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Geomorphic Effects of Engineered Log Structures and Response to a Catastrophic Flood Event in a Missouri Ozarks River

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GEOMORPHIC EFFECTS OF ENGINEERED LOG STRUCTURES AND RESPONSE TO A CATASTROPHIC FLOOD EVENT IN A MISSOURI OZARKS RIVER

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Joseph Steven Nash

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ABSTRACT

Engineered log structures (ELSs) composed of local tree logs have been installed in river channels throughout the Pacific Northwest as a restoration technique. However, ELSs have not been tested for use in the Ozark Highlands until recently. In October 2016 the U.S. Forest Service installed four ELSs to stabilize banks along the North Fork of the White River in Ozark County, Missouri. The purpose here is to report on monitoring studies of pre- and post-restoration channel conditions and to assess geomorphic responses to floods. Over a ten-day period in April 2017 there were two bankfull floods, and on April 30, 2017 a catastrophic flood event classified as a >500-year flood occurred with a stage of 12.8 m that was greater than 4 m above the previous record flood in 1985. The flood toppled the riparian forest and caused geomorphic changes throughout the study reach. Key findings of this study are: 1) One structure was buried by greater than 3 meters of bar sediment, 2) large woody debris pieces more than doubled from 96 pieces in 2016 to 209 pieces in 2017 in the 1,100 m reach where ELSs enhanced recruitment, 3) a planform change occurred where the thalweg migrated to the opposite side of the channel, and 4) Structures 3 and 4 trapped fluvial wood and enhanced sedimentation in targeted areas on a lateral bar feature. Conclusions of this study are: 1) During the high-magnitude flood, the floodplain acted as a point-bar where floodplain chutes were carved and sediment deposited over the normal floodplain surface; 2) Structures 3 and 4 enhanced LWD recruitment by creating flow separation between the channel and the mouth of a floodplain chute; 3) Managers should incorporate shallow bedrock typically present in the Ozarks into future ELS designs and; 4) Cables helped ELS logs remain in their installed location due to the added shear resistance. The use of ELSs in this research were designed to recruit fluvial wood and enhance sedimentation under more frequent flow conditions but withstood a historic flood. Therefore, further investigation is needed to determine suitability of using ELSs in Ozarks streams under lower magnitude, more frequent flows.

KEYWORDS: Engineered Log Structures, large woody debris, log jam, catastrophic flood, stream restoration, Ozark Highlands

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I dedicate this thesis to my son Jackson Nash.

TABLE OF CONTENTS

Introduction	Page 1
Geomorphic Effects of LWD on Streams	Page 2
Management and Engineering	Page 6
ELS Pilot Project in Mark Twain National Forest	Page 9
Purpose and Objectives	Page 12
Environmental Factors of Concern	Page 12
Benefits of the Research	Page 13
Study Area	Page 20
Regional Location	Page 20
Geology and Soils	Page 20
Native Vegetation and Land Use History	Page 22
Climate and Hydrology	Page 24
April 2017 Floods	Page 25
Methods	Page 41
Channel Surveys	Page 41
Substrate and LWD	Page 44
Photography	Page 46
Survey Data Analysis	Page 47
Channel Capacity and Flood Discharges	Page 49
Results and Discussion	Page 55
Historical Channel Characteristics	Page 56
Response of Channel Morphology to April Flood	Page 59
Flood Discharge and Channel Geometry	Page 60
Substrate and LWD	Page 65
Management Issues	Page 67
ELS Performance	Page 68
Conclusions	Page 105
References	Page 108

LIST OF TABLES

Table 1. Largest groundwater input in the North Fork River (Vineyard and Feder, 1974; Missouri DNR, 1996). Page 28

Table 2. Rain gage locations near the North Fork Watershed. Page 28

Table 3. Daily observed rainfall totals (MRCC, 2017). Page 29

Table 4. Site visits dates and descriptions. Page 51

Table 5. Estimated discharge at NFRA using ungaged area equation (Gubernick et al., 2015) and Tecumseh gage data. Page 52

Table 6. Historical photo analysis of channel widths at key transects at the North Fork Recreation Area. Page 70

Table 7. Overbank floods that occurred between 1985 and 2015. Page 71

Table 8. Historical photo analysis of channel and bar area at the North Fork Recreation Area. Page 71

Table 9. Pre-flood and post-flood comparison of bankfull and extreme flood dimensions at the NFRA. Page 72

Table 10. Comparison of findings between this study and (Kochel et al., 2016). Page 73

Table 11. Change in sediment volume from topographic surveys, Page 74

Table 12. Substrate trends and Riffle 1 and Riffle 4. Page 75

Table 13. Large woody debris piece count per 100 m cell. Page 76

Table 14. Comparison on LWD volume from pre-flood to post-flood. Page 76

Table 15. Engineered log structure performance and NFRA. Page 77

LIST OF FIGURES

Figure 1. Example of an ELJ (Kimbrel, 2014). Page 15

Figure 2. Example of ELS design using whole tree with rootwad for streambank protection (NRCS, 1996). Page 15

Figure 3. ELS location map and log size specifications. Meander Bend Jam #5 was not installed (Gubernick, 2015). Page 16

Figure 4. Profile view of ELS design by USFS Watershed Restoration Geologist Robert Gubernick. Page 16

Figure 5. Construction of ELS 1. Excavator digging a trench in the bed for key piece placement. Page 17

Figure 6. Excavator placing logs in a trench perpendicular to flow positioned over key pieces. Page 17

Figure 7. ELS 1. Flow direction from picture right to picture left. Page 18

Figure 8. ELS 2. Flow direction from right to left and cables for added stability. Page 18

Figure 9. ELS 3. Location on lateral bar and flow direction from right to left. Page 19

Figure 10. ELS 4 in foreground and ELS 3 in background. Flow direction from right to left and burial of key pieces with root fans oriented upstream. Page 19

Figure 11. North Fork of the White River watershed. Page 30

Figure 12. Geology of the North Fork of the White River watershed. Page 31

Figure 13. Cross-section of geologic composition. Page 32

Figure 14. Cross-section of soils near the North Fork Recreation Area (USDA-NRCS, 2000). Page 33

Figure 15. Floodplain and terrace formations in the North Fork of the White River (Ray, 2009). Red line is approximate floodplain elevation at the NFRA. Page 34

Figure 16. North Fork of the White River land use map with pinery area and mills from Sauer, 1920. Page 35

Figure 17. Blue Spring located at the downstream limit of the NFRA. Page 36

Figure 18. Annual peak streamflow from North Fork River from 1956-2017 (USGS, 2018). Page 36

Figure 19. Pre-Flood Reach Map of the North Fork Recreation Area from 2015 (MDNR, 2015). Page 37

Figure 20. Construction disturbance to the North Fork Recreation Area including clearing for proposed boat ramp and construction access road (MDNR, 2015). Page 38

Figure 21. Rainfall totals from a stationary front on April 28-30, 2017 (NWS, 2017). Yellow polygon in approximate location of the North Fork watershed. Page 39

Figure 22. Hydrograph from April 16, 2017- May 5, 2017. Near bankfull floods on April 22 and April 27, and extreme flood on April 29-30 (USGS, 2018). Page 39

Figure 23. Highway CC bridge at NFRA. Deck of bridge washed downstream of road. (Aerial Ozarks, 2017). Page 40

Figure 24. Typical bed landforms in the Ozarks (Panfil and Jacobson, 2001). Pebble counts were conducted on riffle, glide, and bar landforms. Page 53

Figure 25. Example of median axis of pebble that is measured for substrate survey (Kline et al., 2009). Page 53

Figure 26. Orientation positions of LWD from Magilligan et al., 2008. Page 54

Figure 27. Post-Flood Reach Map of the North Fork Recreation Area from March 2018 (Dogwiler, 2018). Page 78

Figure 28. Historical photo analysis of bars and channel positions in 1990. Page 79

Figure 29. Historical photo analysis of bars and channel positions from 2007 over 1990 bars and channels. Page 80

Figure 30. Historical photo analysis of bars and channel positions from 2015 over 1990 and 2007 bars and channels. Page 81

Figure 31. Floodplain deposition visible on aerial photos in 1990, 2007, and 2015. Page 82

Figure 32. Comparison of longitudinal profile between pre-flood and post-flood periods. Page 83

Figure 33. Post-flood aerial photo showing thalweg shift toward bedrock bluff on the river-right side of the channel. Page 84

Figure 34. Movement of the riffle and glide located downstream of ELS 4. Page 85

Figure 35. Post-flood channel widening and bar location change. Page 86

Figure 36. Floodplain-bar complex with floodplain splay lobes and chutes. Page 87

Figure 37. Existing boat ramp after extreme flood event. Bar head acting as a ramp with coarse sediment (top) and looking downstream at the head of the high-flow chute (bottom). Page 88

Figure 38. High-flow chute development and floodplain sedimentation (top) (Kochel et al., 2016). Dashed red line is the chute and A (bottom) shows similar coarsening of ramp at NFRA. Page 89

Figure 39. Cross-sectional survey comparisons at ELS1 (top), ELS 2 (middle), and ELS 3 (bottom). Page 90

Figure 40. Post-flood LWD and toppled riparian forest on lower floodplain surface at ELS 3 (A), and backwater flooded chute near ELS 4 (B). Page 91

Figure 41. Pre-flood, post-flood, and net elevation change DEMs at ELS 1. Page 92

Figure 42. Slip face deposition caused by April Flood at ELS 1. Arrows show new bank line. Page 93

Figure 43. Deposition caused by April Flood at ELS 2 where bank angle lowered. Arrows show cut ends of logs in ELS 2. Page 93

Figure 44. Pre-flood, post-flood, and net elevation change DEMs at ELS 2. Page 94

Figure 45. Pre-flood, post-flood, and net elevation change DEMs at ELS 3 and ELS 4. Chute in pre-flood DEM indicated by arrow. Page 95

Figure 46. Flow separation between floodplain chute and main channel at ELS 3 and ELS 4 location. Arrows show areas of flow separation that resulted in bar deposition between the structures. Page 96

Figure 47. Riffle 1 near existing boat ramp where riffle, glide, and bar locations were surveyed for substrate composition. Page 97

Figure 48. Riffle, glide, and bar pebble count frequency distribution at existing boat ramp (A) riffle, (B) glide, (C) maximum clast, (D) bar head, (E) bar middle, and (F) bar tail. Red arrow is D50. Page 98

Figure 49. Floodplain splay lobe between ELS 1 and ELS 2 looking downstream. Page 99

Figure 50. Floodplain splay lobe between ELS 1 and ELS 2 looking upstream. Page 99

Figure 51. Riffle 4 located downstream of ELS 3 and ELS 4 where riffle, glide, and bar locations were surveyed for substrate composition. Page 100

Figure 52. Riffle, glide, and bar pebble count frequency distribution at Riffle 4 downstream of ELS 4 (A) riffle, (B) glide, (C) maximum clast, (D) bar head, (E) bar middle, and (F) bar tail. Red arrow is D50. Page 101

Figure 53. Distribution of LWD pieces and size classes. Page 102

Figure 54. Pre-flood and post-flood LWD from 0-1,100 m. The highest recruitment of LWD was in cell 800-900 m where ELS 3 and ELS 4 are located. Page 103

Figure 55. Imbricated asphalt pieces and toppled riparian trees caused by the April Flood. Page 104

Figure 56. Deck of the Highway CC Bridge that was destroyed during the April Flood. Page 104

INTRODUCTION

Large woody debris (LWD) is defined as any piece of wood measuring at least 1.5 m in length and at least 0.1 m in diameter within the bankfull channel (Gippel, 1995; Faustini and Jones, 2003; Kreutzweiser et al., 2005; Morris et al., 2006; Martin et al. 2016). Forested watersheds contribute to fluvial LWD as a result of recruitment processes such as tree mortality, windfall, mass wasting or landslides, river bank erosion, and channel migration (Keller and Swanson, 1979; Collins and Montgomery, 2002; Gurnell et al., 2002; Montgomery et al., 2003a; Hassan and Woodsmith, 2004; Kreutzweiser et al., 2005; Magilligan et al., 2008; Webster et al., 2008; Ortega-Terol et al., 2014; Ruiz-Villanueva et al., 2014; Roni et al., 2015; Martin et al., 2016). Recruitment processes are naturally-occurring in forested watersheds and are intensified by human interaction with the landscape. Typically, LWD abundance is lower in watersheds with anthropogenic land use history compared to undisturbed forested watersheds due to increased channel conveyance and tree removal (Gippel, 1995; Wohl, 2005; Webster et al., 2008). However, the period of land use change during European settlement of the US from forest to agriculture was associated with high rates of LWD recruitment due to increased channel instability and bank erosion (Collins and Montgomery, 2002; Gurnell et al., 2002; Magilligan et al., 2008; Martin et al., 2016).

Managers now reintroduce LWD into streams as a restoration tool to stabilize banks, increase aquatic habitat abundance, mitigate against flood damage to infrastructure, and return streams to theoretical natural channel condition (Wohl, 2005; Alexander and Allan, 2006; Pess et al., 2012; Roni et al., 2015). Until recently restoration projects using wood are widely undocumented or are lacking the success or failure rates (Alexander and Allan, 2006; Roni et al., 2015). Of the documented LWD restoration projects most used wood to improve fish habitat in the Pacific Northwest (PNW) and Upper Midwest (Roni et al., 2015). While LWD restoration projects are prevalent in the PNW and Upper Midwest, the effectiveness of LWD for stream restoration in the Ozark Highlands is undocumented. The purpose of this research is to monitor the effectiveness of the first use of Engineered Log Structures (ELSs) by the US Forest Service (USFS) in the Missouri Ozarks. Monitoring of this project is an important contribution since it is rarely done, and related data can be used to improve our understanding of both LWD and ELSs and river geomorphology.

Geomorphic Effects of LWD on Streams

Geomorphic effects of LWD on channels are dependent on variables such as, the size and position of LWD, localized sedimentation, effects of log jams, and long-term effects on channel form. Size of LWD pieces is an important variable relative to the size of the channel (Gurnell et al., 2002). Small streams are less likely to move larger pieces of LWD, so LWD remains in the channel longer to influence stream planform (Keller and Swanson, 1979; Marston, 1982; Abbe and Montgomery, 1996; Gurnell et al., 2002). In steep headwater streams LWD can create a step-pool channel where large trees fall and lodge perpendicular to flow, to provide energy dissipation (Keller and Swanson, 1979; Montgomery et al., 1995; Abbe and Montgomery, 1996; Montgomery and Buffington 1997; Montgomery et al., 2003a). Pieces of LWD that bridge the entire bankfull channel width can create a damming effect that traps sediment (Lancaster and Grant, 2006). Position of LWD is an important factor that affects channel hydraulics and sedimentation rates (Gurnell et al., 2002). Generally, LWD positions are classified as parallel

(A), perpendicular (B), or oblique (C and D) to flow relative to the rootwad orientation if there is a rootwad present (Magilligan et al., 2008).

Key members are stabilized wood or other stationary objects such as living trees, large boulders, or bridge piers that collect mobile LWD during high flow events (Montgomery et al., 2003a; McHenry et al., 2007; Nichols and Ketcheson, 2013; Kimbrel, 2014; Roni et al., 2015).Stabilized LWD that is partially or totally buried in the bed or banks can act as a key member during flows that transport LWD (Magilligan et al., 2008). Log jams are a collection of at least three pieces of LWD on a key member (Abbe and Montgomery, 2003; Martin, 2014). Larger streams usually have the competence to move relatively larger pieces of wood increasing the occurrence of larger log jams at choke points or obstructions along the channel (Keller and Swanson, 1979; Abbe and Montgomery, 1996; Faustini and Jones, 2003). Log jams can facilitate cutoff meanders because they provide higher resistance compared to stream banks and deflect flow direction away from banks (Daniels and Rhoads, 2003).

Channels with instream LWD have different hydraulic flow dynamics, sedimentation patterns, and flow rates compared to channels without instream LWD including increased roughness, more variable flow dynamics, and can have armored bed and banks (Gippel, 1995; Buffington and Montgomery, 1999). Hydraulic roughness is typically determined by the composition of bed and bank substrate size, but in forested streams LWD and logjam volumes can increase roughness and should be included in discharge and shear stress calculations (Shields and Gippel, 1995; Buffington and Montgomery, 1999; Wohl, 2014). When LWD is stable or immobile on the bed roughness decreases with increased channel depth (Gippel, 1995; Gurnell et al., 2002). Removal of LWD is associated with an increase in flow velocity leading to coarsening of bed material (Buffington and Montgomery, 1999). Stabilized LWD can protect the bed and banks from erosion in high flows (Gippel, 1995).

Channel forms such as step-pool, pool-riffle, and cutoff meanders can be forced by the presence of LWD (Montgomery and Buffington, 1997; Faustini and Jones, 2003; Willcox and Wohl, 2006). Stabilized LWD can force channel morphologies by creating flow divergence and influencing local sedimentation (Montgomery and Buffington, 1997). Large wood pieces or jams prevent entrainment of nearby bed sediment, limit transport of sediment, and create a storage mechanism for sediment in steep streams (Faustini and Jones, 2003). Stabilized LWD can create a braided morphology in larger channels (Gurnell et al., 2002). However, long-term channel effects of LWD are influenced by the residence time of the wood in the channel and can be a predictor of the history of flow regime (Hyatt and Naiman, 2001; Gurnell et al., 2002). In the Pacific Northwest (PNW) residence time of LWD can be hundreds of years whereas other warmer climate regions can be only a few years due to variations in tree species and increased decomposition rates (Abbe et al., 1997; Montgomery et al., 2003a; Webster et al., 2008; Wohl et al., 2017).

Occurrences of forced morphologies due to LWD decrease in larger rivers compared to small streams where planforms such as step-pool and pool-riffle sequences can be heavily influenced by LWD (Montgomery et al., 2003a). Pool occurrences and pool spacing in the PNW are heavily influenced by LWD abundance and location (Hassan and Woodsmith, 2004). Moreover, specific pool forms vary according to the size and stability of LWD relative to channel size (Montgomery et al., 1995; Montgomery et al., 2003a). Flow velocity slows as it encounters LWD creating a backwater effect and scours on the downstream side creating localized pools (Montgomery et al., 1995; Wohl, 2014). In addition, bar deposition is a result of flow divergence around stable or dammed LWD (Montgomery et al., 2003a). Large-scale morphologic characteristics such as pool spacing can be influenced by LWD volume and LWD stability relative to channel area (Montgomery et al., 1995; Gurnell et al., 2002). Deposition of sediment caused by LWD is an important contributing factor to sediment storage within channels (Keller and Swanson, 1979; Shields and Gippel, 1995; Gurnell et al., 2002; Faustini and Jones, 2003; Montgomery et al., 2003a; Hassan and Woodsmith, 2004). Sedimentation rates tend to increase in steams with LWD as obstructions decrease flow velocity and conveyance (Shields and Gippel, 1995). Shields and Gippel (1995) found that the removal of LWD increased flow conveyance by 12 to 1000%. Typically, increased conveyance or stream power will result in down-cutting or widening of stream channels and reduction in sediment storage (Wohl, 2014).

Log jams create critical roughness elements that influence flow velocity variability, aquatic habitat, and channel morphology (Collins and Montgomery, 2002; Gurnell et al., 2002; Montgomery et al., 2003b; Faustini and Jones, 2003; Morris et al., 2006). Abbe and Montgomery (1996) define three types of log jams as bar top jam, bar apex jam, and meander jam. Bar top jams are deposited in receding flows and typically not stabilized on the bed (Abbe and Montgomery, 1996; Montgomery et al., 2003a). Bar apex jams are associated with bars in the center of a channel where they promote bar aggradation by providing flow separation (Abbe and Montgomery, 1996). Meander jams are accumulated on the outside margin of a meander in large rivers (Abbe and Montgomery, 1996; Abbe and Montgomery, 2003). While each type of jam has a different geomorphic effect, only the bar apex jam and meander jam have long-term channel form effects (Abbe and Montgomery, 1996; McHenry et al., 2007; Roni et al., 2015). In larger rivers bar apex jams and meander jams accumulate mobile LWD during high flow events and have larger effects on channel planform and aquatic habitat (Gurnell et al., 2002; Montgomery et al., 2003a).

LWD Management and Engineering

Historically, wood snags and LWD tended to be viewed negatively by managers due to navigational hazards (Gippel, 1995). Therefore, wood removal from streams was common practice until the positive geomorphic effects were recognized (Abbe et al., 1997; Boyer et al., 2003). Historically people have channelized rivers by straightening them and unknowingly disconnecting riverbeds and banks from their floodplains (Steinfeld and Kingsford, 2013). Part of the channelization process was the removal of LWD. Removal of LWD took place when it caused a navigational hazard, caused property damage, or was viewed as an obstruction to flow (Shields and Gippel, 1995; Gurnell et al., 2002). Removal of jams was common practice for over a century in the U.S. and for hundreds of years in Europe (Gippel, 1995; Gerhard and Reich, 2000). Forms of LWD hazards included rafted logs that were jammed, naturally occurring log jams or snags, leaning trees, or sunken logs. Hazards were removed by dredging and cutting or were blasted out with explosives. (La Motte, 1922; Napolitano, 1998; Sedell et al., 1991). During timber harvest operations, log drives would jam a river for miles which forced logging companies to de-snag or remove key pieces of the jams to keep sending logs downstream (Napolitano, 1998). In 1922, E. I. Du Pont De Nemours & Company published a book with a section detailing the proper methods of using DuPont dynamite to remove log jams on rivers. Removal of LWD decreased natural roughness and sedimentation controls in river channels which increased stream conveyance that lead to unstable and eroding channels (Shields and Gippel, 1995; Faustini and Jones, 2003; Montgomery et al., 2003a).

Wood reintroduction into streams as a restoration technique has been ongoing throughout the US since the early 1930s when the Civilian Conservation Corps (CCC) conducted over 30,000 projects in over 400 rivers where wood was placed into streams (Roni et al., 2015). Since the 1970s in the PNW, river managers began to replace in-stream LWD primarily to increase abundance aquatic habitat (Keller and Swanson, 1979; Gippel, 1995; D'Aoust and Millar, 2000; Baillie and Davies, 2002; Alexander and Allan, 2006; Stewart et al., 2009; Roni et al., 2015; Kramer and Wohl, 2017). Shortly thereafter, managers recognized added geomorphic benefits such as increased bank stability and thalweg control of LWD (Boyer et al., 2003). Thus, beginning in the 1970s river managers began to use LWD to mimic natural geomorphic processes to affect channel form and sedimentation in the in the PNW and Upper Midwest (Abbe et al., 1997; Bernhardt et al., 2005).

Engineered log structures (ELSs) or engineered log jams (ELJs) were designed to add wood for aquatic habitat rejuvenation, erosion control along stream banks, and flood mitigation (Alexander and Allan, 2006). The National River Restoration Science Synthesis (NRRSS) includes a database of more than 37,000 stream restoration projects across the U.S. that took place from 1970 to 2004. (Bernhardt et al., 2005; Alexander and Allan, 2006). In the Upper Midwest region 1,345 of those projects occurred in Michigan, Ohio, and Wisconsin with the most common goals of habitat improvement, bank stabilization, water-quality management, and dam removal (Alexander and Allan, 2006). Approximately half of these bank stabilization and habitat rejuvenation projects included the re-introduction of wood to channels. Therefore, management of LWD in streams has evolved from removing LWD, as it was viewed as a negative attribute, to replacing LWD to restore streams to pre-settlement conditions (Wohl, 2005).

The initial function of adding LWD to streams was to increase aquatic habitat (Kimbrel et al., 2014) (Figure 1). However, the knowledge and literature base evolved into applications to mitigate flood damage by using LWD as bank protection and thalweg control (Abbe et al., 1997; Gerhard and Reich, 2000; Hall and Moler, 2006; Stewart et al., 2009; Pess et al., 2012; Baird et al., 2015; Kramer and Wohl, 2017). Early attempts of using LWD were developed as log weirs, dams, and flow deflectors (Roni et al., 2015). Since the early implementation of ELSs, design factors have developed to meet individual needs based on specific river systems or regions (Roni et al., 2015). Since the 1990s, design of wood structures moved from placement of riprap and cut wood to installing whole trees with root structures (NRCS, 1996; Roni et al., 2015) (Figure 2). Design factors have also changed due to widely accepted methods of using a natural channel design published by Rosgen (1996). These methods, although not universally applicable, describe a baseline approach to engineering and design of restoration projects (Lave, 2012; Yochum, 2018). River management manuals and protocols have been developed to standardize the use of in-stream wood as a management tool (Rosgen, 1996; Roni et al., 2015; Yochum, 2018). Geomorphically related design goals include irrigation diversions, grade control, bridge protection, and streambank stabilization (NRCS, 2007). Government agencies began to routinely include LWD applications in channel protection, For example, NRCS (2007) describes design applications based on Rosgen (2001) including cross-vanes, W-weirs, and J-hook vanes. Bank and bar stabilization ELS designs used by the U.S. Bureau of Reclamation (USBR) include step jams and valley jams (Abbe et al., 1997; Baird et al., 2015).

Implementation of ELSs requires analysis of potential hazards to recreational users, property, and infrastructure (Wohl et al., 2016). Wohl et al. (2016) defines potential hazards as access, reach characteristics, ability to avoid hazards, prior knowledge, location, snagging potential, strainers, and anchoring. Many of these hazards are related to recreational users such as canoeists, kayakers, or hikers on the floodplain (Wohl et al., 2016). Another challenge to using ELJs is the lack of long term monitoring of the structures to determine success or failure of the design (Alexander and Allan, 2006; Roni et al., 2015). The definition of success or failure of ELJs is debated by researchers and managers where some believe that success of ELJ implementation is the persistence of structures for decades and the other side argues that LWD should have the ability to move to mimic natural LWD processes (Roni et al., 2015).

ELS Pilot Project in Mark Twain National Forest

From 1980-2005 over 37,000 restoration projects throughout the US were documented with over 6,000 of those projects using wood (Roni et al., 2015). In the PNW since 1980 over 2,000 wood placement projects were conducted in the Columbia River (Roni et al., 2015). During the same period in the Upper Midwest over 76% of restoration projects had restoration goals of increasing aquatic habitat or stabilizing stream banks using wood (Alexander and Allan, 2006). While many ELSs have been placed in the PNW and Upper Midwest regions of the United States, ELS applications have only recently been proposed for the Ozark Highlands (Ozarks) in Missouri (Alexander and Allan, 2006; Martin et al., 2016).

This study evaluates the first application of ELSs in the Ozark Highlands. Ozarks streams are known for steep bluffs, chert gravel beds, and being spring-fed (Miller and Wilkerson, 2001). The Mark Twain National Forest (MTNF) managed by the US Forest Service (USFS) covers 1.5 million acres of the Ozarks Highland in Missouri. Within the MTNF is the North Fork of the White River, and the USFS manages the North Fork Recreation Area (NFRA) in the Ava/Cassville/Willow Springs Ranger District of MTNF (Owen et al., 2017). The NFRA has a non-motorized boat launch, swimming area, campground, hiking trails, and is a destination for anglers. The USFS proposed a plan to update the NFRA due to recurring repair costs associated with heavy recreation traffic and flood damage (Gubernick, 2014). Restoration to the site was scheduled to start in October 2016. One of the restoration goals at the NFRA was to protect streambanks on the campground side of the river by installing four ELSs (Gubernick, 2015). Logs used in the ELSs were acquired from clearing for a new proposed boat launch area that was designed to separate non-motorized boat launch traffic and pedestrian day used traffic. The proposed boat launch area was located next to Highway CC at the upstream limit of the study site.

Design of the four ELSs was similar, but locations and geomorphic effects were slightly different (Figure 3). The design for all four structures included embedding 12 to 18 m (40 to 60 ft.) logs approximately 6 to 15 m (20 to 50 ft.) into bed material parallel to flow to act as key pieces. On top of the key pieces 6 to 18 m (20 to 60 ft.) log embedded into the bank perpendicular to flow would be added. Finally, smaller diameter logs would be placed near the upstream side of the structure called racking logs (Figure 4). Structures ELS 1 and ELS 2 were to be designed to be embedded in the banks partially submerged in the wetted perimeter to provide toe protection, whereas ELS 3 and ELS 4 were to be located on top of a lateral bar surface to promote bar deposition (Figure 3).

In October 2016, contractors hired by the USFS removed trees from the proposed boat ramp area to use in the construction of the ELSs. Logs were transported by a skidder to two excavators at the ELS sites. One excavator was equipped with a bucket for digging into the bed and banks, and the other equipped with a claw for positioning logs. ELS 1 and ELS 2 were built by digging a large trench parallel to flow in the channel for a key piece, and then other racking logs were placed perpendicular to flow (Figure 5). The excavator then dug three trenches in the banks to place 15 m logs on top of the key pieces perpendicular to flow (Figure 6). Approximately 10 m of the logs were buried so that the weight of sediment holding the logs down would overcome the buoyant forces of the wood. ELS 3 and ELS 4 were similarly installed on a lateral bar feature approximately 300 m downstream of ELS 2. Due to shallow bedrock at all ELS locations, cables were added to the completed structures in January 2017, for added stability (Figures 7, 8, 9, and 10).

Prevention of flood damage to the campground area and protection of the adjacent stream banks are interrelated. The USFS goal to mitigate against stream bank failure and flood damage was to add four ELSs located on the campground side of the river. The ELSs were designed for toe protection and hardening of relatively steep sandy banks. USFS goals for the project ultimately were designed with pedestrian safety in mind and longevity of the NFRA as a local recreation hub. The USFS recognized the importance of monitoring the site before and after construction and after flood events to determine the effectiveness of the restoration and any potential hazards to aquatic biodiversity. Examples of post-restoration monitoring is lacking in the literature and in practice but is needed to improve designs and effectiveness for ELS projects (Doyle et al., 2007; Baird et al., 2015; Roni et al., 2015). The need for monitoring of this project is also essential as this is a pilot project in the Ozarks region where streams have unique geomorphic factors such as shallow bedrock and excess gravel (Jacobson and Primm, 1994; Miller and Wilkerson, 2001).

Purpose and Objectives

The purpose of this study is to monitor the effectiveness of the ELS structures at the NFRA and assess the suitability of using ELSs as a restoration tool in the Ozarks overall. In April 2017, following the installation of ELSs, there was a period of flooding including two bankfull floods on April 22 and April 27, 2017. However, on April 29, 2017, a >500-year recurrence interval (RI) flood occurred on the North Fork (Heimann et al., 2018). The flood destroyed the Highway CC Bridge at the NFRA, and damaged infrastructure and riparian forest throughout the watershed. Therefore, a new challenge was added to this project: To evaluate ELSs and channel stability due to the effects of such a large flood. Therefore, monitoring of the ELSs was conducted before, during, and after construction and following flood events to determine suitability of using ELSs as a restoration tool in the Ozarks. Specific objectives identified are:

1) Perform repeat geomorphic assessments at the NFRA during pre- and post-construction and post-flood periods;
2) Monitor geomorphic changes around the ELS locations due to flood events;
3) Assess flood and LWD sedimentation characteristics observed at the study site; and
4) Evaluate the applicability of using ELSs in Ozarks streams considering unique geomorphic and climate factors.

Environmental Factors of Concern

Unique geomorphic variables typical in Ozarks streams include shallow bedrock, narrow valleys, groundwater input, and disturbance associated with land use. Historical land disturbance added gravel and overbank sediment to floodplains. The influence of theses inputs may still be affecting river systems today (Jacobson and Primm, 1994; Miller and Wilkerson, 2001).

Floodplain formations and legacy floodplain deposition are associated with European settlement in the Ozarks that still have disturbed reaches (Jacobson and Primm, 1994; Ray, 2009; Martin and Pavlowsky, 2011). Excess gravel in Ozarks streams is associated with land use change from a forested landscape to agriculture by way of land clearing (Martin and Pavlowsky, 2011). Excess gravel loads exceed the transport capacity of many Ozarks streams creating disturbed reaches with oversized gravel bars (Jacobson and Primm, 1994; Jacobson and Pugh, 1997; Panfil and Jacobson, 2001; Martin and Pavlowsky, 2011). Contemporary disturbances in Ozarks Rivers could also be affected by a changing climate with increases in precipitation and flood frequency and magnitude in the middle U.S. (Villarini, 2013; Pavlowsky et al., 2016).

Contemporary geomorphic processes in Ozarks Rivers may also be affected by a changing climate in the Midwest due to increased rainfall (Villarini, 2013; Pavlowsky et al., 2016). Precipitation events in the Ozarks have been increasing in frequency and magnitude (Mallakpour and Villarini, 2015; Pavlowsky et al., 2016). Pavlowsky et al. (2016) found rainfall days with >3 inches per day have increased from six occurrences in 50 years (1955-2005) to ten occurrences in 10 years (2005-2015) in a watershed less than 100 km east of the North Fork watershed. Increases in rainfall intensity and flooding in the North Fork can accelerate geomorphic processes affecting channel stability and higher sediment loads (Pavlowsky et al., 2016).

Benefits of the Research

This study provides insight to the effectiveness of using ELSs in Ozarks streams. Scientific benefits of this research are the detailed geomorphic response of Ozarks river channels to ELSs and an extreme flood. The implementation of ELSs to stabilize banks is widely documented, but monitoring is lacking in the literature (Wohl et al., 2010; Roni et al., 2015). Also lacking in the literature is assessments of ELS response to a > 500-year flood. The USFS will benefit from this research to add to the understanding of the applicability of using ELSs in the Ozarks because there are other projects proposed in the region based on the outcome of the NFRA project. Management benefits of this study are the evaluation of the use of ELSs to mimic geomorphic processes, remain intact, and be an economical tool for restoration in the Ozarks. Due to increasing flood frequency and magnitude in the Ozarks, managers designing ELSs for use in the Ozarks need to consider how changing climate conditions could affect flow regime.

Figure 1. Example of an ELJ in the Pacific Northwest, (Kimbrel, 2014).

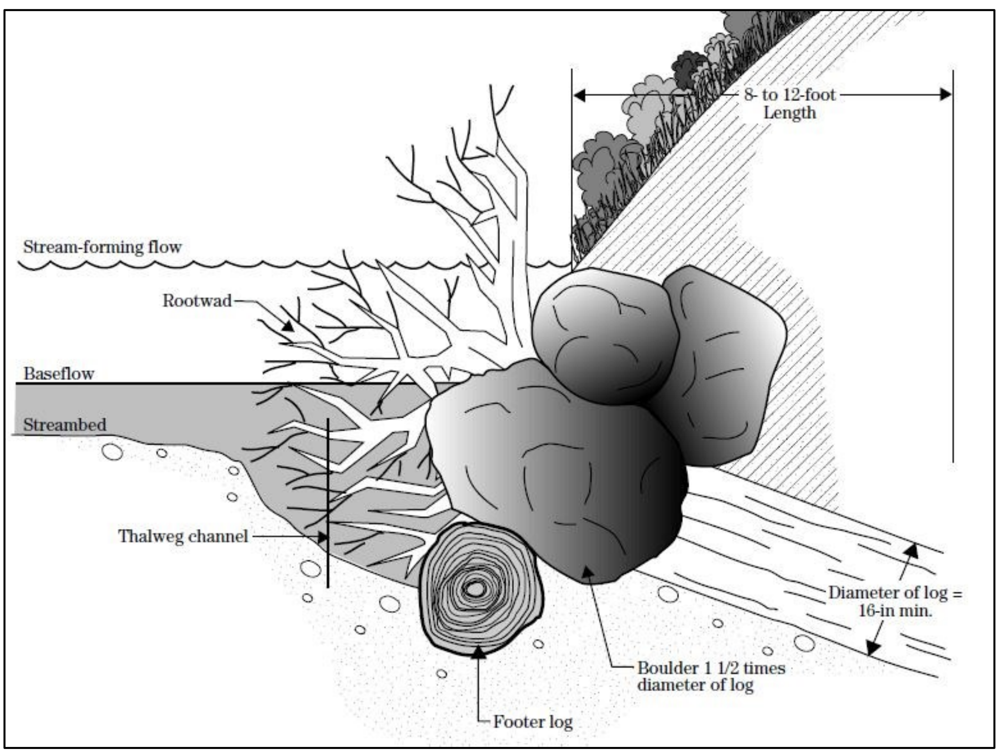
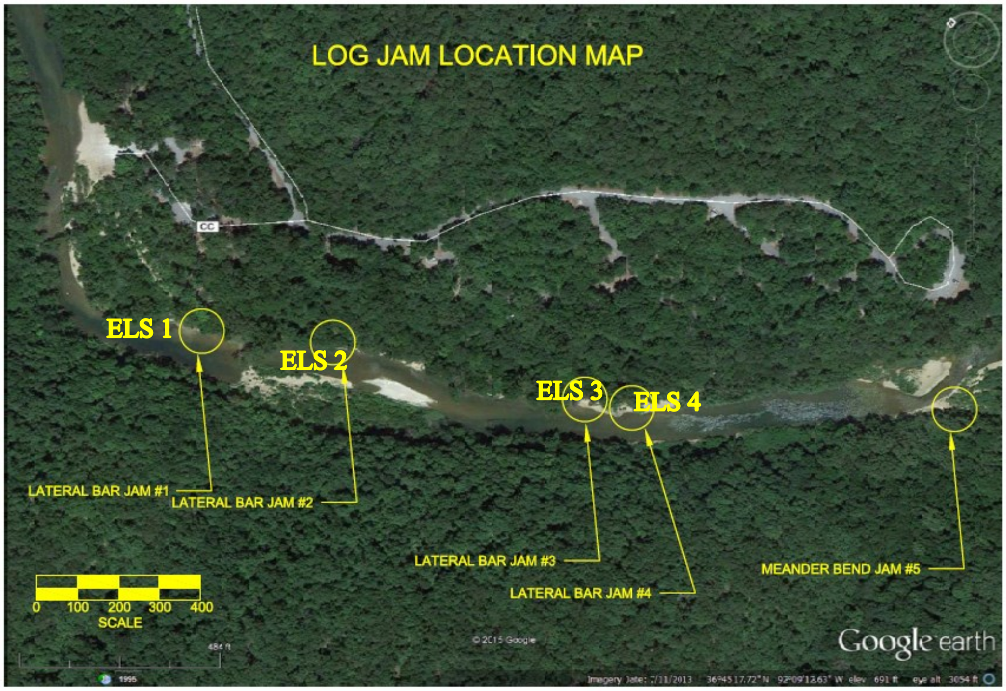


Figure 2. Example of ELS design using whole tree with rootwad for streambank protection (NRCS, 1996).



LOG MATERIALS				
LOCATION	ROOT WAD TREES	LOGS	RACKING LOGS	TREE TOPS
ELS 1	4 TREES @ ~16.8 m X 0.45 m DIA	2 LOGS @ ~ 12.2 m X 0.15 m DIA	6 LOGS @ ~4.6 m X 0.15 m DIA	3 TOPS @ ~4.6 m LONG
ELS 2	4 TREES @ ~16.8 m X 0.45 m DIA	2 LOGS @ ~ 12.2 m X 0.15 m DIA	6 LOGS @ ~4.6 m X 0.15 m DIA	4 TOPS @ ~4.6 m LONG
ELS 3	4 TREES @ ~16.8 m X 0.45 m DIA	2 LOGS @ ~ 12.2 m X 0.15 m DIA	6 LOGS @ ~4.6 m X 0.15 m DIA	5 TOPS @ ~4.6 m LONG
ELS 4	4 TREES @ ~16.8 m X 0.45 m DIA	2 LOGS @ ~ 12.2 m X 0.15 m DIA	6 LOGS @ ~4.6 m X 0.15 m DIA	6 TOPS @ ~4.6 m LONG

Figure 3. ELS location map and log size specifications. Meander Bend Jam #5 was not installed (Gubernick, 2015).

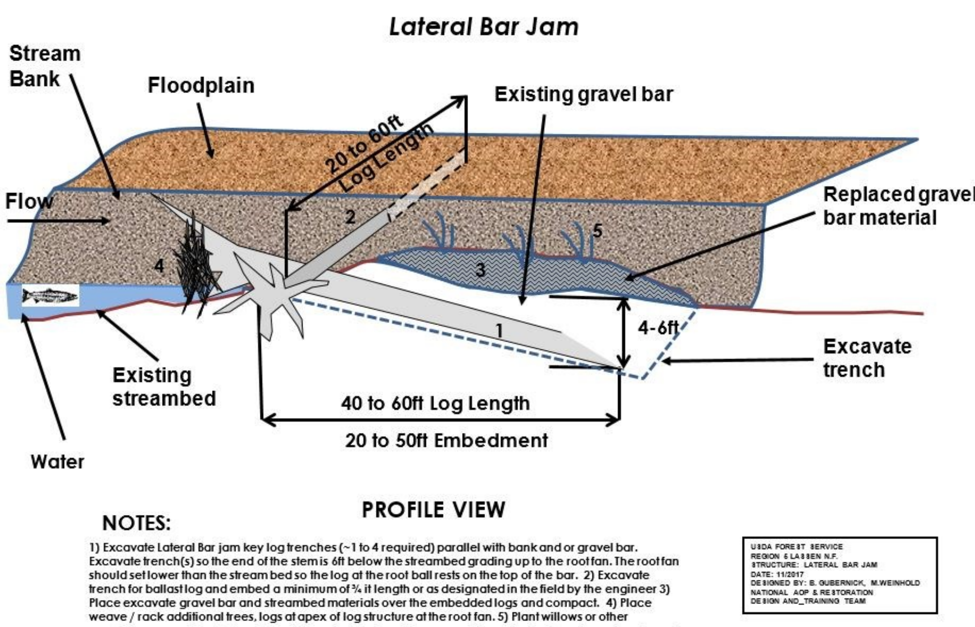


Figure 4. Profile view of ELS design by USFS Watershed Restoration Geologist Robert Gubernick.

Figure 5. Construction of ELS 1. Excavator digging a trench in the bed for key piece placement.

Figure 6. Excavator placing logs in a trench perpendicular to flow positioned over key pieces.

Figure 7. ELS 1. Flow direction from picture right to picture left.

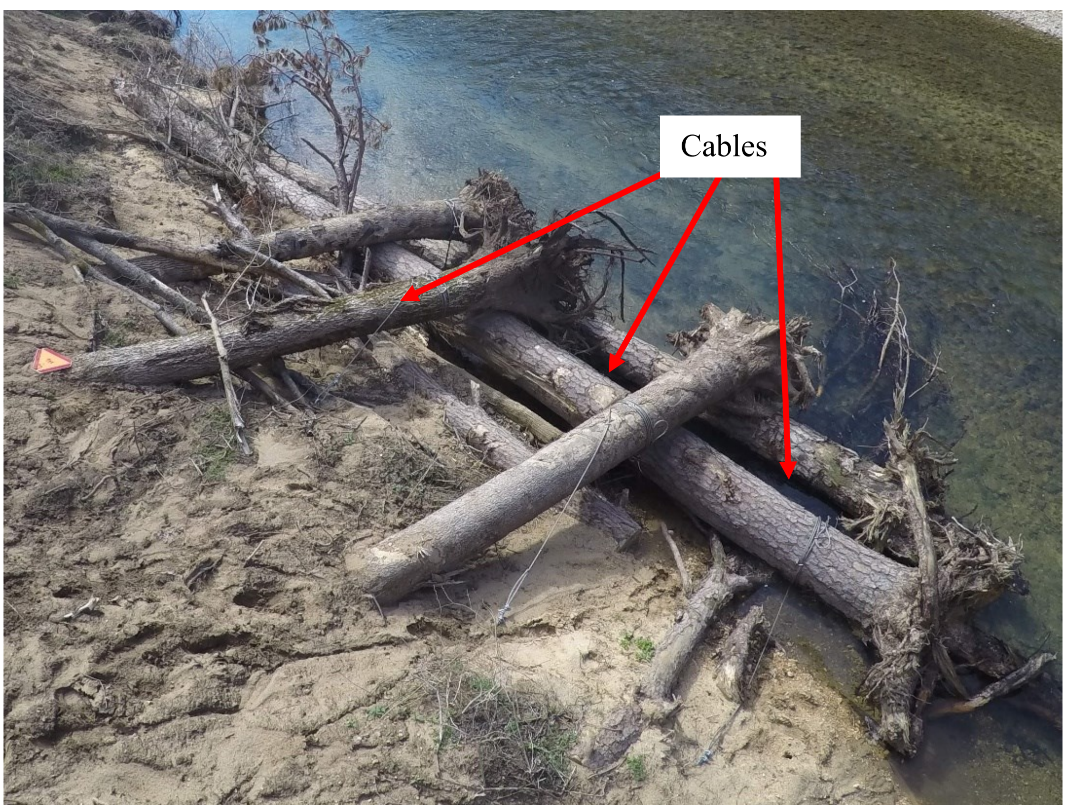


Figure 8. ELS 2. Flow direction from right to left and cables for added stability.

Figure 9. ELS 3. Location on lateral bar and flow direction from right to left.

Figure 10. ELS 4 in foreground and ELS 3 in background. Flow direction from right to left and burial of key pieces with root fans oriented upstream.

STUDY AREA

Regional Location

The North Fork of the White River is a part of the White River basin in southern Missouri and flows into a 22,000-acre reservoir, Norfork Lake near the state line with Arkansas (Miller and Wilkerson, 2001). The drainage area is 1,453 km^2 primarily located in Douglas and Ozark counties, with its headwaters in Wright, Texas, and Howell counties with a relief of 357 m from 510 meters above sea level (MASL) to 153 MASL (Figure 11). From its start around Mountain Grove, Missouri the river flows south toward Arkansas approximately 100 km. The specific study reach for this project is the United States Forest Service (USFS) public access area, North Fork Recreation Area (NFRA), also known as Hammond Camp. The drainage area at the NFRA is approximately 1,044 km^2 and it is located 33 km above Norfork Lake. The NFRA is located southwestern corner of the Ava Ranger District of the Mark Twain National Forest.

Geology and Soils

Geology. The North Fork basin is located on the Salem Plateau, which is part of the Ozark or Interior Highlands of North America (Miller and Wilkerson, 2001; Ray, 2009; Martin and Pavlowsky, 2011). The Salem Plateau formed as the result of Paleozoic uplift that began approximately 450 million years ago (MYA) (Miller and Wilkerson, 2001; Spencer, 2011). Geology in the North Fork basin consists mostly of Ordovician sandstones and dolostones (Miller and Wilkerson, 2001; Ray, 2009). The general stratigraphy at the NFRA is Gasconade Dolomite along the bed, the Roubidoux Formation on valley walls, and Jefferson City Dolomite on the uplands (Skelton and Harvey, 1968; Vineyard and Feder, 1974) (Figures 12 and 13).

Karst. The Ozarks Highlands is an uplifted plateau consisting of almost horizontally bedded sedimentary rocks including limestone and dolomite that form a karst topography (Vineyard and Feder, 1974; Jacobson and Primm, 1994; Shepherd et al., 2011). Therefore, losing and gaining river sections, caves, large spring inputs, and sinkholes are common to the region (Skelton and Harvey, 1968; Orndorff et al., 2001). Uplifted topography and the geologic setting of the North Fork River have created a watershed in which the river has entrenched itself creating relatively high bluffs and narrow valleys (Vineyard and Feder, 1974). Flood events have the potential to generate high stream power due to narrow valleys and high bluffs which confine overbank floods and increase flow depths and velocity.

Upland Soils. Upland soils consist primarily of thin soil layers with underlying fragipans that hinder root penetration (Miller and Wilkerson, 2001). Loess is typically an accumulation of windblown silt from aeolian or glacial processes (Sprafke and Obreht 2016). If loess is present, it is a thin layer over clayey residuum formed from the intense weathering of chert, limestone, and dolomite (NRCS, 2000; Miller and Wilkerson, 2001; Owen et al., 2017). Within the dolomite there is an abundance of residual chert horizons that supply gravel sediment loads to the river (Orndorff et al., 2001).

Alluvial soils. Most bottomland soils formed in thick loamy alluvium over coarse gravel beds (Ray, 2009; Owen et al., 2017). Steep hills and ridges near the river supply gravelly and sandy sediments to the river system from soil units such as the Coulstone-Bender complex composed of very stony sandy loam, and the Coulstone-Bender-Gatewood complex composed of extremely gravelly sandy loam (NRCS, 2000) (Figure 14). Floodplains near the NFRA are composed of the Sandbur series made up of deep fine sandy loam (NRCS, 2000).

Alluvial soils in the North Fork River were previously studied due to the abundance of Native American artifacts that are found in floodplains throughout the watershed (Ray, 2009). Artifacts are commonly found in a floodplain formation made of soil assemblages known as the Black Hawk formation, and a terrace formation known as the Red Cloud formation (Ray, 2009). Ray (2009) shows relative floodplain and terrace formations over 79 km of the North Fork River 79 km (Figure 15). The NFRA has similar landforms, but the floodplain is about 6 m above the channel bed compared to 4 m as described by Ray (2009) due to a narrower valley than what is depicted in the image. Two of the closest study sites to the NFRA in Ray (2009) were 8.2 km upstream and 6.6 km downstream.

Native Vegetation and Land Use History

Pre-Settlement Vegetation. Land cover before European settlement consisted primarily of prairie and savannah like uplands and heavily wooded bottomlands (Jacobson and Primm, 1994). Vegetation along the river included elm, beech, maple, sycamore, oak, and ash (Schoolcraft, 1821; Miller and Wilkerson, 2001). Schoolcraft (1821) describes thick vegetation in the heavily dissected North Fork River valley and having to travel in the uplands near the divide between the North Fork and Bryant Creek to the west. Although there are differing interpretations of pre-settlement vegetation and land use described by early explorers, it is agreed upon that vegetation differs from the contemporary landscape (Jacobson and Primm, 1994). Native American groups such as the Osage are known to have used burning practices to restore grasslands and enhance hunting opportunities (Jacobson and Primm, 1994; Ray, 2009). Land use changes began with the European removal of the Osage and by 1825 land was mostly cleared for livestock (Ray, 2009).

Logging History. Logging began in the in the upper North Fork watershed in Ozark County above the study site prior to the larger logging boom of the 1880's in other areas. Over 330 km^2 of the watershed was a pinery area and three mills were located at stream confluences (Sauer, 1920) (Figure 16). The North Fork and adjacent Bryant Creek pinery areas had white and yellow pines comparable to the forests of Wisconsin and Minnesota and were claimed in the 1850's (Sauer, 1920). Mostly short-leaf pine was harvested in the watershed, and was transported by ox-team to Springfield, Bolivar, and Linn Creek (Miller and Wilkerson, 2001).

Contemporary Land Use. In the 1930s the federal government purchased land in the North Fork watershed for the creation of the Mark Twain National Forest where initial forest management was undertaken by the Civilian Conservation Corps (CCC) (Miller and Wilkerson, 2001). Land use after the timber boom moved to agriculture and cropland during a time of poor land management that contributed to erosion and degraded streams (Jacobson and Primm, 1994; Miller and Wilkerson, 2001). Land use for the North Fork of the White River as of 1997 consisted of forest/woodland (62%) and grassland/cropland (37.5%) with less than 0.5% being urban (Miller and Wilkerson, 2001). The Mark Twain National Forest boundary covers about 58% of the land area in the watershed which contributes to the high percentage of forest/woodland area (Miller and Wilkerson, 2001) (Figure 16). The North Fork of the White River is now one of the most secluded areas in Missouri, which provides many recreational activities. The North Fork Recreation Area and Mark Twain National Forest are recreation destinations for hunting, fishing, hiking, camping, kayaking, and canoeing (Miller and Wilkerson, 2001).

Climate and Hydrology

Climate. The climate in Missouri is continental with cold winters, hot summers, and precipitation year-round (Miller and Wilkerson, 2001). The average temperature in Mountain Grove, Missouri, where the North Fork River starts is approximately 13°C, and average annual precipitation is approximately 1,130 mm (MRCC, 2017). Climate change appear to have affected the flow regime of the North Fork River due to increasing rainfall trends over the past three decades (Miller and Wilkerson, 2001). A climate study for Big Barren Creek watershed, less than 100 miles east of the North Fork watershed, was released in March 2016 citing that frequency and magnitude of rain events have been increasing over the last decade (Pavlowsky et al., 2016).

Hydrology. Hydrology for the North Fork River is dependent on baseflow from groundwater input from springs. There are over 200 springs in the North Fork Watershed (Miller and Wilkerson, 2001). Blue Spring has one of the highest flow rates in the watershed and is located at the downstream boundary of the study site at North Fork Recreation Area (Figure 17). Other large spring inputs come from Althea, Big, North Fork, Rainbow, and Topaz Springs (Vineyard and Feder, 1974) (Table 1). The U.S. Geological Survey (USGS) operates a hydrological gaging station near the mouth of the North Fork River at Tecumseh, MO. Discharge has been recording at this station since October 1, 1944. Peak streamflow for the North Fork River has been increasing over the gage record (Figure 18).

The NFRA has an average 100-year floodplain valley width of 222 m with a topographic map slope of 0.12%. The study reach at the NFRA is 1,374 m longitudinally with an upstream limit at Highway CC bridge and downstream limit at Blue Spring with ELSs located at reach distances 435 m, 590 m, 838 m, and 874 m (Figures 19 and 20). The existing campground and parking areas are located on the east side of the river or the river-left side of the valley. The proposed boat ramp is located between Highway CC and the existing boat ramp with a new driveway access that is separate from the existing boat ramp driveway.

During construction of the ELSs there were no measurable changes to channel form, capacity or substrate composition. Changes only occurred at the proposed boat ramp where trees were cleared from river distance 0 m to 166 m, and on the floodplain from 350 m to 830 m where an access road was cleared for equipment to transport logs to ELS sites (Figure 20). After the construction of ELSs was completed, trees were placed over the construction road to mimic downed trees typically seen on a forest floor. Design specifications of the ELSs outlined that bed and banks be replaced to pre-construction condition (Gubernick, 2015). Due to the embedding of logs into the bed and banks, substrate was unconsolidated but local topography remained the same. Erosion control barriers were placed around the ELSs to prevent sediment from entering the river. After the ELS construction cables were wrapped around ELS logs and secured to the banks using anchors driven into the sediment.

April 2017 Floods

Rainfall record. During April and May 2017, the Ozarks in general and specifically the North Fork watershed experienced multiple days of saturating rainfall that generated flooding. The National Weather Service (NWS) released a map of rainfall totals from a stationary front that occurred from April 28-30 showing total rainfall amounts from 8-12 inches (200-300 mm) over a portion of the North Fork watershed (NWS, 2017) (Figure 21). Daily observed rainfall totals at three rain gaging stations within or near the North Fork watershed listed are Mountain Grove 2N at the headwaters, West Plains Municipal Airport located 1.4 km west of the watershed, and Tecumseh 1NE at the mouth of the watershed (Table 2). Daily observed rainfall totals were compiled from April 16, 2017 to May 5, 2017 (Table 3). Rainfall over the 20-day period averaged 476 mm over the North Fork watershed. During this period there were three floods generated at the study site including bankfull flood #1 on April 21, bankfull #2 on April 26, and the flood of record on April 29-30. Floods are described by their annual exceedance probability (AEP) in a fraction derived from gage data or the recurrence interval (RI) which is expressed in a certain year probability where bankfull floods are typically between a 0.66 to 0.43 AEP or 1.5-2.33-year RI (Ries, 2007).

Bankfull flood #1 followed a rainfall event lasting 24 hours began on April 21, 2017 that generated approximately 74 mm over the North Fork watershed. The North Fork River at the Tecumseh gage began rising on April 21, 2017, and peaked at 11:00 Central Daylight Time (CDT) on April 22 at a stage of 3.42 m, and discharge of 362 m^3/s. The hydrograph for bankfull flood #1 lasted about four days until the falling limb leveled to 1.37 m on April 25. Bankfull flood #1 was approximately a 50-percent AEP or 2-year RI event, (USGS, 2018).

Bankfull flood #2 followed a rainfall event that began on April 26, 2017 and lasted 20 hours with approximately 55 mm over the North Fork watershed. River stage began to rise at the Tecumseh gage on April 26, and peaked at 06:15 CDT on April 27, at a stage of 2.92 m, and a discharge of 283 m^3/s. Bankfull flood #2 lasted 54 hours, where the stage dropped to 1.58 m, and then began to rise again starting another flood event. Bankfull flood #2 was approximately a 67-percent AEP, or a 1.5-year RI flood event.

On April 29, 2017 a historic rainfall event began over the Midwest generating rainfall totals greater than 250 mm in localized bullseyes (NWS, 2017). The North Fork watershed was one of the areas that experienced local maximum rainfall of 220 mm that lead to a historic flood event with a stage of 12.7 m, and a discharge of 5,352 m^3/s at the Tecumseh gage (Figure 22).

This flood was reported as > 0.2% AEP, or greater than 500-year RI event (Heimann et al., 2018). The previous peak flood from 73 years of gage record occurred in 1985 with a stage of 8.5 m and a discharge of 2,070 m^3/s. High water marks measured at the NFRA were 14 m above the thalweg near Blue Spring.

Flood damage. The flood of 2017 caused damage to infrastructure, homes, businesses, and forest throughout the watershed. Highway PP and Highway CC bridges were destroyed which were two of the most heavily traveled bridges in this relatively secluded area (Figure 23). Highway CC bridge was located at the upstream boundary of the NFRA and Highway PP was located approximately 26 km downstream of the study reach. Local traffic was detoured for six months until a replacement bridge was completed in October 2018. Damage to the campground area at the NFRA was extensive. Sediment and LWD were deposited throughout the campground area and picnic tables, fire rings, and other campground amenities were destroyed or completely removed. Initial damage clean-up procedures were conducted by a National Type 2 Incident Management Team (IMT) that removed sediment and burned LWD. Clean up lasted for approximately 3 weeks, but the campground area was closed indefinitely.

Table 1. Largest groundwater input in the North Fork River (Vineyard and Feder, 1974).

Spring Name	County	Location (decimal degrees)	Minimum Discharge (m^3/s)	Maximum Discharge (m^3/s)	Average Discharge (m^3/s)	Report Date
Althea	Ozark	36.642125, -92.227122	0.38	0.75	0.53	3/20/1996
Big	Douglas	36.821665, -92.127649	0.09	0.76	0.38	no date
Blue	Ozark	36.751199, -92.148958	0.27	0.85	0.41	3/20/1996
North Fork	Ozark	36.724404, -92.186694	1.87	2.13	1.97	7/26/1995
Rainbow	Ozark	36.719611, -92.187265	1.33	6.57	3.60	7/25/1995
Topaz	Douglas	36.946422, -92.202525	0.10	0.10	0.10	8/11/1995

Table 2. Rain gage locations near the North Fork Watershed.

Station Name	Latitude (DD)	Longitude (DD)	Location relative to North Fork watershed
Mountain Grove 2N	37.1542	-92.2617	headwaters/northern boundary of watershed
West Plains Municipal Airport	36.8781	-91.9025	1.4 km west of watershed boundary
Tecumseh 1 NE	36.5967	-92.2617	Mouth/southern boundary of watershed

Table 3. Daily observed rainfall totals (MRCC, 2017)

Date	MOUNTAIN GROVE 2 N Precipitation (mm)	W. PLAINS MUNICIPAL AP Precipitation (mm)	TECUMSEH 1NE Precipitation (mm)	Average Precipitation (mm)
04/16/17	0	5	0	2
04/17/17	24	30	25	26
04/18/17	0	0	3	1
04/19/17	0	0	0	0
04/20/17	0	23	0	8
04/21/17	15	68	5	30
04/22/17	45	3	64	37
04/23/17	1	0	3	1
04/24/17	0	0	0	0
04/25/17	0	0	0	0
04/26/17	8	55	3	22
04/27/17	35	0	69	35
04/28/17	1	02	0	1
04/29/17	106	176	17	100
04/30/17	114	56	216	128
05/01/17	39	0	9	16
05/02/17	1	0	1	0
05/03/17	15	32	0	16
05/04/17	44	41	38	41
05/05/17	29	0	8	12
Sum:	476	492	459	476
High Value:	114	176	216	169

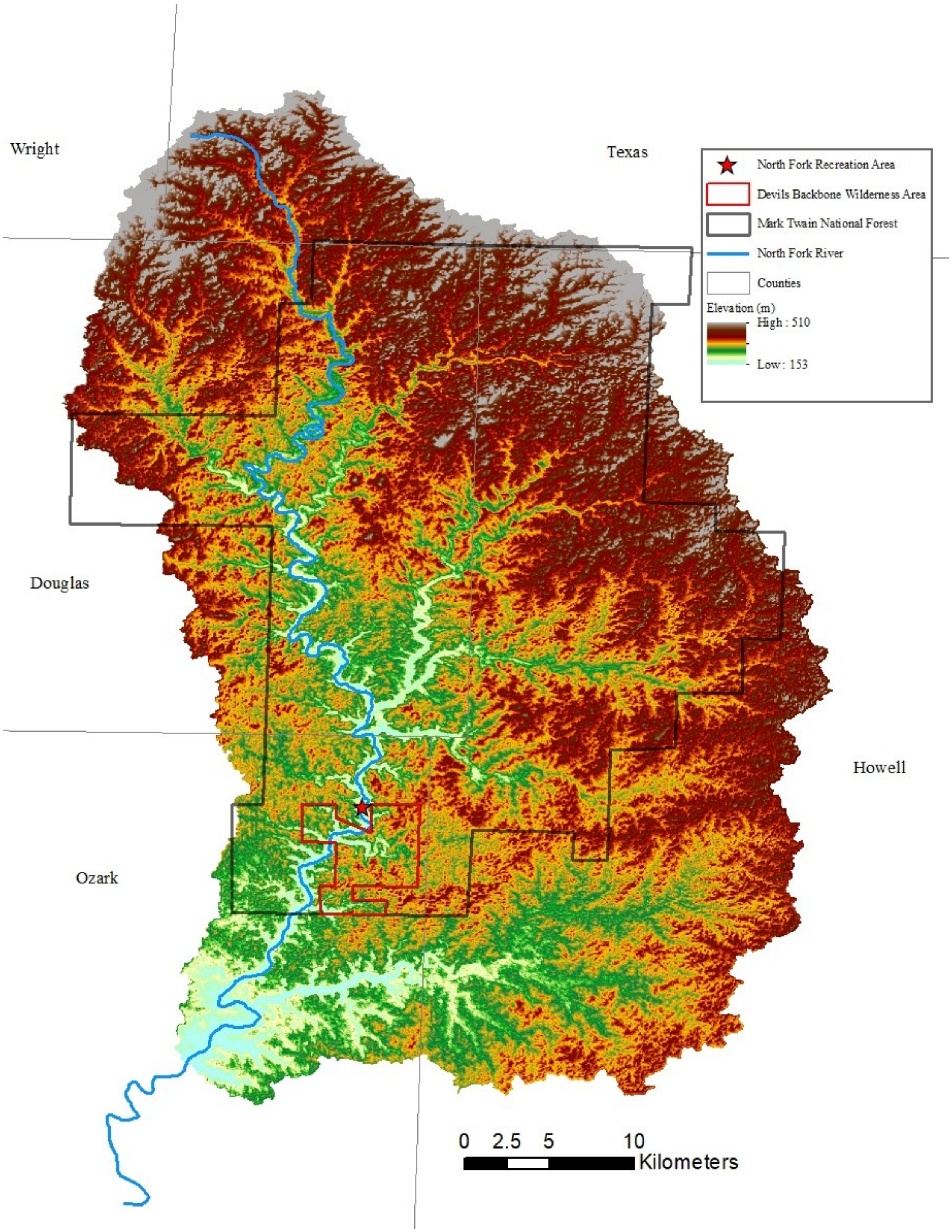


Figure 11. North Fork of the White River watershed.

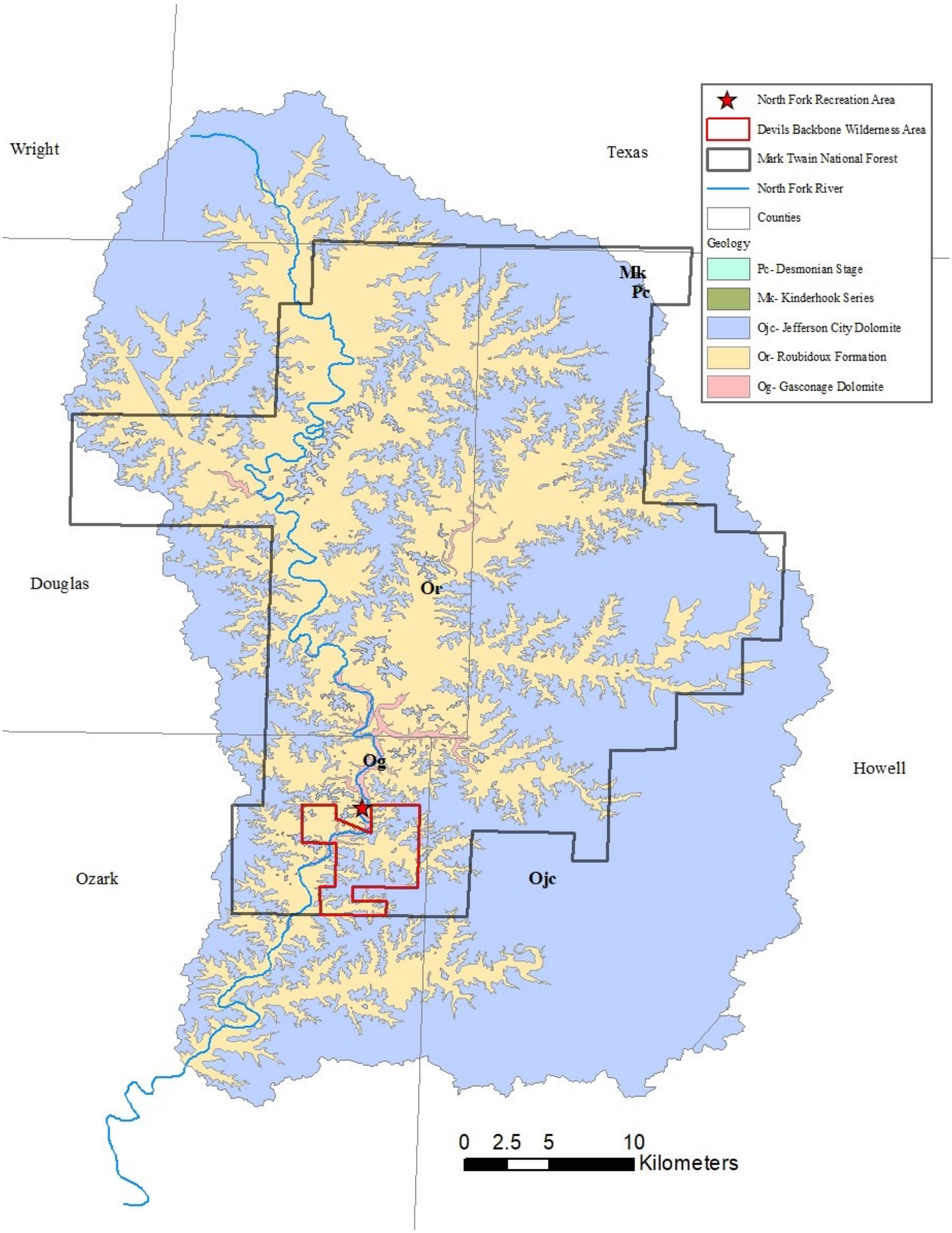


Figure 12. Geology of the North Fork of the White River watershed.

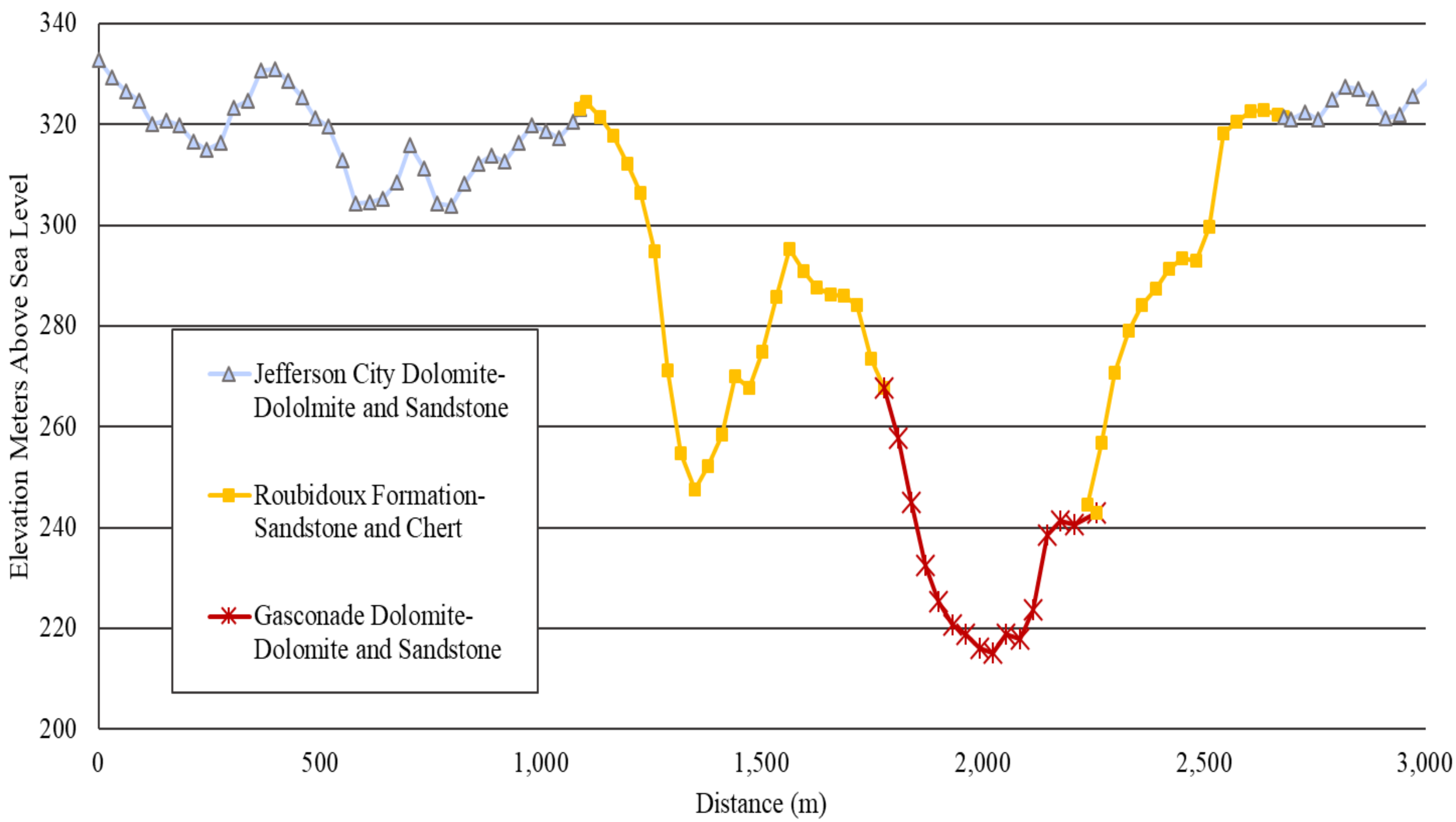


Figure 13. Cross-section of geologic composition.

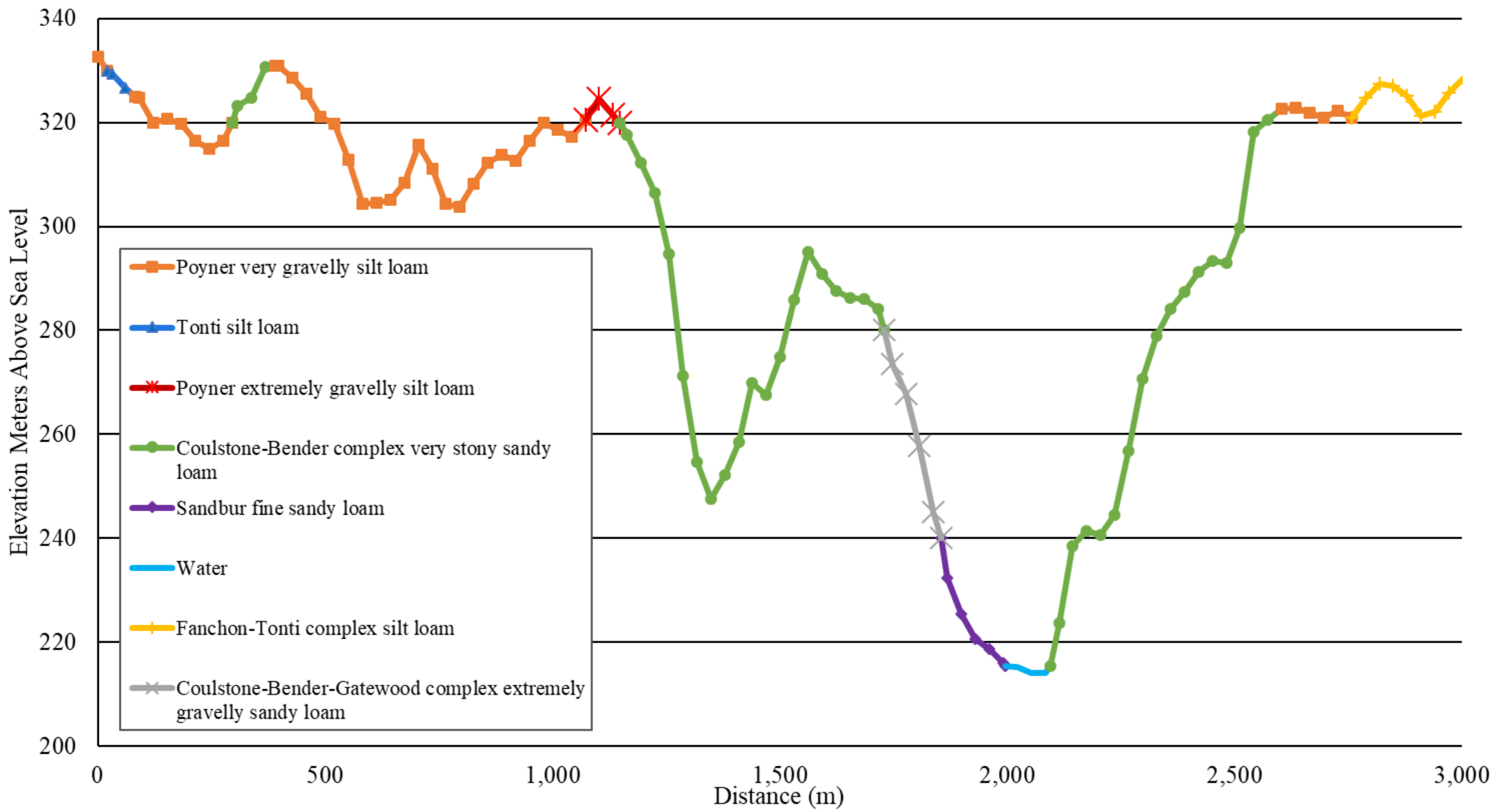


Figure 14. Cross-section of soils near the North Fork Recreation Area (NRCS, 2000).

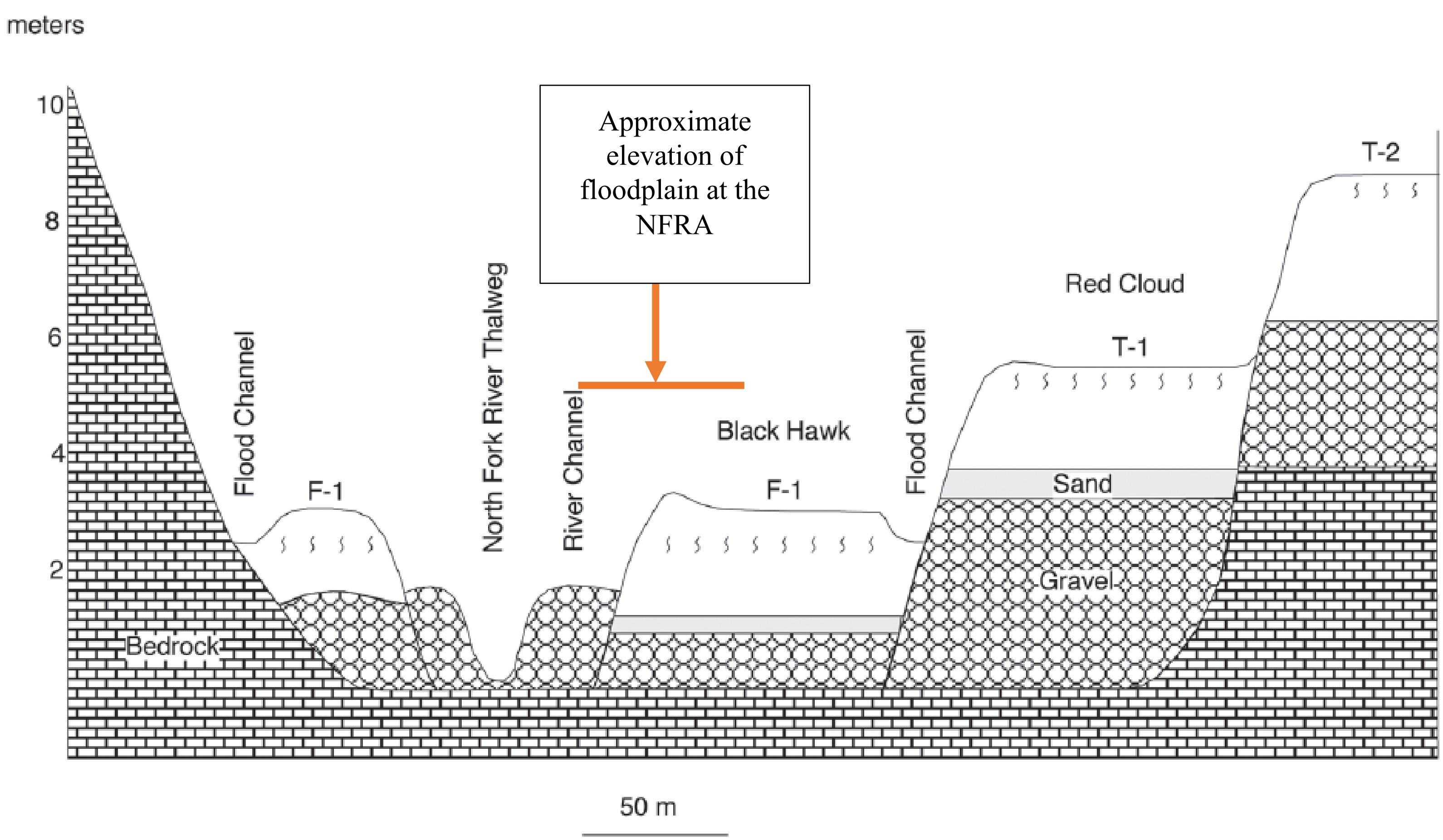


Figure 15. Floodplain and terrace formations in the North Fork of the White River (Ray, 2009). Red line is approximate floodplain elevation at the NFRA.

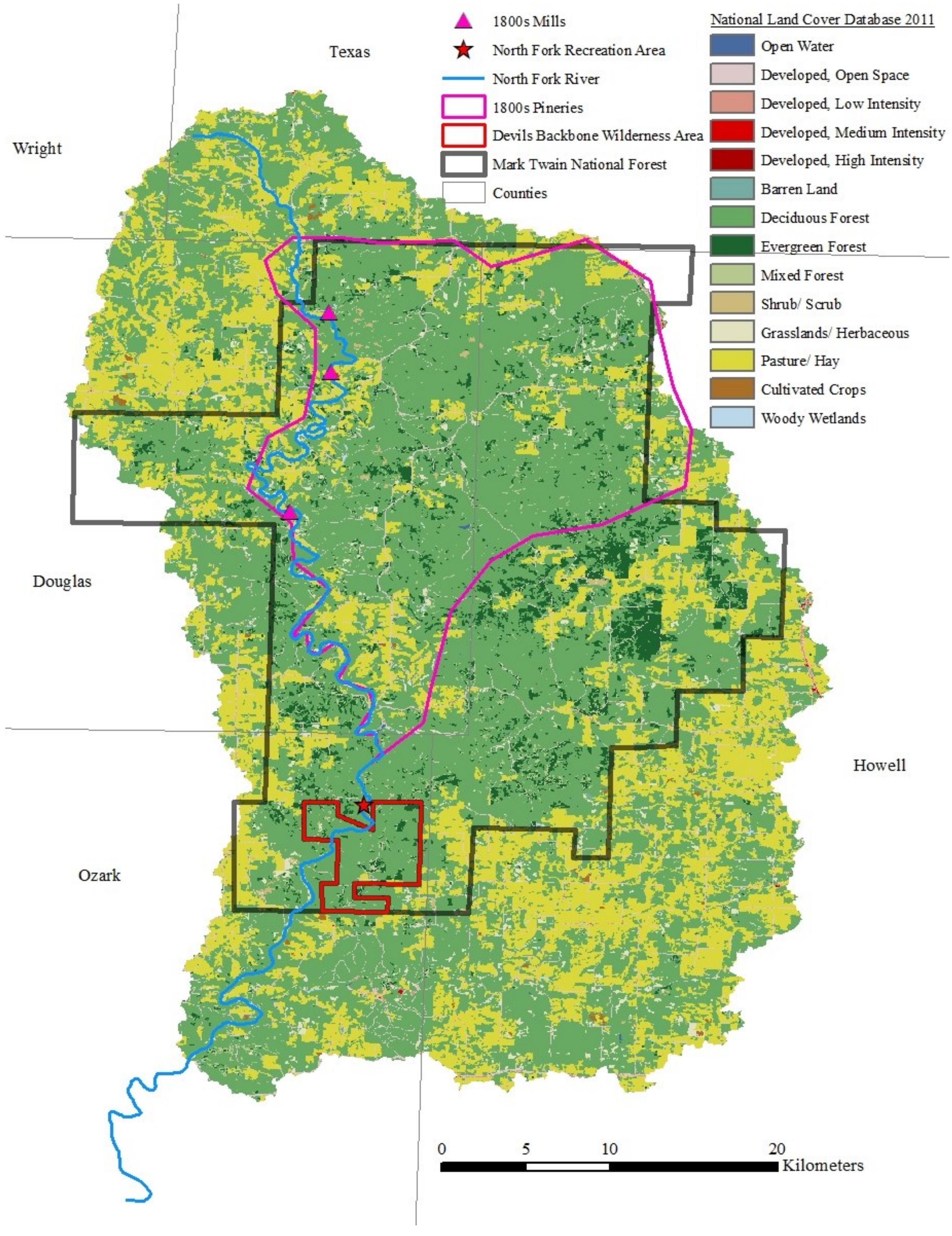


Figure 16. North Fork of the White River land use map with pinery area and mills from Sauer, 1920.

Figure 17. Blue Spring located at the downstream limit of the NFRA.

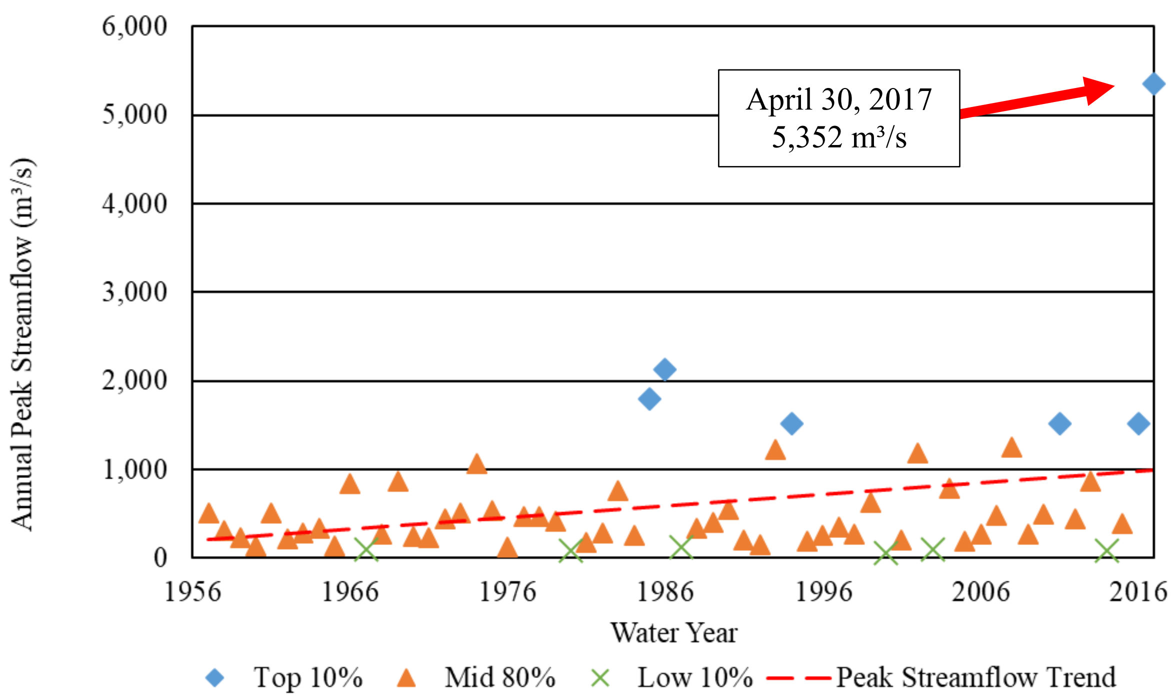


Figure 18. Annual peak streamflow from North Fork River from 1956-2017 (USGS, 2018).

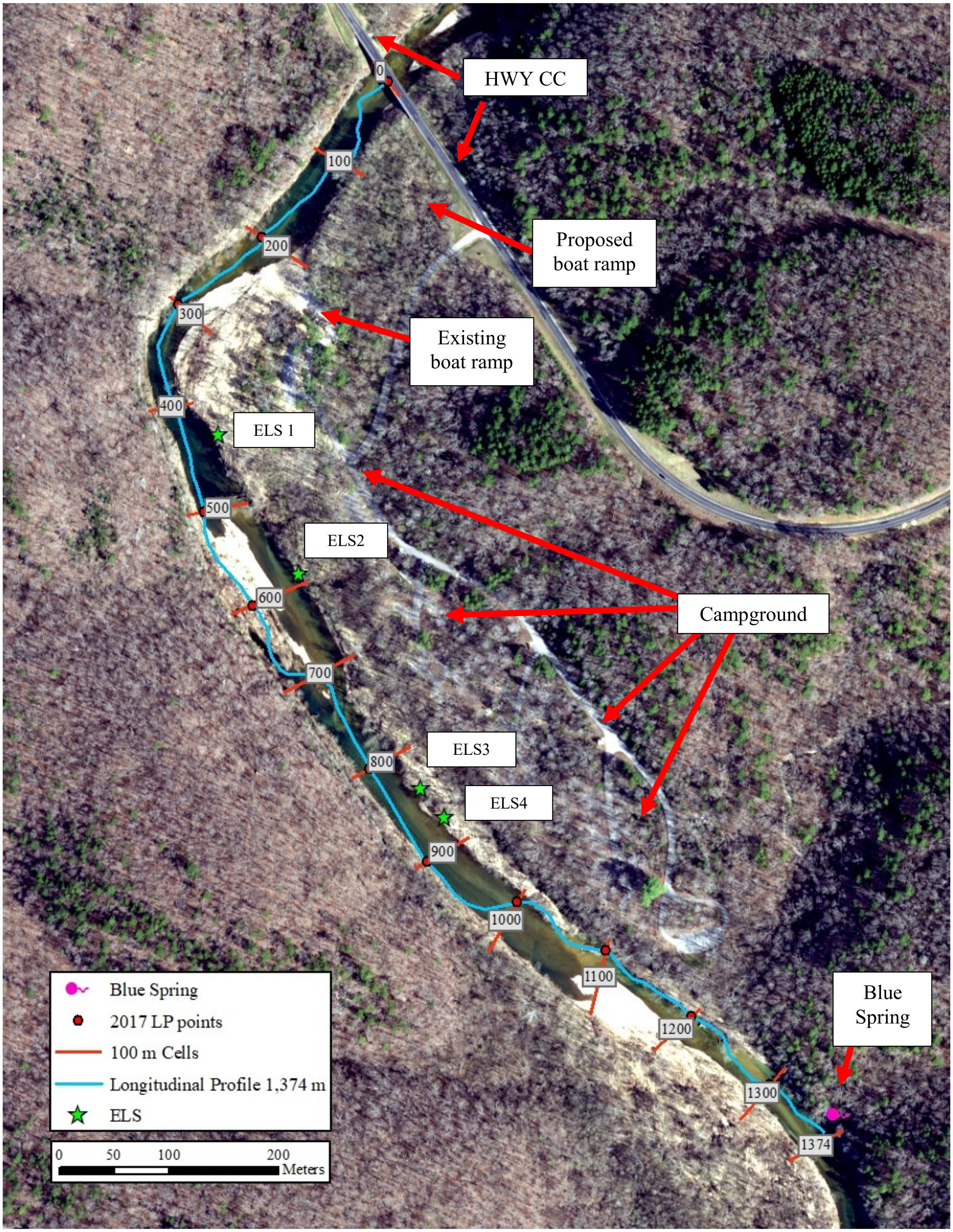


Figure 19. Pre-Flood Reach Map of the North Fork Recreation Area from 2015 (MDNR, 2015).

Figure 20. Construction disturbance to the North Fork Recreation Area including clearing for proposed boat ramp and construction access road (MDNR, 2015).

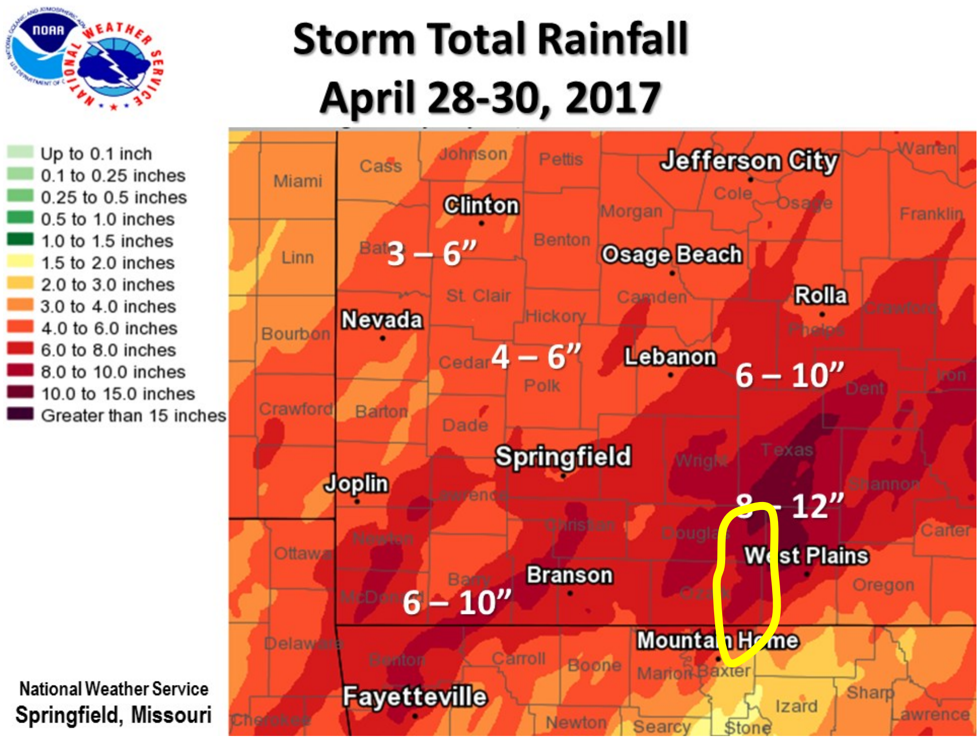


Figure 21. Rainfall totals from a stationary front on April 28-30, 2017 (NWS, 2017). Yellow polygon is approximate location of the North Fork watershed.

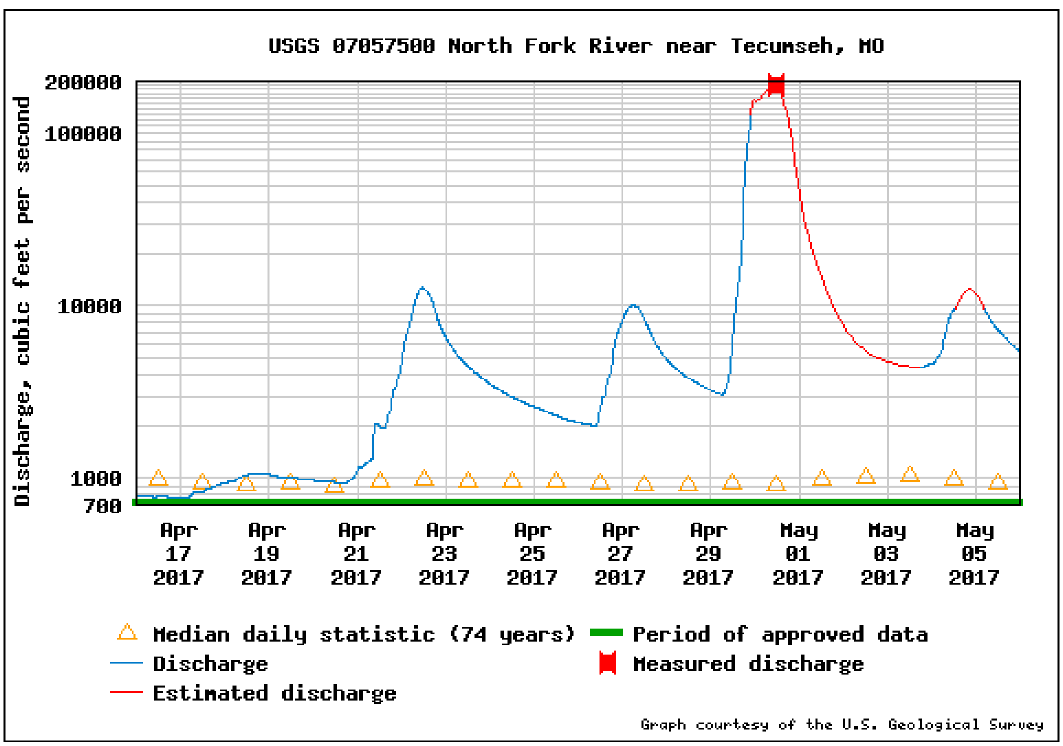


Figure 22. Hydrograph from April 16, 2017- May 5, 2017. Near bankfull floods on April 22 and April 27 and extreme flood on April 29-30 (USGS, 2018).

Figure 23. Highway CC bridge at NFRA. Deck of bridge washed downstream of road. (Aerial Ozarks, 2017).

METHODS

The monitoring approach for this research included historical photograph analysis, channel surveys, pebble and LWD counts, and drone imagery. Historical photograph analysis was conducted to determine channel conditions over a 25-year period prior to the study. Channel surveys were conducted to determine pre-construction and post-construction changes and post-flood effects to topography. Pebble and LWD counts provide insight into sediment and LWD distribution throughout the study area. Post-flood low-altitude drone imagery was conducted to add to the historical photograph database to provide visual evidence of flood effects.

Channel Surveys

Monuments. Field data collection was completed during 15 site visits from 2016-2017 where the first site visits consisted of locating proposed construction areas and setting up a monument network (Table 4). Monuments were set throughout the North Fork Recreation area to aid in locating and georeferencing repeat surveys for geomorphic change detection (OEWRI, 2007). Five types of monuments were used including, pre-existing monuments set by the USFS, an "x" chiseled into a large boulder in the channel, rebar set in concrete on floodplains, t-post stakes, nails in trees on the floodplain, all of which were spray painted with high-visibility orange marking paint and orange flagging tape (Smith, 2010). Different types and locations of monuments were used in the event that monuments be disturbed by recreational users or floods. Two monuments are needed at each survey location (Harrelson et al., 1994). T-post monuments set at each proposed ELS site in June 2016 signified the starting position of channel cross-sections (Harrelson et al., 1994). After the construction period, rebar monuments were set in concrete near ELS locations for permanent hard points (Harrelson et al., 1994). Two t-posts were set at each ELS location signifying upstream and downstream grid-survey limits.

Survey Instrumentation. Surveys of the longitudinal profile, cross-sections, high-density grids, and monuments were georeferenced using a Topcon HiPer Lite+ Real-Time Kinematic (RTK) GPS unit and a Topcon GTS-225 total station. The Ozarks Environmental and Water Resources Institutes (OEWRI) standard operating procedure (SOP) for the RTK provided step by step instructions for setting up and operating the RTK unit derived from the instrument manual (Topcon, 2006; OEWRI, 2016). Setup and operation procedures for the total station followed the instrument manual (Topcon, 2007). Total station surveys used methods that required a minimum of one prism affixed to a prism pole or stadia rod (Topcon, 2007).

Longitudinal profile. Length of a longitudinal profile is typically surveyed for at least 20 stream widths or 2 meander wavelengths (Rosgen, 1996). A total station operator was positioned for maximum line of sight while field technicians used canoe and a four-meter prism pole to survey thalweg positions throughout the study reach (NRCS, 2007; Kline et al., 2009). The spacing between longitudinal survey points is determined by field observed changes in slope. The longitudinal profile was surveyed to calculate riffle-crest slope, riffle-pool formations, and to interpret the hydrological setting (NRCS, 2007). Slope used for calculating velocity and discharge of the historic flood was calculated from map or valley slope from 7.5-minute quadrangle topographic maps, because roughness elements on the bed, such as riffle crests and LWD, are negligible under extreme flood conditions (Magilligan, 1988; Phillips and Tadayon, 2006).

Cross-sections. Cross-sections are typically surveyed near riffles with at least 10 measurements taken within the active channel (NRCS, 2007; Kline et al., 2009). Cross-sections at the NFRA were surveyed at ELS locations with a total station and prism pole from bluff wall to terrace formations. Surveys included 20-40 points with 15-20 points in the active channel. Repeat cross-sections were used to calculate channel dimensions and to determine bed, bank, and bar landforms near ELS sites. Comparisons of pre- and post-flood cross-sections show localized erosion and deposition of sediment. Cross-section dimensions were also used to calculate channel hydraulic variables for bankfull and extreme flood stages.

Topographic Surveys at ELS Sites. High-density grid surveys were collected with the RTK after construction and after the April flood events. Grid survey locations were at ELS 1, ELS 2, and due to their proximity ELS 3 and ELS 4 were combined into the third grid site. Grid areas surveyed at ELS 1 and ELS 2 included portions of the floodplain above the structures, high banks where structures logs were embedded, the bank toe where the bank transitions to the bed, and portions of the bed near the structures. The ELS 3 and ELS 4 grid included a low bar on the instream side of the structures where some ELS log ends were placed, the bar area where most of the structure logs were installed, and into the wetted channel to include the bed. The surveys at ELS sites are 3-Dimensional areas that show spatial patterns from survey points that differ from cross-sections because cross-sections are a comparison of point to point differences whereas grids are comparing pixels from the interpolated values resulting in volumetric changes. Pre-flood grid areas were marked with t-posts, so the repeat survey crew would be able to re-survey the same area however, the April Flood buried or destroyed most of the markers. Therefore, the ELS logs were the only recognizable markers so the grid survey areas were repeated around the structures. This caused the pre-flood and post-flood grid areas to differ so only the overlapping areas were used for calculations.

Substrate and LWD

Substrate survey. Substrate assessments were modified Wolman, (1954) style pebble counts was used that consisted of 30 randomly collected pebbles each from riffle, glide, and bar bed forms. The glide is the channel unit where bed elevation is increasing coming out of a pool and transitioning into a riffle (Panfil and Jacobson, 2001) (Figure 24). Riffle crests are where the bed slope breaks, velocity is increased, and is typically composed of coarse-grain sediment (Panfil and Jacobson, 2001; NRCS, 2007; Bunte et al., 2009). The bar was divided into bar head, middle, and tail sections as a typical bar will have coarser grains on the head, medium grains in the middle, and finer grains on the tail (Bunte et al., 2009). In locations with a bar, 30 pebbles from bar head, bar middle, and bar tail locations were sampled totaling 90 pebbles. At riffle and middle bar locations, maximum clast size was recorded for the five and ten largest visible boulders respectively. Pebble sampling was not conducted in pools due to water depths exceeding wadeable conditions. Measurements of the intermediate or median axis of each pebble was taken using a gravelometer and recorded in a field notebook (Bunte and Abt, 2001; Kline et al., 2009) (Figure 25). Particle sizes were classified into soil/fines, sand, gravel, cobble, and boulder categories based on a scale modified from Wentworth, (1922) where Wentworth's mud and silt classes were combined into soil/fines category. Field-testing of soil and sand cannot be quantified using a gravelometer, when the random particle sample was soil or sand it was noted in the field notebook.

Large Woody Debris. Large woody debris was tallied throughout the study reach before construction and after flood events in 2017. Data collection included using a Trimble GPS to document location of each LWD piece. A field sheet protocol was used to count and measure LWD based on previous methods used by the Environmental Protection Agency (EPA) (Barbour et al., 1999). Notes recorded included location attributes such as LWD type, orientation angle relative to flow, channel unit location, and cell number (Martin et al., 2016). Orientation angle was based on Magilligan et al., 2008 (Figure 26). Physical attribute data collected included piece length, diameter, age, anchor type, geomorphic effect, if the piece was cut, and if the piece was part of a jam or compound stem. The flood events of April 2017 toppled riparian trees and in-channel vegetation. In-channel LWD tallies collected in August 2016 were compared to post-flood tallies conducted during summer 2017. Numbers of LWD were divided into 100 m cells longitudinally over the study reach. Volume of LWD was calculated using a method modified from Martin et al., 2016, which is the equation for the volume of a cylinder as follows:

$$LWD_{volume}\,(m^3) = \Pi r^2 h$$

Where: π is approximately 3.142;
r is the radius of the LWD (1/2 DBH in meters); and
h is height of the cylinder (length of the LWD in meters).

Pieces of LWD throughout the study reach were divided into small, medium, and large size classes where small pieces had a diameter < 0.3 m, mediums had a diameter > 0.3 m and length < 10 m, and large pieces had a diameter > 0.3 m with a length > 10 m (Owen et al, 2017). A graph was compiled for pre-flood and post-flood showing the number of pieces in each size class that were located in each 100 m cell. The number of LWD pieces and size classes in each cell are then related to channel location relative to the ELSs. Cells where there are few LWD pieces are areas of higher flow velocity and lack of key pieces compared to areas with many pieces.

Photography

Historical Photos and Basemaps. Historical photograph analysis used leaf-off imagery from 1990, 2007, 2015, and 2018. Basemaps used for displaying and analyzing spatial data at the NFRA were pre-flood imagery provided by the Missouri Department of Natural Resources (MDNR) in the form of Digital Ortho Quarter Quadrangles (DOQQs), and the U.S. Department of Agriculture under the National Agriculture Imagery Program (NAIP). The 1990 DOQQ is a pre-rectified county wide image with a 1-meter pixel size. The 2007 NAIP imagery has a 0.6-meter spatial resolution with less than 10% cloud cover per quadrangle (MDNR, 2015). NAIP imagery was acquired in compressed county mosaics (CCM) for Douglas and Ozarks counties (USDA, 2018). The 2015 DOQQ is a pre-rectified CCM with a 0.45-meter pixel size. Post-flood imagery was taken using an unmanned aerial vehicle (UAV), commonly referred to as a drone, and processed into a mosaic encompassing the study reach using digital photogrammetry (Berteska and Ruzgiene, 2013). This low altitude drone imagery was taken as an extension of this study in May 2017 and again in March 2018 due to the magnitude of the extreme flood (Dogwiler, 2017). Drone imagery used for the study reach has 5 cm spatial resolution.

Historical Photograph Analysis. Photographs from 1990, 2007, and 2015 were used to determine channel changes at the NFRA over a 25-year period. Planform change, channel area, bar area, and bar locations are digitized on each of the three photographs in ArcMap for the study area providing a record of pre-construction conditions (Martin and Pavlowsky, 2011). Change detection of each variable is completed by calculating the total area of the channel and bars for each year. The percentage of bar area over the channel area is calculated for each year to determine sedimentation patterns. Polygon layers are added to a map for visual inspection where completely overlapped polygons signify no change in channel planform whereas polygons not fully overlapping indicate movement in bars or channel position. The same process was conducted for the post-flood imagery to show changes channel planform and bar area resulting from the flood.

Photographs. Repeat photographs throughout the site were taken during site visits with Nikon COOLPIX GPS cameras. Photographs aid in locating monuments when vegetation consumes them during spring and summer, show visual evidence to support surveys, and provide repeat photograph change analysis (Webb et al., 2010). Useful attributes embedded in each photograph are time photo was taken, focal length, field of view, and bearing. Coordinates and orientation of photographs can be uploaded into ArcMap to show photo locations and ground view in the photo to related to surveys or provide change detection.

Survey Data Analysis

The first step in processing field data is importing or typing raw data into a spreadsheet using Microsoft Excel. Each method of field data collection is imported differently. RTK survey data are sent off to the National Oceanic and Atmospheric Administration (NOAA) for GPS corrections. Total station data are corrected based on RTK-surveyed monuments using Foresight DXM software. Spatial survey data from the longitudinal profile, cross-sections, monument locations, and LWD locations are corrected by rotating all points based on two monument locations in Foresight DXM. Corrected data is imported into a spread sheet containing field identification (FID), Northing (m), Easting (m), elevation (m), and description. Charts and graphs are generated in Microsoft Excel using Easting values as (x) and Northing values as (y).

To plot a longitudinal profile or cross-section, the first step is to make sure the points are organized in a straight line to ensure that no overlapping occurs. Point to point distance is calculated using the distance formula (OEWRI, 2007). The results are organized from the highest point on the left side of the channel oriented downstream, which is usually a terrace or floodplain. Distance is plotted on the x-axis and elevation on the y-axis showing elevation of channel features. Graphed data of the longitudinal profile and cross-sections aid in classifying landforms such as riffles, pools, bars, banks, floodplains, and terraces that might not be easily interpreted in the field. Data is then imported into ArcMap by adding the table from a file connection in the Table of Contents (TOC) and selecting "Display XY data" command. A command window pops up where Easting (m) is as the X Field, Northing (m) as Y Field, and Elevation (m) as Z Field. Spatial data for this study site is projected in the Universal Transverse Mercator 15 North (UTM15N) projection. All field data collected with RTK-GPS, total stations, and Trimble GPS units can be imported into ArcMap.

In ArcMap, grid survey points were converted to triangular irregular network (TINs) using Delaunay Triangulation (Wheaton et al., 2010). Converting grid survey points to a TIN to prevent erroneous interpolation outside of the grid area (Wheaton et al., 2010). The TINs were then converted into digital elevation models (DEMs) using "TIN to Raster" tool with a pixel resolution of 0.25 m. DEM of Difference (DoD) maps are calculated from cell to cell differences to estimate elevation changes (Wheaton et al., 2010). Pre-flood and post-flood DEMs were compared using the "Raster Calculator" tool to subtract pixel to pixel elevation values to calculate net elevation change. This function creates a DoD where positive values correlate to deposition, negative values correlate to erosion, and a value of zero is no change (Zavattero et al., 2016). Adding all pixel values in the DoD results in the overall volume change which is then standardized to the area of the DEM resulting in net gain or loss of sediment in (m/m^2). These calculations quantify localized geomorphic effects of the ELSs following flood events. Grids also provide a visual aid that shows localized pool scour or bar building following high flow event.

Channel Capacity and Flood Discharges

Determining channel capacity and flood discharges requires using channel variables measured during field surveys such as slope from the longitudinal profile and hydraulic radius from cross-sections and applying roughness coefficients based on substrate survey and LWD pieces using Intelisolve (2006) Hydraflow Express software, and were used to compare pre-flood and post-flood channel dimensions of bankfull channel and extreme flood channel. Longitudinal profile surveys were used to calculate slope from riffle crests for the bankfull flows, and a topographic map was used to calculate slope for the extreme flood event due to riffle crests being negligible roughness elements during high flow (Phillips and Tadayon, 2006). Channel dimensions surveyed in cross-sections are used in Hydraflow software where stations are classified by distance and elevation of survey points. Each station also has a flow resistance variable, or Manning's n value assigned. Manning's n values were assigned based on field observations, substrate analysis, and LWD inventory calculations compared to adjustment variables (Chow, 1959; Phillips and Tadayon, 2006). Variables include the degree of irregularity of the channel, variation in cross-section, effect of obstructions, amount of vegetation, and degree of meandering (Phillips and Tadayon, 2006). Up to 50 stations can be input for each cross-section. Once stations are loaded, slope and a stage or discharge value can be input, and the software calculates cross-sectional area, wetted perimeter, stage, and top width of water surface for the given stage or discharge. Manning's n values for roughness are automatically weighted based on stage at each elevation station. Finally, velocity is calculated based on the variables, and roughness coefficients can be changed to model conceptually acceptable velocity values (Yochum, 2018).

The hydraulic record at the Tecumseh gage (27 km downstream of the NFRA) was used to evaluate flows at the study reach (USGS, 2015). The USFS conducted a hydraulic analysis in 2015 to determine a relationship between the ungaged area at the NFRA and the gage at Tecumseh based on drainage area (Gubernick, 2015). The equations used were developed by Ries (2007) using an ungaged site that has a drainage area between 0.5 and 1.5 times the gaged area. Discharge volumes at Tecumseh were updated with return intervals calculated after April 2017 by the USGS (Heimann et al., 2018) (Table 5).

Table 4. Site visits dates and descriptions.

Site visit	Month	Date(s)	Year	Description
1	June	24	2016	Locate proposed ELS sites using coordinates received from USFS.
2	June	29-30	2016	Set monuments, cleared vegetation for surveys, and survey cross-sections and longitudinal profile.
3	August	10-11	2016	Surveyed RTK grids, pebble counts, and LWD inventory.
4	October	21-22	2016	Monitored construction of ELSs with USFS and contracted construction company.
5	November	21-22	2016	Post-construction surveys completed including RTK grids, cross-sections, and longitudinal profile.
6	January	23-24	2017	Site inspection and notes taken of sediment settling around structures.
7	April	25	2017	Flood assessment following Bankfull #1.
8	April	28	2017	Flood assessment following Bankfull #2 and tagged and geocoded ELS logs in preparation for the extreme flood event.
9	April	30	2017	Flood assessment following extreme flood event, photographs taken from west side of the river.
10	May	5	2017	Flood damage assessment. Photographed damage and collected GPS points of HWMs.
11	May	16	2017	Flood damage assessment including drone imagery.
12	June	20-22	2017	Post-flood repeat surveys including RTK grids, cross-sections, longitudinal profile, and LWD inventory.
13	July	13	2017	Pebble counts and LWD inventory.
14	August	31	2017	Post-flood LWD inventory.
15	October	19	2017	Bar complex mapping and measured the height of the new bridge.

Table 5. Estimated discharge at NFRA using ungaged area equation (Gubernick et al., 2015) and Tecumseh gage data.

Estimated discharge at North Fork Recreation Area									
Return Interval	Gage at Tecumseh	95% confidence limits		Exponent coefficient for area	Gage basin area	Ungaged area	North Fork Recreation Area Q (m^3/s)	95% confidence limits	
	Estimate	Lower	Upper				Estimate	Lower	Upper
2	374	317	442	0.733	1,453	1,044	293	249	347
5	759	634	906	0.763	1,453	1,044	590	493	704
10	1,090	892	1,334	0.774	1,453	1,044	844	691	1,033
25	1,577	1,252	1,985	0.784	1,453	1,044	1,217	966	1,532
50	1,963	1,518	2,538	0.789	1,453	1,044	1,512	1,170	1,955
100	2,351	1,779	3,115	0.794	1,453	1,044	1,808	1,368	2,396
500	3,285	2,356	4,616	0.804	1,453	1,044	2,519	1,806	3,539
April 29-30	5,353			0.804	1,453	1,044	4,103		

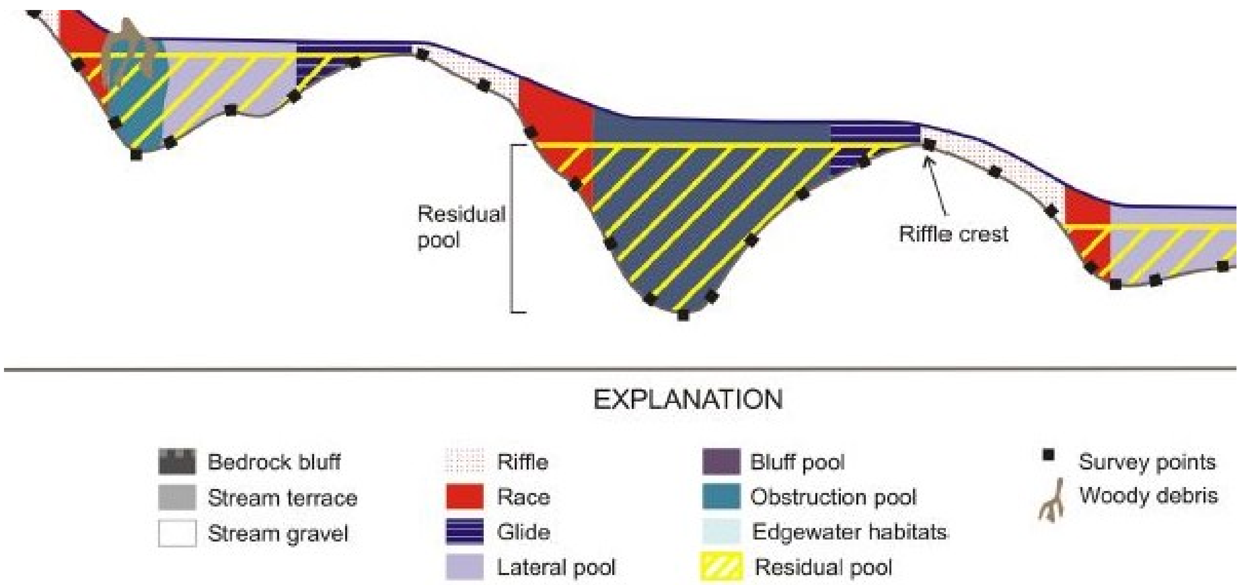


Figure 24. Typical bed landforms in the Ozarks (Panfil and Jacobson, 2001). Pebble counts were conducted on riffle, glide, and bar landforms.

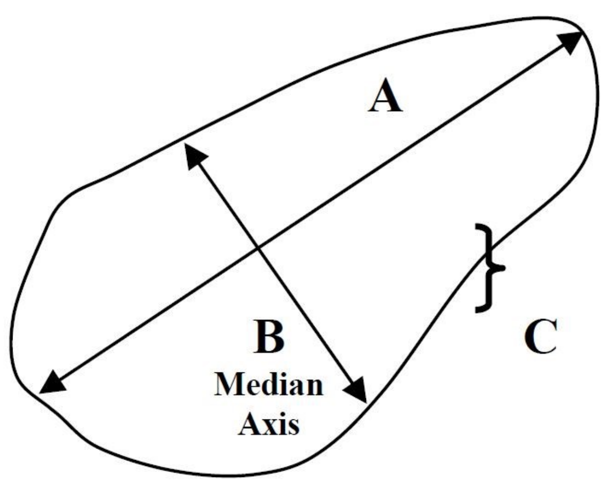


Figure 25. Example of median axis of pebble that is measured for substrate survey (Kline et al., 2009).

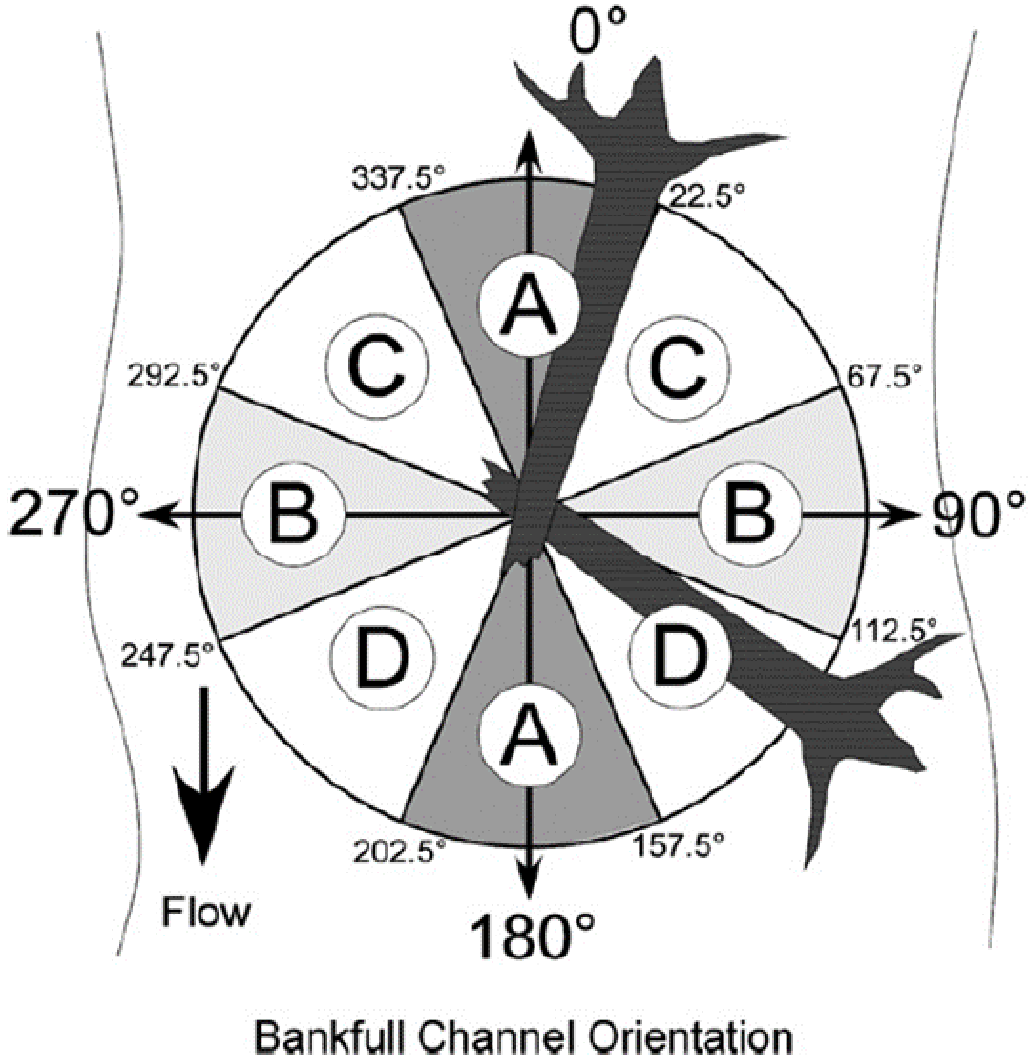


Figure 26. Orientation positions of LWD from Magilligan et al., 2008.

RESULTS AND DISCUSSION

Channel formations and locations where cross-sections were surveyed included a pool near ELS 1, a riffle-run transition near ELS 2, and a lateral bar near the mouth of a floodplain chute at ELS 3 and ELS 4. The repeat surveys were conducted near the pre-flood survey lines, but as with other post-flood data collection problems with locating benchmarks prohibited exact repeat survey lines. The cross-section at ELS 4 was not able to be resurveyed due to LWD collection in the floodplain chute zone. Therefore, cross-sectional dimensions are compared between pre-flood and post-flood surveys at ELS 1, ELS 2, and ELS 3. Changes between the cross-section surveys at ELS locations show localized scour and fill. The cross-section at ELS 1 shows channel fill where the bank line moved instream toward the bedrock bluff. The cross-section at ELS 2 shows downcutting through a bar and deposition on the opposite side of the channel where the thalweg shift in the longitudinal profile occurred. The cross-section at ELS 3 shows deposition near the ELS and minor scour on the instream side of the ELS.

Flood effects are discussed using key terms such as splay, sediment lobes, floodplain chute, and thalweg shift. Gravel and sandy splays are deposits of bedload sediment on the floodplain surface that typically occur during low-frequency high-magnitude floods (Ritter, 1975). During the same floods, scour of the floodplain occurs forming floodplain chutes where fine-grained sediment is eroded leaving behind a high-flow or floodplain chute channel (Lewin and Ashworth, 2014; Kochel et al., 2016). Location descriptions are based on channel units, river distances from Highway CC Bridge to Blue Spring (0 to 1374 m), 100 m cells from those river distances, and sides of the channel where river-left is the left side of the channel looking downstream or the East side of the river (Figure 27).

Historical Channel Characteristics

Channel Characteristics. Over the 25-year period from 1990 to 2015, channel characteristics at the NFRA remained relatively stable throughout the study reach from the Highway CC Bridge to Blue Spring. Channel widths at seven transects throughout the study reach show a minor average width increase from 46 m to 48 m (Table 6). The area of bars varied from 2.13 ha in 1990 to 1.39 ha in 2015, but thalweg position, bar locations, and wetted channel areas remained relatively similar over time (Figures 28, 29, and 30). The ELSs were installed on the campground side of the river to protect the banks from erosion. The right bank was a high bedrock bluff therefore the only direction for channel movement would be toward the campground area with erodible banks. Between 2007 and 2015 the left bank eroded between river distances 425-730 m. The flood record during this period indicates that two large floods (> 10-year RI) occurred during this period (Table 7). ELS 2 was eventually placed in this reach to prevent further erosion.

Gravel Bar Characteristics. To some degree bar area within the study reach have varied in size and percentage of channel area since 1990 (Table 8). However, the locations of bars has remained relatively similar in pattern (Figures 28, 29, and 30). Bar locations since 1990 have been near the existing boat ramp from river distance 200-400 m, on river-right from 500-700 m, on river-left from 800-1,100 m, and river-right from 1,100-1,300 m (Figure 30).

Previous Examples of Splay Deposition on Floodplain. Sand and gravel deposition on the floodplain at the NFRA is visible in 1990, 2007, and 2015. In all three of the leaf-off aerial photographs a portion of the floodplain looks like a typical point bar feature from river distance 225 m to 460 m. The floodplain feature with visible deposition covers an average area of 0.75 ha over channel reach distance of 235 m (Figure 31). Elevation of this surface is approximately 7 m above the thalweg which would require a 1.5 to 2-year RI flood from 249 to 347 m^3/s (Table 5). This area of floodplain deposition is due to the high bedrock bluff on river right slowing in-stream flow velocity in the channel and increasing velocity over the floodplain surface. Floodplain deposition events are reflective of the geologic and topographic setting of the North Fork River. Having shallow bedrock and narrow valley widths confine and elevate flood stages to cause more frequent and coarser-grained floodplain deposition whereas other alluvial rivers having wider valleys allow large floods to spread out over the floodplain dissipating energy (Ritter, 1975; Magilligan et al., 2015).

Longitudinal Profile and Planform. The flood caused measurable changes to the longitudinal profile and channel planform at the NFRA. Four changes to the longitudinal profile included: 1) riffle deposition at all riffle crests; 2) thalweg movement near ELS 2; 3) scour downstream of ELS 4, and; 4) deposition downstream ELS 4 resulting in upstream glide movement. Deposition at riffle crests occurred at reach distances 226 m, 510 m, 626 m, and 1,010 m. Elevation at Riffle 1 changed from 206.3 meters above sea level (MASL) to post-flood elevation of 206.9 MASL, an increase of 0.6 m (Figure 32). Riffle 2 had a 0.2 m elevation increase from 206.6 MASL to 206.8 MASL. Riffle 3 had a 0.6 m elevation increase from 206.3 MASL to 206.9 MASL. Riffle 2 and Riffle 3 are in a depositional zone where the thalweg moved to the opposite side of the channel and encompassed the ELS 2 location. Riffle 4 had a 0.4 m elevation increase from 206.3 MASL to 206.7 MASL. Pre-flood riffle crest slope was 0.08% and decreased to a post-flood slope of 0.06%. Changes to pool depth from pre-flood to post-flood were less than 0.2 m due to shallow bedrock throughout the study reach.

Secondly, a planform change occurred at 460 m where the thalweg shifted to the west side of the channel from 460 m to 730 m on the longitudinal profile. The thalweg position migrated from the river-left side of the channel to river-right side of the channel near the bedrock bluff. This shift was 52 m wide and 270 m in length. ELS 2 was installed partially submerged in the pre-flood wetted channel but the thalweg shift resulted in ELS 2 being separated from baseflow. Within the area of the thalweg shift a 2.7 m high gravel bar with an area of approximately 7,000 m^2 was eroded where the new thalweg position is located, and sediment filled in the pre-flood wetted channel creating a new bar (Figure 33).

Thirdly, bed scour near ELS 3 and ELS 4 occurred between 890 m and 960 m on the longitudinal profile (Figure 32). Maximum scour depth was 0.6 m with pre-flood bed elevation 206.0 MASL and post-flood elevation 205.4 MASL. Lastly, Riffle 4 deposition occurred that moved the glide and riffle location. The riffle crest and glide moved upstream approximately 60 m (Figure 34). Deposition resulted in aggradation of the riffle from pre-flood elevation 206.32 MASL to 206.70 MASL, an increase of 0.38 m. Overall, riffle crest slope calculated from the longitudinal profile changed from 0.08% to 0.06% (Figure 32). However, the overall slope of the reach was unchanged over a total distance of 1 km.

Longitudinal and planform changes that occurred at the NFRA are consistent with high magnitude flashy floods. Short duration high magnitude floods transport material, but large-scale channel widening is infrequent (Magilligan et al., 2015). High magnitude floods will entrain and transport coarse-grain sediment within the channel and deposition can occur in the channel causing channel shifting (Morche et al., 2007; Magilligan et al., 2015). High stream power events created by high magnitude floods in confined channels produce channel transformation at bends where energy becomes more turbulent and velocity variability increases across the channel (Fuller, 2008; Chougale and Sapkale, 2017).

Channel Characteristics. The April Flood caused changes to channel characteristics such as the thalweg shift, bar size and locations, and channel area. Channel widening occurred on the left bank from 100 m to 250 m and 650 m to 800 m. Channel widening occurred on the right bank from 850 m to 1,100 m (Figure 35). The areas of channel widening increased the average channel width previously discussed to an average of 53 m and caused the channel area to increase by > 1 ha (Tables 6 and 9).

The extreme flood event caused sediment to be transported up the existing boat launch on to the floodplain where the floodplain surface acted as a larger-scale point bar feature (Kochel et al., 2016). Flow over the floodplain surface was approximately 7 m deep where floodplain chutes were carved, and lobes or gravel splays were deposited (Figure 36). Gravel and sand splays on the floodplain ultimately buried ELS 1 and partially buried ELS 2 when sediment was transported over the floodplain and back into the channel. The floodplain-bar complex is composed of a bar head with boulder and cobble sized material, bar middle with gravel and sand sized material, and a tail with predominately sand sized material (Figures 36 and 37). This bar complex is consistent with high-magnitude flows in confined channels with shallow bedrock common in the Ozarks (Panfil and Jacobson, 2001; Fuller, 2008; Kochel et al., 2016; Chougale and Sapkale, 2017).

Response of Channel Morphology to the April 2017 Flood

Results Comparison. The North Fork Recreation Area experienced geomorphic changes due to a >500-year RI flood that caused large scale erosion and deposition of sediment and LWD throughout the study reach (Heimann et al., 2018). Kochel et al., 2016 describe similar geomorphic changes to their study site in Pennsylvania caused by more than 250 mm of rainfall from Tropical Storm Lee in September 2011. The study area had evidence of large scale overbank sedimentation, floodplain chute development, and reoccupation of former multithread channels (Kochel et al., 2016). Floodplain chutes were carved across the head of the large point bar feature in both studies which is common during high magnitude flood events (Kochel et al., 2016). At the existing boat ramp fine grain sediment was winnowed out and sediment was transported onto the floodplain through the high-flow cute (Figure 37). Kochel et al., 2016 found similar evidence of sedimentation (Figure 38). A comparison of findings between this study and Kochel et al., 2016 is listed below (Table 10).

Flood Discharge and Channel Geometry

Flood discharge at the NFRA has been calculated based on published discharge values measured by the USGS at the Tecumseh gage. The flood of record had a stage of 12.75 m (41.82 ft.) with a discharge of 5,352 m^3/s (189,000 cfs) at the Tecumseh gage on April 30, 2017 (Heimann et al., 2018). High water marks (HWM) at the NFRA were observed after flood waters receded, and GPS locations were recorded throughout the study reach. Field measurement of the HWM resulted in a stage of 13.72 m (45 ft) near Blue Spring. Since the NFRA is ungaged, a hydraulic analysis conducted by the USFS in 2015 to determine a relationship between the gage at Tecumseh and the NFRA based on drainage area results in an estimated discharge of 4,100 m^3/s (144,000 cfs) (Gubernick, 2015; Heimann et al., 2018). Bankfull and extreme flood channel capacity dimension comparisons are based on changes channel size and roughness. These **c**hanges to channel size and roughness are attributed to aggradation at ELS 1, riparian forest toppling, and instream LWD recruitment. Cross-sectional changes at cross-section 4 were not evaluated due to the inability to access the pre-flood line during post-flood surveys because of LWD accumulation during the flood.

Channel Planform. Channel width at cross-section 1 decreased from 53 m to 39 m resulting from channel filling around ELS 1. Channel width at cross-section 2 increased from 79 m to 96 m due to the bank slope lowering. The cross-section at ELS 2 also had a change in thalweg location where a bar eroded on the right side of the channel and sediment deposition at the pre-flood thalweg location created a new bar. The thalweg shift resulted in an increased cross-sectional are from 215 m^2 to 239 m^2 and wetted perimeter from 82 m to 99 m. Deposition at cross-section 3 resulted from sediment transport in the high-flow chute. Erosion at cross-section 3 resulted from scour near the ELS, but overall channel geometry was relatively unchanged.

Channel Cross-sections. The pre-flood cross-section at ELS 1 had a bankfull width of 53 m and a maximum bank height of 6 m. The cross-sectional area was 194 m^2 with a wetted perimeter of 55 m and a hydraulic radius of 3.52 m (Table 9). The post-flood comparison at ELS 1 shows deposition on the left bank where ELS 1 was buried by sedimentation during the extreme flood event. Aggradation at this cross-section caused the bank edge to move instream toward river-right 7.2 m (Figure 39). The increase in bed elevation at the bank toe was 4.2 m due to slip face deposition of sediment over ELS 1. After the extreme flood event there was no visual evidence of ELS 1 in the field and the survey results are consistent with total burial of the structure.

The cross-section at ELS 2 shows two areas of erosion and one area of deposition. Erosion occurred on the river-left floodplain where a high-flow chute scoured during the flood event (Figure 39). The thalweg migrated toward river-right which down cut through a 2.7 m high bar to form its current baseflow wetted channel. During the flood, bar deposition occurred at ELS 2 due to the shifting thalweg that moved 52 m away from the structure. This bar aggraded by 1.56 m and down cutting on the opposite side of the channel through the pre-flood bar resulted in the new thalweg position. Also, at ELS 2 the high sandy bank where the structure was embedded had a lower slope which widened the bank line approximately 4 m toward the river-left and campground side. ELS 2 was partially buried by sandy sediment transported over the floodplain but remained intact.

At ELS 3 the flood caused sand deposition on the left bank to the level of the floodplain (Figure 39). Structure ELS 3 is located on the head of the lateral bar where flow separates into a chute channel on the left and main channel to the right. The flood deposited a bar downstream of ELS 3 which is typically seen on the downstream side of a log jam obstruction (Keller and Swanson, 1979; Gurnell et al., 2002). This bar deposition was between ELS 3 and ELS 4 and it increased the bar elevation by 1.84 m (Figure 39). A scour pool 0.57 m deep formed on the instream side of ELS 3 behind a large tree and rootwad that was lodged against ELS 3. Chute channel deposition of sand and LWD made it impossible to resurvey the pre-flood ELS 4 cross-section line (Figure 40).

Repeat cross-sections show 2-dimentional changes to channel geometry during the flood. High-flow chutes were carved into the floodplain, floodplain deposition occurred near ELS 1, bar deposition on the left and down cutting on the right side of the channel formed a new thalweg position at ELS 2, and bar deposition occurred at ELS 3. These changes affected channel geometry resulting in a smaller channel capacity at cross-section at ELS 1.

Repeat Topographic Surveys. Topographic surveys using total station grids show spatial differences in sedimentation depths that occurred during the extreme flood event by comparing the pre-flood DEMs with the post-flood DEMs using a modified DEM called a "DEM of Difference" (DoD) that shows changes between DEMs rather than actual elevations (Wheaton et al., 2010). Topographic surveys at the three ELS survey locations had a combined net gain of 3,127 m^3 of sediment volume over a total area of 5,613 m^2 surveyed (Table 11). Sedimentation at ELS 1 was dominated by slip face deposition that buried ELS 1. Sedimentation at ELS 2 was dominated by thalweg migration away from the structure and filled the channel at ELS 2 and high-flow chute scour above the structure on the floodplain. Sedimentation at ELS 3 and ELS 4 was dominated by high-flow chute deposition of sediment and where LWD was recruited creating flow separation resulting in bar deposition typically seen at a bar apex jam (Abbe and Montgomery, 1996). A bar apex jam is typically at the head of a bar where flow separated, and deposition occurs on the downstream side of the jam or bar tail (Abbe and Montgomery, 1996).

The topographic surveys at ELS 1 show bank line position movement toward river-right an average of 9.0 m laterally over 52 m longitudinally (Figure 41). Maximum elevation change here was +3.7 m where slip face deposition occurred, burying ELS 1 (Figure 42). Also visible on the DEM comparison is a chute channel carved into the top of the bank where overbank flow scoured sediment. In this comparison the only area of elevation decrease was the chute channel were maximum elevation decrease was -0.9 m (Figure 41). However, increase in sediment volume at ELS 1 was the highest of the grid surveys with a net gain of 2,096 m^3 (Table 11).

At ELS 2, deposition of sediment partially covered the structure, but the structure remained intact (Figure 43). The bank angle was lowered resulting in the bank line moving toward the campground (Figure 44). The bank line moved away from the channel an average of 3.63 m laterally over 42.6 m in length. This DoD resulted in relatively low net loss of sediment volume. There was relatively high positive (+3.0 m) and high negative elevation change (-2.9 m), but mean elevation change was -0.1 m over the grid area of 1,355 m^2 with net volume change of -94 m^3 (Figure 44). Visible on the grid comparison is where in-channel deposition and bank top scour occurred.

The topographic survey at ELS 3 and ELS 4 is at the mouth of a floodplain chute that deposited sediment creating a lateral bar typically seen as a bar apex jam in a braided channel (Abbe and Montgomery, 1996). Overall the 2,751 m^2 area which was 49% of all area surveyed had mean elevation change of +0.4 m. Net sediment volume gain was 1,125.0 m^3. Most of sediment gain was at the mouth of the floodplain chute where the floodplain landform from the pre-flood topography leveled out with sand, and between ELS 3 and ELS 4 where bar deposition aggraded approximately 500 m^2 of sandy sediment with a maximum elevation change of +1.9 m (Figure 45).

The topographic surveys showed sediment volume changes around the ELSs as a result of the flood. The survey areas are relatively small ranging from 1,507 to 2,751 m^2 compared to the overall study area covering approximately 100,000 m^2, but they show localized sedimentation patterns and captured portions of bank line movement, floodplain chutes, floodplain deposition, and bar aggradation in the vicinity of the structures which was the objective of this study. The DoD at ELS 1 had the highest deposition rate (2,096 m^3/1,507 m^2) where the structure was buried. This deposit was the result of a larger-scale process of floodplain transport and deposition across the inside of the point bar and sediment pulse lobe deposition (Kochel et al., 2016). Therefore ELS 1 was not the agent affecting deposition during the flood, but more the ‘victim’ of a larger process. ELS 2 was also affected by the flood by being separated from flow due to the thalweg switching sides of the channel due to main channel flow and sediment variation during the flood (Morche et al., 2007). The topographic survey at ELS 3 and ELS 4 resulted in a bar aggrading between the structures where flow separation occurred. Flow separation typically occurs at log jams and deposition will occur downstream of the obstacle (Abbe and Montgomery, 1996) (Figure 46). At areas of flow divergence between the chute and main channel which might be expected with ELS influence where ELS 3 and ELS 4 were placed promote deposition and recruit mobile wood. Deposition at this location was enhanced by the structures, especially the bar that aggraded in between the structures due to the recruitment of LWD. However, sedimentation occurred.

Substrate and LWD

Substrate. Pebble counts were conducted at riffle, glide, and bar channel units located at Riffle 1 near the existing boat ramp between reach distance 200-300 m and at Riffle 4 downstream of ELS 4 at reach distances 950-1,250 m. Thirty pebbles were measured on each of the landforms during pre-flood and post-flood surveys with an additional maximum clast measurement of the five largest grains on the riffle and bar middle landforms. Frequency distribution of sizes on each landform is compared at each location for per-flood and post-flood.

Substrate samples at Riffle 1 are located at the head of a larger point bar feature. The riffle and glide landforms experienced a slight shift upstream as mentioned in the longitudinal profile section (Figure 47). During high flow events velocity slows at the thalweg when it encounters the bluff wall on river-right just downstream of Riffle 1. Due to the slowed velocities at the thalweg, velocity increases over the boat ramp causing sediment to ramp over the head of the larger point bar feature and fine-grain sediments will winnow out (Kochel et al., 2016). At Riffle 1 the glide, riffle, bar head, and maximum clast sizes all were coarser-grained following the flood. The bar middle was relatively unchanged, and the bar tail was finer due to slowed velocity as flow moved around the channel bend (Kochel et al., 2016) (Table 12) (Figure 48). Bedload sediment in transport and sediment entrained from the existing boat ramp were deposited on the floodplain surface creating gravel and sand splays (Figures 49 and 50).

Riffle 4 is located in the middle of the larger-scale point bar feature. As a result of the flood the typical floodplain landform was fully inundated by deep flows, effectively behaving geomorphologically as a bar. The sampling locations of the channel units shifted upstream as a result of the flood where new sediment was deposited forming the glide, riffle, and bar head features (Figure 51). Riffle 4 tended to be finer-grained after the flood (Table 12). The glide and riffle maximum D50 were relatively finer, the riffle, bar head, and bar middle maximum were coarser, and the bar middle and bar tail were relatively unchanged (Figure 52).

Large Woody Debris. During a flood event, instream LWD is mobilized and transported downstream while stage rises and deposits when stage is receding (Abbe and Montgomery, 1996). Deposition of LWD occurs on key members or obstacles such as trees, boulders, or stabile LWD (Montgomery et al., 2003a; McHenry et al., 2007; Nichols and Ketcheson, 2013; Kimbrel, 2014; Roni et al., 2015). During the flood event at the NFRA, LWD collected throughout most of the study site increasing the number of pieces and volume of wood due to recruitment processes. The number of LWD pieces more than doubled from 96 pieces before the flood to 209 (+117%) pieces after the flood (Table 13). Large woody debris piece size classes were quantified by 100 m cells from 0 m to 1,100 m. Throughout the study site small LWD pieces increased from 62 to 164 (+164%) pieces, medium sizes decreased from 32 to 29 (-9%) pieces, and large sizes increased from 2 to 16 (+700%) pieces. Throughout the 1,100 m study reach LWD volume increased by 13 m^3 (16%) (Table 14). This relatively small increase in volume can be attributed to the fact that mainly small size pieces were recruited.

Post-flood LWD collected on bar surfaces and on key pieces provided by ELS 2, ELS 3, and ELS 4. Areas where most LWD was recruited was in cell 800-900 m where both ELS 3 and ELS 4 are located (Figures 53 and 54). Recruitment of LWD in this cell is related to this location relative to the floodplain chute where LWD was placed over the access road after construction and riparian trees were toppled during the flood. The LWD transported through the chute was collected in the chute area throughout the 800-900 m cell. This is also a flow separation zone between the main channel and flood chute where LWD collects on the bar head where it deposited near ELS 3. The structure acted as a key member mimicking a bar apex jam (Abbe and Montgomery, 1996). The toppled trees and LWD deposited will add to future LWD recruitment and could add to potential hazards to infrastructure and recreation activities (Wu et al., 2014; Wohl et al., 2016).

Infrastructure damage was caused by the April flood at the NFRA included road and parking lot asphalt being entrained, and Highway CC Bridge was washed out (Figures 55 and 56). It is likely that the Highway CC bridge failure was induced by LWD transportation and damming during the rising limb of the hydrograph. Relatively high recruitment of LWD in a forested watershed can be associated with local infrastructure damage since flood waters transport LWD until there is an obstacle where it accumulates (Ruiz-Villanueva et al., 2014). Transported LWD can also accumulate where cross-sections are constrained such as Highway CC Bridge where fill was used to shorten the span of the bridge, constraining the valley (Ruiz-Villanueva et al., 2014; Wu et al., 2014). Rafted LWD cause a damming effect where local stage increases put pressure on bridge piers (Wu et al., 2014). Kochel et al., 2016 cite similar flood damage which included 9 bridges being washed out in heavily wooded watersheds.

Management Issues

There are management concerns for ELSs as they potentially pose hazards to recreational users such as canoeists, kayakers and hikers. However, following the flood events, the hazards to recreational users related to canoeing and kayaking associated with ELSs such as ability to avoid hazards, prior knowledge, snagging potential, and cable anchoring outlined by Wohl et al. (2016) were negated at ELS 1 and ELS 2. Burial of ELS 1 and the separation of ELS 2 from the wetted channel removes the structures from typical recreation activity areas. However, ELS 3 and ELS 4 still pose potential hazards on the bar surface. Hiking hazards on the floodplain and bar surface are present due to entanglements of LWD and cables from the structures. There are also LWD hazards throughout the study reach due to the increase in pieces and LWD volume from the flood. One of the best methods to prevent injury due to LWD and ELS hazards is to add signage and managers and recreation outfitters informing the public of the potential hazards posed by LWD within the channel (Wohl et al., 2016).

ELS Performance

The ELSs were installed at the NFRA for the primary objectives of providing bank protection and enhancing recruitment of LWD. During the flood the structures were under nearly 9 m of water. At this stage, the ELSs were negligible as roughness elements (Magilligan, 1988; Phillips and Tadayon, 2006). Evidence provided by the surveys prove that ELS 1 was buried by sedimentation due to the location at the upstream side of the channel bend. ELS 2 experienced partial burial, recruited LWD, and is ultimately still in the original location with the original design maintained. The large flood overwhelmed the design limits at the ELS 1 and ELS 2 locations. During the flood, the logs in ELS 3 and ELS 4 moved, but were kept in the proximity of the installed location due to the cabling technique. Although wood pieces in structures ELS 3 and ELS 4 moved during the flood, the key members created by the structures and cables recruited the most LWD throughout the study site and sediment was deposited between the structures (Table 15). However, these structures were designed to modify geomorphic processes during more frequent flood events. More research is needed to evaluate the effect of ELSs on channel morphology and sedimentation during the average flood regime.

Table 6. Historical photo analysis of channel widths at key transects at the North Fork Recreation Area.

	Aerial Photo Width of Channel at Transects (River Distance from Highway CC Bridge)							
Year	Highway CC (0 m)	Riffle 1 (250 m)	Cross-section 1 (436 m)	Cross-section 2 (590 m)	Cross-section 3 (824 m)	Riffle 4 (1,100 m)	Blue Spring (1,360 m)	Average Width
1990	36	38	38	68	57	43	42	46
2007	45	51	35	66	49	36	47	47
2015	40	46	38	71	50	57	32	48
2018	41	44	40	71	54	74	47	53

Table 7. Overbank floods that occurred between 1985 and 2015 at the USGS Gage at Tecumseh.

Water Year	Date	Discharge (m^3/s)	Stage (m)	Estimated Return Interval
1985	February 23, 1985	1,736	8.0	25 to 50-year
1986	November 19, 1985	2,070	8.6	50 to 100-year
1993	September 25, 1993	1,223	6.9	10 to 25-year
1994	November 14, 1993	1,501	7.5	25-year
2002	May 8, 2002	1,187	6.8	10-year
2008	March 19, 2008	1,249	6.9	10 to 25-year
2011	April 26, 2011	1,501	7.5	25-year

Table 8. Historical channel and bar areas.

Year	Channel Area (ha)	Bar Area (ha)	Bar Area (% of Channel Area)	Wetted Area (ha)
1990	6.91	1.95	28	4.96
2007	6.34	1.86	29	4.48
2015	6.87	1.39	20	5.48
2018	8.04	1.98	25	6.07

Table 9. Pre-flood and post-flood comparison of bankfull and extreme flood dimensions at the NFRA.

Bankfull flood dimensions												
Cross-section	Date	C	R	Slope	n	Area (m^2)	Wp (m)	TopW (m)	v (m/s)	MeanD (m)	w:d	Q (m^3/s)
1	Nov. 2016	1	3.52	0.0012	0.048	194	55	53	1.66	3.4	15.65	322
	June 2017	1	3.57	0.0012	0.045	148	41	39	1.78	2.8	14.01	264
2	Nov. 2016	1	2.63	0.0012	0.045	215	82	79	1.46	2.6	29.69	314
	June 2017	1	2.41	0.0012	0.047	239	99	96	1.32	1.9	49.37	315
3	Nov. 2016	1	2.71	0.0010	0.044	246	91	90	1.39	2.7	33.00	342
	June 2017	1	2.94	0.0010	0.044	257	87	85	1.46	2.9	29.46	376
Flood of record April 29-30, 2017												
Cross-section	Date	C	R	Slope	n	Area (m^2)	Wp (m)	TopW (m)	v (m/s)	MeanD (m)	w:d	Q (m^3/s)
1	Nov. 2016	1	5.60	0.0012	0.037	1,276	228	219	2.92	9.5	37.93	3,722
	June 2017	1	5.53	0.0012	0.040	1,395	252	245	2.68	7.8	43.05	3,736
2	Nov. 2016	1	6.98	0.0012	0.044	1,351	194	182	2.84	8.8	24.31	3,836
	June 2017	1	7.02	0.0010	0.041	1,440	205	193	2.79	9.0	25.85	3,885
3	Nov. 2016	1	8.15	0.0010	0.043	1,179	145	134	2.94	9.9	21.87	3,463
	June 2017	1	7.63	0.0011	0.046	1,146	150	141	2.76	8.7	21.46	3,160

Table 10. Comparison of findings between this study and (Kochel et al., 2016).

Kochel et al., 2016	This study	Difference in findings
Large scale avulsions and chute development on the insides of meanders.	Large scale chute development on the inside of the bend.	Chutes were carved because narrow valley constraints would not allow water widening.
Erosion of gravel from channel margins and transport downstream in pulses.	Erosion from channel margins occurred above the bend.	Erosion occurred primarily upstream of the site, and on the cutbank (bluff) side of the channel.
Headwater landslides and alluvial fan activation.	Headwater experienced riparian forest damage and LWD recruitment.	Further investigation of headwaters is ongoing.
Major floodplain erosion and deposition.	Overbank sedimentation occurred throughout the site, where the floodplain surface acted like a large-scale point bar.	Floodplain erosion occurred primarily where chutes developed, and riparian forest was toppled.
Breaching of anthropogenic berms and reconnection of the main channel to prehistoric floodplain anabranches.	Reconnection of the main channel to floodplain and terrace surfaces.	Anthropogenic berms are not present at this site however, two highway bridges were destroyed.

Table 11. Change in sediment volume from topographic surveys.

Grid Site		Maximum Values		Topographic Change	
ELS	Area (m^2)	Erosion (m)	Deposition (m)	Volume (m^3)	Mean Elevation (m)
1	1,507	-0.9	+3.7	2,096	+1.4
2	1,355	-2.9	+3.0	-94	-0.1
3 and 4	2,751	-1.7	+1.9	1,125	+0.4

Table 12. Substrate trends and Riffle 1 and Riffle 4.

Channel Unit	Percentile	Riffle 1 Pre-flood (mm)	Riffle 1 Post-flood (mm)	Riffle 1 Change (mm)	Riffle 4 Pre-flood (mm)	Riffle 4 Post-flood (mm)	Riffle 4 Change (mm)
Glide	D10	27	15	-12	11	4	-7
	D50	45	55	10	32	11	-21
	D90	109	165	56	45	32	-13
Riffle	D10	32	22	-10	16	22	6
	D50	45	64	19	32	32	0
	D90	90	128	38	64	64	0
Riffle Maximum Clast	D50	220	350	130	120	90	-30
Bar Head	D10	22	32	10	16	11	-5
	D50	32	64	32	23	32	9
	D90	64	128	64	45	45	0
Bar Middle	D10	16	5	-11	16	16	0
	D50	32	32	0	32	32	0
	D90	64	64	0	64	64	0
Bar Middle Maximum Clast	D50	150	270	120	125	150	25
Bar Tail	D10	16	10	-6	11	11	0
	D50	39	23	-16	23	23	0
	D90	64	32	-32	33	32	-1

Table 13. Large woody debris piece count per 100 m cell.

Cell distance	Pre-flood			Post-flood		
	Small	Medium	Large	Small	Medium	Large
0-100	1	1	0	0	1	0
100-200	0	0	0	4	0	1
200-300	6	7	0	3	0	1
300-400	3	0	0	3	0	1
400-500	5	6	1	17	2	1
500-600	14	2	0	31	4	6
600-700	7	1	0	28	1	2
700-800	5	5	1	21	7	
800-900	8	4	0	38	11	4
900-1000	7	5	0	8	3	0
1000-1100	6	1	0	11	0	0
Size total	62	32	2	164	29	16
Total	Pre-flood	96		Post-flood	209	

Table 14. Comparison on LWD volume from pre-flood to post-flood.

	LWD Volume (m³)		
Cell	Pre-flood	Post-flood	% Change
0-100 m	1.0	1.8	44
100-200 m	0.0	2.0	100
200-300 m	12.9	1.9	-592
300-400 m	0.2	2.5	91
400-500 m	6.9	9.4	27
500-600 m	10.1	17.5	43
600-700 m	4.5	10.5	57
700-800 m	10.3	8.8	-17
800-900 m	16.2	19.8	18
900-1000 m	2.3	4.1	43
100-1100 m	3.8	2.5	-53
Total	68	81	16

Table 15. Engineered log structure performance and NFRA.

ELS	Channel Location	Objectives	Performance
1	Inside bank partially submerged in wetted channel.	Reduce erosion by providing bank and toe protection.	Large flood buried ELS under 3 m of sediment.
2	Inside bank partially submerged in wetted channel.	Reduce erosion by providing bank and toe protection.	Large flood separated the ELS from the wetted channel when the thalweg migrated to the opposite side of the channel.
3 and 4	Inside bank on top of a lateral bar surface.	Promote deposition on the bar surface and collect LWD.	Deposition occurred between the ELSs and mobile LWD was collected on the upstream side of ELS 3.

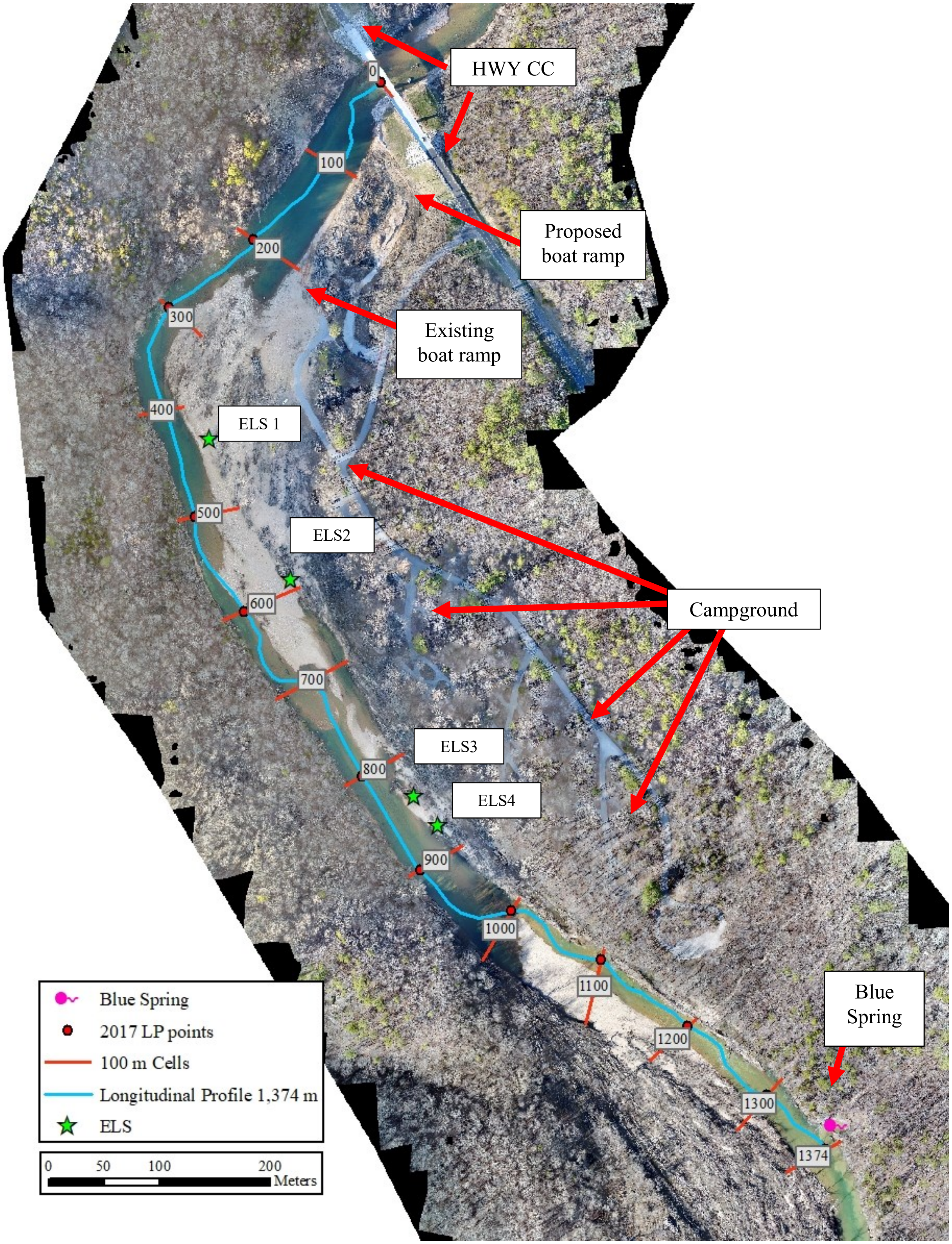


Figure 27. Post-Flood Reach Map of the North Fork Recreation Area from March 2018 (Dogwiler, 2018).

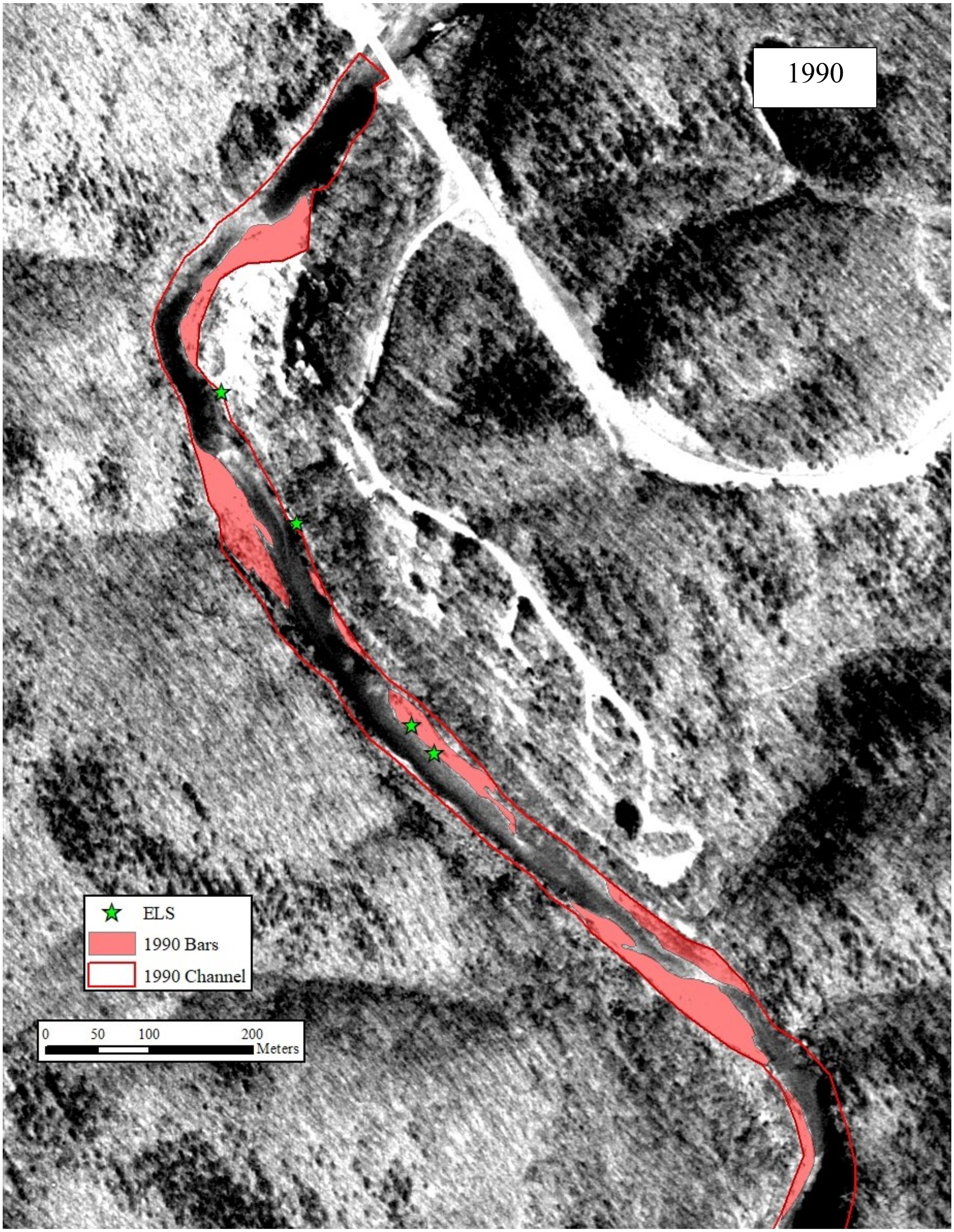


Figure 28. Historical photo analysis of bars and channel positions in 1990.

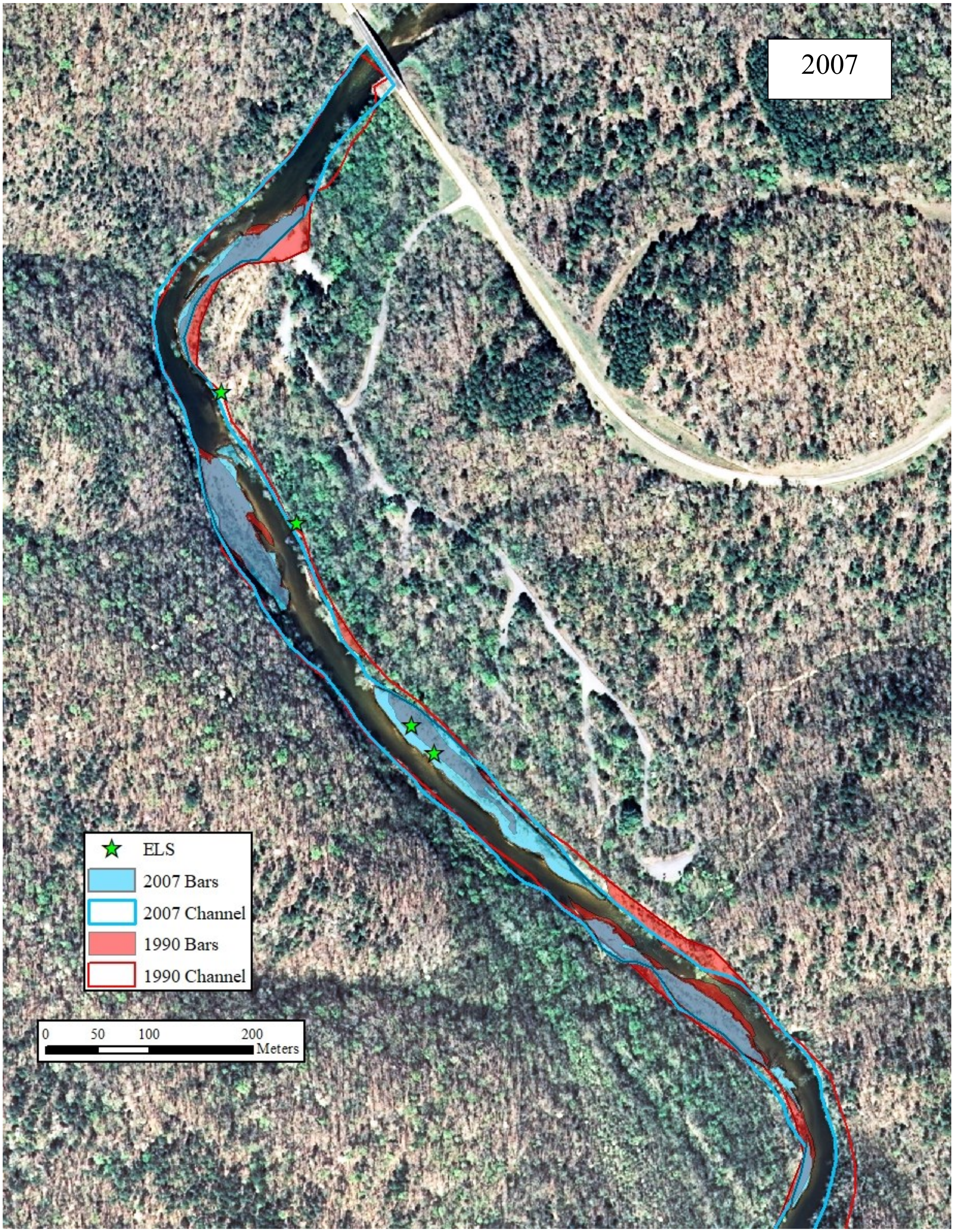


Figure 29. Historical photo analysis of bars and channel positions from 2007 over 1990 bars and channels.

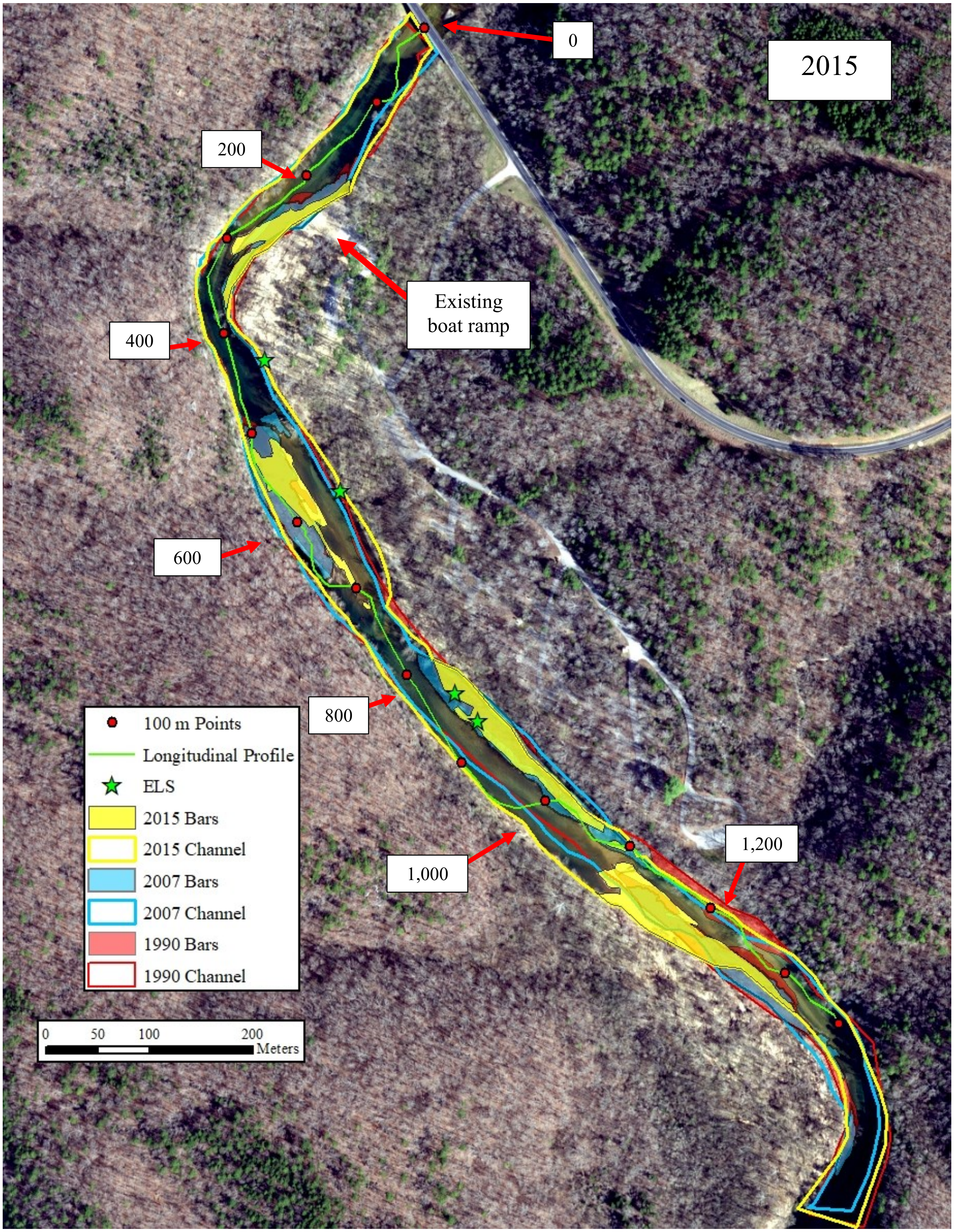


Figure 30. Historical photo analysis of bars and channel positions from 2015 over 1990 and 2007 bars and channels.

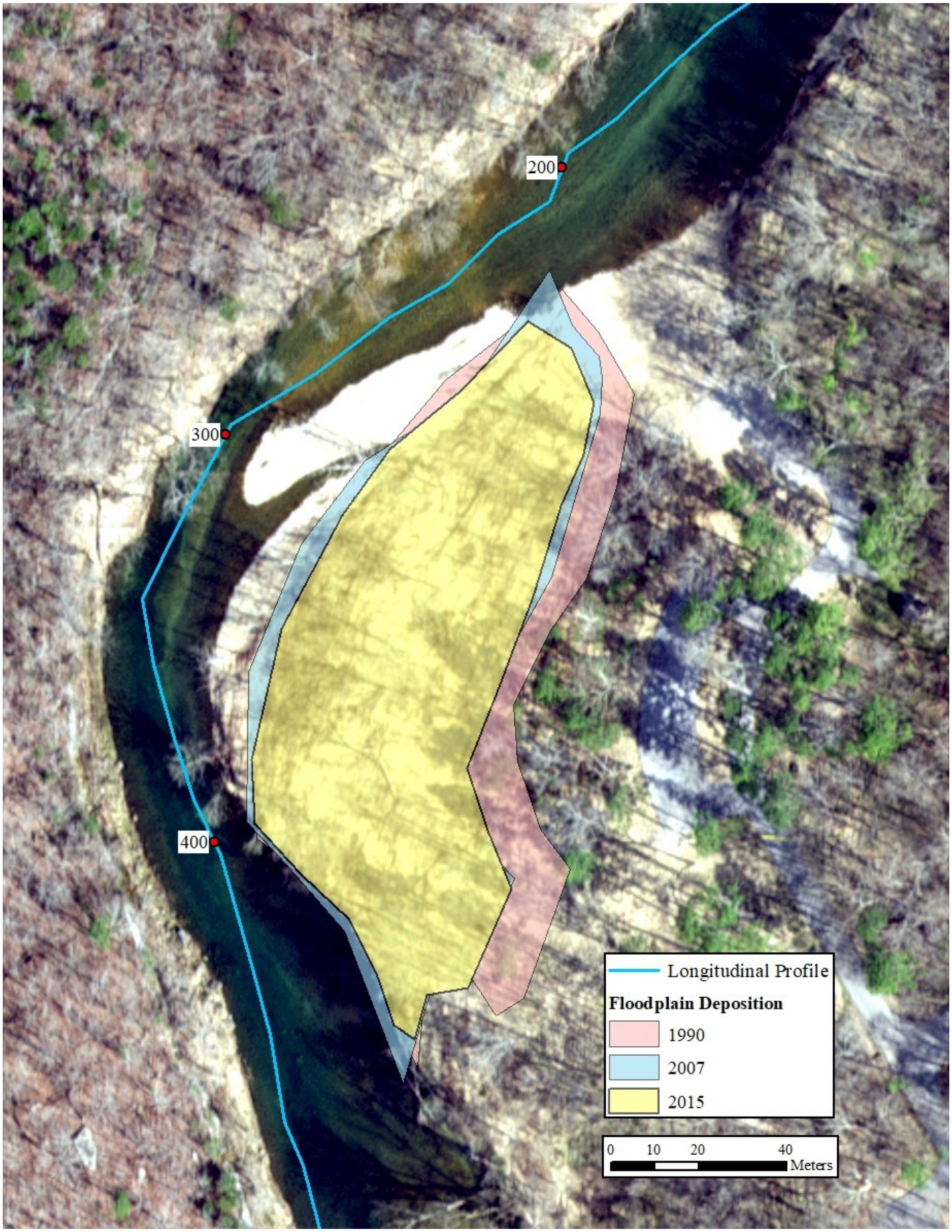


Figure 31. Floodplain deposition visible on aerial photos in 1990, 2007, and 2015.

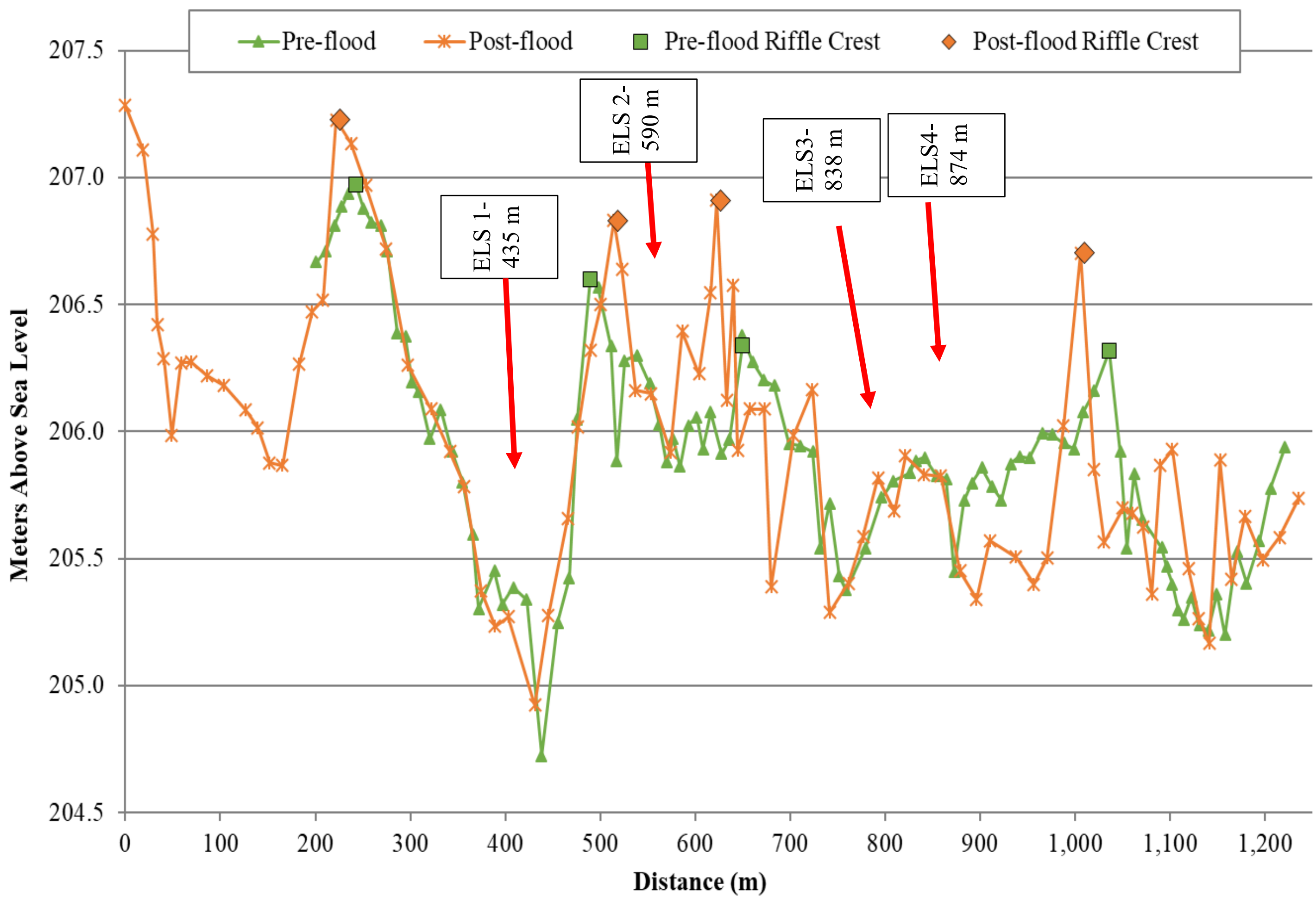


Figure 32. Comparison of longitudinal profile between pre-flood and post-flood periods.

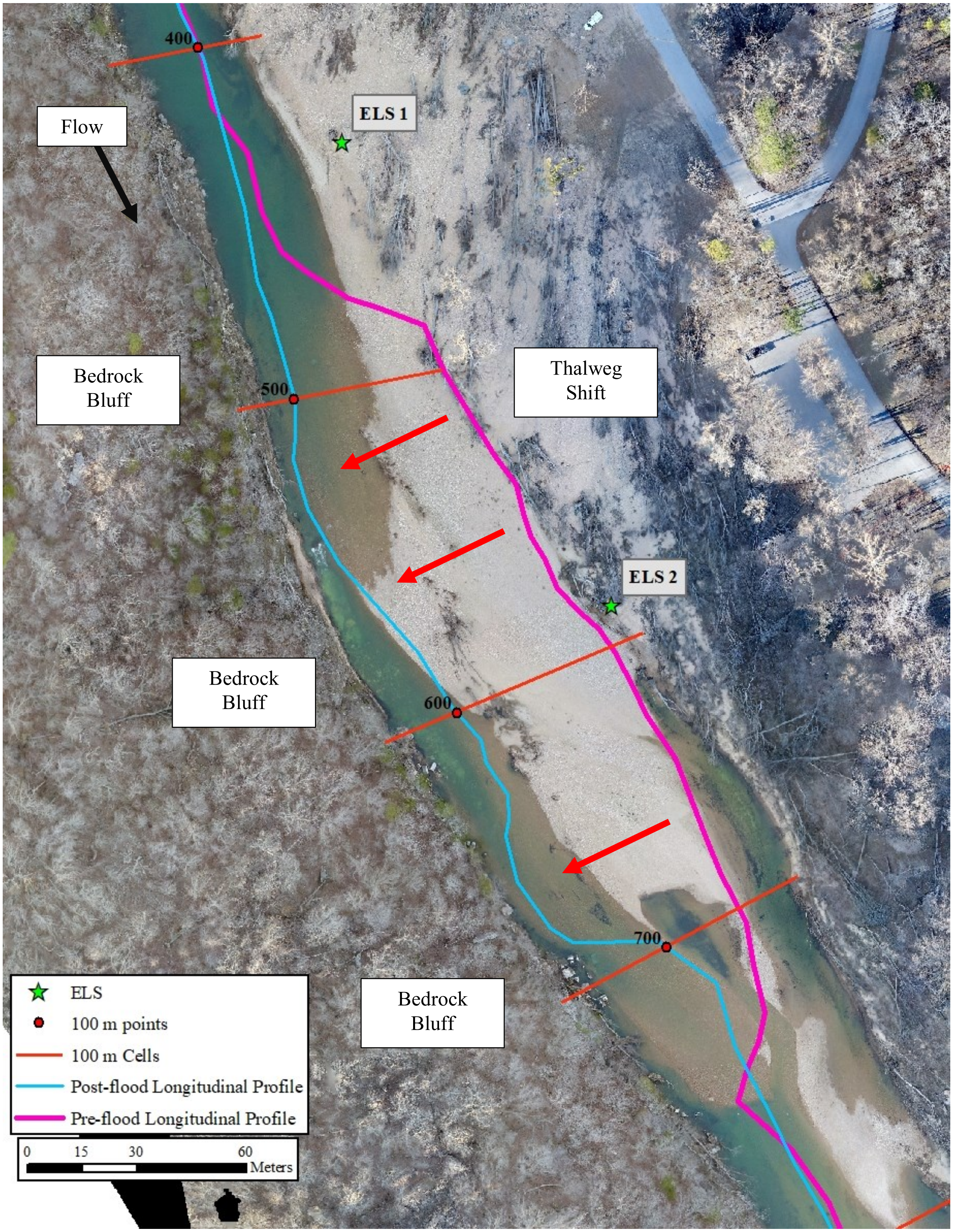


Figure 33. Post-flood aerial photo showing thalweg shift toward bedrock bluff on the river-right side of the channel.

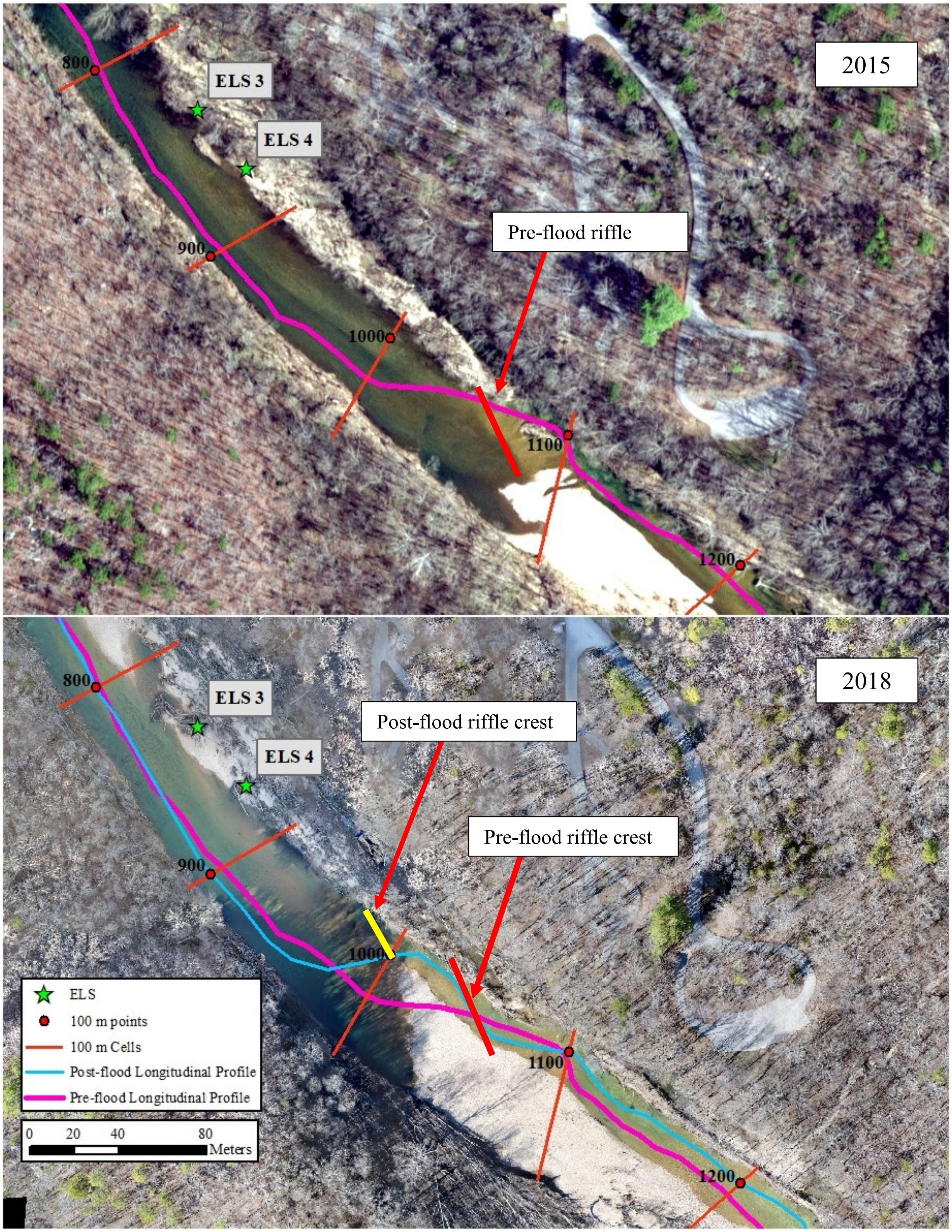


Figure 34. Movement of the riffle and glide located downstream of ELS 4.

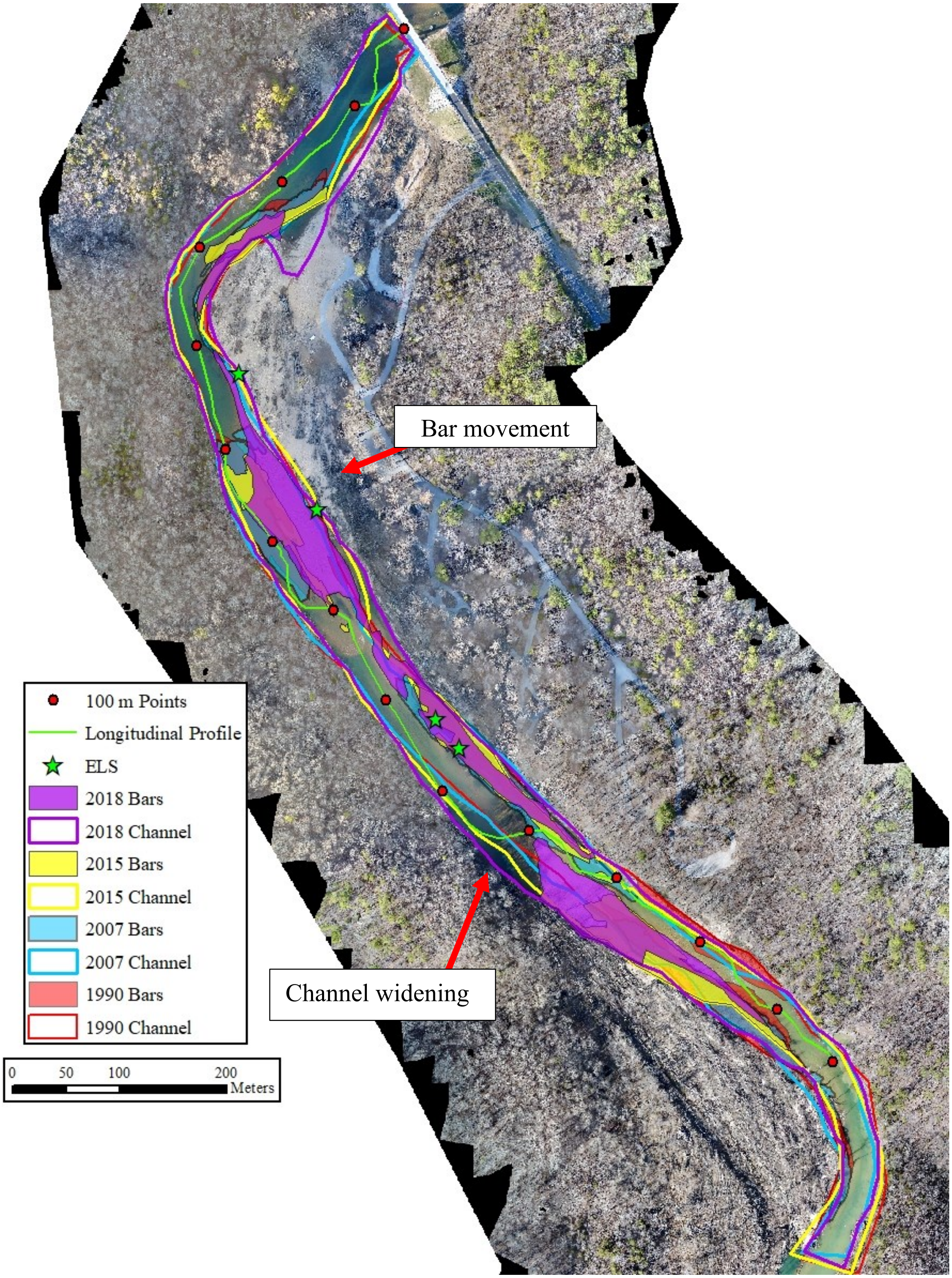


Figure 35. Post-flood channel widening and bar location change.

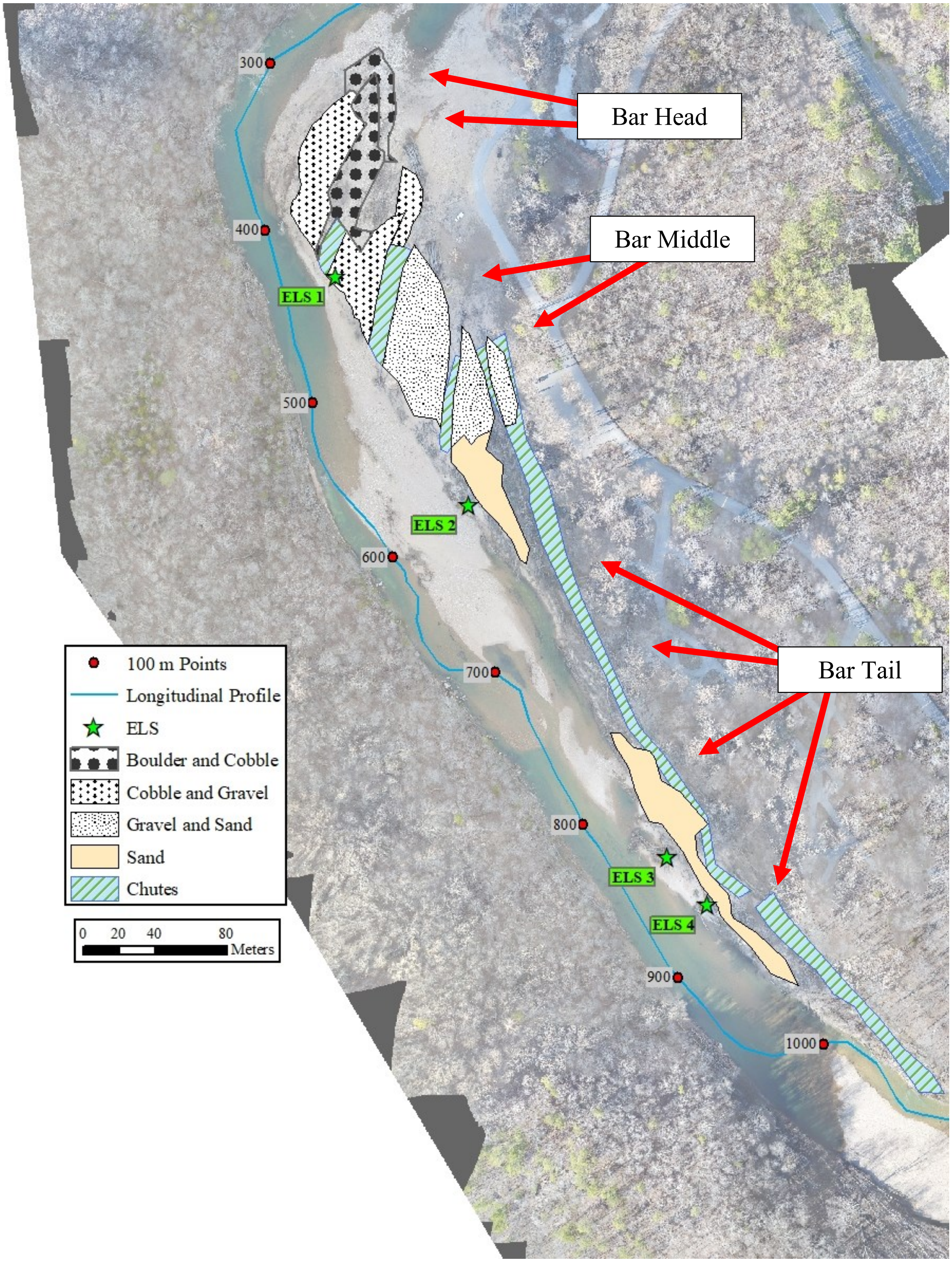


Figure 36. Floodplain-bar complex with floodplain splay lobes and chutes.

Figure 37. Existing boat ramp after extreme flood event. Bar head acting as a ramp with coarse sediment (top) and looking downstream at the head of the high-flow chute (bottom).

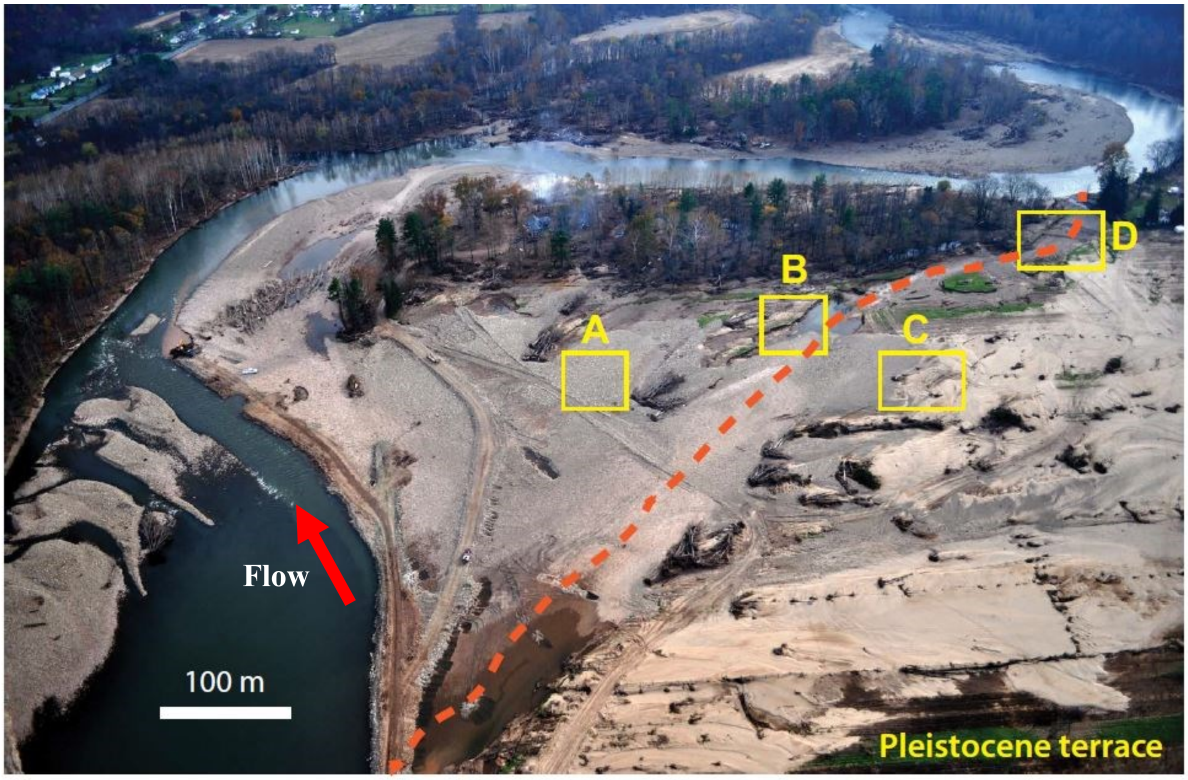


Figure 38. High-flow chute development and floodplain sedimentation (top) (Kochel et al., 2016). Dashed red line is the chute and A (bottom) shows similar coarsening of ramp at NFRA.

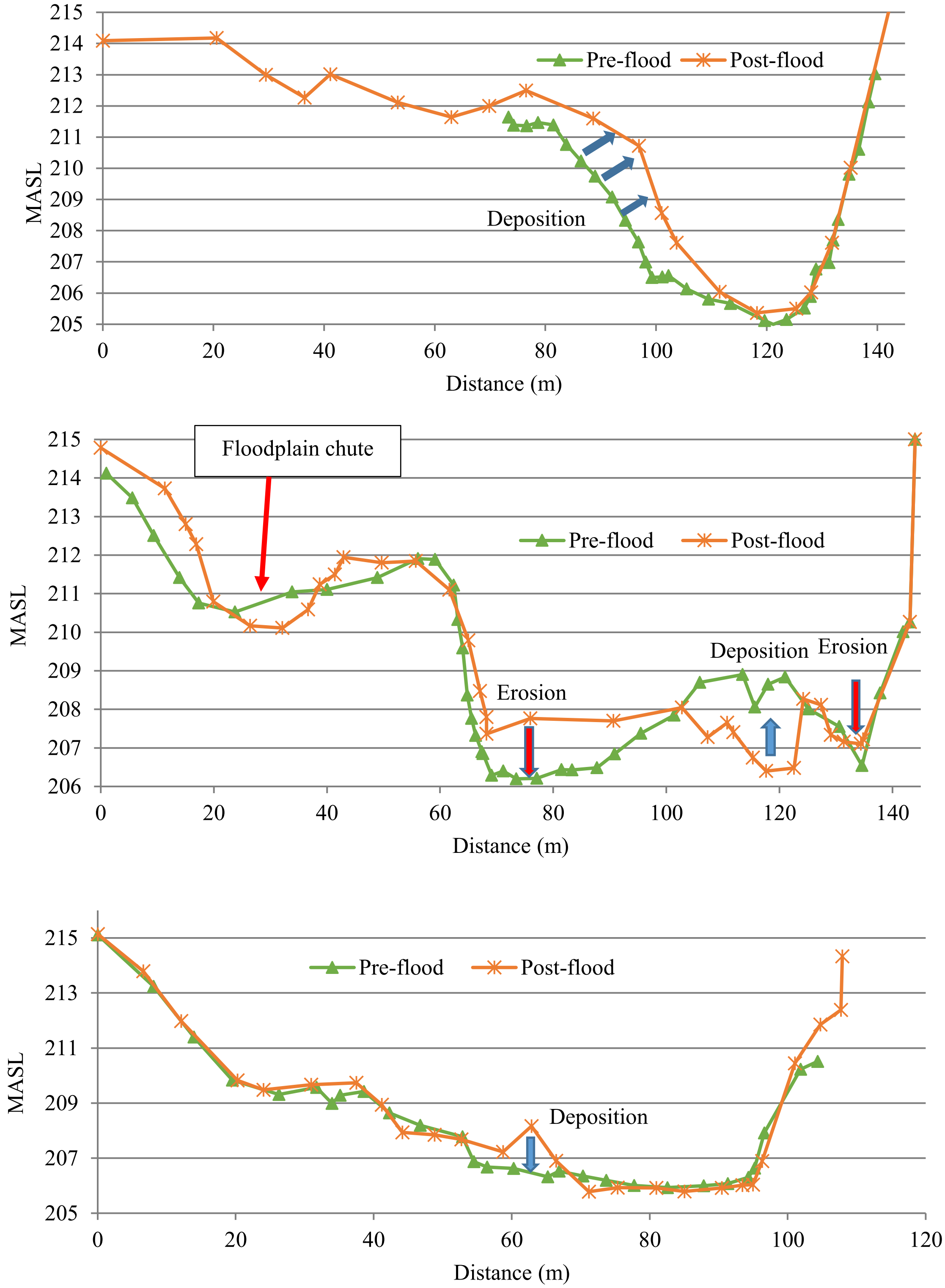


Figure 39. Cross-sectional survey comparisons at ELS 1 (top), ELS 2 (middle), and ELS 3 (bottom).

Figure 40. Post-flood LWD and toppled riparian forest on lower floodplain surface at ELS 3 (A), and backwater flooded chute near ELS 4 (B).

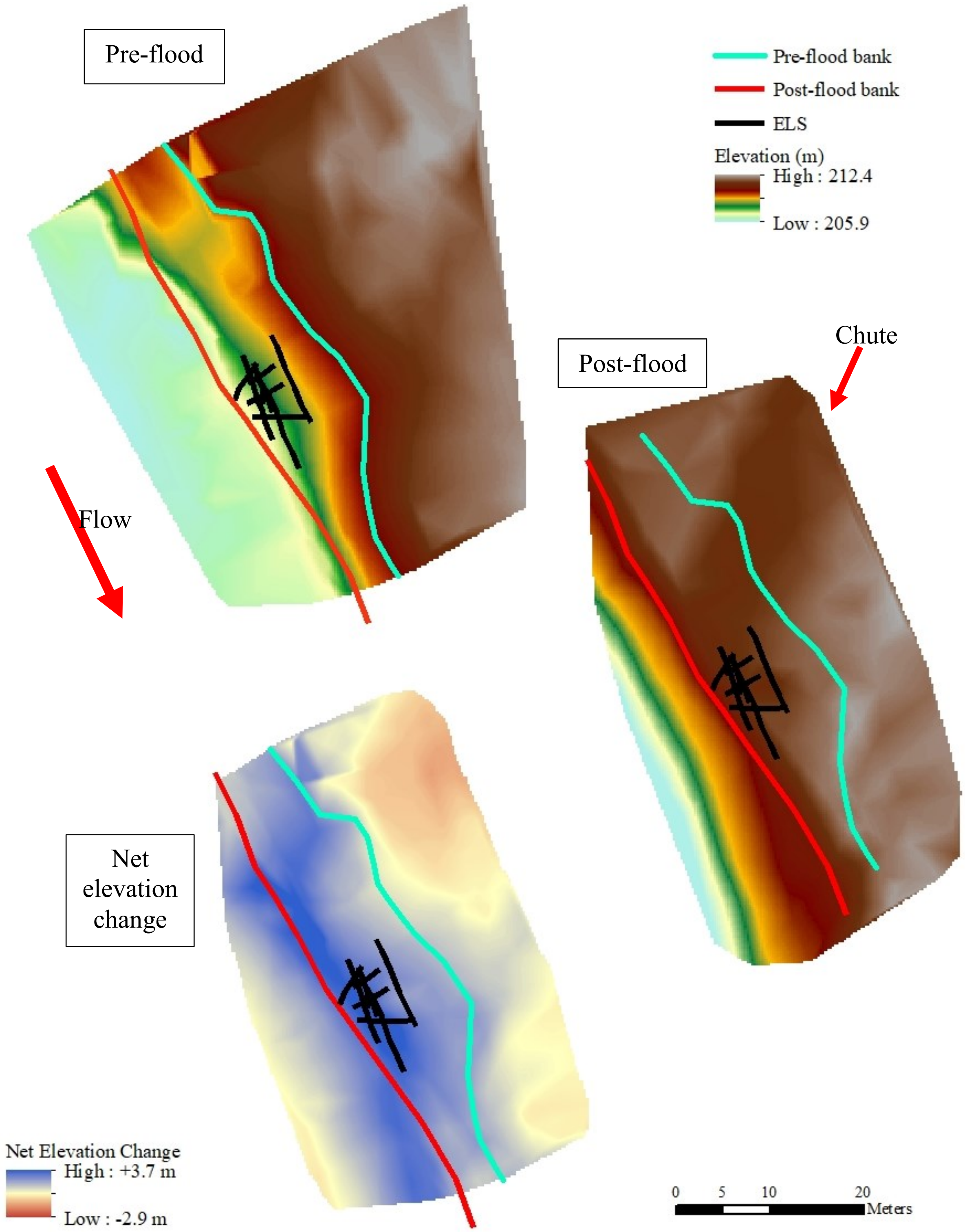


Figure 41. Pre-flood, post-flood, and net elevation change DEMs at ELS 1.

Figure 42. Slip face deposition caused by April Flood at ELS 1. Arrows show new bank line.

Figure 43. Deposition caused by April Flood at ELS 2 where bank angle lowered. Arrows show cut ends of logs in ELS 2.

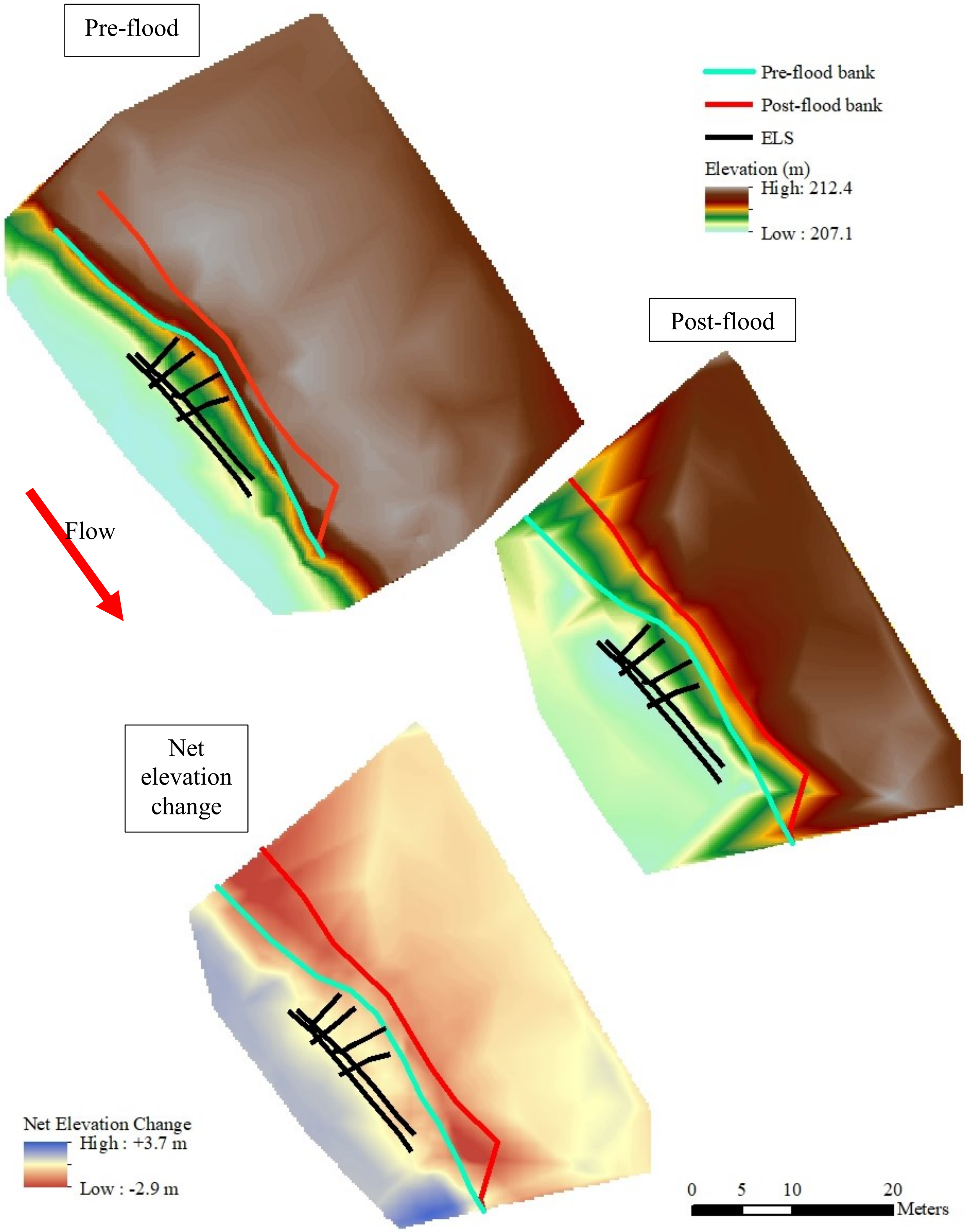


Figure 44. Pre-flood, post-flood, and net elevation change DEMs at ELS 2.

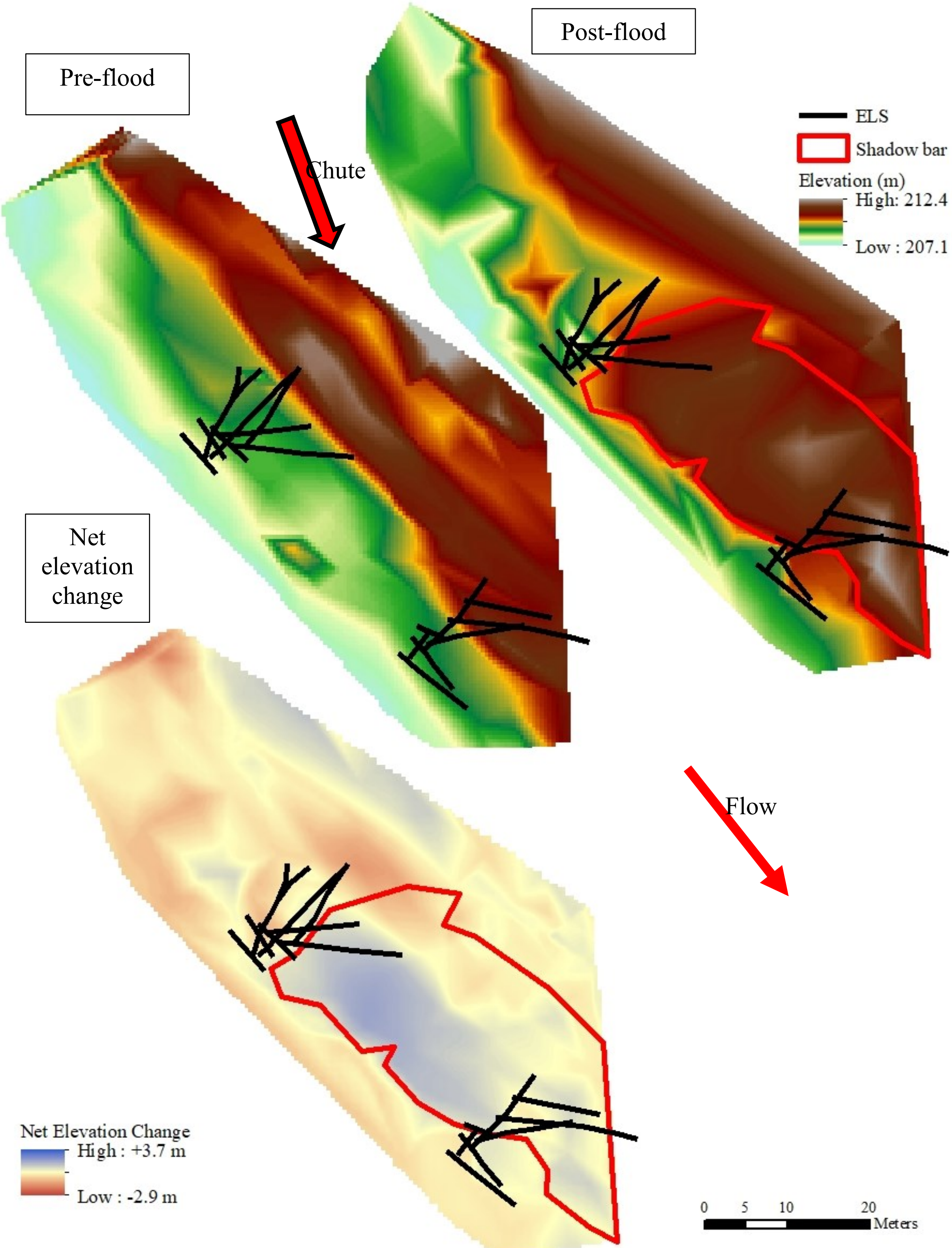


Figure 45. Pre-flood, post-flood, and net elevation change DEMs at ELS 3 and ELS 4. Chute in pre-flood DEM indicated by arrow.

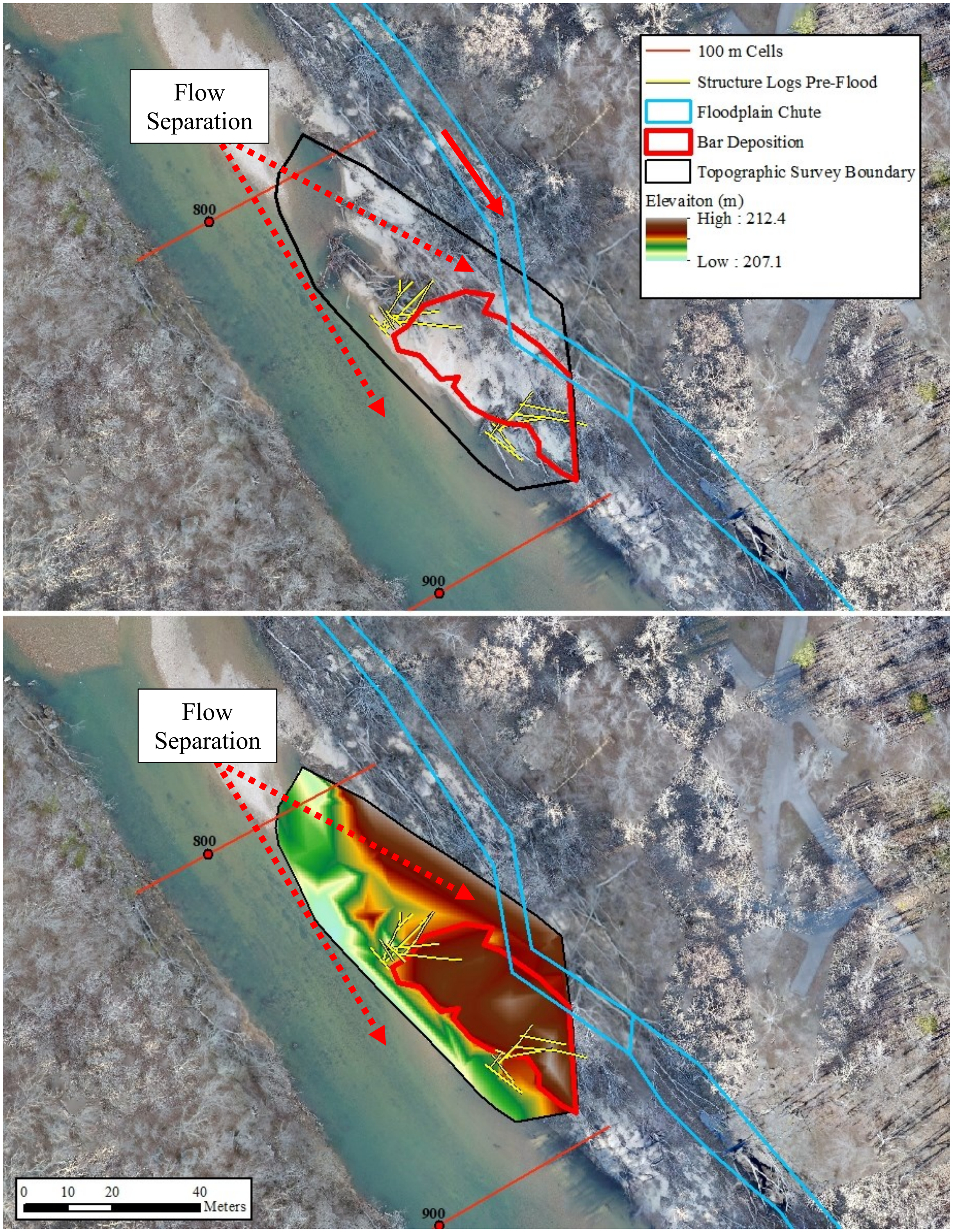


Figure 46. Flow separation between floodplain chute and main channel at ELS 3 and ELS 4 location. Arrows show areas of flow separation that resulted in bar deposition between the structures.

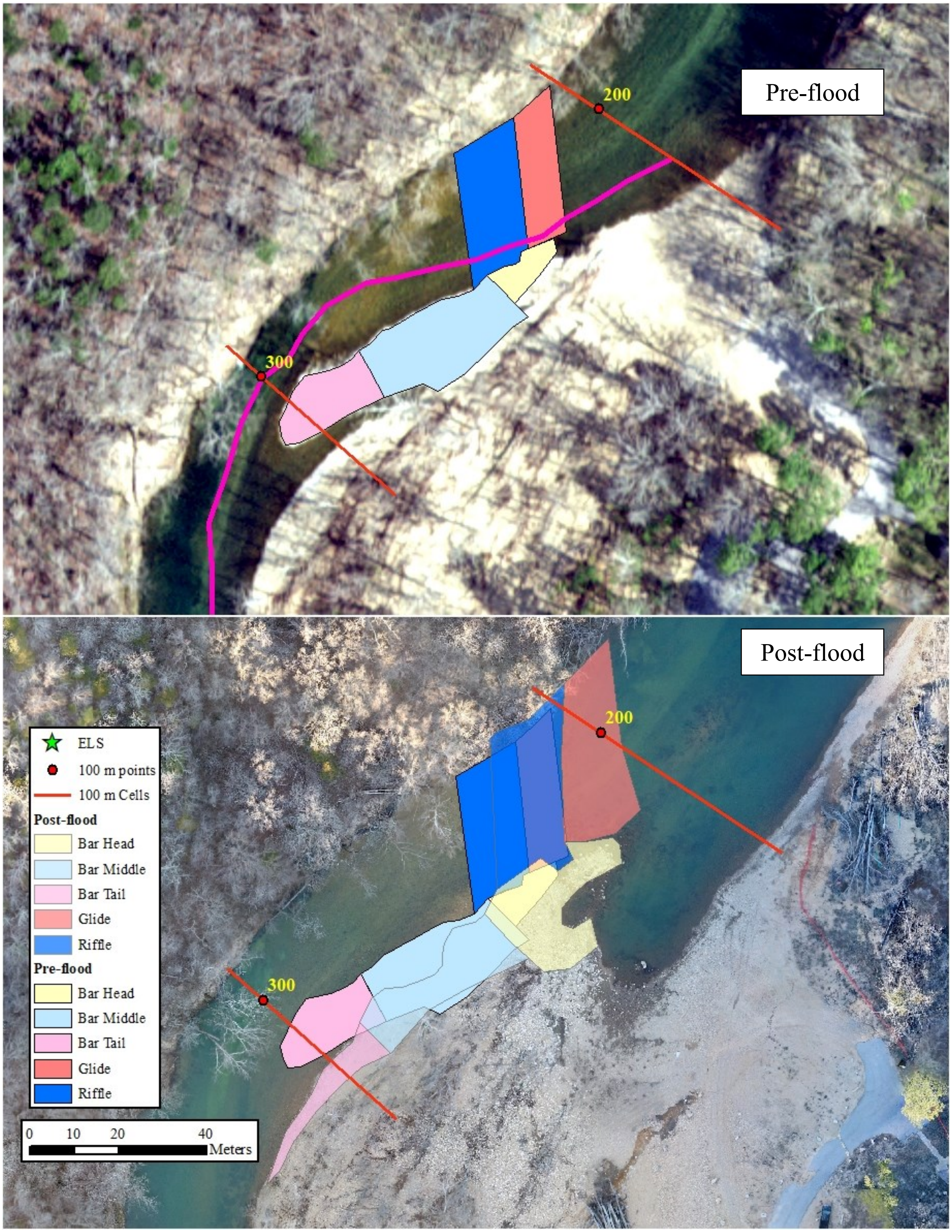


Figure 47. Riffle 1 near existing boat ramp where riffle, glide, and bar locations were surveyed for substrate composition.

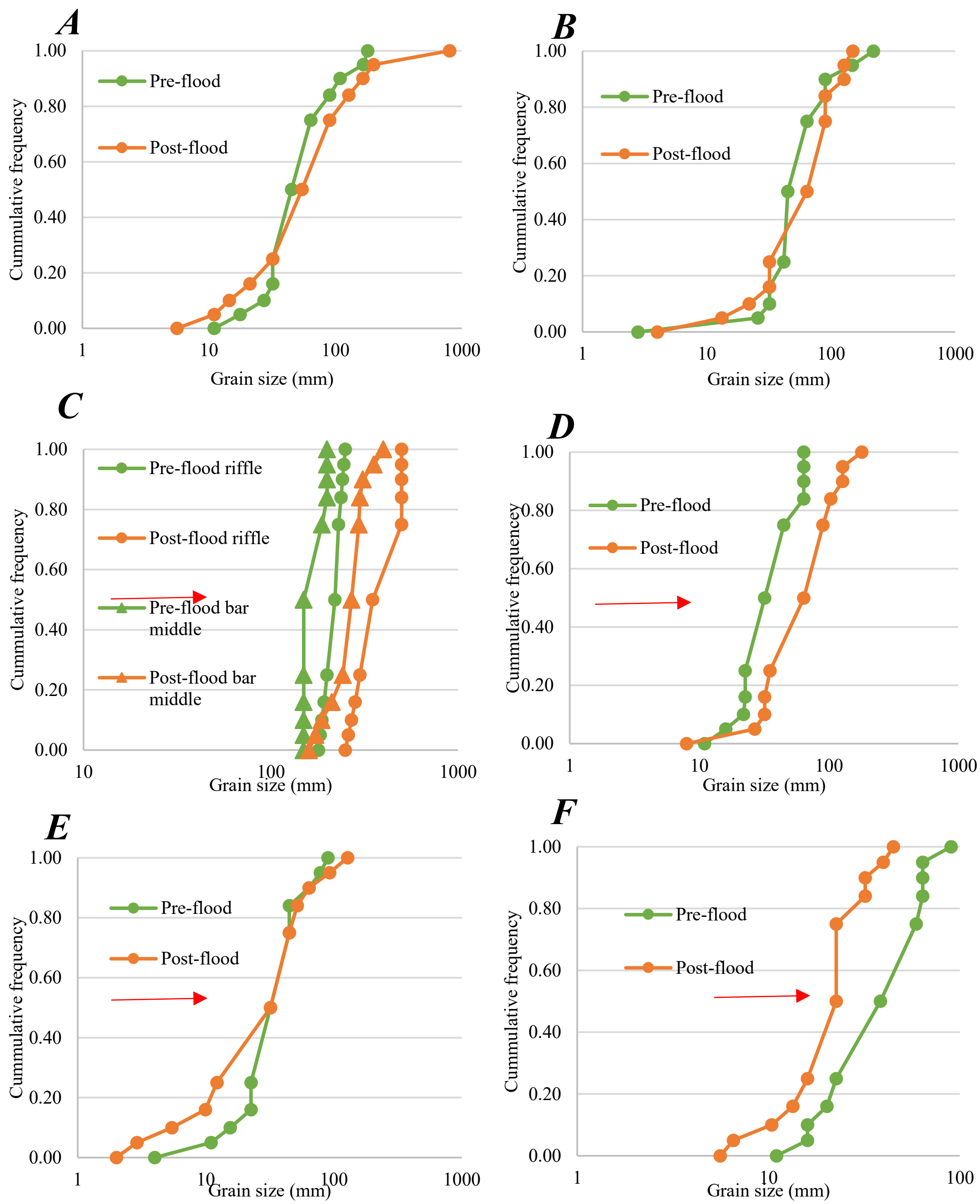


Figure 48. Riffle, glide, and bar pebble count frequency distribution at existing boat ramp (A) riffle, (B) glide, (C) maximum clast, (D) bar head, (E) bar middle, and (F) bar tail. Red arrow is D50.

Figure 49. Floodplain splay lobe between ELS 1 and ELS 2 looking downstream.

Figure 50. Floodplain splay lobe between ELS 1 and ELS 2 looking upstream.

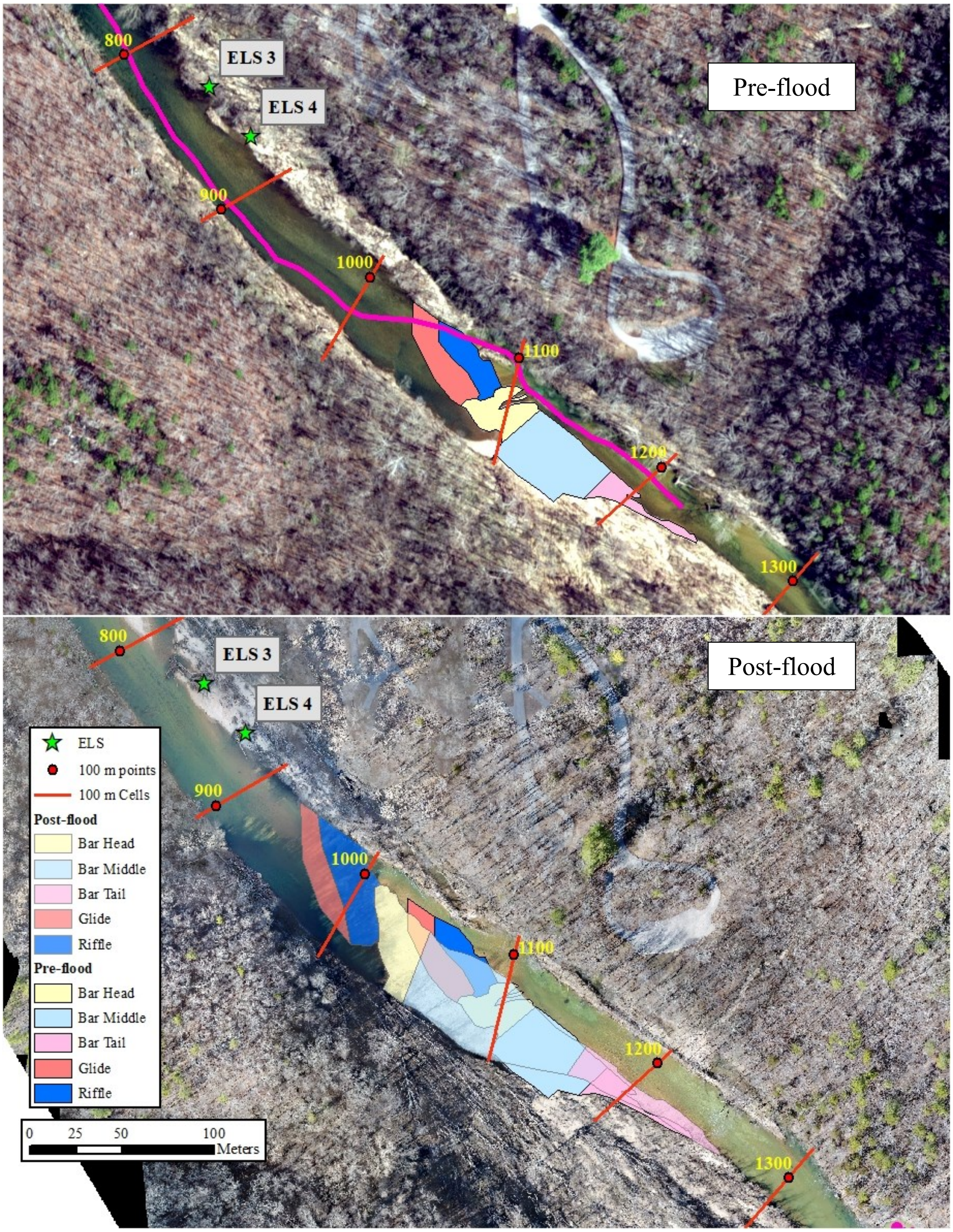


Figure 51. Riffle 4 located downstream of ELS 3 and ELS 4 where riffle, glide, and bar locations were surveyed for substrate composition.

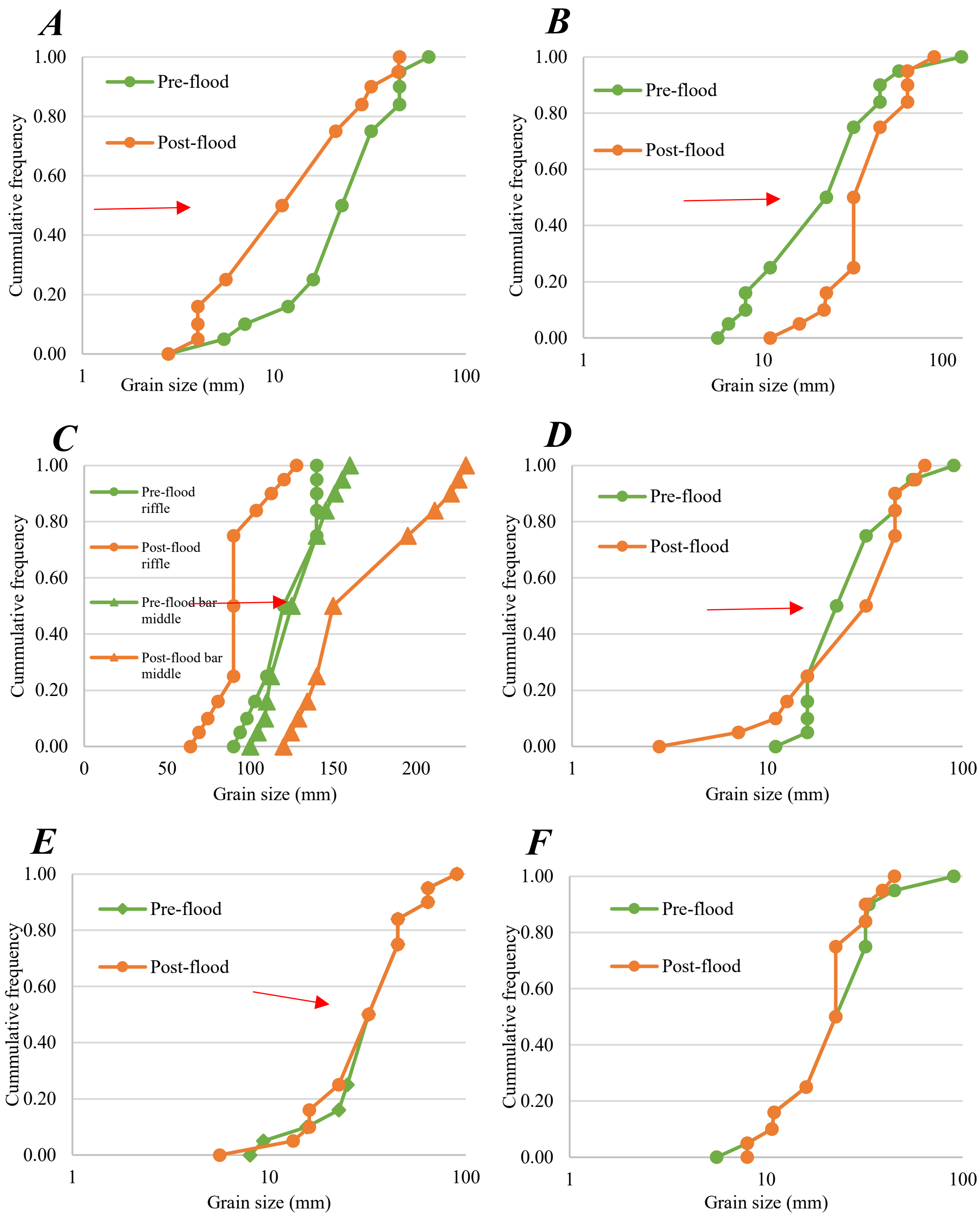


Figure 52. Riffle, glide, and bar pebble count frequency distribution at Riffle 4 downstream of ELS 4 (A) riffle, (B) glide, (C) maximum clast, (D) bar head, (E) bar middle, and (F) bar tail. Red arrow is D50.

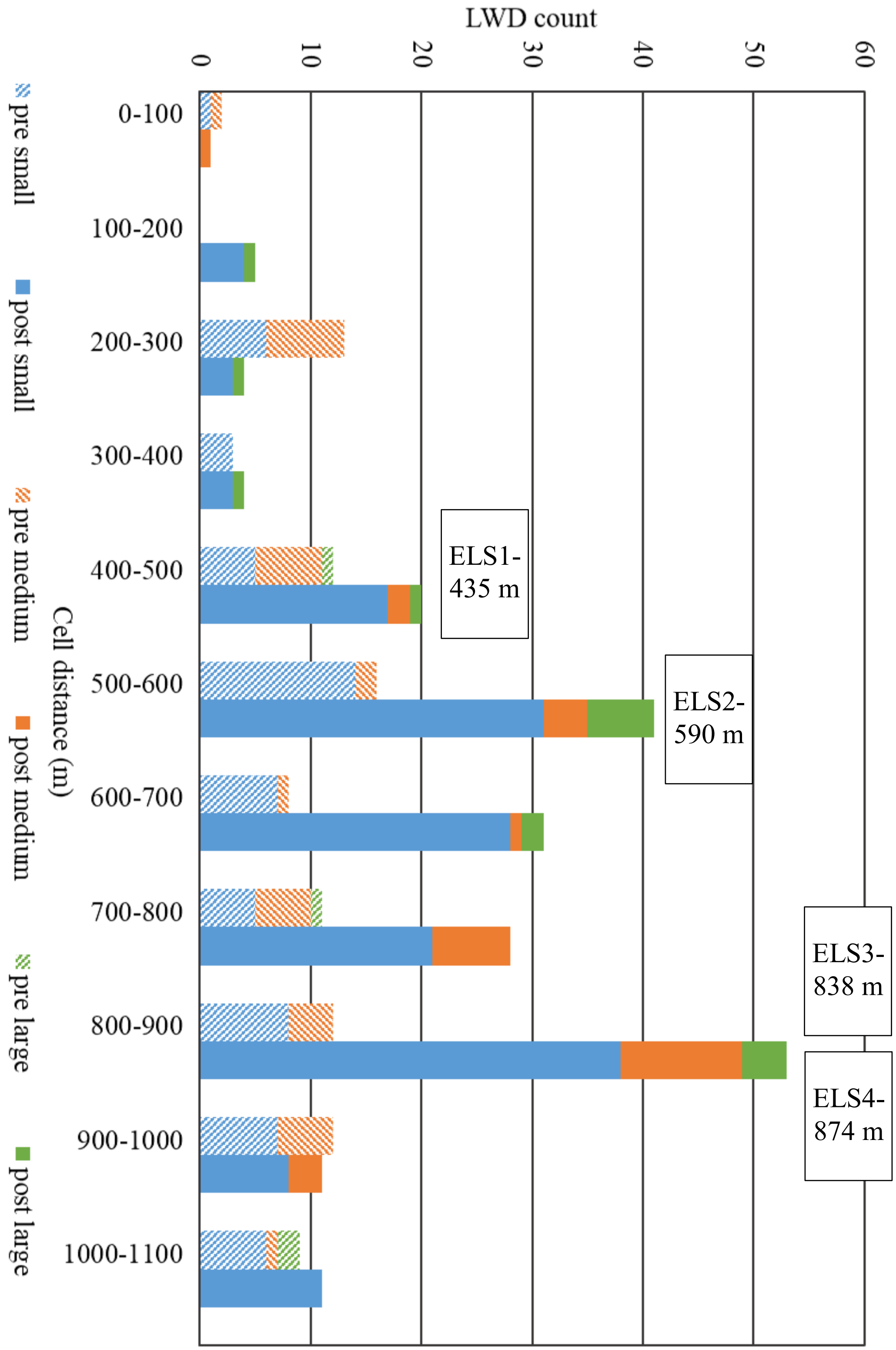


Figure 53. Distribution of LWD pieces and size classes.

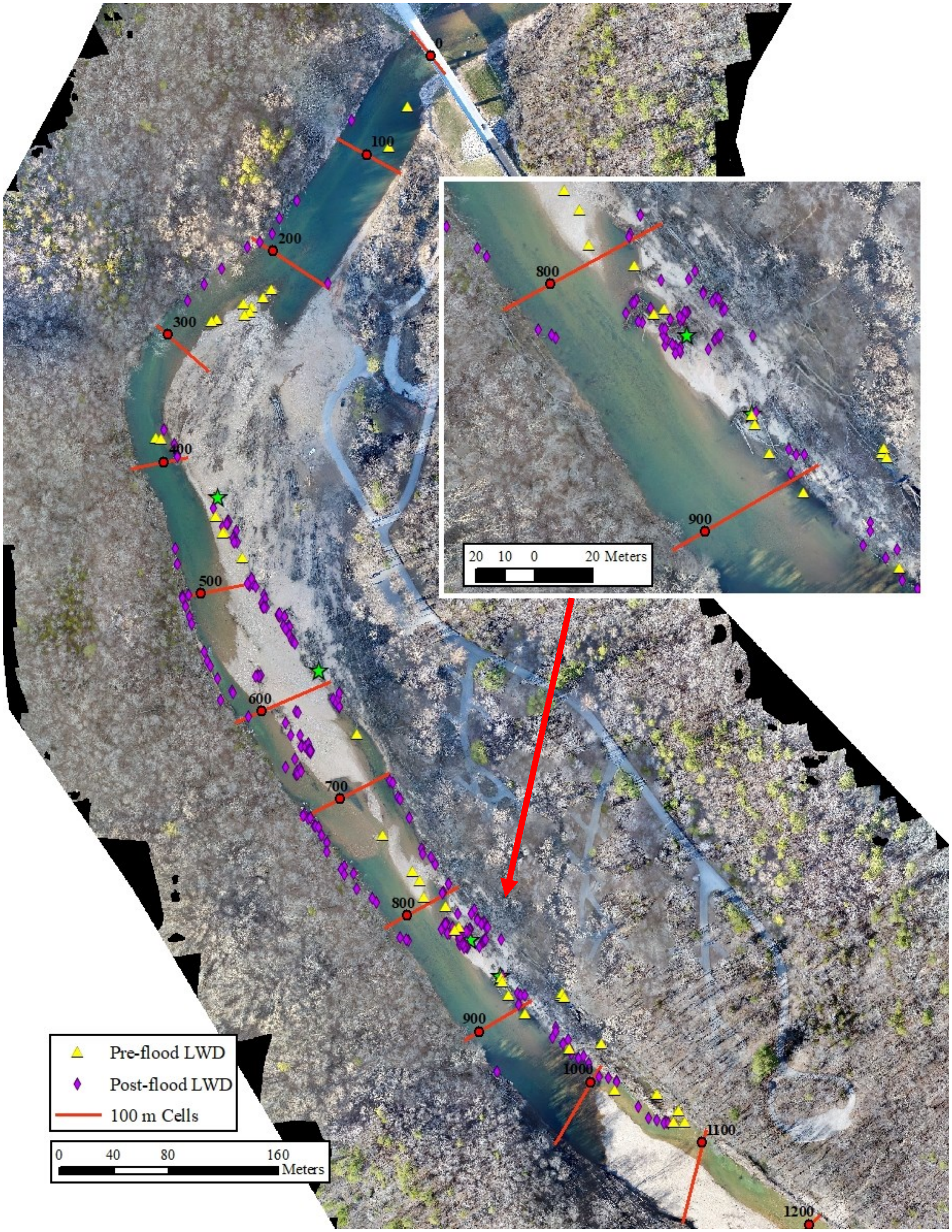


Figure 54. Pre-flood and post-flood LWD from 0-1,100 m. The highest recruitment of LWD was in cell 800-900 m where ELS 3 and ELS 4 are located.

Figure 55. Imbricated asphalt pieces and toppled riparian trees caused by the April Flood.

Figure 56. Deck of the Highway CC Bridge that was destroyed during the April Flood.

CONCLUSIONS

The use of large wood as a river restoration tool is widespread in the Pacific Northwest and Upper Midwest. This is the first study of the effectiveness of using engineered log structures as a river restoration technique in the Ozark Highlands region. The U.S. Forest Service installed four engineered log structures at the North Fork Recreation Area to reduce bank erosion and mitigate disturbance to facilities due to heavy recreation traffic and increase in repair costs due to flood damage. This was a pilot study of the effectiveness of ELS use for channel management and is the first documented study in which these structures have been used and monitored in the Ozark Highlands. The original design of this study was to investigate the geomorphic setting of the North Fork Recreation Area, monitor installation of the ELSs, and monitor any geomorphic effects of the structures on sedimentation patterns. On April 29-30, 2017 a historic flood occurred on the North Fork of the White River with a stage of 12.8 m that was 4.2 m higher than the previous peak flood height during 72 years of record. Flooding caused two highway bridge failures, riparian forest degradation, and damage or total loss of property throughout the watershed. The April Flood added the objective to study effects of a catastrophic flood event using repeat surveying techniques on the channel and ELSs. Results of this study mainly focus on ELS sites due to the abundance of pre-flood data. Conclusions from this study focus on geomorphic changes at the North Fork Recreation Area, ELS effectiveness following catastrophic flooding, and restoration considerations for river managers.

1. Point bar sedimentation occurred in the channel and on floodplain landforms during the flood. Maximum deposition of sediment was observed at +3.4 m where ELS 1 was buried by slip face deposition (Figures 35 and 37). Floodplain chutes were scoured during the flood and sandy and gravel splays were deposited on the floodplain surface at depths >2

m where the floodplain behaved as a bar landform while being under > 6 m of flood water (Figures 45, 46, and 47).

2. Fluvial wood recruitment was observed throughout the study area. Pieces of LWD increased from 96 pre-flood pieces to 209 post-flood LWD pieces within a 1,100 m sample reach (Table 13). The largest increase in LWD occurred in cell 800-900 where ELS 3 and ELS 4 acted as key pieces at the mouth of a cute where it collected mobile LWD (Table 13 and Figures 53 and 54). However, LWD collection would be expected to occur at this location without ELS enhancement.
3. Shallow bedrock channels are common in the Ozark Highlands. Typically, ELSs are entrenched into the bed material to overcome the buoyancy of the logs, but due to the shallow bedrock cables are needed to add transportation resistance. Cabling techniques used in this study kept the ELS logs local and created key pieces that enhanced recruitment of mobile LWD pieces, but logs did break loose and float around and were eventually not in the original constructed position.
4. ELSs installed for channel management in the Ozark Highlands withstood a >500-year flood. While this is an extreme event, design considerations of ELS implementation in the Ozarks should incorporate prediction of increasing flood frequency and magnitude as more intense precipitation and frequency of floods have been affecting Ozarks Rivers over the past several decades.
5. ELS applications during average flood conditions still need to be verified for Ozarks Rivers.

The Ozarks are known for shallow bedrock, mobile gravel bars, and flashy floods. Stream restoration techniques need to be designed considering a changing climate with high-magnitude floods. Previous LWD studies in the Ozarks are limited and this study is the first on the effectiveness of ELS implementation for channel management. Patterns of wood accumulation in Ozarks Rivers is predominantly in log jams as opposed to single pieces and orientation of LWD pieces is primarily parallel to stream flow direction (Martin et al., 2016). Depositional patterns of LWD in the Big River, an Ozarks River similar in geomorphology and topography to the North

Fork River, show seemingly random distribution compared to other large river systems prevalent in the LWD literature (Martin et al., 2018). In the North Fork River, LWD deposition occurred on top of bars through the study area and in an area of flow separation between the main channel and chute channel. Addition of ELSs added key members that enhanced LWD accumulation in an area that had low banks compared to other areas in the study reach.

The use of ELSs for channel management can be an effective technique in the Ozarks where log structures provide roughness for bank protection and promote localized sedimentation. However, cabling techniques should be incorporated into ELS design in shallow bedrock channels. These ELSs with cabling withstood a >500-year RI flood where they were inundated by 8-10 m of flood water. Further investigation into ELS effectiveness should be considered for more frequent floods as this study focused on the effects of a historic flood on channel geomorphology around ELS sites.

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