Creating Digital Elevation Models from Combined Conventional and LiDAR Topographic Surveys

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April 2018

INTRODUCTION

Detailed topographic information is often required for describing and understanding river processes. Engineers map channels and floodplain elevations to help determine flood hazard to buildings and infrastructure. River scientists and managers map channel and floodplain topography to inform restoration and management. Floodplain and channel topography can be used to build hydraulic models to estimate river stage and other important hydraulic properties.

Two commonly applied survey technologies are total stations (i.e. conventional) and survey grade global positioning systems (real time kinematic GPS, also known as RTK). A total station survey requires line of sight between the station and the target and is a high precision method of measuring topography. Survey grade GPS requires satellite coverage for the base station and the receiver. This method maps topography that is both real-world accurate and precise to within a few centimeters or less, which is usually adequate for stream and floodplain applications. Both total station and RTK methods produce maps that contain measured information at a point density that is limited by the time and effort of field sampling. This limitation can make these technologies impractical for mapping large (e.g. >10 hectares) or complex areas. Airborne LiDAR (Light Detection and Ranging) is one alternative that is ideally suited for this task.

Typically, a LiDAR sensor is mounted to an airplane; during a carefully controlled flight over the area of interest, the sensor measures the time it takes for transmitted pulses of light to reach the ground and bounce back to the receiver, while onboard GPS tracks the real-world location of the sensor. LiDAR sensing can penetrate vegetation cover; multiple discrete returns reveal the elevation of the ground surface as well as the elevation of any existing canopy. In this way, airborne LiDAR can map ground surface topography that is real-world accurate to 10 cm or less in the vertical (Heidemann, 2014) with nearly continuous coverage for many acres and kilometers of river channel.

However, LiDAR has important limitations. It typically cannot reliably measure the bathymetric topography of most perennial streams because of turbidity and resulting light scatter and absorption (though, see McKean (2009) for application of Green LiDAR). Additionally, when very thick vegetation canopy exists, the accuracy of the LiDAR-derived ground-surface topography can be less than desirable and depends on the intensity of the light pulses and ability of computer algorithms to parse the numerous return signals.

Thus, it is frequently advantageous to combine a total station and/or RTK survey with a LiDAR survey, so as to have excellent coverage of a floodplain but also accurate and precise sub-canopy and channel bathymetric topography. Combining these two data types into a continuous topographic surface presents a unique challenge. Here, we present one ArcGIS-based approach for merging these data into a single digital elevation model, or DEM.

MERGING SURVEYS

A case study is useful to provide context for explaining the methods and steps for combining point-based surveys (total station and/or RTK) and LiDAR topographic surveys. In 2017 the Humboldt National Forest, in partnership with the State of California, the National Stream and Aquatic Ecology Center (NSAEC), and non-governmental organizations, began developing a restoration plan for the impaired Pickel Meadow reach of the West Walker River, in the foothills of the eastern Sierra Nevada Mountains of California (Figure 1). It was recommended, in part, that hydrologically reconnecting Pickel Meadow through periodic wetting would restore meadow hydrology and function (Yochum and McCann, 2017).

It was decided that a detailed topographic map (i.e. DEM) of the channel and floodplain would help inform decision making around restoration activities and alternatives. An engineering firm was contracted to conduct a LiDAR survey of the floodplain and meadow topography, while NSAEC carried out a conventional survey of channel bathymetry using Trimble R10 RTK equipment. The following workflow was developed (in ArcGIS 10.3) to combine the resulting surveys into a continuous DEM that included both floodplain and channel bathymetry.

This workflow assumes that the survey data has been vetted for quality assurance and control, the two surveys share a common horizontal and vertical datum, and that the root mean square error between the survey datasets is acceptable. Also, this workflow requires the development of elevation-grade breaklines as part of the conventional survey of channel bathymetry. The main steps of this workflow are to:

(1) Extract X, Y, Z points from channel and near-channel portion of LiDAR-derived DEM (DEM_{LiDAR});
(2) digitize the extent of the bathymetric survey and delete those DEM_{LiDAR} points that fall within this area;
(3) create a composite bathymetric + near-channel floodplain DEM (DEM_{bath});
(4) cut a hole into DEM_{LiDAR} to accommodate DEM_{bath}; and
(5) mosaic the rasters into a single final product.

Details for these steps are provided in the following sections.

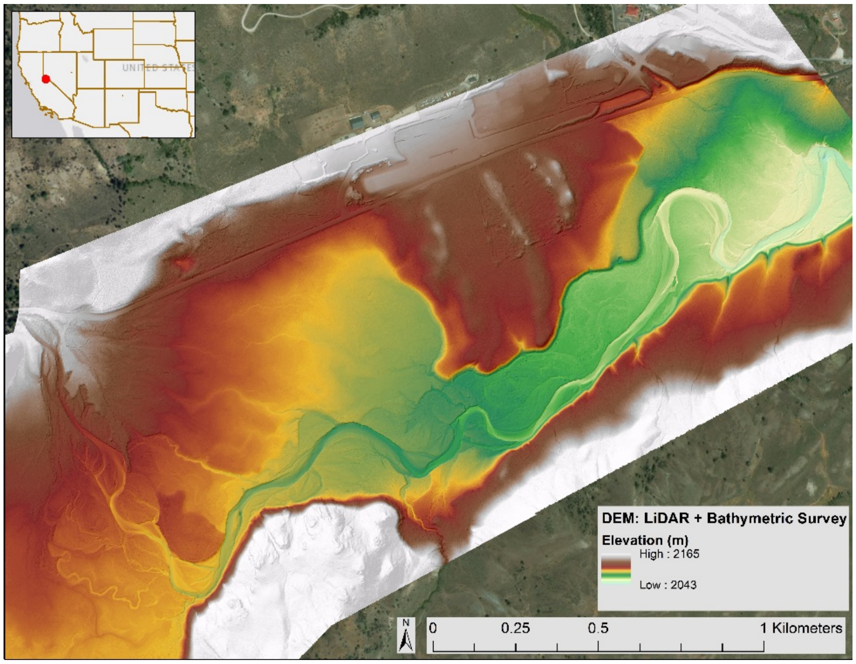

Figure 1: Digital elevation model of West Walker River and Pickel Meadow, CA, showing combined LiDAR and conventional bathymetric data.

Step 1: Extract points from DEM_{LiDAR}

First, isolate the portion of the DEM_{LiDAR} associated with the channel and near-channel floodplain and prepare for merging with the RTK-derived bathymetric data. To do this, first digitize a $polygon_{Inner}$ around the entire channel area, buffered to include several meters of near-channel floodplain (Figure 2). This polygon should include within it the entire extent of the bathymetric survey. Use ArcToolbox "Clip" to cut out the portion of DEM$_{\text{LiDAR}}$ defined by polygon$_{\text{Inner}}$. Next, convert the resulting DEM$_{\text{InnerLiDAR}}$ into points with elevation information. This may be done in a two-step process, by first using the "Raster to TIN" tool to convert the DEM$_{\text{InnerLiDAR}}$ into a high density triangulated irregular network (TIN$_{\text{InnerLiDAR}}$). Ensure that the resulting elevations match closely to the DEM$_{\text{InnerLiDAR}}$ by setting the Z tolerance option to an acceptably small value (e.g. 0.01 meters). Then, use the "TIN Nodes" tool to export TIN$_{\text{InnerLiDAR}}$ nodes as a point feature (Nodes$_{\text{InnerLiDAR}}$). Alternatively, Nodes$_{\text{InnerLiDAR}}$ may be created using the "Raster to Points" tool to extract one point per cell from the DEM$_{\text{InnerLiDAR}}$.

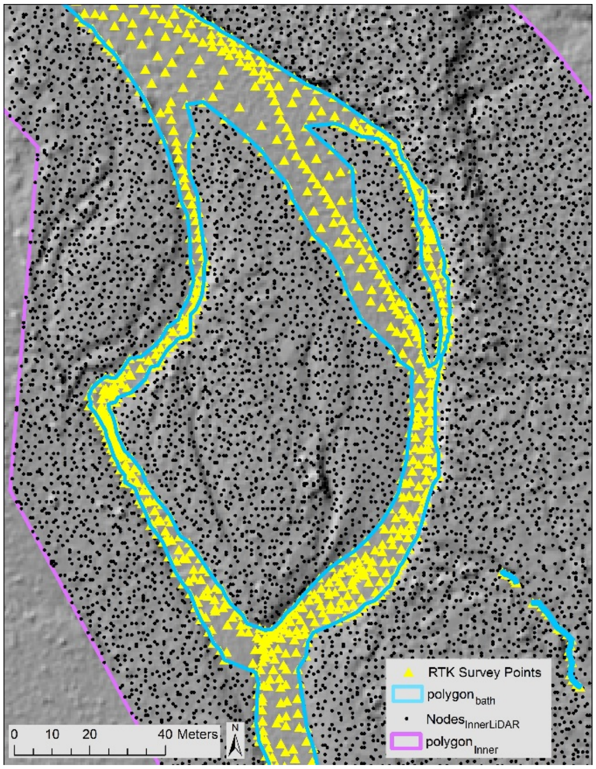

Figure 2: Digitized polygon$_{\text{bath}}$, bathymetric RTK survey points, polygon$_{\text{Inner}}$, and Nodes$_{\text{InnerLiDAR}}$ overlain DEM$_{\text{LiDAR}}$. Polygon$_{\text{bath}}$ differentiates the channel areas that will contain RTK-derived elevation data from those that will contain LiDAR-derived elevation data. Polygon$_{\text{Inner}}$ includes within it the entire extent of the bathymetric survey, extended to contain the near-channel floodplain. It defines the footprint of TIN$_{\text{bath}}$.

Step 2: Delineate bathymetry

The DEM$_{\text{LiDAR}}$ cells of the inundated channel roughly indicate the *water surface elevation* at the time of the LiDAR flight (Figure 3). For example, in the Pickel Meadow project, the "Extract Multi Values to Points" tool reveals that the RTK-measured points of channel bathymetry averaged 0.46 m lower in elevation than the exact locations on the DEM$_{\text{LiDAR}}$, which is an average sampled water depth at the time of the LiDAR survey. Channel depths commonly exceeded 1.2 m, with a maximum of 3 m. This illustrates the need for replacing the LiDAR-derived channel with the RTK-derived bathymetric data.

Now that the Nodes$_{\text{InnerLiDAR}}$ point feature is created, the portion of this dataset that will be replaced by the bathymetric survey must be delineated. First, in ArcGIS start an editing session and digitize the extent of the bathymetric RTK survey, snapping to the outer-most points. Make sure to delineate inner-channel features, such as islands and bars that were not inundated during the LiDAR survey (Figure 2). For complex multi-thread channels, it may be easiest to digitize this bathymetric mask using a line feature, then convert to a polygon using the Editor Toolbar "Construct Polygon" tool. Importantly, setting a topological rule set can be critical to successfully using this tool. Topological rules can be created for feature classes within a feature dataset and can alert you when certain geospatial errors exist (e.g. crossing breaklines or duplicate points). Inspect the final bathymetric polygon (polygon$_{\text{bath}}$) to ensure that it properly differentiates the channel areas that will contain RTK-derived elevation data from those areas that will contain LiDAR-derived elevation data (Figure 2).

Next, delete the Nodes$_{\text{InnerLiDAR}}$ (from Step 1) that fall within the polygon$_{\text{bath}}$ to make room for the RTK points. Create a backup containing the complete set of nodes for future use.

Step 3: RTK + LiDAR = DEM$_{bath}$

Next, create TIN$_{bath}$ of just the channel bathymetry using the “Create TIN” tool. When working with conventional and/or RTK survey data, a TIN is preferred over other methods to create a topographic surface (e.g. raster) because it allows for inclusion of elevation grade breaklines, which delineate breaks in slope and are critical for creating a realistic surface.

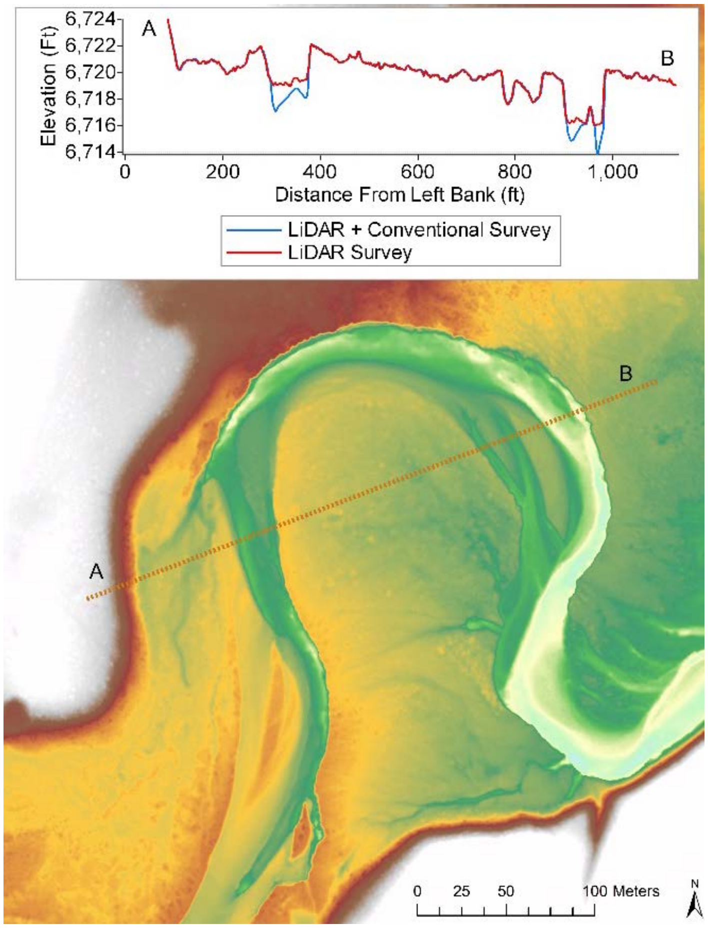

Figure 3: Elevation profiles along cross section AB for two digital elevation maps: a LiDAR DEM alone and the combined LiDAR and conventional bathymetric survey.

The following *Input Feature Classes* should be specified in the “Create TIN” tool: RTK points (*Mass_Points*), Nodes$_{InnerLiDAR}$ (*Mass_Points*), and any elevation grade breaklines (*Hard_Line*), and polygon$_{Inner}$ (*Hard_Clip*). In this case, the hard clip polygon$_{Inner}$ feature defines the extent of the resulting TIN.

Now inspect the resulting TIN$_{bath}$ and make any necessary edits. This is the most time consuming step in the workflow. First, add to the symbology for TIN$_{bath}$ *Contours*, *Nodes*, *Edge types*, and *Elevation*. In order to carry out a detailed inspection of the TIN, select an appropriate elevation *Color Ramp* with as many equal interval classes as is practical. Right clicking the TIN$_{bath}$ in the *Table of Contents* and selecting *Reset Legend Elevation Range* will update *Color Ramp* classes to match current map extent. Carefully inspect the results.

Cliffs, shallow riffles, side channels, islands and bars need particular attention. The primary concern is generating a smooth and realistic interface between the LiDAR-derived data and the RTK-derived data. Look for unrealistic triangle features at the interface, where elevations may be inappropriately linearly interpolated across a grade break.

Next, edit TIN$_{bath}$ to correct these issues. Use the “TIN Editing” toolbar to interactively modify, add, or delete TIN triangles, nodes, and breaklines. Unrealistic triangle features may be eliminated by creating hard breaklines. Be sure to create backups and frequently save edits.

In some cases, it may be desirable to add more information from the LiDAR survey. This can be accomplished using the ArcToolbox tool “Edit TIN”, where a selection of points from the backed-up complete set of Nodes$_{InnerLiDAR}$ may be added to TIN$_{bath}$. This irrevocably changes the TIN, so you must make backups before using “Edit TIN”.

When this step is complete, the final TIN$_{bath}$ must be converted into a raster before it can be mosaicked with the LiDAR DEM for the rest of the floodplain. Use the “TIN to Raster” tool to create DEM$_{bath}$, setting the cell size equal to that of the DEM$_{LiDAR}$.