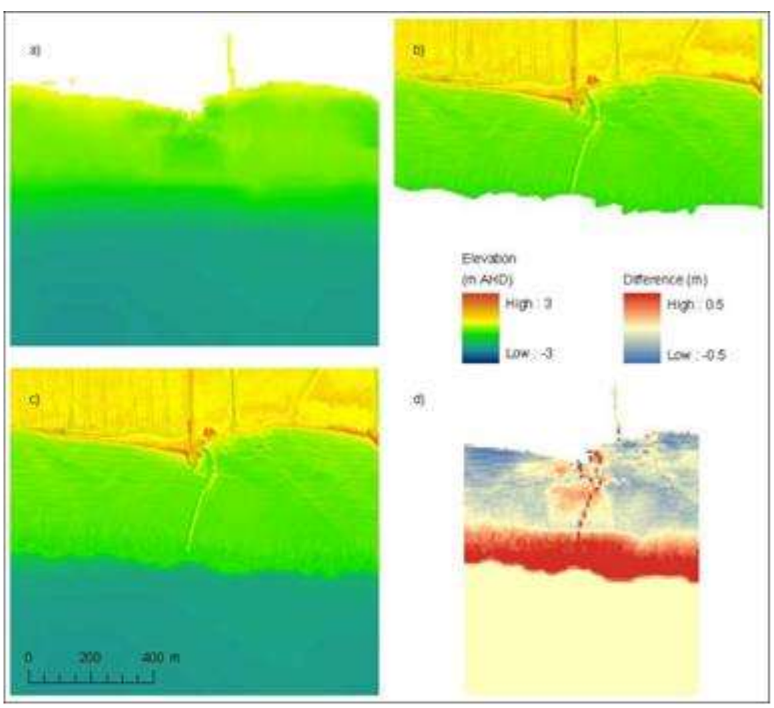

Figure 2. Stitching of lake bathymetry (a) with lidar (b) to produce combined product (c). The area of overlap between the bathy-metry and the lidar is essentially replaced by the lidar data, leaving the lidar data unaltered. The difference (d) between the stitched product (c) and the supplied bathymetry (a) is zero in the deeper areas and is mostly between -0.5 and +0.5 m. From Gallant and Austin (2009)

4. Approach

The guiding principle for the general approach to the problem was that it should remedy the problems stated above so that the resulting DEM could be used by the Mike-SHE hydrological modeling software. The methods used should be quantitative, repeatable, and automatable to the fullest extent possible. Further, the LiDAR-based DEM was considered to be more accurate and of higher quality than the USGS NED grid file, therefore any modifications were to be applied to the USGS DEM. ArcGIS Desktop 10.2.2 (including the Spatial Analyst and 3D Analyst Extensions) was used for all processing steps, on a Windows 7 Enterprise workstation with 4 dual-core Intel i6 processors and 4 GB of RAM. ArcGIS ModelBuilder was used to link the steps together as far as possible for unattended execution. The approach was broken down into four major tasks: LiDAR-to-DEM processing, USGS DEM re-processing, overlap processing and final DEM compositing.

4.1 LiDAR-to-DEM Processing

Because the original floating point elevation values of the LiDAR-based portion of the City's composite DEM covering the watershed area had been rounded to integers, a new LiDAR-based DEM was generated from the classified LAS "tiles" obtained from a 2013 survey by The Sanborn Map Company, Inc. of Colorado Springs, CO. Of almost 250 LAS tiles available, 149 were selected (totaling 123.53 sq mi or 320.77 km^2) to form a simple rectangle with no inside corners, or "zigzag" edges, for this proof-of-concept demonstration. A multi-point feature class was created from the pre-classified ground points (Class Id 2), using the ArcGIS 3D Analyst "LAS to Multipoint" tool, dynamically reprojected to NAD_1983_StatePlane_ Arizona_ Central_FIPS_0202_Feet from the original NAD 83 UTM Zone 12N projection. From the multipoint feature class of 600+ million points, a terrain dataset (TDS) was created using the 3D Analyst "Create Terrain" and "Build Terrain" tools, with parameters "Average Point Spacing" = 2.75 ft, "Pyramid type" = Window Size, "Point Selection Method" = Z Mean, "Pyramid Level" = 1, and "Window Size" = 6. Only the minimum number of pyramids needed to be created since the purpose of the TDS was simply to generate a DEM raster, not to be used for 3D analysis or viewing. Because of the very large number of points in the LAS files, creating a Triangular Irregular Network (TIN) was not feasible. Finally, a DEM was generated from the terrain dataset using the “Terrain to Raster” tool in the 3D Analyst Extension. Appendix B contains a model and details of the LiDAR geoprocessing steps (total processing time: □ 7 hours).

4.2 USGS DEM Re-processing

The USGS NED gridded dataset covering the City’s Rio de Flag watershed study area is identified by the USGS as “grdn35w112_13”: Geographic Coordinate System “GCS_North_American_1983, D_North_American_1983, GRS_1980, North American Vertical Datum (NAVD) 1988”, downloaded in ESRI grid format. The horizontal or cell resolution of this standard dataset is 10 meters, with elevation in meters. The published USGS vertical accuracy assessment of elevation values in the 2003 NED datasets (Gesch, Oimoen and Evans, 2014) shows a variation of -42.64 m to +18.74 m against bench marks associated with GEOID12A from the National Geodetic Survey (NGS), with a mean error of -0.32m, a standard deviation of 2.42m, and root-mean-square error (RMSE) values of between 7m and 15m for Level I datasets (according to Russell, Kumler and Ochis, 1995). There were no metadata as to the accuracy statistics of this specific dataset.

The first processing step was to clip the original 10-meter grid dataset to the watershed bounding rectangle (as described in 4.1 above). From this point forward, all raster outputs were formatted as ArcGIS File Geodatabase Rasters (FGDBR) for simplicity of management using File Geodatabases (instead of file system directories). Next, the meter elevation values were converted to US feet, using a conversion factor of 3.280839895. The raster was then reprojected from Geographic WGS 83 to match the previously constructed LiDAR DEM, using the Cubic resampling method to smooth “quilting pattern” artifacts, and leaving the spatial resolution at 30.6077 ft (□10m). A second processing step resampled the re-projected DEM to a spatial resolution or cell size of exactly 3 ft, matching the LiDAR DEM spatial resolution, with the resulting raster “snapped” (registered) to the LiDAR DEM to ensure exact alignment of cells for overlap processing (see 4.3 below). Appendix C contains a model and details of the USGS DEM geoprocessing steps (total processing time □ 3 hours).

4.3 LiDAR/USGS Overlap Processing

Based on the preliminary analysis in the City’s original composite DEM, the absolute range of elevation differences between the LiDAR and NED cell values was computed as |-99| + |35| = 134 ft. (See figure in Appendix A on pg. 21.) Translating this vertical range to a horizontal range for the overlapping of the two DEMs (as suggested in Gallant and Austin 2009) , an initial multiplication factor of 10:1 was adopted to ensure adequate horizontal "room" for smoothing, yielding a value of 1,340 horizontal feet for the proposed width of the overlap area. As an extra margin of safety, the overlap area width was expanded to 3,000 ft, or 1,000 3-ft pixels (resulting in a total overlap area of 20.44 sq mi 52.93 km^2). This padding was fortuitous, because the final computed range of elevation differences within this 1000-pixel wide overlap zone turned out to be |-186| + |70| or 256 ft. (See figure in Appendix D on pg. 26). The histogram below shows the distribution of elevation differences across the overlap area:

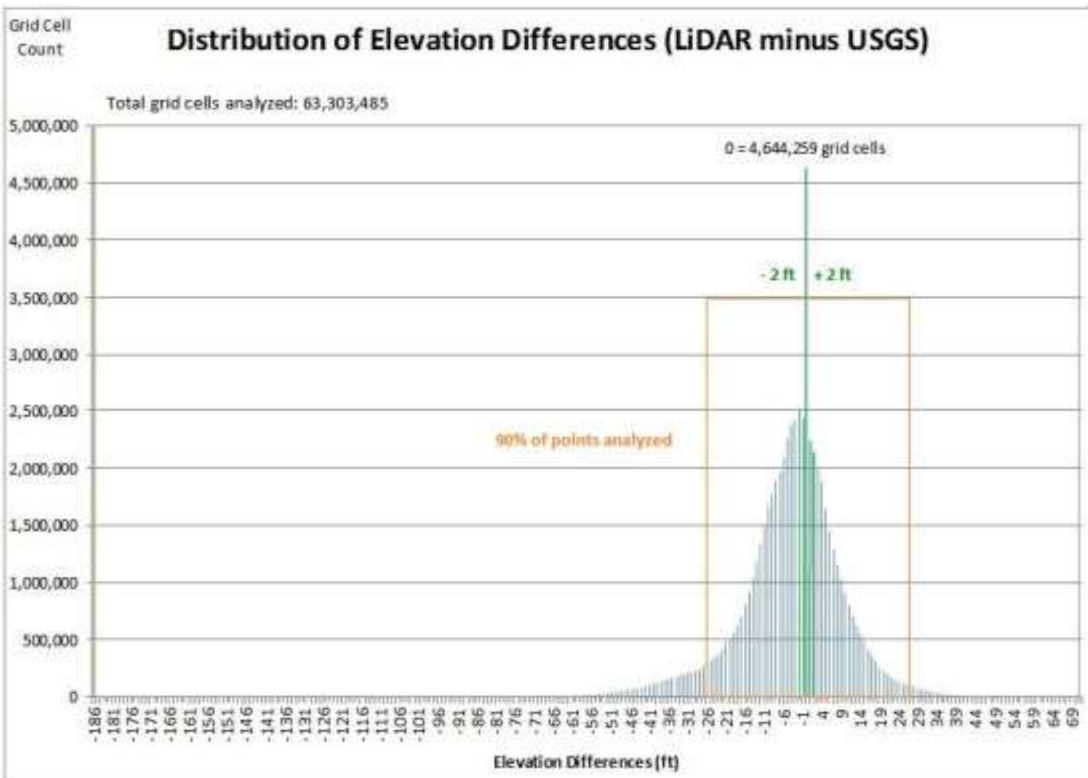

Figure 3. The distribution of elevation differences shows a steep curve, skewed toward a negative difference (LiDAR – USGS < 0, i.e., LiDAR < USGS). Approximately 90% of the elevation differences fall within +/- 22 ft. Of 63+ million pixels analyzed, only 13,986,229 or 22% were within acceptable error limits of +/- 2 ft, as specified by the Project Manager, Jim Janecek.

After accepting the final width of the overlap area, the re-sampled USGS DEM was clipped to the correct extent for overlap processing, resulting in an area of approximately 125.04 sq mi (323.85 km^2).

The general concept was to "feather" the USGS DEM back from its boundary across the overlap area to the edge of the newly processed LiDAR DEM, using the following simplified algorithm:

```
New_USGS = Old_USGS + ((LiDAR – Old_USGS) * Decreasing_Factor)
```

Initially, a “fishnet” approach was attempted, i.e., creating a fishnet of polygons exactly overlaying each pixel in the overlap zone, where each polygon would contain a “Decreasing Factor” value, ultimately to be converted to a raster where each cell would contain the linearly decreasing factor (in this case from 0.999 to 0). However, the number of polygons to be created reached into the hundreds of millions and became too computationally intense, requiring a different approach.

The realization that the “decreasing factor” for feathering was not to be applied randomly, but linearly across the width of the overlap area, enabled the adoption of polygon “strips” covering the overlap area, an approach that would be much more efficient. (See figures in Appendix D on pg. 27.)

A Python script was developed to create the series of polygon strips to cover the overlap area, beginning at the edge of the USGS DEM and working back to the edge of the LiDAR DEM. (See Appendix D, pg. 28.) After a few iterations, the script produced the desired series of 1000 polygon strips, each of which was then attributed with the feathering factor appropriate for its position in the overlap area. The “first” polygon strip received a factor of 0.999 (or 1 – (1/1000)) to be applied in the raster algebra algorithm described above, which would alter the NED elevation values of all pixels directly bordering the LiDAR to most closely match the LiDAR elevation. Each subsequent polygon strip received a “factor” attribute value decreasing by 1/1000 from 0.998 to 0. The factor of 0 would be applied to the last strip of pixels in the overlap area directly adjacent to the USGS DEM. (See figures in Appendix D on pg. 27 for illustrations of the “strip” approach at various scales.)

Once the polygon strips had been correctly constructed and attributed, the polygon feature class was converted to a raster using the ArgGIS “Feature to Raster” tool, setting the processing extent to include only the overlap area. Clipping the “Elevation Difference” raster to the overlap area yielded the final dataset needed for the actual raster algebra step (raster names are simplified here):

```
Con(IsNull(“Smoothing_Factors"), "Old_USGS",
   "Old_USGS" + (“Elevation_Difference" * "Smoothing_Factors"))
```

To illustrate: if a NED cell inside the overlap area had an elevation value of 8667.9440 ft and the corresponding LiDAR cell had an elevation value of 8705. 2396 ft, the difference between the two cells would be recorded in the corresponding “differential” cell as 37.2956 ft (LiDAR minus NED = Difference). If these two cells were located inside the first “L”-shaped strip of the overlap area, the corresponding “smoothing factor” cell would contain a value of 0.999, and the raster operation would be “8667.9440 ft + (37.2956 ft * 0.999)”, resulting in a new elevation value for that cell of 8705.2023 ft, bringing the new value to within 0.037 ft of the LiDAR value. At the midpoint of the overlap area (and using the same elevation values as in the previous example), the smoothing factor would be 0.500 and the raster operation would be “8667.9440 ft + (37.2956 ft * 0.500)”, resulting in a new elevation value for that cell of 8686.5918 ft, adjusting that value to roughly halfway between the LiDAR and NED cell values. At the outermost strip of the overlap area (the outermost extent of the LiDAR data), the smoothing factor would be 0, leaving the new NED cell value identical to the original NED value, thus insuring a smooth transition at both edges.

It was critical for correct processing that all the rasters be “snapped”, or registered, to each other (using the LiDAR DEM as reference), and that the processing extent be set to the extent of the clipped USGS DEM. (See Appendix D, pg. 30 for all processing steps related to this task: total processing time □ 15 minutes.) With the successful completion of the feathering process, the final compositing of the adjusted USGS DEM and the LiDAR DEM could begin.

4.4 Final DEM Compositing

The final composited DEM was produced using the ArcGIS Spatial Analyst Mosaic to DEM tool. An additional cleanup step was performed as a precautionary measure in the Raster Algebra tool, to fill in any NoData cells potentially created at the mosaic seam line that might hinder flow analysis. (Later analysis demonstrated that there were no NoData cells created during the mosaicking process, but this step is nevertheless a useful precaution.) This step was executed by imbedding the Focal Statistics function (ArcGIS 9.3 version) into a conditional statement searching for cells with “Null” (NoData) values and filling them with the average elevation value of the surrounding cells in a 3 x 3 cell window. (See Appendix D, pg. 30 for processing details for the final DEM: total processing time □ 30 minutes.)

Table 1. File Details of Composited, Mosaicked DEM

Columns & Rows	27964, 25877
Bands	1
Spatial Reference	NAD 1983 State Plane Coordinate. System Arizona Central US Feet, False Easting 699998.6, False Northing 0, Central Meridian -111.9166666666667, Latitude of Origin 31, Scale Factor 0.9999, Linear Unit = feet
Cell Size (X,Y)	3,3
Pixel Type & Depth	32 Bit Floating Point
Extent / Size	Top: 1579619.17214, Left: 738027.010135, Right: 821919.010135, Bottom: 1501988.17214 6,512,619,852 ft^2, 233.6 mi^2, 605 km^2
Statistics (ft ASL)	Min 6303.4047851563, Max 12337.979492188, Mean 7472.448924034
Formats	TIFF, ESRI File Geodatabase Raster
Uncompressed Size	2.70 GB

5. Analysis and Results

The stream reaches profiled in the initial problem analysis were re-profiled to determine if the "overlap and feather" approach succeeded in removing both sharp elevation discontinuities and false "walls" or "berms" in the channels. (See figure of stream line segments inside the overlap area in Appendix E, pg. 31, and stream segment descriptions on pg. 32.) These included two upper reaches of the Rio de Flag, a middle reach and an upper tributary reach of Schultz Creek, and numerous upper reaches of Spruce Avenue Wash tributaries. Two additional stream reaches (upper Clay Avenue and Sinclair Washes) that were not included in the original analysis, were also profiled. Appendix E contains the detailed results of the analysis, as annotated comparative stream profile graphs.

The post-correction results were significantly improved over the initial conditions. All upper reaches of Spruce Avenue, Clay Avenue and Sinclair Washes displayed "normalized" (i.e., continuously decreasing) longitudinal profiles. All sharp elevation discontinuities were eliminated. (See Appendix E, starting pg. 33.) Any "bumps" in the profile were accounted for by existing structures such as overpasses or known berms recorded as ground elevation points by the LiDAR survey. Any physically existing depressions (e.g., ponds or "tanks") or berms remaining in the profiles were deemed acceptable, and indeed desirable, for modeling purposes, since the Mike-SHE software can potentially account for them if they are sufficiently large relative to the model grid size, and can use them to calculate ponding behind the berms.

Overpass, bridge and culvert engineered structures are also accounted for in the Mike-SHE model as hydraulic structures that are either inlet-restricted or not.

The post-feathering profile of the Rio de Flag reach revealed topographic details previously masked by the coarse resolution of the original NED dataset, for example: a pond/tank with a berm at distance marker 3496 (ft) , and a gradual increase in elevation (maximum gain 2.6 ft) between markers 3530 and 5757 which may more accurately reflect the physical topography and tendency for the area to pond during flood conditions. An elevated graded roadbed underlain by a culvert marks the end of this rise and a return to decreasing elevations. The stream reach from stream distance 0 to approximately 5900 ft crosses a relict lakebed (Fort Valley / Baderville) constituting extremely flat terrain. The uppermost 950 ft of the stream profile (both pre- and post-feathering) is completely flat at an elevation of 7319.9375 ft, due to the exclusive coverage of this section by the USGS portion of the DEM, which provided only a single value along this length. Ponding does occur in this area, but the "feathering" approach alone here may not be a satisfactory solution.

The lower portion of the Rio de Flag reach (post-feathering) displayed a more realistic slope as well as a tank and berm at marker 10796, with a noticeable dip and subsequent rise of 5.6 ft, not detected in the original NED dataset, but present in the high-resolution LiDAR data available in this section which was used for the smoothing algorithm. A sharp discontinuity at the downstream edge of the DEM overlap area was successfully eliminated.

The post-feathering profile of the Clay Ave Wash reach displayed the most marked changes of all the profiles. Several large discontinuities (> 10 vertical ft) were eliminated; numerous spurious "bumps" were reduced to create a more normal longitudinal profile; details of engineered structures in the lower portion of the reach were revealed, in contrast to the single large elevation "bump" in the pre-feathering profile which could not be modeled. The postfeathering profile of the Sinclair Wash reach produced more subtle changes, although a sharp elevation discontinuity (□ 15 ft elevation gain) at reach marker 1475 that seriously disrupted hydrologic connectivity in the model was successfully eliminated.

All the post-feathering graphs of the upper tributaries of Spruce Ave wash displayed normalized longitudinal profiles. In particular, Spruce Ave Tributary #6, Tributary #7, Tributary #8 and

Tributary #14 displayed complete elimination of sharp elevation discontinuities (including one elevation gain of 50 ft) that hampered successful hydrologic modeling. However, the upper portion of Spruce Ave Tributary #13 outside of the overlap area retained a 3.5 ft elevation gain from the untreated NED dataset.

The profiled reach of Schultz Creek displayed mixed results post-feathering. The lower portion of the reach was fully "normalized"; in particular, an elevation gain of □ 10 ft in the original NED dataset was reduced to less than 1 ft, and a sharp discontinuity at the downstream edge of the overlap area was eliminated. However, the uppermost 600 ft of the profiled displayed residual irregularities or "bumps" of 3 to 4 ft. When the stream distance was measured against the overlap area, it was determined that the irregularities were entirely within the USGS portion of the composited DEM, just outside the "feathered" overlap area. The terrain in this area is steep, and the stream channels had been adjusted from the original USGS NHD stream networks, based on the project manager's direction, to align them better with the stream reaches inside the LiDAR portion of the DEM. The errors with the stream profile in this area are likely a combination of errors in the original USGS Level I 10-meter grid as well as the manual adjustment of the stream channels. Additionally, the "bump" in the stream profile that straddles the upstream edge of the overlap area may not have received sufficient smoothing due to the fact that the smoothing factors were at their minimum values in this location (to produce a satisfactory transition with the untreated NED elevation values). Without LiDAR elevation data in this reach, it is impossible to know what the post-feathering profile would look like.

The reaches of Schultz Creek, Spruce Ave Wash and the Rio de Flag which did not respond satisfactorily to the "overlap and feather" approach could be addressed by "reconditioning" the final DEM along these reaches, also known as "burning" the stream channels. ESRI provides a free extension to ArcGIS: ArcHydro, which contains a DEM Reconditioning" tool. This tool implements the AGREE method of imposing a linear feature such as a stream channel onto a DEM, as developed by Maidment and Hellweger (1997) at the University of Texas, Austin. The DEM is altered to a specified distance on either side of the stream line, and to a specified maximum deviation from the original elevations, to "reverse-engineer" the DEM for stream channels not derived from the DEM itself. Because the ArcHydro software is free, and the process is both quantitative and automatable, "Dem Reconditioning" could be a final treatment for reaches that do not respond satisfactorily (within acceptable error limits) to the “overlap and feather” approach, although it is doubtful whether the AGREE algorithm alone could handle the sharp and significant elevation disparities found in this project.

6. Recommendations for Future Work

Given the success of this pilot project, multiple future advances are possible. For example, in order to accommodate the maximum number of LAS tiles, a more complex overlap area could be attempted, e.g., one with a ““saw tooth” or “zigzag” edge produced by staggered LAS tiles, rather than a simple “L” shape with minimal vertices (which in this case sacrificed twenty or more tiles of better-quality LiDAR elevation data). It should be noted that if the LAS-to-DEM process is performed in ArcGIS, and the edges of the produced DEM contain any inside corners (as opposed to a simple rectangle), some clipping of this DEM will be required to remove spurious interpolations of the point cloud across these inside corners. These unwanted interpolations produce “triangles” of nonsensical elevation data which must be removed.

In conjunction with a more complex overlap area, the python script used to construct the polygon “strips” could be enhanced to accept as input a set of vertices from a Point feature class, defining (at the minimum) the leading edge of the border area, with enhanced algorithms to compute the positions of the remaining vertices and the positions of the vertices for each successive polygon strip, based on the initial inputs provided.

Further, some experimentation could be done by varying the overlap area width, i.e., the number of polygon “strips” and therefore the number of feathering steps. For example, a width of 500 pixels could be attempted i.e., a multiplication factor of 5 instead of 10, with each sequential feathering factor being reduced by 0.002 (1/500) instead of 0.001 (1/1000). Stream profile and transect profile analysis could determine if the new number and granularity of feathering steps produces equally satisfactory results. Iterative attempts could determine the optimum number of steps for a given differential elevation histogram, yielding the following algorithm:

$$\frac{\text{Absolute range of elevation differences} * \textit{a multiplication factor}}{\text{Cell width}} = \text{Number of steps}$$

And: `Decreasing Factor Interval = 1/Number of Steps`

So, for example, if the absolute range of differences in elevation across the overlap area were only 65 feet, and if a multiplication factor of 8 were deemed adequate, and the raster cell width (i.e., polygon strip width) were 3 ft, then the "optimum" number of steps might be (65 * 8) / 3 = 173.33, perhaps rounding up to 200 for ease of calculation. The decreasing interval would then be calculated as 1/200 or 0.005; each step applying a smoothing factor of [1 – (0.005 * n^{th} step from 1 to 500)]. Thus the process could conceivably be optimized to preserve the greatest amount of high resolution data in favor of the lower resolution or less accurate elevation dataset.

Success with the above enhancements would render this process more generalizable to other map configurations, although non-contiguous overlaps would have to be processed separately, and would add some additional work to the final step of combining the LiDAR-based DEMs with the corrected areas.

It is hoped that this paper will assist in solving a problem that may plague many organizations and governmental entities which cannot afford full LiDAR coverage of a basin-scale watershed, but may still need to produce a better result than could be achieved by relying solely on 10-meter (or coarser) USGS elevation datasets. Indeed, based on personal conversation with the City Project Manager Jim Janecek, this problem was a topic of discussion at the latest meeting of the Arizona Hydrological Society in November 2016.

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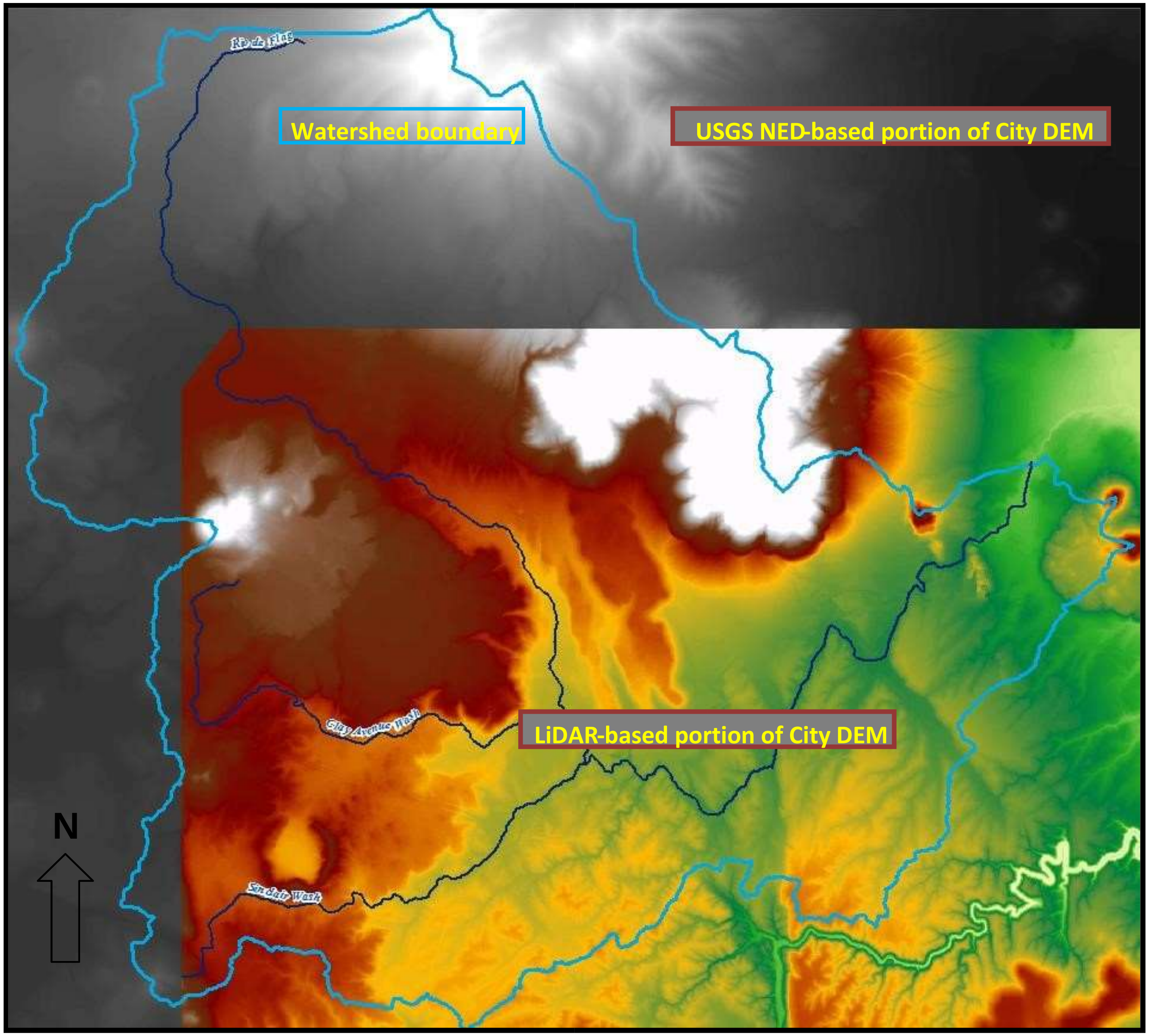
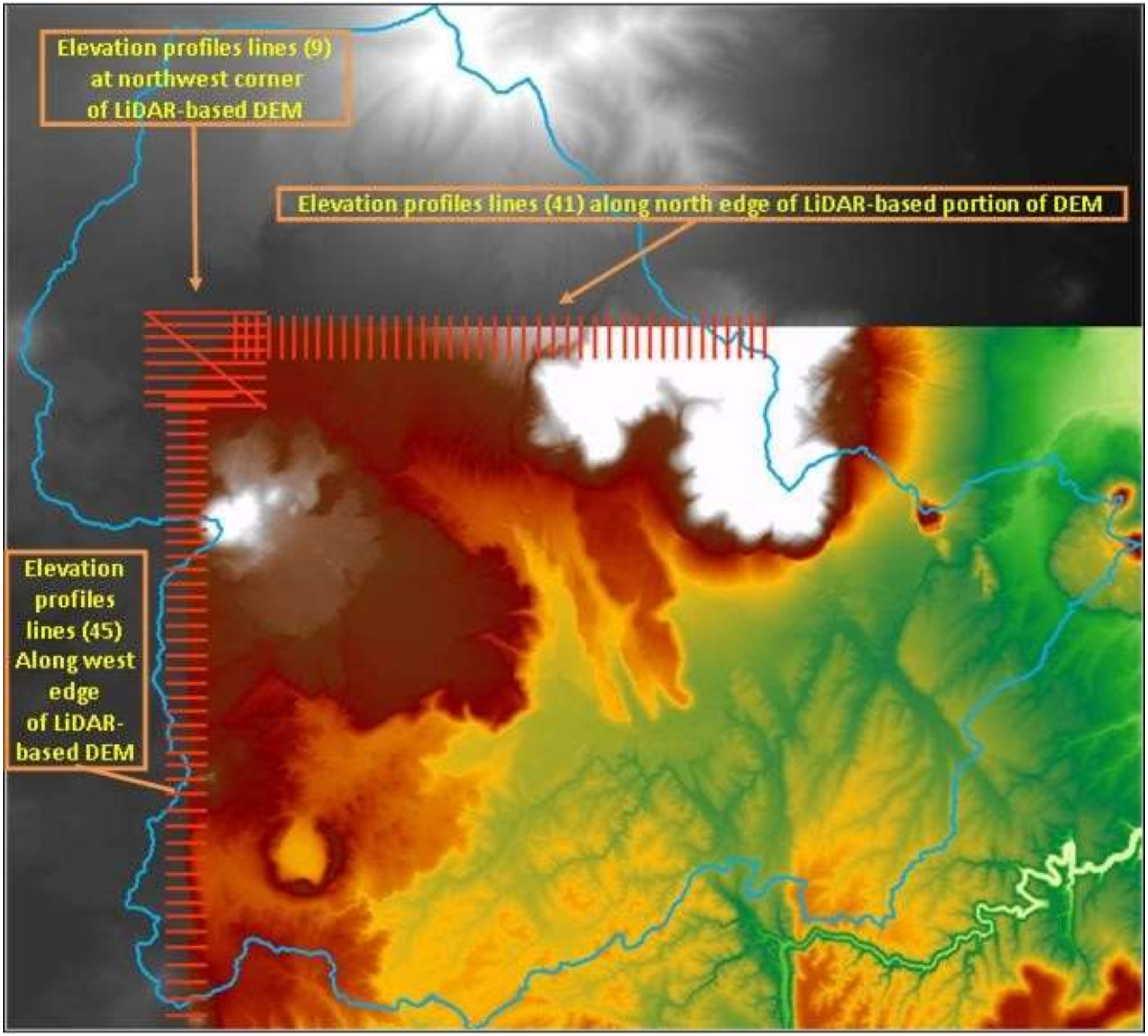
Appendices

Appendix A: Problem Analysis Details

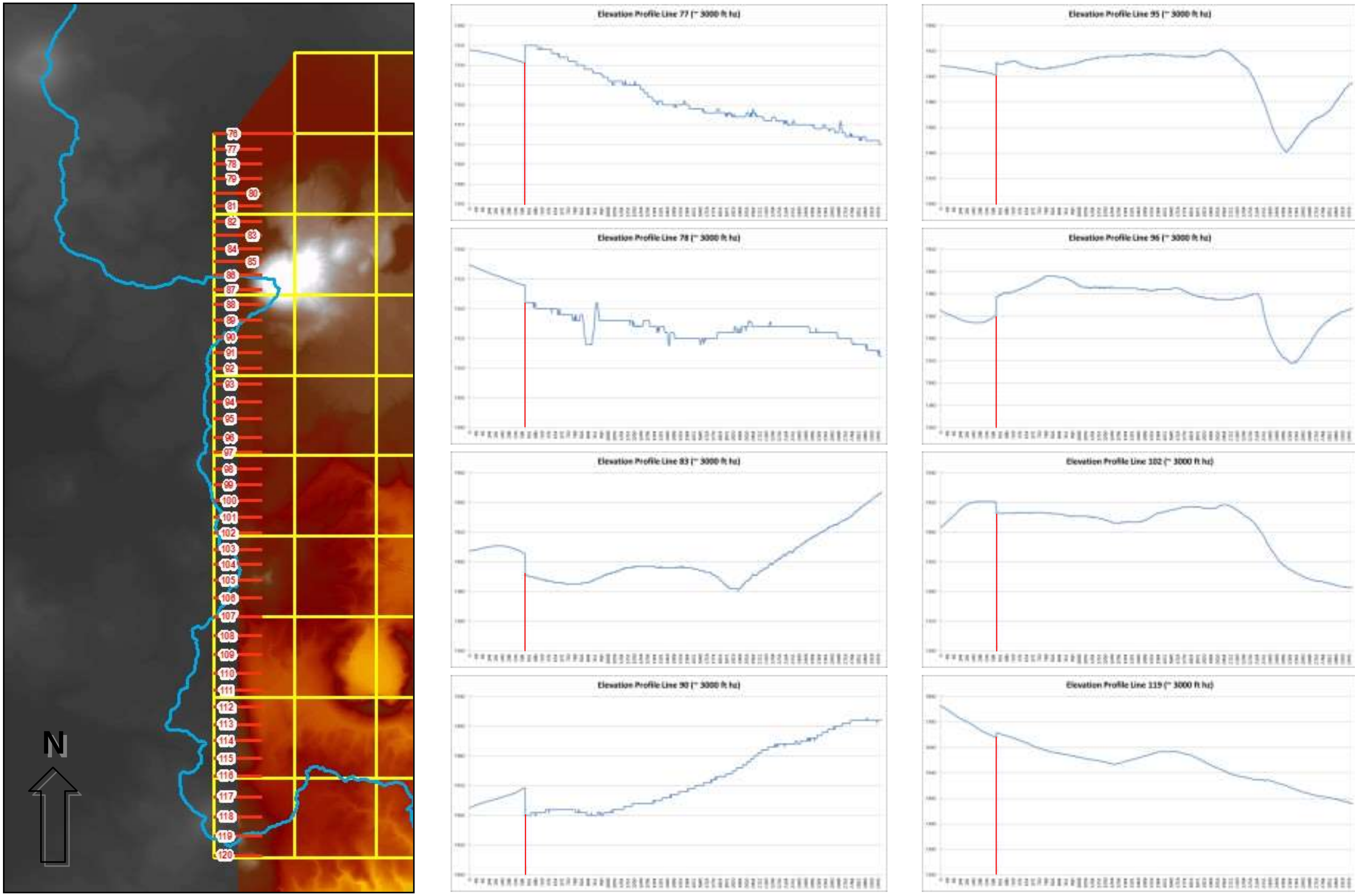
Elevation Data Initially Available for Rio de Flag Watershed Analysis



Starting point of elevation data (city composite DEM) data quality review

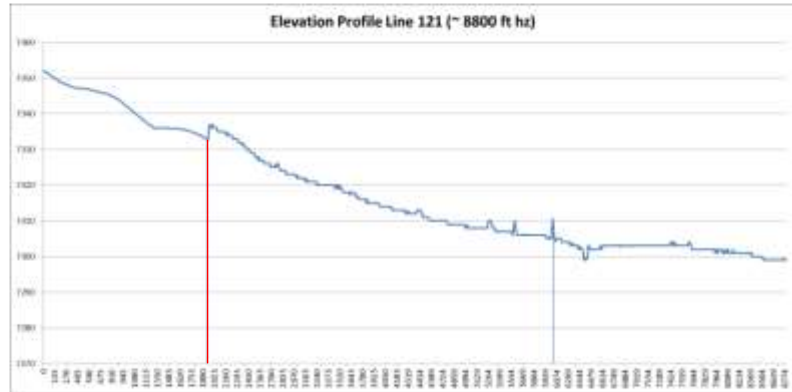


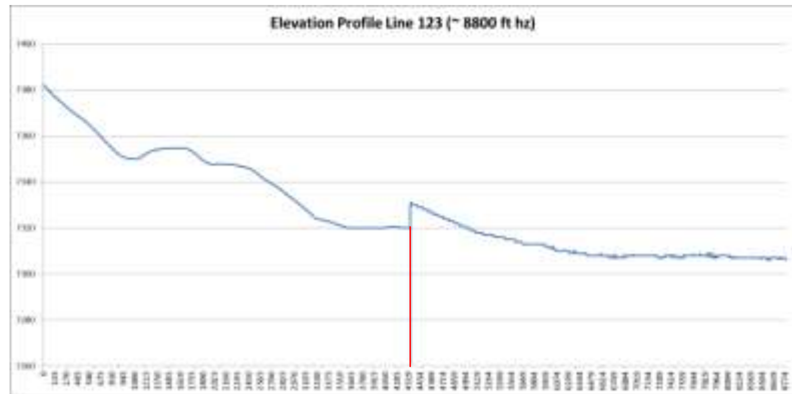
Analysis of profile lines along west edge (numbered from north to south)

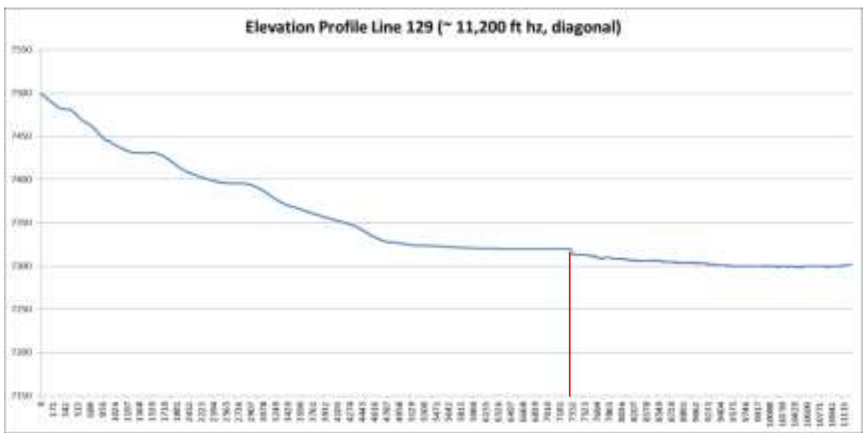


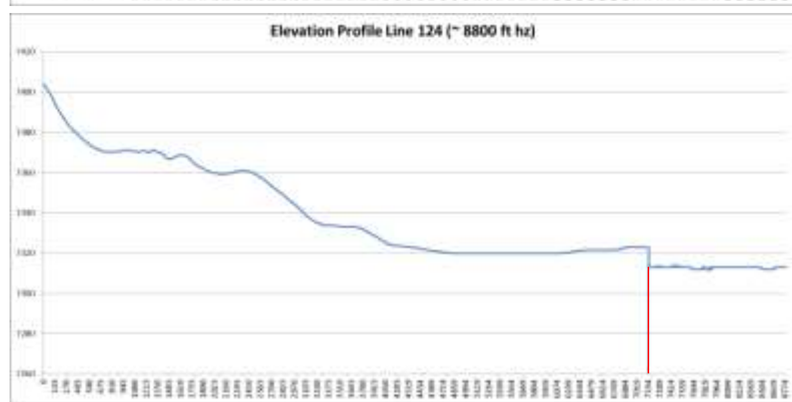
Note elevation discontinuity at same point on each profile line

Analysis of profile lines at northwest corner (numbered from north to south)



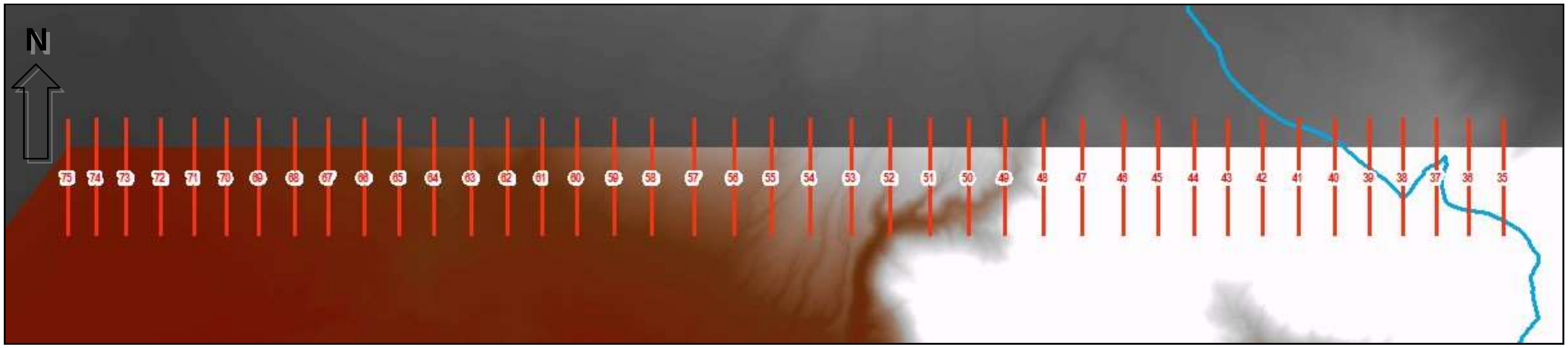


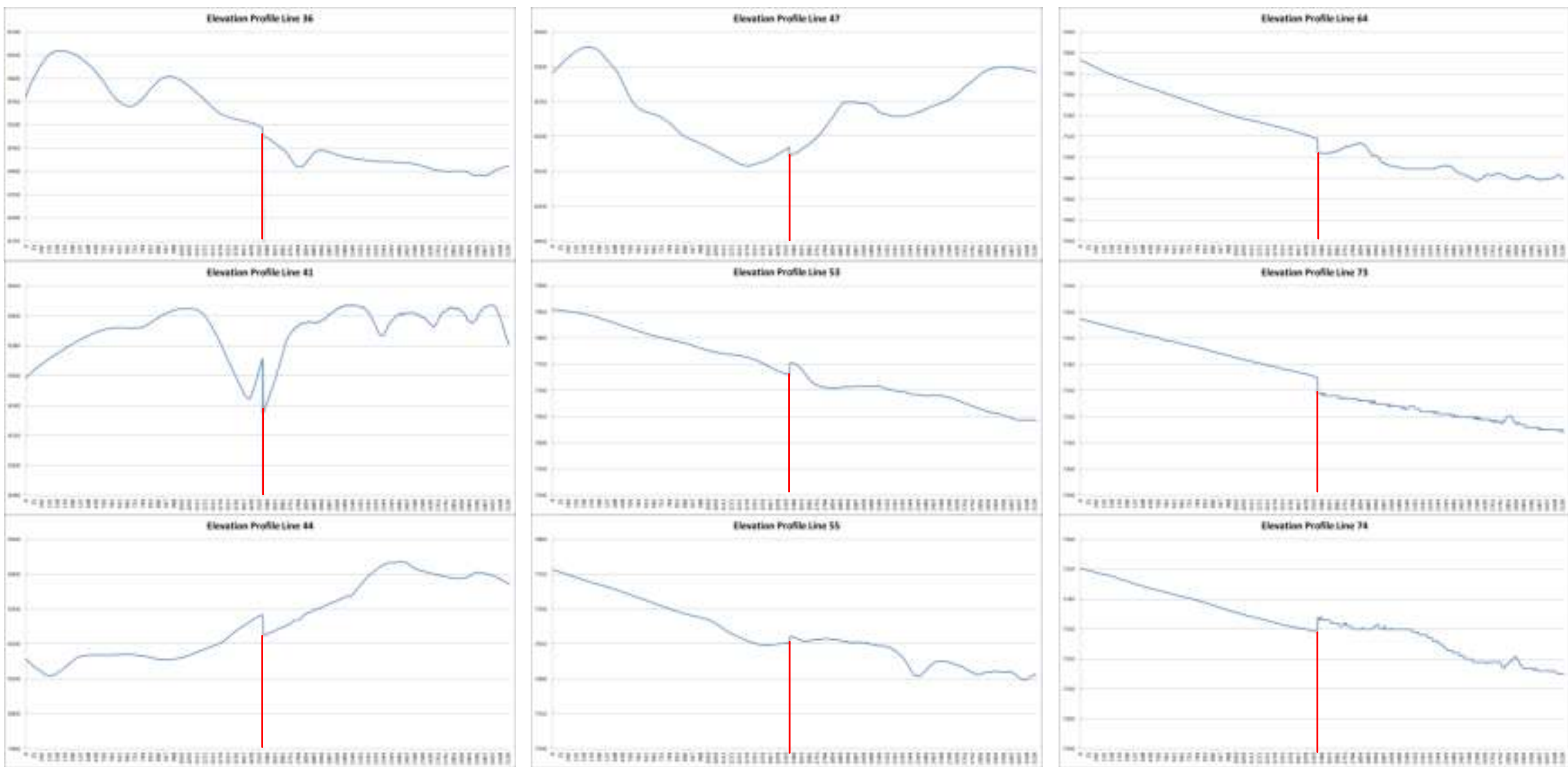




Note variable elevation discontinuities

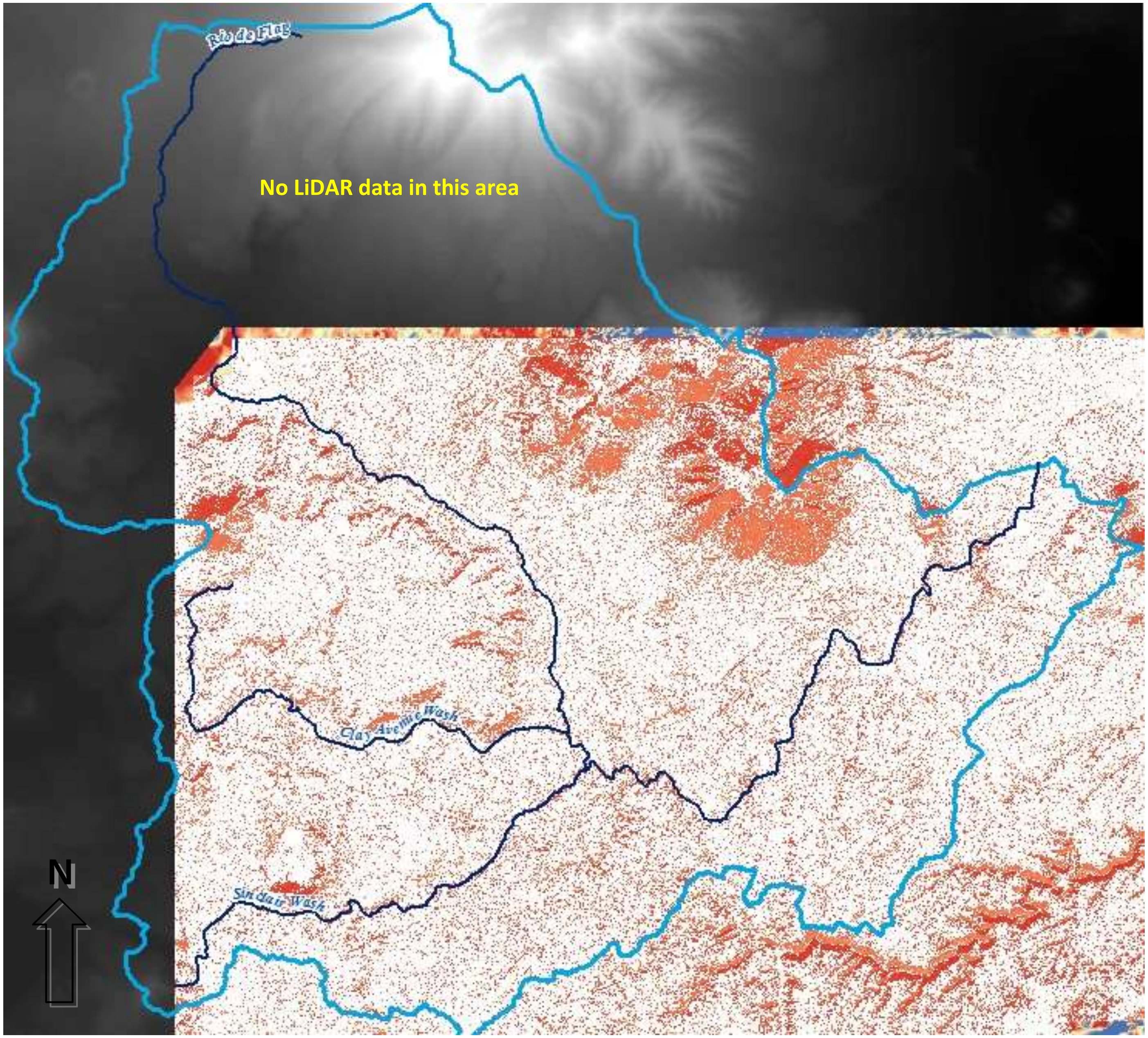
Analysis of profile lines along north edge (numbered from east to west)





Note elevation discontinuity at same point on each profile line

Differential analysis of City composite DEM and LiDAR-based DEM only (should be 0)



City DEM pixel value

>

LiDAR DEM pixel value

Max □ = 99 ft

City DEM pixel value

<

LiDAR DEM pixel value

Max □ = -35 ft

LiDAR DEM pixel value

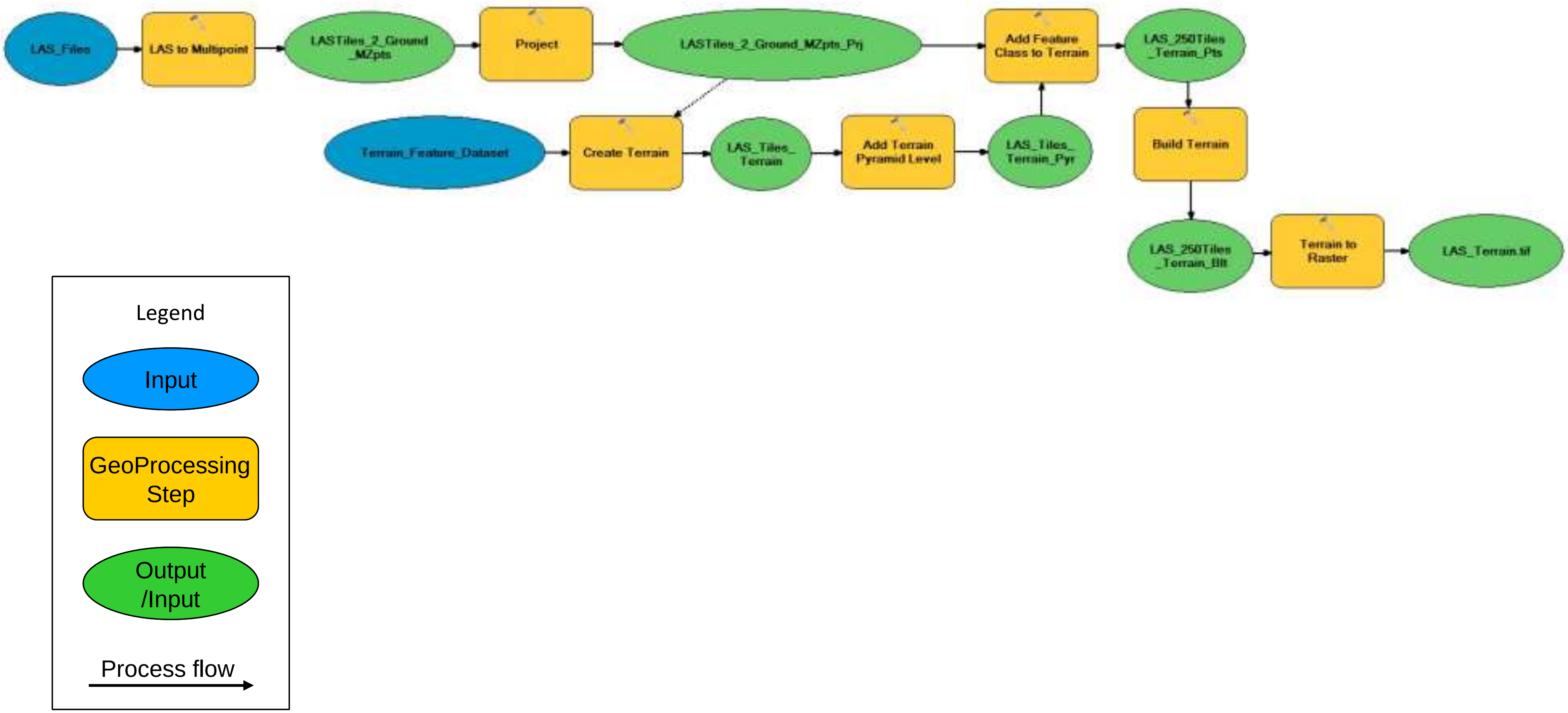
=

City DEM pixel value

□□□

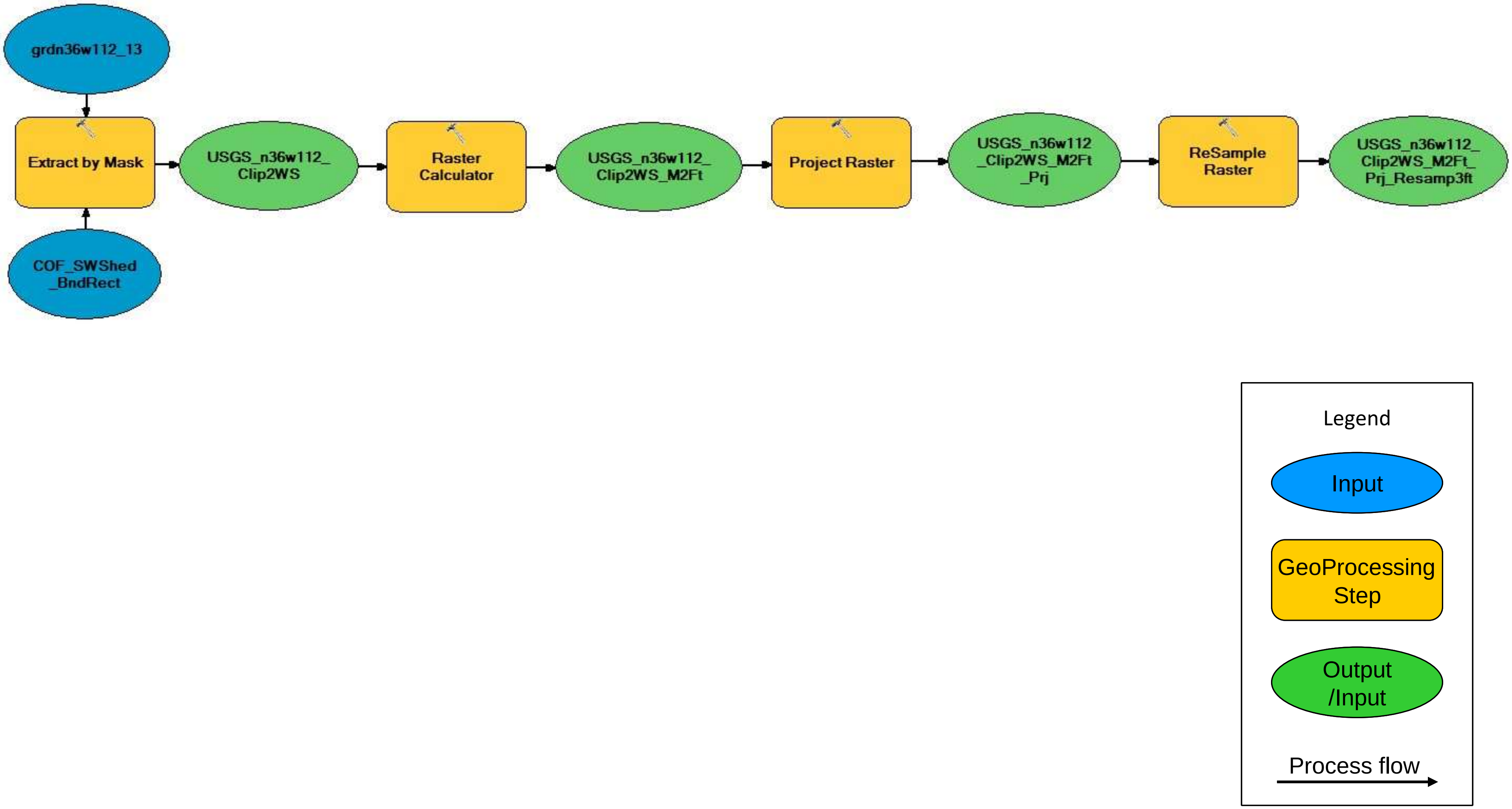
Note sharp band of highly differential values: Edge of band corresponds with sharp discontinuities in elevation seen on profile slides.

Appendix B: LiDAR ArcGIS GeoProcessing Details



Source file(s)	Format	GP Step	Output file	Comments
C:\Users\pbergman\Documents\LiDAR_2013\LAS\UseForNewDEM2016 149 tiles: 7550-01.las,7550-02.las,7550-03.las,7550-04.las,7551-01.las,7551-02.las,7551-03.las,7551-04.las,7552-01.las,7552-02.las,7552-03.las,7552-04.las,7553-01.las,7553-02.las,7553-03.las,7553-04.las,7554-01.las,7554-02.las,7554-03.las,7554-04.las,7560-01.las,7560-02.las,7560-03.las,7560-04.las,7561-01.las,7561-02.las,7561-03.las,7561-04.las,7562-01.las,7562-02.las,7562-03.las,7562-04.las,7563-01.las,7563-02.las,7563-03.las,7563-04.las,7564-01.las,7564-02.las,7564-03.las,7564-04.las,7570-01.las,7570-02.las,7570-03.las,7570-04.las,7571-01.las,7571-02.las,7571-03.las,7571-04.las,7572-01.las,7572-02.las,7572-03.las,7572-04.las,7573-01.las,7573-02.las,7573-03.las,7573-04.las,7574-01.las,7574-02.las,7574-03.las,7574-04.las,7580-01.las,7580-02.las,7580-03.las,7580-04.las,7581-01.las,7581-02.las,7581-03.las,7581-04.las,7582-01.las,7582-02.las,7582-03.las,7582-04.las,7583-01.las,7583-02.las,7583-03.las,7583-04.las,7584-01.las,7584-02.las,7584-03.las,7584-04.las,7590-01.las,7590-02.las,7590-03.las,7590-	LAS	LASToMultipoint C:\Users\pbergman\Documents\LiDAR_2013\LAS\UseForNewDEM2016 C:\Users\pbergman\Documents\LiDAR_2013\TerrainDatasets\TDS.gdb\LiDAR_149Tiles_TDS\LASTiles149_Ground_MZpts 2.5 2 ANY_RETURNS # # las 1 NO_RECURSION	LASTiles149_Ground_MZpts	Contains **196,159,897** "MZ" points in 63,880 multipoint features each containing min 1 pts, avg 3070 pts, max 3500 pts. Processing time on 32-bit ~ 10 mins Peak RAM usage: < 3GB
LASTiles149_Ground_MZpts	Multi-Point MZ feature class	Project C:\Users\pbergman\Documents\PamWork\TerrainDatasets\TDS.gdb\LiDAR_149Tiles_TDS\LASTiles149_Ground_MZpts C:\Users\pbergman\Documents\PamWork\TerrainDatasets\TDS.gdb\LiDAR_149Tiles_TDS_SPCSAZC\LASTiles149_Ground_MZpts_Prj to:PROJCS['**NAD_1983_StatePlane_Arizona_Central_FIPS_0202_Feet**',GEOGCS['GCS_North_American_1983',DATUM['D_North_American_1983',SPHEROID['GRS_1980',6378137.0,298.257222101]],PRIMEM['Greenwich',0.0],UNIT['Degree',0.0174532925199433]],PROJECTION['Transverse_Mercator'],PARAMETER['**False_Easting',699998.6],PARAMETER['False_Northing',0.0],PARAMETER['Central_Meridian',-111.916666666667],PARAMETER['Scale_Factor',0.9999],PARAMETER['Latitude_Of_Origin',31.0],UNIT['Foot_US',**0.3048006096012192]] # from: PROJCS['**North_American_1983_Transverse_Mercator**',GEOGCS['GCS_North_American_1983',DATUM['D_North_American_1983',SPHEROID['GRS_1980',6378137.0,298.257222101]],PRIMEM['Greenwich',0.0],UNIT['Degree',0.0174532925199433]],PROJECTION['Transverse_Mercator'],PARAMETER['**false_easting',699998.6],PARAMETER['false_northing',0.0],PARAMETER['central_meridian',-111.916666666667],PARAMETER['scale_factor',0.9999],PARAMETER['latitude**	LASTiles149_Ground_MZpts_prj	Processing time ~ 45 mins on 64b 16GB
TDS.gdb\LiDAR_149Tiles_TDS_SPCSAZC\LASTiles149_Ground_MZpts_prj hydro_breaklines (from 2013)	Multi-Point MZ feature class polyline feature class	Terrain Dataset Wizard **Feature Classes:** - LASTiles149_Ground_MZpts_Prj (SFType=**mass points**, Overview=Yes) - hydro_breaklines (SFType=**hard line**, Overview=Yes) **Approximate point spacing = 2.5* ft** **Pyramid type = Window Size (Point selection method=Z Mean**, 2ndary thinning=None) **Pyramid Levels = 1 (Window Size=6, Max Scale=1000)** *Using the min point spacing of the 149 LAS files	LiDAR_149Tiles_TDS_SPCSAZC_Terrain (Terrain DS)	The settings for this GP wizard were selected from https://desktop.arcgis.com/en/desktop/latest/manage-data/terrains/building-a-terrain-dataset-using-the-terrain-wizard.htm ...which had excellent advice on how to smooth the LiDAR point clusters just enough to produce smoothed contours (from DEM) Also see "Average Point Spacing" page for rationale of selecting 2.5 ft: https://desktop.arcgis.com/en/arcmap/10.3/manage-data/terrains/average-point-spacing.htm "When working with data from different datasets with varying resolutions, **use the smallest point spacing** from all the contributing datasets." **<< RUN THIS IN ARCCATALOG, NOT ARCMAP!!**
LiDAR_149Tiles_TDS_SPCSAZC_Terrain	TDS	Executing: **TerrainToRaster** C:\Users\pbergman\Documents\PamWork\TerrainDatasets\TDS.gdb\LiDAR_149Tiles_TDS_SPCSAZC\LiDAR_149Tiles_TDS_SPCSAZC_Terrain C:\Users\pbergman\Documents\PamWork\Rasters.gdb\LiDAR_149Tiles_TDS_3ft **FLOAT NATURAL_NEIGHBORS [CELLSIZE 3] 0** Start Time: Wed Dec 02 17:07:00 2015 Succeeded at Wed Dec 02 20:30:14 2015 (Elapsed **Time: 3 hours 23 minutes 14 seconds**)	LiDAR_149Tiles_NEW_3ft (FGDBR)	Because of size limitation of TIN, decision to go directly to Raster from TDS - can process all in one piece/step. Resulting raster is **2.23 GB** uncompressed.
LiDAR_149Tiles_NEW_3ft	FGDBR	Executing: **ExtractByMask** C:\Users\pbergman\Documents\PamWork\Rasters.gdb\LiDAR_149Tiles_NEW_3ft C:\Users\pbergman\Documents\PamWork\Rasters.gdb**Temp_LiDAR149Tiles_Bnd** C:\Users\pbergman\Documents\PamWork\Rasters.gdb**LiDAR_149Tiles_NEW_3ft_Clip4NewSWDEM** Start Time: Thu Dec 03 16:12:18 2015 Succeeded at Thu Dec 03 16:15:01 2015 (Elapsed Time: 2 minutes 42 seconds)	LiDAR_149Tiles_NEW_3ft_Clip4Diff	
LiDAR_149Tiles_NEW_3ft_Clip4Diff	FGDBR	Executing: ExtractByMask C:\Users\pbergman\Documents\RastersTemp\RecreateNewSWDEMSteps.gdb\LiDAR_149Tiles_NEW_3ft_Clip4Diff Masks4DEMOverlapWork C:\Users\pbergman\Documents\RastersTemp\RecreateNewSWDEMSteps.gdb\LiDAR_149Tiles_NEW_3ft_Clip4SWDEM Start Time: Thu Apr 28 15:13:56 2016 Succeeded at Thu Apr 28 15:17:27 2016 (Elapsed Time: 3 minutes 31 seconds)	LiDAR_149Tiles_NEW_3ft_Clip4SWDEM	

Appendix C: USGS DEM ArcGIS GeoProcessing Details

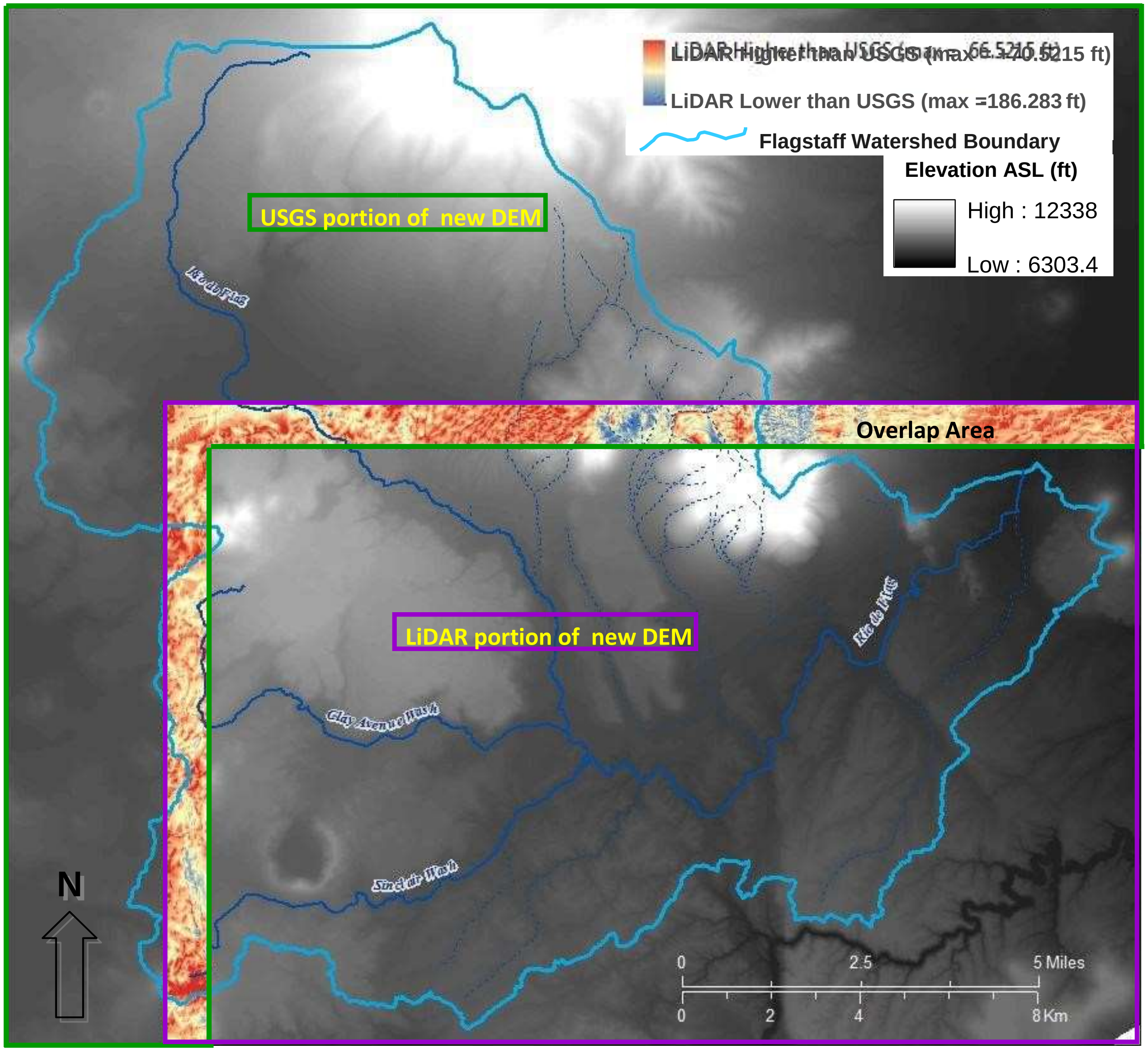


USGS NED Grid Geoprocessing Notes

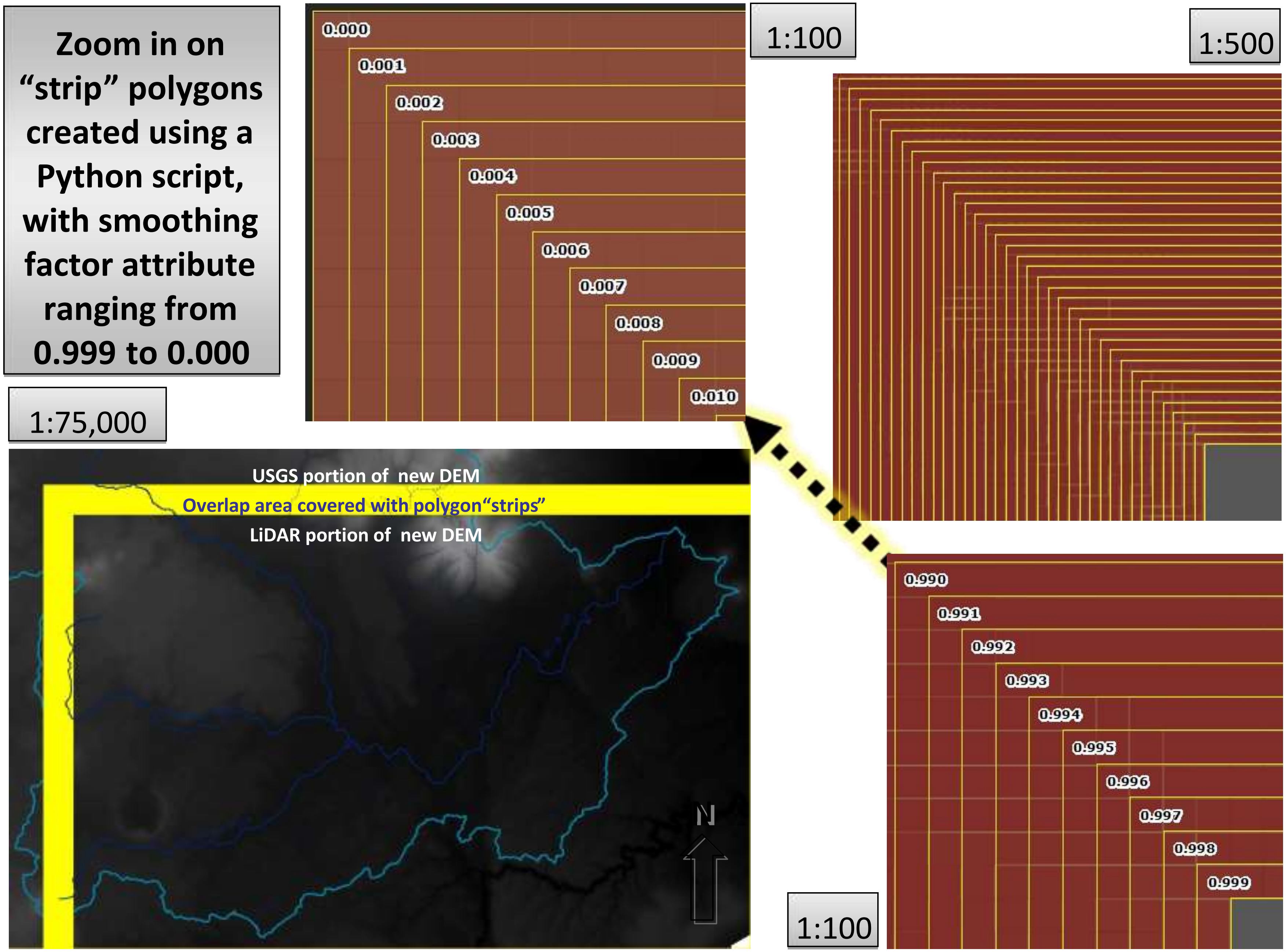
Source File(s)	Output File(s)	CS	Cell size	Format	GP Step	Comments
USGS download	grdn36w112_13	GCS_North_American_1983	0.000093 Degree	ESRI Grid	N/A	
grdn36w112_13	USGS_n36w112_Clip2WS	GCS_North_American_1983	0.000093 Degree	FGDBR	**ExtractByMask** grdn36w112 **COF_SWShed_BndRect** C:\Users\pbergman\Documents\ArcGIS\ElevationData.gdb\USGS_n36w112_Clip2WS	Min Z = 1925.122436523438 M Max Z = 3760.514404296875 Mean = 2277.71618399658 **These are the orignal elevations from USGS**
USGS_n36w112_Clip2WS	USGS_n36w112_Clip2WS_M2Ft	GCS_North_American_1983	0.000093 Degree	FGDBR	RasterCalculator ""USGS_n36w112_Clip2WS" * 3.280839895014" C:\Users\pbergman\Documents\ArcGIS\ElevationData.gdb\USGS_n36w112_Clip2WS_M2Ft	Min Z = 6316.018492532651 ft Max Z = 12337.645683392 ft Mean = 7472.822125988553 ft **These are the orignal elevations from USGS converted to feet using factor "* 3.280839895014"**
USGS_n36w112_Clip2WS_M2Ft	USGS_n36w112_Clip2WS_M2Ft_Prj_SPAZC	NAD_1983_StatePlane_Arizona_Central_FIPS_0202_Feet	30.60770398 ft (default as recommended when p-ing from GCS to PCS)	FGDBR	**ProjectRaster** C:\Users\pbergman\Documents\RastersTemp\IntermediateRasters_WShed.gdb\USGS_n36w112_Clip2WS_M2Ft C:\Users\pbergman\Documents\RastersTemp\IntermediateRasters_WShed.gdb\USGS_n36w112_Clip2WS_Elev_Ft_Prj_SPAZC PROJCS['NAD_1983_StatePlane_Arizona_Central_FIPS_0202_Feet',GEOGCS['GCS_North_American_1983',DATUM['D_North_American_1983',SPHEROID['GRS_1980',6378137.0,298.257222101]],PRIMEM['Greenwich',0.0],UNIT['Degree',0.0174532925199433]],PROJECTION['Transverse_Mercator'],PARAMETER['False_Easting',699998.6],PARAMETER['False_Northing',0.0],PARAMETER['Central_Meridian',-111.9166666666667],PARAMETER['Scale_Factor',0.9999],PARAMETER['Latitude_Of_Origin',31.0],UNIT['Foot_US',0.3048006096012192]] **CUBIC "30.607703975094 30.6077039750943"** ## GEOGCS['GCS_North_American_1983',DATUM['D_North_American_1983',SPHEROID['GRS_1980',6378137.0,298.257222101]],PRIMEM['Greenwich',0.0],UNIT['Degree',0.0174532925199433]]	Min Z = 6313.587380164326 ft Max Z = 12337.70013223532 ft Mean = 7472.488603462548 ft **Z has been altered from predecessor file, but not too much (0.5 ft or less). Was this due to CUBIC resampling mthd? Try BILINEAR?** **This appears to have the least alteration.**
USGS_n36w112_Clip2WS_M2Ft_Prj_SPAZC	USGS_n36w112_Clip2WS_M2Ft_Prj_SPAZC_Resamp3ft	NAD_1983_StatePlane_Arizona_Central_FIPS_0202_Feet	3 ft **Snap to new LiDAR DEM**	FGDBR	**ProjectRaster** USGS_Prep_Work\USGS_n36w112_Clip2WS_M2Ft_Prj_SPAZC C:\Users\pbergman\Documents\RastersTemp\RecreateNewSWDEMSteps.gdb\USGS_n36w112_Clip2WS_M2Ft_Prj_SPAZC_Resamp3ft PROJCS['NAD_1983_StatePlane_Arizona_Central_FIPS_0202_Feet',GEOGCS['GCS_North_American_1983',DATUM['D_North_American_1983',SPHEROID['GRS_1980',6378137.0,298.257222101]],PRIMEM['Greenwich',0.0],UNIT['Degree',0.0174532925199433]],PROJECTION['Transverse_Mercator'],PARAMETER['False_Easting',699998.6],PARAMETER['False_Northing',0.0],PARAMETER['Central_Meridian',-111.9166666666667],PARAMETER['Scale_Factor',0.9999],PARAMETER['Latitude_Of_Origin',31.0],UNIT['Foot_US',0.3048006096012192]] **CUBIC "3 3"** ## PROJCS['NAD_1983_StatePlane_Arizona_Central_FIPS_0202_Feet',GEOGCS['GCS_North_American_1983',DATUM['D_North_American_1983',SPHEROID['GRS_1980',6378137.0,298.257222101]],PRIMEM['Greenwich',0.0],UNIT['Degree',0.0174532925199433]],PROJECTION['Transverse_Mercator'],PARAMETER['False_Easting',699998.6],PARAMETER['False_Northing',0.0],PARAMETER['Central_Meridian',-	MUST SET ENVIRONMENT: Processing Extent = Default **Snap Raster = LIDAR** **HUGE file > 6 GB. Probably should delete after next step.**
USGS_n36w112_Clip2WS_M2Ft_Prj_SPAZC **USGS_DEM_Mask** (same as Masks4DEMOverlapWork.'Clip USGS 4 Diff' feature)	USGS_M2Ft_Prj_SPAZC_Resamp3ft_Clip4LiDARDiff	NAD_1983_StatePlane_Arizona_Central_FIPS_0202_Feet	3 ft	FGDBR	Executing: ExtractByMask C:\Users\pbergman\Documents\PamWork\Rasters.gdb\USGS_n36w112_Clip2WS_M2Ft_Prj_SPAZC_Resamp3ft C:\Users\pbergman\Documents\PamWork\Rasters.gdb**USGS_DEM_Mask** C:\Users\pbergman\Documents\PamWork\Rasters.gdb**USGS_M2Ft_Prj_SPAZC_Resamp3ft_Clip4LiDARDiff** Start Time: Thu Dec 03 13:29:52 2015 Succeeded at Thu Dec 03 13:35:19 2015 (Elapsed Time: 5 minutes 27 seconds)	MUST SET ENVIRONMENT: Processing Extent = Default **Snap Raster = LIDAR**

Appendix D. Overlap Area Analysis and DEM Compositing Processing Details

Post-processing Differential Elevation Analysis of USGS- and LiDAR-based DEMs



Graphical Representation of Polygon Strips with Smoothing Factor Values



Zoom in on “strip” polygons created using a Python script, with smoothing factor attribute ranging from 0.999 to 0.000
1:100
0.000
0.001
0.002
0.003
0.004
0.005
0.006
0.007
0.008
0.009
0.010
1:500
1:75,000
USGS portion of new DEM
Overlap area covered with polygon“strips”
LiDAR portion of new DEM
N
1:100
0.990
0.991
0.992
0.993
0.994
0.995
0.996
0.997
0.998
0.999

Python script to generate polygon strip series

```
# Script to create a series of polygons with specified vertices and
#   insert them into a feature class using an InsertCursor
# Use for loop to increment vertex coordinates as desired
# Note: the original intended shape is a "L" rotated 90 degrees clockwise
# Author:  Pam Bergman
# Date:  12/18/2015

import arcpy

# Target feature class fClass
=
'S:\Utilities\Stormwater\Bergman\DQWork\DEMDQ\NewSWDEM_Analysis.mdb\NAD83_SPCS_AZC_FIPS0202_ft\DEM_New_Overlap_F
a ctor_poly'

# Bounding rectangle coordinates in correct CS and units, could be parameterized.
# NOTE: These are NOT the starting coords for building polygons!!
xMin =  750000.010134913
yMin    =    1502792.003
xMax   =      821916.009
yMax = 1549997.173

# A variable for cell size (square) that could be parameterized  CellSize
= 3

# ... and a variable for number of iterations, ditto
MaxIts = 1000

# "For" loop starts here; Note that 'range' is zero-based, so must increment MaxIts by 1 for
i in xrange(1,(MaxIts+1)):

    # Variables to hold x and y values for each vertex , starting at:
    #   lower left corner of current polygon and going clockwise back to origin
xa = xMin + (((MaxIts - (i - 1)) * CellSize) - CellSize)     ya = yMin
    #   Upper left corner of current polygon
xb = xa
```

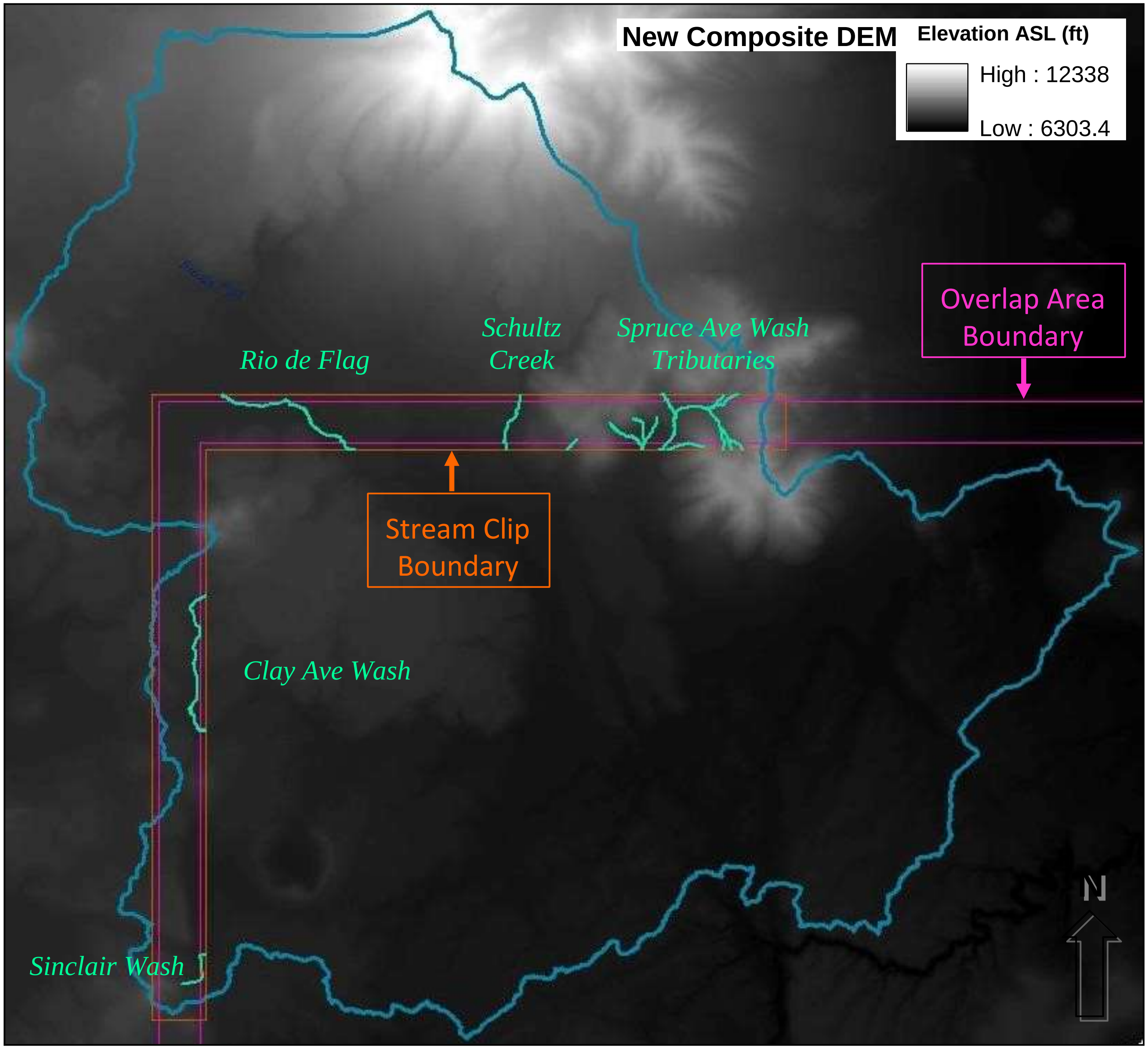
```
    yb = yMax - ((MaxIts - i) * CellSize)
#   Upper right corner of current polygon
xc = xMax     yc = yb
    #   Lower right corner of upper arm of current polygon
    xd = xMax     yd =
yc - CellSize
    #   Inside corner vertex of current polygon
xe = xa + CellSize     ye = yd
    #   Lower right corner of lower arm of current polygon
xf = xe     yf = yMin

    # 2D Array to hold vertex coordinates for each polygon
arVertices = arcpy.Array([arcpy.Point(xa,ya),
arcpy.Point(xb,yb),                                   arcpy.Point(xc,yc),
arcpy.Point(xd,yd),                                   arcpy.Point(xe,ye),
arcpy.Point(xf,yf),
arcpy.Point(xa,ya)])

    # Create the polygon with the designated array of vertices
fPoly = arcpy.Polygon(arVertices)

    # Assign Factor value.  Must cast MaxIts explicitly as Float to ensure
#   result is Float type.
    fltF = ((MaxIts - i)/float(MaxIts))
    # Debug print for test runs only
    #    print ([i,fltF])

    # Create the Insert Cursor
    insCursor = arcpy.da.InsertCursor(fClass, ['SHAPE@', 'Factor'])

    # Create the new feature
insCursor.insertRow([fPoly, fltF])

    # Dispose of the cursor, the polygon and the vertex array
del insCursor, fPoly, arVertices

    # back to top of loop, next iteration...
```

<table>
<tr><th>Source Files</th><th>Format</th><th>GP Step</th><th>Output File(s)</th><th>For mat</th><th>Comments</th></tr>
<tr><td></td><td></td><td>create feature class</td><td>DEM_New_Overlap_Factor_poly</td><td>Polygon</td><td></td></tr>
<tr><td>DEM_New_Overlap_Factor_poly</td><td>Polygon</td><td>Add Field "Factor", Float</td><td>DEM_New_Overlap_Factor_poly</td><td>Polygon</td><td></td></tr>
<tr><td>DEM_New_Overlap_Factor_poly</td><td>Polygon</td><td>Run Python script
"C:\Users\pbergman\Documents\ArcGIS\CreatePolygonSeries.py" to create "Factor" polygons</td><td>DEM_New_Overlap_Factor_poly</td><td>Poly</td><td>After several trial runs, this worked and produced polygons in the exact number, shape and position with the correct multiplication factor in each, to "smooth" the USGS DEM</td></tr>
<tr><td>DEM_New_Overlap_Factor_poly</td><td>Polygon</td><td>FeatureToRaster
DEM_New_Overlap_Factor_poly Factor
C:\Users\pbergman\Documents\RastersTemp\IntermediateRasters_WShed.gdb\
Overlap_USGS_Smoothing_Factors 3
Start Time: Mon Dec 21 14:31:35 2015
Succeeded at Mon Dec 21 14:32:33 2015 (Elapsed Time: 58.36 seconds)</td><td>Overlap_USGS_Smoothing_Factors</td><td>GDRI</td><td>Set Env | Processing Extents | Snap to Raster | LiDAR_149Tiles_NEW_3ft_Clip4Diff</td></tr>
<tr><td>USGS_M2Ft_Prj_SPAZC_Resamp3ft_Clip4NewSWDEM_Final
LiDAR_USGS_Overlap_Diff *
Overlap_USGS_Smoothing_Factors</td><td>FGDRD</td><td>Raster "feathering" algorithm
RasterCalculator RasterCalculator "Con(IsNull("USGS_Reconditioning_Work\Overlap_USGS_Smoothing_Factors"), "USGS_Prep_Work\USGS_M2Ft_Prj_SPAZC_Resamp3ft_Clip4NewSWDEM", "USGS_Prep_Work\USGS_M2Ft_Prj_SPAZC_Resamp3ft_Clip4NewSWDEM" + ("USGS_LiDAR_Diff_Analysis\LiDAR USGS Overlap Differential Elevation Analysis" * "USGS_Reconditioning_Work\Overlap_USGS_Smoothing_Factors")) "
C:\Users\pbergman\Documents\RastersTemp\RecreateNewSWDEMSteps.gdb\
USGS_M2Ft_Prj_SPAZC_Resamp3ft_Clip4NewSWDEM_Feather
Start Time: Thu Apr 28 15:40:28 2016
Succeeded at Thu Apr 28 15:45:49 2016 (Elapsed Time: 5 minutes 21 seconds)</td><td>USGS_M2Ft_Prj_SPAZC_Resamp3ft_Clip4NewSWDEM_Feather</td><td>GDRI</td><td>* This raster was created in the "1st Approach" workflow.
If USGS is higher than LiDAR, the diff is negative, so elevation will be subtracted (+ -).
If USGS is lower than LiDAR, the diff is positive, so elevation will be added (+ +).

BE SURE TO SET PROCESSING EXTENT = TO ALL OF USGS AREA!!</td></tr>
<tr><td>USGS_M2Ft_Prj_SPAZC_Resamp3ft_Clip4NewSWDEM_Feather
LiDAR_149Tiles_NEW_3ft_Clip4NewSWDEM</td><td>FGDRD</td><td>Executing: CreateDEMMosaicFillSeams (Custom Tool)
(C:\Users\pbergman\Documents\RastersTemp\RecreateNewSWDEMSteps.gdb\LiDAR_149Tiles_NEW_3ft_Clip4SWDEM;
C:\Users\pbergman\Documents\RastersTemp\RecreateNewSWDEMSteps.gdb\
USGS_M2Ft_Prj_SPAZC_Resamp3ft_Clip4NewSWDEM_Feather
C:\Users\pbergman\Documents\RastersTemp LiDAR_USGS_Feather_Mosaic.tif
PROJCS['NAD_1983_StatePlane_Arizona_Central_FIPS_0202_Feet',GEOGCS['GCS_North_American_1983', DATUM['D_North_American_1983',SPHEROID['GRS_1980',6378137.0,298.257222101]],PRIMEM['Greenwich',0.0], UNIT['Degree',0.0174532925199433]],PROJECTION['Transverse_Mercator'],PARAMETER['False_Easting',699998.6], PARAMETER['False_Northing',0.0],PARAMETER['Central_Meridian',-111.9166666666667],PARAMETER['Scale_Factor',0.9999], PARAMETER['Latitude_Of_Origin',31.0],UNIT['Foot_US',0.3048006096012192]] 3 32_BIT_FLOAT FIRST 1
C:\Users\pbergman\Documents\RastersTemp\LiDAR_USGS_Feather_Mosaic_Final.tif
Executing (Mosaic To New Raster): MosaicToNewRaster
Start Time: Fri Apr 29 15:52:50 2016; Succeeded at Fri Apr 29 16:04:22 2016 (Elapsed Time: 11 minutes 32 seconds)
Executing (Raster Calculator):
RasterCalculator Con(IsNull("C:\Users\pbergman\Documents\RastersTemp\LiDAR_USGS_Feather_Mosaic_TST.tif"), FocalStatistics("C:\Users\pbergman\Documents\RastersTemp\LiDAR_USGS_Feather_Mosaic_TST.tif", NbrRectangle(3,3,"CELL"),"MEAN","DATA"),
"C:\Users\pbergman\Documents\RastersTemp\LiDAR_USGS_Feather_Mosaic_TST.tif")
C:\Users\pbergman\Documents\RastersTemp\LiDAR_USGS_Feather_Mosaic_Final.tif
Start Time: Fri Apr 29 16:04:22 2016; Succeeded at Fri Apr 29 16:17:47 2016 (Elapsed Time: 13 minutes 24 seconds)
Executing (Build Pyramids And Statistics): BuildPyramidsandStatistics
C:\Users\pbergman\Documents\RastersTemp\LiDAR_USGS_Feather_Mosaic_Final.tif
Start Time: Fri Apr 29 16:17:47 2016 Succeeded at Fri Apr 29 16:24:12 2016 (Elapsed Time: 6 minutes 24 seconds)
Succeeded at Fri Apr 29 16:24:12 2016 (Elapsed Time: 31 minutes 22 seconds)</td><td>LiDAR_USGS_Feather_Mosaic_Final.TIF</td><td><u>TIFF</u></td><td>BE SURE TO:
1. Run "Calculate Statistics" on both input rasters prior to Mosaicking.
2. Set Processing Extent for Mosaicking to "SW_Bounding_Rect".
3. OUTPUT AS TIFF FILE, <u>NOT</u> FGDBR!!!
(For some reason FGDBR output is defective, plus tif is FASTER.).
4. MANUALLY SET Environment | Raster Storage | Compression = <u>NONE</u>.
MODIFY CUSTOM TOOL ACCORDINGLY.</td></tr>
</table>

Appendix E. Results

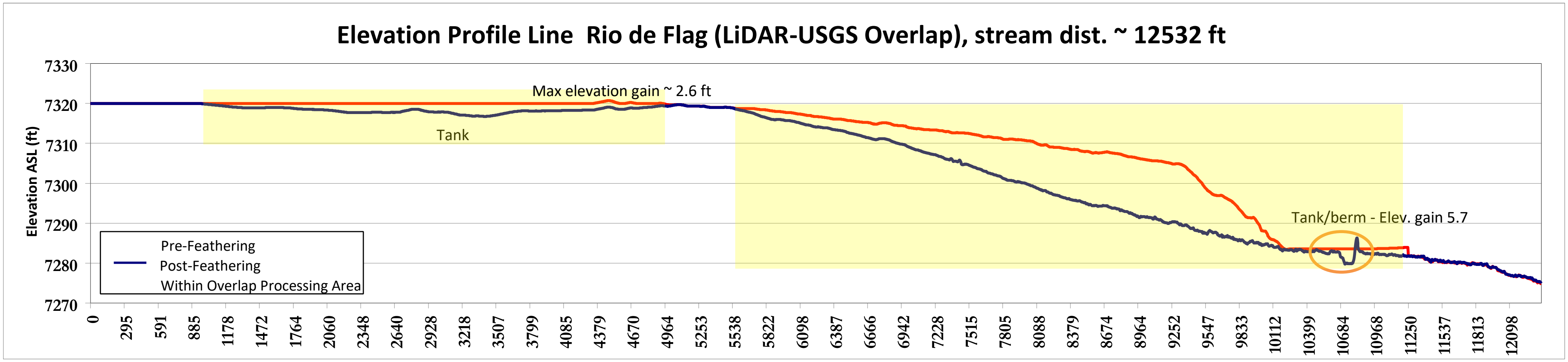
Stream Profiles for Testing in Former Overlap Area of New Composite DEM

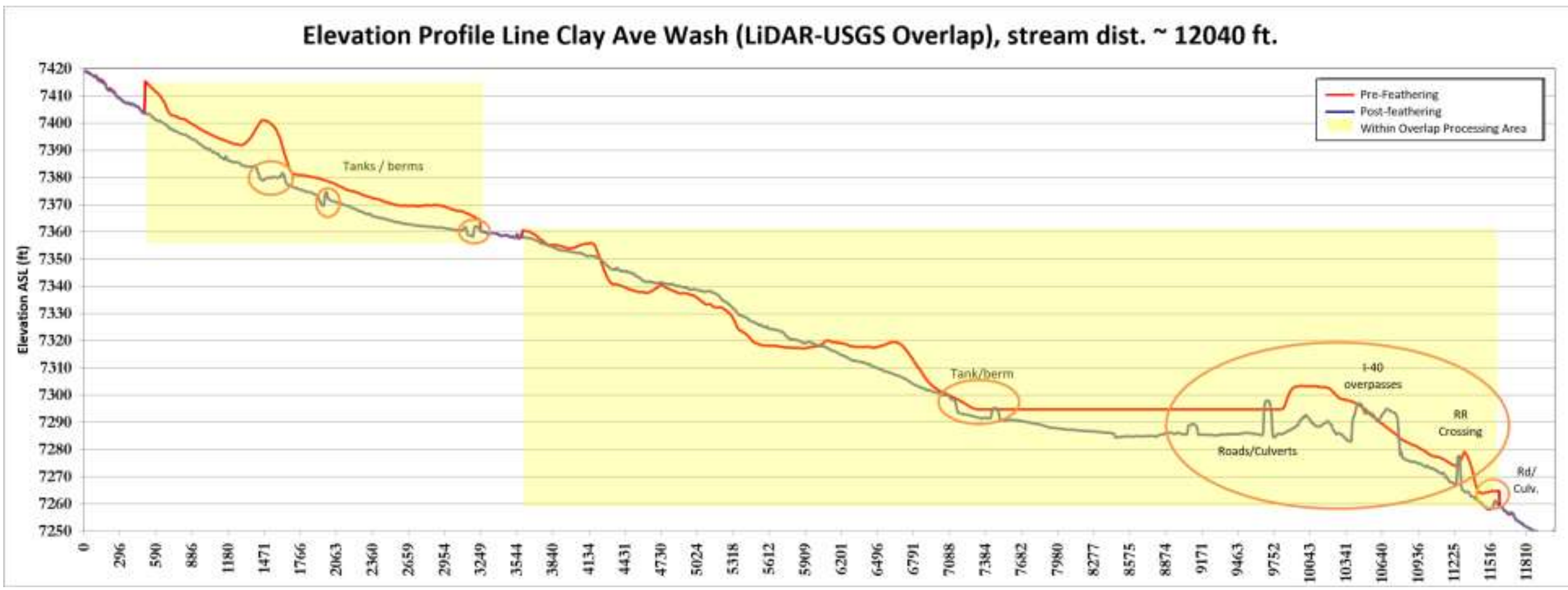


Stream Profile Segment Descriptions

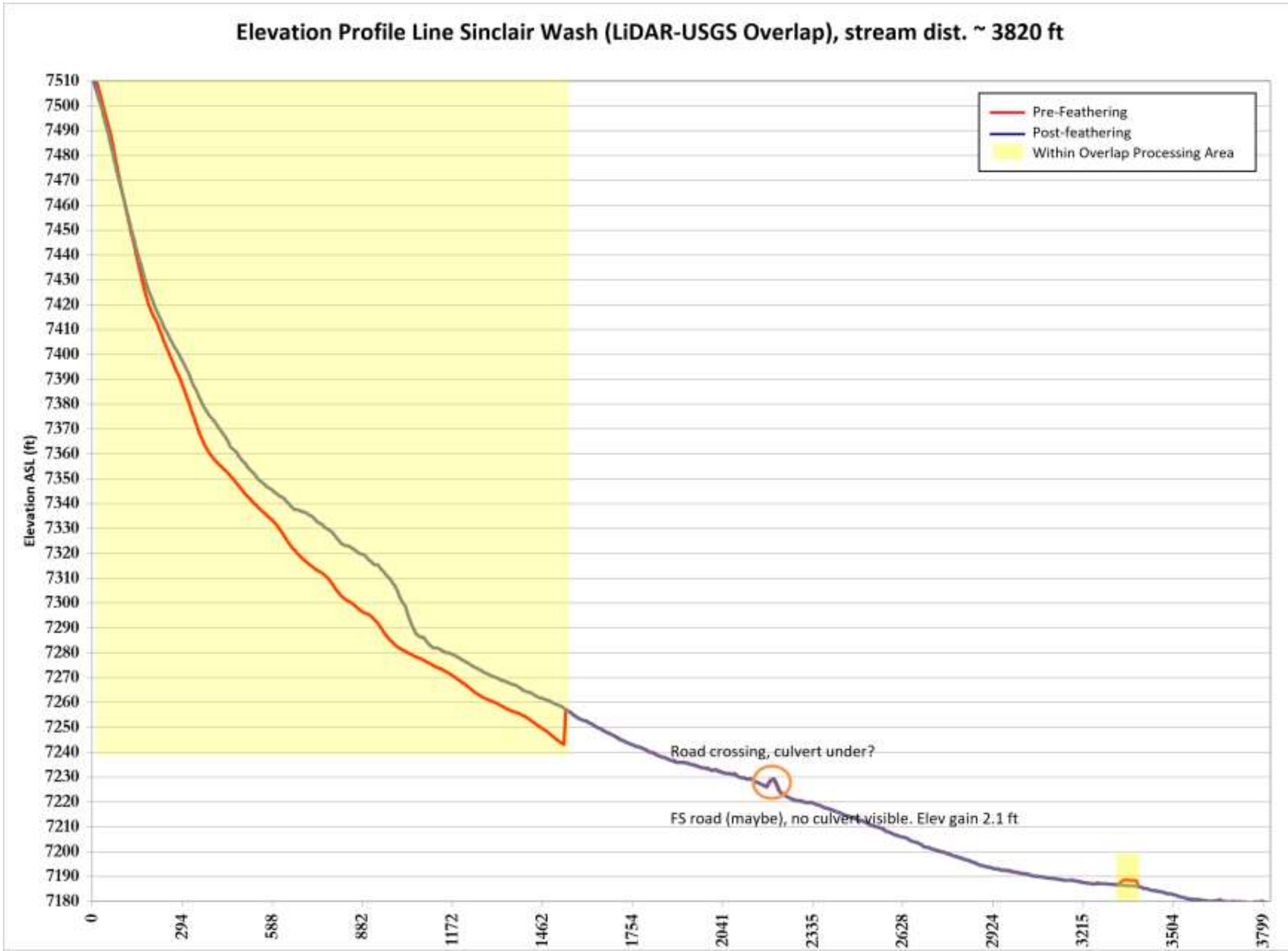
Profile Line ID	Description	Stream Entering Overlap Area at Dist 1 (ft)	Stream Exiting Overlap Area at Dist 1 (ft)	Stream Entering Overlap Area at Dist 2 (ft)	Stream Exiting Overlap Area at Dist 2 (ft)	Comment
1	Rio de Flag	931.320839	5082.990249	5531.224895	11251.99642	2 sections inside overlap
2	Spruce Avenue Wash Upper Tributary 10	890.523722	max	--	--	1 lower section inside overlap
3	Schultz Creek Upper Tributary 1	0	357.106615	--	--	1 upper section inside overlap
4	Spruce Avenue Wash Upper Tributary 12	672.900969	max	--	--	1 lower section inside overlap
5	Spruce Avenue Wash Upper Tributary 8	0	2864.260848	--	--	1 upper section inside overlap
6	Spruce Avenue Wash Upper Tributary 6	737.20469	9020.482449	--	--	1 middle section inside overlap
7	Sinclair Wash	0	1535.607366	3348.270393	3386.954751	2 sections inside overlap
8	Clay Avenue Wash	503.156173	3250.80791	3592.381201	11583.05122	2 sections inside overlap
9	Spruce Avenue Wash Upper Tributary 15	582.071164	max	--	--	1 lower section inside overlap
10	Spruce Avenue Wash Upper Tributary 9	0	max	--	--	Entirely inside overlap
11	Spruce Avenue Wash Upper Tributary 14	555.738635	max	--	--	1 lower section inside overlap
12	Spruce Avenue Wash Upper Tributary 7	0	2256.772513	--	--	1 upper section inside overlap
13	Spruce Avenue Wash Upper Tributary 13	1077.421435	max	--	--	1 lower section inside overlap
~~14~~	~~Spruce Avenue Wash Upper Tributary 11~~	~~--~~	~~--~~	~~--~~	~~--~~	Entirely OUTSIDE overlap - IGNORE
~~15~~	~~Spruce Avenue Wash Upper Tributary 5~~	~~--~~	~~--~~	~~--~~	~~--~~	Entirely OUTSIDE overlap - IGNORE
16	Schultz Creek	549.804765	4097.779848	--	--	1 middle section inside overlap

Stream Profile Results from Smoothed and Mosaicked DEM

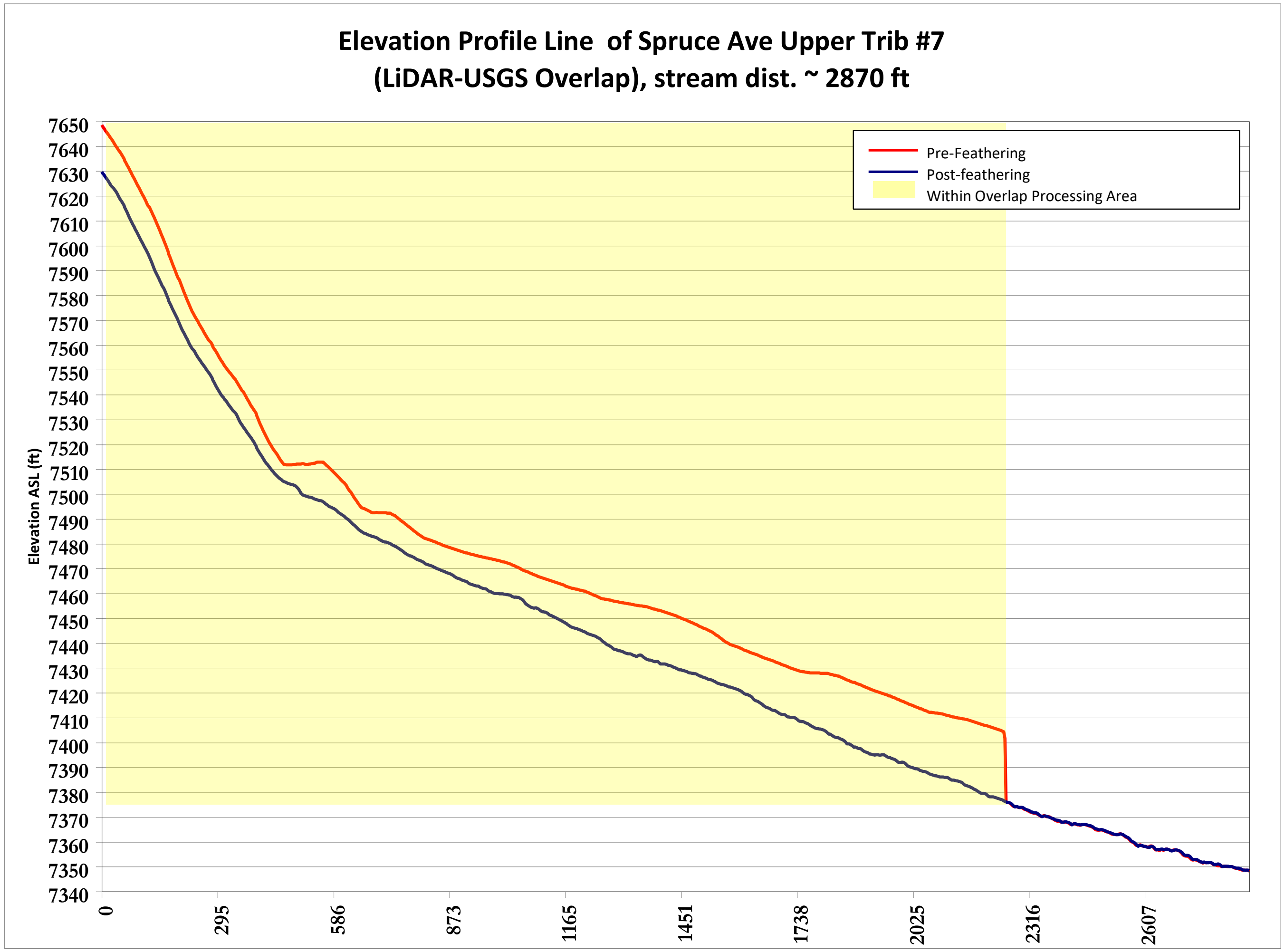




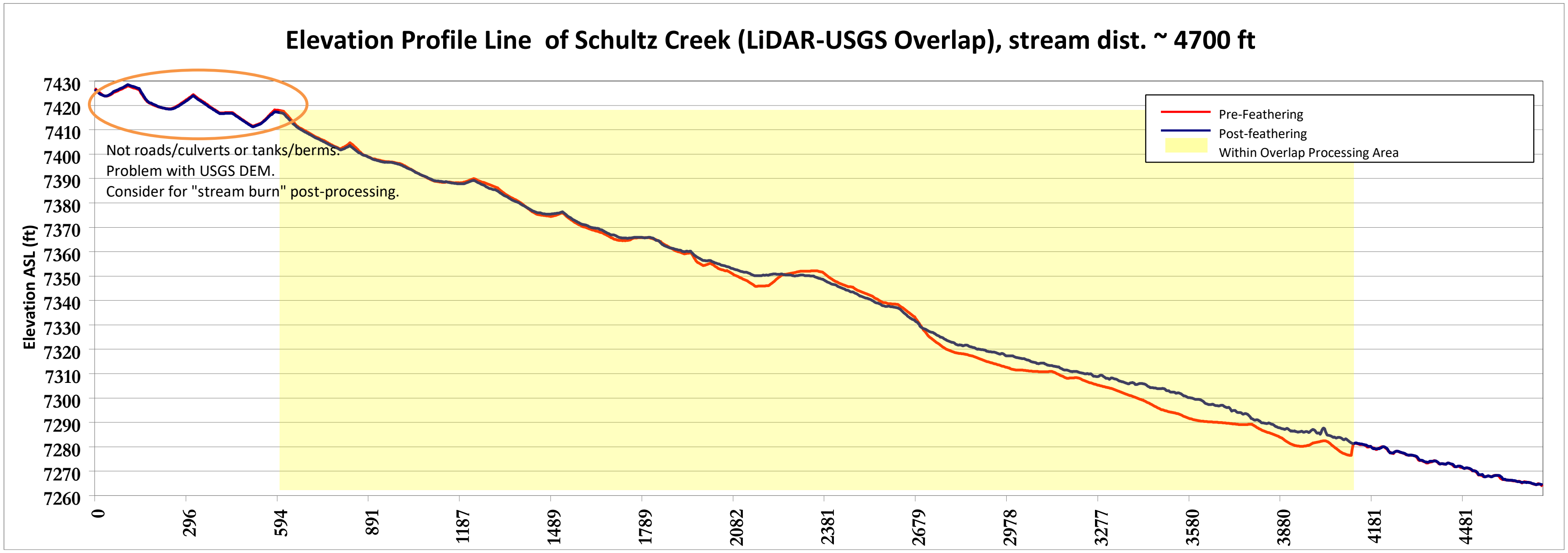
Stream Profile Results from Smoothed and Mosaicked DEM, continued



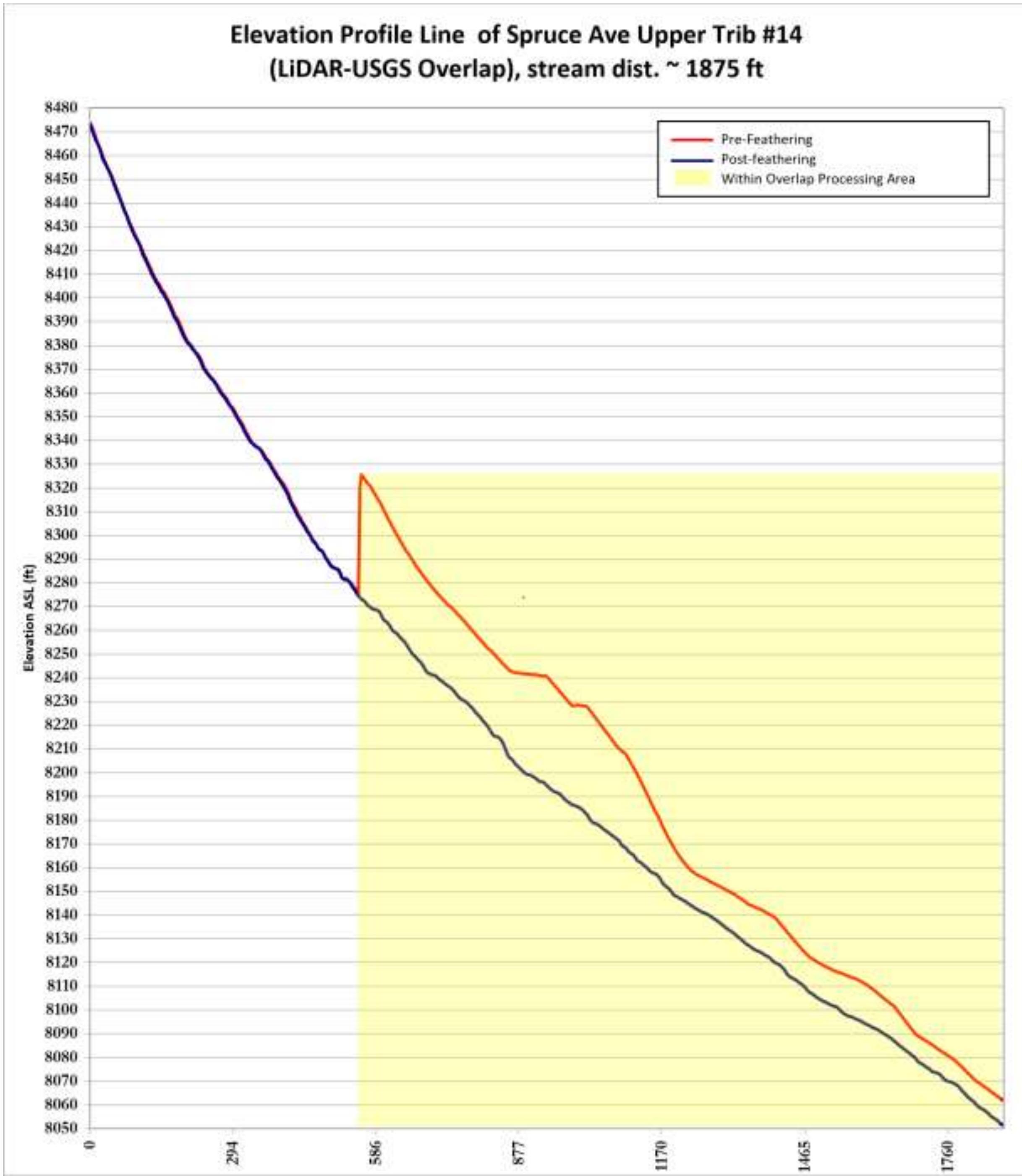
Stream Profile Results from Smoothed and Mosaicked DEM, continued



Stream Profile Results from Smoothed and Mosaicked DEM, continued

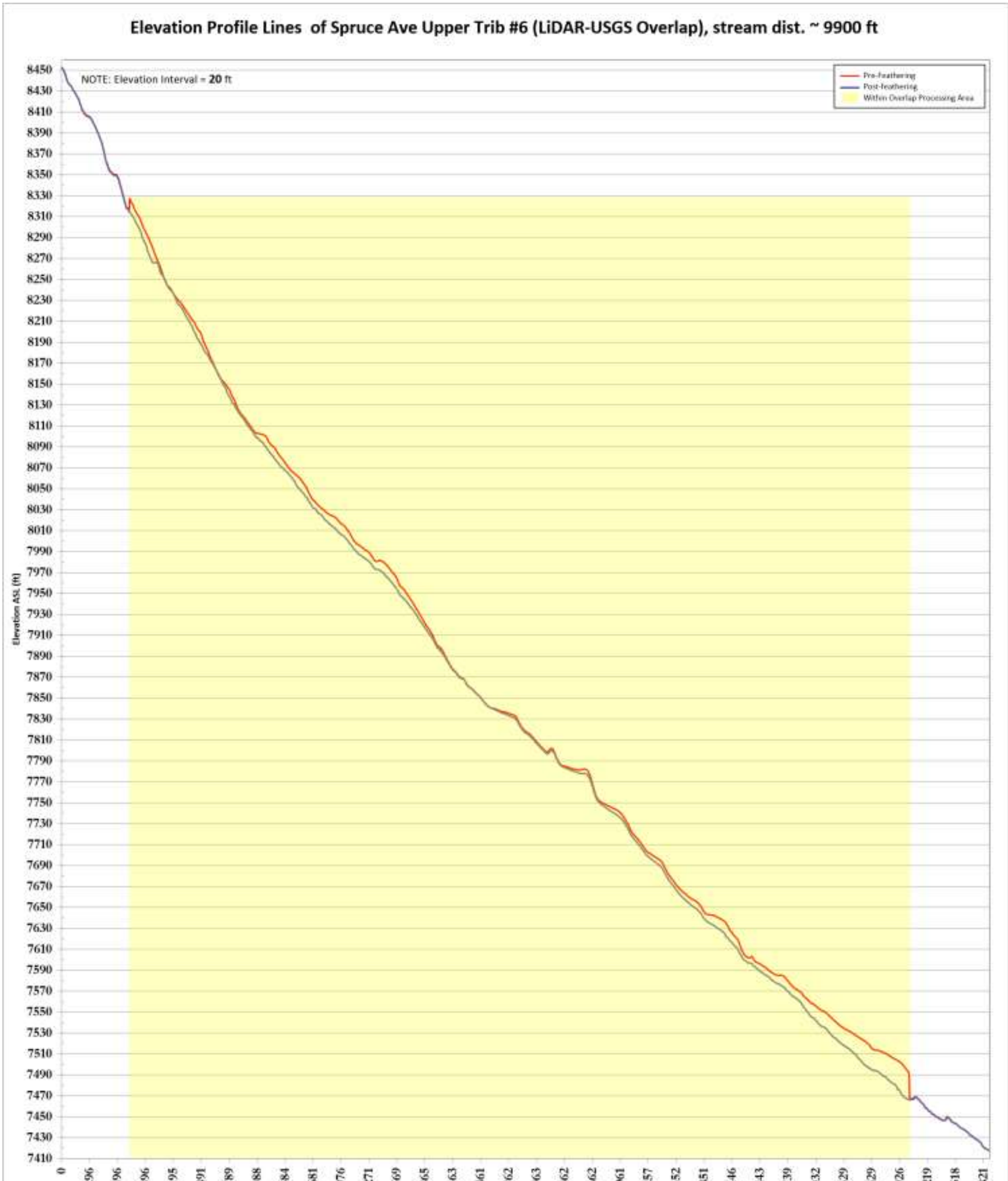


Stream Profile Results from Smoothed and Mosaicked DEM, continued

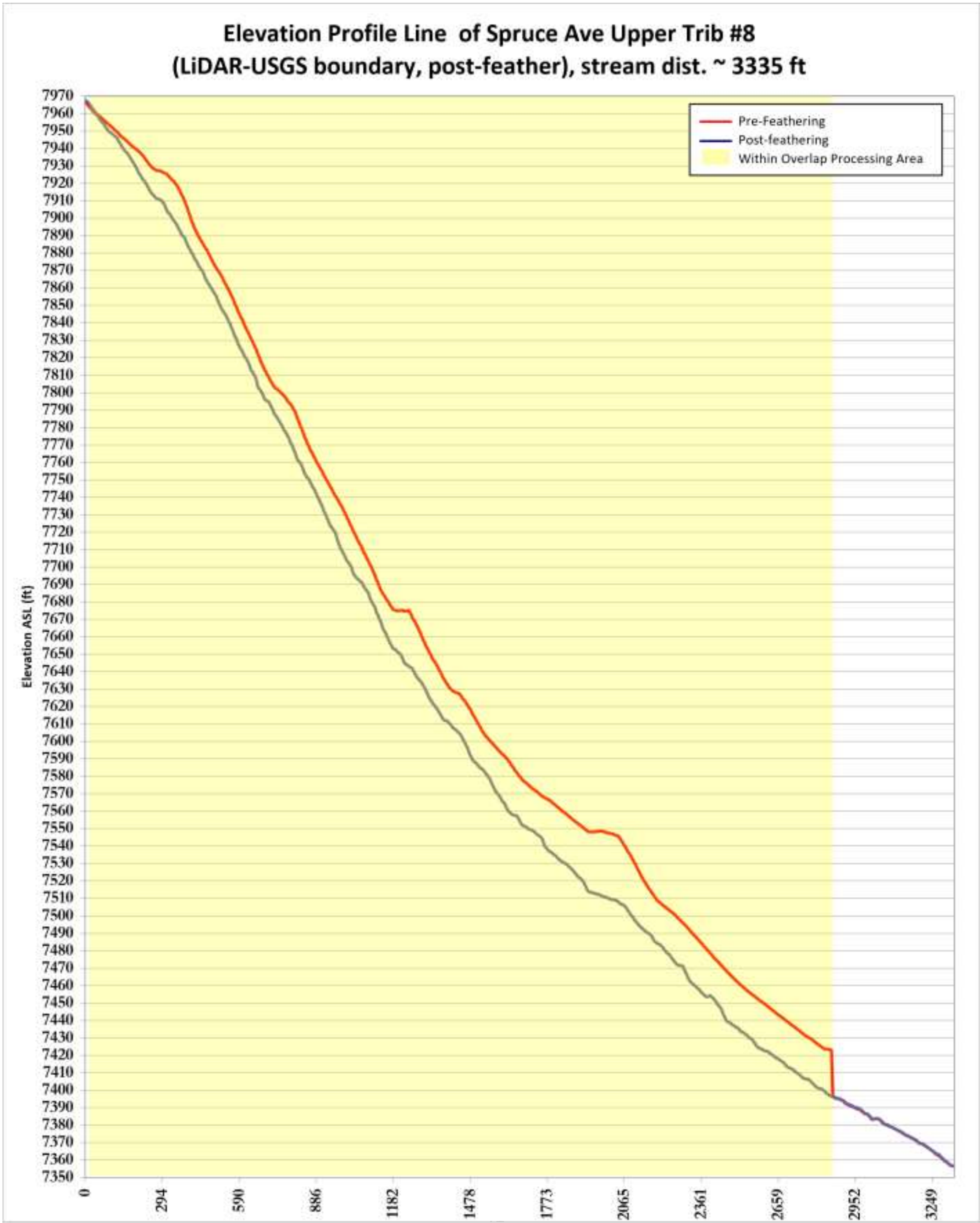


, continued

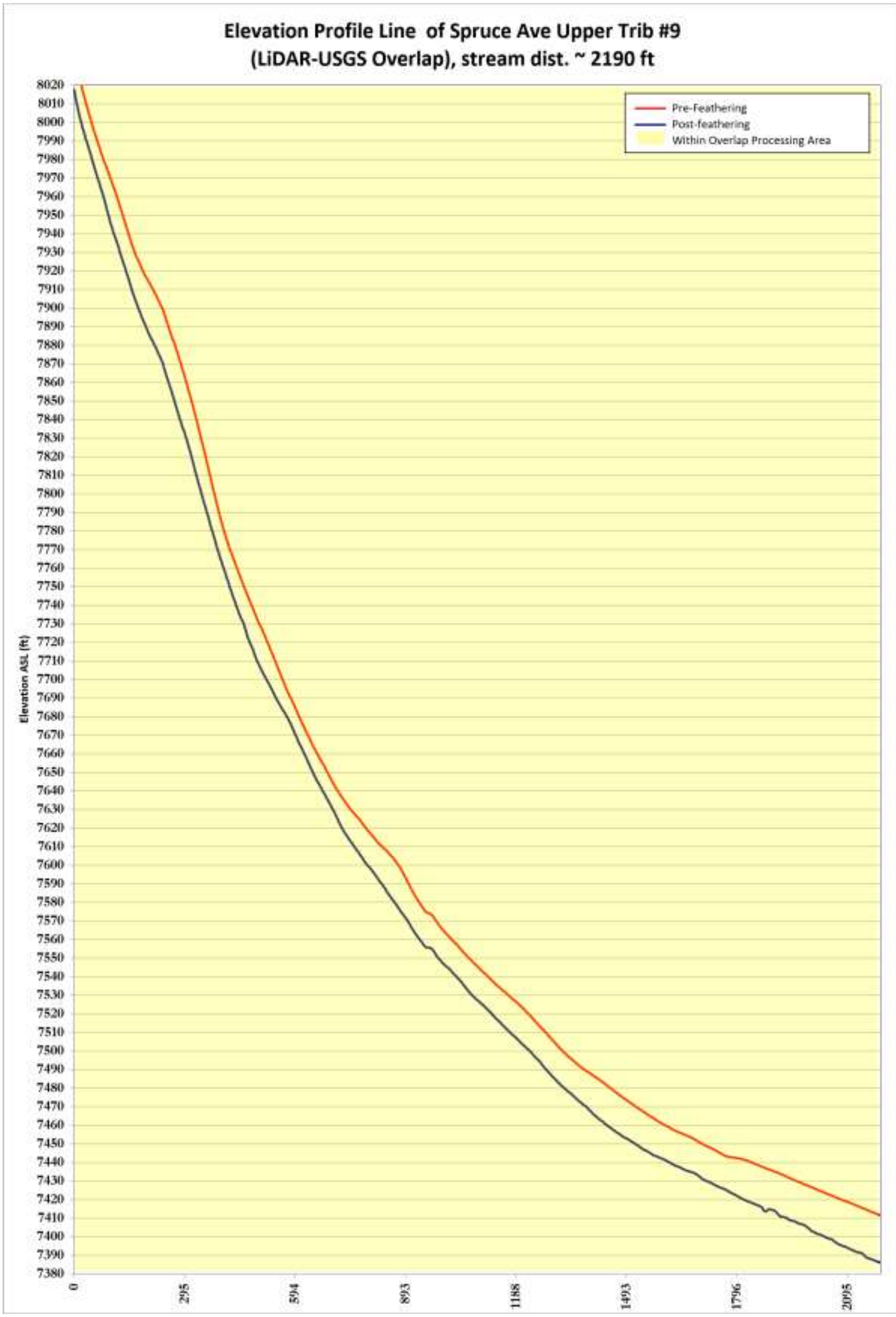
Stream Profile Results from Smoothed and Mosaicked DEM



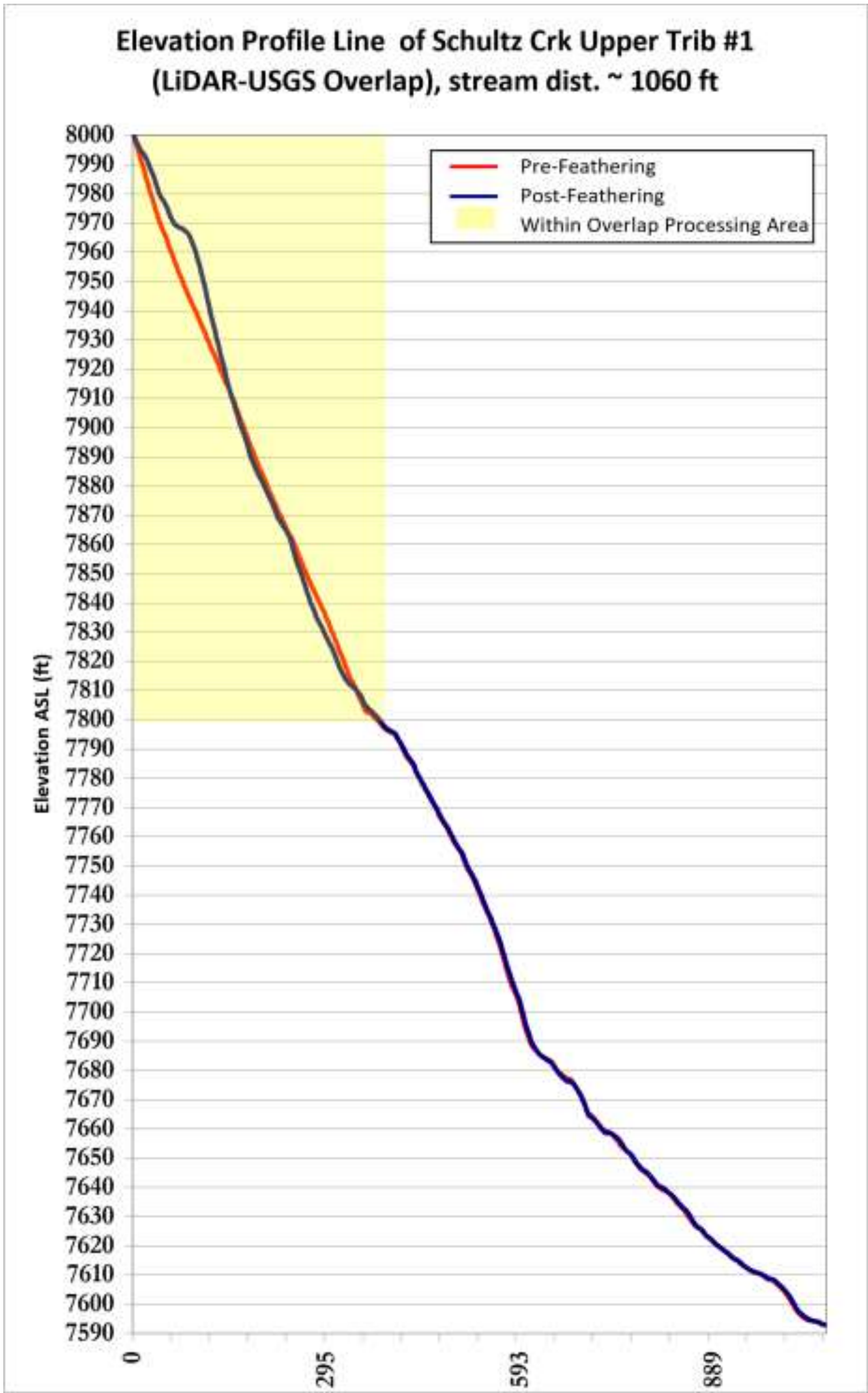
Stream Profile Results from Smoothed and Mosaicked DEM, continued



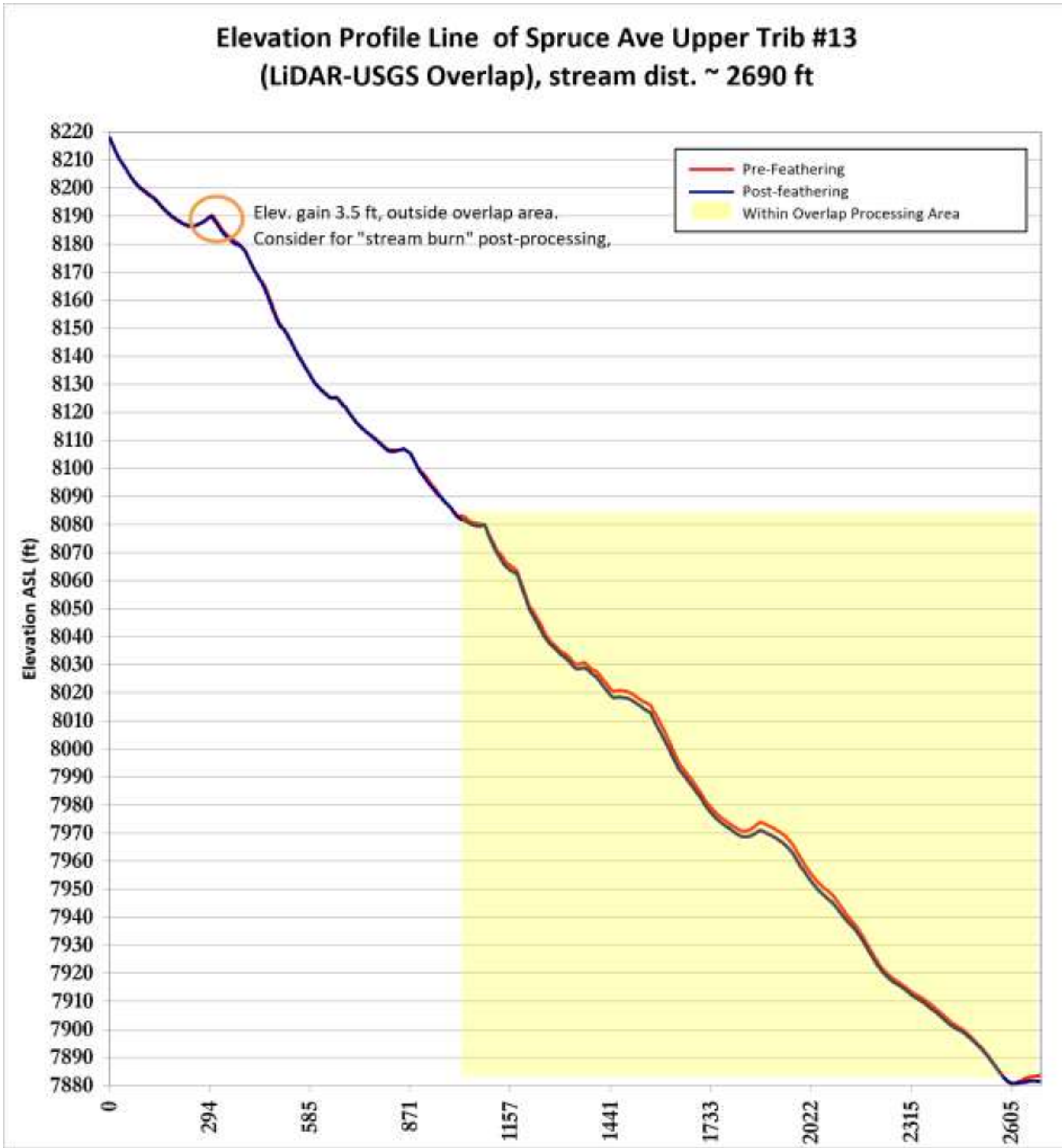
Stream Profile Results from Smoothed and Mosaicked DEM, continued



Stream Profile Results from Smoothed and Mosaicked DEM, continued



Stream Profile Results from Smoothed and Mosaicked DEM, continued



Stream Profile Geoprocessing Details

Source Files	Format	GP Step	Output File(s)	Format	Comments
Masks4DEMOverlapWork."Clip strms 2 profile" SW_Simplified_StreamReaches	Polygon Polyline	Clip "Stream Channels" Masks4DEMOverlapWork S:\Utilities\Stormwater\Bergman\DQWork\DEMDQ\NewSWDEM_Analysis.mdb\NAD83_SPCS_AZC_FIPS0202_ft\Streams_Clip_4_Profile # Start Time: Wed Dec 23 14:38:57 2015 Assembling Features... Reading Features... Cracking Features... Succeeded at Wed Dec 23 14:39:02 2015 (Elapsed Time: 4.45 seconds)	Streams_Clip_4_Profile	Polyline	
LiDAR_USGS_Feather_DEM_NoFill Streams_Clip_4_Profile	FGDRD Polyline	Executing: GetStackProfilesExportToExcel Streams_Clip_4_Profile LiDAR_USGS_Feather_DEM_NoFill S:\Utilities\Stormwater\Bergman\DQWork\DEMDQ\NewSWDEM_Analysis.mdb\New_DEM_Overlap_Stream_Profiles S:\Utilities\Stormwater\Bergman\DQWork\DEMDQ\New_DEM_Overlap_Stream_Profiles.xls Start Time: Wed Dec 23 16:33:57 2015 Executing (Stack Profile): StackProfile Succeeded at Wed Dec 23 16:33:59 2015 (Elapsed Time: 2.19 seconds) Executing (Table To Excel): Succeeded at Wed Dec 23 16:34:07 2015 (Elapsed Time: 5.01 seconds) Succeeded at Wed Dec 23 16:34:07 2015 (Elapsed Time: 10.12 seconds)	New_DEM_Overlap_Stream_Profiles.xls	Excel	**Small problem on Rio going thru lwr Ft Valley.** **Bigger problem on Schultz at upper end of feathering. Could these spots be fixed using "DEM Reconditioning/AGREE method" (Arc Hydro tool).** **All other elevation irregularites can be attributed to known features on landscape, i.e., not a processing artifcact.**