Implementing Diverse Bank Stabilization Measures to Contain and Capture Lead-Contaminated Sediment

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Figure 1. Bank 3 pre- and post-construction. Facing upstream.

Abstract

The Southeast Missouri Lead District was the world leader in lead production for nearly 100 years, until the early 1970's. Mining operations introduced gravel, sand, and silt-sized waste material into the Big River. During elevated flows, this waste is transported downstream and most of it is deposited into the channel and floodplain. Most impacted areas of the watershed are now encompassed by a U.S. Environmental Protection Agency (USEPA) superfund site. The U.S. Army Corps of Engineers (USACE) entered into a cost-share agreement with USEPA, in coordination with funding from state partners, to design and construct a series of bank stabilization features in a highly erosive reach of the Big River.

A project area was identified on the Big River in Jefferson County, MO. Weirs, longitudinal peaked stone toe protection (LPSTP), and toe wood were used to stabilize three separate banks within this project area, which spans about 0.8 miles. These stabilization features were implemented to prevent additional erosion of legacy mine waste that had previously deposited in the floodplain and to help capture suspended sediment containing legacy mine waste from upstream during elevated flows. A creek outlet within the project area was also relocated to a more natural orientation that allows for the efficient transfer of sediment into and through the Big River.

This paper summarizes the context, background and existing conditions, measures, design, and the constructed condition. It also discusses post-construction site monitoring and adaptive management actions.

Readers should refer to the original sources cited within for technical design guidance of measures.

Background Information

The Big River watershed is located in south-central Missouri and is a major tributary to the Meramec River, which empties into the Mississippi River near Saint Louis, Missouri. The watershed is 955 square miles and the Big River flows from southwest to northeast over the course of 138 miles, falling from 1,740 feet to 435 feet in elevation. About 67% of this river (the lower 93 miles) are listed as impaired by lead and/or Non-Volatile Suspended Solids (Missouri Department of Natural Resources, 2008). The primary types of bedrock in this watershed is dolomite, with some sandstone (<5%). The soil texture is primarily silt loam (56%) and bedrock (23%). Most of the watershed land use consists of deciduous forest and grassland, at 55% and 23%, respectively. Some agricultural and grazing is present intermittently along the river, while about 4% of the watershed is impervious (HydroGeoLogic, Inc., 2018).

Mining History

In Southeast Missouri, lead, zinc, and barite mining occurred in Jefferson, Washington, St. Francois and Madison Counties from as early as 1720 through to 1972 when the last mine in the Old Lead Belt closed. The mining and milling of ore, particularly after industrialization of this industry in the early 1900s, produced millions of tons of lead by-products, referred to as tailings. These tailings were often piled up or spoiled locally without the benefit of modern best-management practices (BMP) for storm water pollution prevention (SWPP), and large quantities of these waste products washed into the Big River Watershed over time.

Tailings of sand and gravel size have continued to migrate through the Big River, and, likely through the force of water and natural stream-sediment processes, contaminants have concentrated in the fine soil particle fraction (Pavlowsky, Owen, & Martin, 2010; HydroGeoLogic, Inc., 2018) – those particles classified by the United Soil Classification System (USCS) as silts and clays. This effect is potentially a combination of mineral particle disintegration from hydraulic forces and the tendency for the positively charged metal ions to bind to the higher surface area of these smaller particles, which are typically negatively charged.

In the Old Lead Belt, only 20-30% of the metals mass remains at the mining sites. Most of the remaining mass is stored in the Big River floodplain (Pavlowsky R. T., 2017). Since much of this material was transported and deposited during the mining era (through the 1970's), the highest concentrations are generally capped with lower concentration sediment deposits from recent decades. However, recent deposits do contain significantly elevated concentrations, as that sediment was derived largely from natural bank erosion and channel sediment transport processes. Toxic lead exposure to humans and aquatic species is primarily achieved by bank erosion and caving, sod farming, and other destructive activities within river boundary contained by the Big River's 100-year floodplain. Floodplain stabilization is being explored as a way to reduce toxic lead exposure due to bank erosion and caving.

Hydrology

This watershed is unregulated and hydrology is dominated by rainfall runoff during the late winter and early spring months. Elevated flows occur most often in April, while lowest flows occur in August (Figure 2).

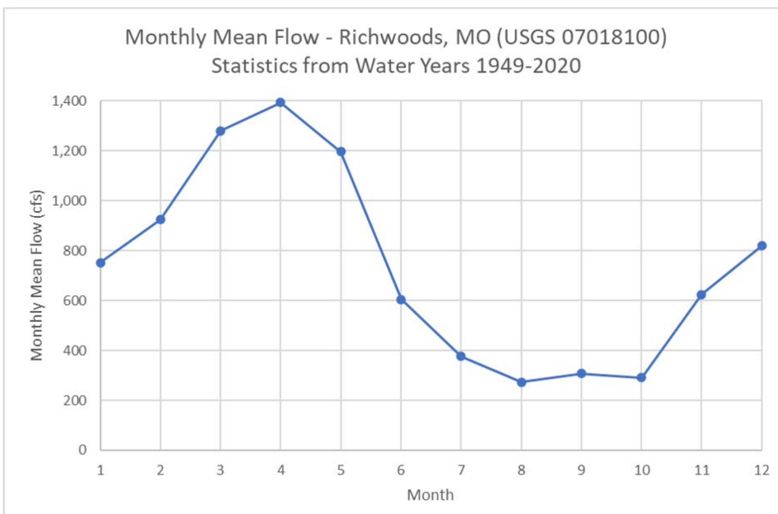

Figure 2. Monthly mean flow trends (1949-2020) for Big River at Richwoods (USGS 07018100)

Additional insight into flow statistics are provided in Figure 3, which shows exceedance probabilities of monthly flow peaks based on 70 years of record from a nearby gage. This data is useful for managing construction risk in a flashy system by more precisely timing in-channel activities to occur during months when damaging flows are highly unlikely to occur.

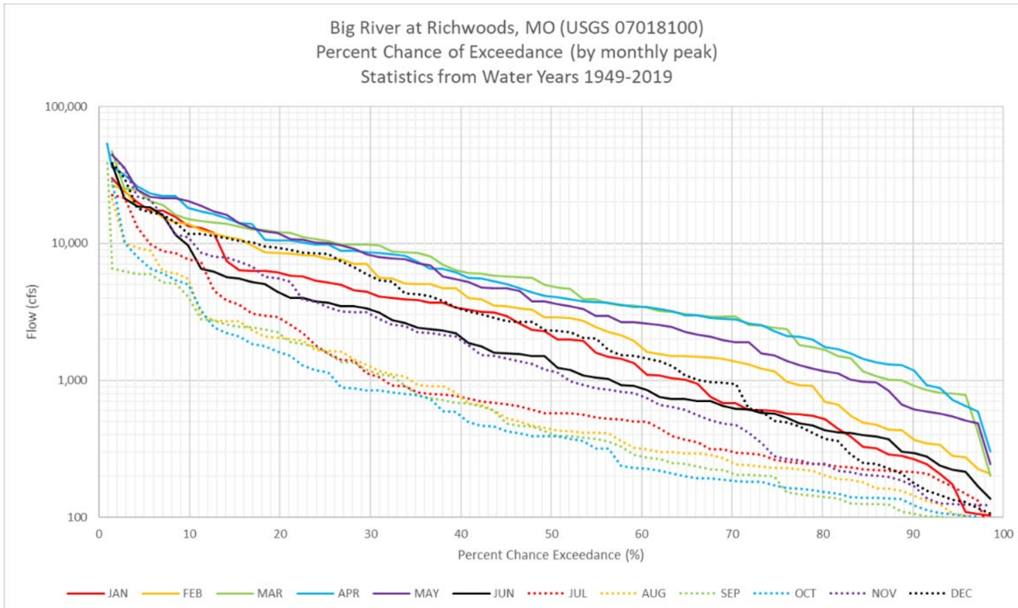

Figure 3. Flow percent chance exceedance by monthly peak (1949-2019) for Big River at Richwoods (USGS 07018100)

Site Background

The Calico Creek Confluence Site is located on the Big River in Jefferson County, Missouri, about two miles downstream of the USGS Gage at Richwoods (07018100). This site is named for its location at the confluence of Calico Creek into the Big River. The site is composed of three separate vertical banks (Figure 4). Initial assessments suggest that bank 1, furthest upstream, is the primary source of the reach instability, owing to the complex hydraulics of the confluence zone with Calico Creek, which enters upstream of bank 1, from the south. X-Ray Fluorescence (XRF) testing from March 2018 indicated that this site was a good candidate for the use of floodplain/bank stabilization to reduce the mass of contaminants released into the river due to bank erosion and caving.

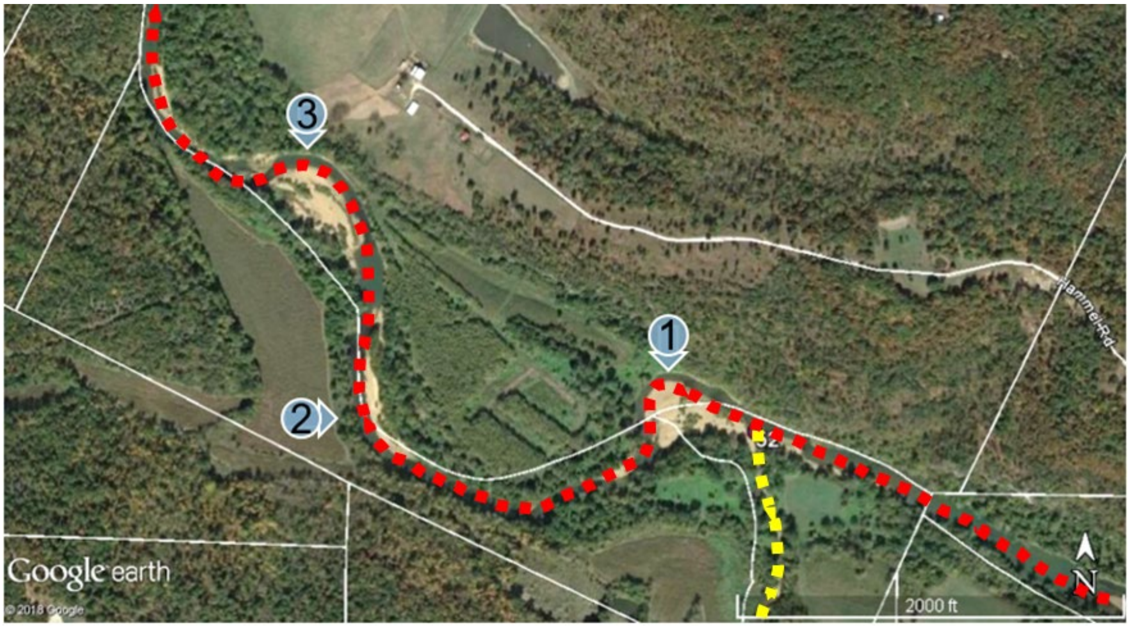

Figure 4. Calico Creek Project Bank Locations and 2011 Parcel Boundaries; flow from right to left; red is Big River, yellow is Calico Creek

The riverbank erosion that is present at this site is consistent with erosion that occurs in many fluvial systems throughout the Midwest. However, riverbank erosion in the Big River watershed is of particular interest due to the release of lead contamination during natural bank erosion processes, which adversely impacts aquatic species and users downstream.

Agency Collaborations

The USACE entered into a cost-share agreement with USEPA, in coordination with state funding and sponsors to develop a holistic site design that addresses potential hazards to human and ecosystem health. By leveraging the authorities and funding of multiple agencies for this effort, the efficiency of the constructed solution was maximized while mitigating regulatory limitations inherent to each agency. Design input on bioengineering measures was obtained from The Nature Conservancy.

Existing Conditions

This project is comprised of three distinct riverbanks (Figure 4) along about 0.8 miles of complex floodplain corridor comprised of multiple bluffs, floodplain forests, a major tributary confluence, riverbanks of various heights, and point bars of significantly different sizes. This corridor is nestled against a tall bluff on the right descending floodplain (northeast) and a high floodplain on the left descending bank (southwest). Due to the tall bluff along the right descending edge of the floodplain, the entire floodplain between banks 1 and 3 (Figure 4) is accessible only from a point adjacent to bank 3. Historic Google Earth imagery shows that riverbanks in this area have experienced significant erosion between 1996 and 2020, cleaving a combined total of about 9 acres of lead-contaminated sediment from the floodplain and re-suspending it in the Big River.

Bank 1 – Upstream Site; Right Descending Bank

Bank 1 (Figure 5) is the furthest upstream bank in this project. It is about 12 feet tall from top of bank to thalweg during low flows.

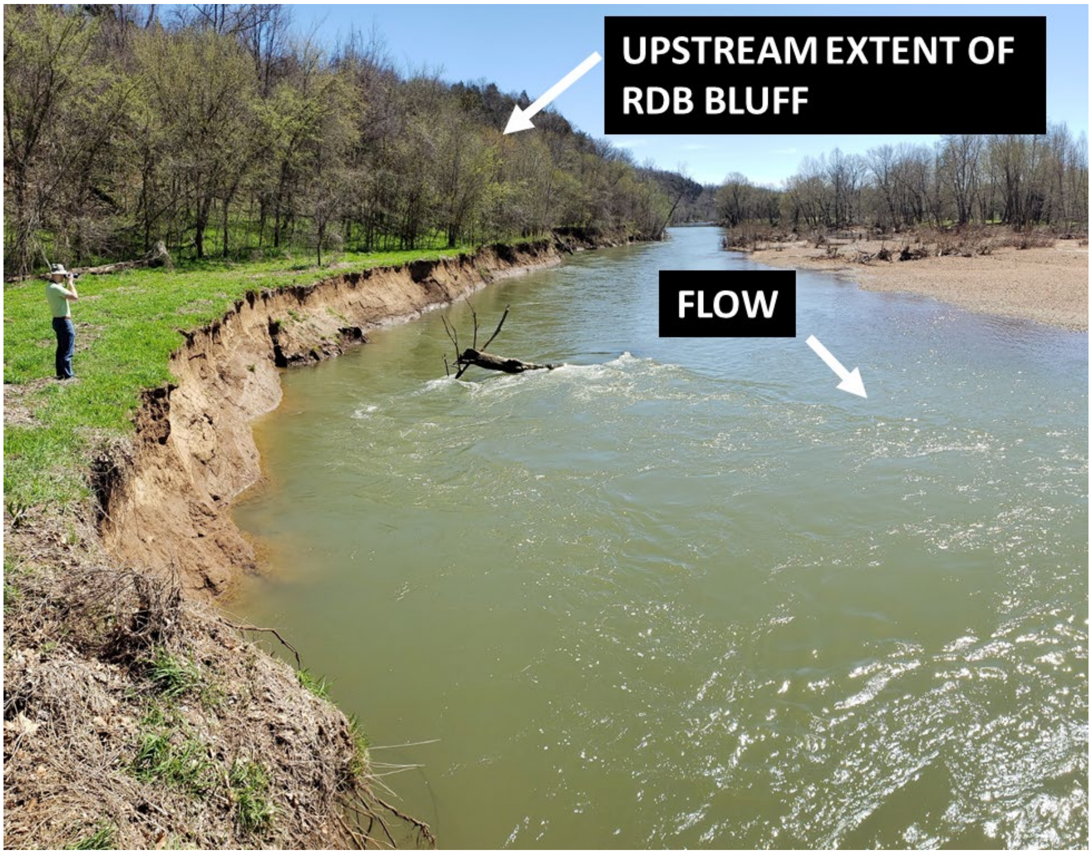

Figure 5. Bank 1 pre-construction condition (2019), facing upstream (east-southeast)

The river is eroding into the low floodplain at bank 1 and ultimately has potential to allow the Big River to cut through thousands of feet of low floodplain (between banks 1 and 3), shortening the length of river and increasing the Big River's gradient. In one location at this bank, floodplain access begins at ~90% ACE (1.1-year) flows (Figure 6).

Figure 6. Bank 1 low floodplain access (2019, higher flow than previous figure), facing downstream

Between 1996 and 2020, bank 1 has eroded laterally by 360 feet at its apex, releasing about 4.0 acres of lead-contaminated sediment into the Big River (Figure 7).

Figure 7. Riverbank erosion at bank 1 between 1996 and 2020; flow from right

The river at this location has excellent access to the right descending bank (RDB) floodplain, but only in the direction the riverbank has already eroded, and only after half the length of the 2020 river as pictured in the above figure. The overbanks immediately upstream of this site include good but narrowing access to the left descending bank (LDB) floodplain, and nearly immediate bluff line on the RDB.

Sometime between 1996 and 2015, one or more stone river training structures (RTS) were constructed at bank 1. By the time of construction, there was evidence of only one of these structures, and it was flanked on the landward side between design and construction, requiring a late alignment change. This is discussed more later in the design and construction section.

Bank 2 – Middle Site; Left Descending Bank

Bank 2 (Figure 8) is the middle bank in this project. It is eroding into a high floodplain on the LDB. It is about 20 feet tall from top of bank to thalweg during low flows. A hard point, thought to be a bedrock shelf, is present at the exit of bank 2 as it transitions into bank 3, immediately downstream.

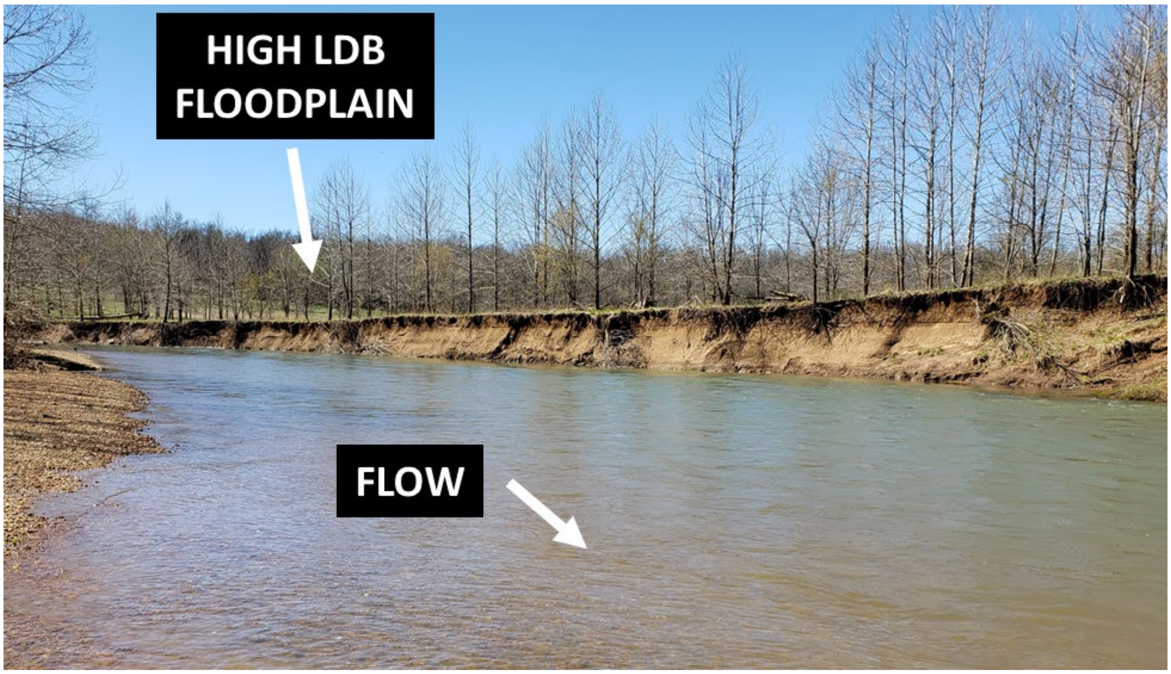

Figure 8. Bank 2 pre-construction condition (2019), facing upstream (southwest)

Between 1996 and 2020, bank 2 has eroded laterally by 110 feet at its apex, releasing about 1.6 acres of lead-contaminated sediment into the Big River (Figure 9).

Figure 9. Riverbank erosion at bank 2 between 1996 and 2020; flow from bottom

The river at this location has very good access to the RDB floodplain, while the LDB floodplain is perched significantly above the RDB floodplain. The overbanks immediately upstream of this site are tall and steep along the LDB, and very good access to the RDB floodplain.

Bank 3 – Downstream Site; Right Descending Bank

Bank 3 (Figure 10) is the furthest downstream bank in this project. It is about 15 feet tall from top of bank to thalweg during low flows. This bank was eroding into the sole access road to the landowner's bottomlands, which was also used for access to bank 1. At the time of construction, the access road, which once had a floodplain buffer of about 180 feet between it and the river, had only 3 feet of buffer.

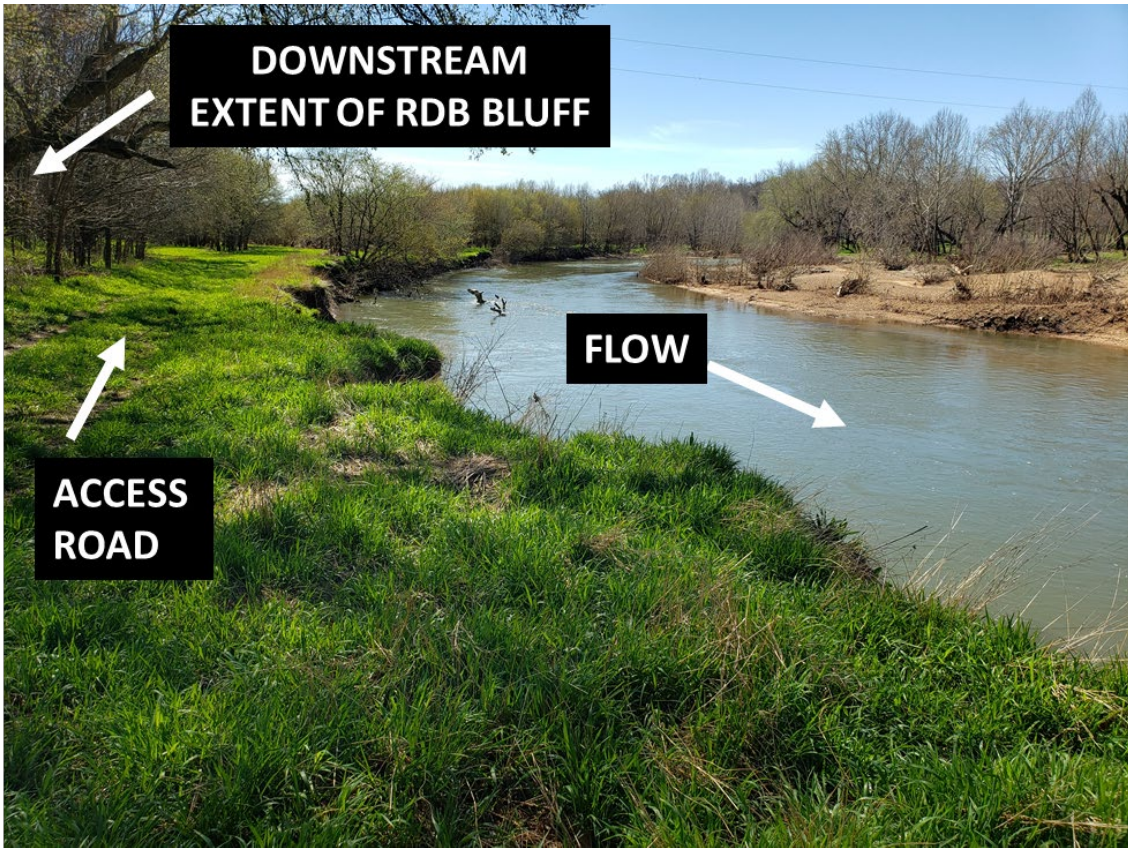

Figure 10. Bank 3 erosion site, pre-construction (2019), facing upstream (east-southeast)

Between 1996 and 2020, bank 3 has eroded laterally by 250 feet at its apex, releasing about 3.3 acres of lead-contaminated sediment into the Big River (Figure 11).

Figure 11. Riverbank erosion at bank 3 between 1996 and 2020; flow from bottom

The river at this location has very good access to the LDB floodplain and RDB floodplain, although the RDB floodplain extends for only a few feet before sloping steeply upward into a receding bluff. The overbanks immediately upstream of this site are accessible along both banks. Downstream of this location, the river pushes into the tall bluff on the LDB, with good access to a floodplain forest on the RDB.

Measures

There are a wide variety of bank stabilization measures that could be used at a site like this, due to the various configurations of each of the three banks. Ultimately, the constructed measures were chosen primarily based on the following considerations:

- Short-term bank protection: The prime directive is to prevent further re-introduction of lead-contaminated sediment into the river due to riverbank erosion.
- Variety of implemented measures: The authority and funding mechanisms of the agencies involved with this project made it necessary to implement a variety of measures, to include biotechnical bank stabilization solutions.
- Long-term sustainability: A standard project life of 50 years was used, so materials and construction methods needed to allow for that longevity.
- Construction cost: As with every project, budget limitations dictate the extent of the project features and the conservativity of their design and construction.
- Landowner cooperation: Measures have differing levels of invasiveness onto a landowner's property. Landowners have differing appetites for constructed features on or adjacent to their property.

A site-level overview of the conceptual design is provided below (Figure 12). The next three sections discuss each bank by referencing drawings from late in the design phase and providing an overview of the measures that were ultimately constructed at each bank. The design specifics of these measures will be discussed more later.

Figure 12. Conceptual design of overall site; flow from right

Bank 1 Measures

This bank was experiencing a high rate of erosion prior to stabilization. Between 1996 and 2020, a substantial point bar grew from the LDB in the direction of the eroding bank. The planform of the river at this site had become highly sinuous during this timeframe (Figure 7), resulting in an inefficient flow path for the river. This condition provided an opportunity to realign the river to a more efficient flow path while providing overbank storage for landward deposition of suspended sediment from upstream.

The selected measures at bank 1 (Figure 13) include:

1. Longitudinal Peaked Stone Toe Protection (LPSTP), with tiebacks to the existing bankline. This method of protection was chosen because it eliminates further erosion of bank material by creating a new, designated bankline that is offset from the existing bankline. It effectively resists river forces from all angles of attack. Tiebacks are constructed between the LPSTP and the existing bankline to mitigate the chance of the structure being flanked between the new LPSTP and the existing bankline. The initial intention of this measure was to provide robust bank erosion protection while simultaneously providing the river with a place to deposit excess material, since the area landward of the LPSTP was excavated naturally, since it was formerly the main channel. For this reason, LPSTP crest was intentionally constructed to a lower elevation than is typically recommended.
2. Short weirs were included on the riverward side of the LPSTP to further redirect entering flows, while improving bathymetric diversity. The initial intention of this measure was to

provide a robust solution at this bank for only a small additional cost, since the LPSTP would function to redirect flows and protect the bankline in the absence of these weirs.

3. Pilot Channel excavation through the existing point bar, on an alignment that provided the Big River with a smooth preferential path to take during its transition from existing condition to constructed condition. This pilot channel was also intended to improve the ease of construction of the other measures at this bank by reducing the "in the wet" work that the contractor would need to do.
4. Bank Shaping of the existing bankline to provide access to the above features during construction, and to establish a robust vegetative protection solution in subsequent years. In addition to simple sloping of the bankline, the top of the sloped bank was adjusted slightly to conform to a single, fixed elevation to allow for uniform overtopping during high flows that access the floodplain.
5. Floodplain check berm about 200 feet downstream of the crest of bank 1. This heavily vegetated soil check berm spans across the existing low floodplain channel (Figure 6). The berm was conceptualized to serve two primary purposes: the first is for site access across the low floodplain channel during construction and before planting vegetation; the second is to allow for flows that overtop bank 1 to dissipate in a contained pool between the berm and bank 1. The contained pool would fully backwater from downstream prior to receiving headwater flows and would drain into groundwater shortly after the recession of any flow condition that activates it.

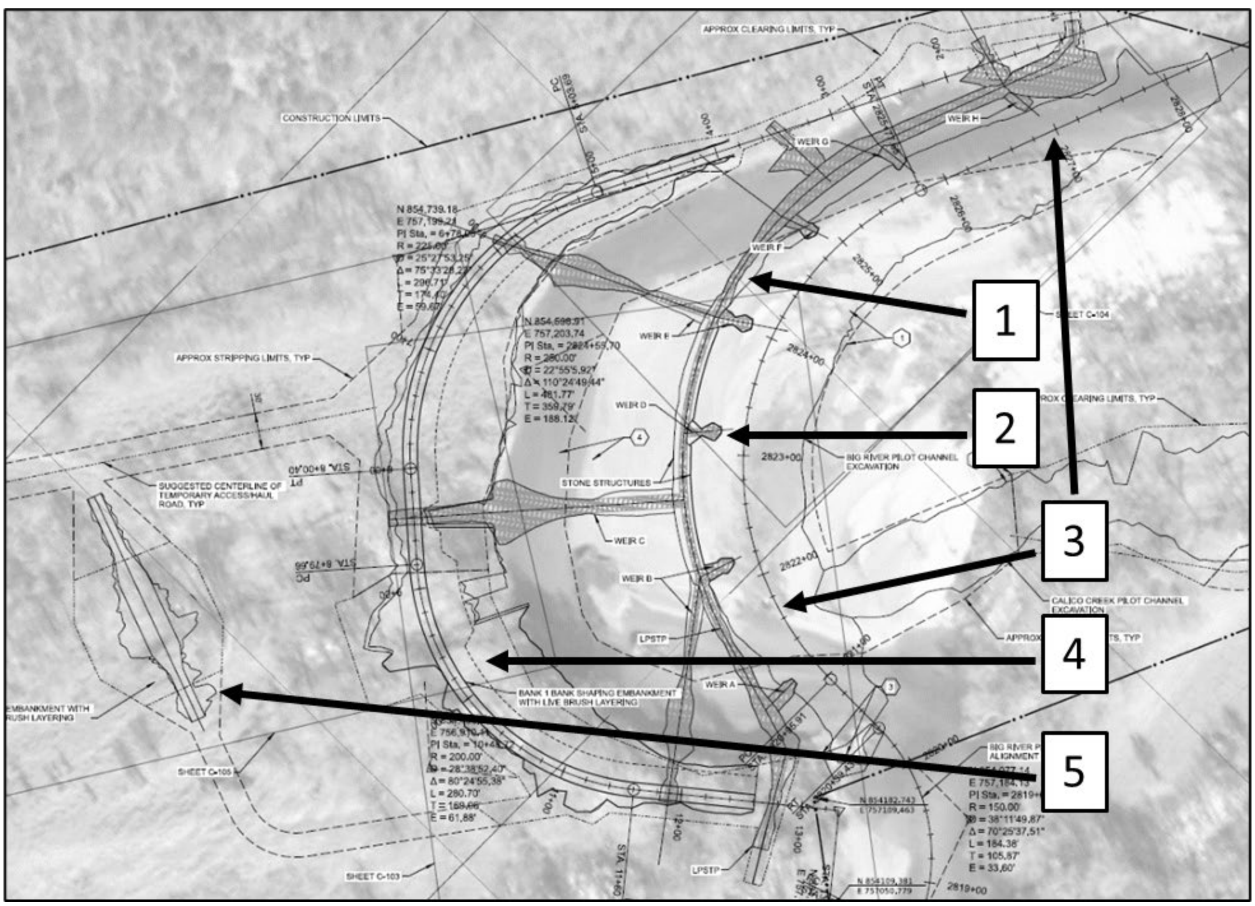

Figure 13. Bank 1 measures conceptual design plan view; flow from top right

Bank 2 Measures

This bank was experiencing a moderate rate of erosion prior to stabilization. Between 1996 and 2020, a small point bar grew from the RDB in the direction of the eroding bank. The planform of the river at this site was becoming more concerning as the angle of attack into the bankline was beginning to sharpen as erosion progressed (Figure 9). This warranted a protective measure to stop the erosion. The landowner at this bank was not interested in providing any additional land for conversion to permanent riparian zone, so only measures that minimized permanent impact to their floodplain land could be considered. Therefore, weirs were chosen (Figure 14) since they function exclusively below top of bank and require only minimal permanent land interest for keys, which could be buried if the landowner chooses.

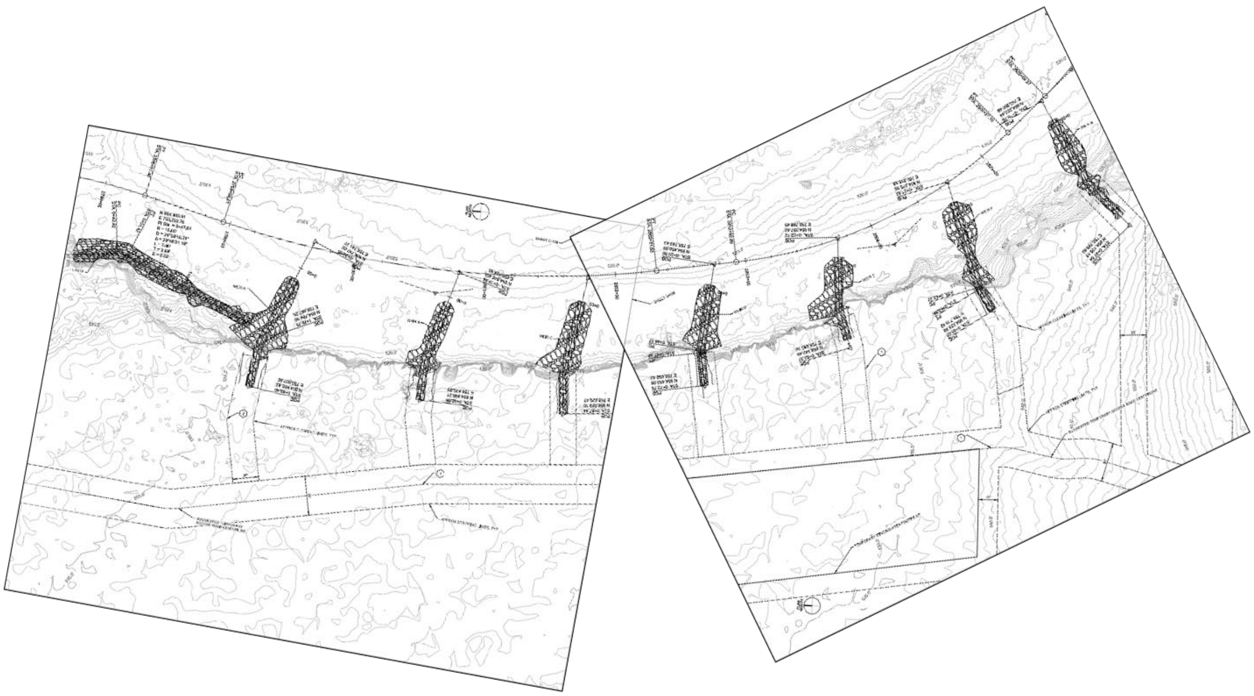

Figure 14. Bank 2 measures conceptual design plan view; flow from right

Bank 3 Measures

This bank was experiencing a high rate of erosion prior to stabilization. Between 1996 and 2020, a large point bar grew from the LDB in the direction of the eroding bank. The planform of the river at this site had become extreme and was infringing on the only access point to the entire floodplain from the RDB. This portion of the site offered a great area to heavily rely on biotechnical stabilization techniques.

The selected measures at bank 3 (Figure 15) include:

1. Toe wood protection, comprised of short trees with their rootwads sticking out into the channel at approximately baseflow elevation, and their trunks buried underneath fill consisting of stone, woody debris, and soil. This measure creates a new, designated bankline that is offset from the existing bankline.

2. A floodplain bench, the result of establishing a new bankline with toe wood and filling the area between the toe wood and the existing bankline. This will be filled primarily with material from the excavation of the pilot channel. The floodplain bench will be capped with a 6-inch soil layer and then vegetated with hydroseed and topped with Temporary Erosion Control Fabric (TECF), then live stakes will be driven through the TECF in some areas.
3. Pilot Channel excavation through the existing point bar, on an alignment that provided the Big River with a smooth preferential path to take during its transition from existing condition to constructed condition. This pilot channel was also intended to improve the ease of construction of the other measures at this bank by reducing the "in the wet" work that the contractor would need to do.
4. A buried valley grade control constructed using stone within the floodplain upstream of bank 3 between the river and the bluff. This measure was included to provide additional resilience of the overall site, both to flanking at bank 3 and to a floodplain cutoff or downcutting between banks 1 and 3.

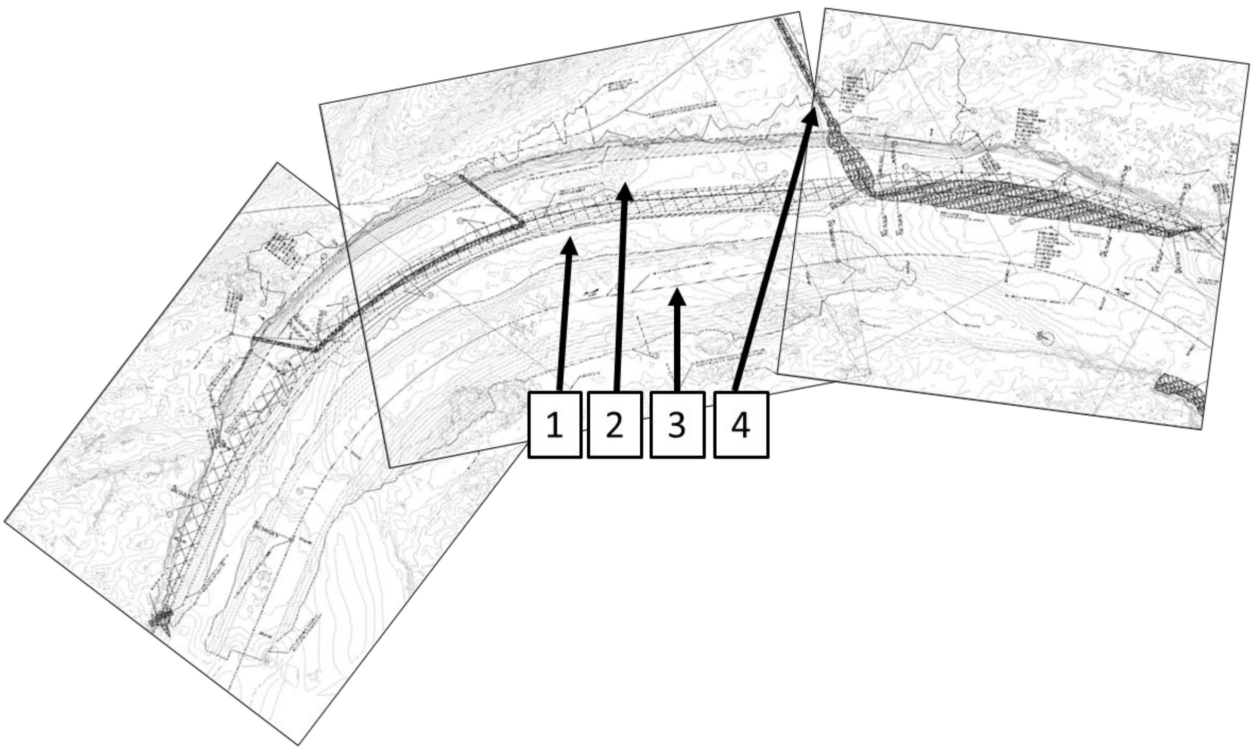

Figure 15. Bank 3 measures conceptual design plan view; flow from right

Design

Conceptualized measures provided a starting point for the design team to begin iterating through the design process. For each bank an idealized future channel planform was sketched in Google Earth. Then measures at each bank were put into configurations that would sustain that idealized channel. The overall site design was informed by a 2D hydrodynamic model, which provided inputs into other design guides and tools for placement and sizing of bank stabilization features.

Hydrodynamic River Modeling

The dynamic nature of Calico Creek confluence at bank 1 and the overall scope of the project warranted a detailed 2D hydrodynamic model to compare existing and design conditions. A fixed-bed, 2D hydraulic model was created using HEC-RAS 5.0.7. The existing conditions model provided baseline ranges of velocities and water surface elevations for various flows of interest. Then the model terrain was adjusted to a proposed design condition and modeled to refine the design of the selected measures. The proposed condition is the result of hydraulic design, iterative terrain changes, geometry changes, and modeling insights. The primary interests of this model are as follows:

- Water surface elevation throughout the project area at baseflow, bankfull, the 4% AEP (25-year), and the 1% AEP (100-year) events for both existing and proposed conditions.
- Velocity at features throughout the project area at bankfull, the 4% AEP (25-year), and the 1% AEP (100-year) events for the proposed condition.
- General changes to site flow resulting from the proposed condition.

The model extends a total of 4.2 miles along the Big River, plus 1.7 miles of Calico Creek, which converges with the Big River just upstream of Bank 1. The first boundary is upstream at the Big River gage at Richwoods, MO (USGS 07018100), which is located at RM 53.9. This gage provides stage and discharge data. For this model, this boundary was populated with discharge inputs. The second boundary is also upstream at the Highway H bridge on Calico Creek in Fletcher, MO, which is an un-gaged location about 1.7 miles upstream of the confluence with Big River. The inundation from Big River during a 100-year flood extend about 1.1 miles upstream into Calico Creek from the confluence with Big River. The third boundary is downstream on the Big River at RM 50.7. For this model, this boundary was set to a normal depth with a friction slope of 0.00025

The terrain development process is as follows (Figure 16):

A. 2011 LiDAR – from Missouri Spatial Data Information Service (MSDIS) – used as base layer
B. 2019 LiDAR – from USACE's Cold Regions Research and Engineering Laboratory (CRREL) – modifies base layer (A), where present
C. 2019 Interpolated Channel – from model-extent single-beam surveys – modifies B
D. 2019 High-Res Channel – from localized multi-beam surveys – modifies B and/or C (only where multi-beam surveys are present)
E. Visually Smoothed Existing Channel – gently modifies obvious vertical discontinuities between C and D and provides for a logical thalweg orientation and elevation based on visual observations from clearwater aerial imagery and multiple field visits
F. Proposed Condition – modifies E by burning in the proposed terrain(s)

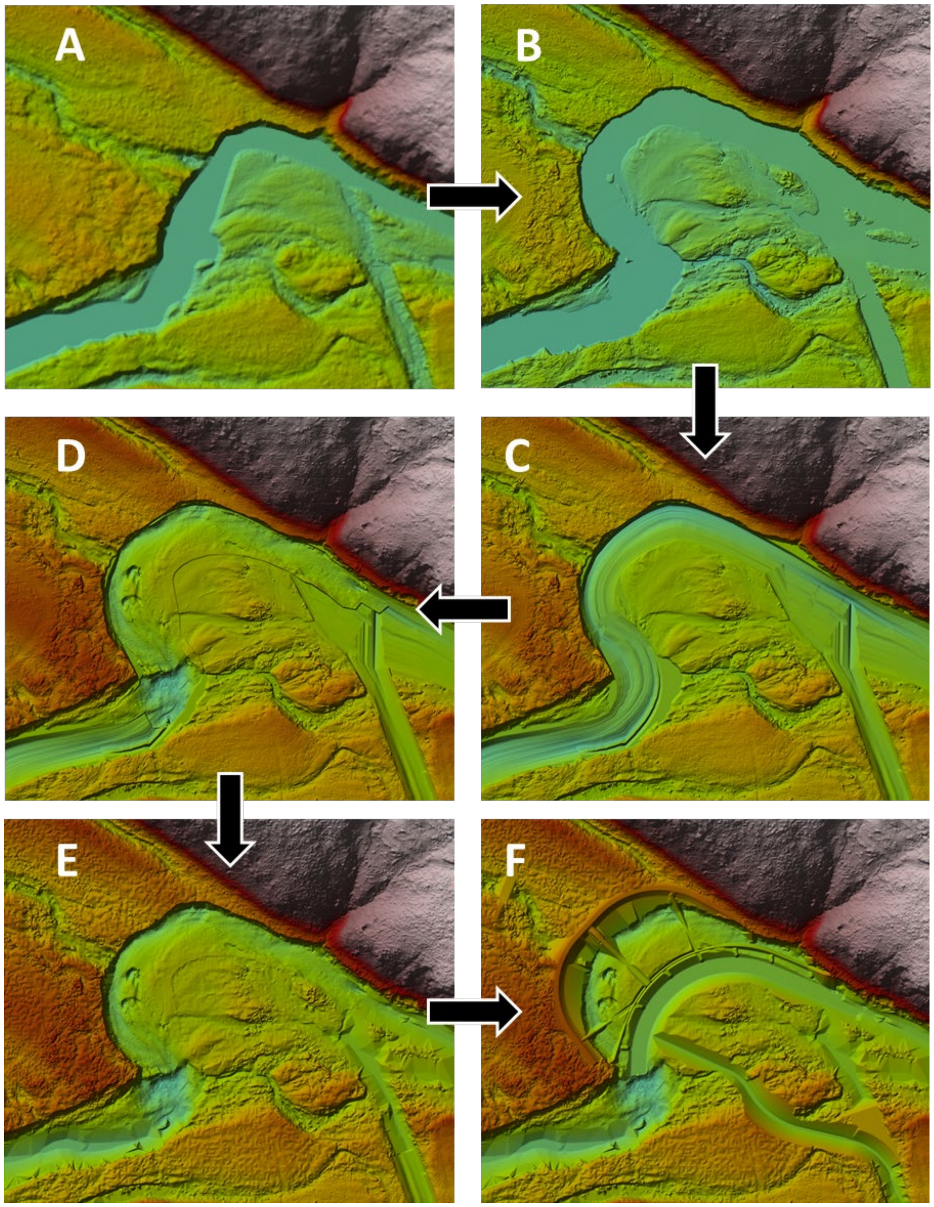

Figure 16. Sample model terrain at bank 1

The model mesh was constructed using 60-ft grids, with breaklines along major topographic features such as banklines and ridges, and along features in the proposed condition such as weirs, LPSTP, and berms. One large refinement area spans the entire project area using a 12-ft grid. Breakline cells were sufficiently small to capture structure detail in the proposed condition, typically about 3-ft. The geometry was developed and improved through an iterative process.

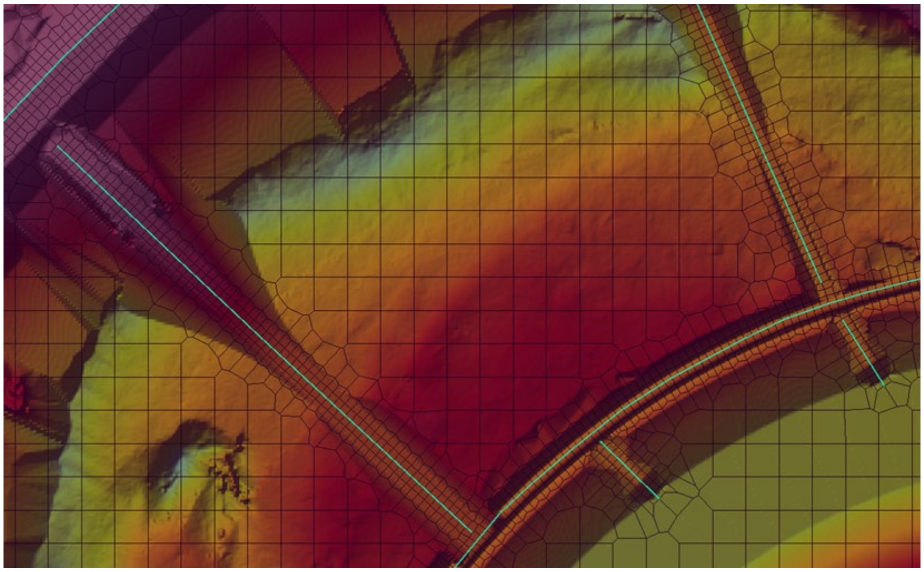

Figure 17. Sample mesh at bank 1

Land cover was hand-drawn due to the small extent and fine details required for this project.

Five flows were modeled in this study:

1. Baseflow – considered to be ~1,000 cfs at Richwoods gage (99.9% AEP)
2. Bankfull – considered to be ~9,000 cfs at Richwoods gage (~75% AEP)
3. 25-Year – considered to be ~41,700 cfs at Richwoods gage (4% AEP)
4. 100-Year – considered to be ~54,000 cfs at Richwoods gage (1% AEP)
5. Calico Creek – boundary is not gaged; used USGS StreamStats to calculate an approximate 100-year discharge of 6,430 cfs and tested various combinations of flows on Big River and Calico that maximized loading at bank 1.

Various loading conditions were identified at each bank – usually peak velocity, which was calculated to be about 8 feet per second.

Scour Estimation and Stone Sizing

For each bank, scour was calculated using a suite of scour equations, referenced by the U.S. Bureau of Reclamation (USBR, June 2015) and compiled for easier application in the PBS&J Scour Spreadsheet (Kreymborg & Williams, 2008). This spreadsheet uses seven methods to compute general scour and four methods to compute bend scour. Many of the inputs for this model were derived from 2D model outputs. In application, this bank stabilization project computed all eleven scour methods and designed to the average scour, with consideration for the upper bounds. For example, calculated scour depths at bank 2 during bankfull flow ranged from two feet to twelve feet, with an average of six feet.

Stone was sized at each bank in compliance with EM 1110-2-1601 Hydraulic Design of Flood Control Channels (USACE, June 1994). A design velocity of 8 ft/s was selected at bank 1 using the 2D model. This velocity represents the highest velocity at any of the three banks, but stone was sized to protect against this velocity at all three banks to simplify construction and provide additional conservativity at banks 2 and 3 for a trivial increase in overall cost. R-400 was selected as the final stone size because it provides protection up to 8.8 feet per second in turbulent conditions using a thickness of 30 inches.

Bank 1 Design Process

Engineering judgement was central to the design of bank 1 (Figure 13). An idealized planform was developed in Google Earth, and then the LPSTP was laid out along that idealized line, along with regular tie-backs angled to direct flow downstream while mitigating the chance of flanking. The LPSTP was keyed into the banklines at either end.

LPSTP is typically designed to a height that is approximately equal to the height of the opposing point bar. The large, 150-foot offset of the LPSTP from the existing bankline and the collaborating agencies interest in capturing lead-contaminated sediment led the design team to reduce the height of the LPSTP to just three feet above estimated baseflow, which is about two to four feet below top of opposing bar. This was hypothesized to allow the zone between the LPSTP and the existing bankline to quickly fill with river sediment, while maintaining toe protection of the LPSTP. The filled section will quickly recruit vegetative growth and become a stable floodplain bench.

Bendway weirs were designed riverward of the LPSTP to provide bathymetric diversity and additional conservativity to the LPSTP since it was designed to lower height than is standard. Weirs were designed to a height of Weir design followed the process outlined in the Bank 2 Design Process section, below.

The existing bankline was bulldozed into a stable slope then hydroseeded and covered by TECF. Live stakes were planted along lines spanning from edge of LPSTP to top of sloped bank. The crest of the bankline was formed to a single elevation in order to spread overtopping flow uniformly along the sloped bank's crest. This required some portions of the existing bankline to be raised by a few feet, especially in the location of the former high flow channel (Figure 6).

The high flow channel plug was designed to an elevation that would slowly overtop from downstream backwater during a typical flood, as indicated by the 2D river model. This would result in a pooled condition between the crest of bank 1 and the high flow plug, thus providing an area to dissipate some energy from flows that overtop bank 1 into the remnant high flow channel. The high flow plug was also used for site access during construction. Upon site completion, the plug was planted with live brush layering. The plug provided some reassurance that the floodplain will not become a preferential flow path if the crest at bank 1 erodes.

Bank 2 Design Process

Design of bendway weirs generally followed the clear and concise guidance of the Federal Highway Administration's Hydraulic Engineering Circular (HEC) No. 23 (FHWA, Sept 2009). Still, there is significant need for site-specific engineering judgement. The main inputs required for this design were:

- radius of curvature of the bend,
- mean channel width through the bend,
- distance from bank to existing thalweg, and
- bank height.

Initially, spacing was estimated at between 75-150 feet based on visual evaluation of the bend in Google Earth, tracing a thalweg through an idealized bend and then fictionally forming it using weirs drawn on the map in planform (Figure 18). Weirs were angled at between 5 and 15 degrees from perpendicular to flow, with the central weirs having the sharpest angle of attack.

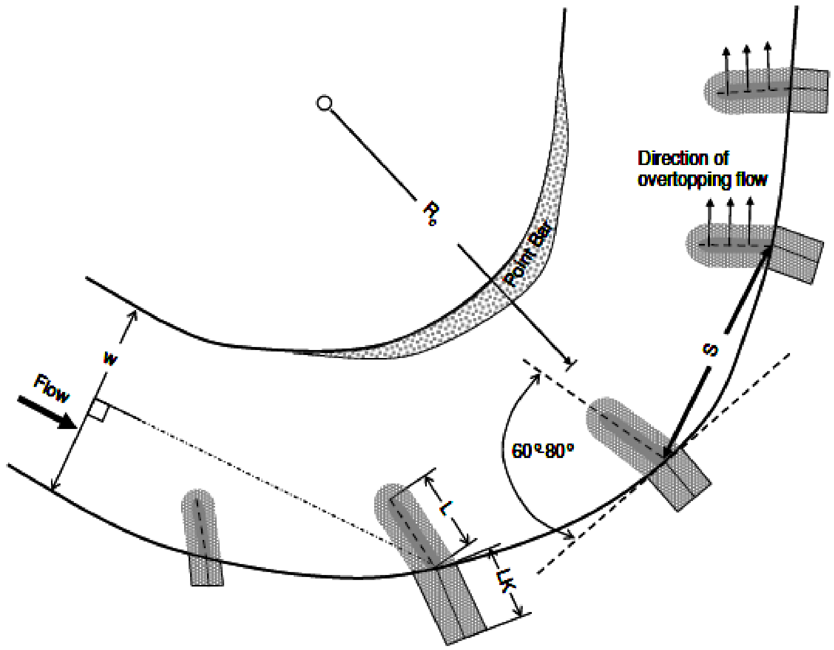

Figure 18. Bendway weir typical plan view. From HEC 23, Design Guideline 1 (FHWA, Sept 2009).

Then, using the four inputs from above, a reasonable weir length of 36 feet was selected. This length met project needs and was within the 22 to 75-foot range calculated as acceptable for the geometry at this bank.

All spacing calculations rely on a selected length. With the length selected, recommended spacings ranged from 36 to 237 feet. Finally, a conservative key length of 1.5 times the bank height was selected. Weir heights were designed to median flow.

Bank 3 Design Process

Design at bank 3 start with an idealized planform that was developed in Google Earth, which was considerate of the exit conditions created by the design at bank 2, which is immediately upstream of bank 3. This bank was identified as the most likely bank within this project to be able to accommodate a bioengineered bank stabilization solution due to landowner cooperation and the bank's position within the overall site. Forces at this bank are less complicated than at bank 1, which involves a highly dynamic tributary confluence. The idealized planform at this bank also took overall site cut/fill balance into account. The bankline was ultimately shifted slightly to result in a more balanced cut/fill while maintaining reasonable and logical hydraulics. The design of this bank allows flow to spread out onto the constructed "bankfull bench" at about 3,000 cfs, which is between baseflow and bankfull flow. By spreading flow out over a larger cross-sectional area, it reduces the rate at which shear forces in the main channel increase (Figure 19).

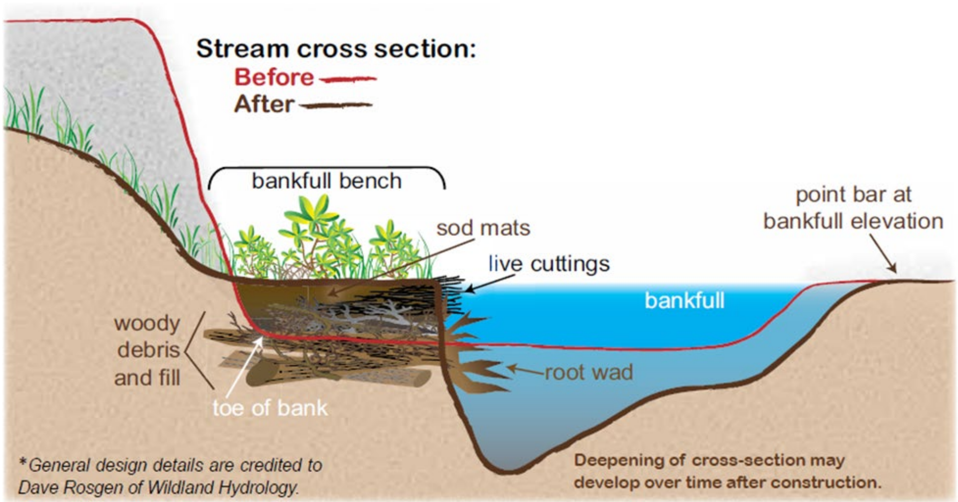

Figure 19. Conceptual sketch of a Toe Wood type structure (Minnesota Department of Natural Resources, December 2010).

The toe wood design concept and criteria were taken from lecture notes by Rosgen (Minnesota Department of Natural Resources, December 2010), and modified to site conditions and available materials. Locally harvested timbers were used for the toe wood, while the bankfull bench was constructed primarily using material cut from the pilot channel excavation. To improve stability, stone fill was used as ballast along the upstream half of the bankline, which receives directed flow from weirs at the exit of bank 2.

Specific design was completed using a spreadsheet developed by the U.S. Forest Service: "Computational Design Tool for Evaluating the Stability of Large Wood Structures" (Rafferty, 2016). This tool uses dozens of inputs including hydraulics parameters, soil and wood characteristics, and bank geometry. The result is an iterative optimization of toe wood design with particular attention to balancing forces from a free body diagram (Figure 20).

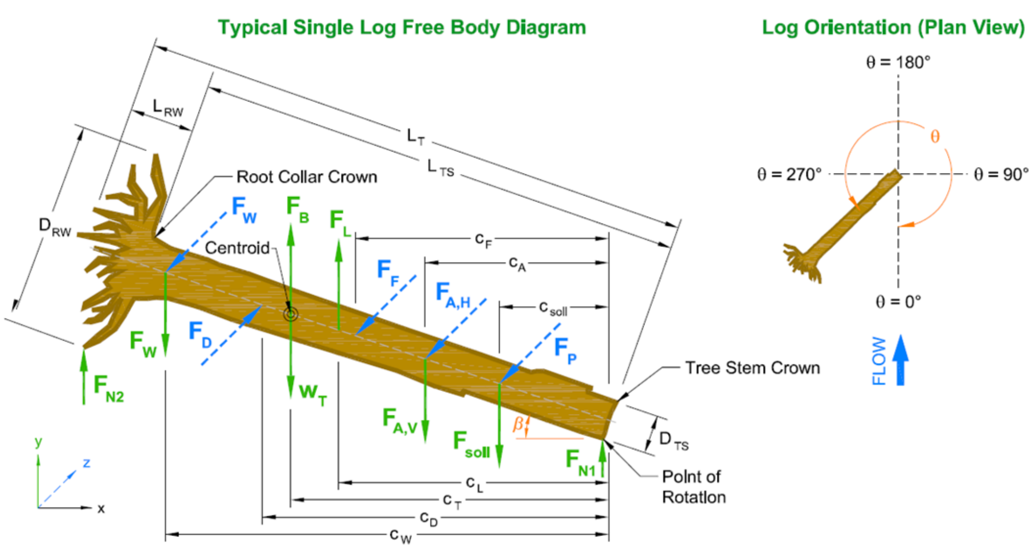

Figure 20. Large Woody Debris free body diagram (Rafferty, 2016).

The floodplain bench was capped with six inches of topsoil, hydroseeded, and then covered with TECF. Live stakes were planted along lines spanning from edge of river to edge of existing bank.

Constructed Condition

Representative photos of the constructed condition are provided in this section.

Figure 21. Bank 1 pre- and post-construction. Facing downstream.

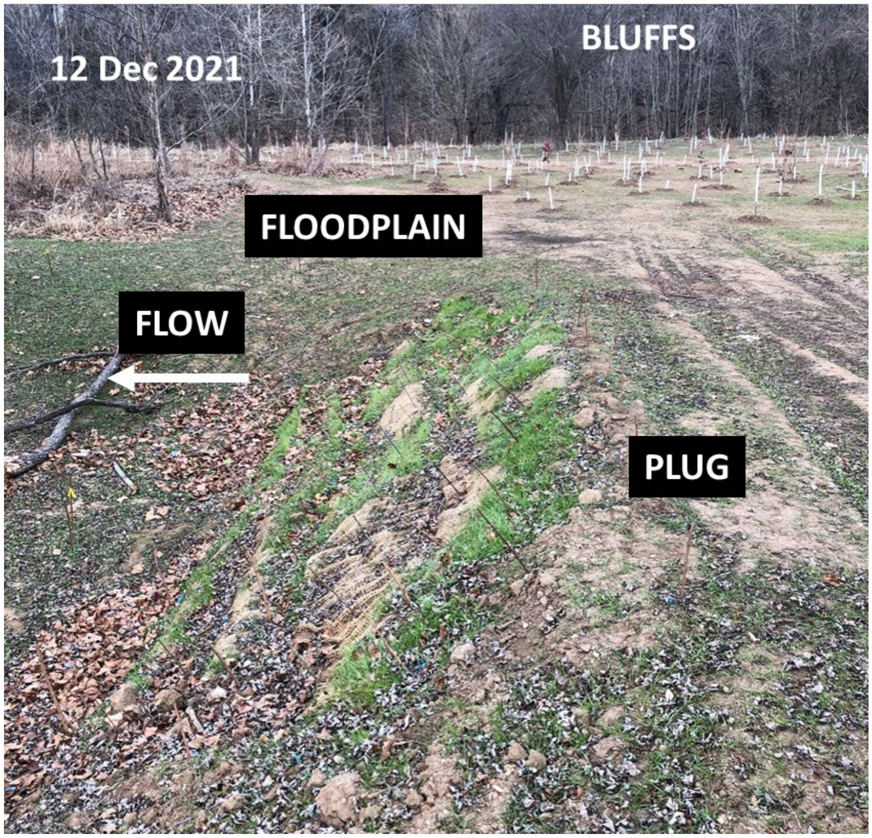

Figure 22. Floodplain and plug, facing RDB bluff; immediately downstream of bank 1, on floodplain.

Figure 23. Bank 2 pre- and post-construction. Facing upstream.

Bank 3 photos are shown in Figure 1.

Monitoring and Adaptive Management

Monitoring for this project was relatively straightforward. In general, the three banks should no longer erode, the vegetation on and around the stabilization areas should initially re-establish over the course of 1-3 years, and the river should maintain sediment transport through the reach without any significant changes to reach-scale deposition or scour. This section describes the initial plans for monitoring, actual observations after 6-9 months of project performance, and adaptive management plans.

All four of the areas on this site had unique challenges ranging from philosophical to geometric. As constructed, all three of the areas, plus the floodplain between them, have provided valuable lessons that both affirm and challenge some of the original design assumptions. After two 2-year floods, which occurred within a few months of the completion of the site, the project is performing as intended and within expectations. All three stabilized banks are performing as designed after multiple floods and are judged to have a very low risk of failure. Minor adaptive management actions have been identified at banks 1 and 3 that will help ensure that these banks continue to perform as designed well into the future.

Floodplain Monitoring Plan

In the floodplain between banks 1 and 3, the high-flow channel and check-berm should be checked for any new deposition or scour. Deposition is expected. Vegetation should remain intact and growing throughout the floodplain to ensure energy is dissipated through the reach, and floodplain soils are held in place.

Floodplain Monitoring Observations within 6-9 Months

Containerized trees were significantly damaged (Figure 24), with an estimated survival rate of <10%. This does not factor in natural mortality due to factors beyond damage due to flooding.

A portion of the floodplain was used as a haul road and staging area for stone, which was designated to be removed prior to contract closure. Individual riprap stones and large quantities of road gravel and geogrid foundation material are still present in the floodplain (Figure 24). The presence of discrete sections of gravel hundreds of feet from bank 1 (and likely deposition distance) suggest that much of this material may have been covered or buried instead of removed and has since been exposed by soil erosion due to overbank flooding. Pre-construction photos also indicate that some quantity of similar material was present in some locations of the floodplain prior to construction.

Figure 24. Floodplain monitoring - damage to containerized trees and presence of gravel and stone from construction

Floodplain Adaptive Management Plan

No major adaptive management work is planned in the floodplain because observations do not warrant it.

Bank 1 Monitoring Plan

At bank 1, all stone structures (LPSTP, tie-backs, and weirs) should be visually inspected for signs that they have changed due to localized erosion, such as scour holes and change in structure elevation or orientation. Excessive erosion may reduce the level of protection or create vulnerabilities in the structure. These vulnerabilities should be considered in the context of the long-term sustainability of the situation, especially with respect to the establishment of mature riparian vegetation. The sloped bank and its crest should be visually inspected for signs of scour.

Bank 1 Monitoring Observations within 6-9 Months

- The LPSTP and weirs are performing well and keeping most high energy flow contained within the channel.
- One area contained by the LPSTP and tie-backs was used to hold haul road material (4 inch minus gravel) after construction was complete. However, some portion of this material may have been plucked up and transported over the top of the bank and into the floodplain during floods exceeding ~2-year.

- Significant deposition of suspended sediment has occurred in most of the areas bounded by the LPSTP, tie-backs, and sloped bank.
- One section of upper bank has been eroded by high flows exceeding ~2-year floods (Figure 25). The eroded section is about 20-30 feet wide, and the surrounding 30-40 feet shows very minor scour as well. The total width of eroded and scoured area is about 60 feet. This area is a concern because it will continue to be eroded deeper and wider during future floods. In the process, this deepening and widening will result in more concentrated floodplain flow within the high flow channel between banks 1 and 3, which is not consistent with how the project was intended to function overall.

Figure 25. Bank 1 monitoring - scour at crest of shaped bank. Bluff behind photographer; floodplain to the right; Big River flowing from left.

The primary negative consequences of not applying a corrective action here are primarily short-term, and include:

  - The high flow channel in the floodplain will be loaded with headwater flows more frequently and with a higher intensity. The floodplain high flow channel was designed to backwater from bank 3 during most floods prior to headwater flows crossing the floodplain from bank 1 to 3. Especially during the first few growing seasons, the floodplain plug may not have enough mature vegetation to resist such intense and frequent flows.
  - The floodplain will receive more frequent, high intensity flows (low depth, high velocity) that could cause damage particularly to recently planted trees. This is a concern primarily during the first few growing seasons as those trees attempt to establish strong roots to resist the river’s flow during larger floods.

Bank 1 Adaptive Management Plan

Adaptive management actions at this bank focus on restoring the scoured areas of the sloped bank back to the original designed geometry. The scoured backslope of the embankment will be regraded using existing embankment material and some borrow from the floodplain. The regraded areas will be hydroseeded and covered with TECF. Option items include additional live staking and/or trench packing with live stakes on the backslope of bank 1. These options could be executed if budget allows.

Bank 2 Monitoring Plan

At bank 2, all weirs should be visually inspected for signs that they have changed due to localized erosion, such as scour holes and change in structure elevation or orientation. Excessive erosion may change the level of protection or change the exit angle of the structure(s). It is common for the bankline between weirs to erode some since it is still subject to secondary currents from the flow that is redirected by the weirs. Over the course of a few years, the bankline should adjust slightly until it is no longer impacted by these secondary flows.

Bank 2 Monitoring Observations within 6-9 Months

- There are no present concerns about the functionality or performance of this portion of the site. There is no obvious evidence of the typical bank scalloping that tends to occur between structures at many weir and/or barb installations. The weirs at this bank are directing flow as designed. They have caused a moderate portion of the opposing gravel bar to be eroded away as the river re-establishes a new thalweg.
- The LPSTP along the left bank downstream of the final weir is also holding well and appears to be preventing excessive erosion along that bankline. Currently, there is space between the crest of the LPSTP and the top of bank. Over time, that LPSTP will likely fill with soil from the bank that it is protecting, to form a smooth slope from top of bank to top of LPSTP. That slope will then vegetate and lock the sloped soil in place. This is considered the final condition, but it may take quite some time (many years) to fully establish.

Bank 2 Adaptive management Plan

No adaptive management is warranted at this bank.

Bank 3 Monitoring Plan

Bank 3 has unique monitoring requirements. Toe wood condition should be monitored over time to identify if it is deteriorating at an acceptable rate. Deterioration is strongly affected by timber placement elevation due to the damaging effects of repeated wetting and drying by the river. The floodplain bench should be monitored for scour and deposition. Deposition is preferential, while scour could be concerning if it continues to grow, as it could impact the engineering loading conditions of the toe wood if overlying material is no longer present. Vegetation should also be monitored to ensure it is growing well.

Bank 3 Monitoring Observations within 6-9 Months

- This bank is performing well overall (Figure 26). The riprap on the entry portion is holding well and there is fresh deposition on top of the riprap, covering it to the point of hiding it in some places. The floodplain bench also has fresh deposition and is showing strong vegetative growth. The upper bank is also holding well, with no signs of damage.

Figure 26. Bank 3 monitoring - performing well overall. Facing downstream.

- The toe wood appears to be holding well in most places. However, there is one section about 80 feet long that contains two sections of significant erosion about 60 feet long in total (Figure 27). This erosion extends from the top of the logs to the top of the low floodplain bench, or about 4-5 feet vertically and about 20-25 feet laterally into the low floodplain bench.

Figure 27. Bank 3 monitoring – scour above one section of toe wood. Facing downstream.

There are several potential reasons why this erosion may be occurring in this specific location. These reasons may include, but are not limited to:

- The location of this erosion is coincident with the downstream end point of where ballast was placed on toe wood. Roughly where the ballast ends, this section of erosion has begun, suggesting that the ballast was an essential (rather than optional) component of design for this type of bank protection or in this specific location in this bank.
- The location of this erosion is at the apex of the bend, about 2/3 the length of the overall bend, which is where the highest erosive forces manifest in a typical bend. In addition, this point is in line with flow vectors that are present at higher flows, suggesting that this specific portion of the bend may receive unique hydraulic forces that are beyond its design and/or capability to resist.
- The transition between the top of the logs and the bottom of the soil-wrapped bankline was not designed and/or constructed to provide maximum protection. The current, as-built configuration has a single "wrap" or lift of the soil using erosion control fabric, spanning from top of logs to top of low floodplain bench, or about 4-5 feet vertically. The most protective design/construction of this type of feature would prescribe wraps/lifts that are less than 18 inches tall, but ideally even less. A 12-inch wrap/lift may have been the most appropriate in this instance to ensure the soil is firmly contained until the bank vegetation takes hold.
- While the depth of the logs appears to be appropriate to prevent damaging toe scour, the overall constructed height of the logs may be insufficient to protect against scour immediately above the logs. This would allow erosive flow to erode laterally along

and above the top of the logs. Portions of this bank that used stone above the toe wood are performing well.

Bank 3 Adaptive Management Plan

The primary failure mechanism causing scour is hydraulic, with the river attacking the portion of the bench between the toe wood and the top of the constructed floodplain bench. Therefore, portions of the toe wood that were not initially ballasted with stone and are not yet scoured will be supplemented with stone revetment. Portions of the bank that have been scoured will be spanned with LPSTP along the originally constructed bankline. The portion of the bank between top of LPSTP and top of bench will be built up using soil lifts (live brush layering) wrapped by TECF.

Additional live stakes will be planted on the slope between the stone and the floodplain bench and in lines along the constructed floodplain bench.

Conclusions

The diverse measures implemented at this site are effectively containing and/or capturing lead-contaminated sediment from the Big River using weirs, LPSTP, toe wood, and plantings. All three stabilized banks are performing as designed after multiple floods and are judged to have a very low risk of failure. Minor damages during flooding that occurred shortly after construction highlight the importance of incorporating adaptive management into the project scope and cost from the beginning. This site will continue to be monitored, and these measures will be used at other sites along the river as appropriate.

References

FHWA. (Sept 2009). *Hydraulic Engineering Circular No. 23.*

HydroGeoLogic, Inc. (2018). *Hydraulic and Sediment Transport Modeling Report Remedial Investigation Southwest Jefferson County Mining Site Operable Unit 4 Jefferson County, Missouri.*

Kreymborg, L. R., & Williams, D. T. (2008). *The PBS&J Scour Spreadsheet: A Tool for Stream Restoration, Utility Crossings and Streambank Protection Projects.*

Minnesota Department of Natural Resources. (December 2010). *Stream Habitat Program, Toe Wood-Sod Mat Fact Sheet.*

Missouri Department of Natural Resources. (2008). *Total Maximum Daily Loads (TMDL) for Big River, Flat River Creek and Shaw Branch.*

Pavlowsky, R. T. (2017). Legacy sediment, lead, and zinc storage in channel and floodplain deposits of the Big River, Old Lead Belt Mining District, Missouri, USA. *Elsevier Geomorphology 299*.

Pavlowsky, R. T., Owen, M. R., & Martin, D. J. (2010). *Distribution, Geochemistry, and Storage of Mining Sediment in Channel and Floodplain Deposits of the Big River System in St. Francois, Washington, and Jefferson Counties, Missouri.* Springfield, MO: Ozarks Environmental and Water Resources Institute, Missouri State University.

Rafferty, M. (2016). *Computational Design Tool for Evaluating the Stability of Large Wood Structures. Technical Note TN-103.1.* Fort Collins, CO: U.S. Department of Agriculture, Forest Service, National Stream & Aquatic Ecology Center.

USACE. (June 1994). *Hydraulic Design of Flood Control Channels.*

USBR. (June 2015). *Bank Stabilization Design Guidelines.*