ASSESSMENT OF METHODS FOR MONITORING RESPONSES TO RIVER RESTORATION: RIVERBED AND CHANNEL FORM CHANGES

by

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THESIS ABSTRACT

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On the Middle Fork John Day River (MFJD), a low gradient, meandering river in eastern Oregon, restoration includes engineered log structures intended to increase in-stream complexity and habitat diversity. Effects of log structures on riverbed topography can be captured through repeat topographic surveys, digital elevation model (DEM) of differencing (DoD), and aerial imagery. This study evaluates the (1) potential for remote sensing analysis, (2) effect of survey point density on DEMs, and (3) application of DoDs, in monitoring riverbed changes in the MFJD. An average point spacing and density finer than 0.50m and 1.25pts/m^2 captures riverbed complexities. Although elevation changes were expected to be minimal, DoDs revealed -0.9 to 0.5m elevation changes associated with log structure designs. Incorporating numerical thresholds into future monitoring survey methods will improve the modeling of MFJD riverbed surfaces. Monitoring riverbed changes through DoDs can inform improvements to future restoration design and the effectiveness of log structures.

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TABLE OF CONTENTS

LIST OF FIGURES

Figure Page

LIST OF TABLES

CHAPTER I

INTRODUCTION

Each year, millions of dollars are invested in river restoration in the Pacific Northwest, but only nominal effort is expended to assess the effectiveness of these projects (Bernhardt *et al*., 2005; Katz *et al.*, 2007). Quantitative process-based restoration monitoring is important to identify and understand the impacts of restoration on physical and ecological processes (Katz *et al.*, 2007; Kondolf *et al*., 2007; Palmer *et al.*, 2005). This understanding is, in turn, critical in the effort to restore populations of listed threatened and endangered aquatic species (Katz *et al.*, 2007). Evaluating the effectiveness of past and current restoration projects provides insight on potential improvements to future designs and the most effective allocation of restoration funds (Bernhardt *et al*., 2005; Katz *et al.*, 2007; Kondolf *et al.*, 2007; Palmer *et al*., 2005).

Because time and budget are usually limited in river restoration, efficient and accurate assessments are essential. Advances in technology for both data acquisition and analysis create opportunities to understand river morphological changes with greater precision and at larger spatial scales (Marcus and Fonstad, 2008; Milan *et al*., 2011; Wheaton *et al*., 2010). Remote sensing could provide rapid and easily repeatable high precision river channel morphology data. Similarly, analysis of repeated surveys of channel morphology can provide understanding of the local influences of restoration actions on river processes. While prior studies analyzing channel morphology change with digital elevation models (DEM) from different dates (such as Brasington *et al.*, 2000 and Lane *et al.*, 1994 focused on dynamic, braided systems, this study aims to test the application of current methodologies in a small, low gradient, single-thread meandering channel. In our study, the goal is to refine methods for tracking riverbed changes in response to in-stream structures for fish habitat. This is a three part study which explores (1) the potential for remote sensing analysis in restoration monitoring, (2) the effect of survey point spacing and density on digital elevation modeling (DEM), and (3) the application of DEM of differencing (DoDs) to monitor riverbed changes in a small river system.

CHAPTER II

BACKGROUND

Study catchment: Middle Fork John Day River

The Middle Fork John Day River (MFJD) is a subbasin of the John Day River, which, in turn, is a tributary to the Columbia River (Figure 1, see Appendix B for all figures). The MFJD is a 2087.5 km^2 drainage basin originating in the Malheur National Forest in the Blue Mountains of northeastern Oregon, with elevations ranging from 671 to 2,469m (U.S. Bureau of Reclamation, 2008). The MFJD is designated as an Intensively Monitored Watershed, resulting in a collaboration of state, federal and local agencies for restoration monitoring (MFJD Intensively Monitored Watershed Committee, 2009).

The MFJD supports wild populations of threatened and endangered fish species including spring and fall Chinook salmon (*Oncorhynchus tshawytscha*), summer steelhead (*O. mykiss)*, bull trout (*Salvelinus confluentus),* Pacific lamprey (*Lampetra tridentate)*, and west slope cutthroat trout (*O. clarkii lewisi*) (MFJD Intensively Monitored Watershed Committee, 2009). However, anthropogenic alterations to the MFJD basin have decreased river habitat complexity, thereby reducing spawning and rearing fish habitat. While there are no dams in the MFJD watershed to alter the hydrologic regime, past land management practices such as livestock grazing and logging, have altered sediment regimes and floodplain and river morphology (Bureau of Reclamation, 2008; Turo and Cochran, 2011). Restoration actions throughout the MFJD basin include grazing closures, riparian planting, re-opening of historic channels, removal of rock spurs, and construction of engineered log structures. Restoring river function and increasing fish habitat are the primary goals of these on-going restoration efforts.

Study site: Forrest Reach of the MFJD

The study site for this research is a reach within the Forrest Conservation Area of the Confederated Tribes of the Warm Springs Indian Reservation (Forrest reach) of the MFJD restoration project (Figure 1). This study site is located downstream of the former mill town of Bates, OR, and is the upper most reach of the MFJD restoration program. The Forrest reach has a valley gradient of 0.54%, a channel gradient of 0.50% and an average bankfull width of 13.8m. The median sediment size (D50) is 73mm. The Forrest reach channel is characterized by an average sinuosity of 1.17, a riffle-pool morphology and an unconfined floodplain with an average valley width to bankfull width ratio of 15. Historically, this reach was logged and used for livestock grazing (U.S. Bureau of Reclamation, 2008; Turo and Cochran, 2011).

In the Forrest reach, specific restoration goals include increasing floodplain connectivity by increasing frequency of side channel and overbank inundation, reestablishing natural channel morphology, and stabilizing channel banks while providing habitat diversity (U.S. Bureau of Reclamation, 2010; Turo and Cochran, 2011).

In 2008, to accomplish these restoration goals, engineered log structures with dug pools (DPs) were constructed, and man-made structures such as rock spurs and sediment plugs in side channels were removed. Log structures were constructed along straight reaches and on the outer bank of meander bends. While no hydraulic modeling was conducted, log structure designs were based on hydraulic principles dictating scour and deposition, and were designed to mimic natural tree fall and wood accumulation. Log structures were constructed with three to seven 18” diameter immobile log pieces buried into one bank with rootwads positioned within the channel and angled upstream, and a similar number of mobile log pieces placed on top of and around the buried pieces. The rootwads were intended to initiate scour effects, create in-stream hydraulic complexity, and increase holding zones for juvenile and adult Chinook. DPs were constructed under log structures or slightly midstream to establish pools for fish habitat diversity. Past studies recognize the ecological importance of in-stream log structures for nutrient retention and fish habitat (Abbe and Montgomery, 1996). At a variety of different scales, log structures affect "channel roughness, bed surface composition, in-stream features, channel patterns and floodplain formation" (Montgomery and Piegay, 2003).

Change in riverbed topography associated with engineered log structures in the Forrest reach is an important indicator of their effectiveness in increasing spawning and rearing habitat, increasing floodplain connectivity and reestablishing natural channel morphology. In addition, evaluating and refining monitoring methods may help to improve restoration monitoring in other similar small rivers.

Remote sensing in fluvial environments

Remote sensing allows for understanding of river processes through spatially continuous data, increasing the ease of repeatability, and facilitating the study of river systems in inaccessible locations. A range of remote sensing methodologies can be used in bathymetric mapping in fluvial environments including optical remote sensing, ground penetrating radar, photogrammetry and bathymetric LiDAR (Feurer *et al*., 2008). Historical bathymetric mapping was limited to near shore marine environments, reservoirs and large rivers that could be characterized in satellites imagery (Fonstad and Marcus, 2005, Legleiter *et al.*, 2009; Legot *et al.*, 2007). However, advancements in methods for obtaining low altitude, high resolution imagery have increased opportunities to use optical remote sensing analysis in a wide range of riverine systems.

Historically, most optical, remotely-sensed bathymetric maps were generated through coupling aerial imagery with ground-based measurements (Fonstad and Marcus, 2005; Legleiter *et al.*, 2004; Legot *et al.*, 2007; Marcus *et al*., 2003). A barrier to the implementation of these methods was the time consuming field components that needed to be coordinated with capturing imagery (Legleiter *et al*., 2004). However, Fonstad and Marcus (2005) created a method which estimated river depths from aerial imagery without the use of ground-truth measurements. This method, called hydraulically assisted bathymetry (HAB-2), uses discharge data, valley gradient and the Manning's n roughness coefficient along with optical characteristics of imagery to estimate river depths. River depths are estimated with the Beer-Lambert law of light absorption in a water column (Fonstad and Marcus, 2005). This method is useful for bathymetry comparison over time where the older aerial imagery may not have ground-truthed data (Fonstad and Marcus, 2005). Overall, aerial imagery and remote sensing analysis can increase spatial extent and shorten the time for generating bathymetry maps (Carbonneau *et al*., 2006; Fonstad and Marcus, 2005).

DEM of difference

Repeat topographic surveys of river reaches are used to identify spatial patterns of erosion and deposition. Changes in riverbed elevation can be represented by DEMs of difference (DoD) that give insight into the influence of log structures on in-stream complexity and fish habitat diversity in the MFJD. DoDs are generally created from field survey points by first converting the survey data to triangular irregular networks (TINs). TINs are vector representations of topographic data that preserve much of the precision and complexity of the initial survey of riverbed topography (Brasington *et al*., 2000; Heritage *et al.,* 2009; Milne and Sear, 1997; Valle and Pasternack, 2006). TINs are then converted to digital elevation models (DEMs), which are raster (grid-based) representations of topographic data (Milne and Sear, 1997; Wheaton *et al.*, 2010). DoDs are generated from repeated survey data by finding the elevation difference between years for each cell of the repeated DEM (Brasington *et al*., 2000; Heritage *et al.,* 2009; Lane *et al.*, 1994; Milan *et al.*, 2011; Wheaton *et al.*, 2010). Significant topographic change can be more accurately estimated by accounting for error within individual DEMs and error propagation in DoDs. Major sources of error in survey implementation arise from systematic, human and random error.

To quantify error in individual DEMs, previous studies used uniform error (Brasington *et al*., 2000; Fuller *et al*., 2003; Lane *et al*., 1994; Milan *et al*., 2007) or spatially distributed error assessments (Heritage *et al.* 2009; Milan *et al.*, 2011; Wheaton *et al*., 2010). Uniform error assessments often quantify the uncertainty within individual DEMs by the root mean square error through a comparison of modeled verses ground truthed measurements. In contrast, Milan *et al.* (2011), Heritage *et al. (*2009) and Wheaton *et al.* (2010) developed spatially varied error assessments. The underlying premise to all three methods was that high topographic variability generated greater local elevation uncertainty, while flat topography produced lower local elevation uncertainty (Milan *et al.*, 2011; Wheaton *et al.*, 2010). Wheaton *et al.* (2010) used fuzzy inference of point density and slope to estimate spatially varied uncertainty in individual DEMs. Heritage et al. (2009) and Milan *et al.* (2011) established a linear relationship between the standard deviation of elevation error and local topographic roughness variation to estimate spatially varied uncertainty in individual DEMs.

Both uniform and spatially varied error evaluations used a minimum level of detection (LoD) to account for propagated error when combining two DEMs. The LoD separated significant elevation change from changes within the noise of the system (Brasington *et al*., 2000). Uniform minimum LoDs are subject to the problem of over or underestimating volumes of scour and fill (Milan *et al*., 2011; Wheaton *et al*., 2010). However, incorporating a spatially varied detection threshold improved sediment volume estimates and detection of overall spatial patterns of scour and fill (Milan *et al*., 2011; Wheaton *et al*., 2010).

CHAPTER III

RESEARCH QUESTIONS AND METHODS

This research investigates the following questions:

(1) What is the feasibility of using low altitude, high resolution aerial imagery to map riverbed topography?

(2) How do the spacing and densities of data points affect the accuracy of digital elevation modeling (DEM)?

(3) On a reach scale, how has bed scour and aggradation changed over time and to what degree is this associated with engineered log structures?

1. 2009 Riverbed topography comparison: aerial imagery vs. total station

Riverbed topography was mapped between June and August 2009 in the Forrest reach of the MFJD using two different methods: low-altitude high resolution photography and total station surveys. Locations where imagery overlapped total station surveys included log structures 1, 3, 8 and 12 (Figure 1).

Field surveys used a Nikon Pulse Laser Station NPL-522 total station and reflector system. The total station's horizontal precision is +/- 10.5 mm for every 100 m distance between total station and prism (Nikon-Trimble Co., 2006). The vertical distance precision is +/- 10 mm for every 100 m distance between total station and prism. Distances between the total station and survey locations in this project were less than 200m. Traditional total station survey methods generate irregularly spaced surveys, but have the advantage of user flexibility in choosing survey points to reflect important geomorphic features, transition regions and breaks in slopes (Milan *et al.*, 2011). We conducted field surveys at an approximate point spacing of 0.7m, delineating channel wetted edge and highlighting riverbed features including dug pools and changes in slope. From survey point features, we constructed TINs which were then converted to DEMs to optimize the use of raster tools in ESRI ArcMap (Milne and Sear, 1997; Wheaton *et al.*, 2010). We removed data points from the survey when they did not characterize realistic riverbed morphology (Valle and Pasternack, 2006). A range of 0-6 points were eliminated from surveys containing 300-500 points/survey area. To minimize survey edge effects, we clipped each log structure survey area using a riverbed boundary polygon (Wheaton *et al.*, 2010). We used 3D Analyst and Editor tools in ESRI ArcMap for this data processing.

The second method for estimating river bed topography used low-altitude high resolution photographs from a balloon camera platform obtained by United States Bureau of Reclamation (USBR). We georetified images in ArcMap and used the remote sensing model, HAB-2. Water depth (D) was estimated from digital number value (DN) for each pixel (Fonstad and Marcus, 2005):

$$D = \ln(DN/DN_o)/-\beta \qquad \textit{equation (1)}$$

The β coefficient value is a diffuse attenuation coefficient that indicates the strength of absorption per unit depth and is calculated by the HAB model (Fonstad and Marcus, 2005). DNo is the digital number at the wetted edge of the river cross section. Inputs were collected from several sources: discharge was obtained from summer stage readings operated by the non-profit organization Freshwater Trust (Appendix E). The average valley gradient within the Forrest reach, 0.54%, was calculated from the 2006 bare earth LiDAR imagery flown by the USBR. Cross section digital values necessary to run the HAB-2 model were extracted from the color imagery using ArcMap.

2. *Digital elevation modeling: effect of survey point density and spacing*

In July and August 2010, we conducted a dense field survey at log structure 3 in the Forrest reach (Figure 1) with an average point spacing of 0.15m following techniques outlined above. From this dense field survey we evaluated the effect of point density and spacing on modeling topographic complexity using two approaches. In the first approach, topographic complexity was calculated using the ratio of the 3D surface area to the 2D planimetric area (Brasington *et al,* 2000; Lane *et al.,* 1994). The dense set of data points surveyed in 2010 was thinned progressively. Thinned datasets containing between 1.5 and 100 percent of the original survey points were converted into TINs and then into DEMs.

As a second approach we compared volumetric changes from the original dense survey as point density and spacing coarsen. 3D Analyst and Spatial Statistics tools in ESRI ArcMap were used to extract surface area, planimetric area, volume, and average point density and spacing for subsequent datasets. These numerical experiments graphically showed the thresholds at which topographic complexity is lost as survey density and point spacing decrease (Brasington *et al.*, 2000; Lane *et al.,* 1994).

Based on previous studies, we generated DEMs with 0.1 m cell size. An analysis by Milne and Sear (1997) and Brasington *et al.* (2000) compared volume estimates corresponding to different cell sizes. In these studies as raster cell sizes increased, volumes were increasingly underestimated. Brasington *et al*. (2000) used a 0.25m cell size and Milne and Sear (1997) used a 0.20m cell size. At these coarser cell sizes as compared to the original fine cell sizes, little volumetric change occurred. However, coarser cell sizes allowed for more efficient processing and storage. Milne and Sear (1997) surveyed river reaches between 325 and 1010m in length, and the reach length surveyed by Brasington *et al.* (2000) was 200m. In contrast, our smaller river contained survey areas with an average reach length of 21m. Since we were not limited by storage space and our DEM generations were for smaller survey areas, we used a fine cell size of 0.1m.

3. Riverbed topographic change between 2008 and 2010

We used the same field survey methods to conduct repeat topographic surveys of log structure sites in the Forrest reach in 2008 and 2010 in order to establish spatial patterns of erosion and deposition.

The change in riverbed topography between 2008 and 2010 was calculated through DoDs. A DoD based on a spatially varied error assessment was calculated with methods outlined in Milan *et al*., 2011. Using this technique, a gross DoD was established through raster subtraction of the 2008 DEM from the 2010 DEM. Then the minimum LoD was subtracted from the gross DoD to generate a final DoD for each survey site. The minimum LoD is:

$$LoD= t\surd\ (\sigma_{e1})^2 + (\sigma_{e2})^2 \qquad \textit{equation (2)}$$

where σ_{e1} and σ_{e2} are spatially varied error assessments for individual 2008 and 2010 DEMs. σ_{e1} and σ_{e2} are established through a linear relationship between topographic variability and the standard deviation of elevation error. Standard deviation of elevation error is calculated from elevation error within local variability intervals (Appendix D). The t value is the confidence interval (in this case t = 1.96 for a 96% confidence limit). The LoD establishes the threshold separating significant elevation changes from elevation changes less than the magnitude of uncertainty of the modeled surfaces. Both 3D Analyst in ArcMap and linear regressions generated in Microsoft Excel were used to generate subsequent DoD rasters. Final 2010-2008 DoDs were analyzed for seven log structure sites in the Forrest reach (log structure 1, 3, 4, 5, 8, 9 and 12 in Figure 1). These log structure sites were chosen to represent the diversity of log structures within the

Forrest reach including the larger log structure designs and different structure orientations.

CHAPTER IV

RESULTS AND DISCUSSION

1. 2009 Riverbed topography comparison: aerial imagery vs. total station

The HAB-2 modeling technique is not an appropriate remote sensing model for this type of river. The MFJD channel banks are characterized by overhanging vegetation, in-stream aquatic macrophytes, vegetated bars and cut banks. Without regions of exposed sediment, these types of channel banks make it challenging to choose an accurate DN_o value (Figure 2a). The DN_o value is essential in calibrating the HAB-2 algorithm. In our imagery, the reflectance of vegetation is equal to or lower than the reflectance of water. This creates unrealistic cross section extraction from DN pixel values. Minimal elevation differences are distinguished between higher banks and immersed riverbed (Figure 2c).

In addition HAB-2 is dependent on accurate DN values to estimate river depth (equation 1). Uncompressed files such as .tiffs instead of .jpegs are essential for this analysis. Image compression and other alterations during the image processing distort the spectral properties of the imagery. Water should have a higher reflectance in the green band than the red band (Legleiter *et al*., 2004). However, the natural log ratio between green and red bands produced negatives values from extracted MFJD imagery DN values, indicating that red reflectances were higher than green. This indicated DN values were altered by the compression process in a way that made them unsuitable for the HAB-2 algorithm.

While HAB-2 has its limitations (outlined in Fonstad and Marcus, 2005), previous studies have shown that HAB-2 is accurate in predicting river depths without the need for ground truth data (Fonstad and Marcus, 2005, Walther *et al.*, in press). When appropriate, HAB-2 modeling in restoration could provide efficient assessments of current and past bathymetry.

2. *Digital elevation modeling: effect of point density and spacing*

Through a systematic thinning of the dense survey at log structure 3, we investigated the effect of point density and spacing on DEMs.

Figure 3 shows that topographic complexity (where greater complexity is a higher ratio of 3D to 2D area) decreased as data points were thinned from the original DEM raster. Complexity leveled off at an average point density of 15-10 points/m^2, which corresponded to average point spacing of 0.16-0.19m. The slope break occurred where densities and point spacing were coarser than 10pts/m^2 or 0.19 m respectively (Figure 3). Plateaus and thresholds were difficult to characterize in the topographic complexity numerical experiment.

In the volumetric change numerical experiment a threshold was observed at 0.50m point spacing (1.25 pts/m^2) (Figure 4). Minimal net volumetric change from the original survey area occurred between 20.54 and 1.25 pts/m^2 (0.15-0.50 m point spacing). A threshold occurred when negative net volumetric changes increased with the coarsening of point spacing and density. As point density and spacing coarsen, negative change exceeds positive change resulting in larger negative net volumetric change. At a point distribution coarser than 1.25 pts/m^2 or 0.50m, negative volumetric changes increased. The volumetric change experiment compared to topographic complexity experiment more clearly demonstrates a threshold as point density and distribution coarsen. The coarser threshold exhibited in the volumetric change numerical experiment suggests there might be a threshold which is not visible in the topographic complexity numerical experiment. Greater confidence in the volumetric change numerical experiment leads us to choose the numerical experiment results shown in Figure 4. This volumetric change experiment suggests that field surveys in the MFJD conducted with average point density and spacing finer than 1.25pts/ m^2 or 0.50m are appropriate to capture bedform complexity.

Brasington *et al.* (2000) assert that river study sites with different reach scales will exhibit different thresholds at which bedform changes can be captured. Average bankfull width was used to compare our study site to previous studies (Table 1, see Appendix A for all other tables). While average bankfull width is difficult to characterize in dynamic systems like braided rivers, this comparison revealed a wide range of thresholds to support statements made by Brasington *et al.* (2000). The average point spacing per bankfull width ranged from 0.015 to 0.050 m/m, corresponding to average point density per bankfull width from 0.005 to 0.500 pts/m^2/m. The MFJD thresholds per bankfull width were 0.044m/m and 0.110 pts/m^2/m (Table 1). The MFJD thresholds are most similar to that of the high gradient, step-pool river studied in Valle and Pasternack (2006). In contrast, the braided rivers in Brasington *et al.* (2000) and Lane *et al.* (1994) produced numerical thresholds per bankfull width ranging from 0.005 to 0.350 pts/m^2/m. This comparison suggests that thresholds may be more dependent on variations in bankfull width than channel pattern type.

In contrast to the thresholds, 10pts/m^2 (0.19 m) from the topographic complexity experiment and 1.25 pts/m^2 (0.50m) from the volumetric change experiment, the current 2010 topographic log structure surveys were conducted with an average point spacing of approximately 0.70m. At the average point spacing of 0.70m, each log structure survey took 1 to 1.5 field days, producing approximately 300 to 500 points/survey area.

Surveying at the level of detail suggested by the numerical experiments would not be efficient or possible in this type of on-the-ground restoration monitoring. Combining current methods and numerical thresholds can provide an efficient yet more detailed survey protocol. For example, survey spacing on relatively flat topography could continue at 0.70m spacing, but geomorphic features of interest could be surveyed at 0.4m spacing. These types of improvements to survey methodology would better capture riverbed complexity and improve long-term monitoring of geomorphic change.

3. Riverbed topographic change between 2008 and 2010

Overbank flow, estimated to be less than 5 year flood events, occurred in both winter and spring floods between the construction of log structures in 2008 and repeat topographic surveying in 2010 (Cochran, 2011; Appendix E). The spatial distribution of fill and scour is illustrated in Figures 5-10. The areas of elevation change less than the minimum LOD (gray regions) tend to be between regions of aggradation and scour where there is higher error associated with local variability. The 2008 and 2010 DEMs are in Appendix C. The riverbed morphology changes in response to engineered log structures are described below.

Log structure 1

Log structure 1 is located along a tight meander bend where rock spurs were removed along the outer bank (Figure 5). Two rock spurs remain along the outer bank entering the meander to prevent lateral migration into the main MFJD road and a gate. A 0.9m deep DP was constructed directly under log structure 1, along the downstream end of the meander bend and along the right bank (Appendix C1).

Log structure 1 DoD indicated regions of scour along the right bank under the log structure. Negative values indicate a lowering of channel bed from 2008 to 2010. A region of similar elevation change was located along the right bank and slightly downstream of the log structure site. Both scour regions were shallow in 2008 and deepened 0.1 to 0.9m. Pool formation is expected along the downstream end of meander bends like this location. With the removal of rock spurs, the river can now scour along the outer banks. These regions of scour may indicate a location at which the river is reclaiming its natural morphology. Additionally, log structure 1 DoD indicates a zone of slight aggradation just outboard of the log structure and approximately in the deepest part of the original 2008 DP (Appendix C1). Aggradation values were up to 0.2m. While there is slight aggradation within the deepest sections of the original DP, pool morphology is maintained or continuing to scour. Log structure 1 DoD reveals that classic meander bend and point bar migration are now occurring.

Log structure 3

Log structure 3 is located along the right bank with a DP constructed under the rootwads and approximately 0.6m deep. The aggradation in the deepest portion of the orginal DP indicates the original DP morphology was not stable and possibly was too deep (Appendix C2). Possibly due to the configuration of wood, deflection of flow is creating a large region of scour along the left edge of the DP, with scour up to -0.3m. The combination of aggradation within the deepest sections of the orginial DP and scour along the shallower left edge of the DP is creating a larger and shallower pool morphology. Upstream and downstream of log structure 3, minimal elevation changes are seen, with both deposition and scour are between 0.1 to -0.1m.

Log structures 4 and 5

Log structure 4 was constructed with rootwads and a 0.6m deep DP positioned in the thalwag of the river flow. Log structure 4 DoD indicated erosion was dominant within the survey area (Figure 7). Minimal elevation change of 0.1 to -0.2m occurred within the DP. The overall dug pool form and depths created in 2008 (Appendix C3) are being maintained and are continuing to scour. Downstream of the log structure along the right cut bank was the largest degradation region, with elevation change between 0 and -0.5m.

Log structure 5 was constructed downstream of a remnant side channel by removing rock spurs along the right bank and creating a 0.6m DP under log structure rootwads. In-stream boulders upstream of the side channel remain (Figure 7a). The inlet of the remnant side channel was excavated and graded to encourage inundation during high flows.

Log structure 5 DoD indicates that a region of high degradation occurred upstream of the log structure with elevation changes between 0 and -0.9m. In 2008, this was a shallow region in and around the remaining in-stream boulders (Appendix C3.). Elevation changes indicate smoothing of bed topography in and around in-stream boulders, but slight deposition associated with the side channel just upstream of log structure 5. Changes observed around the boulders may be an artifact of differences in surveying in 2008 and 2010. In contrast to log structure 4, regions under log structure 5 are aggrading with elevation changes up to 0.2m.

Log structure 8

Log structure 8 was constructed with a 0.6m deep DP under rootwads, upstream of spanning log (Figure 8). The spanning log is embedded into the right bank, but was not embedded along the riverbed.

Log structure 8 DoD indicated minimal elevation changes, including both deposition and scour from 0.1 to -0.1m in the original DP (Figure 8). The elevations from 2008 and the form of the pool are being maintained (Appendix C4.) There are two regions of scour along the left bank, upstream and downstream of the log structure, with elevation changes between 0 and -0.5m. In 2008, these were shallow zones possibly related to bank slumping during construction, and the scour has produced a more regular bed and bank morphology along the left bank. In addition, there is slight scour (mainly less than 0.1m) upstream and downstream of the spanning log. The regions of scour upstream and downstream of the spanning log indicate that this spanning log may have little to no effect on bed topography changes.

Log structure 9

Log structure 9 was constructed along the left bank with a 0.6m deep DP under the rootwads and a key log piece parallel to river flow (Figure 9).

The log structure 9 DoD indicated complex midstream patterns of aggradation and degradation (Figure 9). Minimal elevation changes occurred upstream and downstream of log structure 9. The most significant region of deposition occurred along the log piece parallel to river flow. The deposition ranged up to 0.3m. This region of aggradation occurred in the deepest regions of the 2008 DP (Appendix C5). However, scour, ranging from 0 to 0.3m, under and downstream of the rootwads may be extending pool form. The combination of scour and aggradation associated with the log structure may be creating a larger but shallower pool than the original DP (Appendix C5). In addition to the midchannel elevation changes, there was a region of scour (up to 0.8m) behind the log structure that appears to be removals of bank aggradation or slumping similar to that observed in log structure 8.

Log structure 12

Log structure 12 was located where rock spurs were removed along the left bank and a 0.6m DP was constructed under the rootwads. Log structure 12 DoD indicated overall aggradation with elevation changes from 0 to 0.2m (Figure 10). The overall survey area reveals little to no change associated with log structure 12.

Log structure discussion

Riffle-pool sequences in gravel rivers, such as the MFJD, are important in establishing habitat for anadromous fish such as steelhead and Chinook salmon (Clifford and Richards, 1992). Log structures are recognized to indirectly improve fish habitat by increasing the frequency of riffle-pool sequences (Abbe *et al*., 2003; Montgomery and Piegay, 2003). In addition, log structures create in-stream habitat including pools (Abbe and Montgomery, 1996). In this study, MFJD riverbed topographic changes associated with log structures, over a 2-year period with only moderate peak flows, range between -0.9 and 0.5m.

Log structures 1 and 5 survey areas exhibited the greatest scour, up to -0.9m (Figure 5, 7). These scour regions occur at different locations in their respective survey areas; log structure 1 scour occurs along the outer bank at shallow bed margin locations under the log structure, whereas log structure 5 scour occurs midstream upstream of the structure. Log structure 1 scour may be attributed to the removal of rock spurs, allowing deepening and removal of slump along the outer banks. In contrast, log structure 5 scour may be an artifact of differences in surveying in 2008 and 2010 around in-stream boulders. In addition, the greatest aggradation, up to 0.5m, occurred in log structure 1, 8 and 9 survey areas (Figure 5, 8 and 9). High aggradation along the banks is associated with post-2008 bank slumping or sediment accumulation behind the log structure 1, 8, and 9. The majority of constructed DPs maintained original elevation with minimal elevation changes, between 0.1 to -0.1m. However, log structure 3 and 12 DoDs (Figures 3, 10) may indicate a shallowing of pool morphology. At log structure 8 (Figure 8), the spanning log design appears to have little to no effect on riverbed topographic changes.

Net volumetric changes ranged from 2.55m^3 to -8.29m^3 (Table 2). Net scour was present in all log structure surveys except for log structure 12. The highest net volumetric change per survey area occurred in log structure 5 with -0.097 m^3/m^2 (Figure 7), but most of the degradation may be an artifact of differences in surveying in 2008 and 2010 around in-stream boulders. In contrast, the smallest net volumetric change per survey area occurred at log structure 3 with -0.026 m^3/m^2 change (Figure 6). This is most evident in the log structure 3 DoD which indicates a flattening of pool morphology, continued aggradation along riffle just upstream of the log structure and aggradation along the cut bank downstream of the log structure. Because the net riverbed elevation change at most structures is negative, it is fair to say that the overall effect of the structures between 2008 and 2010 was slight but positive for fish habitat diversity.

Topographic changes may increase as the river continues to respond to restoration work. Continued topographic monitoring and DoD analysis will help assess the effectiveness of log structures and the potential increase in fish habitat in the MFJD.

CHAPTER V

CONCLUSION AND IMPLICATIONS

Incorporating aerial imagery analysis into restoration design, including pre-project assessments or post-project monitoring, could provide efficient evaluations across a large spatial extent. Due to river characteristics and image compression, the HAB-2 model could not accurately estimate river depths in the MFJD. In the future, obtaining uncompressed tiff images and using correlation-based approaches rather than the HAB-2 model will be important in estimating river depths.

Conducting a numerical experiment similar to Lane *et al*. (1994), Brasington *et al.* (2000) and Valle and Pasternack (2006) has provided insight to ideal survey point distribution and density that best captures riverbed complexity. Incorporating a 0.50 m spacing (1.25pts/m^2 density) into future on-the-ground surveying methods would capture more river complexity of the MFJD. Due to time constraints of on-the-ground surveying, the numerical experiment thresholds may represent the idealized point distribution and density necessary to capture riverbed complexity. Survey methods could incorporate these thresholds for geomorphic features of interest including slope changes, DPs and log structures. These types of adaptations to surveying methods could improve the ability to capture riverbed complexity without compromising field time. As Brasington *et al*. (2000) asserted, our comparison of numerical thresholds (Table 1) suggests that thresholds are more dependent on varying average bankfull width than channel pattern type.

In a relatively short timeframe of two years, detectable -0.9 to 0.5m elevation changes occurred in and around MFJD log structure sites. The application of DoD analysis in river restoration monitoring indicates the potential direction of riverbed change. Pairing log structure design with removal of rock spurs can create opportunities for increased scour along the outer banks of meanders. In addition, rootwads of log structures are contributing to scour effects and contributing to pool morphology. The effectiveness of log structures, the removal of rock spurs and reactivation of a side channel in the MFJD Forrest reach to achieve restoration goals may be better characterized on a 5- 10 year timescale, when responses to restoration work have matured. Continued monitoring of geomorphic changes and conducting DoD analysis are not only important for sediment budgets (Brasington *et al.*, 2000; Milan *et al.*, 2011; Wheaton *et al.* 2010), but also important in evaluating and improving restoration structure design.

APPENDIX A

TABLES

Studies	Bed configuration	Channel Pattern	D50 (mm)	valley gradient (%)	Average point spacing (m)	Average point density (pts/ m^2)	Average bankfull width (m)	Average point spacing per study bankfull width (m/m)	Average point density per study bankfull width (pts/ m^2/ m)
MFJD Forrest reach	gravel bed river	riflle-pool channel	73	0.54	0.5	1.25	11.4	0.044	0.110
Valle and Pasternack, 2006	bedrock, boulder river	step - pool channel	85	4.3	0.4	7	14	0.029	0.500
Brasington *et al.*, 2000	gravel bed river	braided channel	65	1	1.0	0.3	65	0.015	0.005
Lane *et al.*, 1994	gravel bed river	braided proglacial channel	n/a*	n/a*	0.5	3.5	10	0.050	0.350

Table 1. Average point spacing and average point density threshold comparison. *information not provided in Lane *et al.* (1994)

Log structures	**1**	**3**	**4**	**5**	**8**	**9**	**12**
Net scour (m^3)	-9.44	-3.75	-2.85	-9.78	-3.11	-3.82	-0.25
Net fill (m^3)	1.15	1.44	0.44	1.60	1.05	1.31	2.80
Net change (m^3)	-8.29	-2.31	-2.41	-8.18	-2.06	-2.52	2.55
Area surveyed (m^2)	92.71	88.97	69.55	84.21	57.76	71.29	53.69
Volume (m^3)/survey area (m^2)	-0.089	-0.026	-0.035	-0.097	-0.036	-0.035	0.048

Table 2. Volumetric changes for log structure survey sites between 2008-2010.

APPENDIX B

FIGURES

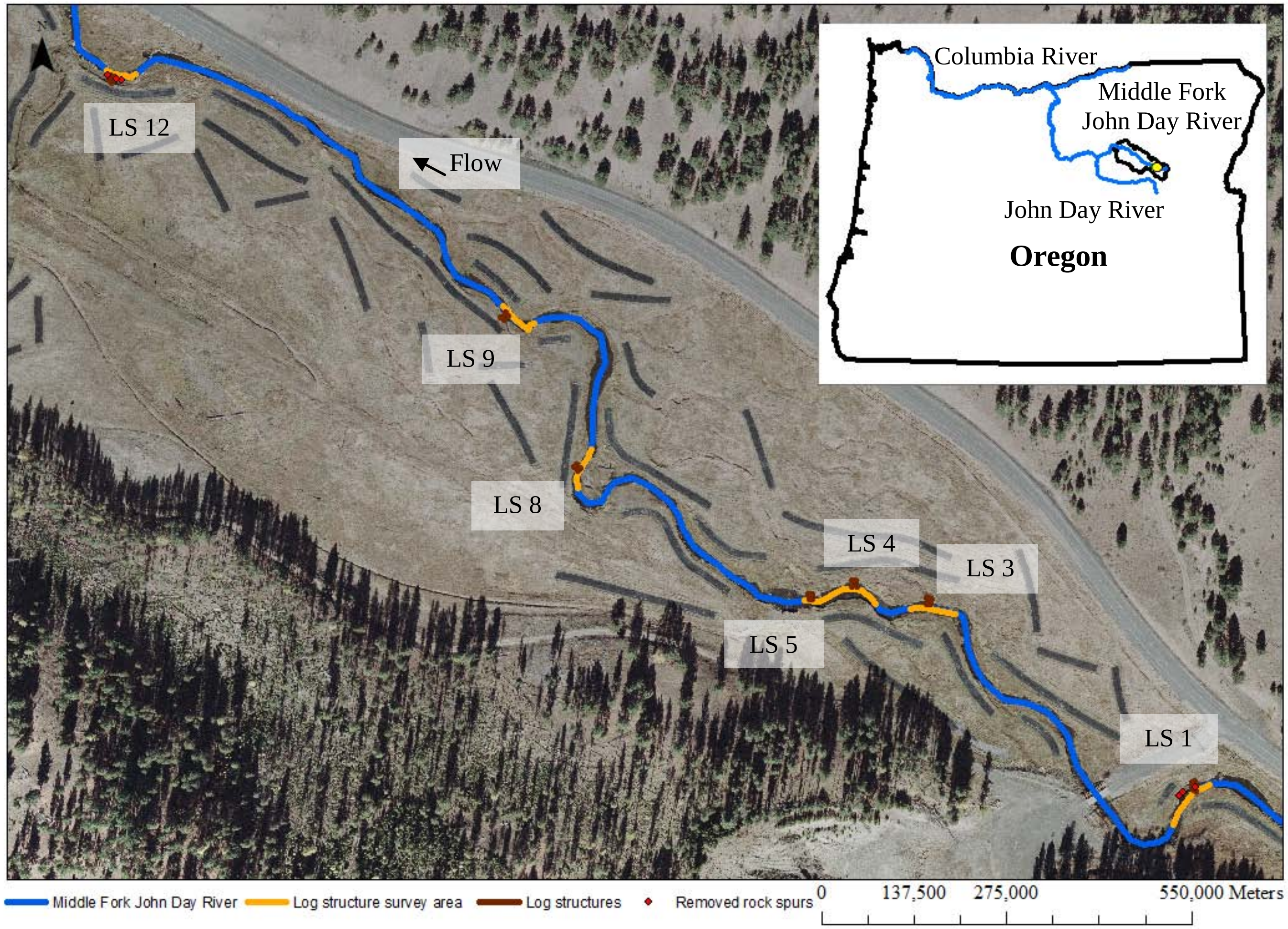


Figure 1. Middle Fork John Day River Forrest reach study site is located in Eastern Oregon in the Middle Fork John Day basin. Inset map shows location of the study reach with a yellow dot.

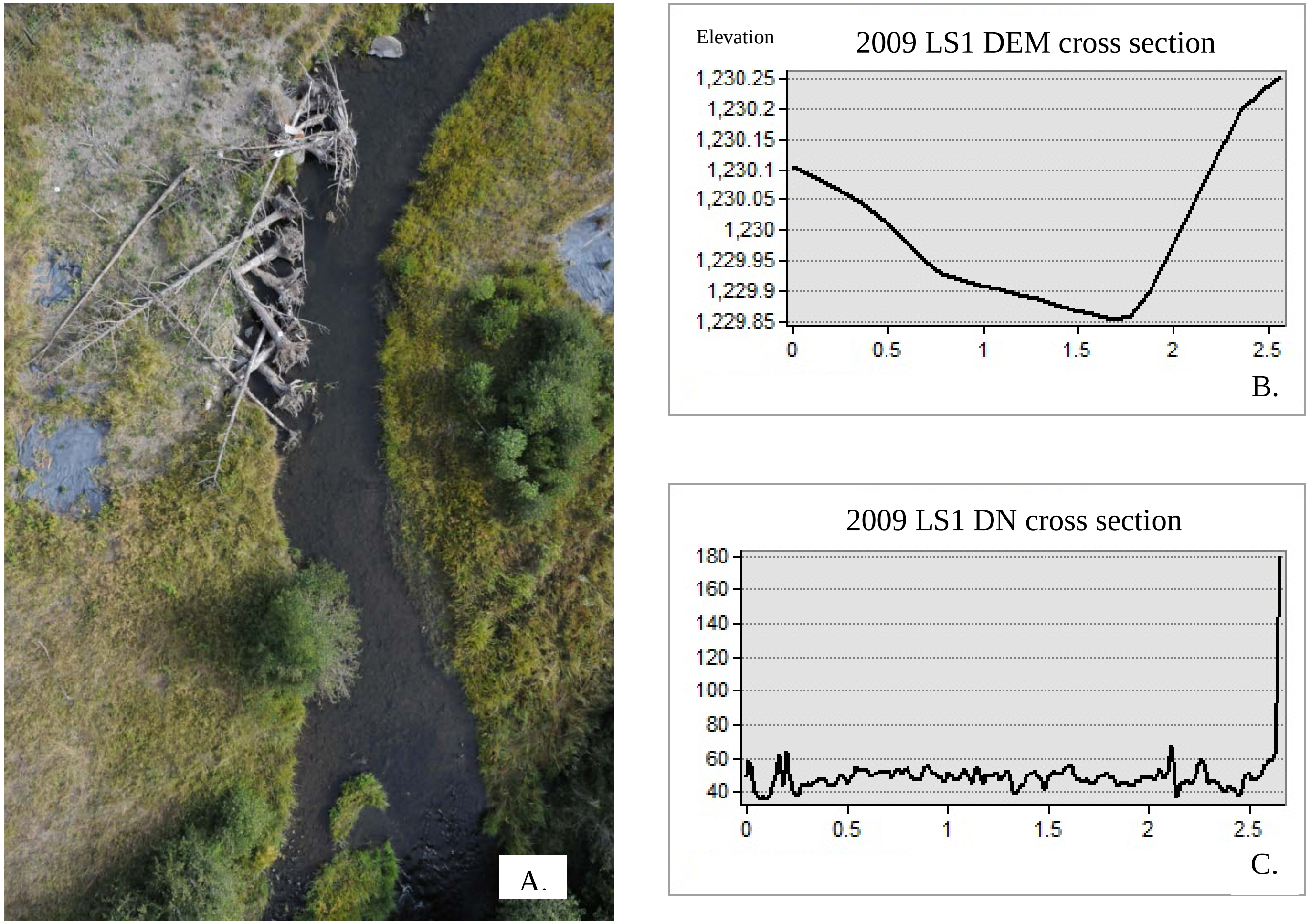


Figure 2. Unsuitable conditions to run HAB-2 algorithm to estimate river depths where a) is the 2009 aerial imagery of LS 1; b) is the extracted cross section from 2009 DEM raster; c) is corresponding extracted DN cross section

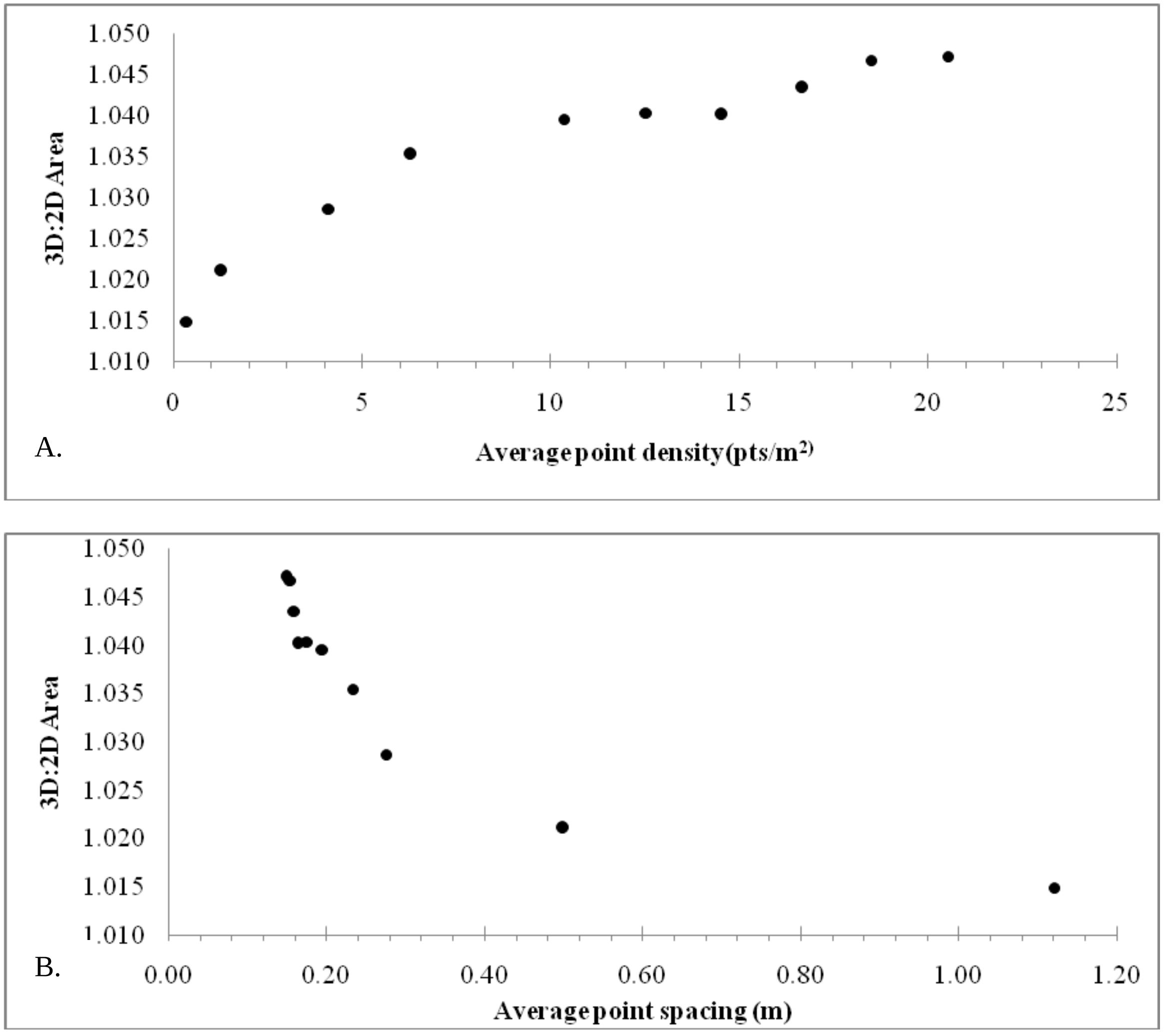


Figure 3. The ratio of 3D surface area to 2D planimetric area verses a) average point density (pts/ m^2); b) average point spacing (m).

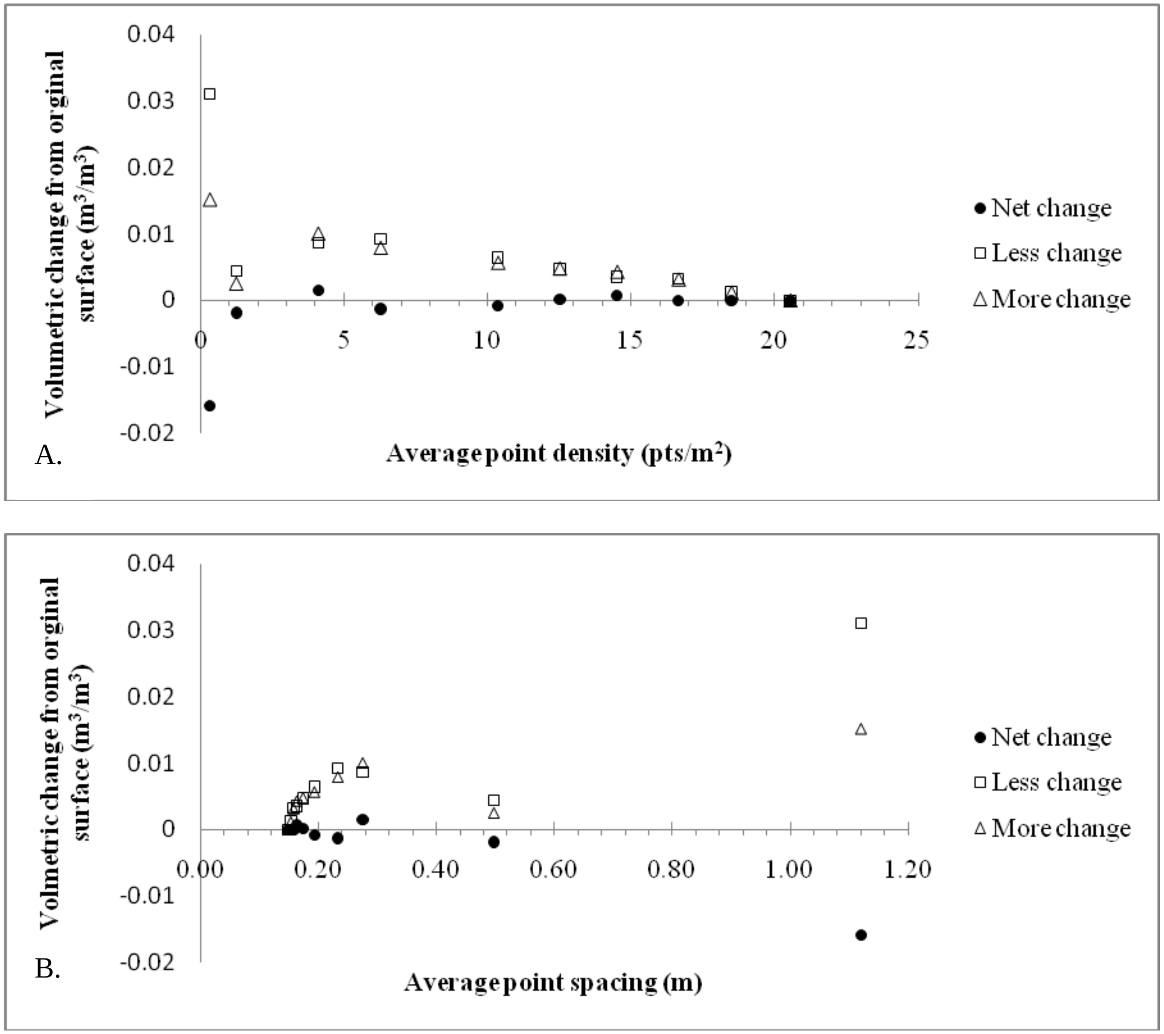


Figure 4. Net volumetric change per unit area verses a)average point density (pts/ m^2); b) average point spacing (m)

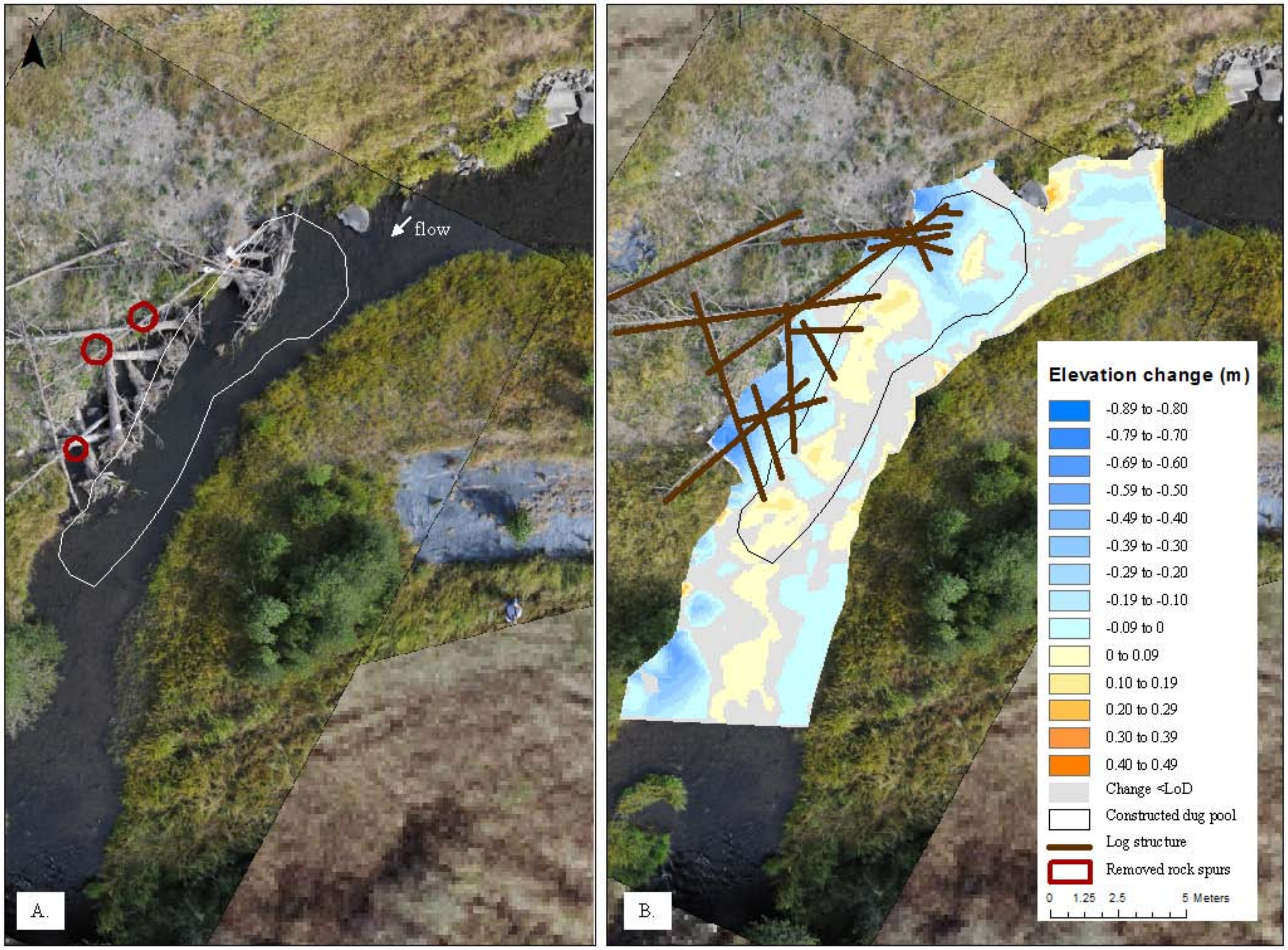


Figure 5. Log structure 1, MFJD Forrest reach a) is the log structure and rootwad orientation. Red circles indicate locations of rock spur removal and the white line delineates the original constructed dug pool. b) is 2010-2008 DEM of difference (DoD) showing elevation change (m)

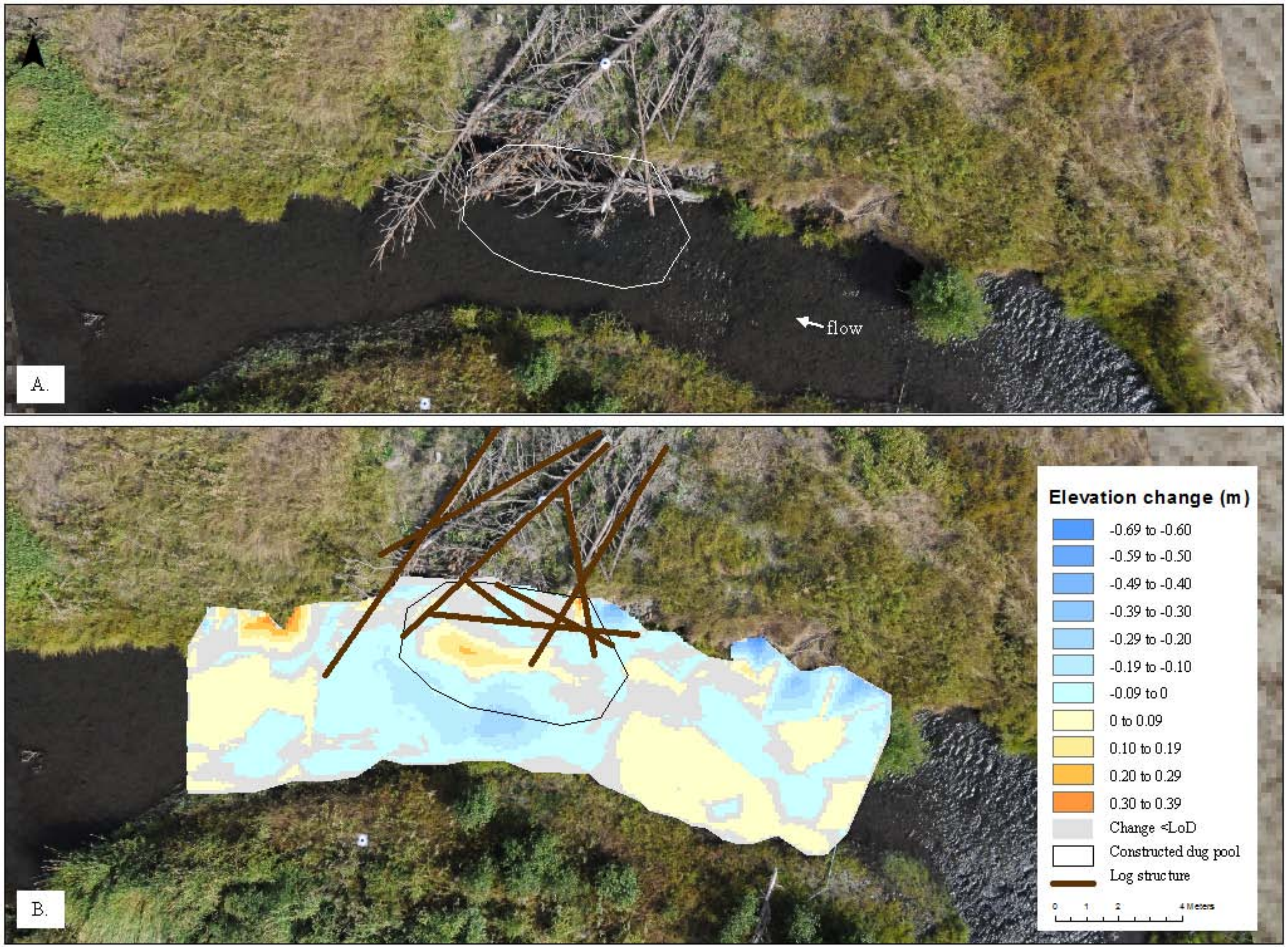


Figure 6. Log structure 3, MFJD Forrest reach a) is the log structure and rootwad orientation. The white line delineates the original constructed dug pool. b) is 2010-2008 DEM of difference (DoD) showing elevation change (m)

Figure 7. Log structures 4 and 5, MFJD Forrest reach a) is the log structure and rootwad orientation. Red circles indicate locations of rock spur removal and the white line delineates the original constructed dug pool. b) is 2010-2008 DEM of difference (DoD) showing elevation change (m)

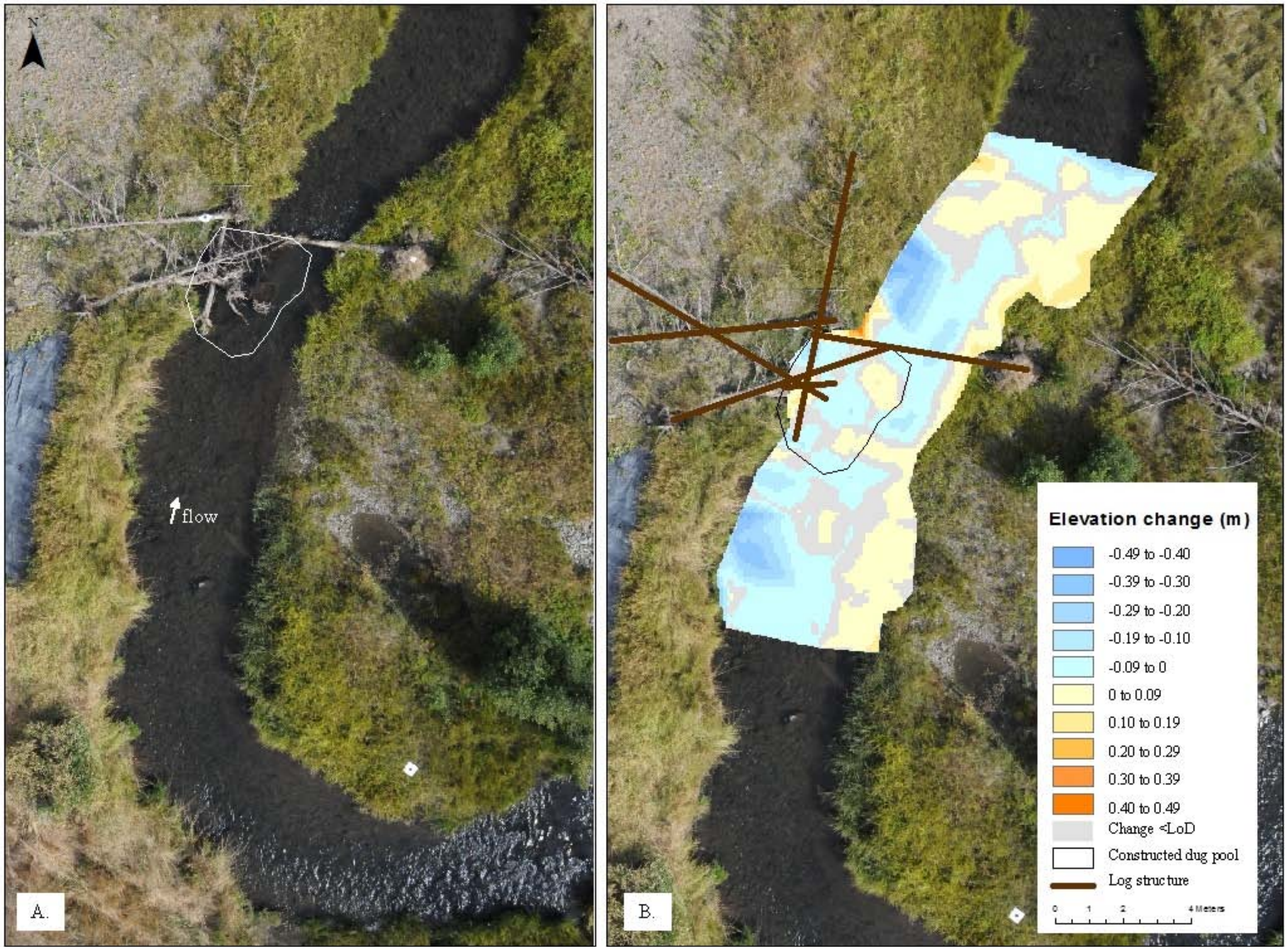


Figure 8. Log structure 8, MFJD Forrest reach a) is the log structure and rootwad orientation. The white line delineates the original constructed dug pool. b) is 2010-2008 DEM of difference (DoD) showing elevation change (m)

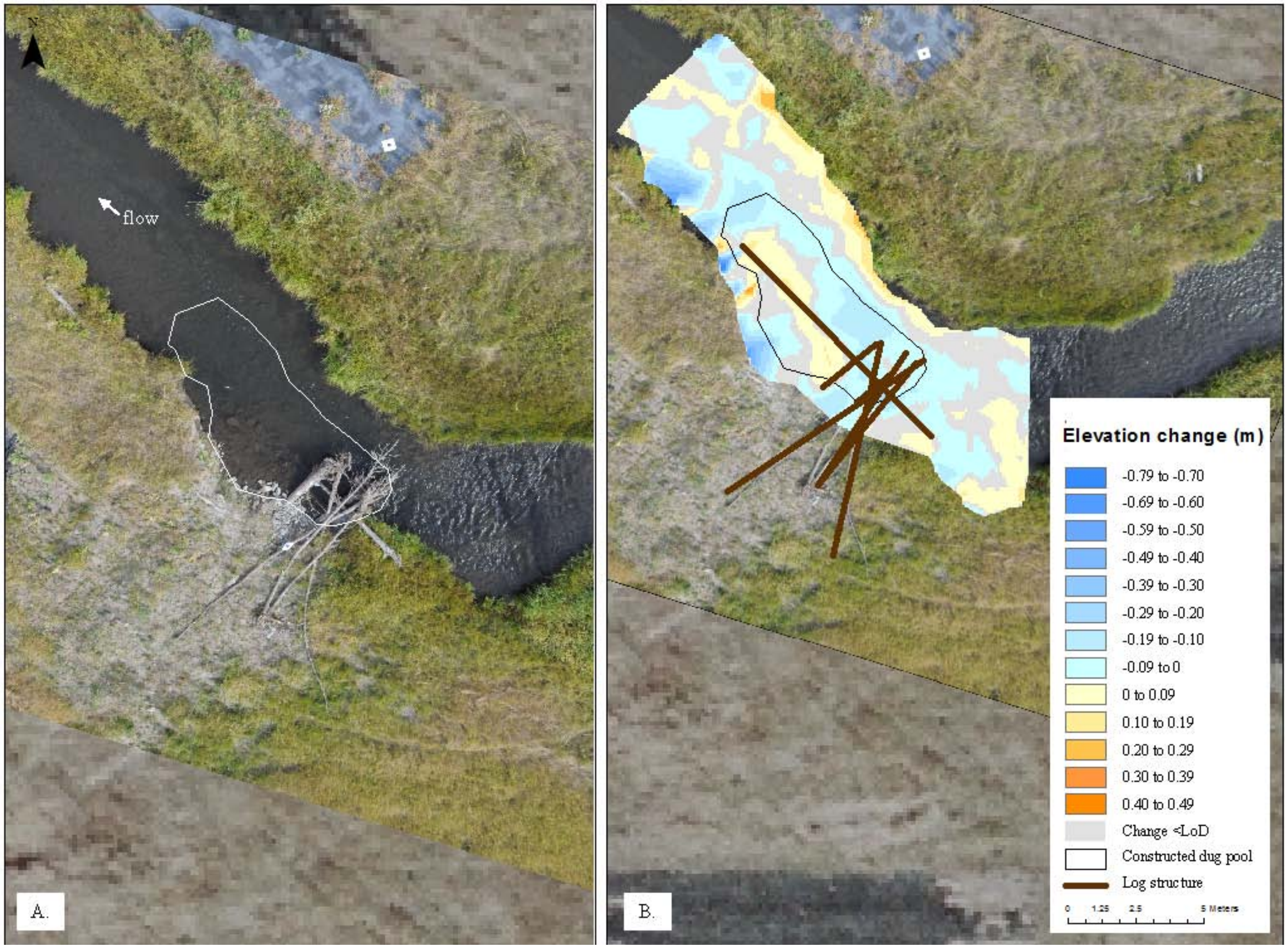


Figure 9. Log structure 9, MFJD Forrest reach a) is the log structure and rootwad orientation. The white line delineates the original constructed dug pool. b) is 2010-2008 DEM of difference (DoD) showing elevation change (m)

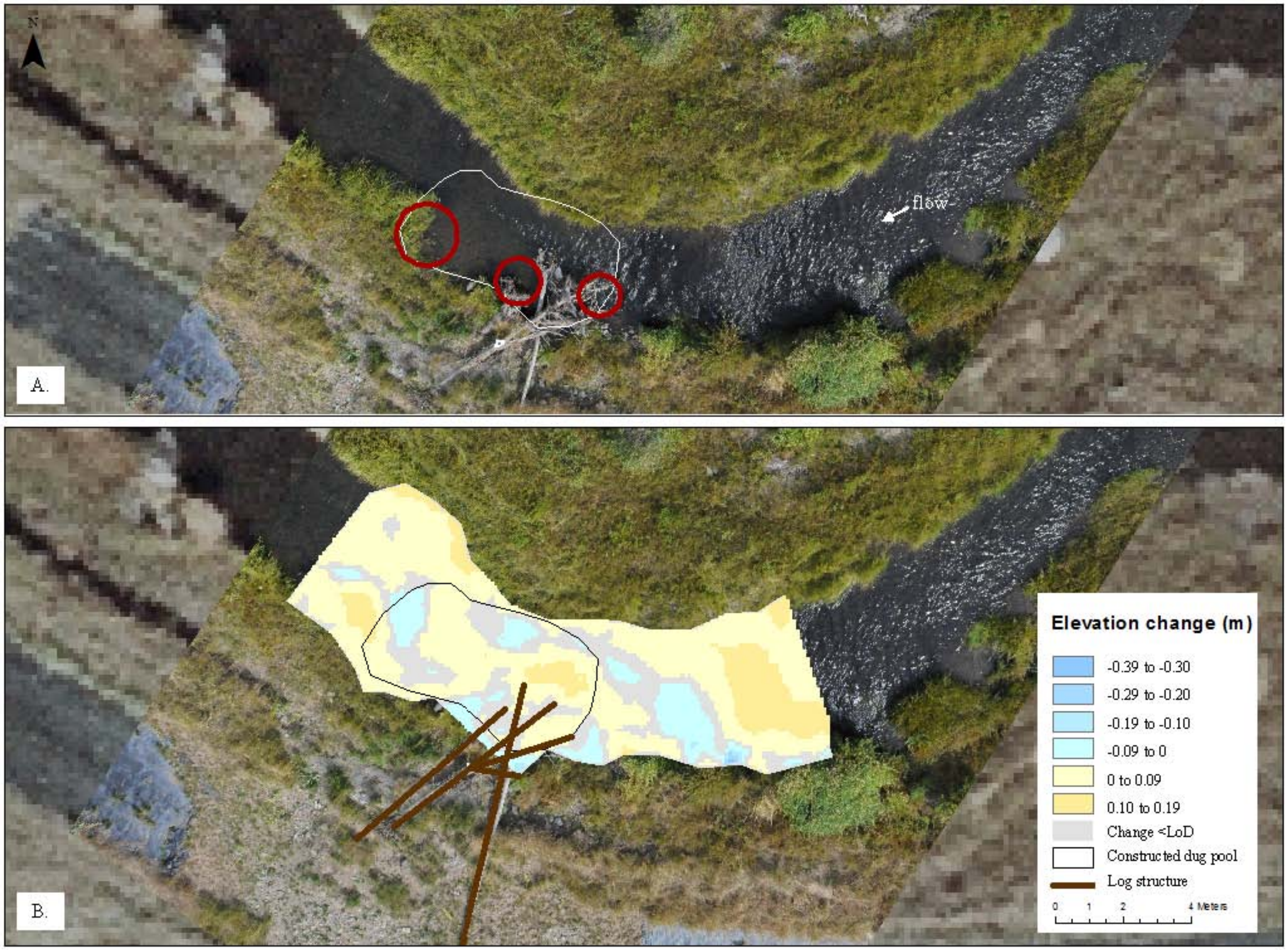
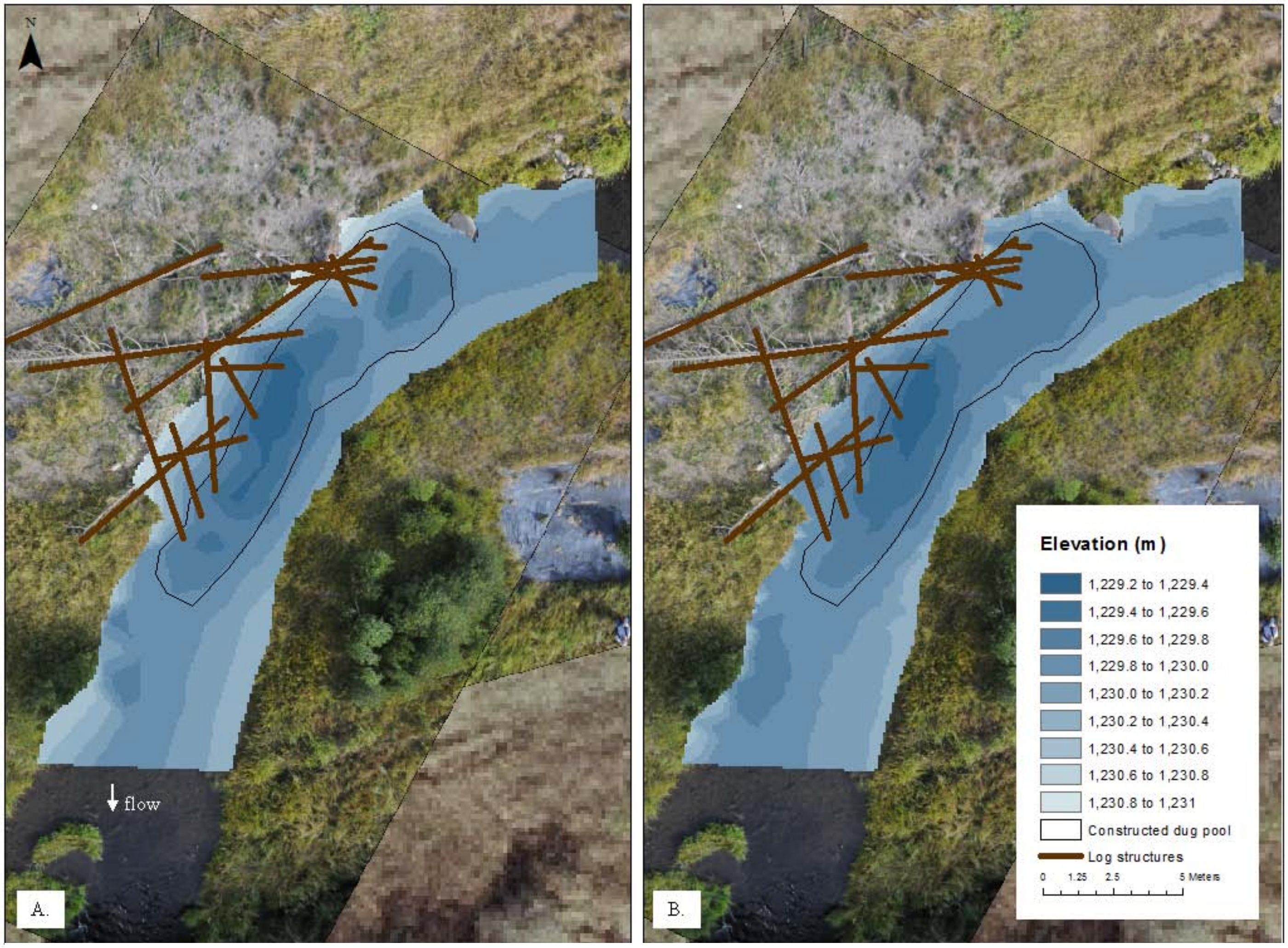


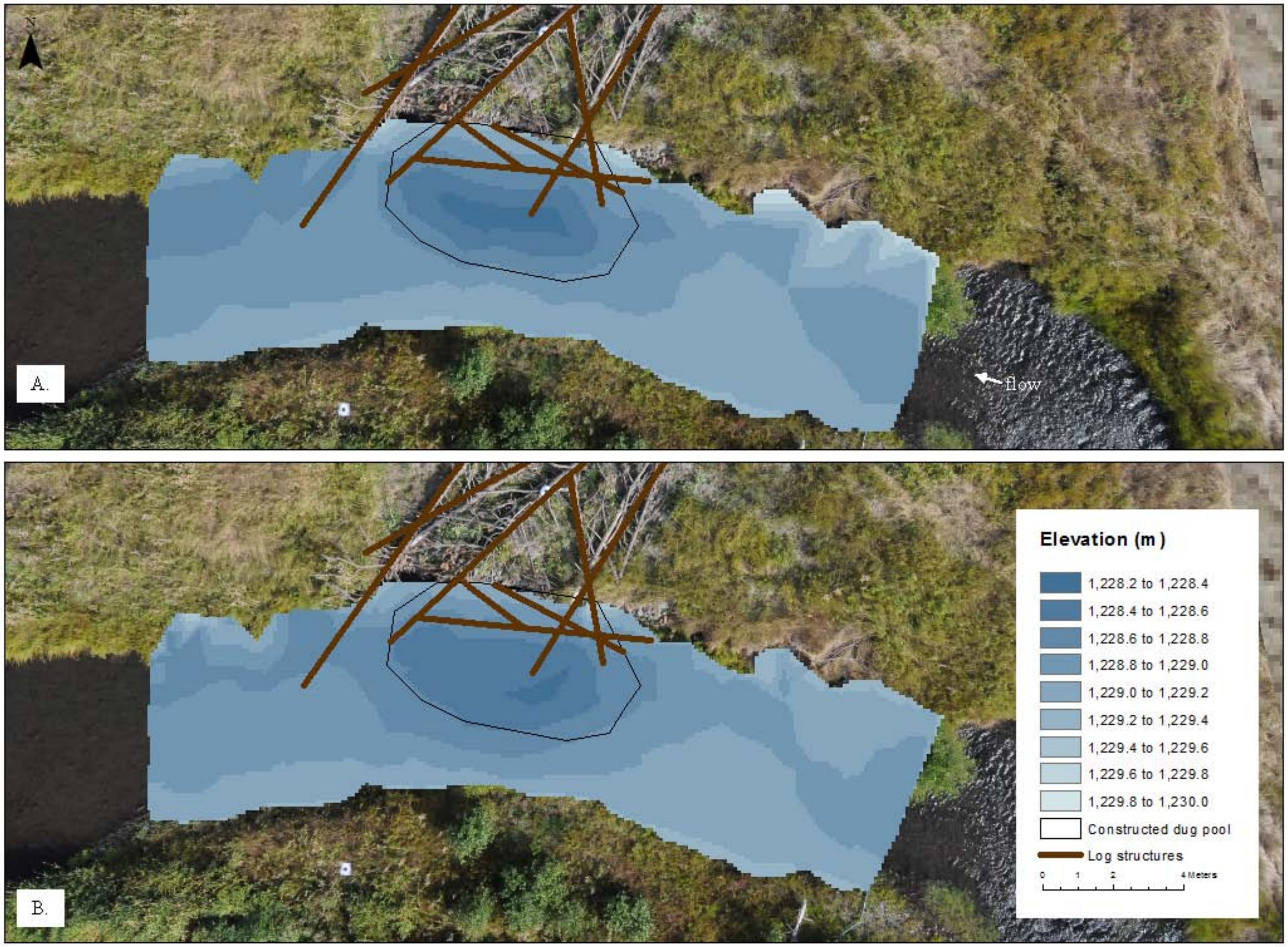
Figure 10. Log structure 12, MFJD Forrest reach a) is the log structure and rootwad orientation. Red circles indicate locations of rock spur removal and the white line delineates the original constructed dug pool. b) is 2010-2008 DEM of difference (DoD) showing elevation change (m)

APPENDIX C

2008 AND 2010 DEM MAPS

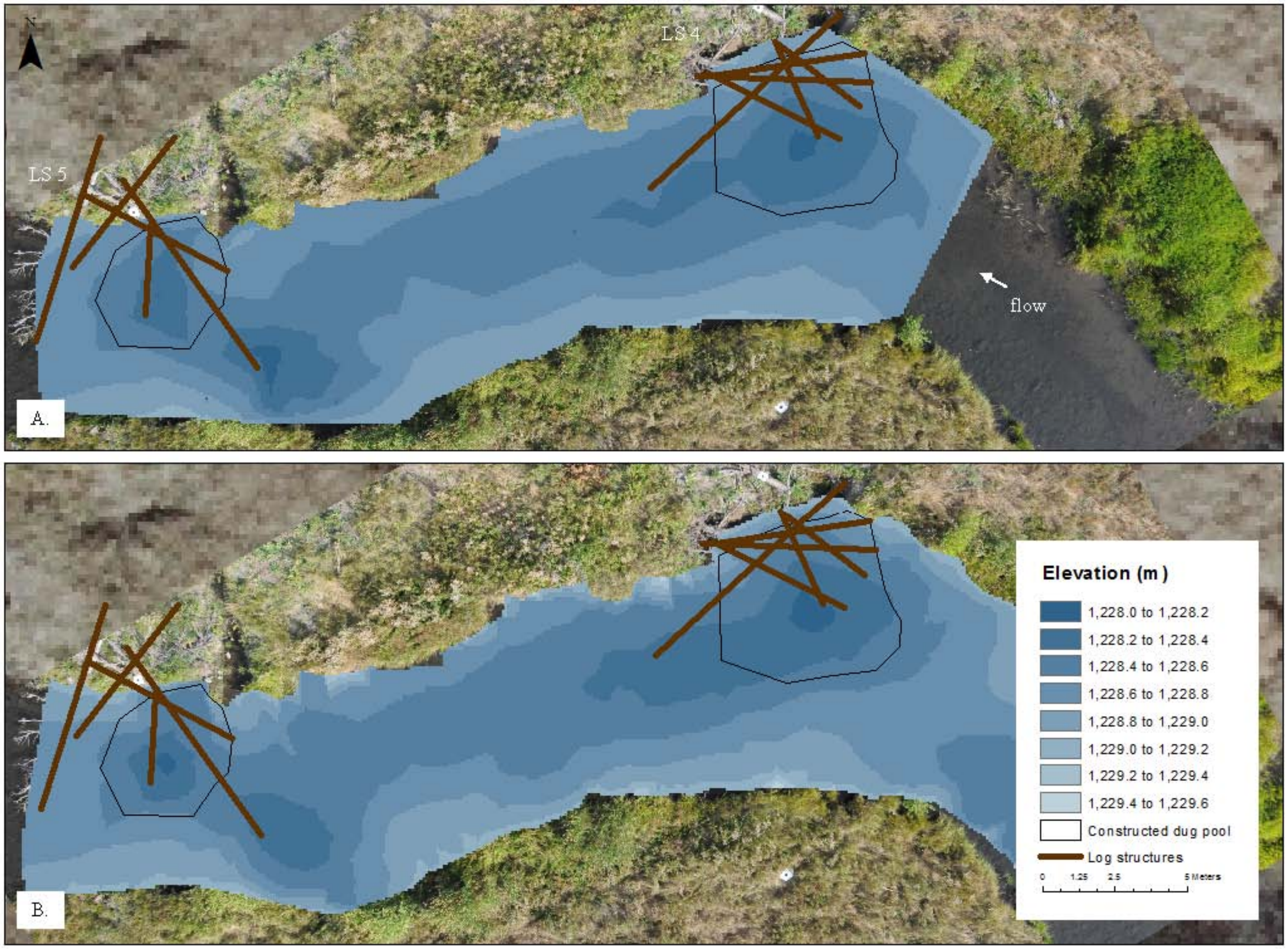


C1. Log structure 1, MFJD Forrest reach a) is 2008 DEM elevation map b) is 2010 DEM elevation map.

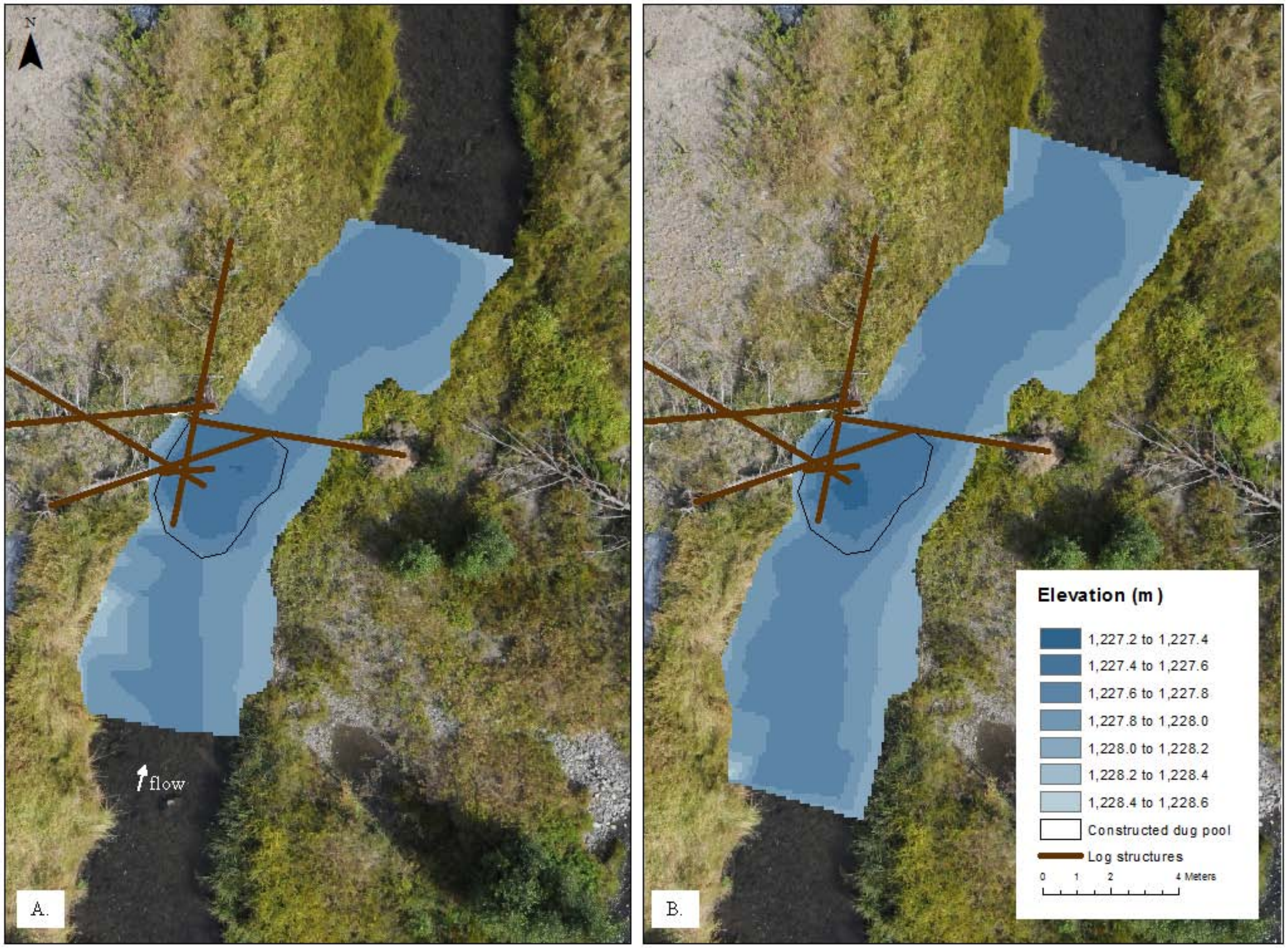


A2.

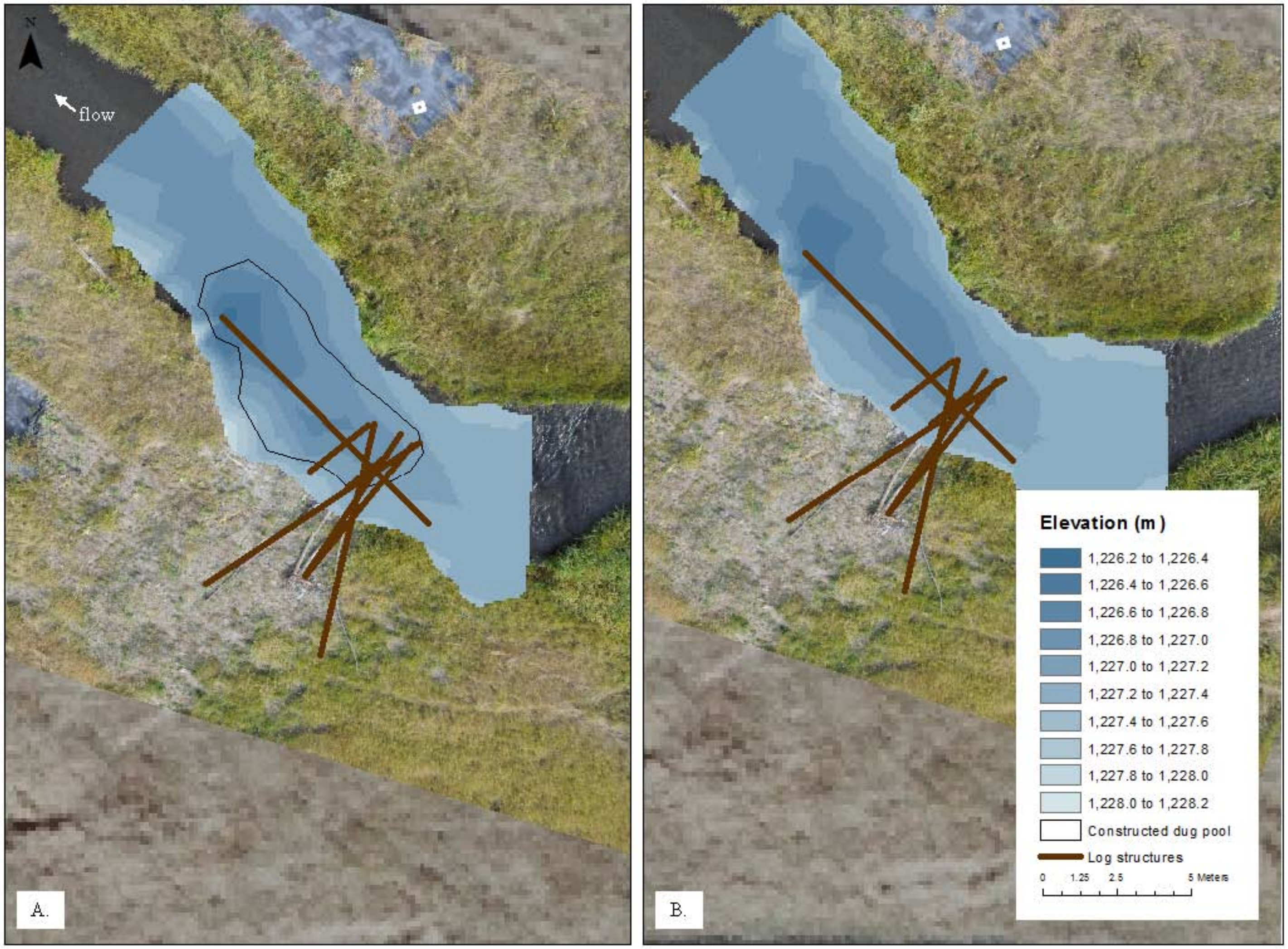
C2. Log structure 3, MFJD Forrest reach a) is 2008 DEM elevation map b) is 2010 DEM elevation map.



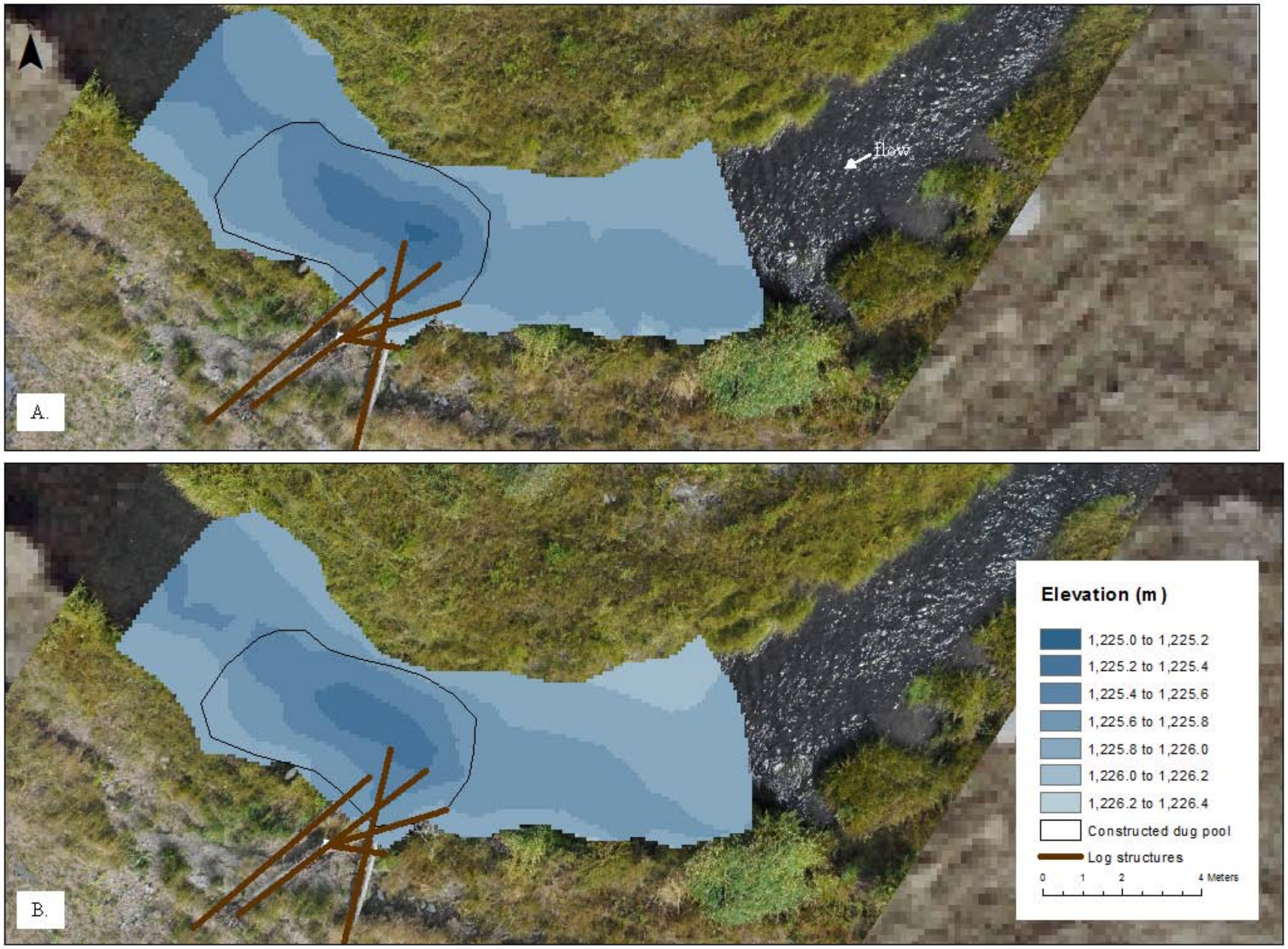
A3. C3. Log structures 4 and 5, MFJD Forrest reach a) is 2008 DEM elevation map b) is 2010 DEM elevation map.



A4. C4. Log structure 8, MFJD Forrest reach a) is 2008 DEM elevation map. b) is 2010 DEM elevation map.



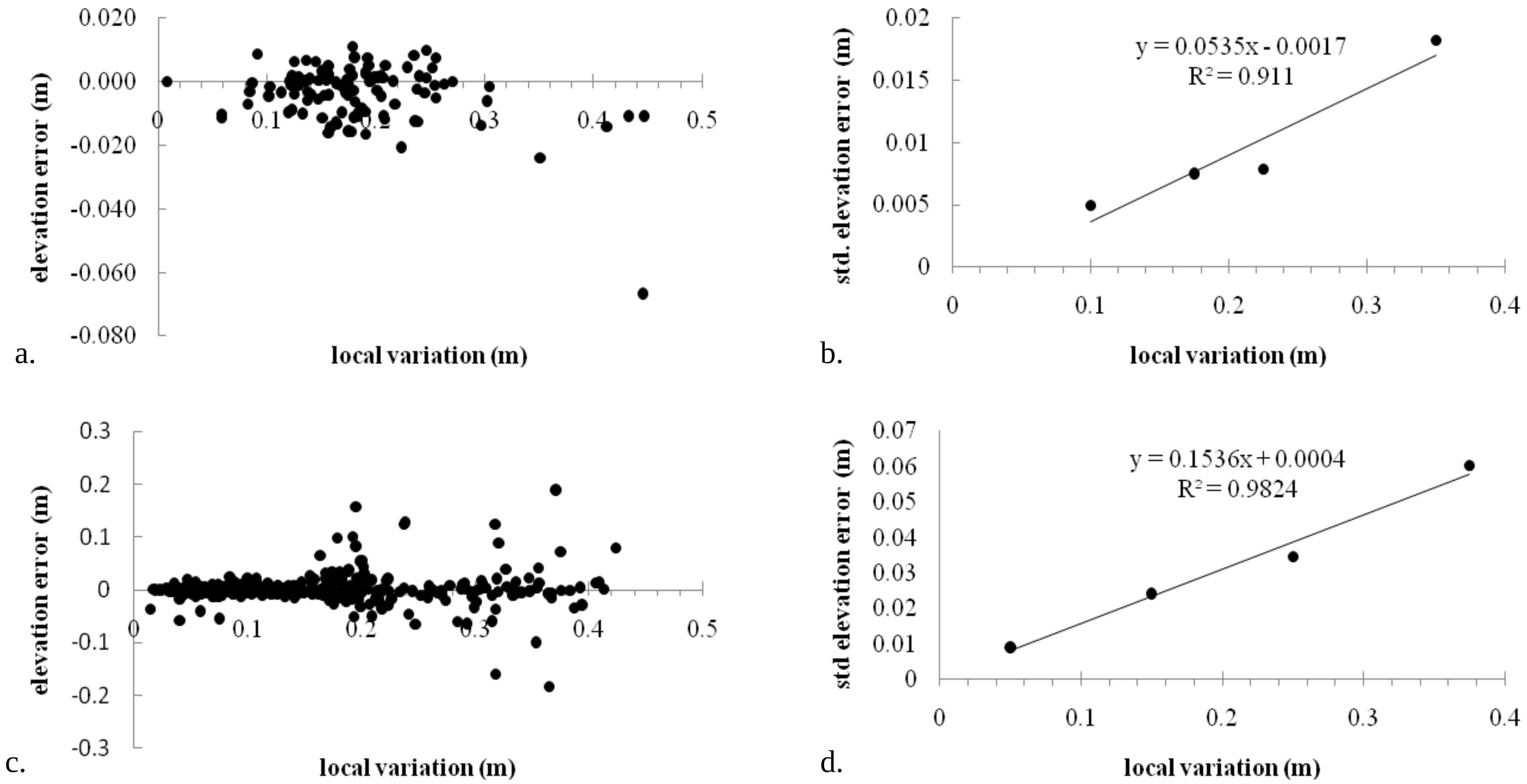
A5. C5. Log structure 9, MFJD Forrest reach a) is 2008 DEM elevation map b) is 2010 DEM elevation map.



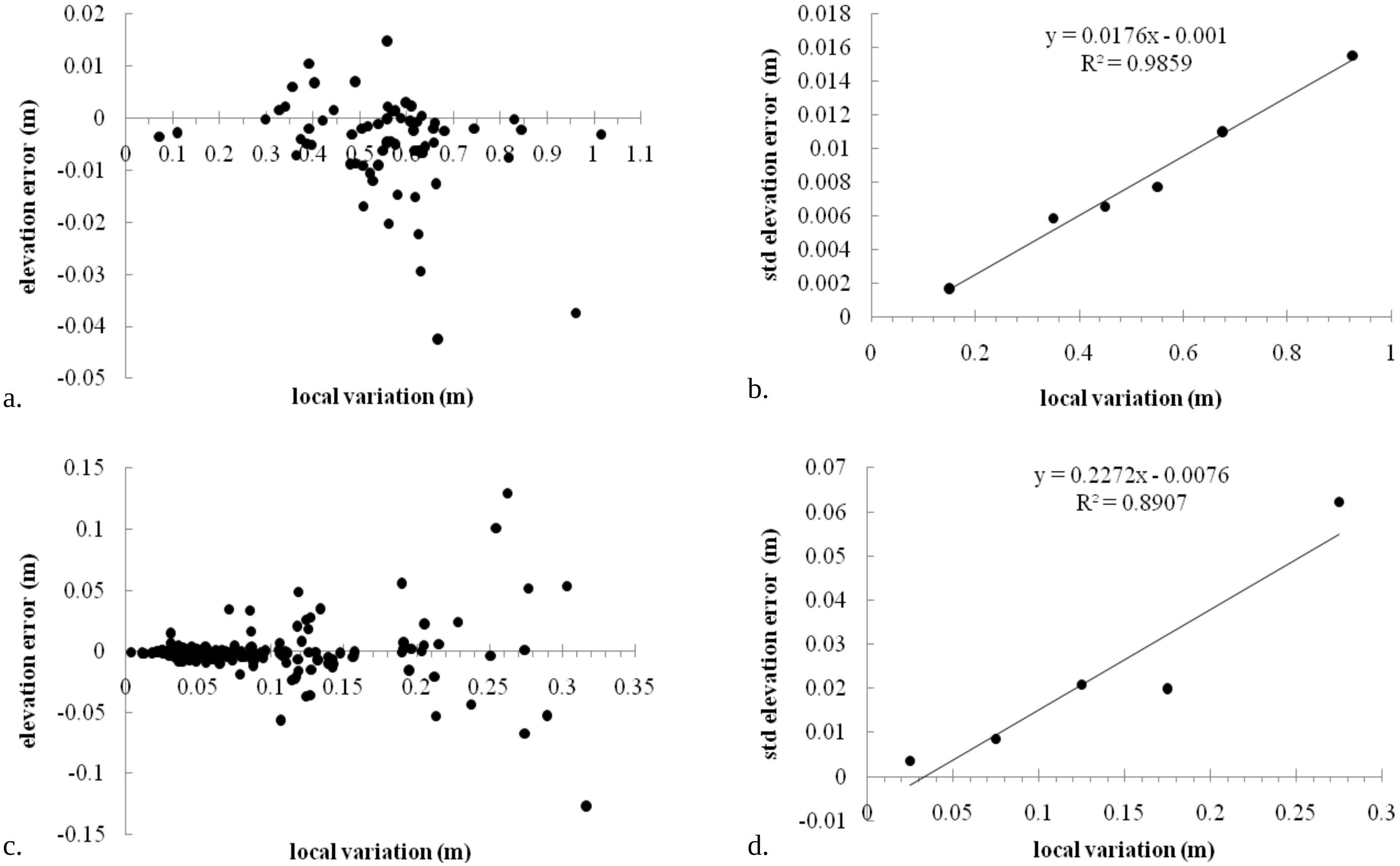
A6. C6. Log structure 12, MFJD Forrest reach a) is 2008 DEM elevation map b) is 2010 DEM elevation map.

APPENDIX D

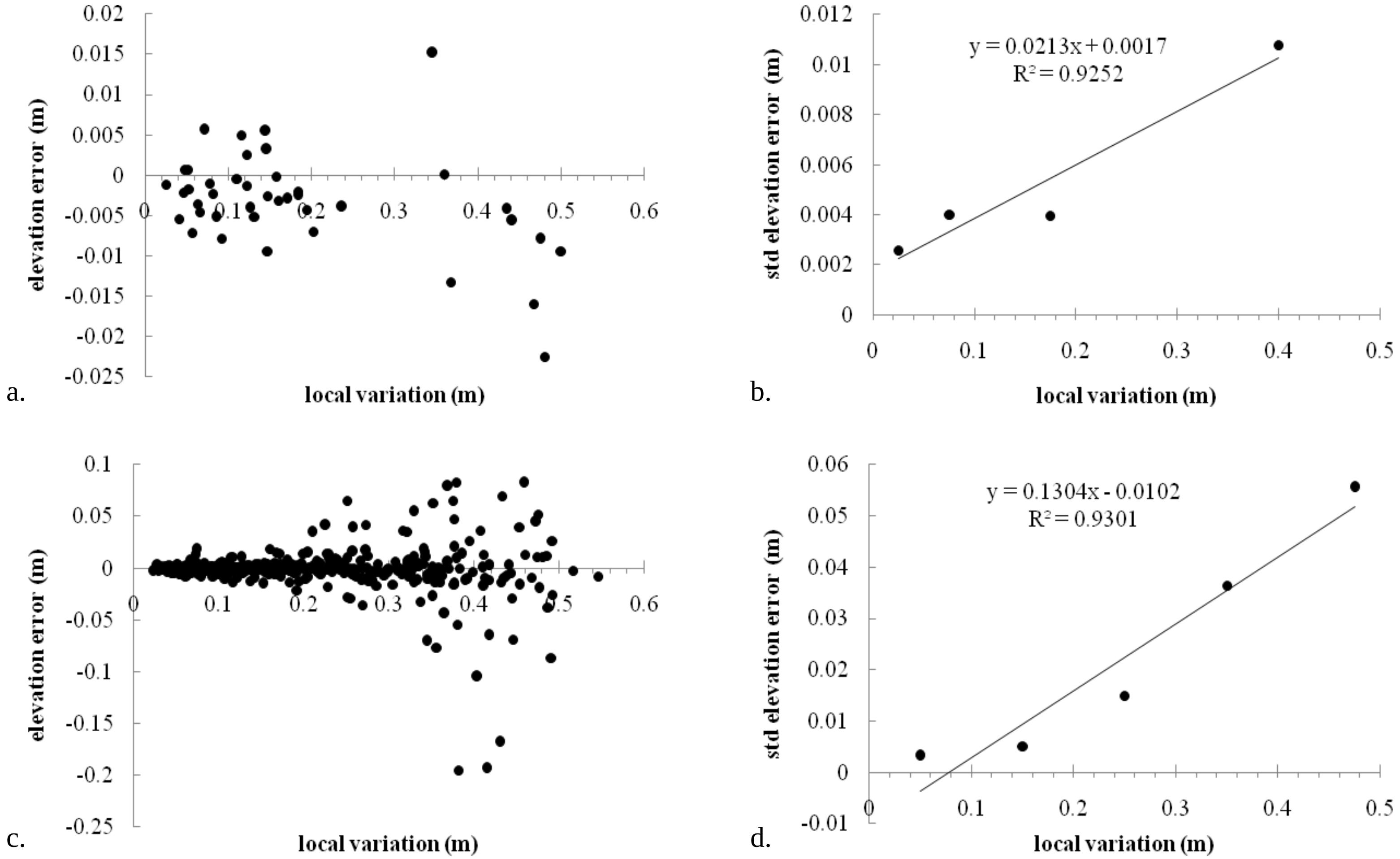
2008 AND 2010 LINEAR REGRESSIONS: LOCAL VARIABILITY VS. STANDARD DEVIATION OF ELEVATION ERROR



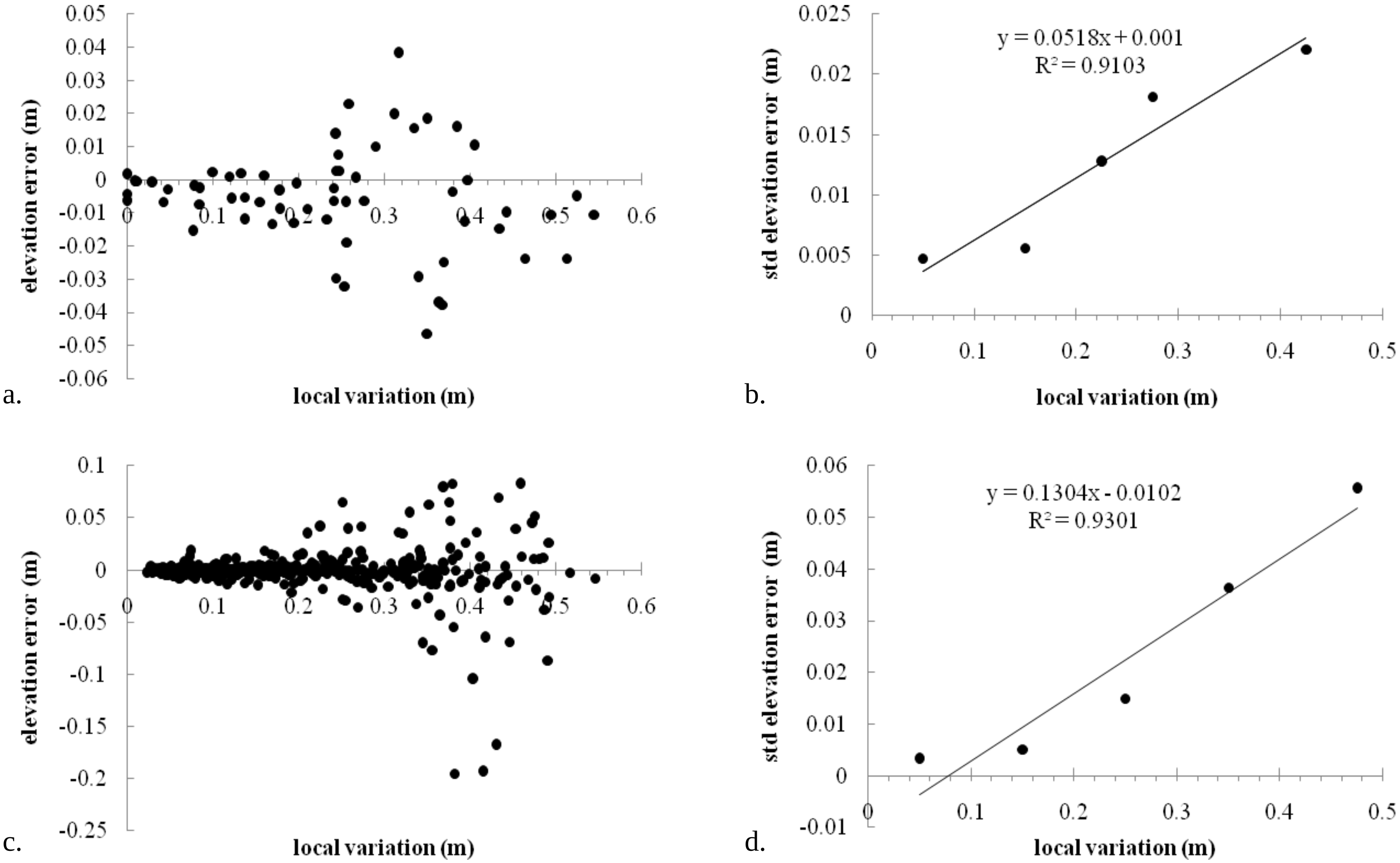
D1. Log structure 1: 2008 a) local variability verses elevation error b) linear regression between local variation and standard deviation of elevation error; 2010 c) local variability verses elevation error d) linear regression between local variation and standard deviation of elevation error



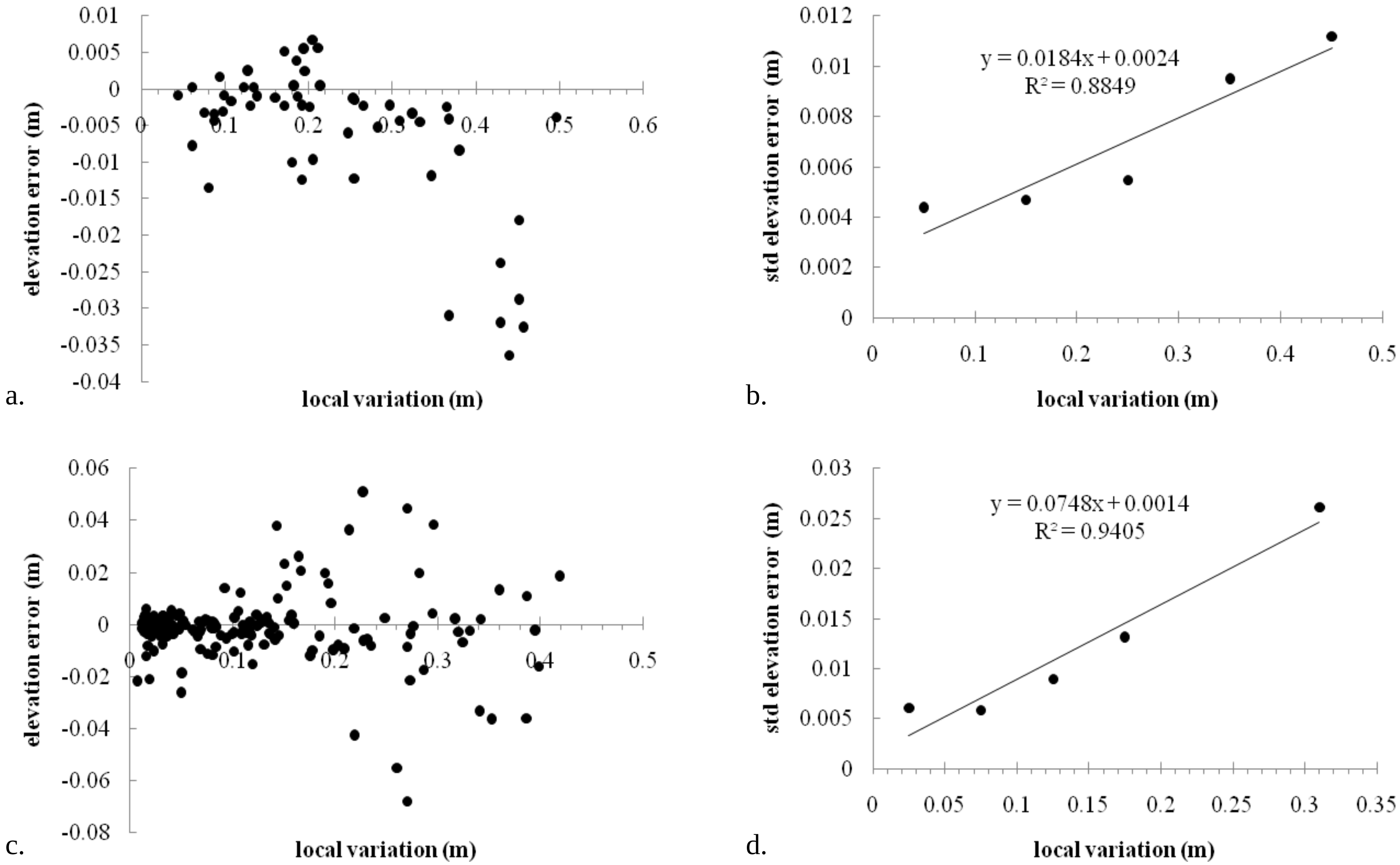
D2. Log structure 3: 2008 a) local variability verses elevation error b) linear regression between local variation and standard deviation of elevation error; 2010 c) local variability verses elevation error d) linear regression between local variation and standard deviation of elevation error.



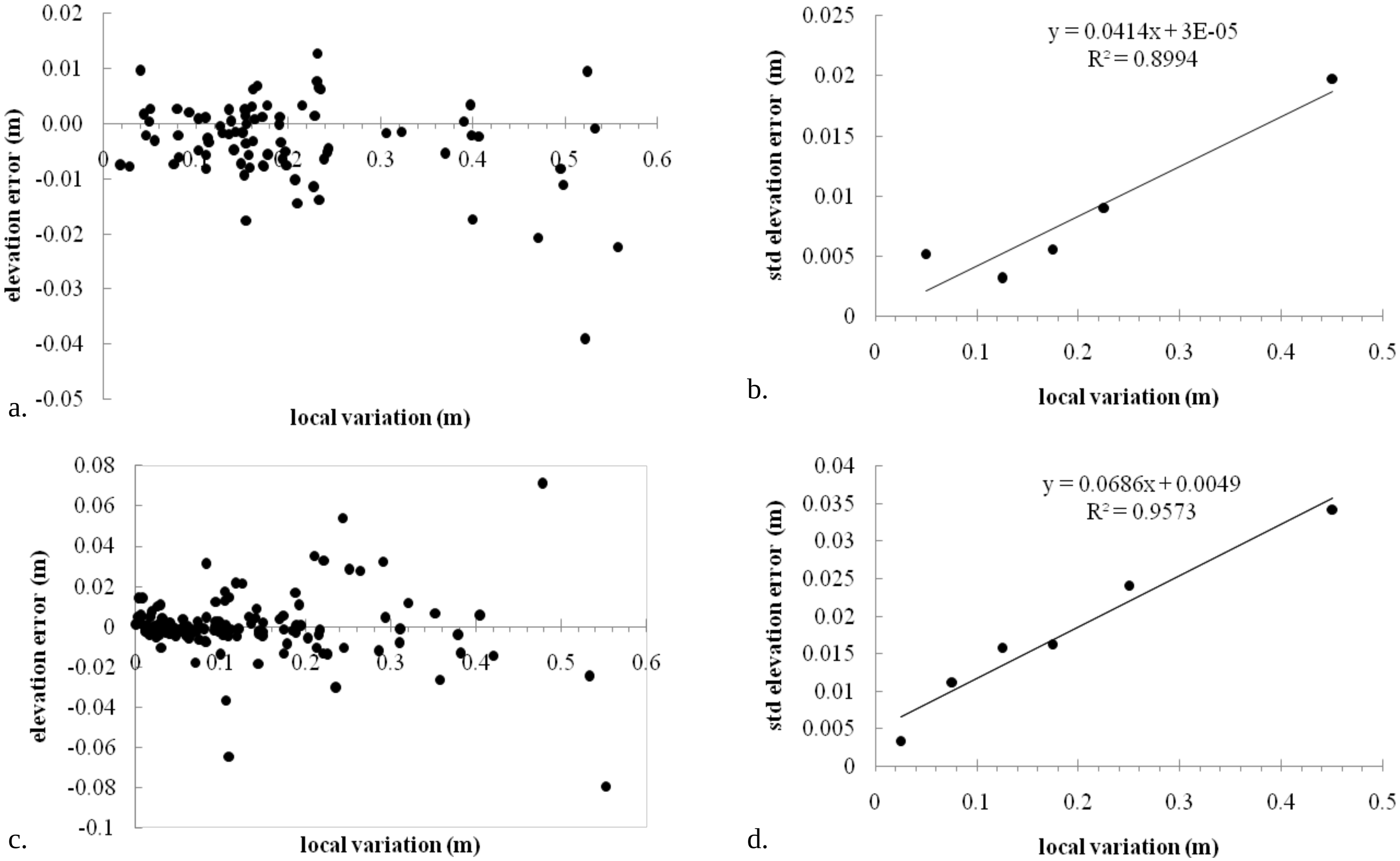
D3. Log structure 4: 2008 a) local variability verses elevation error b) linear regression between local variation and standard deviation of elevation error; 2010 c) local variability verses elevation error d) linear regression between local variation and standard deviation of elevation error



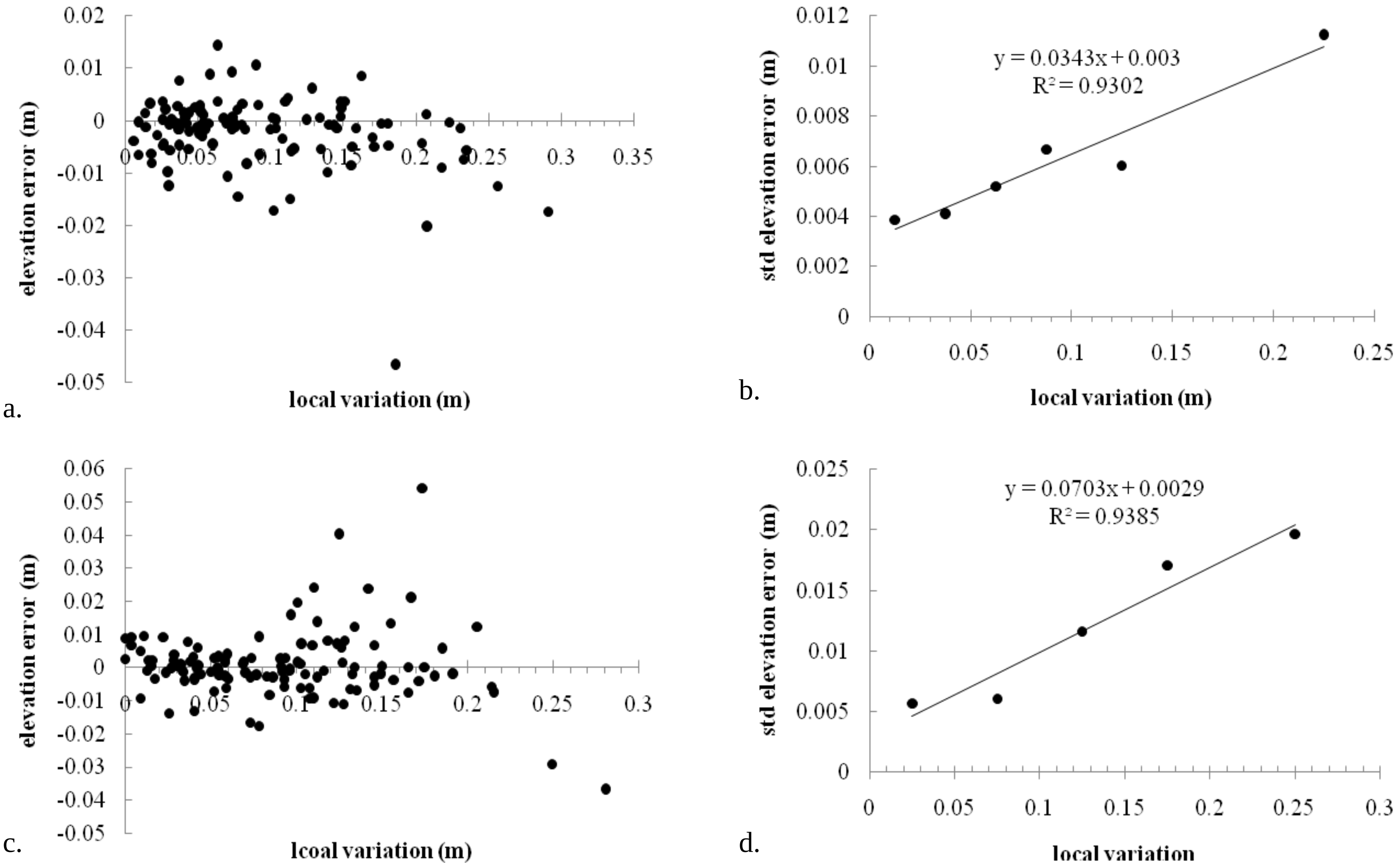
D4. Log structure 5: 2008 a) local variability verses elevation error b) linear regression between local variation and standard deviation of elevation error; 2010 c) local variability verses elevation error d) linear regression between local variation and standard deviation of elevation error



D5. Log structure 8: 2008 a) local variability verses elevation error b) linear regression between local variation and standard deviation of elevation error; 2010 c) local variability verses elevation error d) linear regression between local variation and standard deviation of elevation error



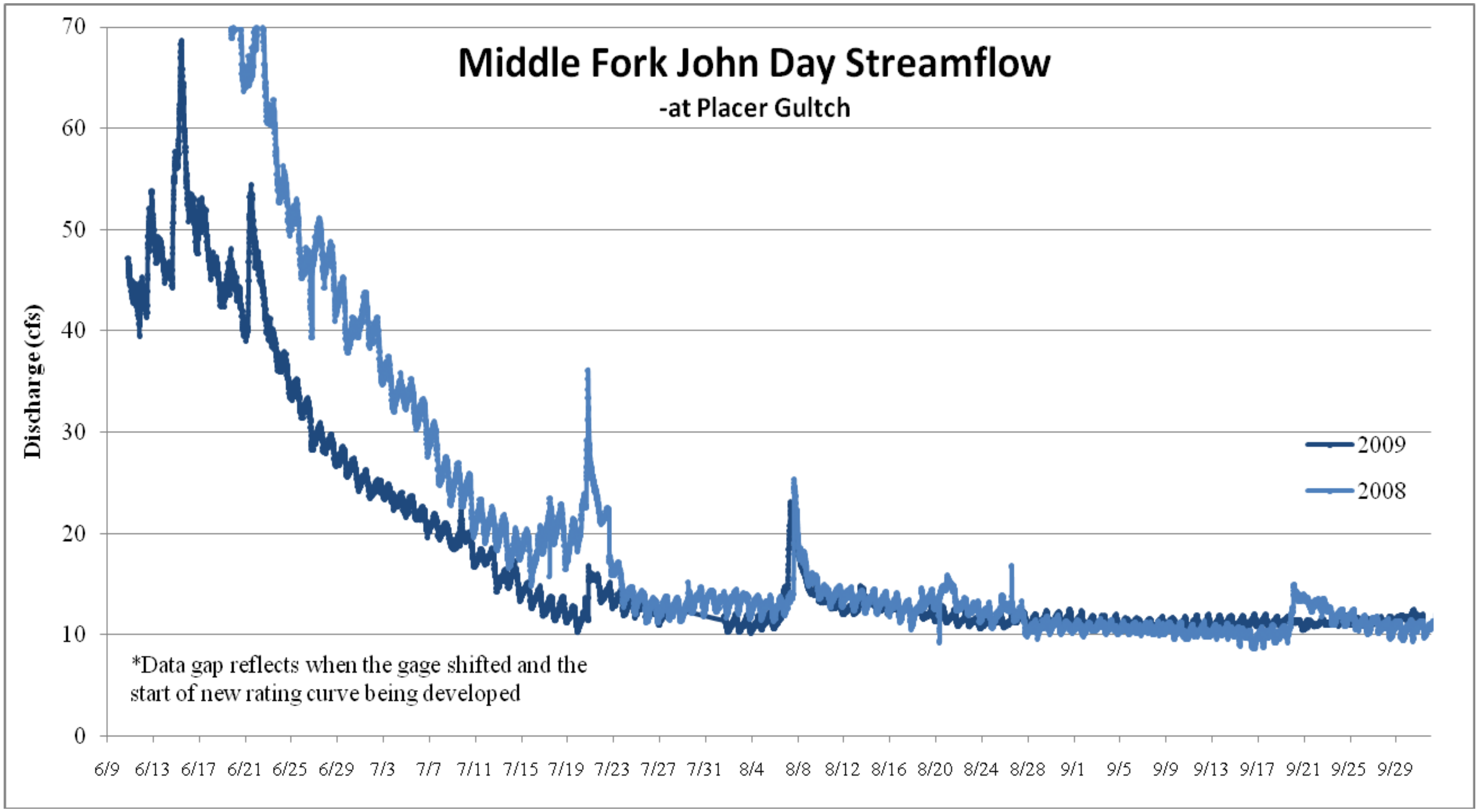
D6. Log structure 9: 2008 a) local variability verses elevation error b) linear regression between local variation and standard deviation of elevation error; 2010 c) local variability verses elevation error d) linear regression between local variation and standard deviation of elevation error



D7. Log structure 12: 2008 a) local variability verses elevation error b) linear regression between local variation and standard deviation of elevation error; 2010 c) local variability verses elevation error d) linear regression between local variation and standard deviation of elevation error

APPENDIX E

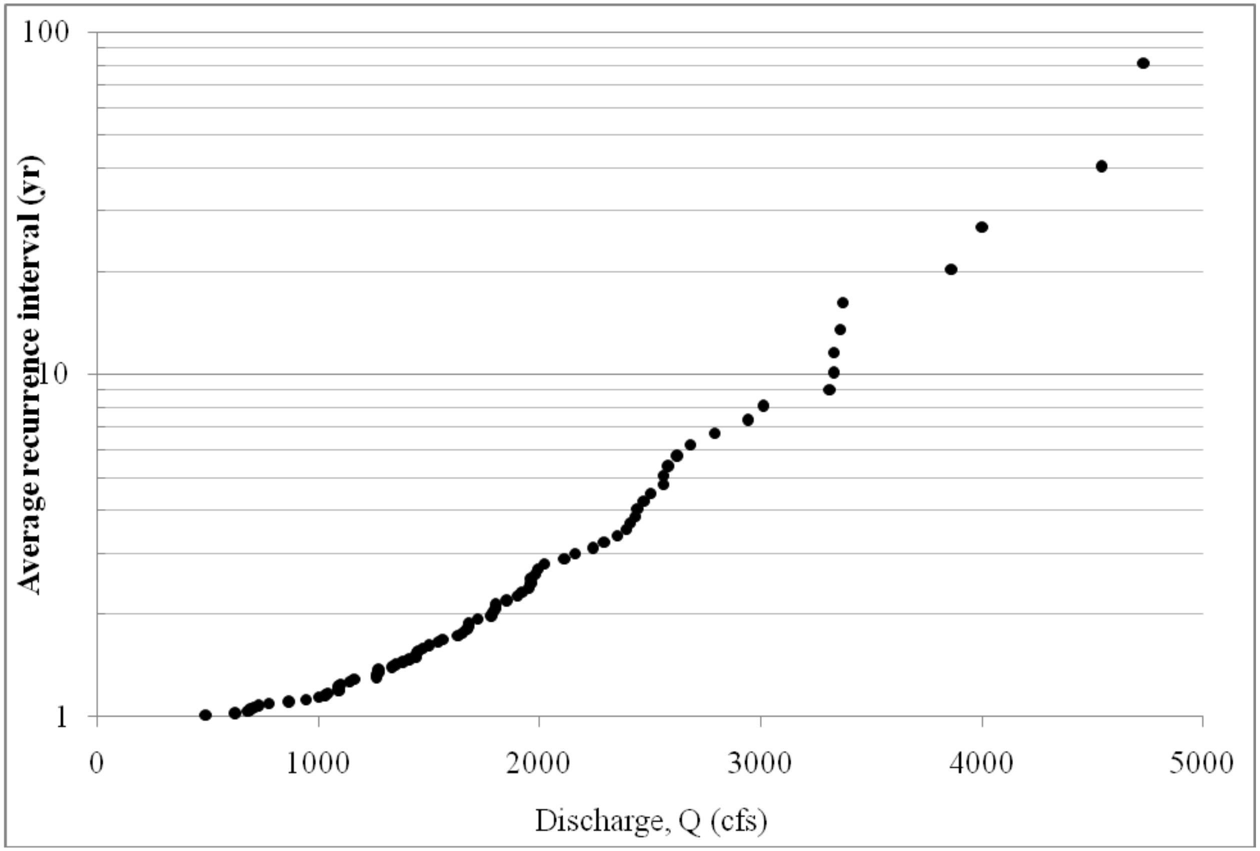
FRESHWATER TRUST SUMMER HYDROGRAPH: MFJD PLACER GULCH, SUMMER 2009



E1. Hydrograph for MFJD Placer Gulch stage readings, summer 2009. Operated and managed by the Freshwater Trust

APPENDIX F

FLOOD FREQUENCY GRAPH: MIDDLE FORK JOHN DAY RITTER, OR GAGING STATION



F1. Flood frequency graph from Ritter gaging station on the Middle Fork John Day River. Ritter, OR gaging station is located approximately 80.5 km downstream from the Forrest reach on the MJFD. This flood frequency graph is intended to show trends within the watershed, but do not reflect discharges of the upper reaches of the MFJD where the Forrest reach is located. In 2009 peak discharge was recorded at 1,800 cubic feet per second (cfs) and in 2010 peak discharge was recorded at 2,840cfs. These peak discharges, between the construction of LSs in 2008 and repeat surveys in 2010, correspond to equal or less than a 5-year flood event.

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