Quantifying Sediment Deposition within Constructed River Restoration Sites using Repeat Aerial LiDAR

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Abstract

Hydrologic and geomorphic effects of dams, land use, infrastructure constraints, and channelization have altered habitat for native fishes including the Rio Grande Silvery Minnow (silvery minnow). Primary stressors to silvery minnow populations and life cycle include decreased river flow and loss of river-floodplain connectivity. To address these limiting factors, restoration projects create low-velocity habitat for retention of semi-buoyant eggs during spawning and development of larvae into juvenile fish. The Middle Rio Grande Collaborative Program and agency partners have constructed about 300 restoration sites since 1998 to mechanically lower the floodplain using a variety of techniques. Restoration methods include bank lowering, side channels, backwater areas, embayments, spoils placement, and vegetation clearing. Constructed restoration sites are initially effective but often lose functionality because of sediment deposition that increases the discharge required to inundate a site.

We quantify sediment deposition using four sets of LiDAR data (2010, 2012, 2017, and 2018) to analyze geomorphic change. Our method includes a novel approach to calculate detection limits for each pair of LiDAR years by comparing stable surfaces such as parking lots and roads. Geomorphic change is represented by a distribution of values within each stable surface or restoration site. Most restoration sites have a median elevation change within the detection limits, indicating that median erosion or deposition is not significant relative to the uncertainty of the LiDAR data. However, assessing the spatial distribution shows how elevation change along the channel margins affects connectivity. Deposition is often concentrated to areas where flow enters restoration sites, such as near the bank or a side channel inlet, thereby progressively disconnecting the features so that design flows no longer inundate the constructed projects. Our analysis indicates that the spoils placement and embayment feature types tend to have the most deposition, followed by side channel and bank lowering sites. Vegetation clearing and backwater areas tend to have the least deposition. The results inform recommendations for future restoration projects during the different phases of planning, construction, monitoring, and analysis.

Introduction

Middle Rio Grande Geomorphic Evolution

The Middle Rio Grande (MRG) flows through central New Mexico while providing a multitude of ecosystem services and ecological functions. Water from the river supports fish, riparian vegetation, birds, mammals, and human uses such as agriculture. Floods historically caused the river to migrate across the valley while depositing sediment in the main channel and overbank areas (Nelson et al. 1914; Happ 1948; Scurlock 1998; Makar and AuBuchon, 2012). High sediment loads and a variable flow regime were reflected in the channel planform evolution: a wide braided channel would narrow during periods of low flows, aggrade so that the channel was perched above the floodplain, and then avulse during a high flow event (Massong et al. 2010). The impact of a dynamically shifting river channel on infrastructure, and the need for water diversions in an arid environment, has continued throughout the 1900s to the present. Agriculture suffered from damage to riverside facilities and the loss of productive farmlands before larger-scale efforts to control the river began in the mid-1900s (Scurlock 1998). Many reaches were channelized, drains and levees were constructed, and Kellner jetty jacks were installed to narrow the channel (Reclamation 1961). The current river is a narrow single thread channel that is less connected to its floodplain and less geomorphically complex than historical conditions.

Rio Grande Silvery Minnow Habitat and Restoration Goals

The Rio Grande Silvery Minnow (RGSM) was listed as endangered in 1994 and occupies only about 7 percent of its historical range, an indicator of the ecologic deterioration of the Rio Grande ecosystem (USFWS, 2010). Hydrologic and geomorphic effects of water diversions, flood control dams, and channelization have directly and negatively modified RGSM habitat. Primary stressors to RGSM populations and life cycle include the following (Mortensen et al., 2019; Makar & AuBuchon, 2012; Scurlock, 1998; Swanson et al., 2011; Tetra Tech, 2014): decreased peak flow, increased river drying, channel narrowing and incision, infrastructure within the river-floodplain corridor, and decreased lateral and longitudinal connectivity.

Shallow-water areas with low velocity promote egg and larvae retention with primary production and suitable food resources for developing juvenile fish. Therefore, recovering the RGSM population depends on the river-floodplain connection (Tetra Tech, 2014). Without floodplain inundation, spring runoff flows linked to spawning will only cause downstream egg displacement and high mortality rates (Medley & Shirey, 2013). Therefore, RGSM restoration projects have the fundamental action of increasing river-floodplain connectivity. Related goals include increasing the available area of shallow depth and low velocity zones while increasing hydraulic complexity and refugia during high flow events. Restoration features ultimately seek to counter the trend of floodplain disconnection by reducing the discharge required to inundate various topographic surfaces.

Constructed Habitat Restoration Sites and Elevation Data

Partner agencies have constructed about 300 floodplain lowering sites on the MRG since 1998, and most of these sites are located near Albuquerque or Belen, New Mexico (Figure 1). The projects were typically designed by using fixed bed hydrodynamic models to simulate water surface elevation at a target flow rate (e.g., 1500 cfs). Designers then applied these water surface elevations to determine appropriate elevations for excavating restoration features. Figure 2 shows that the most active construction period was between 2006 and 2011, with additional work between 2012 and 2019. To analyze geomorphic change for the restoration sites, we obtained LiDAR data of the river corridor collected during 2010, 2012, 2017, and 2018. These data provided digital elevation models (DEMs) before, during, and after project construction. Flows during the LiDAR analysis period were relatively low, except for spring runoff in 2010 and

2017 and a high flow monsoon in 2013 (Figure 3). New Mexico is in an ongoing drought and the constructed restoration projects were not inundated as frequently because of lower flows.

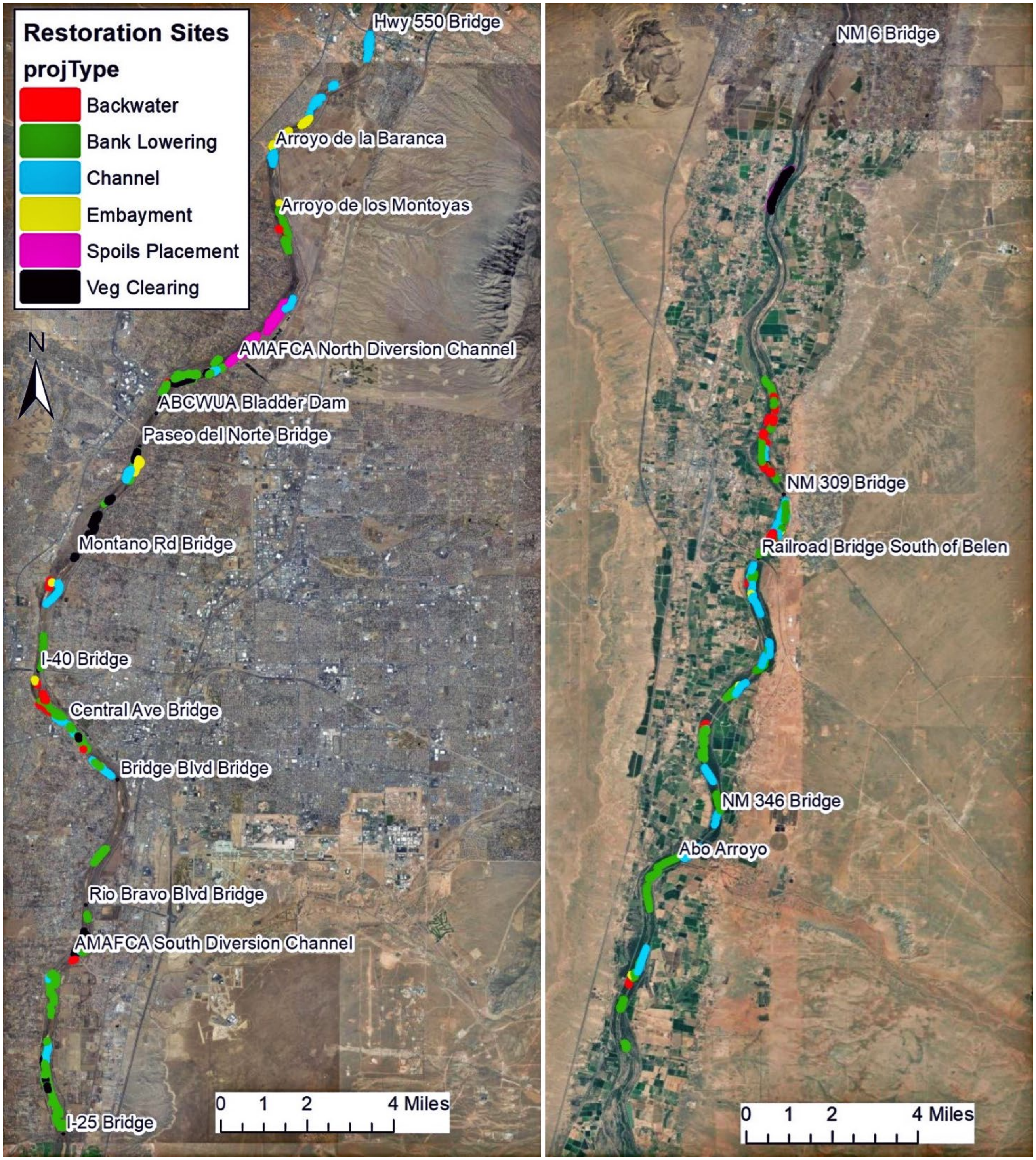


Figure 1. Location map for restoration sites near Albuquerque (left) and Belen (right). Left panel: northern sites from Hwy 550 to Isleta Diversion Dam (182 sites). Right panel: sites from NM 6 to Rio Puerco (99 sites).

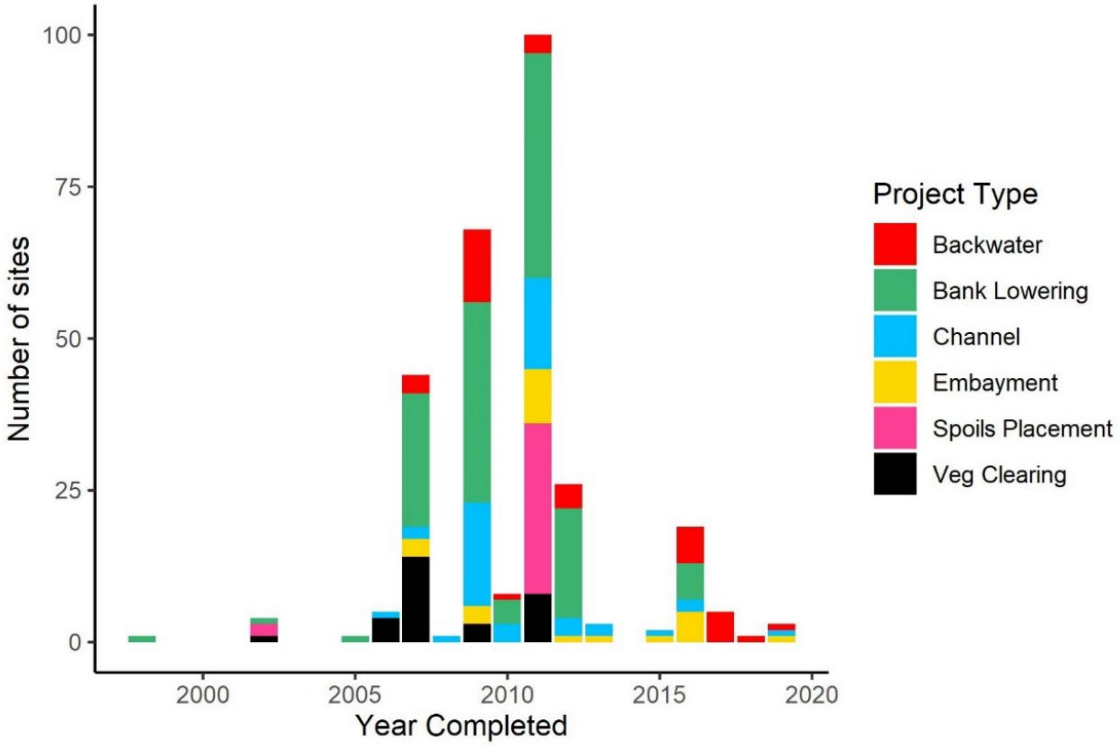


Figure 2. Number of restoration sites constructed by year

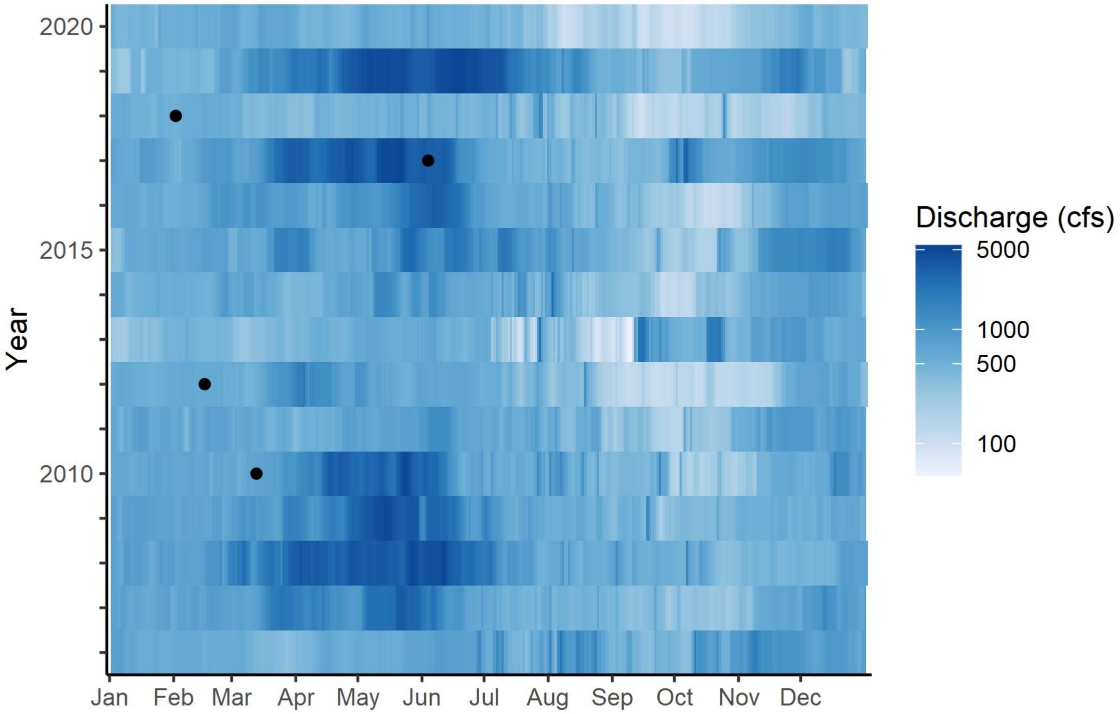


Figure 3. Mean daily discharge at the Central Avenue bridge (USGS 08330000) from 2006 through 2020. LiDAR collection dates are represented by the black points in 2010, 2012, 2017, and 2018.

Study Goals

This study aims to complement other monitoring efforts to improve understanding of the geomorphic evolution of constructed restoration sites. The premise of floodplain lowering is to create surfaces that will inundate at lower flows (e.g., 1500 cfs instead of 3500 cfs) to increase the availability of shallow, low-velocity zones to provide habitat for RGSM during spring runoff. These restoration sites, like the entire MRG, are dynamic and experience morphologic changes in response to flow and sediment. Elevation changes at restoration sites are not well documented or understood. There have been observations of sediment deposition along banks or within features, but quantification is limited.

The goal of this study is to quantify and document elevation changes within restoration sites. As-built and monitoring survey data are limited, so we rely on LiDAR DEM comparisons for different time intervals. Quantifying elevation change provides insight into how much deposition occurs at constructed restoration sites. This will inform expectations of longevity and maintenance needs. Our second goal is to compare different feature types, different geomorphic reaches, and different time periods to examine any trends or patterns. These observations may improve future designs by understanding if different feature types or geomorphic reaches are expected to have greater longevity or be more resilient to varying flow and sediment conditions.

Methods

Level of Detection

To distinguish real geomorphic change at project sites from measurement error in the LiDAR surveys, we developed a method to determine the minimum amount of erosion or deposition that we can detect with confidence. We identified 40 areas such as roads, bridges, or parking lots in the aerial imagery that presumably experienced no elevation change between LiDAR surveys. We outlined these areas by drawing polygons in GIS software and generated a grid of points spaced 5 ft apart within the bounds of each polygon (Figure 4). These points were assigned elevations from each surface and the elevations for each survey pair were differenced (2012 minus 2010, 2017 minus 2010, 2018 minus 2010, 2017 minus 2012, 2018 minus 2012, and 2018 minus 2017).

Stable surfaces such as parking lots should have zero elevation change at every point on the surface. Therefore, any measured change reflects the uncertainty and accuracy limitations of the survey technology. We determined the level of detection for each pair by generating a Cumulative Distribution Function (CDF) that relates elevation differences to percent exceedance. The lower detection limit, set at 95% exceedance from the CDF, defines the erosion threshold and the upper detection limit, set at 5% exceedance from the CDF, defines the deposition threshold. Detection limits at stable sites, which have a constant elevation, establish the range of LiDAR uncertainty. If a restoration surface near the river has an elevation change that is within the stable surface detection limit, then the geomorphic elevation change is not measurably different from a parking lot. Small elevation changes may be real, but they are not detectable within the uncertainty of the LiDAR comparison.

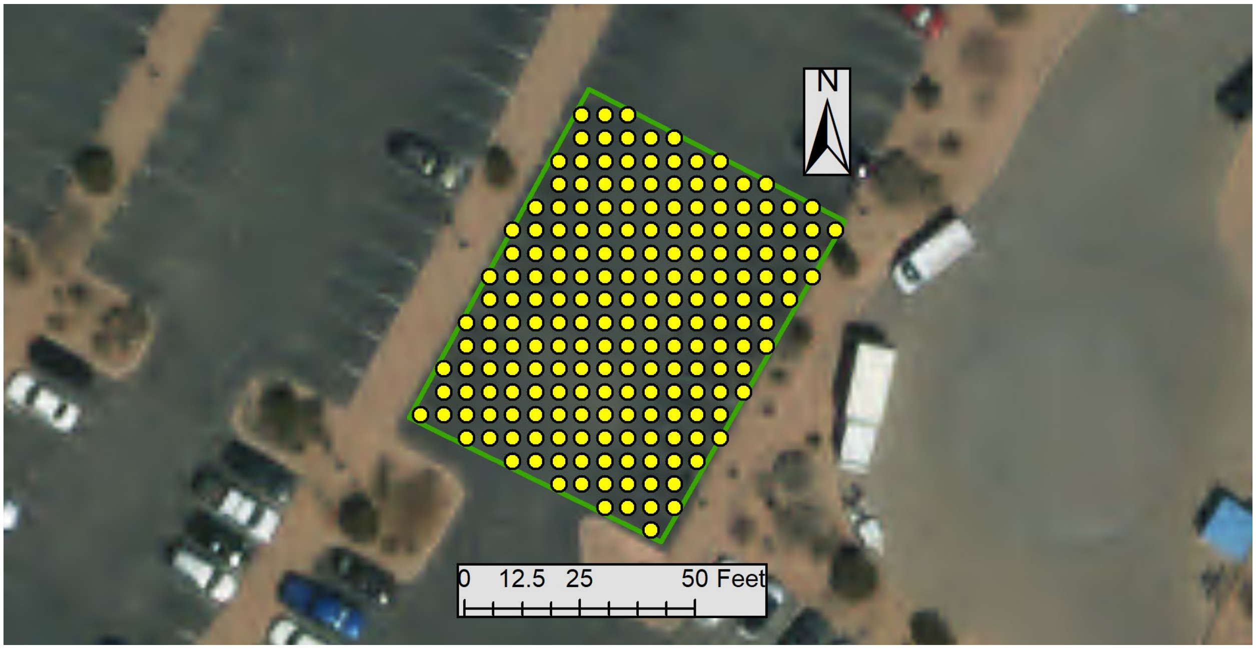


Figure 4. Elevation comparison points in a parking lot that was assumed to have experienced no elevation changes during the four LiDAR surveys

Restoration Site Elevation Change

We determined the elevation change at project sites using the same method as the stable surface comparisons. Within each project site polygon, we generated a regularly spaced (5 ft) grid of points and assigned elevations to the points from each topographic surface. The elevations were differenced for each survey pair and the set of points clipped to represent only points that were above water during both surveys. Inundated area polygons were included with the 2012, 2017, and 2018 LiDAR datasets. These inundated polygons were erased from the restoration boundary polygons to create a new set of polygons for the non-inundated portion of each site. The non-inundated elevation difference points constitute the nodes of a DEM of elevation change.

Results

Level of Detection

Figure 5 presents the CDFs for stable surface comparisons between each pair of LiDAR years. The lower detection limit (95% exceedance) varies between -0.91 ft (2018 minus 2012) and -0.19 ft (2012 minus 2010). The upper detection limit (5% exceedance) varies between 0.26 ft (2017 minus 2012) and 1.27 ft (2018 minus 2010). We have the most confidence in elevation changes between 2012 and 2017. This CDF has a median of 0, is symmetrical about 0, and has a steep slope between the 95% and 5% exceedance, which indicates that nearly all data are within a narrow band of elevation change. Comparisons between other years have a wider band of uncertainty, are often not symmetrical, and have a bias in the median CDF value above or below 0. Elevation differences less than 0.5 ft or 1 ft are within the range of uncertainty for comparisons between most LiDAR years.

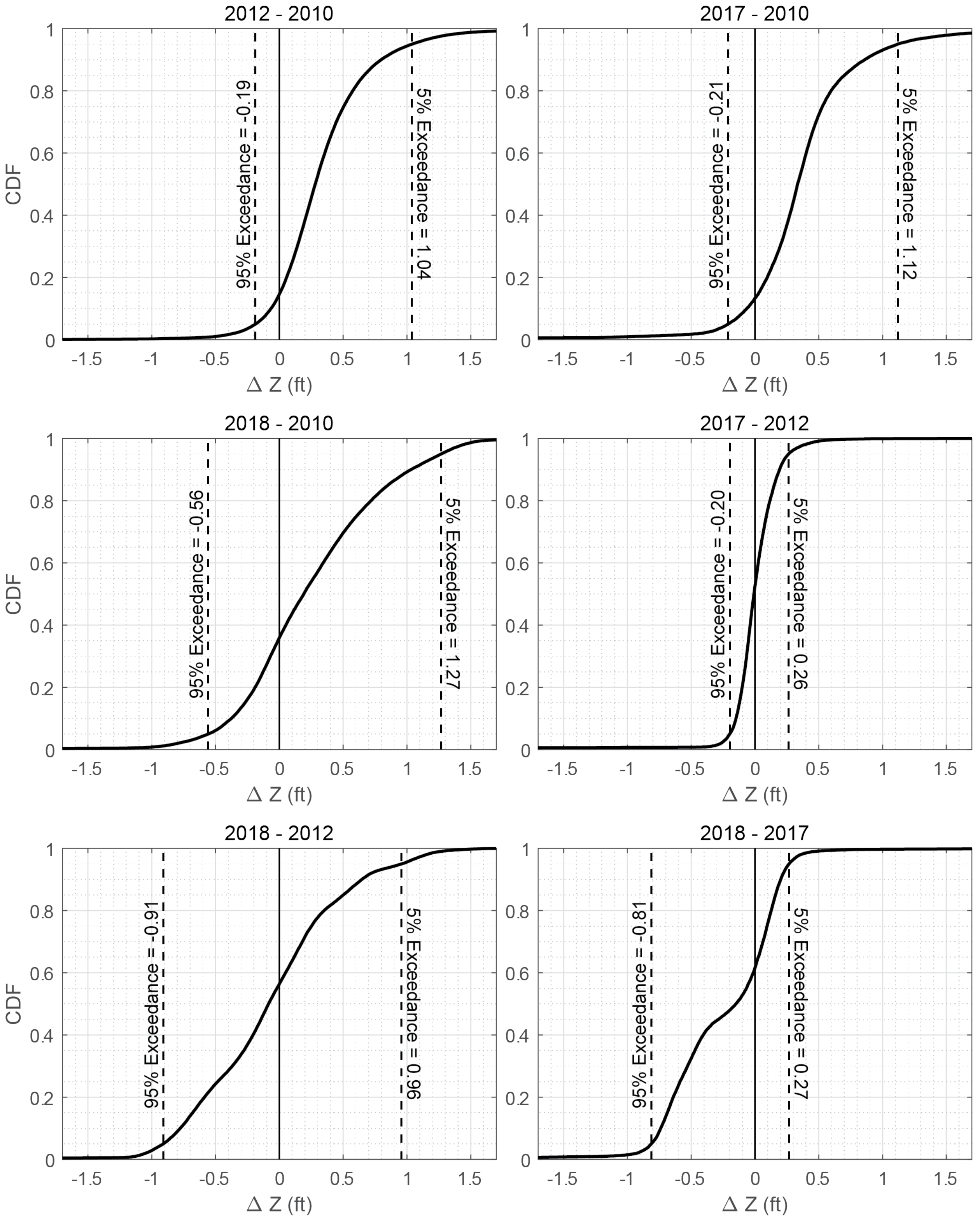


Figure 5. Stable surface comparison for various LiDAR intervals at about 40 sites (primarily roads and parking lots) near restoration features

Restoration Site Elevation Change

Figure 6 represents median elevation change between 2012 and 2018 for every restoration site. The top panel classifies sites by feature type and the bottom panel classifies sites by construction date relative to the LiDAR period (before, during, after). Detection limits are plotted as horizontal dashed lines. The 2012 to 2018 period provides the largest sample size because most restoration sites were constructed before 2012 and the 2017 LiDAR did not include the full study area. Projects constructed before 2012 were mostly depositional during the 2012 to 2018 period. The largest deposition occurred at spoils placement feature types upstream of Paseo del Norte Bridge. Bank lowering sites upstream of the I-25 bridge experienced minor erosion within the detection limit. The bottom panel shows that the LiDAR analysis reliably detects surface lowering for projects excavated during the 2012 to 2018 interval.

Figure 7 compares median elevation change between different feature types for all sites constructed before the LiDAR interval for all time periods. Horizontal lines are median values for each feature type, boxes are the interquartile range (25% to 75% values) and dots represent outliers. The project types in order from most to least deposition are typically spoils placement, embayment, channel, bank lowering, vegetation clearing, and backwater. The spoils placement and embayment sites are similar because they are constructed along the water's edge, mostly parallel to the direction of flow, without a defined inlet or outlet. These sites are more frequently inundated at lower discharges than other project types. Channels are only connected to the river at inlets and outlets. Most deposition is concentrated at these connection points, which results in lower median elevation change than spoils placement or embayments.

Similar to spoils placement and embayments, bank lowering is a linear feature parallel and adjacent to the main channel. Bank lowering may have experienced less deposition than these features because it was often constructed to a higher design discharge and inundated less frequently. Vegetation clearing sites are usually islands or banks where vegetation is removed without excavating the surface. We hypothesize that excavated sites tend to fill to their pre-construction elevation and vegetation clearing sites are less likely to deposit because they were not excavated. Finally, backwater sites had the least amount of elevation change. This may be caused by the orientation of the river connection relative to the streamline patterns, which allows less sediment to enter the site.

Figure 8 plots elevation change CDF curves for the 2012 to 2018 period using data from sites constructed before the interval. There are three curves for each feature type: low, median, and high. The low curves are the average of five sites with the least deposition, the median curves are the average of five sites nearest to the middle deposition value, and the high curves are the average of five sites with the most deposition. The CDFs have a range of 1 to 3 ft between the 10% and 90% exceedance values, indicating that elevation change within most sites varies by 1 to 3 ft. Differences between the low and high sites within each feature type vary from about 1.5 ft (embayment and vegetation clearing) to about 3 ft (bank lowering). Bank lowering has the most sites and variety of locations along the river, which likely explains the increased variability between sites with low and high deposition. Trends between feature types are generally the same as discussed for the tables above, with the exact comparison depending on the CDF curve. The median curve shows that embayments tend to have more deposition than bank lowering, but the high curve shows that bank lowering sites have more deposition than embayments.

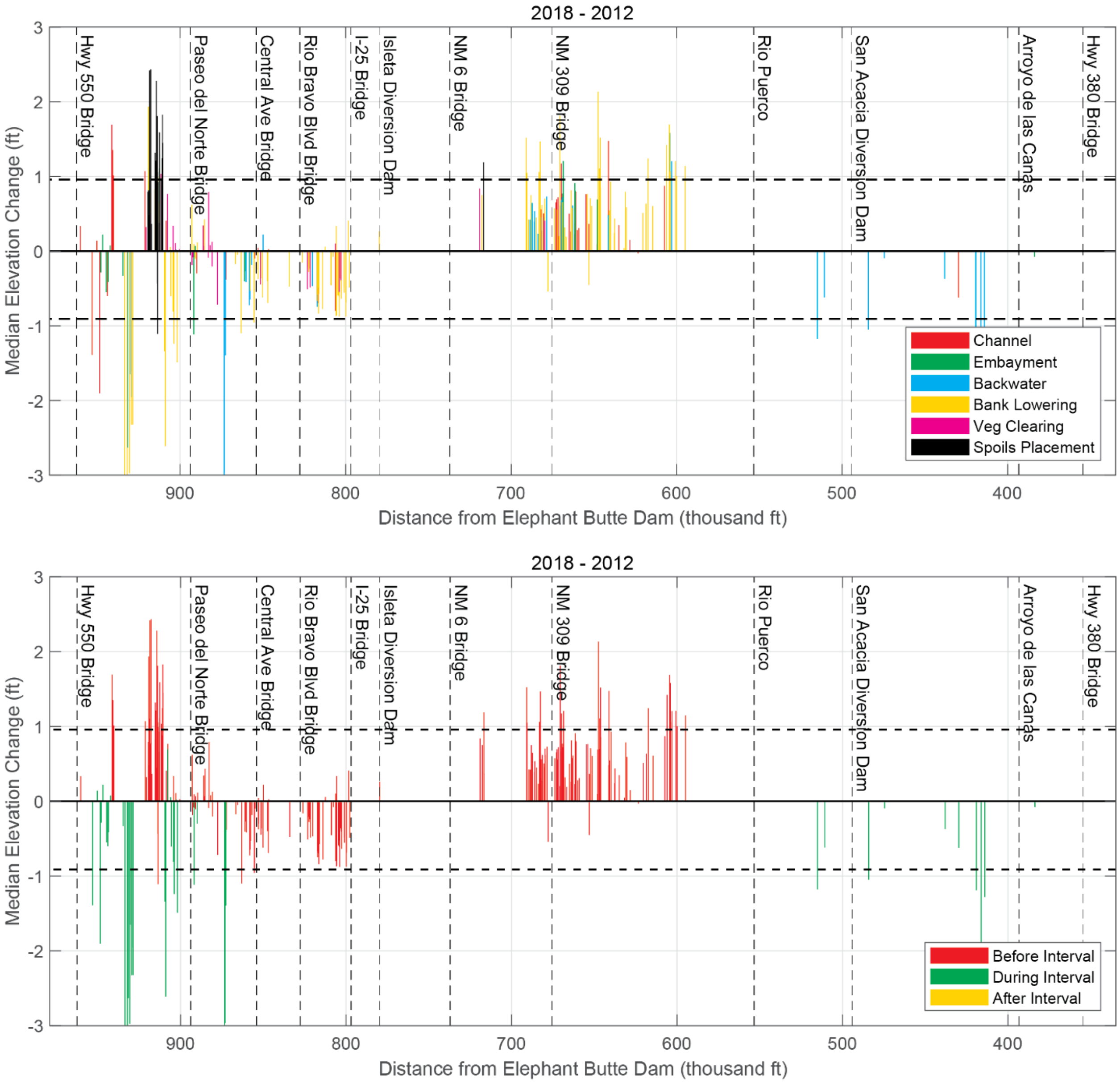


Figure 6. Median elevation change for restoration sites between 2012 and 2018. Top panel: sites categorized by feature type. Bottom panel: sites categorized by construction date relative to LiDAR period. Horizontal dashed lines represent detection limits (95% and 5% exceedance from stable surface comparisons).

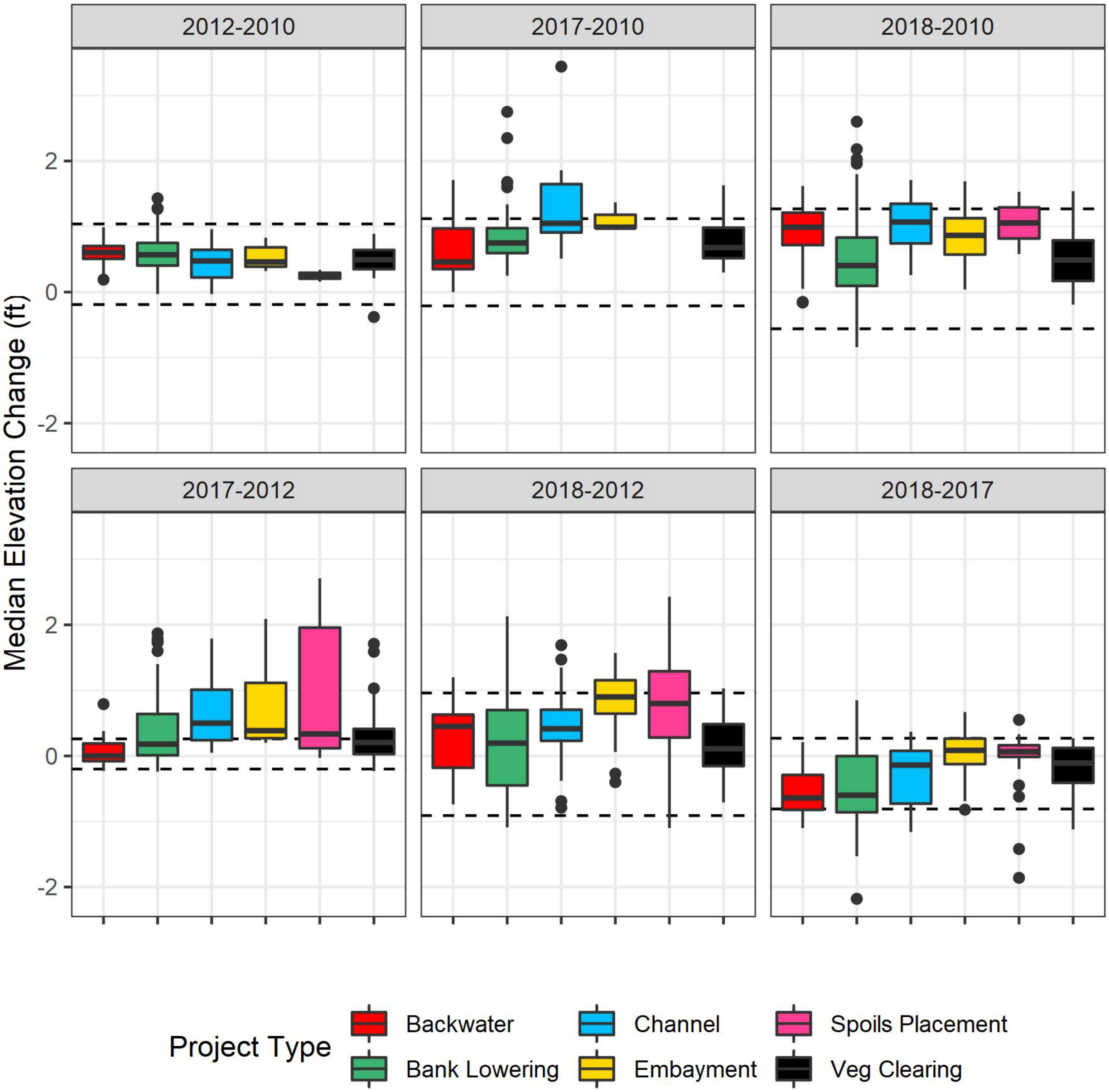
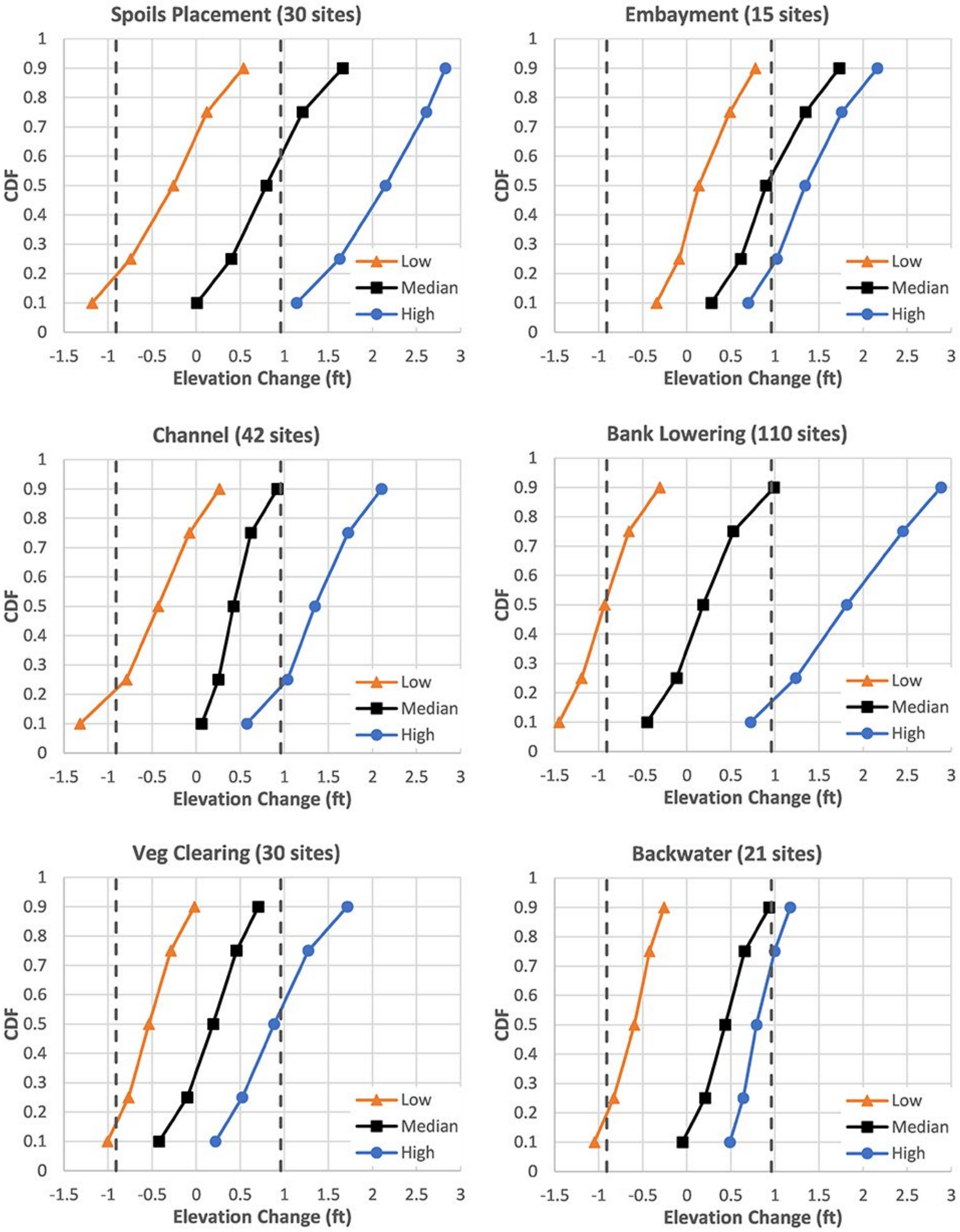


Figure 7. Median elevation change for all restoration sites for each project type constructed prior to the LiDAR period of interest. Horizontal dashed lines represent detection limits (95% and 5% exceedance from stable surface comparisons).



Spoils Placement (30 sites)

Embayment (15 sites)

Channel (42 sites)

Bank Lowering (110 sites)

Veg Clearing (30 sites)

Backwater (21 sites)

Figure 8. Elevation change (2018 minus 2012) for different feature types constructed before 2012. Low, Median, and High are the average of five sites with the least, middle, and most deposition, respectively.

Discussion

The preceding results established that elevation change has spatial variability within restoration sites, but the implications are not clear until viewing maps of the sites. Sites with less deposition also tend to have less variability within a site. Therefore, we include elevation change maps for a side channel and embayment site that have measured deposition above the detection limit. Figure 9a is a 2012 to 2018 elevation change map for a side channel site constructed in 2009. There is preferential deposition near the inlet. Deposition progressively decreases downstream from the inlet until reaching the detection limit about midway through the channel (Figure 9b). Elevation change remains constant until deposition increases within about 200 ft of the outlet. The inundation boundary shows that the full length of the channel was wet during the 2017 LiDAR, although the inlet is nearly disconnected. Deposition has mostly blocked the original inlet location but there are narrow flow paths slightly upstream and downstream that allow water to flow into the site. Elevation change from the LiDAR also indicates that there are a few areas of localized bank erosion within the side channel. Inundation extents generally match these erosional areas near the outside of bends. The channel was constructed as a relatively uniform trapezoid, which demonstrates that post-construction geomorphic change can increase planform variability.

Figure 9c is a 2012 to 2018 elevation change map of a nearby embayment site constructed in 2011. This site also includes spoils placement where excavated material from the embayment was pushed toward the river to create a bank-attached bar at a similar elevation as the embayment. The most notable change observed during field visits was the vegetation growth within the site. The site was cleared during construction and is now densely vegetated, except for a narrow path along the toe of the embayment bankline. This path has remained unvegetated, possibly because of higher velocities during overbanking flow that prevent seedlings from germinating. There is a consistent gradient of elevation change where the most deposition occurs near the river at the upstream end of the site and the only erosion is at the toe of the embayment bankline, especially at the downstream end. The inundation extents during the 2017 LiDAR are consistent with this depositional pattern. The site was not connected to the river at the upstream end, although it may have been connected earlier in the runoff near the peak flow. Surface water is only connected to the site at the downstream end at a flow of about 3400 cfs. Preferential deposition near the upstream bankline has essentially converted the site from an embayment to a backwater at all but the largest flows.

Maps of bank lowering sites depict the formation of “natural levees” caused by bankline deposition. Water carrying high suspended sediment loads encounters increased roughness when overtopping a bank, which induces sediment deposition. Continued deposition along banklines raises the bank height, thereby requiring a progressively larger discharge to inundate the floodplain depending on the relative change to the channel bed elevation. This process presents a risk to nearly all restoration sites because deposition near the inlet or bankline may disconnect the rest of the feature so that its habitat value decreases over time.

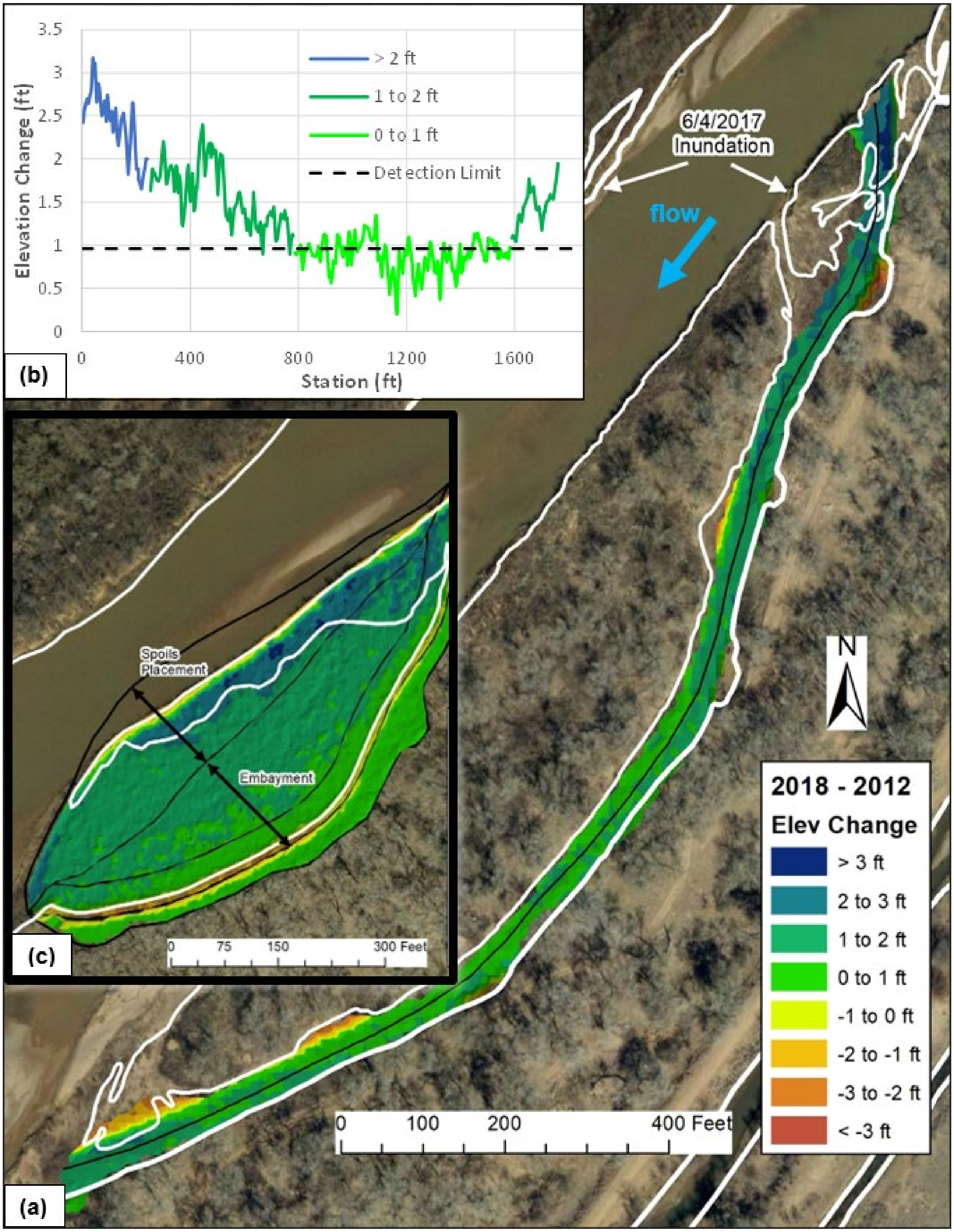


Figure 9. Elevation change (2018 minus 2012) for (a) side channel site constructed in 2009 with (b) inset profile graph of elevation change along centerline from upstream to downstream. (c) Elevation change for embayment site constructed in 2011. Inundation boundary (white line) is at a discharge of about 3400 cfs during 2017.

Conclusions

Summary

We used LiDAR data to assess elevation change for restoration sites on the MRG. The study developed a method to generate DEMs of difference for multiple LiDAR datasets and hundreds of polygons across a large area. Comparing stable surfaces such as parking lots and roads provided the detection limits for determining if measured erosion or deposition was reliable or the result of uncertainty in the LiDAR. Most time intervals required that deposition heights exceed about 1 ft to be above the upper detection limit threshold.

LiDAR differencing reliably showed elevation decreases for sites constructed during various intervals, which represented nearly all areas of "erosion" beyond the lower detection limit. Other results were initially inconclusive due to the large number of sites with median elevation change values within the detection limits. The dry hydrology during the study period, except for a few high flow events, likely caused a smaller amount of geomorphic change than if the frequency, duration, and magnitude of high flows had been larger. However, further analysis showed differences between feature types. Deposition rates were highest for spoils placement sites, followed by embayments, channels, and bank lowering. Vegetation clearing and backwater sites generally had the lowest amount of deposition.

Analyzing the spatial distribution of elevation change, rather than a single representative value for each location, provided further insight. Median values did not represent localized areas of deposition such as the interface between the river and restoration site. The number of sites where deposition exceeded the detection limit increased 20% to 40% when using the 10% CDF exceedance value rather than the median value. DEM of difference maps were useful to visualize deposition gradients across restoration sites. Deposition was usually concentrated where flow enters a restoration site, such as near the riverbank or side channel inlet. This caused the site to be disconnected at the target design discharge, requiring progressively larger flows to achieve the intended restoration benefits.

Recommendations

Performing quality assurance and quality control checks is important to ensure reliable LiDAR comparisons, such as the 2012 to 2017 interval, instead of uncertain or skewed comparisons, such as the 2010 to 2018 interval. Verifying that LiDAR products are accurate and consistent will improve monitoring because completing ground surveys at all restoration sites is not practical. We provide recommendations organized by project stages from planning to analysis.

Planning
Clearly define project goals to establish target design discharges for restoration features. Features that are constructed to inundate at lower discharges will inundate more frequently and thereby be more susceptible to deposition. Consider potential lifecycle evolution trajectories and future maintenance. For example, side channels often adjust by starting as a flow-through channel, then the inlet becomes filled with sediment creating a backwater, and finally, the backwater becomes vegetated transitioning the site from aquatic to terrestrial habitat. A maintenance plan should consider if this evolution is acceptable or if deposition thresholds should trigger mechanical intervention to maintain flow-through aquatic habitat.

Construction

Complete an as-built ground survey of both the constructed feature and the main river channel. Use the as-built survey data to create a polygon of the site boundary for use in future monitoring. Also, create breaklines to document the location of important features such as the top of bank and toe of slope.

Monitoring

Establish a discharge threshold to guide the frequency of monitoring surveys. The number of surveys can be increased or reduced depending on hydrology, which is a driver of geomorphic change. Periodically survey the channel bed near the restoration sites to assess the relative effect of main channel erosion or deposition compared to elevation change within the sites.

Analysis

Quantify the spatial distribution of elevation change within restoration sites by developing a local grid to analyze elevation change as a function of lateral distance from the edge of river and the longitudinal distance from the upstream edge of the site. This local grid would quantify spatial distribution observed on the elevation change maps. Site boundaries could also be subdivided to include regions of interest near the interface with the main channel.

References

Happ, S. 1948. “Sedimentation in the Middle Rio Grande Valley, New Mexico,” Bulletin of the Geological Society of America, 59, 1191–1216.

Makar, P., and AuBuchon, J. 2012. Channel Conditions and Dynamics of the Middle Rio Grande. Bureau of Reclamation, Technical Service Center and Albuquerque Area Office.

Massong, T., Makar, P., and Bauer, T. 2010. “Planform Evolution Model for the Middle Rio Grande, New Mexico,” Proc. 2nd Joint Federal Interagency Conference on Sedimentation and Hydrologic Modeling, Las Vegas, NV.

Medley, C., & Shirey, P. 2013. “Review and reinterpretation of Rio Grande silvery minnow reproductive ecology using egg biology, life history, hydrology, and geomorphology information,” Ecohydrology, 6(3), 491–505.

Mortensen, J., Dudley, R., Platania, S., and Turner, T. 2019. Rio Grande Silvery Minnow Habitat Synthesis. University of New Mexico, Albuquerque, NM.

Nelson, J., Holmes, L., and Eckmann, E. 1914. Soil Survey of the Middle Rio Grande Valley Area, New Mexico. U.S. Department of Agriculture, Bureau of Soils, Washington, DC.

Reclamation. 1961. Sediment Studies for Channelization of the Rio Grande between Cochiti and Mouth of Rio Puerco. Bureau of Reclamation, Albuquerque Project Office, Albuquerque, NM.

Scurlock, D. 1998. From the Rio to the Sierra: An Environmental History of the Middle Rio Grande Basin, General Technical Report RMRS-GTR-5. U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, Fort Collins, CO.

Swanson, B., Meyer, G., and Coonrod, J. 2011. “Historical channel narrowing along the Rio Grande near Albuquerque, New Mexico in response to peak discharge reductions and engineering: magnitude and uncertainty of change from air photo measurements,” Earth Surface Processes and Landforms, 36, 885-900.

Tetra Tech. 2014. Ecohydrological Relationships along the Middle Rio Grande of New Mexico for the Endangered Rio Grande Silvery Minnow. Prepared for U.S. Army Corps of Engineers, Albuquerque District, Albuquerque, NM.

U.S. Fish and Wildlife Service (USFWS). 2010. Rio Grande Silvery Minnow (Hybognathus amarus) Recovery Plan, First Revision. Albuquerque, NM.