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Data Collection Tools for River Geomorphology Studies: LiDAR and Traditional Methods

by Christopher Haring

PURPOSE: The purpose of this review is to highlight LiDAR data usage for geomorphic studies and compare to other remote sensing technologies. This review further identifies survey efficiencies and issues that can be problematic in using LiDAR digital elevation models (DEMs) in completing surveys and geomorphic analysis. US Army Corps of Engineers (USACE) geospatial data collection guidance (EM 1110-1-1000) (USACE 2015) aligns with the American Society for Photogrammetry and Remote Sensing Positional Accuracy Standards for Digital Geospatial Data (ASPRS 2014). Geomorphic assessment technologies are rapidly evolving, and LiDAR data collection methods are at the forefront. The FluvialGeomorph (FG) toolbox, developed to support USACE watershed planning, is a recent example of the use of LiDAR high-resolution terrain data to provide a new, efficient approach for rapid watershed assessments (Haring et al. 2020; Haring and Biedenharn 2021). However, there are advantages and disadvantages in using LiDAR data compared to other remote sensing technologies and traditional topographic field survey methods.

BACKGROUND: In the 1960s and 1970s, the first LiDAR remote sensing instruments were developed for lunar research and satellite laser ranging for oceanography and atmospheric research. The first commercial airborne LiDAR was developed in the mid-1990s with the technology developing rapidly since.

LiDAR is an optical remote-sensing technique that uses laser light to densely sample the surface of Earth, producing highly accurate x, y, and z measurements. LiDAR is used primarily in airborne laser mapping applications (Figure 1) and has emerged as a cost-effective alternative to traditional Global Positioning System (GPS), Global Navigation Satellite System (GNSS)-based field surveys and other remote sensing techniques such as photogrammetry (Faux et al. 2009; Haring et al. 2019).

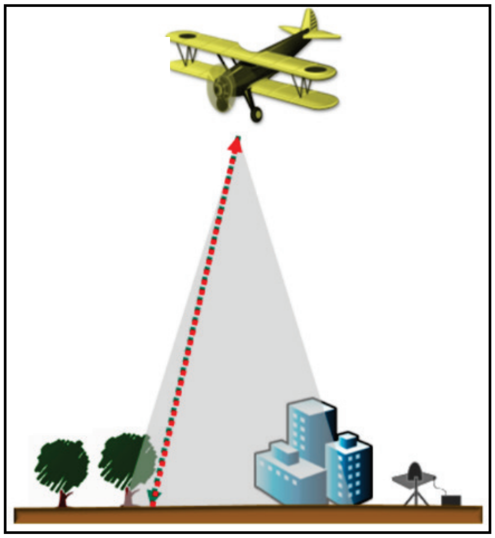

Figure 1. Active airborne LiDAR capture (from ESRI 2018).

LiDAR produces a mass point cloud dataset that can be managed, visualized, analyzed, and shared using GIS capabilities. The major hardware components include a collection device, GPS, laser scanner, and an Inertial Navigation System (INS) that measures the heading and movement of the collection device.

Active optical sensors transmit laser beams to a target (e.g., water surface, ground, vegetation, structures) while completing coverage routes for specific geographic surveys[1]. The reflection of the laser from a target is detected and analyzed by receivers that record the time from when the laser left the system to when it returned (Figure 2). By combining the returns with the GPS and INS systems, distance measurements can be transformed to three-dimensional (3D) points of the reflective target. The points are organized in a Triangulated-Irregular-Network (TIN) that is a vector data structure that partitions geographic space into contiguous, non-overlapping triangles (NOAA 2012). The TIN networks are constructed of a series of triangles with 3D vertices (x, y, z). TINs are the basis for storing and displaying surface models and provide the background structure for terrain models. TINs are commonly converted to a raster (a regular grid of pixels containing ground elevations) DEM for ease of display and performing calculations.

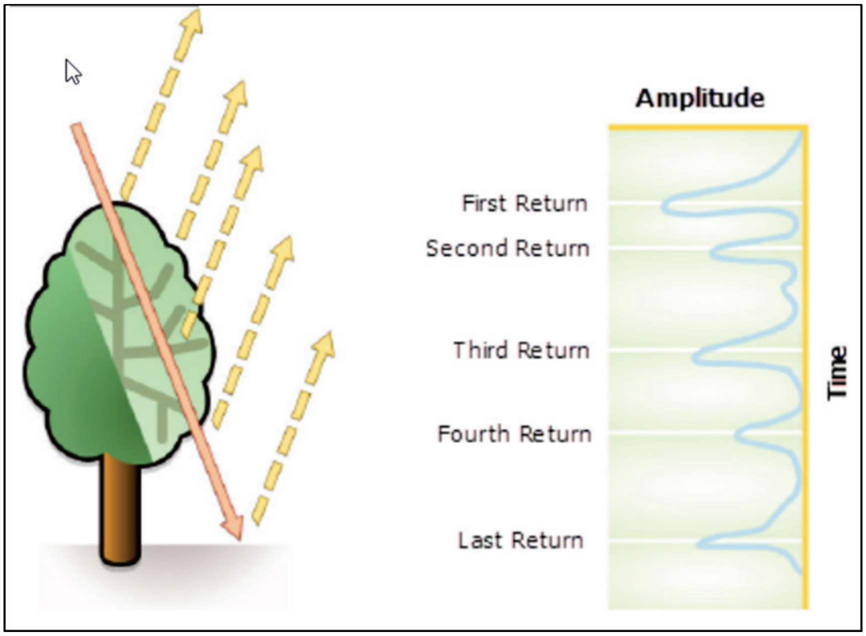

Figure 2. LiDAR attributes points (from ESRI 2018).

Some of the most important points of LiDAR laser return interpretation as outlined in ESRI (2018) are the following:

- laser pulses emitted from a LiDAR system reflect from vegetation, bare ground, buildings, bridges, and other features (i.e., targets)

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[1] Beaverson, S. K. 2017 (unpublished). *Elevation Data for Illinois – the LaSalle County Project*. PowerPoint presentation for Illinois Flood Zone Alliance Meeting. Illinois State Geological Survey.

- any emitted laser pulse that encounters multiple reflection surfaces as it travels toward the ground is split into as many returns as there are reflective surfaces (i.e., through forest leaves to ground) (Figure 2)
- the first returned laser pulse is the most significant return and will be associated with the highest feature in the landscape like a treetop or rooftop
- multiple returns are capable of detecting the elevations of several objects within the laser footprint of an outgoing laser pulse (i.e., the height of canopy trees and understory shrubs above forest floor)
- the intermediate returns are used for vegetation structure and the last return for bare-earth terrain models
- the last return will not always be from a ground return. For example, consider a case where a pulse hits a thick branch on its way to the ground and the pulse does not actually reach the ground. In this case, the last return is not from the ground but from the branch that reflected the entire laser pulse.

LiDAR can be collected from satellite, airborne, and terrestrial systems with most of the large-scale LiDAR data collections derived from airborne systems. Airborne LiDAR is being used to develop high-resolution topographic and vegetation models. LiDAR uses near-infrared pulses that reflect off multiple surfaces, which can be used determine the nature of the return impulse to distinguish surface types. Post-processing techniques include filtering the point cloud to determine which returns are needed to identify desired characteristics such as Earth’s surface or vegetation layers. Most filtering methods combine automated algorithms with manual correction.

LiDAR terrain data support a variety of applications for capturing fluvial geomorphic channel and floodplain characteristics not only at specific site locations but also for large spatial areas. The two common methods are near-infrared and green-wavelength LiDAR. Near-infrared LiDAR cannot penetrate water and is therefore used to map topography above the wetted channel. Green-wavelength devices can penetrate water to determine water depth and provide seamless maps of both the aquatic and terrestrial environments (Wright et al. 2006; Kinzel et al. 2007; McKean et al. 2008). Although green-wavelength LiDAR can map many of the physical channel characteristics used in aquatic monitoring in a continuous and spatially extensive manner, near-infrared LiDAR is capable of significantly higher pulse rates and can map terrestrial environments at higher topographic resolutions (Faux et al. 2009). Despite the potential for small-footprint green-wavelength LiDAR (Wright et al. 2006) to significantly change how underwater bathymetric surveying is conducted, its commercial availability is limited, and the widespread application of this technology is still not fully developed.

Near-infrared LiDAR data and derived products for topographic and vegetation modeling are becoming increasingly available to resource managers (Faux et al. 2009). For example, in 2017, Illinois had LiDAR data available for 90 of 102 counties[1]. In 4 yr[2], the additional 12 counties

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[1] Beaverson, S. K. 2017 (unpublished). *Elevation Data for Illinois – the LaSalle County Project*. PowerPoint presentation for Illinois Flood Zone Alliance Meeting. Illinois State Geological Survey.

[2] For a full list of the spelled-out forms of the units of measure used in this document, please refer to US Government Publishing Office Style Manual, 31st ed. (Washington, DC: US Government Publishing Office 2016), 248-52, *https://www.govinfo.gov/content/pkg/GPO-STYLEMANUAL-2016/pdf/GPO-STYLEMANUAL-2016.pdf*.

either have complete LiDAR data or they are in the final steps of processing data, and there are plans to start collecting and replacing old LiDAR data in additional counties with the oldest existing data (Beaverson 2020).

LiDAR PLATFORMS: Common LiDAR data collection platforms include fixed-wing, helicopter, Unmanned Aerial Vehicles (UAV), and ground-based applications. Airborne topographic LiDAR are the most used systems for collecting elevation data and generating DEMs for large areas (NOAA 2012). The fixed-wing approach is the most effective and efficient method for collecting terrain data over thousands of square miles (NOAA 2012). The helicopter is more mobile and can be used for smaller study extents where greater resolution is required. The UAV and ground-based approaches provide smaller study area support while providing greater elevation resolution. Tripod-based stationary units can be used to collect detailed terrain data on sections of levee systems, grade-control structures, bridges, and other fixed studies. The systems can also be mounted on All-Terrain Vehicles and boats to collect data for a variety of study types. The tripod-based LiDAR systems produce point data with centimeter accuracy and are often used for local terrain-mapping application that require frequent surveys (NOAA 2012).

Emerging technologies are allowing for LiDAR to be collected via UAV, which provides even more flexibility for field survey. Recently, the US Army Engineer Research and Development Center (ERDC), Environmental Laboratory, in partnership with the Coastal and Hydraulics Laboratory (CHL) geomorphic research unit completed evaluation studies for Phoenix Mini-Ranger (Riegl LiDAR integrated by Phoenix LiDAR) survey-grade LiDAR, which flies with a 42-megapixel Sony camera to create colorized point clouds at a 0.4–0.8 in. (1–2 cm) vertical accuracy (Figure 3). The UAV collected terrain data for geomorphic channel studies on the Bayou Pierre, Clear Creek, and Big Black tributary in southwest Mississippi locations.

Figure 3. The ERDC Environmental Laboratory Phoenix Mini-Ranger UAV platform.

GEOMORPHIC ANLAYSIS USING LiDAR: LiDAR terrain mapping applications include glacier monitoring, forest inventory, shoreline and beach volume change mapping, subsidence studies, derivation of DEMs, and others. Several studies show the potential for using LiDAR to map common physical stream channel parameters. The ERDC in partnership with USACE Rock Island District through the Environmental Management and Restoration Research Program (EMRRP) have developed a rapid geomorphic assessment and analysis FG toolbox to identify channel instability to target watershed stabilization and restoration efforts (Haring et al. 2020). As a precursor to the FG toolbox, the LiDAR-Hydraulic Geometry Relationship (HGR) approach was developed using LiDAR to assess and measure bankfull channel conditions and develop regional hydraulic geometry curves for Southern Driftless Area gage reaches (Haring et al. 2019).

In Oregon, Jones (2006) used LiDAR-derived DEMs to map side channels and to identify potential sites for restoration of salmon habitat. In Oregon, Faux et al. (2009) investigated channel cross-section characteristics and monitoring of aquatic habitat. James et al. (2007) documented the potential for using LiDAR to map headwater streams under a forest canopy in an Eastern United States National Park. Cavalli et al. (2008) used LiDAR to detect the spatial extent of different stream types in an alpine setting. In California, Dietterick et al. (2012) compared LiDAR-generated cross-sectional profiles in forested mountain streams and documented improvements in LiDAR technology over time. In Italy, Caroti et al. (2013) compared channel cross-section resolution in heavily vegetated and high sloping small stream systems. Hamshaw et al. (2017) analyzed streambank movement by comparing photogrammetry to terrestrial LiDAR methods. Automated bankfull detection methods based on LiDAR were developed in a study by De Rosa et al. (2019) for Italian rivers comparing remotely sensed bankfull limits to those obtained from field surveys.

COMPARISON OF DATA COLLECTION METHODS: Because of the expansion of LiDAR technologies, there is a direct competition with standard traditional field survey (GPS) and photogrammetric methods. This section provides direct comparisons of LiDAR versus GPS-traditional survey, and photogrammetric methods.

Airborne LiDAR Versus Topographic Field Survey (GPS). LiDAR surveys are becoming more common with the expansion of collection capacities of airborne (fixed-wing), UAV, and land-based technologies. LiDAR technology continues to increase collection capabilities (i.e., accuracy, density) providing greater resolution for terrain development and interpretation. Cost, time, and type of study are also factoring in what survey methods are chosen for a study.

In *The Mapping Match: LiDAR versus Traditional Topo*, Mayfield (2015) compares airborne (fixed wing) LiDAR versus conventional high-resolution GPS topographic survey data for a dike system survey. The study compared 25 mi (40.2 km) of topographic surveys on a dike system in the southeastern United States. The dike surveys were completed in open terrain, so both LiDAR and topographic surveys were relatively unrestricted in data collection. The topographic surveys were collected at 100 ft (30.5 m) intervals with a maximum of 12.5 ft. (3.8 m) spacing between the cross-sectional points. The LiDAR data were collected on 153 mi (246 km) of dikes flown at a height of 3,168 ft (966 m) with a point density of 17.6 points per square meter. The topographic survey cross-section points provide less coverage than the LiDAR point cloud (Figure 4) (Mayfield 2015). Despite the limited spatial coverage, the overall output of vertical accuracy between the two methods was very close. The topographic surveys had a vertical root mean square error (RMSE) of 0.059 ft. (1.8 cm), and the airborne LiDAR had an RMSE of 0.057 ft (1.7 cm). This example provides valuable insight into the quality of the LiDAR data compared to topographic survey methods. Both methods have good vertical resolution, but the LiDAR offers significantly greater data density and spatial coverage.

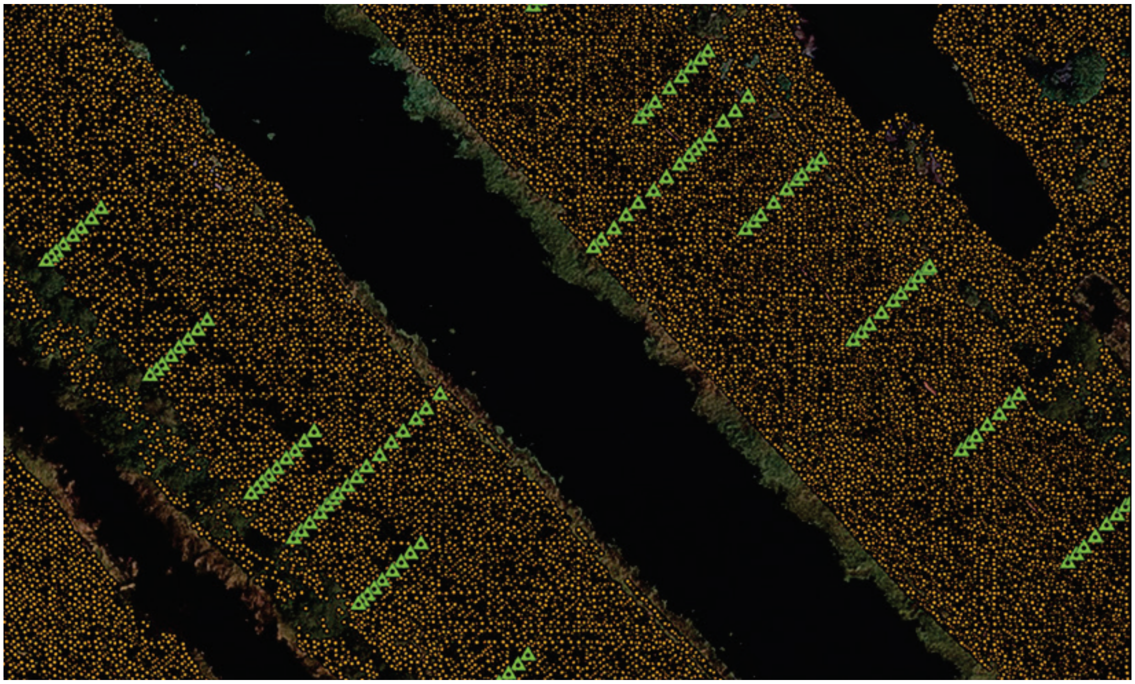

Figure 4. Dike study survey illustrating high-resolution GPS (green) and high-resolution LiDAR (brown) survey points (from Mayfield 2015).

Time and cost comparisons of the topographic surveys to LiDAR survey yields interesting insight. Mayfield (2015) compared the time spent for surveying 25 mi (40.2 km) of dike with conventional topographic (GPS) surveys to airborne LiDAR surveys for 153 mi (246 km) of the same dike system. Mayfield (2015) found that 1,921 hr were spent collecting 26,241 measurements or 13.75 measurements per hour for the topographic survey. In contrast, 373 hr were spent on collecting and producing a much larger area of interest that yielded 2.9 billion measurements or a little more than 7.7 million measurements per hour (Mayfield 2015). Based on survey type comparisons, the dike study provides interesting results when considering how much more data at similar resolution can be produced by using LiDAR data collection.

It is very costly to complete topographic surveys due to significant time, travel, and additional expenses for personnel, trucks, ATVs, fuel, instrumentation, and other equipment. The cost to complete and provide the 25 mi (40.2 km) of dike survey was approximately $106,000 with a cost-per-line mile of $4,225 (Mayfield 2015). The total cost to complete the 153 mi (246 km) of dike survey using airborne LiDAR was $75,500 with a cost-per-line mile of $493 (Mayfield 2015). Based on this comparison of data collection methods, LiDAR is a highly efficient survey tool that significantly expanded the coverage and quality of topographic data; however, it does not replace all field survey requirements.

Airborne LiDAR Versus Photogrammetry Survey Collection Methods. Digital photogrammetry uses computer analysis to obtain measurements of objects in a photograph (Goodman 2021). The method uses multiple photos of the object or study terrain to interpret and determine spatial relationships. The point cloud data can be used to produce 2D and 3D models and topographic maps. Photogrammetry provides point cloud data that show the surface of objects such as vegetation, roads, buildings, structures, and others (King 2017). Tully (2017) reports that photogrammetry is "significantly cheaper than LiDAR in many cases, especially when both photography and elevations are needed, it remains useful and important in many applications and that's why we're seeing drones and even manned aircraft often fly borrow pits and coal piles to calculate volume and things like that using only aerial photography and photogrammetric-derived elevations. Because there is little or no vegetation obscuring the ground, the 3D point clouds derived from the photography are accurate enough for those purposes."

LiDAR uses an active sensor technology that can "push through vegetation" and reflect off the ground providing a distinct advantage of providing both surfaces (King 2017). Tully (2017) goes on to indicate that as LiDAR sensors and mapping become less costly as he indicates "the day of building 3D models of things under the sensor can't be produced as efficiently using photos only because the LiDAR sensors will be powerful and cheap enough to make the photos-only method of remote sensing unnecessary." Photogrammetry appears to have good applications to field study sites that are open with little or no vegetation where LiDAR can be used to collect data under existing areas that have vegetation. If LiDAR data are collected for fluvial geomorphic studies with leaf-off, low-water, and no snow or ice present on the stream, then the LiDAR has very little interference in collecting elevation data from multiple targets of vegetation, ground, water, and other landscape features.

AIRBORNE LiDAR ADVANTAGES: Mayfield (2015) states that some traditional surveys are required to support LiDAR accuracy, but overall, the LiDAR surveys produce similarly accurate measurements that have advantages over traditional surveys. LiDAR data quality greatly increased over the past 20 yr with increased intensity (signal return strength), laser technology in the number of pulses and returns, and point cloud densities (Contreras et al. 2017). The resolution increase in the LiDAR data was described by Dietterick et al. (2012) as averaging 9.8 ft (3.0 m) in 2002; 3.3 ft (1.0 m) in 2008; and 1.6 ft (0.49 m) in 2010. LiDAR sensors 20 to 30 yr ago were capable of 2,000 to 25,000 pulses per second but are now capable of over 1 million pulses per second with up to 0.02 ft. (5 mm) resolution (Gaurav 2017).

Depending on the terrain resolution needed for a study, LiDAR is likely a lower-cost option to gather data, and data collection may be easier in restricted and difficult surveying areas. Survey locations may be difficult to navigate based on large elevation differences, thick vegetation or understory, and lack of access to site. In addition, less public relations coordination is required for airborne (fixed wing) LiDAR data acquisition since the data are collected remotely and landowner access permissions are not required. An important access limitation of high-resolution GPS surveys is lack of satellite reception, especially in conditions associated with heavy vegetation, steep valley walls, and mountainous terrain where signals may be lacking or non-existent. In contrast, airborne LiDAR data can be collected even when satellite reception is inconstant or interrupted.

AIRBORNE LiDAR DISADVANTAGES: Potential disadvantages of using existing LiDAR is the variability and lack of resolution of older data as mentioned in the advantages section. When considering using existing LiDAR for studies, great care needs to be considered in determining limitations of each dataset. However, in some instances, there are opportunities to reassess LiDAR derived DEMs and enhance final resolution by reprocessing original LASer (LAS, a standard file format for storing point cloud data) files to a greater resolution as discussed in the LiDAR Demonstration and Evaluation Section of this technical note.

Additional disadvantages to LiDAR collects are the restrictive nature of appropriate flying time associated with seasons. Coordinating flight schedules and approval and dealing with weather conditions that can change the collection times available for proper collection are additional issues. Cloudy skies or foggy conditions can limit LiDAR collection dates as the LiDAR cannot penetrate clouds to collect ground data. In addition, heavy vegetation with leaf-on conditions can prohibit data collection. When collecting stream geomorphic data, low water level conditions are necessary to collect the maximum in-channel topographic data and minimize channel geometry loss below water. While this collection method works well for small- and intermediate-sized streams, medium to large river systems have limited value due to larger proportions of depth loss. The inability of LiDAR to penetrate deep or murky water to collect underwater channel dimensions in larger rivers is the main limitation. However, green-wavelength LiDAR (Wright et al. 2006) continues to technically advance and may soon be able to fill this void.

LiDAR ground elevation measurement errors generally increase with vegetation cover, amount of understory, and variability in terrain slopes (Contreras et al. 2017). However, this can also affect ground survey using high-resolution GPS as satellite, base-station sighting, and lines of sight can be problematic for ground survey crews as well.

DATA ANALYSIS USING EXISTING AIRBORNE LiDAR: Multiple issues with off-the-shelf LiDAR-derived DEMs were discovered as part of the LiDAR-HGR study (Haring et al. 2019). The issues included hydro-modification, low resolution, considerations for stream conditions during LiDAR collection, and data dropout zones. Data for the study were developed from 28 stream gages in the Southern Driftless Area of the Midwest (Haring et al. 2019). For this analysis, the Sinsinawa River site was selected to illustrate issues encountered in using existing LiDAR DEMs. Existing off-the-shelf LiDAR DEMs available from Illinois, Wisconsin, and Iowa were used for developing geomorphic data at each stream gage site.

Hydro-Modification (Water Surface Slope Resolution). Lack of elevation or slope change along the stream profile compared to the terrestrial terrain data was the first issue identified. Field surveys determined that there was much more channel slope than that being displayed from the existing LiDAR DEM as illustrated in Figure 5. The LiDAR-HGR approach was developed to assess geomorphic channel analysis. Therefore, riffle cross-over locations are very important to provide the least amount of depth loss (error) when interpreting LiDAR channel data. Riffle cross-over locations are key to assessing channel morphology that the LiDAR-HGR approach focuses on interpreting for developing LiDAR-based hydraulic geometry regional curves.

LiDAR applications in the fluvial environment are typically restricted to floodplain mapping and connecting topographic channel surveys to overbank LiDAR coverage. The original processing of the Sinsinawa River LiDAR data was completed for interpretation of terrestrial elevation, vegetation, and non-fluvial mapping environments. Depicting water surface elevation change or slope was not a priority. A point cloud processing method termed *hydro-modification* or *hydro-flattening* was applied to the existing LiDAR-derived DEMs produced for the general public by state agencies to remove the gradual elevation changes of the water surface slope to create a stream surface on an even plain for aesthetically pleasing cartographic display purposes. Therefore, hydro-flattening needed to be removed to obtain existing water surface slope elevation data to plot and compare for bankfull channel indicators and water surface profiles. This was accomplished by collecting original LAS files and reprocessing the water surface TIN (vector) to construct a new DEM (raster) for the channel.

Figure 5. The Sinsinawa River near Menominee, IL, illustrating channel slope change at the cobble riffle location looking downstream.

LiDAR Resolution. Previous DEMs for the Sinsinawa River site were developed to 3 ft (1 m) resolution, and new DEMs were reprocessed from the original LAS files to 1.0 ft (0.27 m) resolution. It is not known why the original point cloud data and off-the-shelf DEMs were processed to produce 3.28 ft (1 m) resolution. The original DEMs resolution was likely chosen to limit storage space or based on common research initiative's standardized data resolution. The Sinsinawa River plan-view illustrates cross sections five and six and the original point cloud (brown dots) data in the off-the-shelf original resolution DEM maps of 3.28 ft (1 m) (Figure 6 and 7. The cross sections are not perfectly straight as these represent the actual points taken during the field survey.)

For FG toolbox analysis, a Banks Polygon (BP) (USFS-RBT 2010) tool is used to focus analyses on channel data ignoring outside overbank elevation points. The BP provides a visual estimate of the bankfull extent within the stream channel and can be compared to top-of-bank floodplain indicators for validation of bankfull discharge. The 3.28 ft (1 m) resolution DEM (Figure 6) shows very little channel resolution as the surface within the BP shows shades of light blue and green elevations in the center of the channel progressively getting a darker green toward the margins. The figure depicts very little elevation change with a relatively flat surface. Local channel slope was further enhanced by using the Environmental Systems Research Institute grid-based slope algorithm (ESRI 2018) to provide better insight on terrain changes in Figure 7.

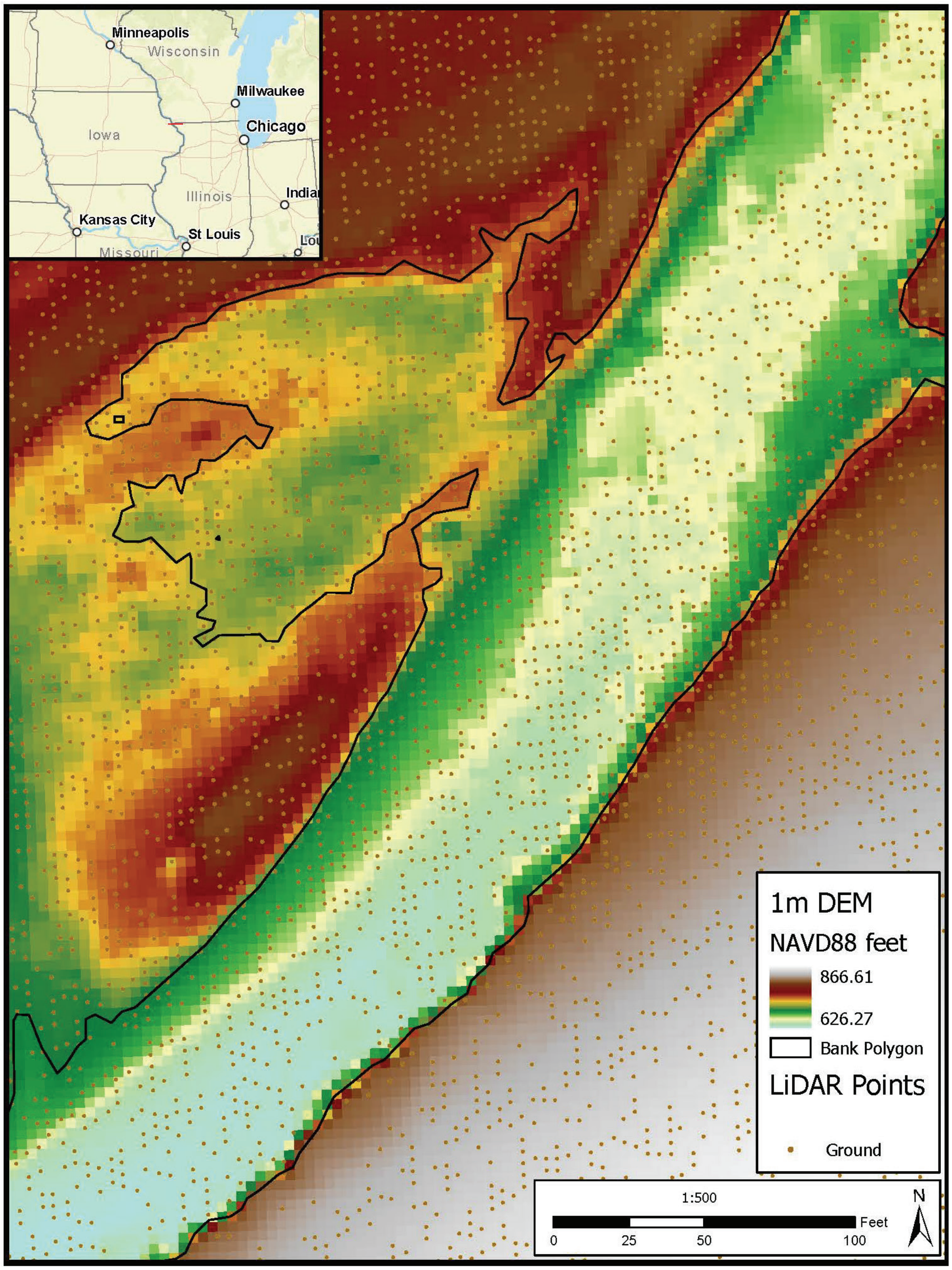

Figure 6. The reprocessed Sinsinawa River DEM with 3.28 ft (1 m) resolution.

The slope algorithm (ESRI 2018) DEM (Figure 7) illustrates blue regions as low slope areas (flat) transitioning to tan-light red to red areas depicting steeper slope areas primarily associated with the channel margins. The slope DEM provides a better identification of flat pool areas within the pool-riffle complex.

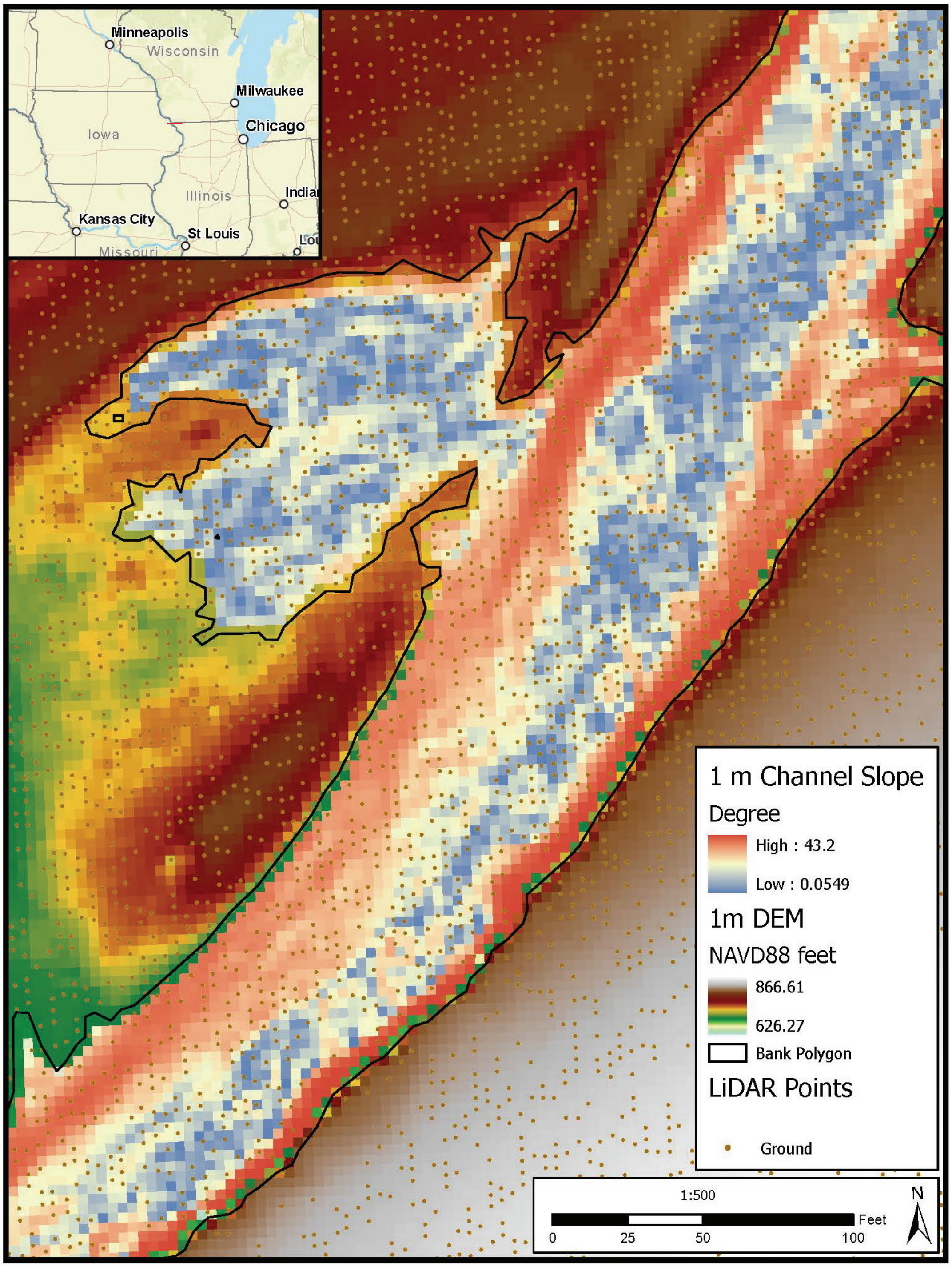

Figure 7. The Sinsinawa River slope algorithm enhanced DEM with 3.28 ft (1 m) resolution.

Since there was good coverage of LiDAR data points within the channel, the 3.28 ft (1 m) DEM was reprocessed to a higher raster resolution of 1 ft (0.27 m). To develop greater resolution, the original point cloud data were reprocessed (Figure 8) (Haring et al. 2019).

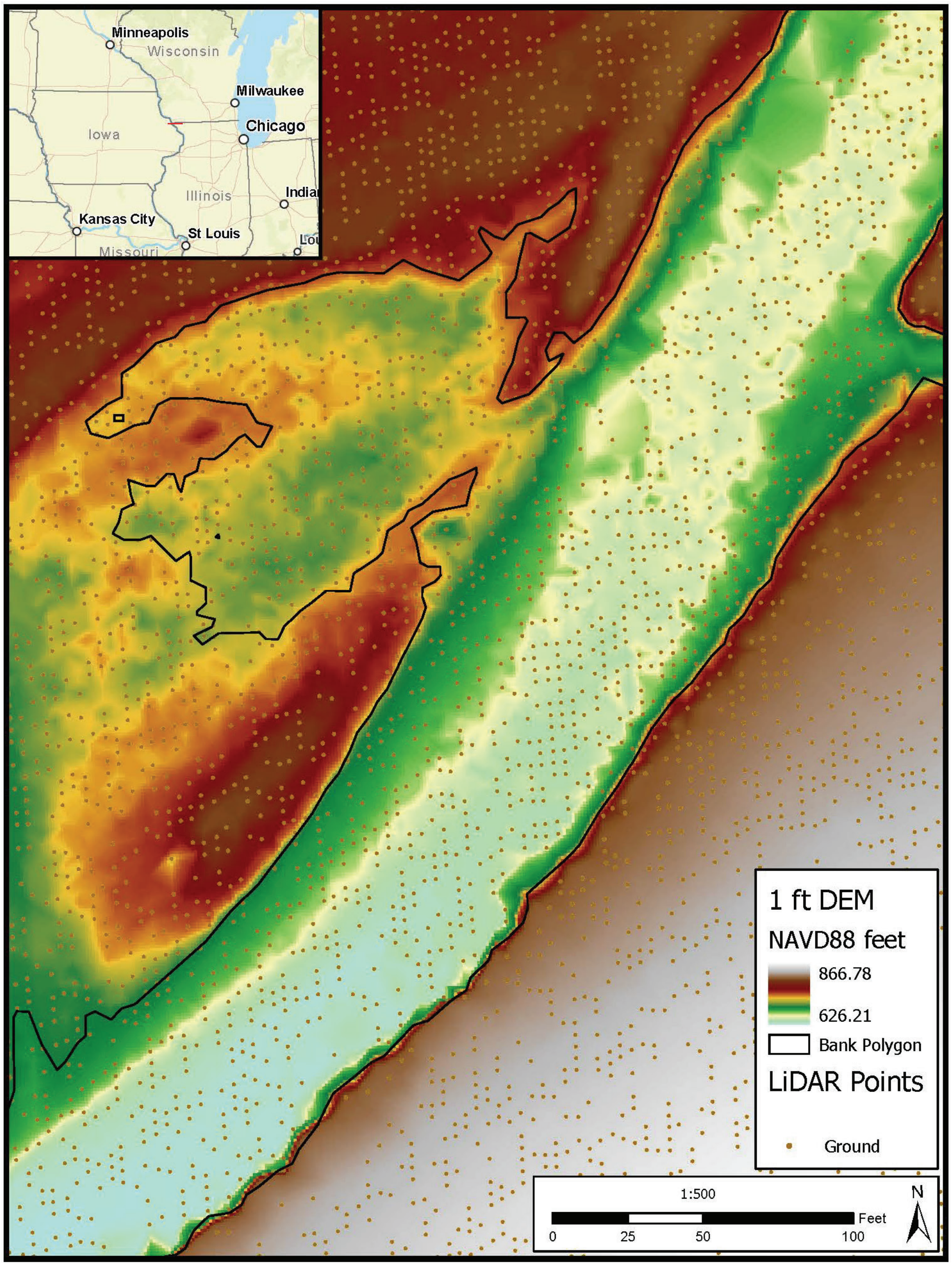

Figure 8. The reprocessed Sinsinawa River reach DEM with 1 ft (0.27 m) resolution.

To provide more detailed channel feature delineation, additional analysis was completed using the new 1 ft (0.27 m) resolution (Figure 9). The surface can then be used to compare slope changes throughout the reach and bankfull indicators developed at cross-section locations. The increased resolution allows for the determination of bed forms like the riffle-run and pool sequences that are illustrated. The pool areas are depicted with green squares; riffle-run areas as yellow ovals; point bar as purple squares; and connected overbank floodplain areas as orange oval. Mapping these morphological channel characteristics and habitats within the channel and adjacent floodplain margins provides valuable information for habitat assessments and focused near-channel floodplain-connected restoration areas.

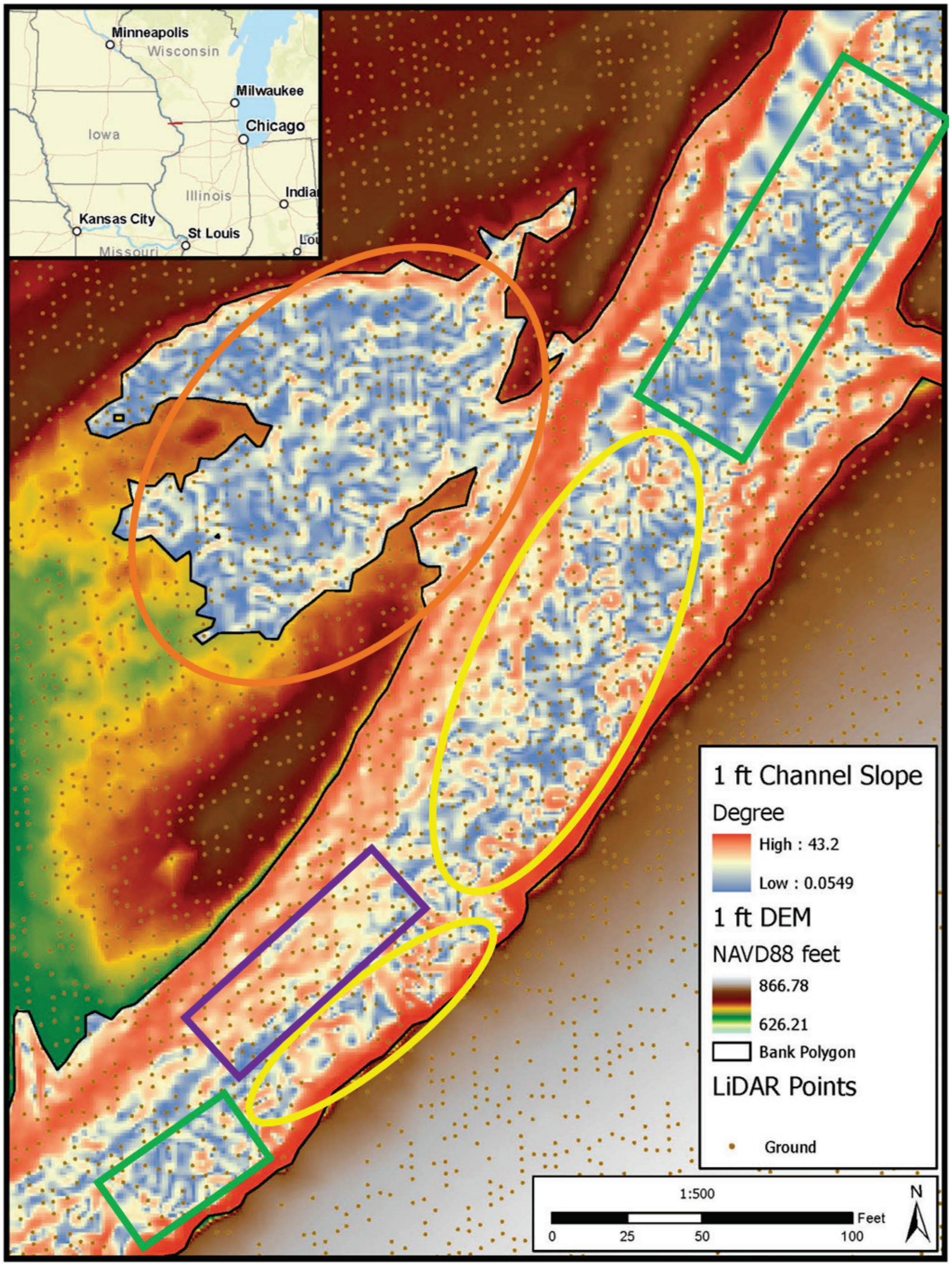

Figure 9. The reprocessed Sinsinawa River enhanced DEM with slope algorithm 1 ft (0.27 m) resolution; green squares are pool; yellow ovals are riffle-run; purple is point bar; and orange oval is connected overbank floodplain area.

Channel Conditions and Data Dropout Zones (DPZ). The timing and physical stream channel conditions when LiDAR data are collected can greatly impact the accuracy and usefulness for geomorphic analysis. For example, high water, ice, or snow can have substantial impact on LiDAR collection accuracy. High water conditions result in deeper channel conditions, so loss of depth can be an issue. Ice and snow can cause reflection and data collection issues, decreasing terrain resolution. During summer growing seasons, vegetation can affect the vertical data point collection extent and accuracy. Thick, heavy vegetation cover or understory generally increase LiDAR ground elevation errors (Contreras et al. 2017). For example, in the LiDAR-HGR study (Haring et al. 2019), LiDAR data were collected over several years and at different times during the year. Seven Illinois sites, nine Iowa sites, and twelve Wisconsin sites were collected between May 2007 through December 2011. After reviewing aerial photos and hydrologic data from each gage site in Illinois and Wisconsin, all sites were determined to be ice and snow free with no discernable vegetation. However, some of the Iowa sites were collected in May and June of 2007 and had well-established vegetation during LiDAR data collects. The gage sites were located on the North Fork of the Little Maquoketa River in Iowa.

LiDAR acquisition for the North Fork of the Little Maquoketa River occurred during the months of May and June with full vegetation conditions limiting data coverage in some locations. DPZ were encountered where hanging or thick vegetation, or possibly the angle of the bluff line blocked LiDAR data acquisition sensor pulses and returns from gathering underlying ground and water surface data points (Figure 10). When the DPZs occurred, cross sections were adjusted upstream or downstream where greater confidence in the LiDAR point cloud data and associated DEM coverage were available. If there are excessive amounts of data dropout areas, then a field survey may be required to gather the required data for those locations.

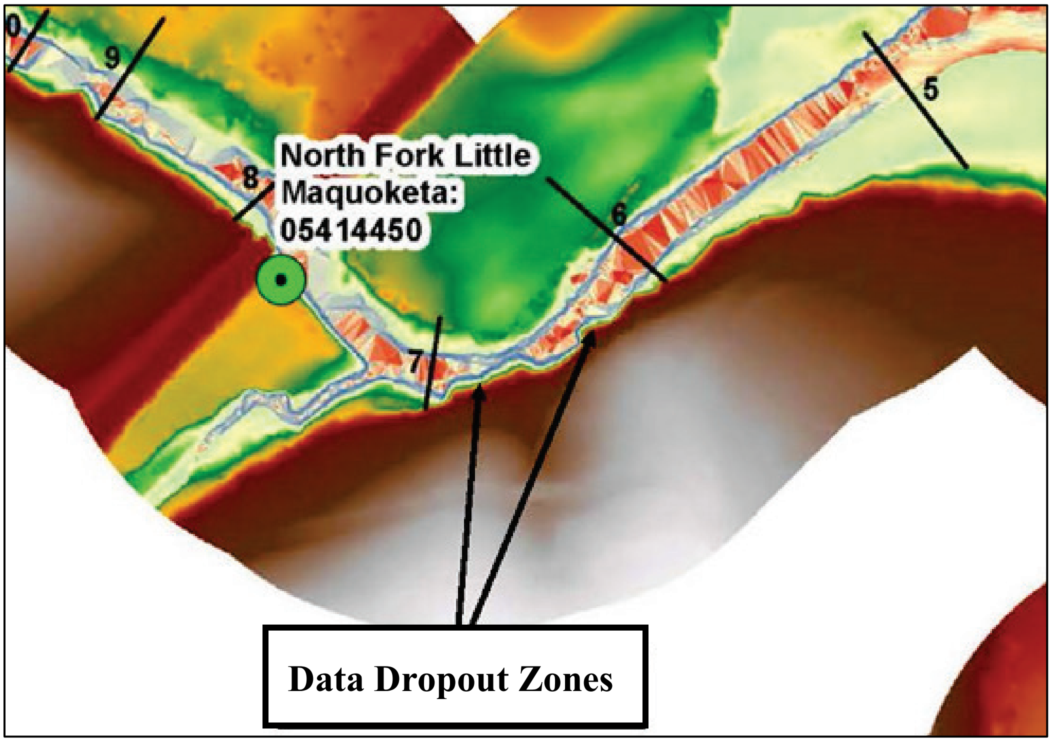

Figure 10. Example of a LiDAR DPZ on the North Fork Little Maquoketa River.

CONCLUSION: LiDAR high-resolution terrain data are being used extensively in geomorphic studies as technology continues to improve and geomorphologists discover new applications. In recent studies in Italy (Caroti et al. 2013: De Rosa et al. 2019) and the United States (Haring et al. 2019; Haring et al. 2020; Haring and Biedenharn 2021), geomorphic assessment methods and tools (FG) were developed to study morphological channel signals within the active river channels and floodplains. As a precursor to FG, the LiDAR-HGR (Haring et al. 2019) approach was successfully developed to derive region hydraulic geometry relationships exclusively using LiDAR high-resolution terrain data. LiDAR data usage provides important lessons learned on the use of hydro-modifications, data resolution enhancement capabilities, criteria for the best riverine geomorphic assessments, and identification of data dropout areas. Moreover, there are time and costs saving advantages for LiDAR surveying applications as they will continue to be improved as the technological advances increase (Mayfield 2015; Contreras et al. 2017). Further applications of LiDAR in geomorphic studies are currently being developed using the FG toolbox (Haring et al. 2020). As LiDAR resolution and usage increases and is coupled with cost decreases, more detailed temporal and spatial geomorphic watershed studies will be possible. Additional LiDAR applications and research are imperative to further the science of geomorphic studies and interpreting high-resolution terrain data.

Additional Information: This Coastal and Hydraulics Engineering Technical Note (CHETN) was prepared by Christopher Haring (*Christopher.P.Haring@usace.army.mil*) of ERDC, CHL, River Engineering Branch. At the time of publication of this CHETN, David May was Chief of the River Engineering Branch. This CHETN should be cited as follows:

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