Grand River Ecosystem Restoration Study

Final Integrated Feasibility Report and Environmental Assessment

Appendix C: Sediment Analysis

October 2020

US Army Corps of Engineers ®
Kansas City District

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Appendix C1: Pershing State Park Sediment Model Calibration and Future Without Project Analysis

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1.0 Introduction

This appendix documents (1) the creation of a 1D sediment model for the Pershing State Park area in conjunction with the Grand River Basin Ecosystem Restoration Study and (2) the Future Without Project sediment projections using the model. The model starts near the USGS gage at Linneus, MO on Locust Creek, labeled Higgins Ditch in the model as explained later, and the USGS gage at Fountain Grove on the Grand River. The model ends at the USGS gage at Sumner on the Grand River. Figure 1 provides the model schematic with labeled flow and sediment boundary conditions.

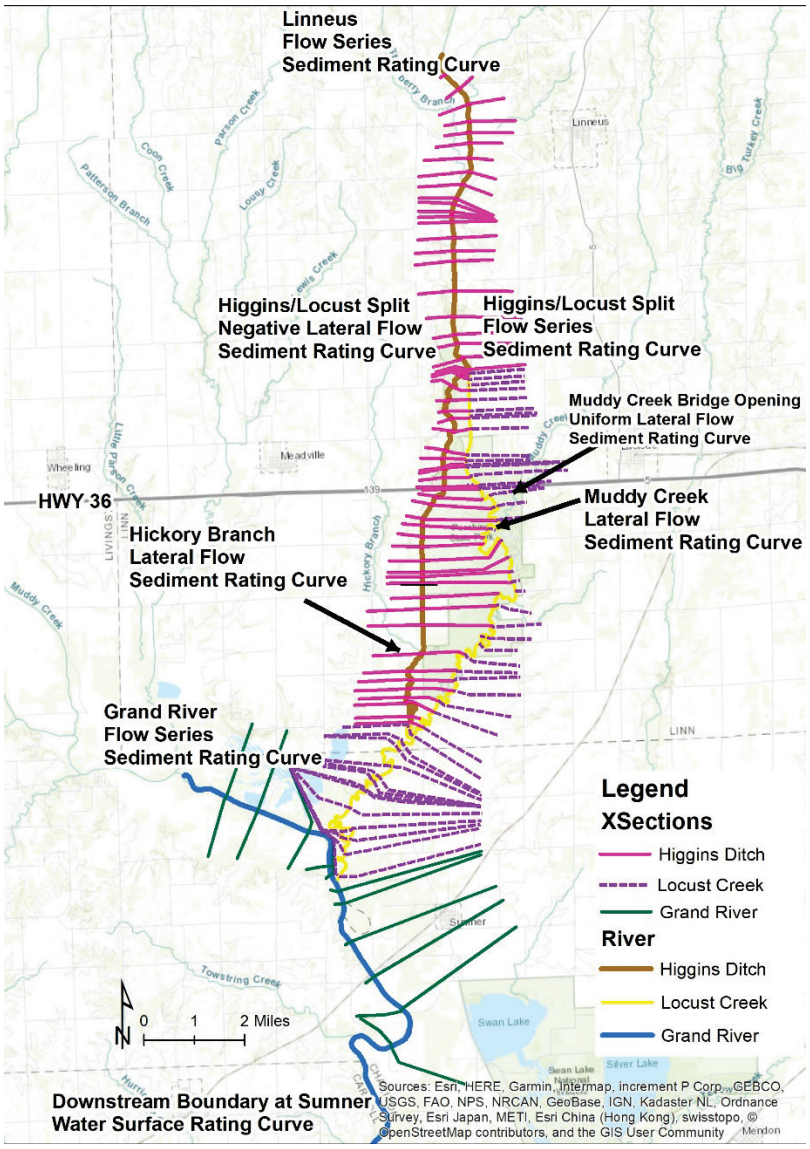

Figure 1. Model Schematic and Boundary Conditions

2.0 Model geometry

The model geometry was developed from channel cross sections surveyed from November 2016 to April 2017 merged with overbank LIDAR data collected December 2016. The geometry includes 118 cross sections.

Upstream of HWY 36, multiple channel avulsions pirate water from Locust Creek to Higgins Ditch (Figure 2). For model simplicity, all flow pirated upstream of HWY 36 was included in a single flow split at the location of the largest upstream pirate channel.

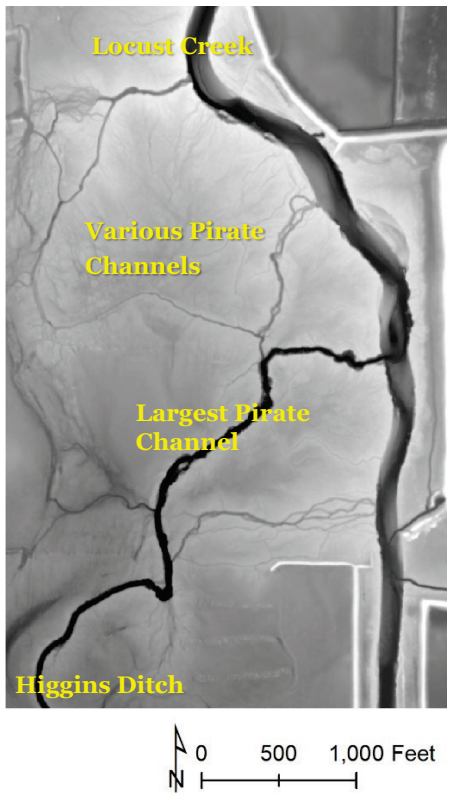

Figure 2. LIDAR indicating pirate channels that steal water from Locust Creek

Because Higgins Ditch now conveys more than 90% of the flow and the backwater on the upstream Locust Creek is more a function of Higgins Ditch than Locust Creek flows, the upstream reach is associated with and named "Higgins Ditch" rather than "Locust Creek" in the model. The flow split was included as a negative lateral flow series on this Higgins Ditch reach rather than a modeled flow split. The lateral flow split was computed from the 2D hydraulic model (see Appendix A2) as explained later in this document. For clarity, the stationing of the cross sections in this segment retain the river mileage of Locust Creek. 1D RAS sediment models can become unstable when floodplain depressions are deeper than the main channel. To increase stability, floodplain depressions were removed from Higgins Ditch cross-sections 6.81, 6.77, 6.74, 6.66, 6.60, 6.57, 6.28, and 6.10. The Higgins Ditch cross sections encompass the

floodplain between Higgins Ditch and Locust Creek. The Locust Creek cross sections truncate at the natural levee or top of the right descending bank (see Figure 3).

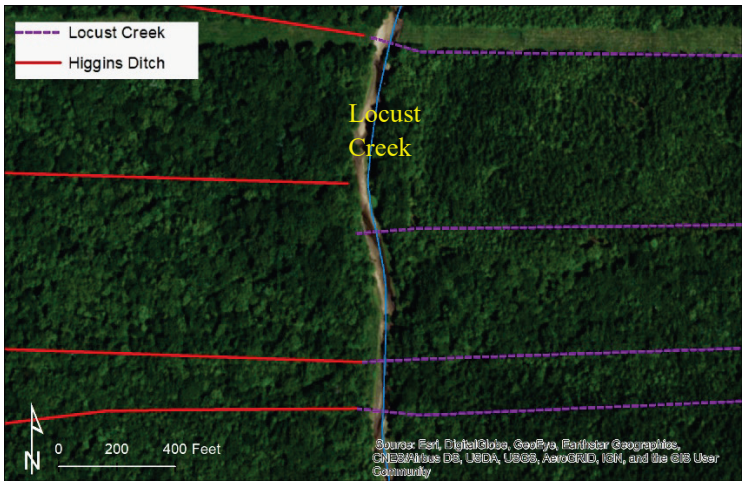

Figure 3. Transition from Locust Creek to Higgins Ditch Cross Sections on the Right Bank of Locust Creek

Channel roughness varies from 0.029 for the channelized upstream portion of Locust Creek (named Higgins Ditch in the model) to 0.065 in reaches of Locust Creek with the heaviest influence from woody debris. Floodplain roughness varies from 0.056 to 0.1.

A simplifying assumption was made that channel only adjusts vertically; the channel does not widen over time. Attempt was made to use the Bank Stability Toe Erosion Model (BSTEM) channel widening features in RAS (still labeled BETA in HEC-RAS 5.05), but these models proved to be unstable. In order to correct unrealistic floodplain deposition in the most upstream reaches of Higgins Ditch, the FWOP model widths were widened to more closely match the widths further downstream. This simplification helps account for the widening of the avulsion channel that will occur over time.

A number of grade controls are present along Higgins Ditch. These locations often resulted in unrealistic patterns of deposition or scour in the model reach. Model instabilities were addressed by setting the cross sections that reflect these grade controls to pass-through nodes (see Table 1). Over the 50-year simulation, leaving these cross sections unchanged creates a saw-tooth bed profile. Attempts to smooth out the saw-tooth pattern included smaller time steps, interpolated cross sections, and giving these nodes a minimum floor elevation rather than making them pass thru. These attempts did not improve the resulting profile and were not included in the final model.

Table 1: Cross sections set as pass-thru nodes

River	Reach	RS
Higgins Ditch	Higgins Ditch	6.99
Higgins Ditch	Higgins Ditch	6.52
Higgins Ditch	Higgins Ditch	6.18

Higgins Ditch	Higgins Ditch	6.14
Higgins Ditch	Higgins Ditch	5.76
Higgins Ditch	Higgins Ditch	5.72
Higgins Ditch	Higgins Ditch	3.41
Higgins Ditch	Higgins Ditch	2.25
Higgins Ditch	Higgins Ditch	1.76

3.0 Flow data

Flow data for the Calibration model was obtained from a combination of USGS 15-minute flow data and HEC-HMS model output (see Appendix A1), averaged into hourly flows. USGS gage data was obtained for stations 06899680 (Chillicothe), 06900800 (Fountain Grove), and 06901500 (Linneus) for February 2017 through October 2017. Data was missing from the Fountain Grove record from 9/25 through 10/3, a period of low-flow; these missing values were interpolated based on evidence of stable low-flow conditions during this period from the Chillicothe flow record. Flow data for Muddy Creek and Hickory Branch were extracted from the DSS file from the HEC-HMS model output.

The 2D model indicates that flow originating in Locust Creek spills into the floodplain in multiple locations upstream and downstream of the main pirate channel. During moderate and higher flows, all four bridge openings under Highway 36 convey flow (see Figure 4).

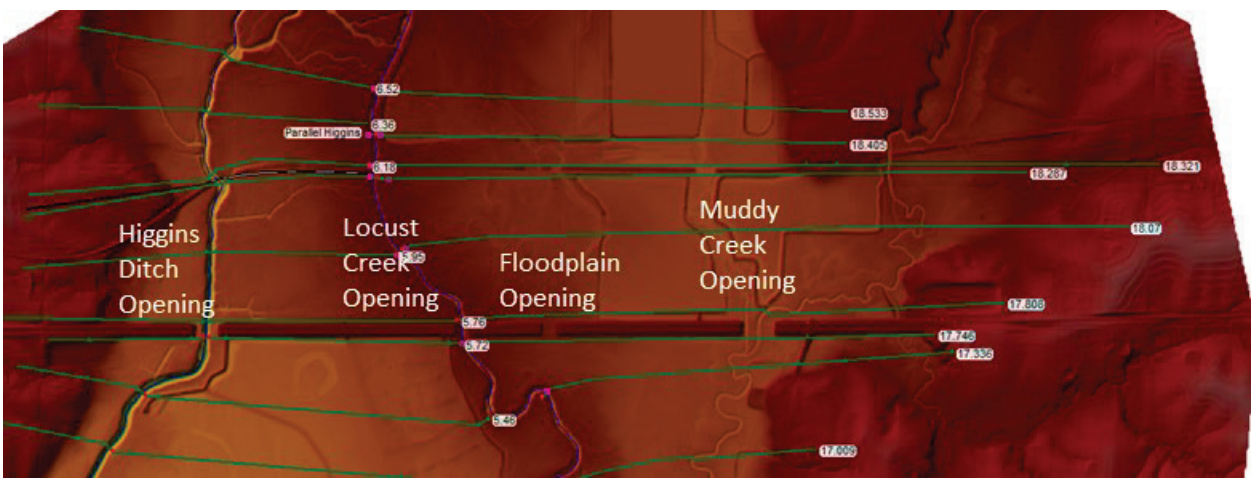

Figure 4. Bridge Openings on Highway 36

The flow in each segment of the 1D model was defined by the 2D model output at each of these bridge openings. The flow for the upstream end of the modeled Locust Creek (RS 20.145) was set to the flow at the Locust Creek Opening. The flow at the Muddy Creek Opening and Floodplain Opening were included as a uniform lateral inflow from RS 17.746 to RS 16.384. A negative lateral inflow was included on Higgins Ditch, such that the remaining Higgins Ditch flow matches the 2D flow at the Higgins Ditch opening. Table 2 provides the flow split as a function of the flow at Linneus. The flow from Muddy Creek itself was included as a separate lateral inflow at RS 15.857, which is not reflected in Table 2.

Table 2. Flow Split Under Highway 36

LC1 Existing Conditions - Flows (cfs)			
Linneus	Higgins Ditch Opening	Locust Creek Opening	Muddy Creek Opening
50	49.5	0.5	0
200	185	15	0
1,000	881	119	0
2,500	2,163	306	20
5,500	4,700	509	288
7,300	6,268	556	419
9,150	7,400	580	460
14,500	13,170	645	669
18,200	16,745	683	740
22,800	21,170	728	840
26,200	24,397	773	942
29,500	27,532	815	1,025

The Future Without Project (FWOP) plans were run with daily flows from 01 Oct 1966 to 30 Sep 2016 derived from daily flows developed using HEC-HMS as explained in Appendix A1. The period of record included some extreme low-flow (< 1 cfs) periods for Locust Creek at Linneus; to maintain model stability, the minimum flow at Linneus was adjusted to 2 cfs. The HEC-RAS software limits the number of rows that can be entered through the quasi-unsteady flow editor to 40,000. This precludes using hourly flows for a 50 year simulation. After some iteration, a daily flow increment was selected. The highest daily flow on Locust Creek at Linneus during this period was 29,794 cfs (peak hourly 30,306 cfs), which is just higher than the flow with a 1% annual exceedance probability (29,500 cfs). As during the calibration period, minimum flows were set to 2 cfs for model stability. Table 3 summarizes the drainage area for each of the external flow locations.

Table 3. Summary of Flow Inputs

Stream	Drainage Area (sq mi)
Locust Creek (Higgins Ditch)	554
Grand River at Fountain Grove	6,240
Muddy Creek (Locust Cr trib)	23
Hickory Br (Locust Cr trib)	8
Grand River at Sumner	6,900

The computational increment varies with flow in Locust Creek and the Grand River, as given in Table 4. The computational increment for the remaining flow boundary conditions was set to the minimum of the computational increments for Linneus and the Grand for that day.

Table 4. Computational Increment

Linneus		
Minimum Flow	Maximum Flow	CI
0	100	24
100	200	12
200	400	6
400	800	2
800	2000	1
2000	100000	0.5

Grand		
Minimum Flow	Maximum Flow	CI
0	1000	24
1000	2000	12
2000	3000	6
3000	6000	2
6000	200000	1

4.0 Hydraulic Calibration

The model water surface was compared against the measured water surface at the Linneus gage for given flow rates, as shown in Figure 5. (A comparison of water surfaces over time was not instructive, as the flows differ, particularly at hydrograph peaks. USGS provides an instantaneous water surface and flow in 15-min increments while the sediment model averages the 15-minute flows into daily increments and produces a water surface from the daily values.) Notwithstanding, calibration was able to provide reasonable agreement. No gages downstream from Linneus were available for calibration. (Sumner was used for the downstream boundary condition.)

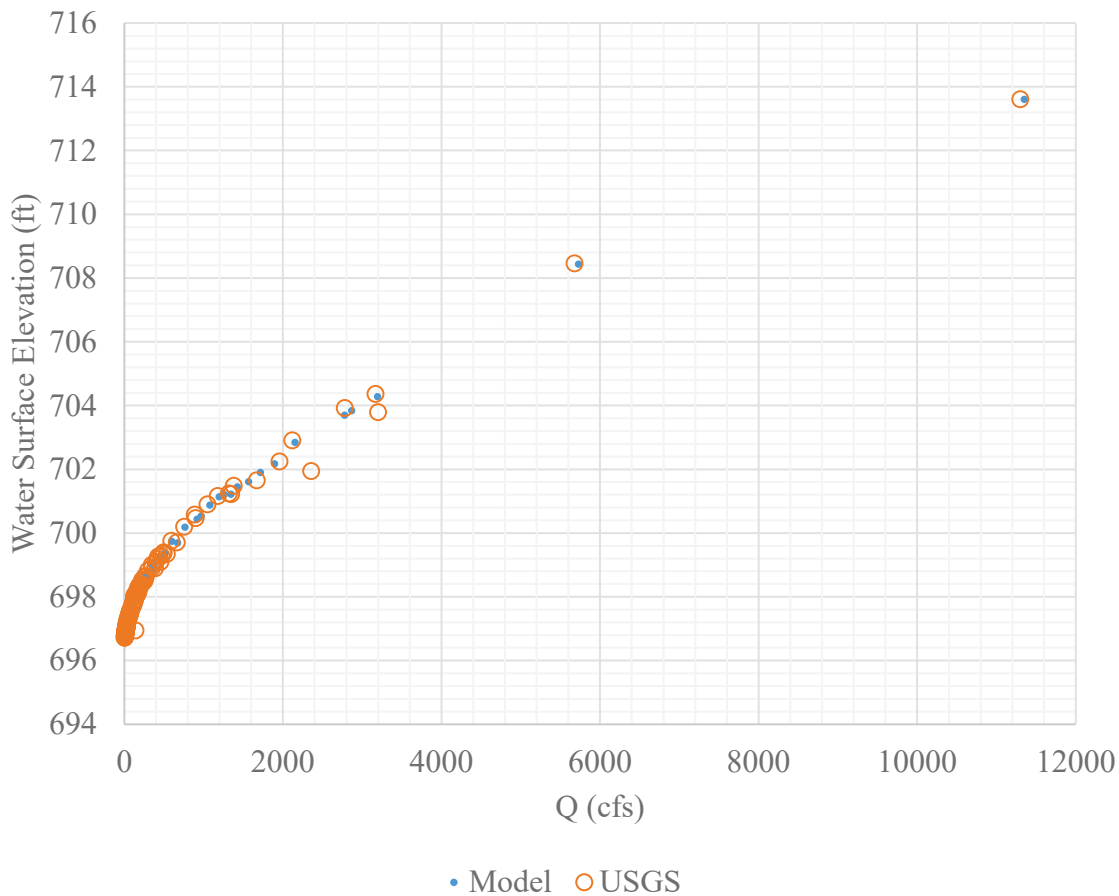

Figure 5. Model vs. USGS measured water surfaces for Locust Creek at Linneus, MO (Higgins Ditch RS 26.456)

5.0 Sediment data

Bed gradation data

Measured bed sediment samples indicate that the bed of both Higgins Ditch and Locust Creek is predominantly medium and coarse sand (see Figure 6). Model cross-section bed gradations were specified at ten locations based on measured bed samples collected on Locust Creek and Higgins Ditch. Most bed samples were co-located with surveyed cross-sections; sample gradations were assigned to the nearest model cross section, and bed gradations were interpolated across the remaining cross sections. Some of the downstream cross sections in Higgins Ditch contained larger percentages of fines. During calibration, it was found that the high fines content lead to unrealistic bed changes and model instabilities. Attempts to incorporate RAS algorithms for cohesive material proved unsuccessful. To correct, gradations with high fines content were substituted with measured gradations further upstream that were predominantly sands.

Figure 6. Locust Creek near Highway 36 (20 December 2017). Sandy bed is evident.

No measured bed gradations were collected on the Grand River. By observation, the bed of the Grand River is composed of sand. The size gradation for the Grand River bed was set to roughly equal amounts of fine, medium, coarse, and very coarse sand (with trace amounts of additional sizes). Sediment output from the Grand River itself was ultimately not used in decision making for this study.

Sediment load boundary conditions

The sediment boundary conditions of the calibration model were specified using flow-load rating curves based on measured sediment data during the calibration period. The flow-load rating curve for the upstream of Locust Creek (Higgins Ditch in the model) was based on suspended sediment measurements at the USGS gage# 6901500 (Locust Creek near Linneus, MO) from 2011 to 2017 for flows > 100 cfs. In conjunction with this study, USGS collected three bedload measurements on Locust Creek near the Linneus gage. The bedload measurements equated to less than 1% of the total load, an unreasonably small number. Given the uncertainties and inaccuracies in physical measurement of bedload on sand-bed streams, the assumed bedload percentage was increased to 5%. A higher or lower percentage affects the upstream end of the model, but does not alter alternative selection.

It was found that the flow/load data could be approximated by two functions of the type Qs = aQ^b, one for flows < 2,000 cfs and one for flows ≥ 2,000 cfs. The "a" coefficients in these functions were then adjusted so that the total volume of sediment brought into the model over the calibration period (29 Mar 2017 – 30 Sep 2017) equals the sum of daily loads computed by USGS using continuous turbidity measurements plus an assumed 5% bedload. Three bedload measurements by USGS indicated Figure 7 provides the rating curve. Figure 8 compares the cumulative mass that enters the model to the sum of the USGS daily loads multiplied by 1.05 to account for bedload.

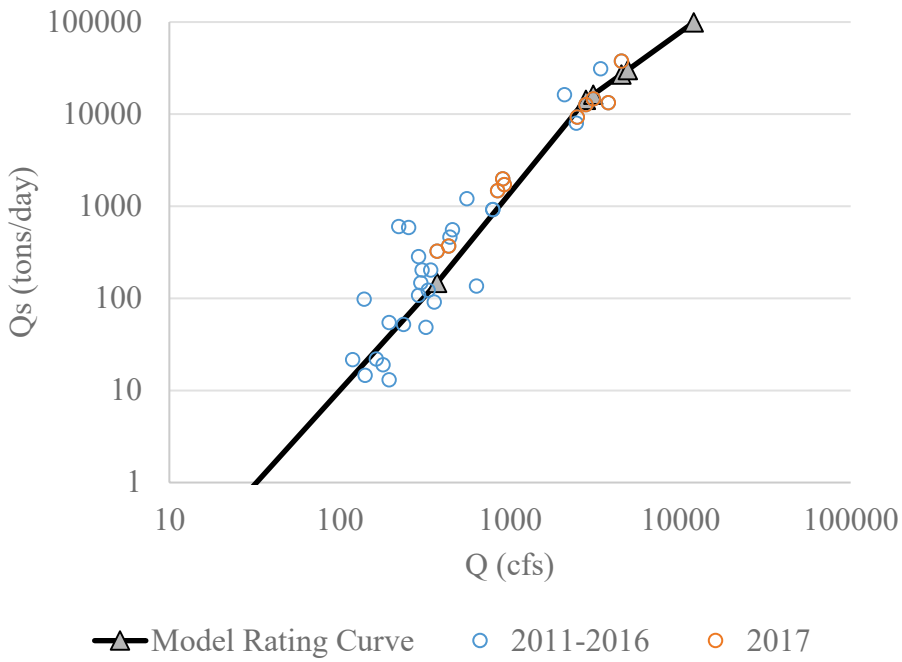

Figure 7. Model Rating Curve at Upstream End of Locust Creek (Higgins Ditch RS 26.456)

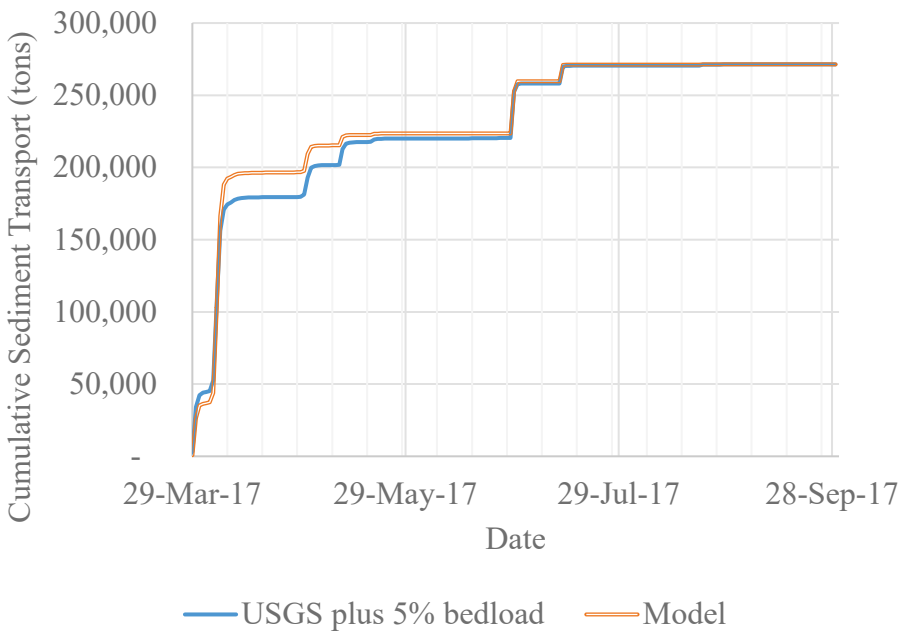

Figure 8. Cumulative Incoming Sediment Load at Upstream End of Locust Creek (Higgins Ditch RS 26.456)

The flow-load rating curve for the Grand River at Fountain Grove was based on 13 suspended sediment measurements at USGS Gage# 06899680 (Grand River at Chillecothe, MO) and USGS Gage# 06900800 (Grand River near Fountain Grove, MO). The size gradation for the rating curve was computed based on the size breakout for those 13 physical samples. The initial rating curve was then adjusted such that the total model output at the downstream end of the model matches the sum of daily loads computed by USGS using continuous turbidity measurements at USGS Gage# 6902000 (Grand River near Sumner, MO) plus an assumed 5% for bedload. Figure 9 provides the rating curve and Figure 10 illustrates how the cumulative sediment transport compares to the USGS data (with 5% bedload). A comparison of the total cumulative loads in Figures 8 and 10 indicates that the majority of the sediment passing through the downstream boundary of the model at the Sumner gage derives from upstream on the Grand, not from Locust Creek. This is as expected, given the 6,900 sq mi watershed that drains to the Grand vs. the 554 sq mi watershed that drains to Locust Creek.

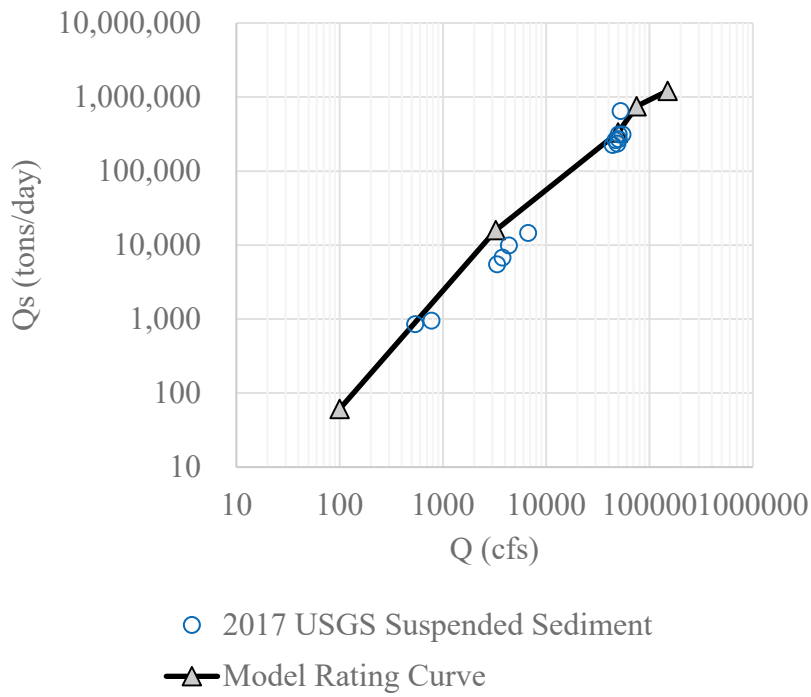

Figure 9. Calibrated Sediment Rating Curve for the Grand River near Fountain Grove (Model RS 40.40)

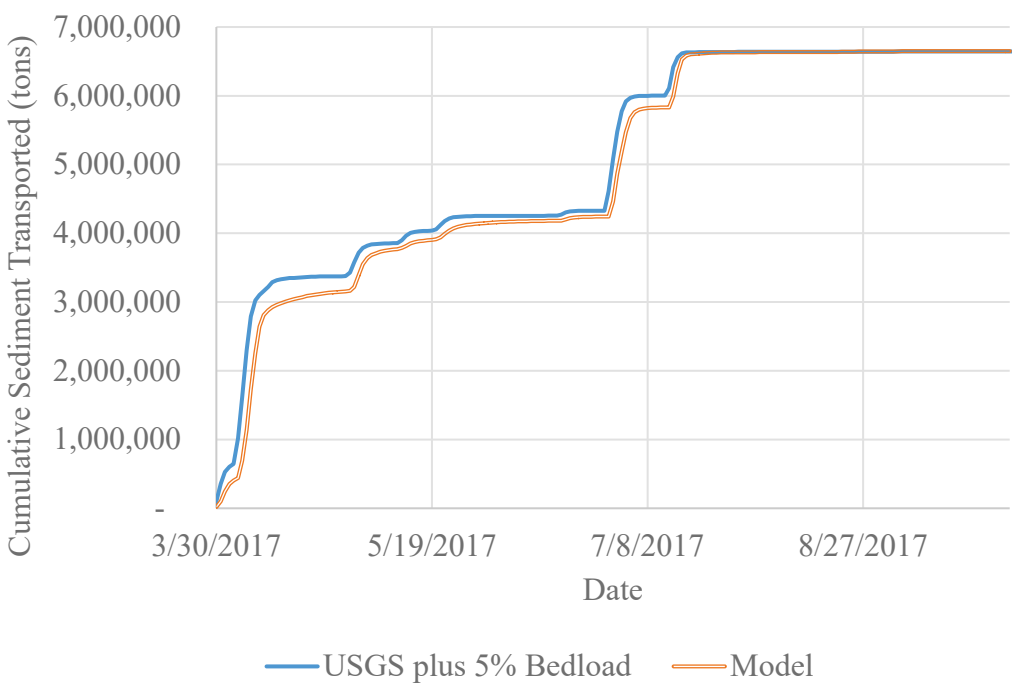

Figure 10. Cumulative Outgoing Sediment Load at Sumner (Grand River RS 33.36)

Two additional tributaries (Hickory Branch and Muddy Creek) are included in the model as lateral flows with associated flow/load rating curves. As no suspended sediment data was available for either tributary, data from Muddy Creek near Chula, MO (USGS Gage #06900640), a different (though similarly named) nearby river with a similarly-sized watershed was used instead. A correction (Duan 1983) of 1.58 was applied to the best-fit power curve to un-bias the results. Figure 11 provides the rating curve.

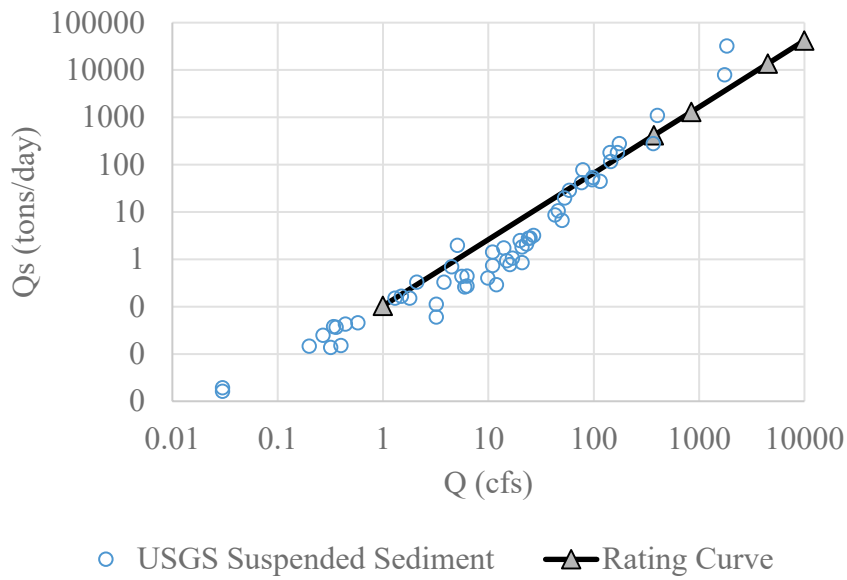

Figure 11. Sediment Rating Curve for Muddy Creek and Hickory Branch

No sediment load measurements were available at the Locust Creek-Higgins Ditch split. Instead, the load removed was assumed to be the same percentage as the flow removed.

Bed change or floodplain change over this time period was not available. Attempt was made to compare LIDAR collected during leaf-on conditions in 2008 with LIDAR collected in 2017. However, the 2008 survey was found to be unreliable and without any way to correct the data with known points. Therefore, other than the use of flow split information from the calibrated existing conditions 2D model, the model output downstream of Linneus gage was primarily validated for reasonableness against known erosion and deposition patterns, with emphasis on developing a tool to compare alternatives.

6.0 Sediment Model Parameters

The Laursen-Copeland transport function was selected for this model, primarily for its applicability for silt transport. Over the calibration period, the maximum velocity in the model is 6.9 ft/s, the max depth is 20.4 ft, and the median sediment size ranges from 0.02 to 10.8 mm. The data used to develop the Laursen-Copeland equation includes velocities up to 9.4 ft/s, 54 ft max depth, and sediment size ranging from 0.011 to 29 mm (USACE 2016). The Exner 5 (Thomas) sorting method and the Ruby Fall velocity method were used.

7.0 Model Instabilities

The perched channels proved to be highly unstable in the 1D sediment modeling during high flow events. The multiple grade control structures and low-water crossings set as pass-thru nodes exacerbated a see-saw bed profile on Higgin's Ditch. Multiple trials to improve stability did not prove successful, including much shorter timesteps, interpolated cross sections, increased floodplain n values to decrease conveyance, etc. Refinement to floodplain ineffective flow and levees improved stability, but was not able to eliminate instabilities during the highest flows. Notwithstanding, the overall trends for floodplain deposition appear reasonable and believable.

8.0 Sediment Budgeting Results

Table 5 lists the modeled tons of sediment entering the 6-month calibration period and the total during the FWOP. Muddy Creek and Hickory Branch contribute minor amounts of sediment compared to the upstream Locust Creek channel.

Table 5. Sediment Inputs

River	Drainage Area (mi^2)	6-month Calibration Period (tons)	FWOP Average Annual (tons)	FWOP Yield / mi^2 ($tons/mi^2$)
Grand River at Fountain Grove	6240	6,563,403	6,737,923	1080
Locust Creek at Linneus	554	271,368	1,025,594	1851
Muddy Creek	23	7,968	21,818	949
Hickory Branch	8	1,440	5,116	640

It was found that the model put too much sand in the floodplain, which resulted in too much degradation in the channel. This is a limitation of HEC-RAS 5.05; deposition occurs via the "veneer method" which overlays an equal depth and equivalent size gradation of sediment on all wetted nodes without regards to it being in the floodplain vs. the channel. For more accurate floodplain deposition amounts, the total longitudinal cumulative volume change metric was used, rather than attempting to subtract out the bed change portion (which, because it was negative, would have further increased the computed floodplain deposition.)

9.0 FWOP Floodplain Deposition Results

Figures 12-14 provides the longitudinal cumulative volume change curves for floodplain deposition at Higgins Ditch, Locust Creek, and the Grand River at the end of the 50-year simulation.

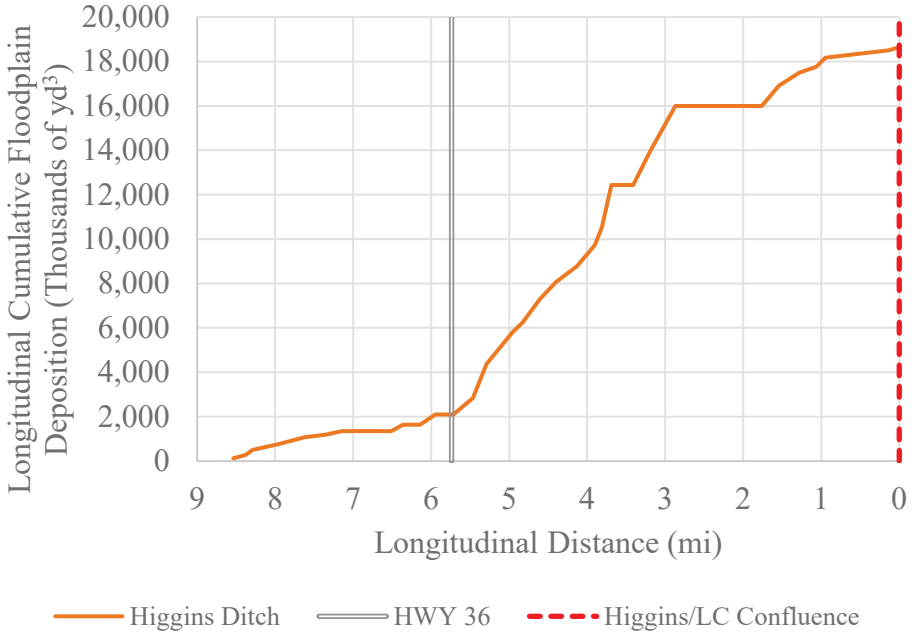

Figure 12. Longitudinal Cumulative Floodplain Deposition along Higgins Ditch

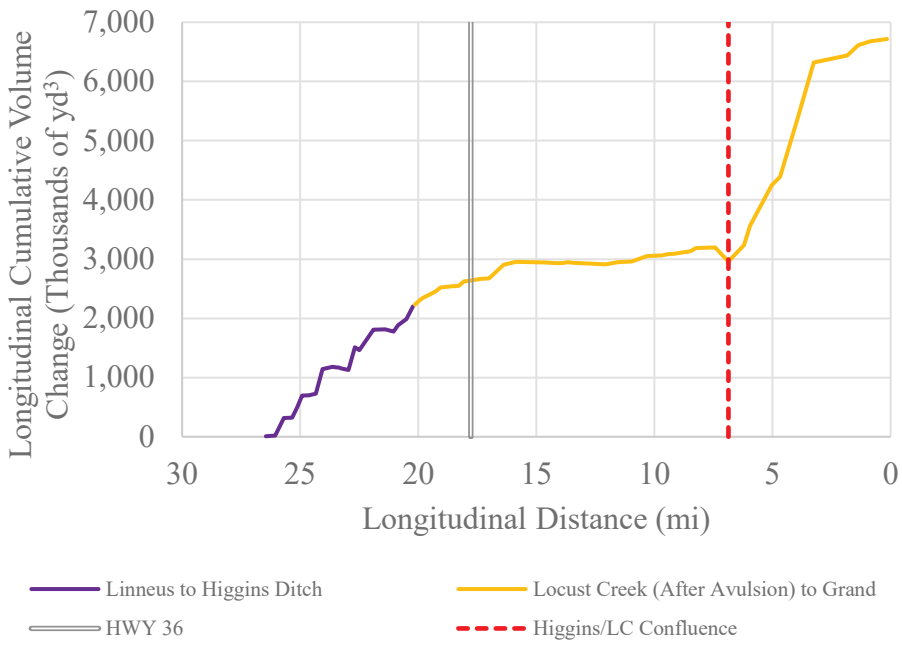

Figure 13. Longitudinal Cumulative Floodplain Deposition along Locust Creek

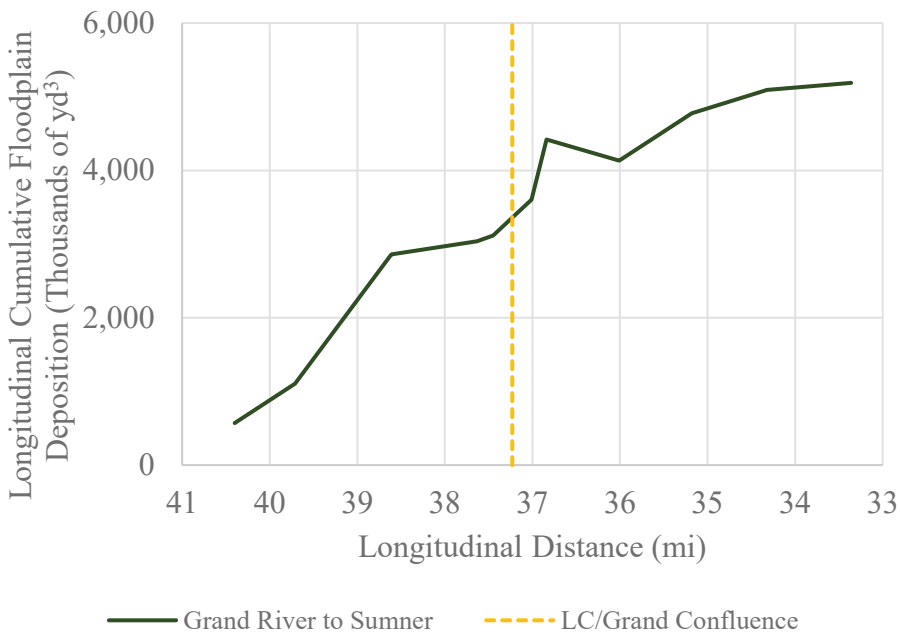

Figure 14. Longitudinal Cumulative Floodplain Deposition along the Grand River

The lateral distribution of the floodplain sediment deposition is required in order to compute the average deposition in each habitat area. Hydraulic output from the RAS 2D model was used to approximate the sediment distribution following these steps:

1. Three representative overbank hydrographs were run through the 2D hydraulic model, with a 10%, 20%, and 50% annual exceedance probability (i.e. a 10 year, 5-year, and 2-year flow, respectively). See Appendix A2. The rising and falling limb of the hydrograph was included, but not the long low-flow tail of the hydrograph.
2. The 2D model produced raster output for the duration of inundation of at least 0.1 ft and for the maximum depth.
3. A weighting factor was generated in GIS according to the following equation:

$$W = 0.2 * D_{10}t_{10} + 0.2 * D_5t_5 + 0.6 * D_2t_2$$

Where W = the weighting factor for an individual cell within a habitat area.

t = the duration of inundation for a given cell for the 10-year, 5-year, or 2-year hydrograph, days

D = the maximum depth of inundation for a given cell for the 10-year, 5-year, or 2-year hydrograph, feet

This weighting accounts for the relative frequency of each event. One event peaks at a 10-year (0.1 AEP), one at a 5-year (0.2 AEP), and 3 at a 2-year (0.5 AEP). Because the 10-year event also counts as having met or exceeded a 5-year event and a 2-year event and the 5-year event also counts as having met or exceeded the 2-year event, this

weighting correctly simulates 10 years in which there is one 10-year event, two 5-year events, and 5 two-year events.

This weighting produces reasonable lateral trends in that areas more frequently inundated will deposit more and that areas inundated to greater depths will deposit more. (See Figure 15.) However, this approach tends to fill small pirate channels and other minor conveyances that physically have sufficiently high shear stresses to avoid deposition.

4. Sum the weighting factors in each habitat area.
5. Use these summed weighting factors to laterally apportion sediment volume from the 1D sediment model in locations where the model cross sections span more than one habitat area. e.g. If a range of cross sections span habitat areas LC4 and LC5, then the volume of deposition applied to LC4 = $V_{total} \frac{\sum W_{LC4}}{\sum W_{LC4} + \sum W_{LC5}}$.
6. Divide each weighting factor value by the summed weighting factor for the habitat area to create a raster of normalized weighting factors, i.e. weighting factors that sum to 1 in each habitat area. (See Figure 15.)
7. Multiply the normalized weighting factor for each cell by the total deposition volume for the habitat area to create a per-cell deposition volume.
8. Divide by the cell area to create a per-cell deposition depth.

The result of this analysis is that the upstream-to-downstream distribution of sediment is a function of the 1D sediment model. The lateral distribution of sediment is a function of the 2D hydraulic model. These deposition depths are reasonable estimates for informing future habitat values in the Future Without Project condition.

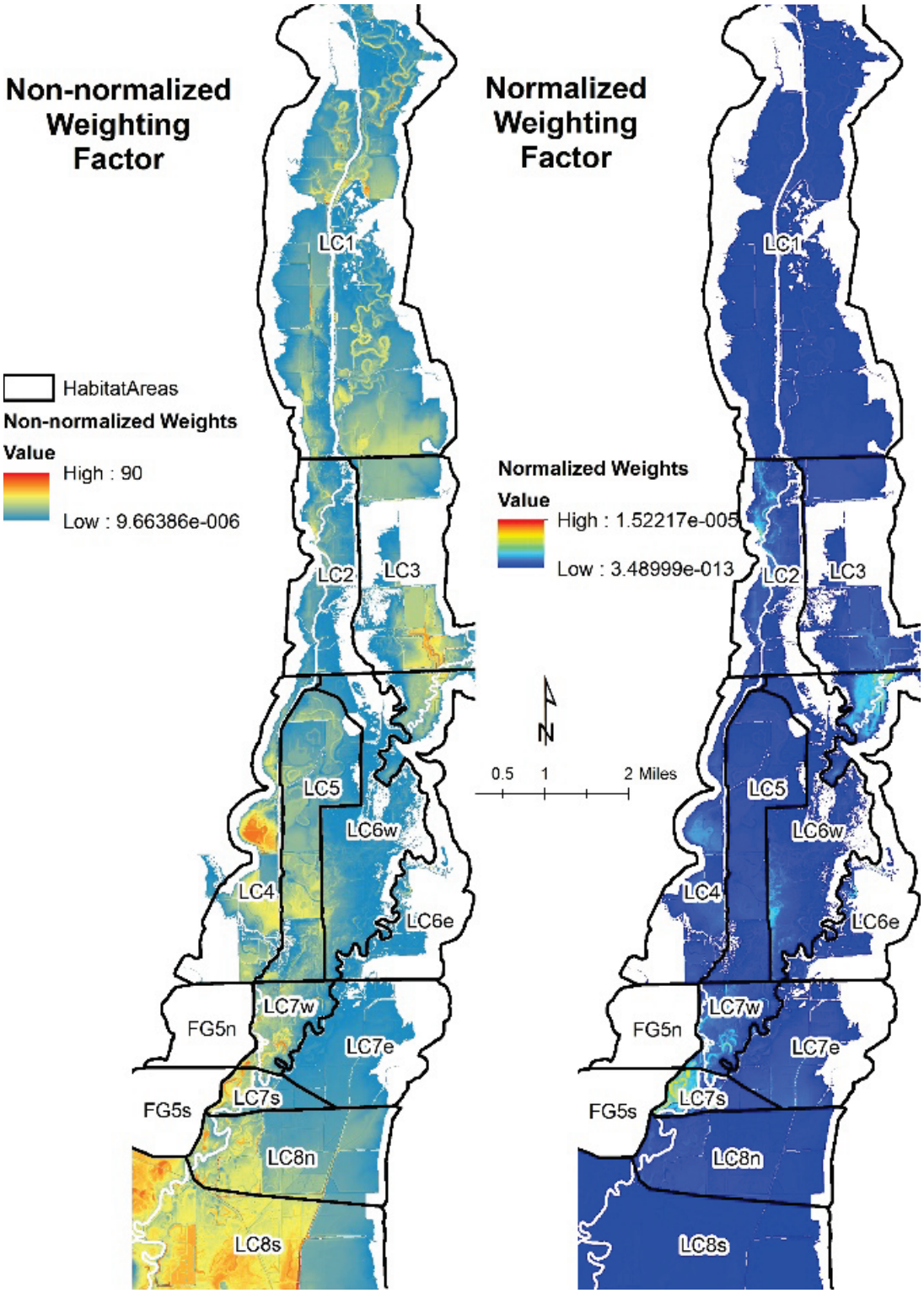

Figure 15. Weighting Factors from Steps 3 and 6

Table 6 provides the average deposition amount in each habitat area by the end of 10, 25, and 50 years. Note that some habitat areas have been subdivided because the sediment behavior is significantly different. The average deposition provided in Table 6 was computed as the total

volume of deposition for a given habitat area divided by the total surface area in the respective habitat area on which sediment deposits.

Table 6. Floodplain Deposition by Habitat Area

Habitat Area	Area of Deposition (ac)	Average Deposition (ft)		
		10 Years	25 Years	50 Years
LC1	3,864	0.06	0.15	0.30
LC3	1,035	0.06	0.16	0.32
LC2	713	0.34	0.86	1.71
LC6w	1,165	0.18	0.45	0.89
LC6e	497	0.06	0.15	0.31
LC4	686	0.94	2.36	4.72
LC5	1,345	0.58	1.45	2.90
LC7e	851	0.01	0.03	0.07
LC7w	443	1.06	2.65	5.30
LC7s	276	0.12	0.31	0.62
FG5n	3	0.77	1.93	3.87
FG5s	8	0.34	0.85	1.70
LC8n	1,393	0.12	0.31	0.62
LC8s	4,950	0.08	0.21	0.41

Figure 16 provides the average sediment deposition at the end of 50 years of simulation. Though the methods of computation are different, these values are fairly similar to the floodplain sedimentation rates computed by extending historic trends for the Fountain Grove and Yellow Creek habitat areas.

The thresholds plotted in Figure 16 equate to habitat impairment thresholds. Deposition of 1 ft over 50 years was the recommended target (see Appendix E). As seen in Figure 16, floodplain deposition well exceeds the recommended target for much of the region.

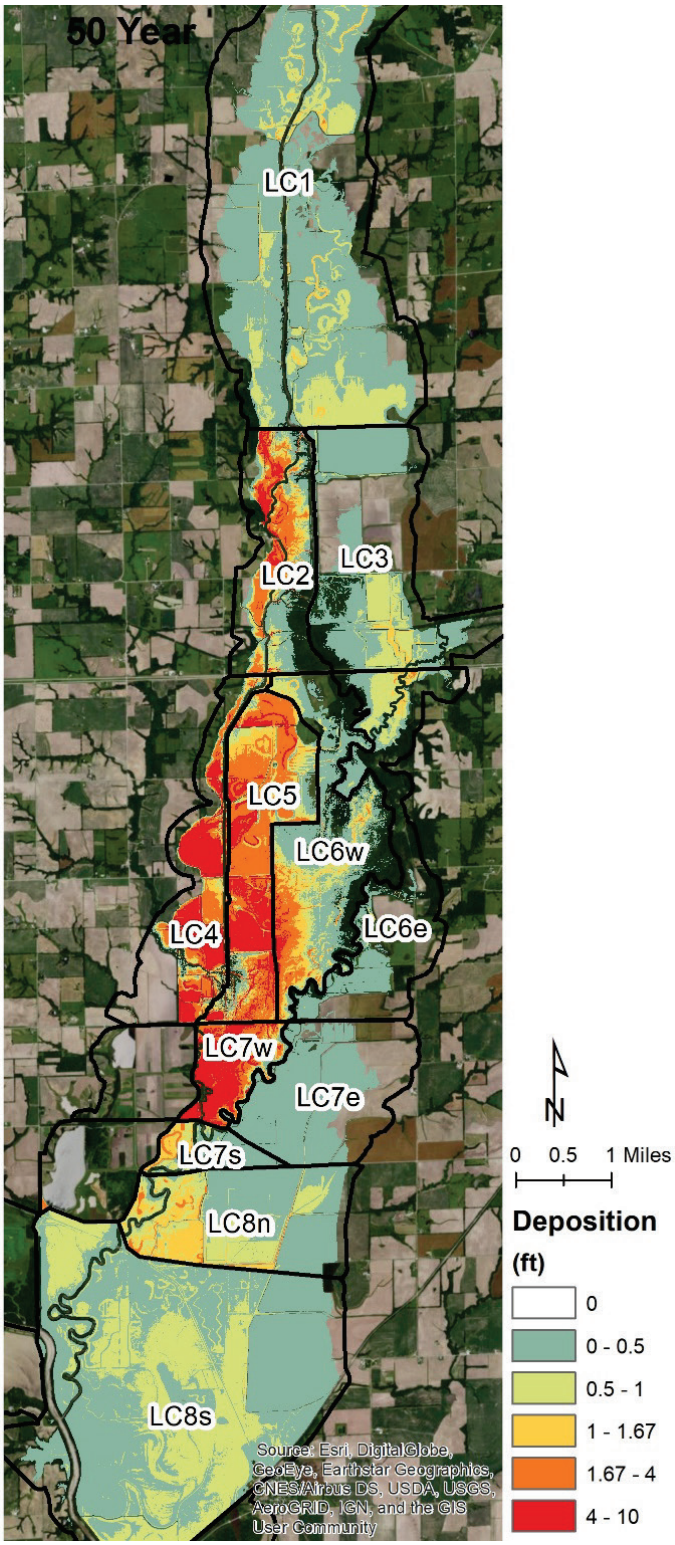

Figure 16. FWOP Floodplain Deposition by Year 50. Floodplain deposition begins to affect forest productivity at 0.5 ft of depth over 50 years. Deposition of 0.5 to 1 ft indicates that habitat is likely to survive, 1 to 1.67 ft indicates the start of habitat destruction, 1.67 to 4 ft indicates major habitat destruction to complete loss, and greater than 4 ft indicates total habitat loss.

11.0 Conclusion and Limitations

This report documents the setup and calibration of a 1-dimensional sediment model for the Pershing State Park area and its use in FWOP projections. The total sediment inputs to the model are well characterized based on continuous turbidity measurements and discrete concentration and size gradation measurements over six months. The sediment concentration for the higher flows are based on extrapolation rather than measured values and are subject to high uncertainty. More robust calibration was not possible due to the limited time frame of sediment data collection a lack of repeat channel cross sections.

The approach of using the 2D hydraulic model to supply flow split information and post-processing is not as accurate as a fully-coupled 2D flow/sediment model. However, a fully 2D, long-term flow/sediment model was deemed untenable. (For comparison, the 50-year sediment simulation runs in under three hours on a personal computer, which is faster than running even a single year of fixed-bed hydraulics through the 2D model.) Notwithstanding the limitations, the approach documented in this report provided more reasonable and actionable results than a 1D modeling approach by itself could provide.

Estimates for floodplain deposition values range from 0.07 to 5.30 ft (depending on the habitat area) averaged over the portion of the habitat area that sees at least 0.1 ft of flow. Individual locations within each habitat area can have much higher deposition amounts, as shown in Figure 16.

These analyses provide reasonable results to inform future habitat values for feasibility-level decisions. Continued monitoring and further calibration during design is recommended.

12.0 References

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Grand River Ecosystem Restoration Study

Final Integrated Feasibility Report and Environmental Assessment

Appendix C2: Pershing State Park Sediment Model Alternatives Testing

October 2020

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1.0 Introduction

This appendix compares the sedimentation implications of multiple alternatives for habitat restoration in Pershing State Park. Appendix C1 describes the calibration and creation of the Future Without Project condition. This appendix documents the changes required to model the alternatives and compares the model outputs.

The purpose of these alternatives is to restore flow to Locust Creek and its adjacent wet prairie and to reduce floodplain sedimentation in Pershing State Park. Ultimately, four geometric configurations were assessed. Three were modeled and retained: LC1 (FWOP) and alternatives LC3 and LC15. Additional model runs using preliminary model parameters were performed to screen other alternatives to varying degrees. Appendix C1 describes the FWOP. In addition to the modeled alternatives, sediment budgeting and model output was used to interpolate output for an additional alternative LC18. The following paragraph provides a basic description of the sediment features in the assessed alternatives. See Appendix E for a more a complete description including habitat features. Overtopping protection, scour protection, and maintenance as needed are assumed for each alternative such that exterior berms and levees persist at design elevations over the 50-year project life.

LC3 (East Side Large Basin)

This alternative includes building a pilot channel to divert Locust Creek to the east side of the floodplain into a large sedimentation basin. Exterior levees are raised where needed to be 6 ft higher than the interior basin. A structure at the upstream diverts flows up to 1,500 cfs into the basin. Additional flows predominantly flow down Higgins Ditch. The outlet structure at the downstream allows 1,500 cfs to flow into Muddy Creek, which rejoins Locust Creek downstream of HWY36. When flow volume exceeds the sedimentation basin volume water flows over a spillway to the west and enter Higgins Ditch.

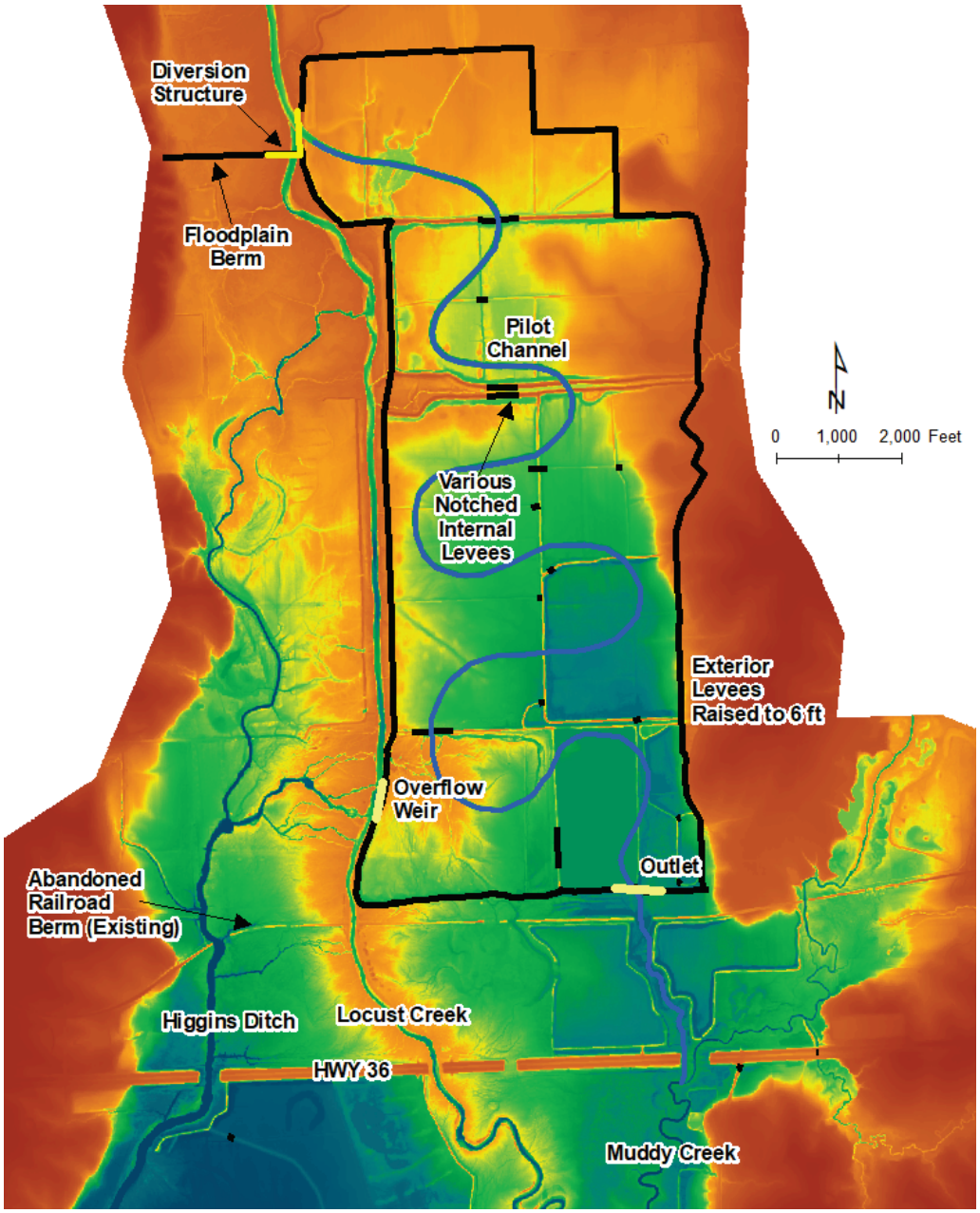

Figure 1. Key Components of LC3

LC15 (East Side Large Basin plus Higgins Ditch Grade Control)

LC15 includes all the features of LC3 plus an additional grade control feature on Higgins Ditch (see Figure 2). This grade control feature raises the bed and fills a notch in the existing railroad berm (see Figure 1) to induce lower velocities and more deposition upstream of Highway 36. The grade control structure was included in the model as an inline structure.

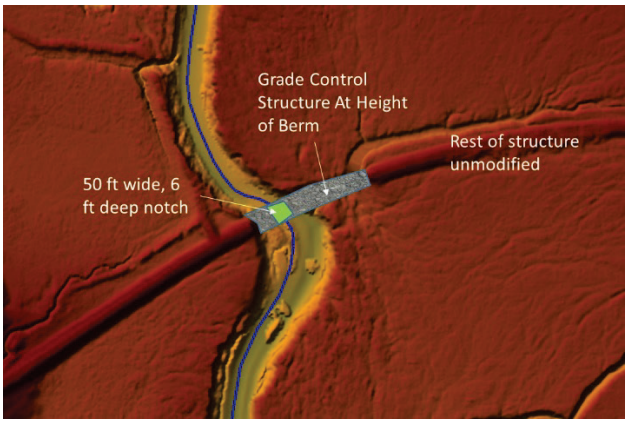

Figure 2. Grade Control Structure for LC15

LC18 (East Side Small Basin with No Flow Split)

LC18 utilizes a smaller basin than LC3. Rather than discharging low and moderate flows to Muddy Creek, all flows are discharged back to Higgins Ditch. This option does not restore flow to the old Locust Creek channel, but does provide some sediment and log capture to decrease floodplain deposition on the Higgins Ditch floodplain. As explained later, this alternative was assessed by interpolating from model output for LC3 and LC1 by taking into account differences in the sediment budget and Brune Curve analysis.

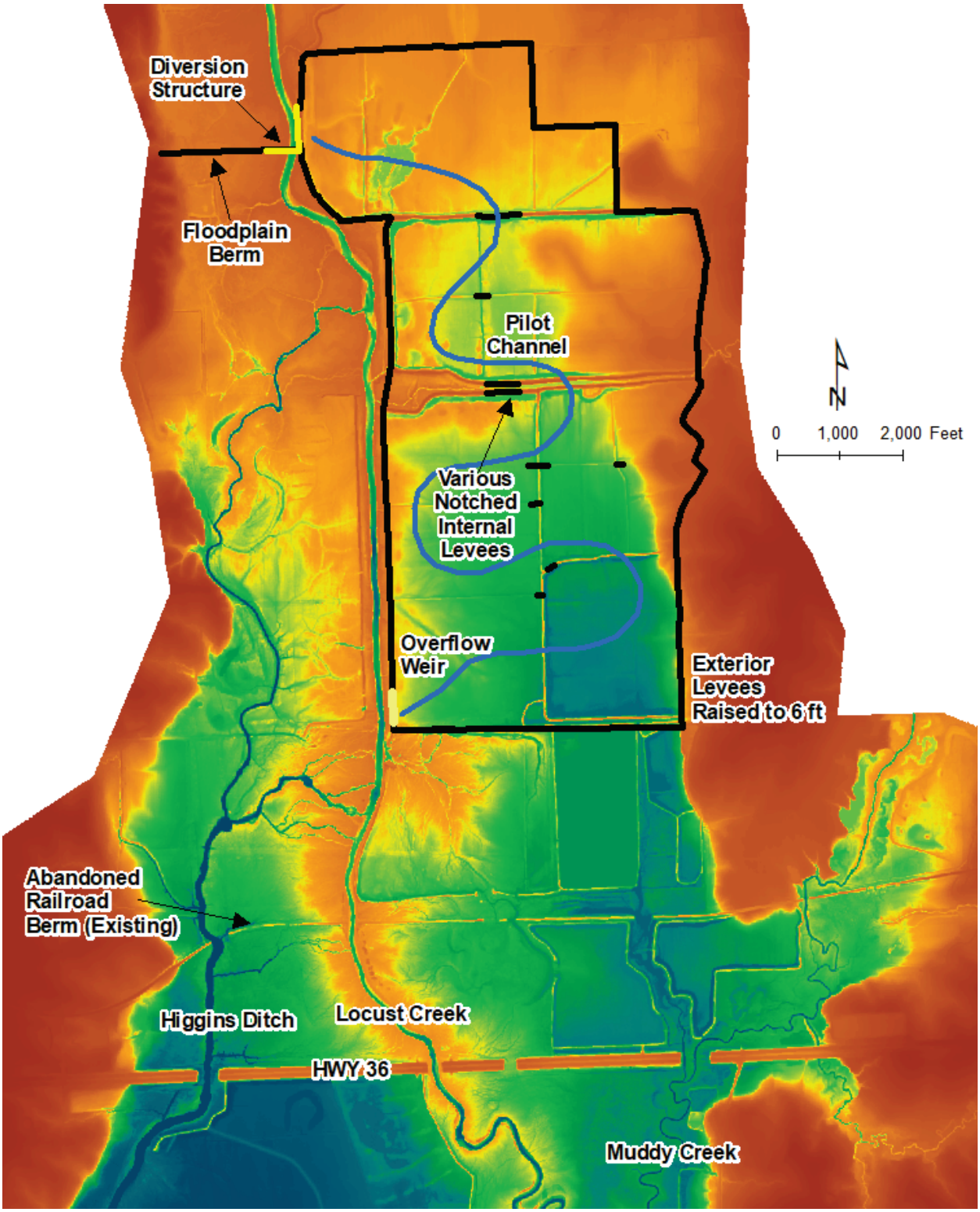

Figure 3. Key Components of LC18

2.0 Flow and Sediment

The sedimentation basins include complex, multi-dimensional flow patterns and unsteady flow hydraulics which could not be adequately modeled in an HEC-RAS 1D, quasi-unsteady sediment model. Rather than attempting to model the sediment basin directly, the effects of the sediment basin were included by adjusting the flow boundary conditions and sediment rating curves.

New flow boundary conditions were determined for LC3 and LC15 using the 2D RAS model values at the HWY36 bridge openings (see Figure 4 and Appendix A2). 2D RAS results indicated that LC15 flows were essentially the same as LC3, so the same flow split has been used for both. As LC18 returns all the water to Higgins Ditch, the flow split was assumed equivalent to LC1. Table 1 compares the flow splits in each alternative. All "Muddy Creek Opening" values include both the Muddy Creek Opening and the Floodplain opening and display flow that originates from Locust Creek at Linneus; flow from Muddy Creek itself is added separately and does not differ between alternatives.

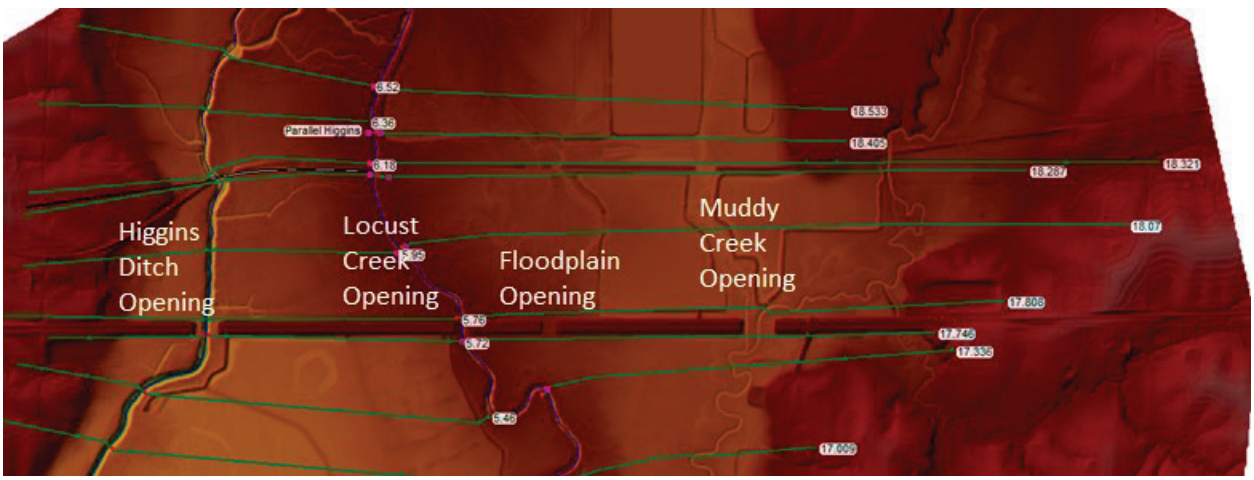

Figure 4. Bridge Openings on Highway 36

As seen in Table 1, the major difference between LC1 (FWOP) and LC3 or LC15 is that lower flows are diverted into the sediment basin. At higher flows Higgins Ditch continues to carry the majority of the flow under any scenario. For each alternative, sediment was apportioned proportional to flow. This means that the highest, most sediment-laden flows continue to flow down Higgins Ditch (and as shown later in this document, continue to deposit in much the same places). A major benefit of LC3 and LC15 is the restoration of low and moderate flows to Locust Creek via the Muddy Creek Opening.

Table 1. Flow Split in the Alternatives (values in cfs)

Linneus	LC1 (FWOP)/ LC18			LC3/LC15		
	Higgins Ditch Opening	Locust Creek Opening	Muddy Creek Opening	Higgins Ditch Opening	Locust Creek Opening	Muddy Creek Opening
50	49.5	0.5	0	0.5	0.5	49
200	185	15	0	0.5	0.5	199
1,000	881	119	0	0.5	0.5	999
2,500	2,163	306	20	898	156	1,445
5,500	4,700	509	288	3,445	555	1,500
7,300	6,268	556	419	5,037	735	1,528
9,150	7,400	580	460	6,399	850	1,560
14,500	13,170	645	669	11,809	922	1,706
18,200	16,745	683	740	15,515	941	1,744
22,800	21,170	728	840	20,048	957	1,788
26,200	24,397	773	942	23,424	960	1,819
29,500	27,532	815	1,025	26,675	965	1,861

A benefit to LC3, LC15, and LC18 is sediment trapping in sedimentation basin itself. The percent trapping was estimated using a Brune curve (Brune 1953), which relates the trapping efficiency (TE) of the reservoir to the ratio of inflowing water to basin volume. The following equation was used for the Brune Curve analysis, which approximates the "low" curve:

$$TE = 95\left[1 - 2e^{-5.37V_*^{0.35}}\right]$$

where V_* = Basin Volume / Annual Inflow Volume

Table 2 lists the parameters for the Brune Curve analysis. Daily sediment inflows to the basin were multiplied by the trapping efficiency to compute the deposition, which slightly reduces the basin volume (and hence the trapping efficiency) for the next day's sediment inflow. By the end of 50 years of sediment inflows and deposition, the trapping efficiency resulted in the Trapping Efficiency (End) values listed in Table 2. The Trapping Efficiency (Modeled) values in Table 2 indicate the value used to factor down the rating curves in the model, which are very close to the mean trapping efficiency value. (As slight changes over the course of the analysis occurred, the modeled trapping efficiency is no longer exactly the mean.) See Section 10 for sensitivity analysis with different trapping efficiency computations.

Table 2. Brune Curve Analysis

	LC3/LC15	LC18	units
Basin Area	64,203,148	50,703,840	sq ft
Depth	5.89	5.89	ft
Inflow	10,051,112,750	10,051,112,750	ft^3/year

Initial Basin Capacity	378,220,745	298,696,321	ft^3
Initial V_*	0.038	0.030	years
Trapping Efficiency (Start)	60	55	%
Trapping Efficiency (End)	29	19	%
Trapping Efficiency (Modeled)	46	37	%

The Brune method was intended principally for normally-ponded reservoirs. As a check, the maximum velocities during a 10-year flow event (at Linneus) were examined. As seen in Figure 5, the maximum velocities in the basin are mostly less than 1 ft/s. This indicates a highly depositional environment.

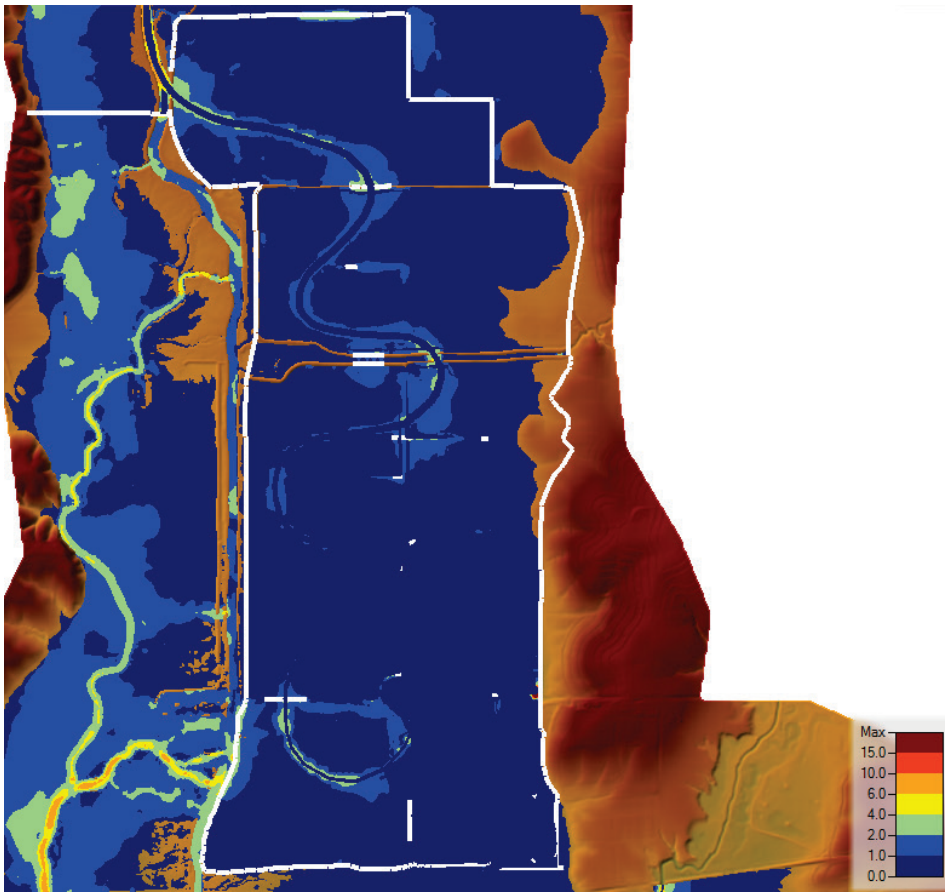

Figure 5. Maximum velocity in the sediment basin (at year 0) during a 10-year flow at Linneus, MO

5.0 Sediment Rating Curves

Three sediment rating curves were modified to reflect the alternatives. First, the Locust Creek and Muddy Creek Opening rating curves were adjusted proportionally with their flow split. Second, the diversion load rating curve at Higgins Ditch (RS 20.229) was adjusted so the sediment leaving Higgins Ditch at the Locust Creek/Higgins Ditch split equals the sum of the

loads computed for Locust Creek and the inflow to the sediment basin. Third, the incoming sediment load from the sedimentation basin was reduced by 46% (LC3/15) or 37% (LC18) to account for sediment trapping by the basin. Tables 3 and 4 provide the resulting rating curves for LC1 and LC3/LC15, respectively. Appendix C1 provides the sediment boundary conditions for Locust Creek at Linneus (Higgins Ditch in the model), Muddy Creek, Hickory Branch, which are unchanged amongst these alternatives.

Table 3. Sediment Rating Curves for LC1

Locust Creek (Locust Creek RS 20.145)							
Q (cfs)	0.001	31.6	334	360	462	483	640
Qs (tons/day)	0.0000001	12.5	1,712	1,907	2,760	2,925	4,728

Muddy Creek Opening (Locust Creek RS 17.746)							
Q (cfs)	0	0	34.4	51	170	214	577
Qs (tons/day)	0	0	177	273	1,015	1,296	4,263

Diversion (Higgins Ditch RS 20.229)							
Q (cfs)	-0.001	-31.6	-368	-411	-631	-697	-1,217
Qs (tons/day)	0	12.5	1,889	2,180	3,776	4,221	8,991

Table 4. Sediment Rating Curves for LC3/15

Locust Creek (Locust Creek RS 20.145)							
Q (cfs)	0.001	0.77	185	216	397	458	927
Qs (tons/day)	0.0000001	0.31	937	1,133	2,365	2,764	6,832

Muddy Creek Opening (Locust Creek RS 17.746)							
Q (cfs)	0.098	372	1,531	1,600	1,685	1,693	1,708
Qs (tons/day)	0.00001	80	4,255	4,592	5,454	5,551	6,835

Diversion (Higgins Ditch RS 20.229)							
Q (cfs)	-0.099	-373	-1,716	-1,815	-2,082	-2,151	-2,636
Qs (tons/day)	0.00001	148	8,797	9,619	12,485	13,222	20,977

6.0 Sediment Basin Volume

Figure 6 displays sediment accumulation in the sedimentation basin volume over time. Mass was converted to volume assuming the RAS default unit weights for clay, silt, and sand of 30, 65, and 93 pcf, respectively. As seen, the larger basin included in LC3/LC15 traps more sediment than the smaller basin in LC18. At the end of 50 years, the LC3/LC15 sedimentation

basin is 74% full of sediment. The LC18 basin is 78% full. The basins will also accumulate woody debris, which are not included in Figure 6.

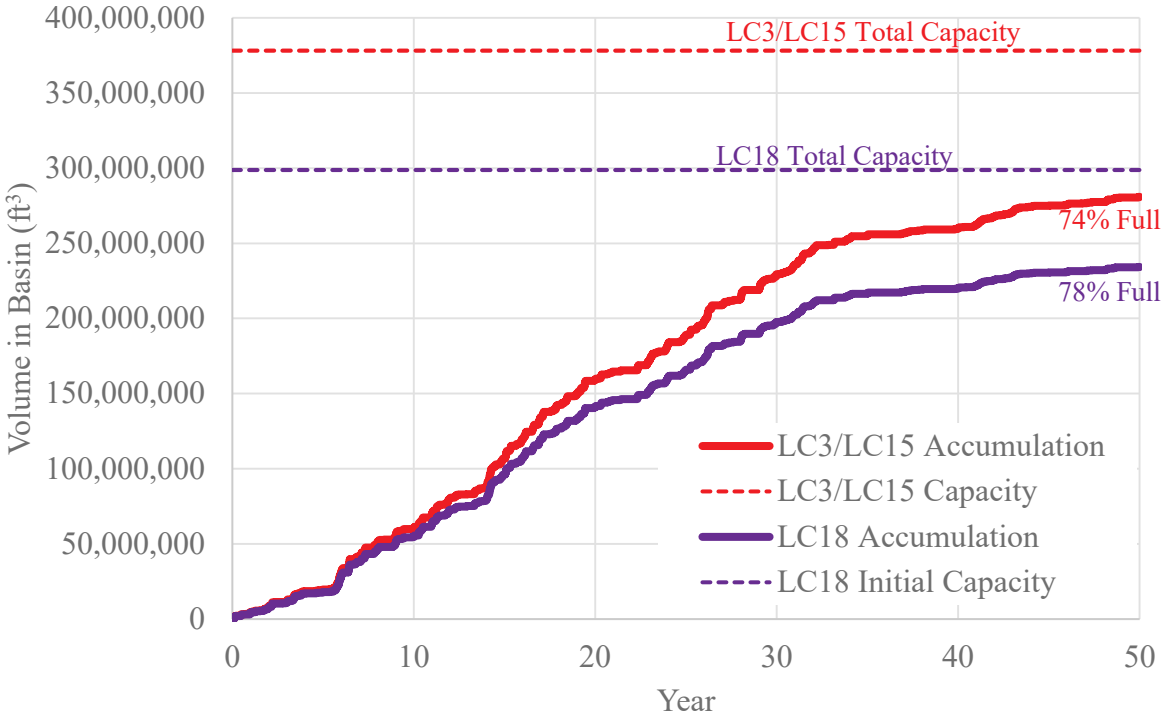

Figure 6. Sediment Accumulation in the Sedimentation Basins over Time

6.0 Sediment Model Parameters

Sediment model parameters were retained from the calibration and FWOP modeling (Appendix C1), including the Laursen-Copeland transport function, Exner 5 (Thomas) sorting method, and the Ruby Fall velocity method.

7.0 LC1, LC3, LC15 Longitudinal Cumulative Volume Change

Figures 7-9 provide the model longitudinal cumulative volume change curves for floodplain deposition at Higgins Ditch, Locust Creek, and the Grand River at the end of the 50-year simulation for LC1, LC3, and LC15. Output for LC18 was developed via interpolation, as explained later.

Figure 7 indicates that LC3 and LC15 both result in significantly less deposition along Higgins Ditch. LC3 results in less deposition overall, while LC15 results in the least deposition downstream from HWY36.

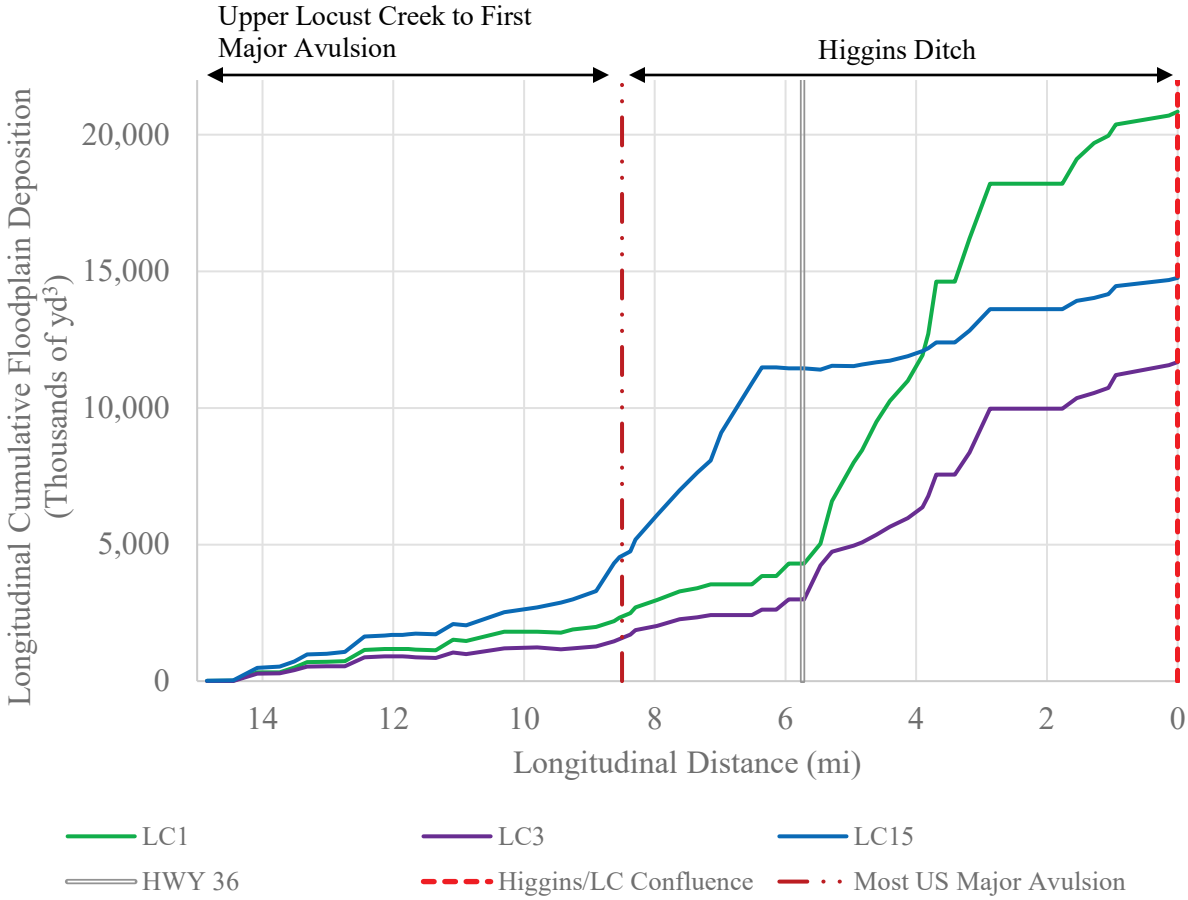

Figure 7. Longitudinal Cumulative Floodplain Deposition along Upper Locust Creek/Higgins Ditch

Figure 8 indicates that floodplain deposition along Locust Creek is fairly similar for LC1, LC3, and LC15. As expected, LC3 and LC15 result in slightly more floodplain deposition as a result of restoring flow to Locust Creek. The major difference between the alternatives, however, is a difference at the very first cross section, which is more likely a numerical artifact than a real difference.

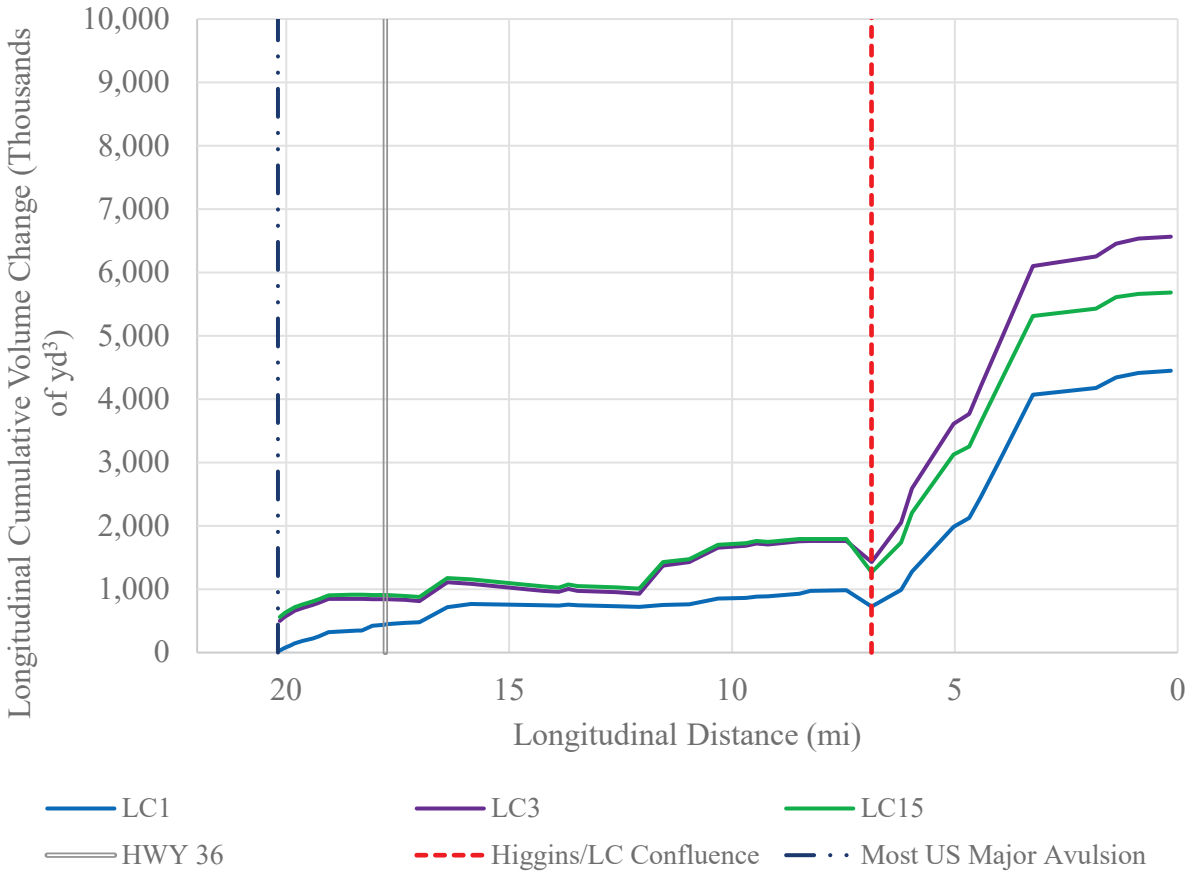

Figure 8. Longitudinal Cumulative Floodplain Deposition along Locust Creek (Starting after the Most Upstream Major Avulsion)

Figure 9 indicates that for the Grand River, the Locust Creek alternatives LC3 and LC15 are not appreciably different than the Future Without Project (LC1). The Grand River is relatively insensitive to the alternatives due to the small drainage area of Locust Creek (554 sq miles at Linneus) compared to the rest of the Grand River basin (6,240 sq miles at Fountain Grove).

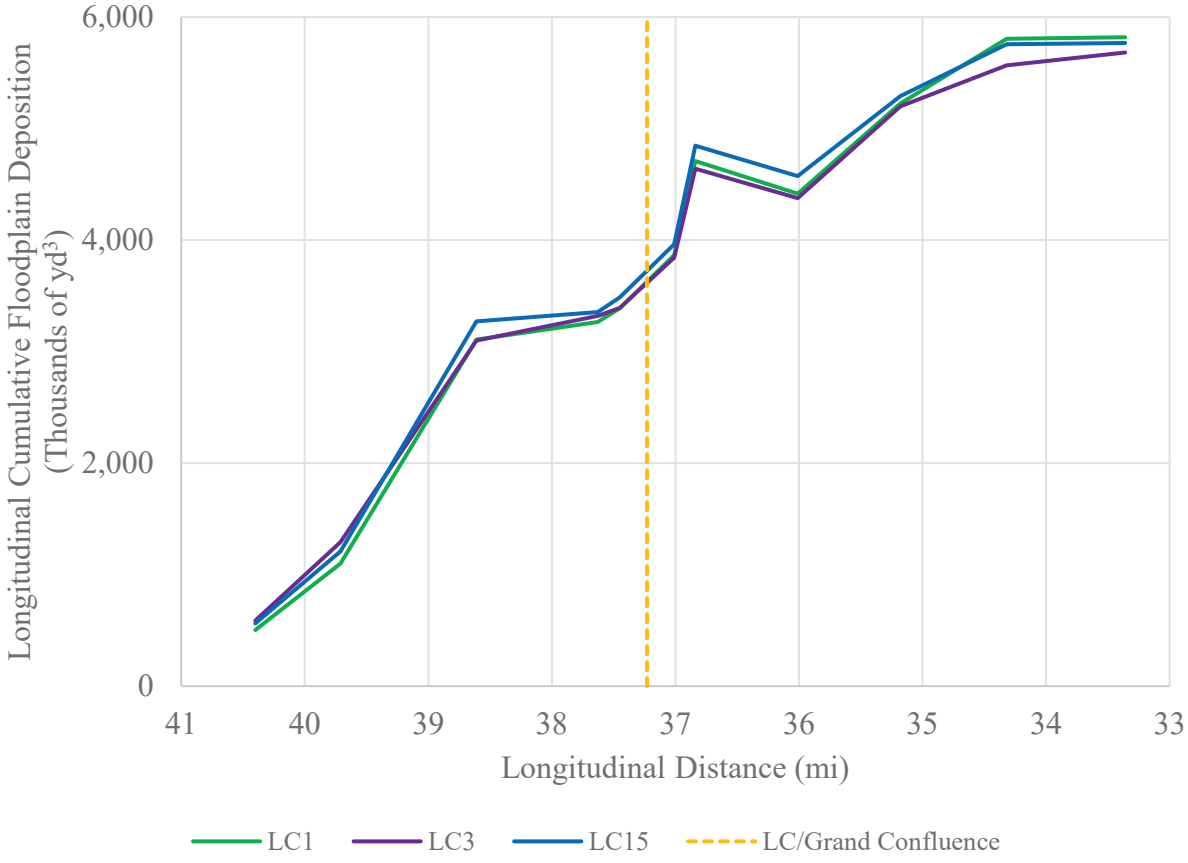

Figure 9. Longitudinal Cumulative Floodplain Deposition along the Grand River

8.0 Interpolation for LC18

LC18 removes sediment via a sediment basin, but returns all flow to Higgins Ditch (as in LC1) rather than redirecting flow to the Old Locust Creek channel (as in LC3 and LC15). The results of this alternative are bounded by other model runs. For LC3, 34% of sediment load that passes HWY36 on Higgins Ditch deposits on the floodplain along Higgins Ditch. The floodplain deposition along Higgins Ditch for LC18 was computed by subtracting the Brune Curve estimate for sediment deposition for the LC18 basin (see Table 2) from the LC1 sediment load passing HWY36, then multiplying by 34%.

9.0 Floodplain Deposition Comparisons and Mapping

Table 5 lists the total volume of floodplain deposition that deposits along Higgins Ditch and Locust Creek with LC1, LC3, LC15, and LC18. As seen, the alternatives result in reductions in floodplain deposition ranging from 18% to 61%, depending on the alternative.

Table 5. Percent Reduction in Floodplain Deposition Below Highway 36

Alternative	Floodplain Deposition below HWY36 along Higgins Ditch and Locust Creek (CY)	% Reduction from FWOP
LC1	20,548,551	NA
LC3	14,400,807	30%
LC15	8,083,089	61%
LC18	16,776,198	18%

Following the same process as for the FWOP analysis (see Appendix C1), the 2D RAS output (see Appendix A2) was used to post-process the 1D sediment data in order to produce floodplain deposition maps. Model runs with similar flow splits (LC1/LC18 and LC3/LC15) used similar 2D RAS output to as a post-processor. Figure 10 provides the 50-year deposition maps. Online versions of these maps were provided to the biologists and ecologists for assessing habitat quantity and quality for the Locust Creek alternatives.

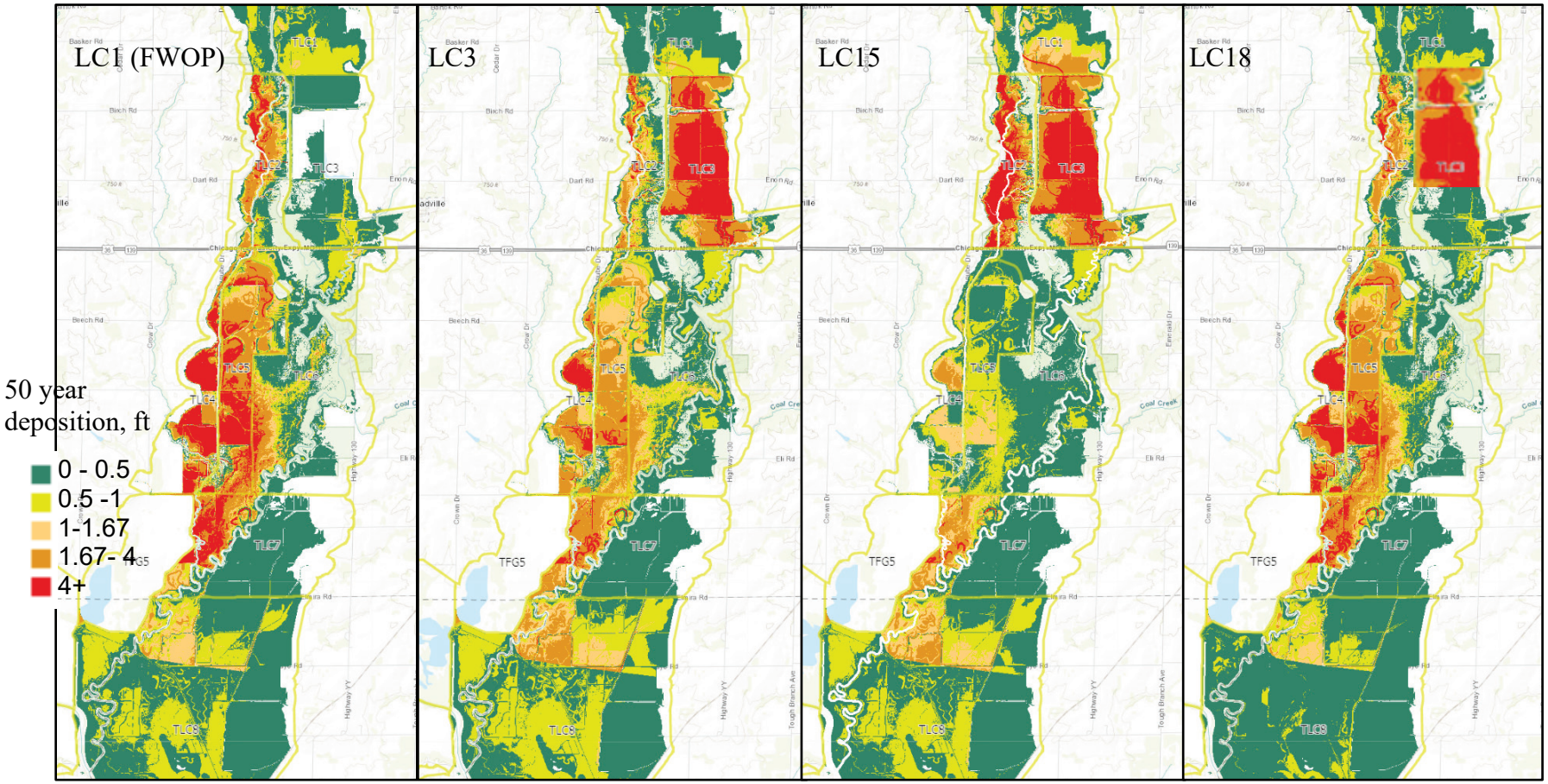

Figure 10. 50-year floodplain deposition.

10.0 Sensitivity and Sediment Reduction

The shallow ponding, presence of a pilot channel, and output from earlier model versions that included cross sections in the basin lead to the selection of the "low" Brune Curve. As a sensitivity test, the deposition in the basin was also computed via the "medium" and "high" Brune Curves and via the Churchill method.

The Churchill method was developed using data from reservoirs in Tennessee and is generally assumed to be more applicable to dry detention basins than the Brune method. In most situations, the Churchill Method will estimate a lower trapping efficiency than the Brune method. However, when the ratio of capacity to inflow is small, as is the case with the proposed sedimentation basin, the Churchill Method tends to estimate a higher trapping efficiency.

As seen in Figure 11, while all three Brune Curves indicate the basin will continue to have capacity over the 50 year period, the Churchill method indicates the basin will be completely full within 32 years.

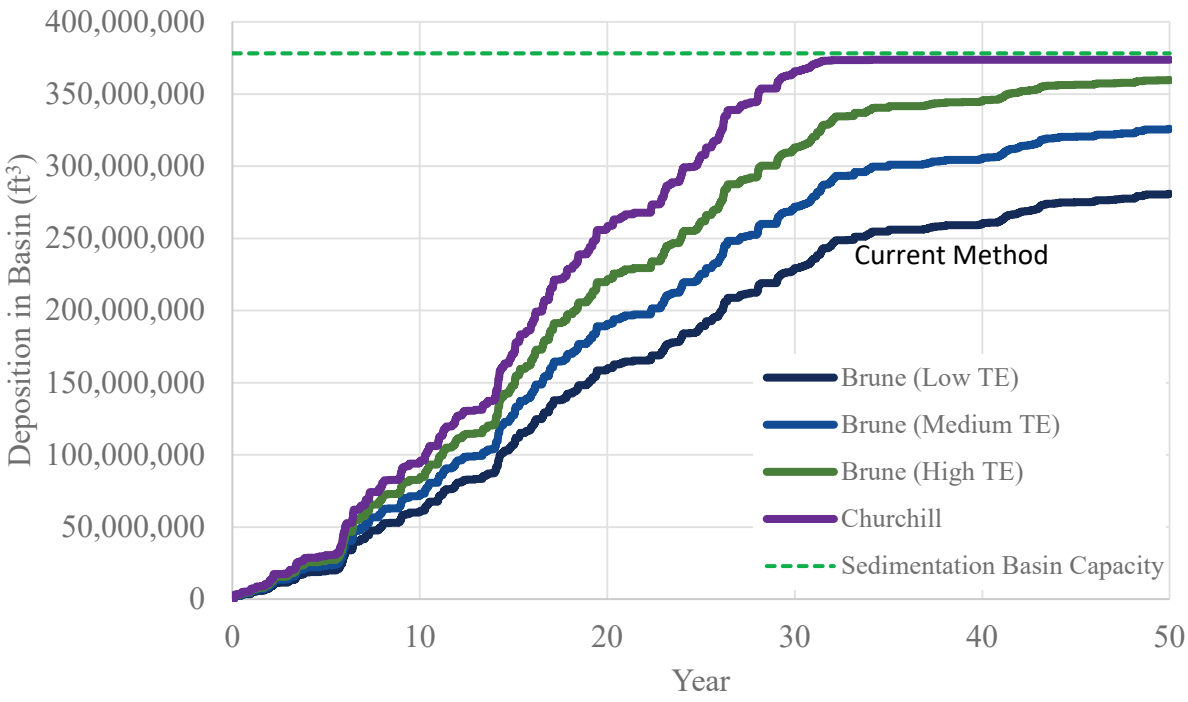

Figure 11. Sensitivity Analysis for Trapping Efficiency Method for the LC3/LC15 Sediment Basin

The results of this sensitivity analysis suggest two considerations for the selection of a Tentatively Selected Plan. (1) With current sediment loads, there is a possibility that the basin will fill before the end of the 50-year planning horizon. Reduced incoming sediment loads are required to have reasonable confidence that the sediment basin continues functioning over the entire planning horizon. (See Appendix C3 for discussion of sediment load reduction.) And (2)

if the sediment basin fills in appreciably, the water may re-avulse to the west (Higgins Ditch side). Given this possibility, the most robust (as well as the most effective, as seen in Table 5 and Figure 10) is alternative is LC15, which induces deposition on both sides of the floodplain. If the full floodplain deposits, eventually Locust Creek will no longer be perched.

11.0 Conclusion and Limitations

This report documents sediment analysis for alternatives in the Pershing State Park area. These results derive from 1D sediment model output (or interpolation from output), Brune Curve trapping efficiency analysis, and 2D hydraulic model output. Alternatives LC3 and LC15 restore water to the old Locust Creek channel and result in reductions in floodplain deposition of 37% and 61%, respectively. LC18 does not restore water to the old Locust Creek channel and results in an 18% reduction in floodplain deposition.

Sensitivity analysis suggests that sediment reduction measures need to be employed to have reasonable confidence that the basin can continue reducing downstream deposition through the 50-year planning horizon. Furthermore, LC15, which induces deposition on both sides of the perched Locust Creek, is more robust than depositing only in the sediment basin (LC3).

The same data limitations listed in Appendix C1 apply to the alternatives analysis, including simplified analyses, short time-series of sediment data, and uncertainty about sediment loading during large floods. Notwithstanding, these analyses provide reasonable results to inform future habitat values for feasibility-level decisions. Continued monitoring and further calibration during design is recommended.

Grand River Ecosystem Restoration Study

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Appendix C3: Trapping Efficiency, Risk and Uncertainty, and Sediment Reduction Analyses for Pershing State Park Under Alternative LC15

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1.0 Introduction

This appendix documents analyses related to the sediment basin and to watershed sediment reduction. First, it presents refinements to the analysis methodology for computing the trapping efficiency of the basin. Second, it documents a risk and uncertainty analysis estimating the risk of increased sediment loads. Third, it summarizes a watershed reconnaissance effort to locate erosional hotspots. Fourth, it summarizes a bank erosion analysis that indicates the linear feet of bank stabilization needed to reduce the incoming fine sediment loading to the system. Finally, it lists limitations and recommendations for design phase relative to the sediment basin. Figure 1 presents the sediment-trapping features of LC15, including the sedimentation basin on the east side of Locust Creek. (Note that this alternative includes additional features to prevent head cutting, induce sheet flow, and enhance habitat which are not shown in Figure 1.)

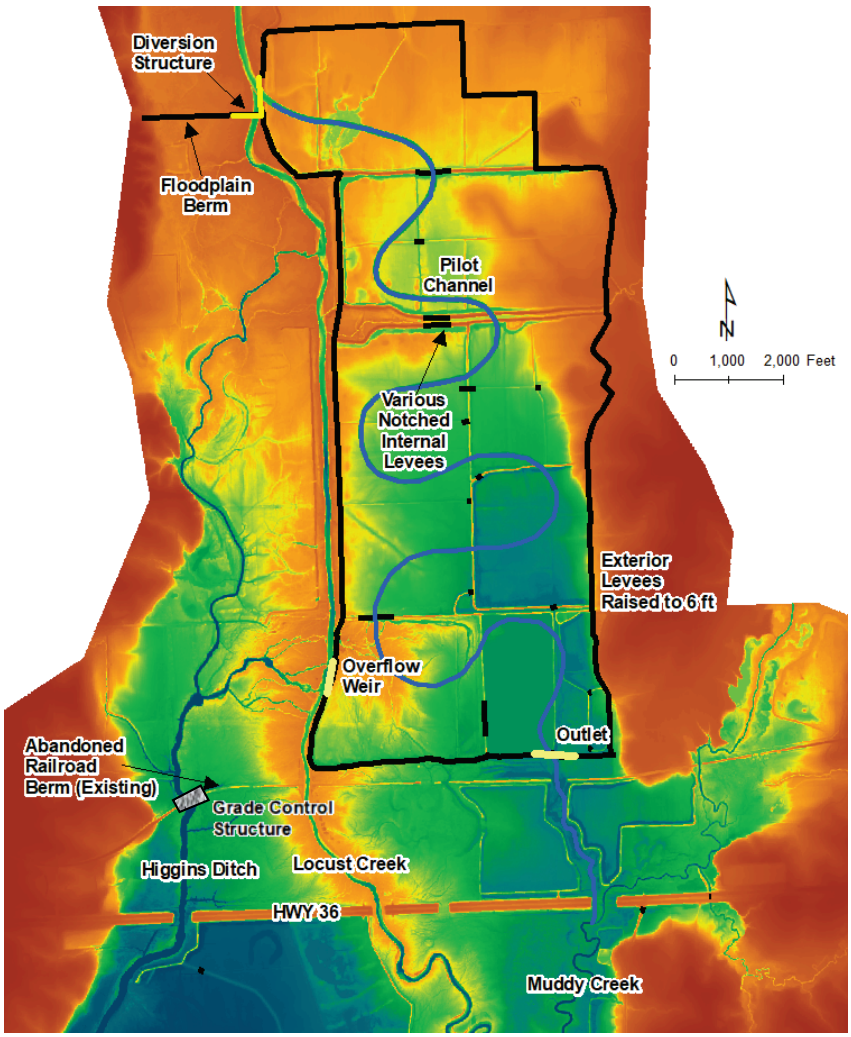

Figure 1. Major Sediment-Trapping Features of LC15

This alternative decreases floodplain deposition of sediments in three ways. (1) The sediment basin becomes a "sacrificial floodplain" where sediments can deposit, rather than depositing

downstream of sensitive habitats. (2) The grade control structure and railroad berm on Higgins Ditch induce additional deposition on the west side of the floodplain. Overtime, deposition on both sides of Locust Creek creates a more natural floodplain compared to the existing perched condition. And (3) By more fully utilizing Locust Creek in addition to Higgins Ditch to convey flow, more flow is conveyed before overtopping the banks, resulting in less floodplain deposition. The "sacrificial floodplain" benefit of the sediment basin decreases over time as it fills with sediment. The speed that the basin fills depends on the incoming sediment loads and the trapping efficiency.

2.0 Trapping Efficiency, Pilot Channel, and Basin Filling

Without any sediment reduction, an estimated 55 million tons of sediment reaches the diversion structure, with 19 million tons entering the sediment basin over 50 years. The amount of sediment that is trapped in the basin depends on the basin trapping efficiency. Figure 2 (repeated from Appendix C2) depicts the basin filling by four different trapping efficiency methods. By the low, medium, and high Brune Curve trapping efficiency estimates the sediment basin is expected to last beyond the 50 year design life. However, the Churchill Method estimates a higher trapping efficiency, which indicates that the sediment basin may fill in about year 31. (See Appendix C2 for additional discussion). Figure 2 included simplifying assumptions for expeditious comparison amongst alternatives. As the tentatively selected plan includes this basin, the issue of basin longevity (and the longevity of the associated benefits) warrants further analysis.

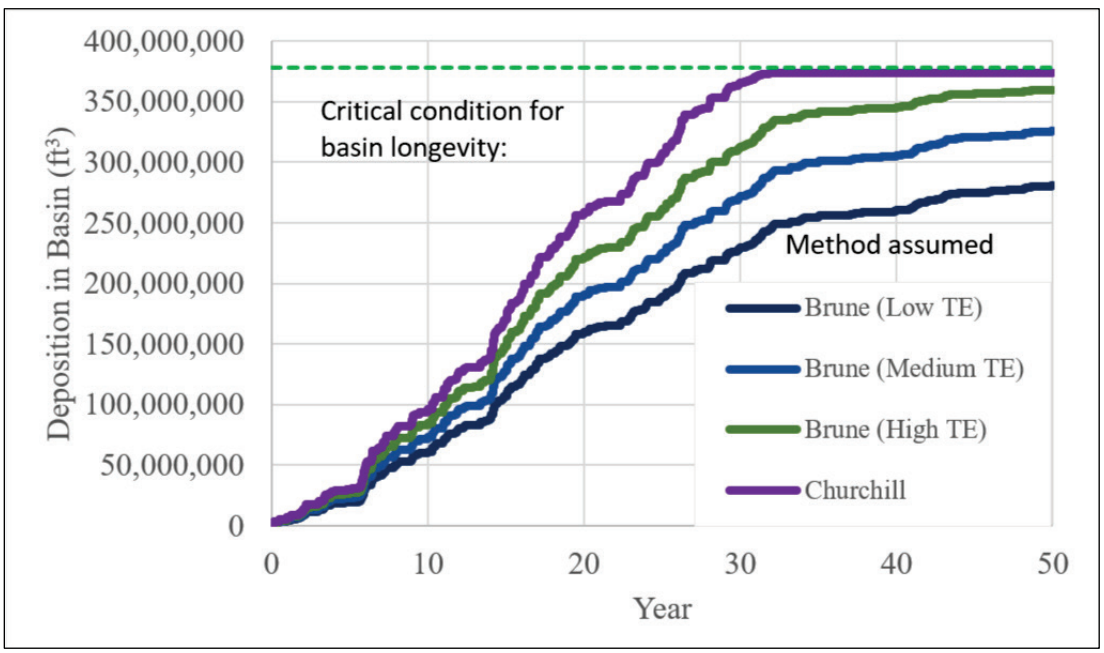

Figure 2. Preliminary Sensitivity Analysis for Trapping Efficiency Method for the LC15 Sediment Basin

The analysis presented in Figure 2 included the simplifying assumption that the sediment trapping applies to all flows that travel through the basin to the downstream outlet. In reality,

only flows that exceed the bankfull capacity of the pilot channel will deposit sediment in the depositional area of the basin. Geomorphic principles assert that the under-sized pilot channel will enlarge over time, gradually increasing its bankfull capacity until it can convey the flow supplied to it.

The eventual bankfull capacity of the pilot channel was approximated using an effective discharge analysis. Figure 3 divides the sand and gravel bed material load into bins based on the flow. As seen, flows from 1400 to 1600 cfs bring in the the most sediment over the 50-year period. Correspondingly, when the flow at Linneus is 5,500 cfs (approximate bankfull flow with a return period of 1.25 years), flow into the basin is 1,500 cfs.

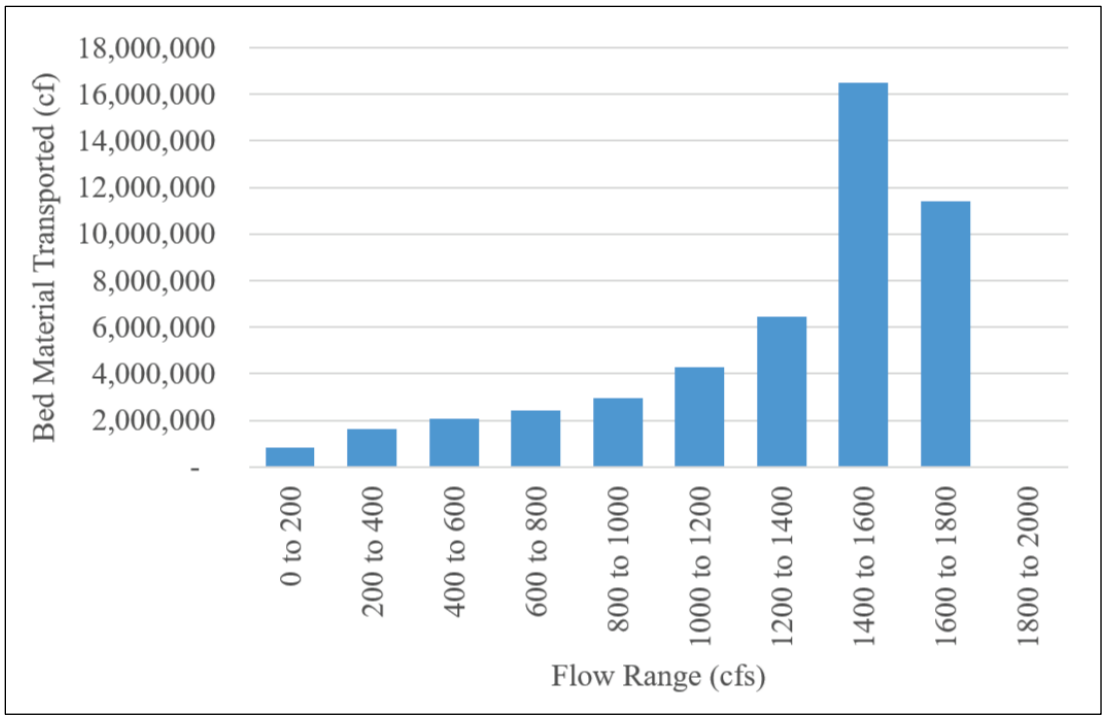

Figure 3. Effective Discharge Analysis

An assumption was made that the pilot channel grows from its initial capacity of 50 cfs (at the most constricted point) to a capacity of 1,480 cfs by year 20, then fully to 1,500 cfs by year 50. At flows below these thresholds the basin was assumed to have a zero trapping efficiency. Even for high flows that do exceed the pilot channel capacity, the trapping efficiency decreases over time as the basin accumulates sediment (see Figures 4 and 5). At around year 44 the trapping efficiency drops below the Brune Curve level which was assumed for the habitat modeling, and the basin is essentially full of sediment.

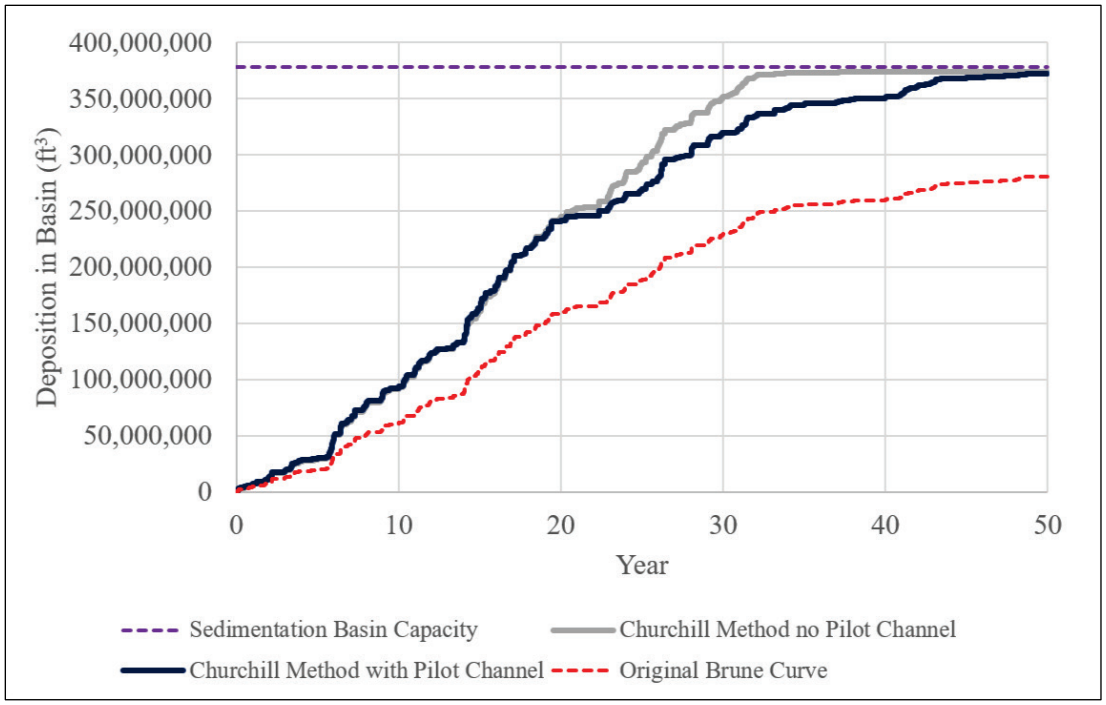

Figure 4. Basin Filling Over Time by Two Trapping Efficiency Methods

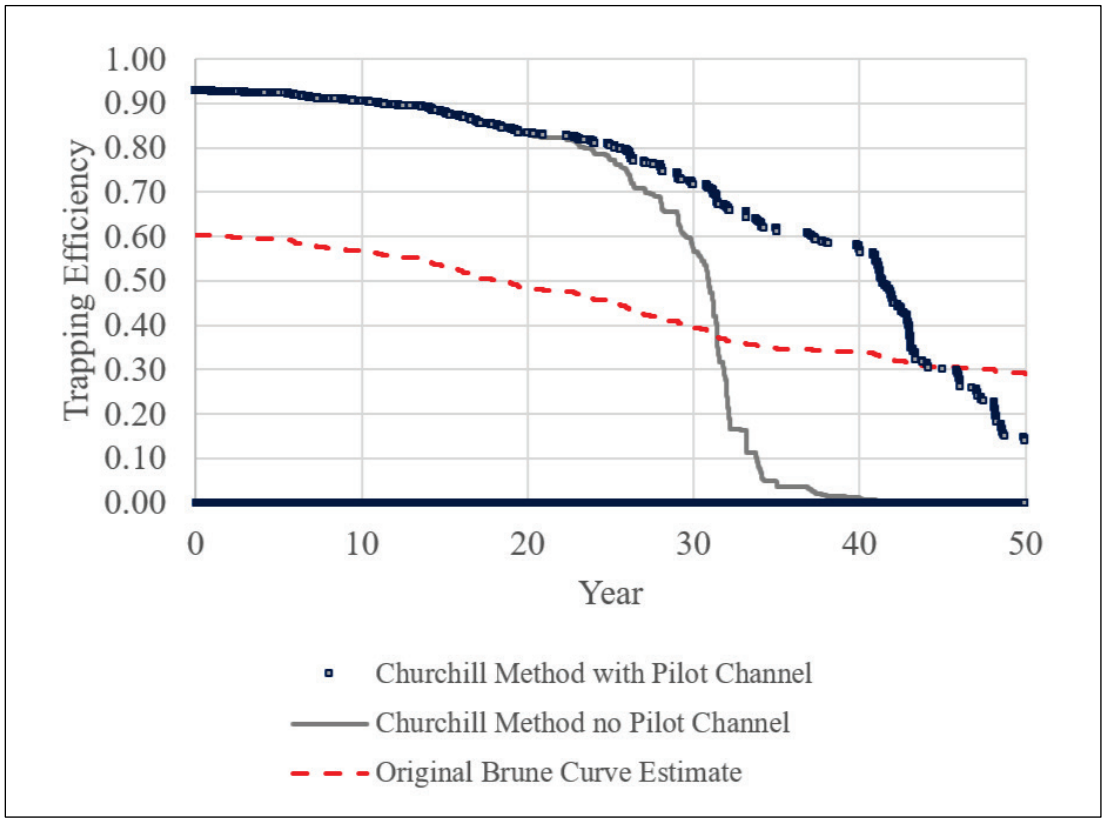

Figure 5. Trapping Efficiency Over Time by Two Methods

Figures 4 and 5 reflect the risk for a significant drop in trapping efficiency near the end of the 50-year design life due to accelerated basin filling. This risk can be mitigated by opening or closing an additional outlet. The rate of filling is highly sensitive to assumptions for how long the pilot channel takes to develop. If the pilot channel develops more quickly the basin will last longer than shown in Figure 4. If the pilot channel develops more slowly or for any other reason the trapping efficiency is higher than estimated, an additional outlet should be opened to reduce the trapping efficiency to more evenly pace the benefits over the 50 years. The basin outlet structures should be designed to allow this flexibility.

3.0 Risk of Increased Sediment Loading

As explained in Appendix C1, the sediment rating curve was based on 37 flow/load measurements from 2011 to 2017 then calibrated so the cumulative incoming sediment load during the calibration period (29 Mar 2017 to 30 Dec 2017) matched the sum of USGS-computed daily sediment loads over that time period (plus an assumed 5% bedload). Furthermore, the modeling assumed that the next 50 years is a repeat of the previous 50 years of daily flows. Due to the limited sampling period and the hydrologic uncertainty of which flows will occur over the next 50 years, the actual volume of sediment entering the modeled reach at Linneus (and the sediment basin and downstream habitats) could be higher or lower than estimated. This section quantifies the risk that the sediment loads are higher than expected by combining uncertainty in the rating curve with hydrologic uncertainty to create a composite standard deviation. One standard deviation away from the calibrated result is presented as a reasonable range of uncertainty.

3.1 Sediment Rating Curve Uncertainty

On any given day, the relationship between sediment load and water discharge can vary by more than an order of magnitude. This occurs due to a number of physical phenomenon such as hysteresis (e.g. loads are generally higher on the rising limb than the falling limb of a hydrograph), storm centering (some parts of the watershed may contribute more sediment than others for the same flows), measurement errors, and other reasons. Sufficient measurements over a long enough period of time allows the integration of this variability into a single, long-term flow/load relationship. Measured data on any given day may still differ from the long-term relationship by over an order of magnitude, but on the decadal scale the relationship produces the correct volume of sediment.

The sediment data at Linneus spans only 6 years of data and the calibration period only spans 9 months, leading to a strong possibility of bias in the flow/load rating curve. To assess this risk, a bootstrap method was employed using the following steps:

1. The measured data pairs were sampled to created 100 random sets of 37 data points. A single measured pair could be included once, more than once, or not at all.
2. New rating curves were developed for each random realization. The rating curves followed the same form as the calibrated curve: $Qs=aQ^b$ for flows up to 4908 cfs, then a flattening of the curve such that Qs at 12,000 cfs = 3.227 * Qs at 4908 cfs. As using

this process on the original data yields a total mass of sediment that is 33% higher than the calibrated relationship, no additional increases were included to account for bedload or to unbias the results for logarithmic transformation.

3. 50 years of flow was run through each rating curve to compute the cumulative mass of incoming sediment load. The cumulative loads are shown in Figure 6. Table 1 provides the results of this analysis.

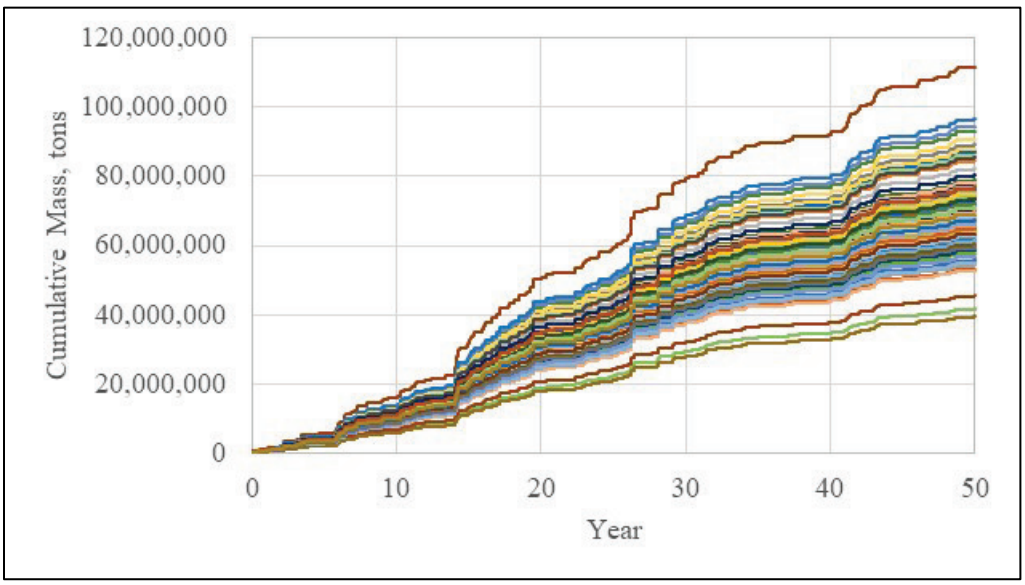

Figure 6. Cumulative Sediment Load Using 100 Different Rating Curves

Table 1. Summary of Estimates for Cumulative Sediment Loading Using 100 Different Rating Curves

	Cumulative 50-year Load (tons)
Min	39,522,740
Max	111,645,696
Median	68,305,358
Model	51,279,704
25% Percentile	60,737,116
75% Percentile	75,887,177
Range	72,122,956
Standard Deviation	11,835,930

3.2 Hydrologic Risk

The modeling used to compare alternatives estimated the next 50 years of daily flows using a synthesized daily flow record from 1966 to 2016 (see Appendix A). If the future 50 years of flow differs from the previous 50 years, the sediment loads entering the model space and sedimentation basin could be higher or lower than predicted. To quantify this risk, the following method was employed:

1. Annual sediment loads were computed for each year using the daily flows from 1966 to 2016 and the calibrated rating curve. The partial years of 1966 (3 months) and 2016 (9 months) were combined into a single complete year.
2. These years were randomly sampled (with replacement) to generate 100 sets of 50 years. Any given year could be included once, more than once, or not at all.
3. The annual loads were summed to compute the cumulative sediment load for each 50 year realization. Table 2 summarizes the results.

Table 2. Summary of Estimates for Cumulative Sediment Loading Using 100 Different Flow Series

	Cumulative 50-year Load (tons)
Min	42,781,574
Max	63,576,761
Median	51,958,396
Model	51,279,683
25% Percentile	48,757,650
75% Percentile	54,917,326
Range	20,795,188
Standard Deviation	4,680,524

The composite standard deviation was computed using the following equation (which mirrors Equation 5-5 in EM 1619):

$$SD_{composite} = \sqrt{SD_{rating\ curve}^2 + SD_{hydrologic}^2}$$

$$= \sqrt{11835{,}930^2 + 4{,}680{,}524^2}$$

$$= 12{,}727{,}786 \text{ tons}$$

As silts and clays comprise 85.8% of the incoming sediment load, 12,727,786 tons of incoming sediment = 10,923,069 tons of incoming fines, which is 25% of the incoming fine sediment load by mass. The ideal solution to reduce the risk is to reduce the incoming sediment loads through watershed restoration. Such actions contribute to overall ecosystem health and long-term

sustainability as well as decrease risk. The next several sections discuss ways to reduce sediment loading.

If insufficient watershed restoration is implemented, increased sediment loading may necessitate maintenance activities such as dredging, raising the height of the exterior levees, or expanding the surficial footprint of the basin.

4.0 Helicopter Reconnaissance to Locate Features for Sediment Reduction

This section discusses the results of helicopter-based reconnaissance to identify erosional "hotspots" in rivers and streams that could be restoration sites. On March 14-15, 2017, personnel from the Kansas City District, the Missouri Department of Natural Resources, and the Missouri Department of Transportation performed helicopter-based reconnaissance to locate erosional features in the watershed. Appendix C3.1 presents the full report with excerpts and summaries provided here. Figure 7 indicates the streams that were flown.

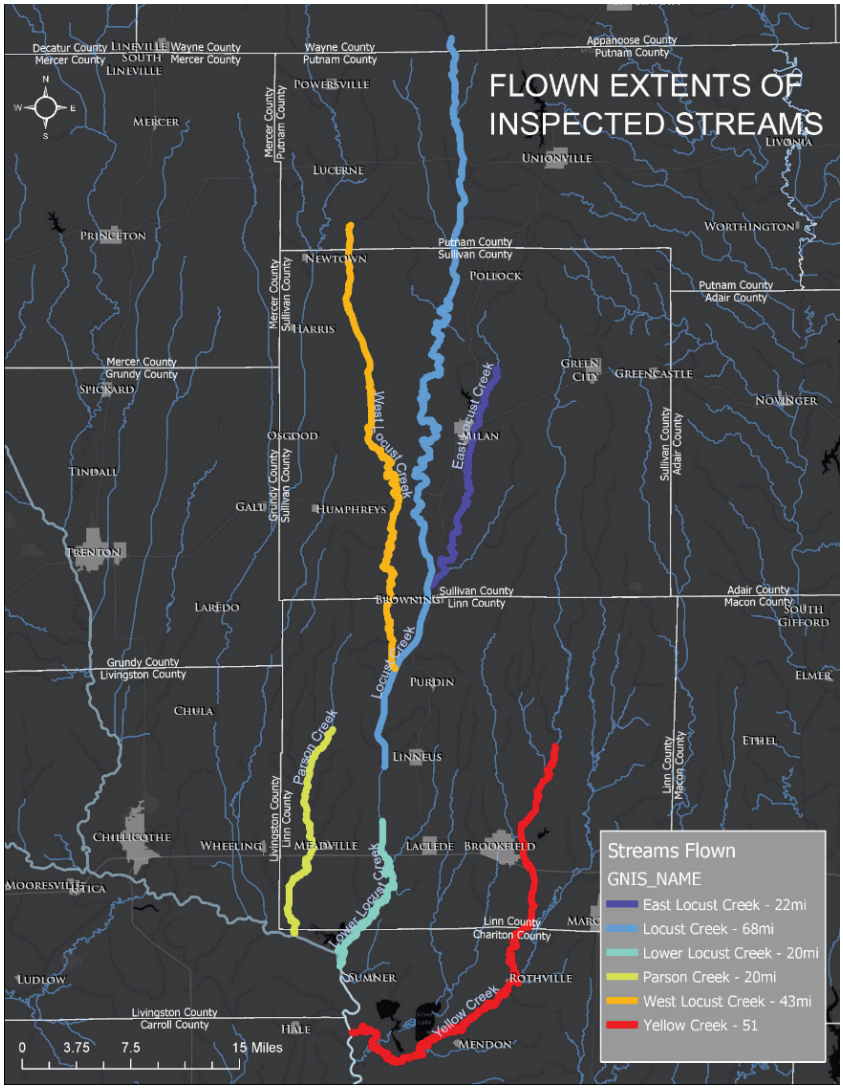

Figure 7. Streams flown in helicopter-reconnaissance

Contrary to initial expectations, only one active headcut was observed on the main channel of all streams inspected. Presumably, other headcuts have already migrated much further upstream through the system. The active site is located on Locust Creek approximately one mile upstream from the low water crossing for Thrush Road as seen in Figure 8.

Figure 8. Location of active headcut

The conditions upstream of the site are such that the amount of sediment load that could be mitigated by arresting the headcut is limited to approximately 50,000 cubic yards of sediment. It appears to have moved 100-200 feet upstream in the avulsion between 2015 and 2017. Table 3 quantifies the instances of other observed features. As noted, numerous instances of bank erosion and field drainage erosion were observed. See Appendix C3.1 for more information, including photographs. Table 3 should not be seen as a comprehensive accounting of the number of eroding banks as only major streams were inventoried; tributaries to these streams are similarly experiencing bank erosion. Moreover, analysis of aerial photography indicates additional eroding banks not photographed.

Table 3. Site Photographed in Each Inspected Creek

Stream Name (miles flown)	Erosion Banks	Erosion Field Drainage	LWD	Rock Bed	Bridge	Beaver Dam
Locust Creek (68mi)	80	45	23	35	20	6
Lower Locust Creek (20mi)	6	4	11	8	7	1
East Locust Creek (22mi)	27	8	19	21	4	17
West Locust Creek (43mi)	53	30	31	28	7	11
Yellow Creek (51mi)	30	1	26	5	1	0
Parson Creek (20mi)	12	2	17	5	4	3

5.0 Bank Erosion Assessments

Aerial photography analysis coupled with LiDAR was used to quantify the sediment input from eroding banks in the watershed. This analysis is described in Appendix C3.2 with excerpts and summaries provided here.

Thirteen sites, with some sites comprising multiple consecutive bends, were assessed to determine an annual erosion rate utilizing an 18 year range of observation (1997-2015). Typically sites were chosen based on a river bend with minimal bank vegetation and coinciding with "hot spots" from the 2013 PAS study "North Central Missouri Locust Creek Watershed Study Final Report". Figure 9 depicts the locations analyzed.

Having minimal vegetation cover allowed for Google Earth imagery of high bank extents along Locust Creek to be compared from 1997 to 2015. This comparison would often show areas both of substantial erosion and deposition that occurred at the chosen locations. An area was measured by drawing a polygon in Google Earth encompassing the eroded or deposited location, and calculating the square footage. That area was then multiplied by the high bank height extracted from a 2017 LiDAR terrain to estimate a volume for the 18 year period. This volume was divided by the 18 years to estimate a cubic yard per year erosion/deposition rate. At each analyzed bend, if the outer bend eroded while material deposited within the inside bend, the volume of deposition was subtracted from the erosion volume to compute a net volume of eroded material. The bank material was assumed to be 55% fines based on other bank stabilization projects in the Grand River Basin.

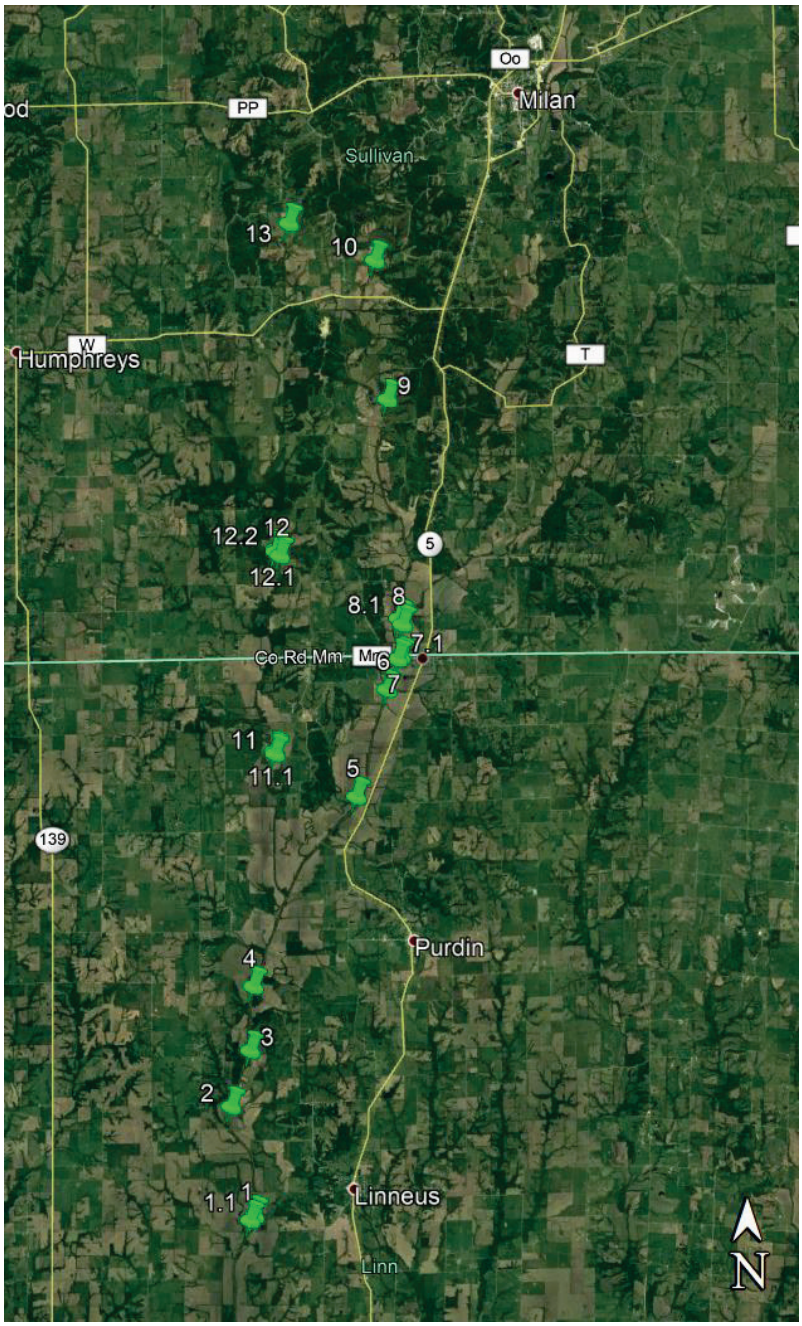

Figure 9. Bank Erosion Sites Analyzed

Because most sites experienced substantial bank movements within just a few of the total 18 years related to high flow events, the reported annual erosion rate does not represent a volume that will consistently erode every year. Rather, the rates approximate long-term averages. Table 4 summarizes the analysis for these thirteen sites.

Table 4. Bank Erosion Summary at 13 Sites (19 Bends)

Site	Bank Height (ft)	Bank Length (ft)	Net Erosion Rate (yd^3/yr)	% Bank Wash Load (Assumed)	Bulk Density of Fines (pcf)	50-Year Reduction in Fines (tons)
1	22	492	670	55%	60.6	15075
1.1	25	662	720	55%	60.6	16200
2	21	834	589	55%	60.6	13252
3	20	903	2143	55%	60.6	48216
4	25	1107	2206	55%	60.6	49634
5	22	844	837	55%	60.6	18832
6	27	491	428	55%	60.6	9630
7	24	429	777	55%	60.6	17482
7.1	25	515	903	55%	60.6	20317
8	26	618	1077	55%	60.6	24232
8.1	26	658	1293	55%	60.6	29092
9	25	720	1265	55%	60.6	28462
10	19	783	1915	55%	60.6	43087
11	17	491	459	55%	60.6	10327
11.1	13	362	532	55%	60.6	11970
12	18	477	627	55%	60.6	14107
12.1	16	377	337	55%	60.6	7582
12.2	18	843	981	55%	60.6	22072
13	14	338	234	55%	60.6	5265

The combined tonnage reduction of fine sediments sourced from these 13 sites (19 bends) is 404,834 tons over a 50 year period. These eroding banks have an average height of 21 ft. In order to achieve significant sediment reduction, smaller bank erosion sites further upland in the watershed will also need to be stabilized. Smaller sites also offer opportunities for lower-cost stabilization measures such as cedar tree revetments. Table 5 lists the number of smaller sites needed to achieve given levels of stabilization. The Quantified Risk is 10,923,069 tons of fine sediment, as computed in Section 3 of this document. In Table 5, a "small site" is assumed to stabilize 250 ft of 12 ft high eroding banks. The shorter banks on smaller streams are assumed to result in proportionally less sediment reduction per linear foot compared to those presented in Table 4. The exact composition and location of sites will be determined during design.

Table 5. Number of Bank Stabilization Sites Needed to Achieve Given Levels of Sediment Reduction

# Small Sites	Reduction in Fine Sediment (tons)	% of Quantified Risk
95	455,000	4%
190	911,000	8%
316	1,515,000	14%
721	3,456,000	32%
1,264	6,060,000	55%
1,738	8,332,000	76%
2,278	10,923,000	100%

6.0 Specific Locations

A sediment reduction of 1,515,000 tons was selected for the recommended plan, which corresponds to approximately 50,000,000 cubic feet of sediment reduction. The exact locations and mix of project sizes and types (small sites vs. large sites, bank stabilization vs. grade control) will be determined during PED. Sufficient stabilization locations are available in the watershed for this reduction. The sediment reduction of 1,515,000 tons over 50 years can be achieved with approximately 15 miles of bank stabilization. The National Hydrography Dataset reports 521 miles of perennial stream length in the watershed upstream from Pershing State Park. An aerial photo approximation indicates 140 miles on the major tributaries to Locust Creek.

The sediment reduction will be achieved through a large number of very small projects. The effect of every project is additive; no single project is uniquely significant. Cost-effectiveness and landowner willingness will guide selection of sites during PED. If a landowner is unwilling then the bank stabilization project can be moved to a different meander with only minor impact.

Table 5 indicates that 316 small bank stabilization sites would achieve the desired reduction. Even fewer than 316 sites may be required to achieve the sediment reduction when other geomorphic treatments, such as headcut stabilization or induced sinks through grade control, are employed. A greater sediment reduction from some of the sites reduces the total number of sites required to achieve the desired sediment reduction.

7.0 Limitations and Recommendations

This appendix documented refinements to the sediment basin analysis, a risk and uncertainty analysis, and watershed reconnaissance and bank erosion analysis. The complex nature of the

geomorphic interactions necessitated several simplifying assumptions and results in uncertainty in the deposition and erosion estimates.

First, the time it will take the pilot channel to adjust is unknown.

Second, not all sources of uncertainty were included in the uncertainty analysis. For example, the entire watershed experienced a record flood in 2019, likely resulting in geomorphic change throughout the watershed. For example, channels may be scoured of readily available fine sediments which deposited on floodplains throughout the watershed, which would induce a downward shift in the flow/sediment rating curve. However, this event could also have destabilized banks or mobilized additional sediments which have not yet reached Pershing State Park, resulting in an upward shift in the flow/sediment rating curve.

Third, only a subset of bank erosion sites were analyzed, and these sites were mostly lower in the watershed. Sites higher in the watershed may be actively incising, leading to opportunities for grade stabilization as well as bank stabilization which could be more cost effective. However, banks at sites higher in the watershed will not be as tall and therefore may not contribute as much sediment per site.

Fourth, all bank erosion analysis was performed using remote sensing data (LiDAR and aerial photos) without site-specific sediment samples. The assumed fine percentage of 55%, derived from other locations in the Grand River Basin, may not be valid in every location. Moreover, both the erosional and depositional side of the bank were assumed to be composed of 55% fine sediments. In reality the erosional side may contain more fines than the depositional side, which would make stabilization at these sites more effective.

Given these assumptions and uncertainties regarding sediment loads and sediment load reduction, the following items are recommended for the project design phase:

1. Re-start sediment monitoring at Linneus and continue collecting through the end of the adaptive management period in order to assess the impact of the 2019 flood on sediment loads.
2. Conduct geomorphic and bank erosion assessments further upstream to find additional bank erosion and (if present) headcut locations.
3. Consider additional sediment sinks from reconnecting channels to their floodplains.
4. Collect additional sediment samples from eroding and depositing banks in the watershed to determine the particle size distribution (i.e. % fines).
5. Design the outlet structures with the flexibility to decrease the trapping efficiency of the basin, e.g. with an additional culvert that can be opened if needed.

Grand River Ecosystem Restoration Study

Final Integrated Feasibility Report and Environmental Assessment

Appendix C3.1: Trip Report from Helicopter Reconnaissance

October 2020

US Army Corps of Engineers ®
Kansas City District

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MEMORANDUM FOR RECORD

SUBJECT: Trip Report from Helicopter Survey of Locust Creek, East Locust Creek, and West Locust Creek

1. PURPOSE: Aerial inspection of Locust Creek, East Locust Creek, and West Locust Creek to identify problems areas (specifically headcuts) to be remediated for the purpose of sediment load reduction. Identify primary sources of woody debris along flight path. Flight followed creeks to allow for visual identification, GPS location, and photo documentation of problem areas.

2. ISSUE: As part of the Grand River Basin Feasibility Study, Locust Creek and its major tributaries have been identified as contributing excessive sediment loads that have caused detrimental impacts downstream including in Pershing State Park. The sediment loads are suspected to be a major factor in the avulsion between Locust Creek and Higgins Ditch due to the severe aggradation and subsequent perched nature of lower Locust Creek.

   In order to aid in sediment modeling of Locust Creek that will help demonstrate the impacts of reduced sediment load, reconnaissance of the Locust Creek basin was requested to attempt to identify major headcuts that were migrating upstream and could be arrested resulting in reduction of sediment loads. Secondary goals of the reconnaissance were the identification of sources of Large Woody Debris (LWD) resulting in problematic log jams in the lower system, identification of other sediment sources (in addition to headcuts), and general assessment and documentation of the basin.

3. SCOPE: A helicopter inspection was conducted on March 14-15, 2017. Participants included Michael Gossenauer (CENWK-ED-HR), Don Meier (CENWK-ED-HH), Tracy Brown (CENWK-ED-S), Tom Woodward (MDNR), and Scott Stephens (MoDOT).

   Locust Creek was flown from its confluence with the Grand River upstream to the Iowa-Missouri state border. For the purpose of inspection, Locust Creek was divided into segments referred to as Lower Locust Creek from the confluence of the Grand River upstream to the northern end of Pershing State Park, and simply Locust Creek upstream of that. East Locust Creek was flown from its confluence with Locust Creek upstream to the location of the proposed dam for a new reservoir. West Locust Creek was flown from its confluence with Locust Creek upstream to the Sullivan-Putnam county line.

   In addition to the three branches of Locust Creek, Parson Creek to the west, and Yellow Creek to the east were also flown. Parson Creek was flown from its confluence with the Grand River upstream to a point just south of Argo Road in Linn County, MO. Yellow Creek was flown from its confluence with the Grand River upstream to a point just south of Jansen Road in Linn County, MO. Figure 1 shows the location and extents of the inspected streams.

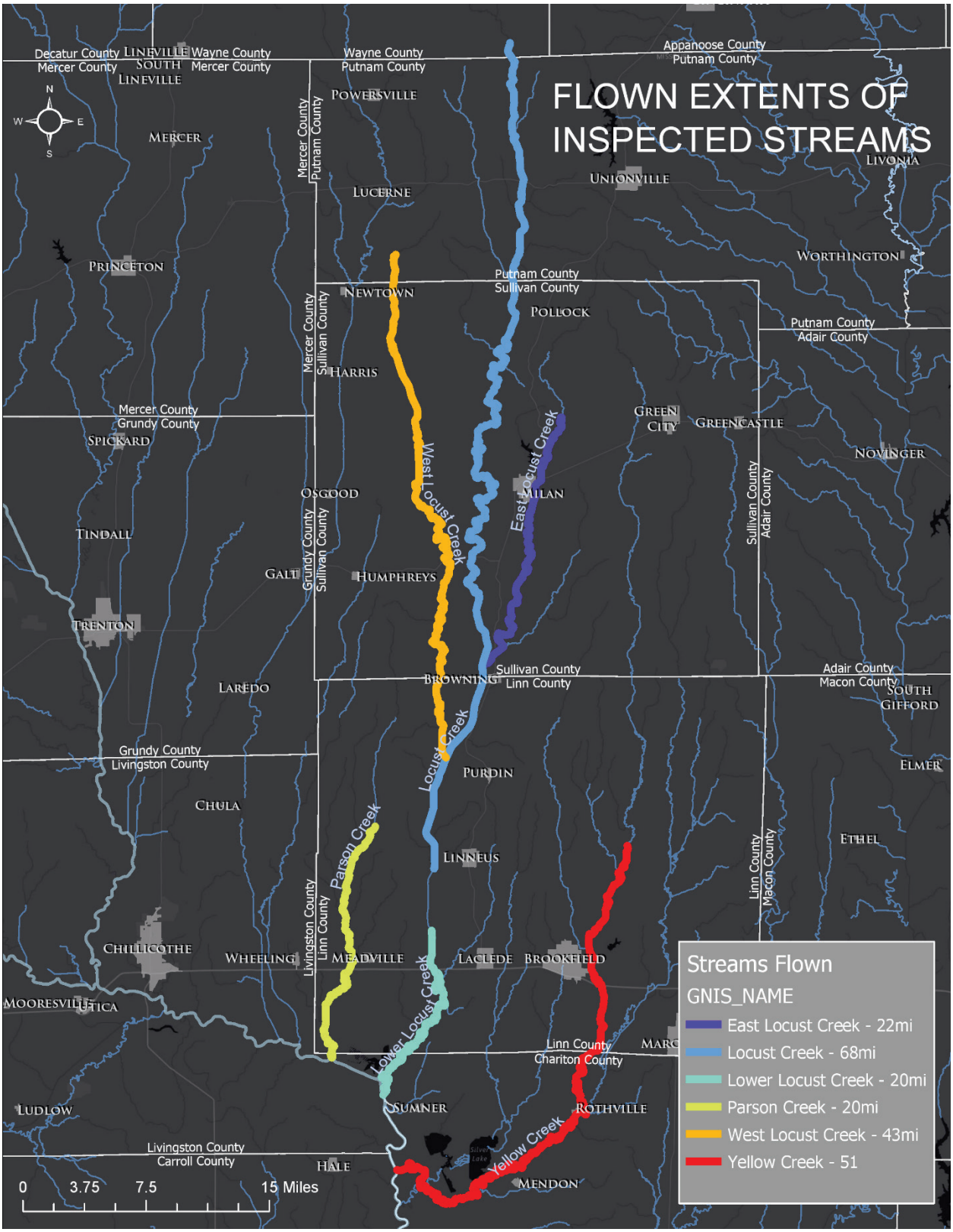

Figure 1: Stream Reaches Inspected by Helicopter

The helicopter flights followed the course of the creeks at a low elevation to allow visual inspection of features of interest within the creeks. Photographs were taken of many points on each creek to provide documentation and further assessment of the condition of the creeks.

4. RESULTS: Only one active headcut was observed on the main channel of all streams inspected. The active site is located on Locust Creek approximately one mile upstream from the low water crossing for Thrush Road as seen in Figure 2.

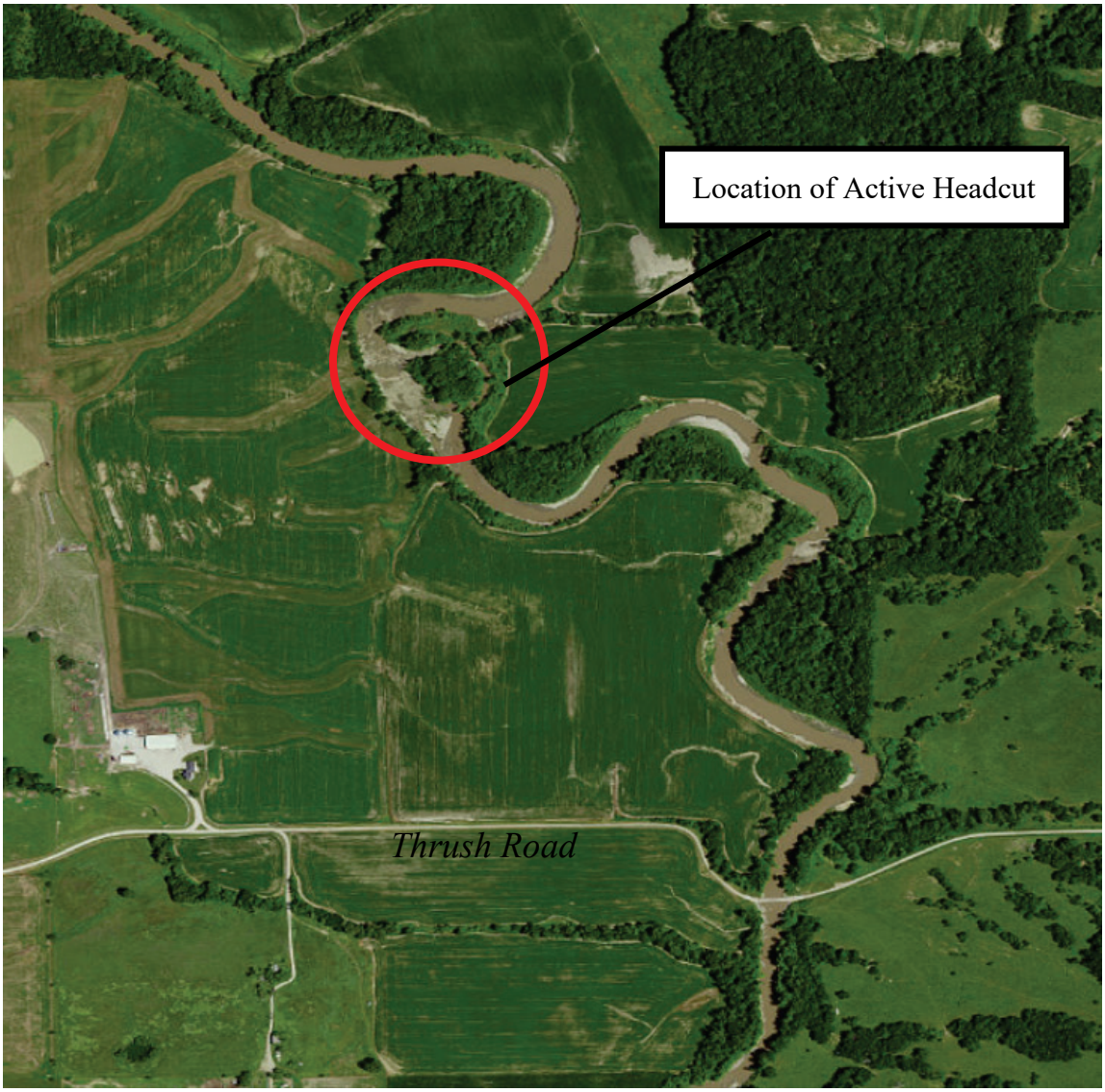

Figure 2: Location of Active Headcut

The headcut was located in an active avulsion adjacent to a bend of the current Locust Creek channel that had significant rock outcropping in the bed. The avulsion contained a significant amount of LWD and was approximately 700 feet in length and bypassed approximately 1,300 feet of channel. The headcut is located approximately 500-600 feet

up the avulsion from where it reconnects to the main channel and appeared to be about three to four feet in height and is shown in Figure 3.

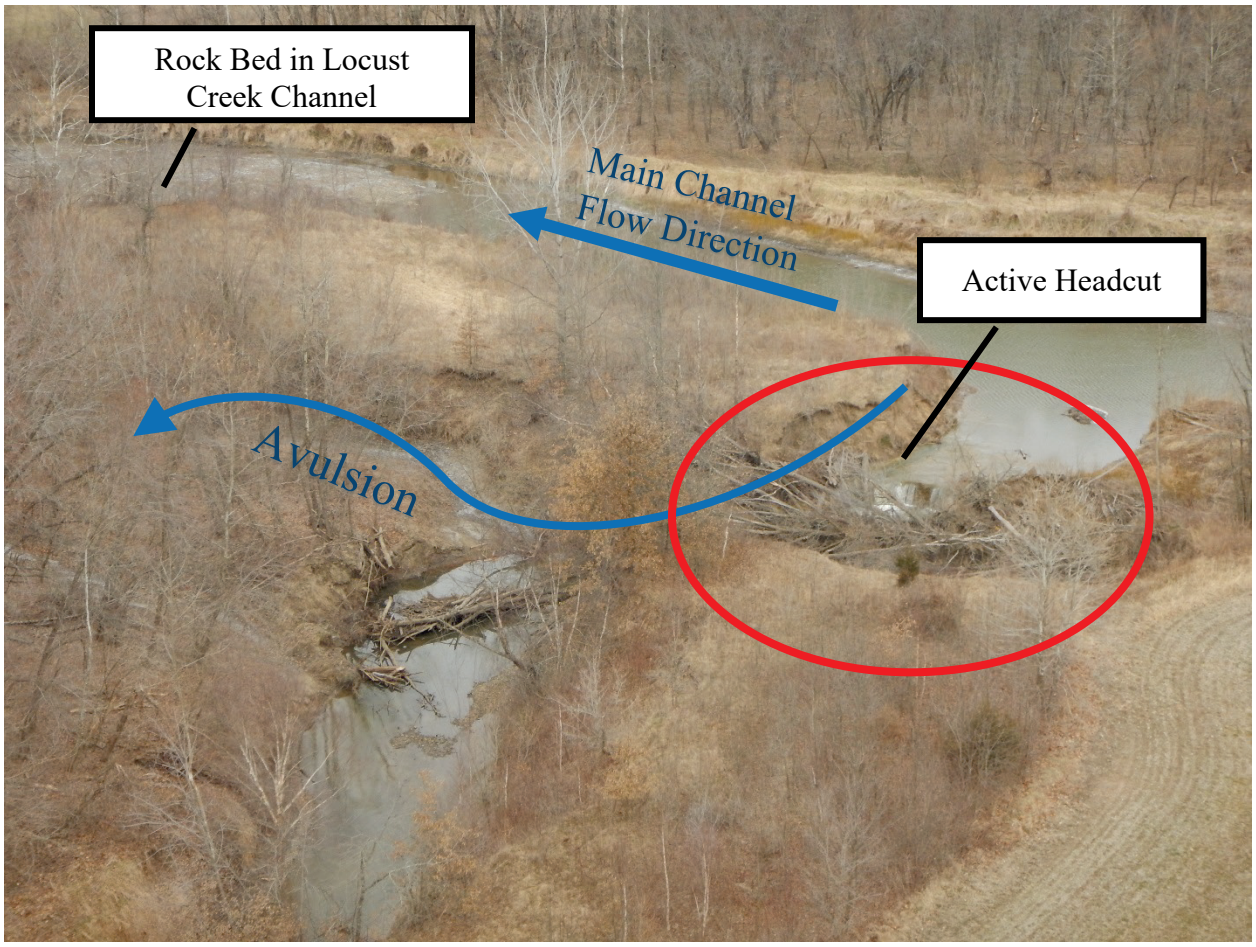

Figure 3: Headcut on Locust Creek Avulsion

In addition to the single active headcut, sites with the following features were documented and photographed: Bank erosion (Figure 4); drainage ditches (Figure 5) or adjacent fields with runoff headcuts (Figure 6); LWD accumulation in the channel (Figure 7); streambed reaches with rock outcropping or significant gravel or cobble bed material (Figure 8); beaver dams (Figure 9); and bridges (Figure 10).

Figure 4: Bank Erosion on West Locust Creek (Photo: WLocCrk_BankErosion (71).jpg)

Figure 5: Drainage Ditch Erosion on Locust Creek (Photo: LocCrk_FieldErosion (43).jpg)

Figure 6: Field Erosion on West Locust Creek (Photo: WLocCrk_FieldErosion (15).jpg)

Figure 7: Large Woody Debris on Yellow Creek (Photo: YelCrk_LWD (4).jpg)

Figure 8: Streambed Rock Outcrop on East Locust Creek (Photo: ELocCrk_RockBed (4).jpg)

Figure 9: Beaver Dam on West Locust Creek (Photo: WLocCrk_BeaverDam (3).jpg)

Figure 10: Bridge (Hwy-36) over Parson Creek (Photo: ParCrk_Bridge (4).jpg)

Table 1shows the number of each of these sites that were identified in photos in each of the inspected creeks. It should be noted that features such as eroding banks and field erosion were so common that not all sites were documented. Attempts were made to photograph and document severe cases as well as a large number of typical sites.

Table 1: Sites Photographed in Each Creek Inspected

Stream Name (miles flown)	Erosion Banks	Erosion Field Drainage	LWD	Rock Bed	Bridge	Beaver Dam
Locust Creek (68mi)	80	45	23	35	20	6
Lower Locust Creek (20mi)	6	4	11	8	7	1
East Locust Creek (22mi)	27	8	19	21	4	17
West Locust Creek (43mi)	53	30	31	28	7	11
Yellow Creek (51mi)	30	1	26	5	1	0
Parson Creek (20mi)	12	2	17	5	4	3

As can be seen in Table 1, multiple types and locations of erosion were common throughout all inspected streams and watersheds. While erosion from streambanks, drainage ditches, and field gullies were all common, it should be noted that the different types of erosion likely have differing impact on the sediment loads in the streams.

Appendix A contains the photographs from the helicopter survey organized by stream and feature type. Appendix B contains maps showing the locations of the photographs taken and feature types present at each site.

5. DISCUSSION: Initial expectations of conditions on Locust Creek and surrounding streams was that, due to prior channelization and watershed development, there would be active headcuts making their way upstream and acting as a source of significant sediment load. The state of the streams as viewed from the helicopter appears much more complex with the streams in various stages of alternating stability and readjustment along the length of each of the streams inspected. In addition, all streams intermittently flowed over deep glacial material and shallow rock areas resulting in bed elevation control at multiple points throughout inspected reaches.

   The natural grade control provided by the bedrock or gravel bed did not appear to be significantly correlated with bank stability with some banks immediately upstream of bedrock sections still showing significant erosion and over steepened conditions. Additional bank erosion is evident even in un-channelized reaches typically adjacent to farming and loss of trees on the outside bends.

   In the one instance noted in Section 4 of an active headcut, the conditions upstream of the site are such that the amount of sediment load that could be mitigated by arresting the headcut is limited. The banks immediately upstream are already eroding and over steepened, so mitigating the headcut would not necessarily prevent de-stabilization of stable banks. In addition, there is an instance of natural grade control with rock in the streambed approximately 3,500 feet upstream from the avulsion that would likely arrest the headcut if it makes it that far upstream. Considering the stream conditions in the area, increased sediment load from this headcut would likely be limited to the bed material displaced as it worked upstream to the next grade control. With a cut depth of three to four feet, stream width of about 100 feet, and a distance to the next natural grade control of 3,500 feet, a total sediment load of approximately 50,000 cubic yards of sediment that could potentially be introduced before the headcut is naturally arrested by current stream conditions. Aerial imagery from prior years indicate that the lower portion of the avulsion is a preexisting slough. With unknown elevation and dimensions of the slough, it is difficult to identify where the headcut started and how it has progressed over time. However, it does appear to have moved 100-200 feet upstream in the avulsion between 2015 and 2017.

   The widespread nature of bank erosion and intermittent nature of stable banks with over steepened banks regardless of the vicinity of natural grade control would make sediment reduction by artificial grade control challenging if not entirely ineffective. The observation of the majority of erosion occurring either in areas of over steepened banks or off channel in drainage ditches or field runoff gullies, suggests that continued focus on Best Management Practices (BMP) in the watershed might be the best avenue to enact sediment reduction in the inspected streams, but further analysis and discussion would be

needed to determine what BMPs are already being utilized and what new efforts would be most relevant and helpful.

The erosion from banks, drainage ditches and adjacent fields likely contribute differing types of sediment load that have varying impact on downstream aggradation. While surface runoff from farm fields likely contains a high percentage of fines that will eventually wash through the system, erosion of banks, is likely predominantly sand that will be more difficult to transport and more likely to contribute to aggradation problems downstream. The contribution of erosion in drainage ditches and field gullies could vary widely depending on the depth of the cut and percentage of fines verses sand in those areas. Localized BMPs would need to work on a site-by-site basis for those features to determine the potential for reducing sand sediment load and the best methods for mitigating erosion.

A general assessment of the source of LWD in the streams that has been contributing to logjams failed to identify a single source. A large percentage of banks in the area are lined with riparian vegetation and in areas where banks are over steepened and sloughing, these riparian trees are being deposited into the streams. In addition, multiple areas of felled trees were observed in areas that appeared to be either cleared for farming or actively harvested for timber. In either case, some woody debris was left available for transport in the floodplain near the streams.

Regardless of the source of LWD, it was present throughout the extents of all inspected streams with significant accumulations occurring occasionally.

6. SUMMARY: The conditions in Locust Creek and nearby streams were not as expected. Streambeds did not have clearly identified headcuts moving upstream in response to previous channelization or reaches. Areas of stable banks and eroding, over steepened banks were interspersed through all streams inspected. The complex responses of the bed and banks make it difficult to identify discrete, in-channel projects that would likely reduce sediment load downstream.

   The occurrence of multiple points of rock bed grade control in all streams inspected with no apparent spatial correlation to reaches of either stable or eroding banks raise doubts as to the efficacy of grade control to have long term sediment reducing potential.

   One headcut was identified on Locust Creek with some limited potential for short term sediment load reduction. However, with rock bed reaches adjacent to the headcut as well as a short distance upstream both the spatial and temporal impact of potential mitigation efforts in that area would be limited. Streambanks upstream of the headcut are already over steepened and would likely continue to contribute sediment load even with mitigation of the headcut in the streambed.

   Large woody debris appears endemic throughout all streams inspected. Sources of LWD appeared to be from the riparian vegetation along a large percentage of the banks for the entire length of the streams. Over steepened banks throughout much of the basin likely

contribute to an accelerated rate of LWD being introduced into the active channel of streams.

Eroding banks in the streams appeared to be a major source of sediment load in the streams. Erosion in adjacent fields and small drainage ditches that feed into the streams were prevalent throughout the basin and have potential to be a significant source of sediment load downstream but soil type, extent, and location of this type of erosion would need to be determined on a site-by-site basis to determine its overall impact relative to streambank erosion. Because reducing sediment load in the inspected streams is likely to require individual site remedies throughout the basin it is likely that basin-wide efforts to implement, or continue, BMPs for reduction of both point and non-point sources of sediment into the streams is the best way to affect long term sediment load reductions in this area. Investigation into the existing use of BMPs and potential future BMPs would need to be conducted before pursuing this avenue.

Grand River Ecosystem Restoration Study

Final Integrated Feasibility Report and Environmental Assessment

Appendix C3.2: Grand River Basin Erosion Analysis

October 2020

US Army Corps of Engineers ®
Kansas City District

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1. Purpose

The purpose of this appendix is to document the details and method of analysis used to assess and quantify the annual erosion rate at specific sites along Locust Creek and West Locust Creek within the Grand River Basin.

2. Erosion Assessment

Thirteen sites, with some sites comprising multiple consecutive bends, were assessed to determine an annual erosion rate utilizing an 18 year range of observation (1997-2015). Typically sites were chosen based on a river bend with minimal bank vegetation and coinciding with "hot spots" from the 2013 PAS study "North Central Missouri Locust Creek Watershed Study Final Report". Having minimal vegetation cover allowed for Google Earth imagery of high bank extents along Locust Creek to be compared from 1997 to 2015. This comparison would often show areas both of substantial erosion and deposition that occurred at the chosen locations. An area was measured by drawing a polygon in Google Earth encompassing the eroded or deposited location, and calculating the square footage. That area was then multiplied by the high bank height extracted from a 2017 LiDAR terrain to estimate a volume for the 18 year period. This volume was divided by the 18 years to estimate a cubic yard per year erosion/deposition rate. At each analyzed bend, if the outer bend eroded while material deposited within the inside bend, the volume of deposition was subtracted from the erosion volume to compute a net volume of eroded material. The bank material was assumed to be 55% fines based on other bank stabilization projects in the Grand River Basin. Site-specific sediment size gradations will update this number as the study progresses.

Because most sites experienced substantial bank movements within just a few of the total 18 years related to high flow events, the reported annual erosion rate does not represent a volume that will consistently erode every year. Rather, the rates approximate long-term averages.

Figure 1 maps the locations of each site. Table 1 summarizes the results.

Figure 1.Overall site location map.

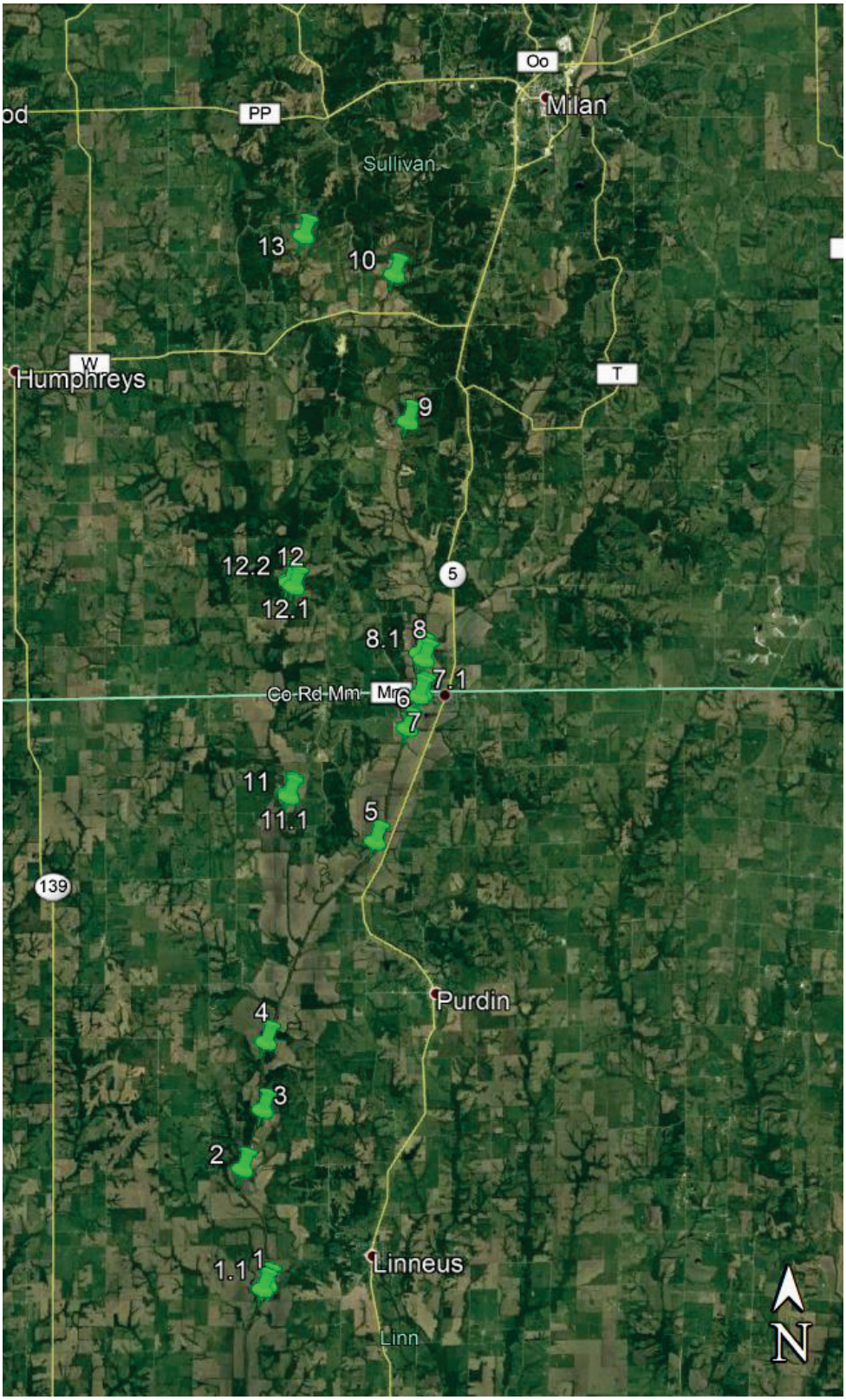


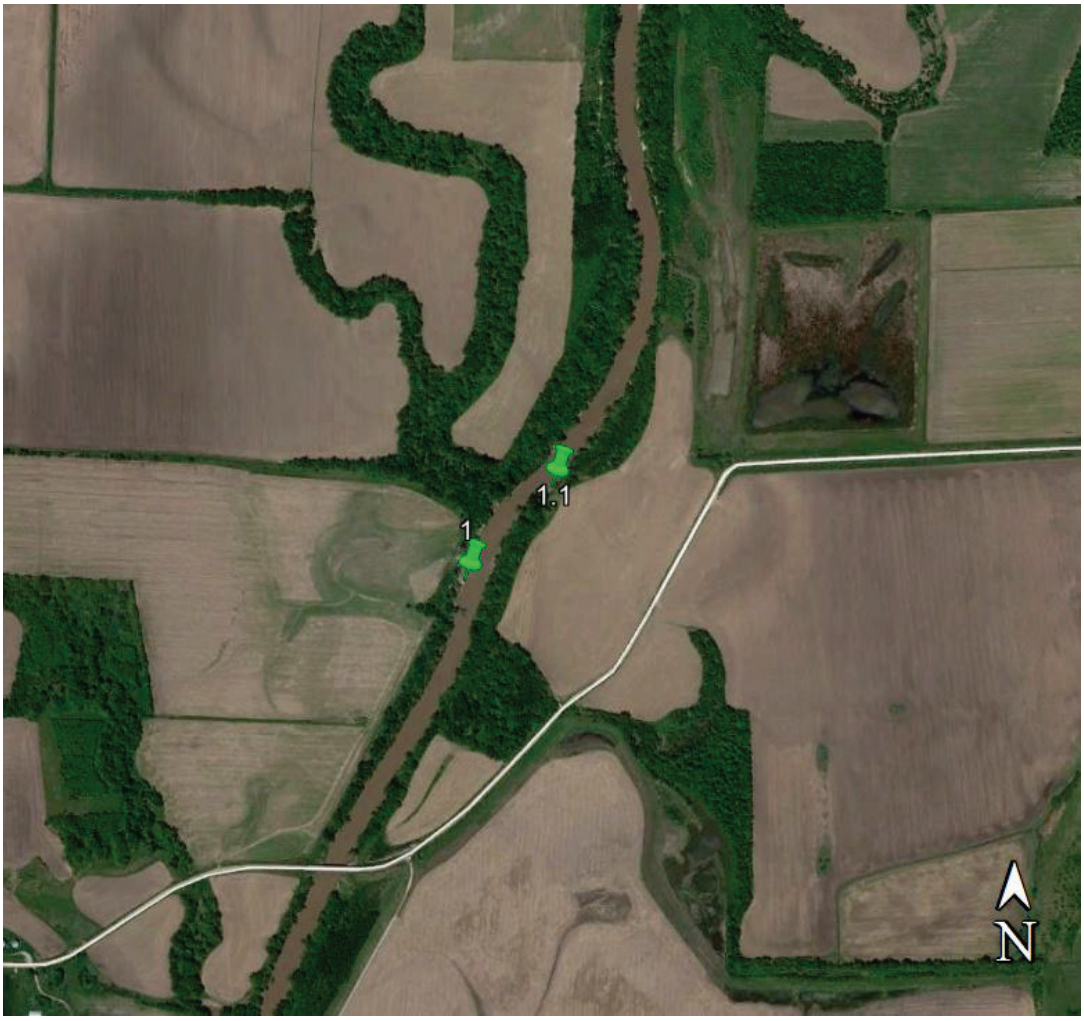
Table 1. Overall summary

Site	Bank Height (ft)	Net Erosion Rate (yd^3/yr)	% Bank Wash Load (Assumed)	50-year Wash Load Reduction (yd^3)	Bank Length (ft)	50-year Sediment Reduction per 1 ft of Eroding Bank (yd^3/ft)
1	22	670	55%	18425	492	37
1.1	25	720	55%	19800	662	30
2	21	589	55%	16198	834	19
3	20	2143	55%	58933	903	65
4	25	2206	55%	60665	1107	55
5	22	837	55%	23018	844	27
6	27	428	55%	11770	491	24
7	24	777	55%	21368	429	50
7.1	25	903	55%	24833	515	48
8	26	1077	55%	29618	618	48
8.1	26	1293	55%	35558	658	54
9	25	1265	55%	34788	720	48
10	19	1915	55%	52663	783	67
11	17	459	55%	12623	491	26
11.1	13	532	55%	14628	362	40
12	18	627	55%	17243	477	36
12.1	16	337	55%	9268	377	25
12.2	18	981	55%	26978	843	32
13	14	234	55%	6435	338	19

The combined volume of fine sediments sourced from these 13 sites (19 bends) is 495,000 cubic yards over a 50 year period. Rates of sediment reduction per unit length of eroding bank range from 19 to 67 cubic yards per linear foot.

Figures 2 to 14 show site locations with 2015 imagery, a detailed table, and helicopter inspection photos where available.

Figure 2. Site 1.



Site	1	1.1
Bank Height (ft)	22	25
Net Erosion Rate (yd^3/yr)	670	720
% Bank Wash Load	55%	55%
50-year Wash Load Reduction (yd^3)	18425	19800
Bank Length (ft)	492	662

Figure 3. Site 2.

Site	2
Bank Height (ft)	21
Net Erosion Rate (yd^3/yr)	589
% Bank Wash Load	55%
50-year Wash Load Reduction (yd^3)	16198
Bank Length (ft)	834

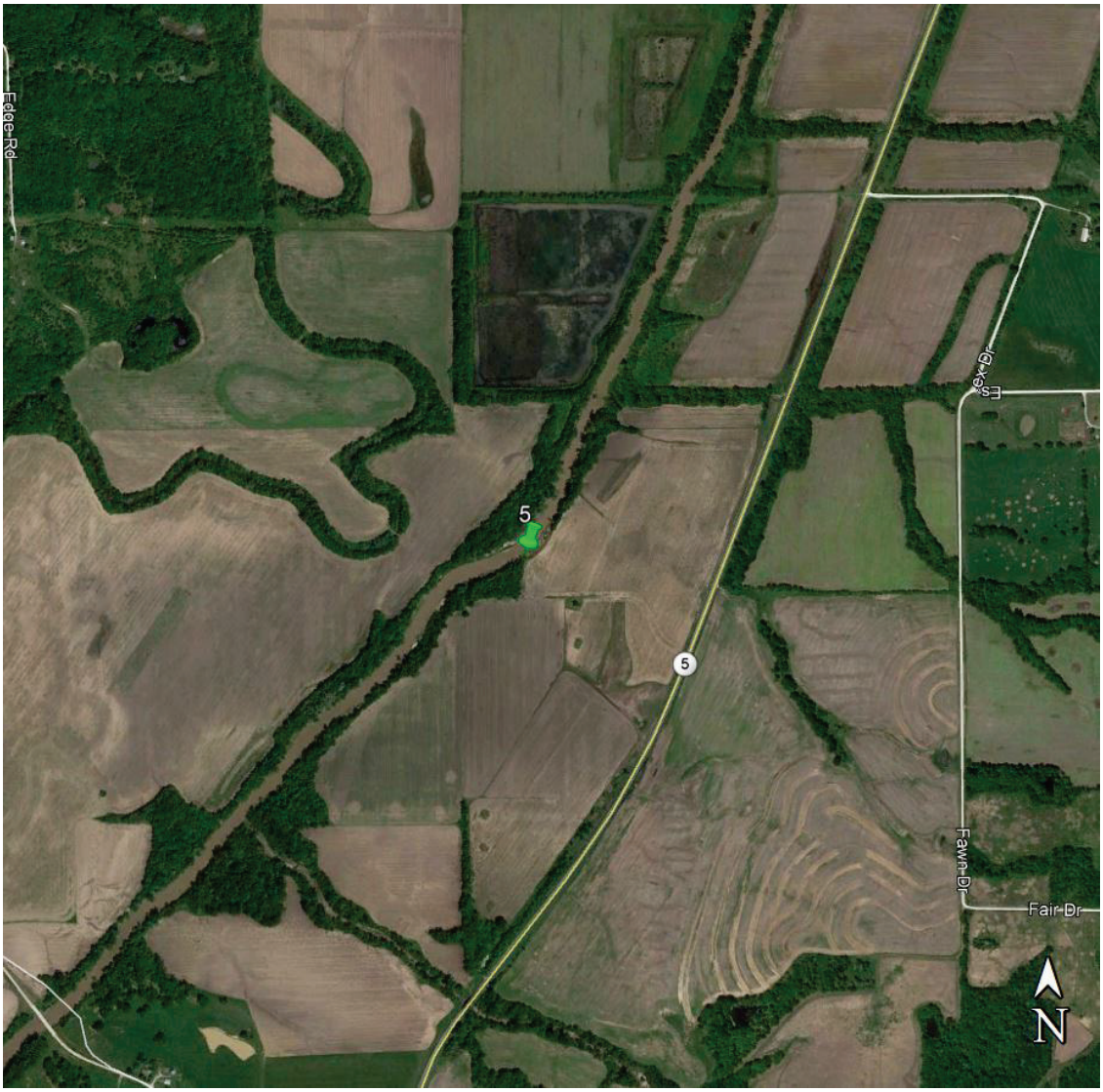
Figure 4. Site 3.

Site	3
Bank Height (ft)	20
Net Erosion Rate (yd^3/yr)	2143
% Bank Wash Load	55%
50-year Wash Load Reduction (yd^3)	58933
Bank Length (ft)	903

Figure 5. Site 4.

Site	4
Bank Height (ft)	25
Net Erosion Rate (yd^3/yr)	2206
% Bank Wash Load	55%
50-year Wash Load Reduction (yd^3)	60665
Bank Length (ft)	1107

Figure 6. Site 5.



Site	5
Bank Height (ft)	22
Net Erosion Rate (yd^3/yr)	837
% Bank Wash Load	55%
50-year Wash Load Reduction (yd^3)	23018
Bank Length (ft)	844

Figure 7. Site 6.

Site	6
Bank Height (ft)	27
Net Erosion Rate (yd^3/yr)	428
% Bank Wash Load	55%
50-year Wash Load Reduction (yd^3)	11770
Bank Length (ft)	491

Figure 8. Site 7.

Site	7	7.1
Bank Height (ft)	24	25
Net Erosion Rate (yd^3/yr)	777	903
% Bank Wash Load	55%	55%
50-year Wash Load Reduction (yd^3)	21368	24833
Bank Length (ft)	429	515

Figure 9. Site 8.

Site	8	8.1
Bank Height (ft)	26	26
Net Erosion Rate (yd^3/yr)	1077	1293
% Bank Wash Load	55%	55%
50-year Wash Load Reduction (yd^3)	29618	35558
Bank Length (ft)	618	658

Figure 10. Site 9.

Site	9
Bank Height (ft)	25
Net Erosion Rate (yd^3/yr)	1265
% Bank Wash Load	55%
50-year Wash Load Reduction (yd^3)	34788
Bank Length (ft)	720

Figure 11. Site 10.

Site	10
Bank Height (ft)	19
Net Erosion Rate (yd^3/yr)	1915
% Bank Wash Load	55%
50-year Wash Load Reduction (yd^3)	52663
Bank Length (ft)	783

Figure 12. Site 11.

Site	11	11.1
Bank Height (ft)	17	13
Net Erosion Rate (yd^3/yr)	459	532
% Bank Wash Load	55%	55%
50-year Wash Load Reduction (yd^3)	12623	14628
Bank Length (ft)	491	362

Figure 13. Site 12.

Site	12	12.1	12.2
Bank Height (ft)	18	16	18
Net Erosion Rate (yd^3/yr)	627	337	981
% Bank Wash Load	55%	55%	55%
50-year Wash Load Reduction (yd^3)	17243	9268	26978
Bank Length (ft)	477	377	843

Figure 14. Site 13

Site	13
Bank Height (ft)	14
Net Erosion Rate (yd^3/yr)	234
% Bank Wash Load	55%
50-year Wash Load Reduction (yd^3)	6435
Bank Length (ft)	338

Grand River Ecosystem Restoration Study

Final Integrated Feasibility Report and Environmental Assessment

Appendix C4: Additional Woody Debris, Sedimentation, And Flooding Analyses for the Tentatively Selected Plan at Pershing State Park

October 2020

US Army Corps of Engineers ®
Kansas City District

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1.0 Introduction

The Tentatively Selected Plan (TSP) for Pershing State Park includes re-routing flows from Higgins Ditch into a sedimentation basin, into Muddy Creek, then back to old Locust Creek. On Higgins Ditch, a grade control structure will be built to create backwater to induce sediment deposition on State property upstream of Highway 36 in order to protect more important habitats downstream of Highway 36. Since the selection of the TSP additional analyses on the woody debris loading were undertaken and public comments questioning the flooding impacts of the TSP were received. This appendix summarizes the TSP refinements to reduce the impacts of woody debris jams and flooding.

2.0 Refinements to Reduce Woody Debris Impacts

The watershed upstream of Locust Creek generates significant woody debris loads (see Appendix C3) which result in frequent, extensive log jams. Historically, these jams have formed every few years and have persisted and grown until manually removed; hydraulic forces have been insufficient to dislodge them. Appendix C4.1 provides an analysis of large woody debris volume and decay based on historic log jams at Pershing State Park. Table 1 summarizes the calculated average annual wood loading and the annual loading assuming a safety factor of 2 and a bypass factor as listed, and the final storage volume occupied by large wood or decomposed large wood.

Table 1. Summary of Woody Debris Loading Cases. See Appendix C4.1 for Details.

Scenario	Annualized Loading (cy)	Bypass %	Basin Inflow with Safety Factor (cy)	Sediment Burial %	Interval Single Piece Decay Rate (years)		End of Year 50 Storage Volume	
					50% Decay	95% Decay	cy	acre-ft
Low	6623	33%	8875	25%	8	36	1.4E+05	90
Medium	20052	33%	26870	25%	10	44	4.7E+05	293
High	20052	0%	40104	50%	13	57	7.9E+05	490
Worst Case	42480	0%	84960	50%	14	62	1.7E+06	1078

The Future Without Project (FWOP) assumes the Medium scenario for woody debris loading but also assumes that the State of Missouri removes woody debris jams in a timely manner. This introduces risk that significant jams could occur and induce upstream flooding and avulsions prior to the log jams being removed. The consequences of that risk for the FWOP have not been quantified.

For the TSP, the High scenario was used, which assumes all of the wood deposits in the sedimentation basin and 50% of the wood is buried in sediment (resulting in a slower decay rate). See Appendix C4.1 for more information on how these volumes were derived.

The TSP directs the woody debris into the sedimentation basin on the east side of Locust Creek. The TSP assumption is that most of the wood transports towards the downstream end of the basin where it deposits, eventually decays, and becomes a permanent part of the landscape and ecosystem. The pilot channel that diverts Locust Creek into the sedimentation basin will be built with a 90 ft bottom width, 2:1 side slopes, and a depth averaging 4 ft to more easily pass wood. Figure 1 illustrates the pilot channel configuration in the sedimentation basin.

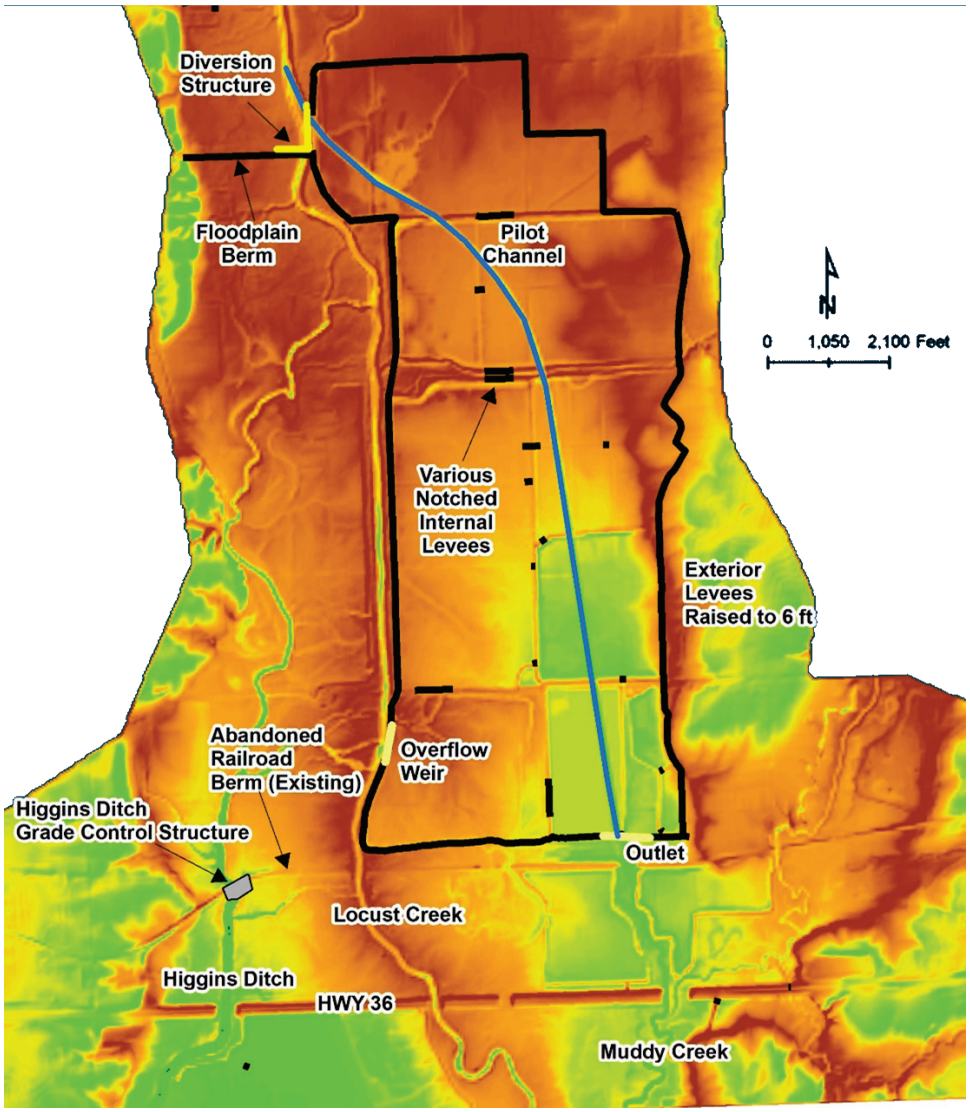

Figure 1. Major Features of the TSP Upstream of HWY 36

The pilot channel maintains a velocity of aprx. 3.5 ft/s until it reaches backwater from the basin. Figure 2 shows the effect of backwater on the velocity in the pilot channel for a 2-year steady-

state model run. As seen, the velocity decreases quickly as the channelized flow reaches the backwater. The upstream extent of the backwater fluctuates with pool elevation which rises and falls over the course of the inflow and outflow hydrographs. Individual pieces of wood may float further downstream as the pool drains. Wood that has floated out of the channel into the basin floodplain or formed a log jam may remain where it initially lodges.

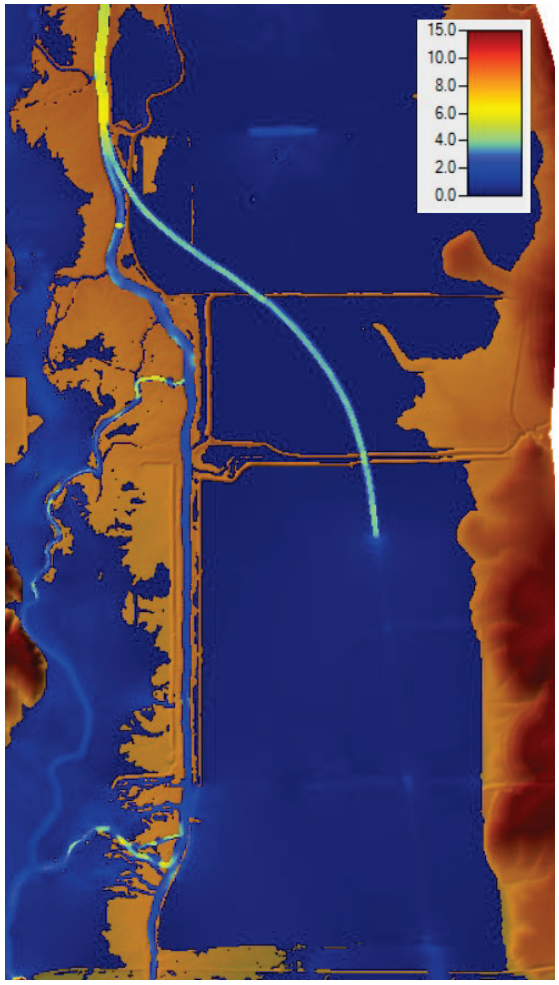

Figure 2. Velocity in the Pilot Channel in the TSP

The dimensions and planform of the pilot channel are expected to change over time. As log jams form, the channel is expected to aggrade, avulse, and ultimately cut around the deposits, which will introduce sinuosity to the channel. The flow capacity of the channel is expected to size itself to the outflow. At the project start, the outflow to Muddy Creek is around 1,500 cfs (up to 2,000 cfs during the largest floods). In Year 10, additional outlets will be opened to increase the discharge to around 4,000 cfs. The remainder of the inflow to the basin passes over an overflow weir back to Locust Creek then back to Higgins Ditch.

A revised basin volume computation was performed which includes the accumulation of the wood as well the change from a 1,500 cfs to a 4,000 cfs pilot channel in Year 10. The increase in outflows leads to less sediment trapping in the basin, as sediment entering the basin while the

flow is within the banks of the pilot channel is assumed to pass through the basin without depositing. The goal is to pass sediment downstream while flow in the downstream channel is likewise within banks and thus maximize basin longevity while minimizing sediment deposition on sensitive floodplain habitats downstream of HWY 36.

Figure 3 plots the deposition in the basin over time. As the basin deposits, the trapping efficiency decreases, as shown in Figure 4. Figures 3 and 4 were computed using the Churchill method for trapping efficiency, which out of the four methods tested yielded the highest trapping efficiency (see Appendix C2). This provides a conservative estimate for basin longevity, meaning the basin may not fill in as quickly. As indicated in Figure 4, the trapping efficiency is zero much of the time, corresponding to days the flow is below the channel banks and therefore not depositing on the floodplain. Figure 4 also plots the trapping efficiency of the Brune curve used for the computation of project benefits for comparison.

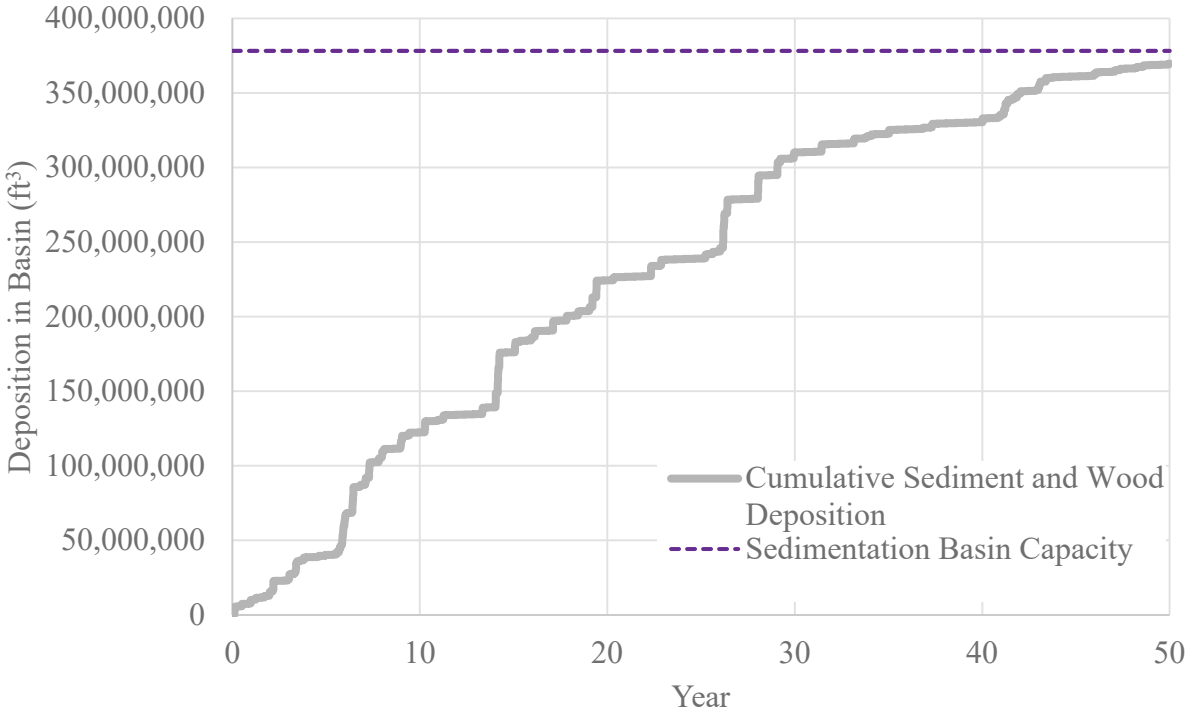

Figure 3. Wood and Sediment Deposition in the Sedimentation Basin Over Time

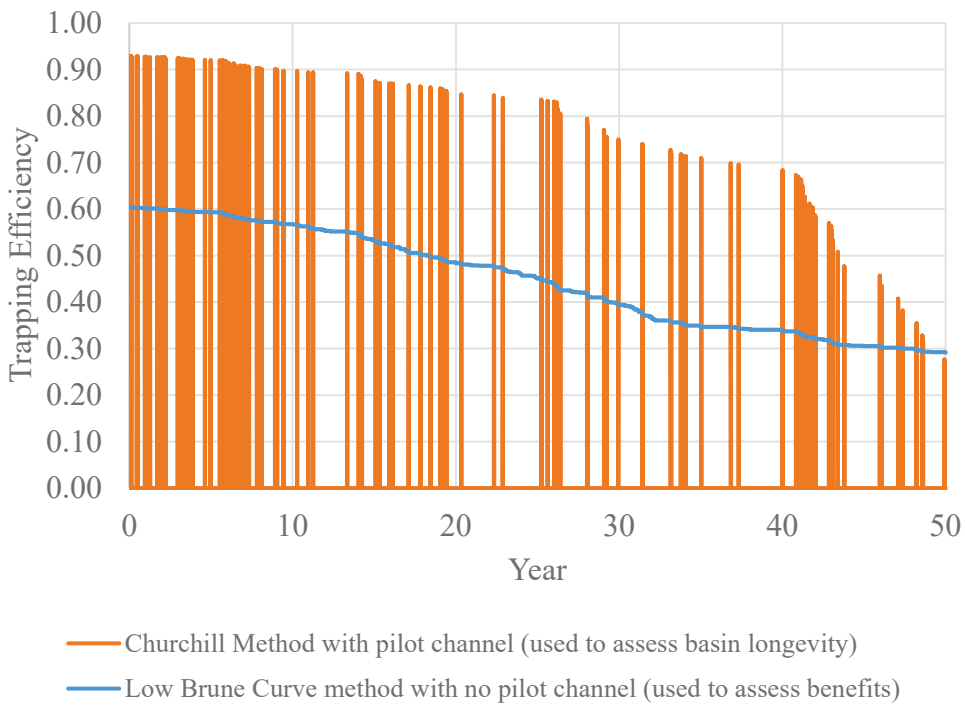

Figure 4. Trapping Efficiency over Time

Feasibility-level analysis indicates that with a 4,000 cfs pilot channel starting in Year 10, the sediment basin will have sufficient volume for both woody debris and sediment over a 50-year project life. However, this is based on a limited amount of sediment measurements and analyses. More detailed analysis is recommended during design to optimize the inflow and outflows to the basin for habitat lift and basin longevity.

Figures 3 and 4 indicate performance using the Churchill method for computing trapping efficiency. As indicated in Appendix C3, the Churchill method predicts the highest trapping efficiency of the four methods analyzed, and hence the fastest accumulation of sediment. If trapping efficiency is in fact lower than that predicted by the Churchill method, increasing the flow rate in Year 10 may not be necessary.

However, this analysis assumes deposition in the basin is evenly distributed or at least occurs from downstream to upstream. As indicated earlier in the document woody debris could lodge further upstream in the channel, particularly at the upstream extent of typical backwater for the basin. Disproportionate deposition further upstream in the basin could reduce the useful life of the basin even while storage capacity remains in the basin overall. Further analysis during design and monitoring during adaptive management may indicate adjustments to the increase at Year 10 suggested here.

2.0 Refinements to Reduce Flooding Impacts

Several public comments questioned the impact this project will have on flood heights, particularly upstream of the State lands. In the as-built condition, the TSP actually lowers water

surface elevations upstream of State lands, as shown in Figure 5. This occurs because additional conveyance is opened up through the pilot channel and sedimentation basin. See Appendix B.1 for more information.

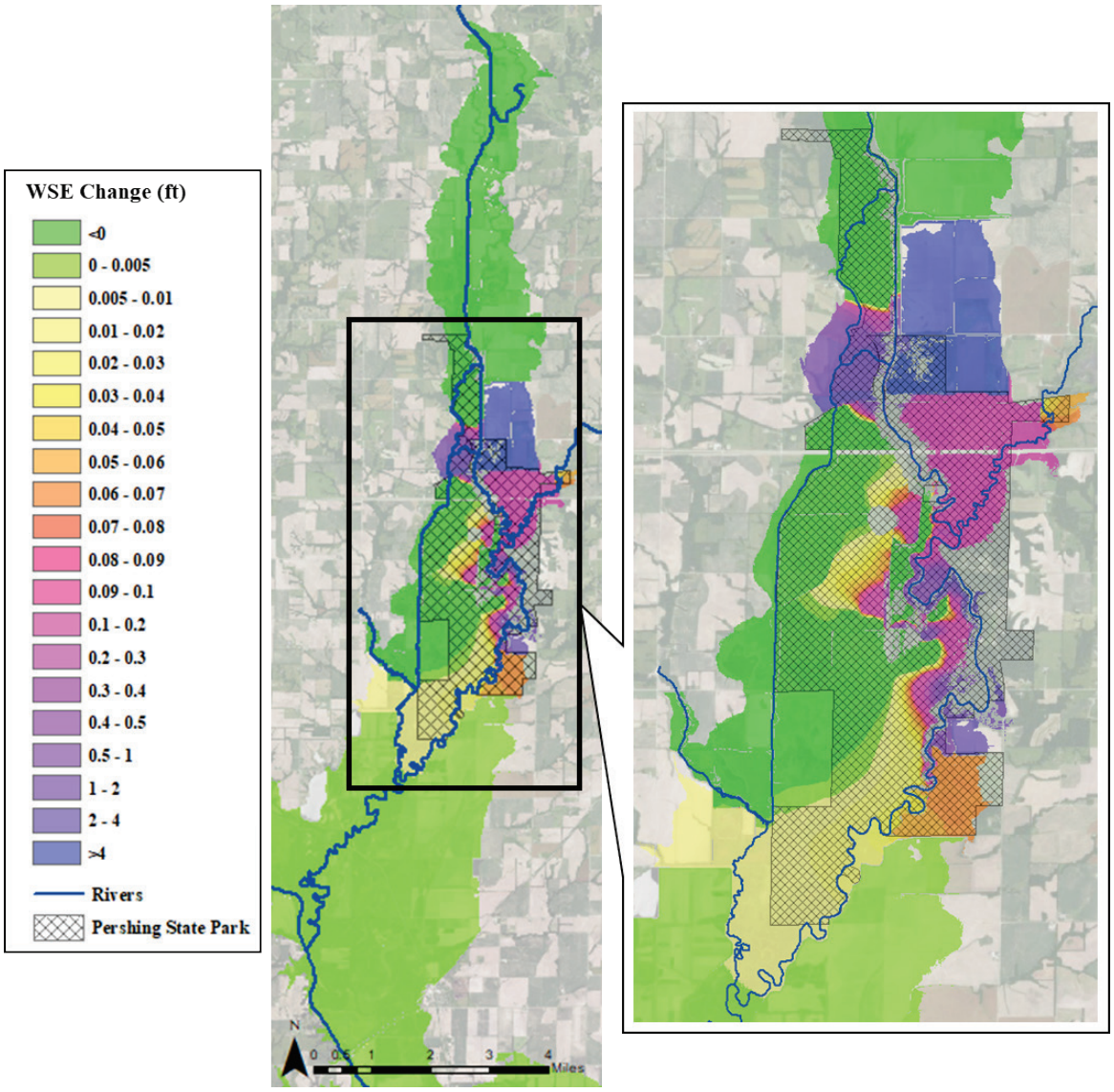

Figure 5. 100-year Water Surface Elevation Changes between FWOP and LC15.5 (Similar to TSP) in Year 0. From Appendix B.1. Note that upstream of the park boundary and the area for the sedimentation basin, the change is less than 0.

The long-term effect of the project on flooding is much more difficult to ascertain due to opposing processes. One the one hand, opening up additional conveyance allows for lower water surfaces. Moreover, decreasing the incoming sediment load through bank stabilization and other sediment reduction strategies decreases conveyance loss from floodplain deposition. On the other hand, the grade control structure on Higgins Ditch induces a backwater effect which increases deposition upstream on State lands and would tend towards higher water surfaces.

The Specific Gage tool in the HEC-RAS sediment was used to assess the 100-year (0.01 AEP) flood profile at the end of the 50 years of sediment simulation. Figure 6 graphs the difference between the FWOP and the TSP.

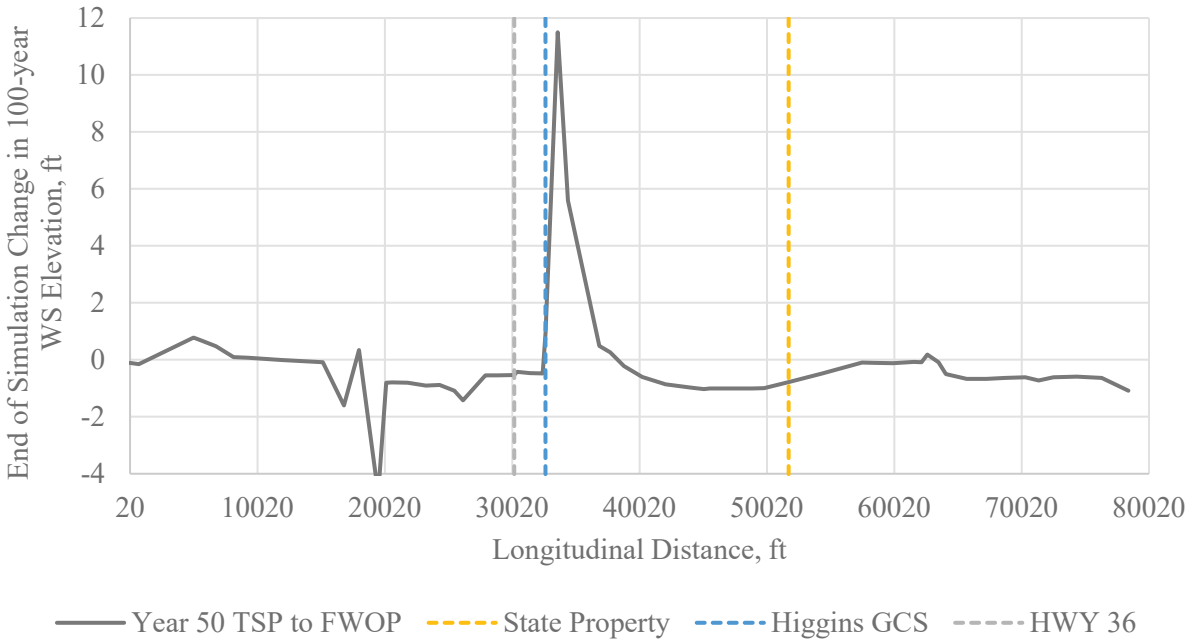

Figure 6. End of Simulation Effect on the 100-year Flood Profile

As seen in Figure 6, the TSP significantly raises flood heights on state property just upstream of the grade control structure. But the effect is limited to State property. Further upstream indicates either lower flood profiles or essentially no change from the FWOP to the TSP.

This finding, while encouraging, is by no means definitive. The 1D sediment model was developed to predict habitat impacts, particularly on sensitive habitats downstream of HWY36. Its use for flooding impacts upstream of HWY36 where the channel is perched and avulsions are prevalent contains significant uncertainty. During the design phase, 2D sediment modeling is recommended so potential water surface effects from laterally distributed sediment deposition, both upstream of the grade control structure and in the sediment basin, can be taken into account.

To reduce the risk of excessive deposition on the west floodplain, the crest of the proposed grade control structure is set lower compared to the original LC15.5 concept in order to more readily pass moderate flows without ponding. This will allow moderate discharges on Higgins ditch, those that would be within the bankfull channel downstream of Highway 36, to flow downstream in order to reduce deposition upstream of the structure. By passing in-channel flows downstream, floodplain deposition upstream of the grade control structure is minimized without additional floodplain deposition downstream.

3.0 Summary of Refinement to the TSP

Table 1 compares major features in LC Alternative 15.5 to the refined TSP.

Feature	Original LC15.5	Refined TSP
Pilot Channel	Meandering channel with limited width extending from the diversion to the outlet	Straight channel with sufficient width to pass woody debris further into the basin
Diversion Structure	Divert up to 1,800 cfs into the basin	Divert up to 6,300 cfs into the basin
Downstream Outlet	Outlets discharge aprx. 1,500 cfs, up to 2,000 cfs during major flood inflows. Assume 0 trapping efficiency for flows up to 1,500 cfs.	Additional outlet structures opened in Year 10, allowing up to 4,000 cfs discharge during major flood inflows. Assume 0 trapping efficiency for flows up to 4,000 cfs beginning in year 10.
Overflow Spillway	1,500 ft long at elevation 696	No change
Higgins Ditch Grade Control	Rock fill to elevation 686, sidewalls filled in for a 50 ft open crest width	Crest at elevation 680 with a bottom width of 20 ft and 2:1 side slopes, resulting in a top width of 76 ft.

4.0 Items for PED

The following items are recommended for further analysis during PED:

1. Minimize floodplain deposition both upstream and downstream of HWY36 in order to increase basin longevity and decrease flooding potential. Optimize flows into the basin, through the downstream outlet, over the overflow weir, and over the Higgins Ditch grade control structure.
2. 2D and/or physical modeling of sediment and woody debris dynamics at diversion structure/flow split location and throughout the basin.
3. Optimize pilot channel dimensions and internal levee notches for maximum wood transport over a range of potential basin inflows and outflows.
4. Refine modeling of Higgins Ditch grade control structure to account for floodplain conveyance between piers for existing railroad berm.
5. 2D modeling for avulsion channels on Locust Creek downstream from Muddy Creek confluence to optimize avulsion prevention features (berm, etc.)
6. Multidimensional flooding impacts assessment of optimized design features with long-term sedimentation.

The results of these analyses will allow optimization of design features and inform thresholds for adaptive management to maintain deposition within acceptable levels.

5.0 Conclusion and Limitations

This report documents refinements to the Tentatively Selected Plan. These refinements were prompted by expert input on woody debris control and public comments related to flooding impacts. The analysis documented in this appendix suggests that the effect of increasing the flow conveyance is sufficient to offset the impacts of increased deposition upstream of the Higgins Ditch grade control structure. However, given uncertainties in the feasibility-level modeling, the refined TSP includes a lower crest on the grade control to reduce ponding of moderate in-channel flows. This will decrease upstream deposition on the west floodplain with attendant potential for conveyance reduction. The analysis of the basin longevity suggests that the basin can hold 50 years of sediment and woody debris, provided the discharge increases and the pilot channel sizes itself in order to pass 4,000 cfs downstream starting in Year 10. Basin longevity is also subject to the uncertainties in the incoming sediment load, as described in Appendix C3. For both the basin longevity and the upstream flooding analyses, further modeling (specifically multidimensional sediment modeling) is recommended during PED.

Grand River Ecosystem Restoration Study

Final Integrated Feasibility Report and Environmental Assessment

Appendix C4.1: Grand River – Locust Creek Basin Large Wood Loading Estimates

October 2020

US Army Corps of Engineers ®
Kansas City District

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FROM: Zac Corum, PE, Hydraulic Engineer, USACE Seattle District

TO: Dr. John Shelley, PE, Hydraulic Engineer, USACE Kansas City District

SUBJECT: **Grand River – Locust Creek Basin Large Wood Loading Estimates**

BLUF:
Existing historical logjam removal data in Pershing State Park (Park) along Locust Creek were reviewed, along with available data from literature and GIS by Seattle District to estimate the potential future loading of large wood (LW) into the proposed sediment basin downstream of the proposed Locust Creek diversion. No policy or standard exists on basin design for wood loading. 50-year accumulation in the basin was estimated by assuming that the logjams removed by the Park from 1996 to 2016 represent a significant proportion of the upstream watershed wood load to the park. The volume of wood associated with each logjam removal was estimated and summed over the period when data was available, then the total was annualized. Logjam frequency and wood volumes were compared with antecedent flow conditions. The correlation was too poor to provide meaningful flow-load estimates for the basin, necessitating use of annual average loading estimates over the entire period of analysis. Critical assumptions and data gaps require use of sensitivity analysis and result in 20-fold variability in loading estimates. Low, medium and high loading scenario dead wood storage over 50 years is estimated to be 90, 290, 490 acre-ft respectively. Worst case loading is estimated at 1,080 acre-ft but the chances of this occurring are viewed as remote based on current data. Risk informed decision making should be used to help select a load estimate for basin design, and monitoring can be used to validate these estimates if higher accuracy estimates are needed.

Background:
Pershing State Park in Missouri experiences frequent formation of massive channel spanning logjams necessitating frequent removal by the park to maintain channel capacity (Figure 1). The Corps and State of Missouri are partnered to improve habitat conditions within Pershing State Park as part of the Grand River Ecosystem Restoration project (USACE 2019). The project design proposed to divert Locust Creek into a large basin that will form a pool in flood events. The basin is intended to trap sediment which is negatively impacting habitat along downstream reaches. In doing so large quantities of wood supplied by Locust Creek will also be trapped. Because the upper watershed can supply vast quantities of wood in addition to sediment, this MFR was prepared to estimate the volume of large wood (commonly referred to as LWD) that could become trapped in the basin over a 50-year period to help understand implications for basin longevity and project design.

Data and Methods:
The volume of wood stored in the basin at any given time (wood loading) is the volume of dead and live wood present at the beginning of the time interval of interest plus the difference between the volume of wood inputs and volume of wood outputs. Inputs consist of wood fragments, trees, etc. originating upstream of the site that are fluvially transported into the site in addition to the volume of live tree growth. Outputs consist of wood that is bypassed from the site upstream or escapes the basin and flows into Locust or Muddy Creek, and wood trapped in the basin that decomposes, breaks up and floats out, or wood lost to wildfire, infestation, chipping or logging. For an overview of current methods for wood loading estimation and theory see Ruiz-Villanueva et al. (2016).

Wood decomposition which is the result of many biological and physical processes is typically assumed to follow an exponential decay curve (Harmon et al. 1986). Decay rates vary widely by tree species, size and setting. Trees decompose more quickly under warm humid conditions than colder dryer conditions (Russell et al. 2015). Waterlogged or buried wood decays more slowly than wood subject to wetting and drying. In this analysis decay represents any process that physically reduces the volume of a piece of wood over time, including breakdown of large wood into small wood that floats out of the project area. Hardwood species such as oak and hickory dominate the bottomland forests of the Central Irregular Plains ecoregion where Locust creek flows (Wiken et al. 2011), and based on Dec. 2019 site recon observations, observed breakdown rates are rapid, with logs highly decayed after 10-years. Hardwood decay rate constants vary by a factor of 2 or more (Russell et al. 2013). Literature values were scaled as described below to represent the typical conditions found within the Park.

A low, medium, high and worst case wood loading scenario were developed that are based on varying degrees of conservatism of primary parameters driving basin wood storage. Inflow rates derived for logjam volumes (Table 1) were multiplied by a safety factor of 2 to account for “unmeasured” transport of wood through the site prior to logjam formation. (This factor is subjective and could arguably be increased or decreased). Basin wood loading is estimated by applying an exponential decay function to each successive annual trapped wood volume. The volume at the start of the analysis is set equal to the Dobbin’s Notch wood jam volume. Each successive year, an annualized average volume of new wood is trapped, and all previously trapped wood continues to decay. This results in the following equation for the total 50-year volume occupied by dead wood:

$$V_{50} = V_0 e^{-50k} + V_a e^{-49k} + V_a e^{-48k} + V_a e^{-47k} \ldots + V_a e^{-2k} + V_a e^{-1k} + V_a$$

Where:

V_{50} = volume occupied by wood at the end of 50 years (cy)

V_0 = volume of wood present at the start of the analysis (i.e. in the Dobbins Notch area). V_0 = 21,500 cy from Google Earth and MO DNR

V_a = average annual trapped wood (cy) = SF*V_{JAM}*(1- Bypass%)

SF = Safety factor to account for wood missing from the log jams used to develop the annual inflow. SF assumed to be 2.

V_{JAM} = annualized volume of existing logjams. V_{JAM} varies by scenario.

Bypass% = the percent of the incoming wood which does not deposit in the basin. Varies by scenario up to 33%.

k = weighted average wood debris decay constant = (IKF*Ko)(1-S) + (IKF*Ko)(S/SKF)

IKF = Initial decay factor, multiple to account for fact most wood in state of decay before reaching site = 2 (assumed)

ko = Literature decay rate, varies by scenario

S = Sediment burial % (assumed, varies by scenario)

SKF = Sediment burial decay reduction factor = 3 (assumed)

Because logjam volume estimates are based on several uncertain parameters (width, height, porosity, etc.), the primary parameters were varied to estimate the error associated with the estimates. The low and worst case inflow estimates are based on the lower and upper estimates for average annual dead wood inflows respectively. The medium and high inflow estimates are both based on average annual inflow estimates. As seen in Figure 2 the error range is roughly +/- 100% of the median estimate.

The decay rate constant (k_o) was modified from literature values because wood from upstream that deposits in the Park is already in a state of decay. Few pieces we encountered in our December site visit had bark attached, and many were showing signs of internal breakup. Previous work by MO DNR and USGS classified debris removed from jams in the Park as primarily consisting of relatively small, heavily decayed pieces in decay classes III and IV (Heimann 2017). We used an IKF (initial decay factor) of 2, which results in a k value on the upper end of those found for hardwoods in literature (Figure 4). Note that decay rate constants in literature are typically derived from wood density data, which are assumed to linearly scale to volume and mass decay. Many researchers have found the density decay rate constants underestimate biomass depletion because they do not factor in volume changes (Fraver

et al. 2013). The volume decay curves of Fraver et al. provide conservative estimates (lower rate of decay) than the values used in this study.

The decay of wood submerged or buried by sediment is much slower than that for wood subject to wetting and drying. The final k value for the decay constant is a weighted average for both buried and unburied wood. As buried wood can persist for centuries, especially when under water, the k value for the buried proportion of wood is divided by 100 to severely slow the rate of decay and multiplied by the IKF to account for initial decay.

Wood decay is a complex biogeochemical process that results in transformation of solid wood into smaller fragments providing an energy and nutrient source for other plants, animals and microorganisms that eventually convert wood into decay resistant soil fragments, the remainder being respired to the atmosphere or becoming part of the nutrient cycle (Bani et al. 2018). No literature reviewed for this study provided predictive relationships for how much dead wood volume is converted to soil (humus) volume on the forest floor. Long term research on volumetric decay of northern US hardwoods (Aspen) by Fraver et al. (2013) suggests that as much as 20% of the initial log volume remained after 50-years of decay, which is significantly more than would be predicted from decay rates used in this study (developed over wider range of forest types (e.g. Russell et al. 2014, 2015)) based on density. A volumetric decomposition limit of 20% was applied to all computed decay curves, i.e. if the decay function predicted a remaining volume less than 20% for the decaying wood, then 20% was used instead. Thus, the 50 year total volume representing both decaying wood and humus derived from decayed wood is a variation on the previous equation:

$$V_{50} = V_0 \max(e^{-50k}, 0.2) + V_a \max(e^{-49k}, 0.2) + V_a \max(e^{-48k}, 0.2) + V_a \max(e^{-47k}, 0.2) \ldots \\ + V_a \max(e^{-2k}, 0.2) + V_a \max(e^{-1k}, 0.2) + V_a$$

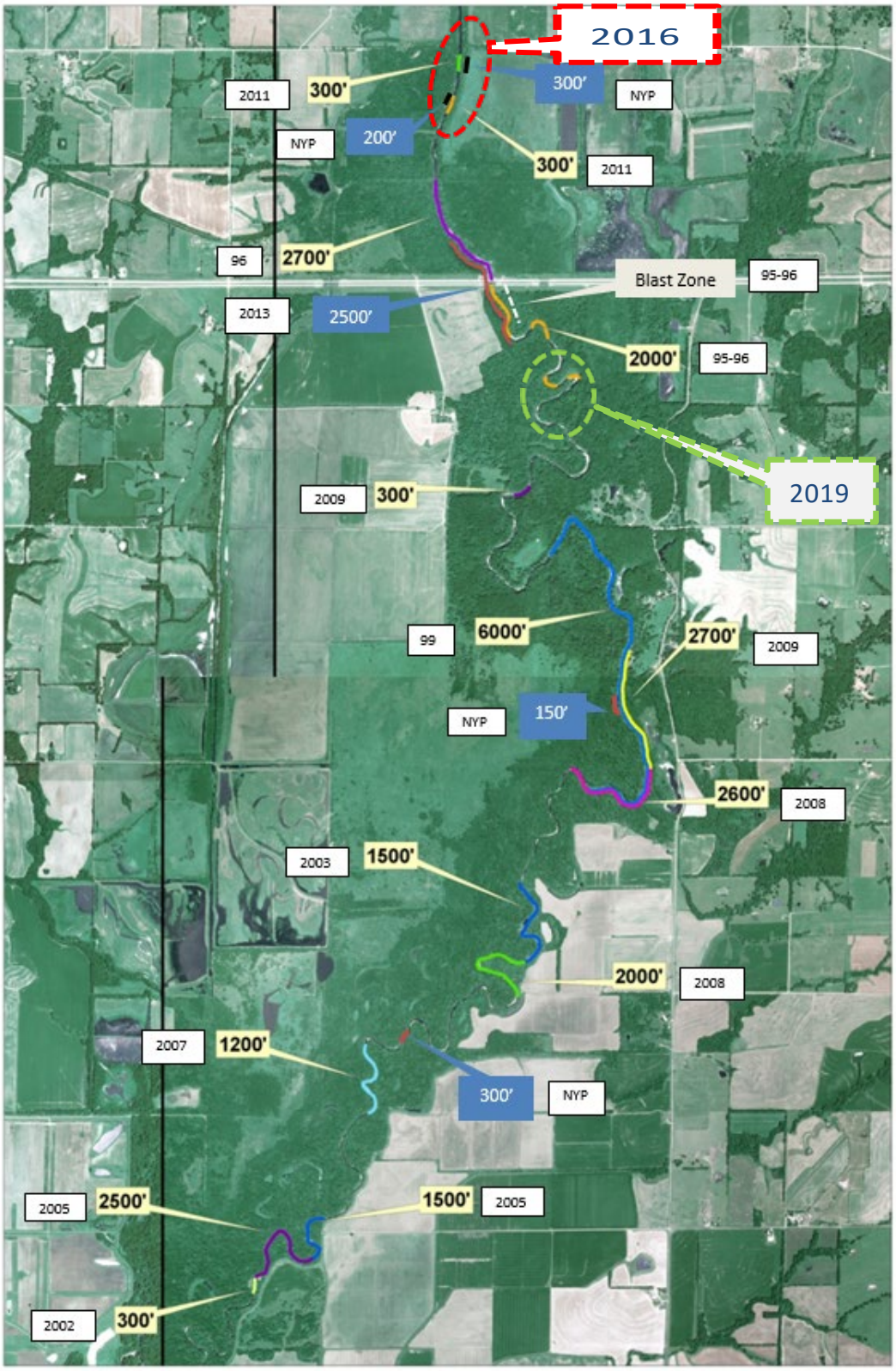

Figure 1: Locust Creek logjam data in Pershing State Park, 1996-2019 (Woodward 2020)

Table 1: Pershing State Park Logjam Wood Volume Estimates 1996-2019

Pershing State Park Logjam Data				Assumed Porosity		50	% (+/- 10%)
Jam ID	total length called out	Removal Year	Location relative to Hwy 36	Assumed Width (+/- 20')	Assumed Height (+/- 3')	Computed Logjam Volume (cf)	(cy)
5	2700	1996	Abv	110	6	891000	33000
7	2000	1996	Bridge - Blw	110	6	660000	24444
9	6000	1999	Blw	110	6	1980000	73333
19	300	2002	Blw	110	6	99000	3667
13	1500	2003	Blw	110	6	495000	18333
17	2500	2005	Blw	110	6	825000	30556
18	1500	2005	Blw	110	6	495000	18333
16	1200	2007	Blw	110	6	396000	14667
12	2600	2008	Blw	110	6	858000	31778
14	2000	2008	Blw	110	6	660000	24444
8	300	2009	Blw	110	6	99000	3667
10	2700	2009	Blw	110	6	891000	33000
2	300	2011	Abv	110	6	99000	3667
4	300	2011	Abv	110	6	99000	3667
6	2500	2013	Bridge	110	6	825000	30556
1	300	NYP	Abv	110	5	82500	3056
3	200	NYP	Abv	110	6	66000	2444
11	150	NYP	Blw	110	6	49500	1833
15	300	NYP	Blw	110	6	99000	3667
16	2520	2016	Abv	110	6	831600	30800
17	2700	2019	Abv	110	6	891000	33000
18	550	2019	Abv	110	6	181500	6722
19	1330	2019	Blw	110	6	438900	16256
sum	36450					12012000	444889

Data and parameter estimates courtesy of Mr. Tom Woodward, MO DNR (Woodward 2020).

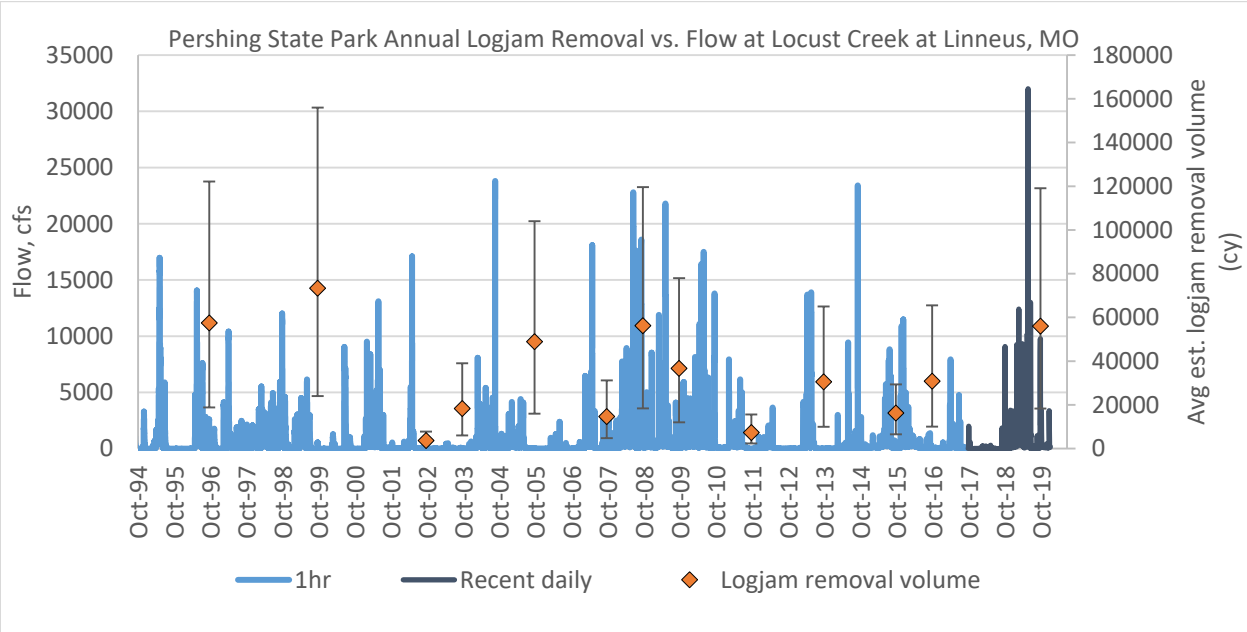

Figure 2: Flooding and logjam removal data 1996-2019

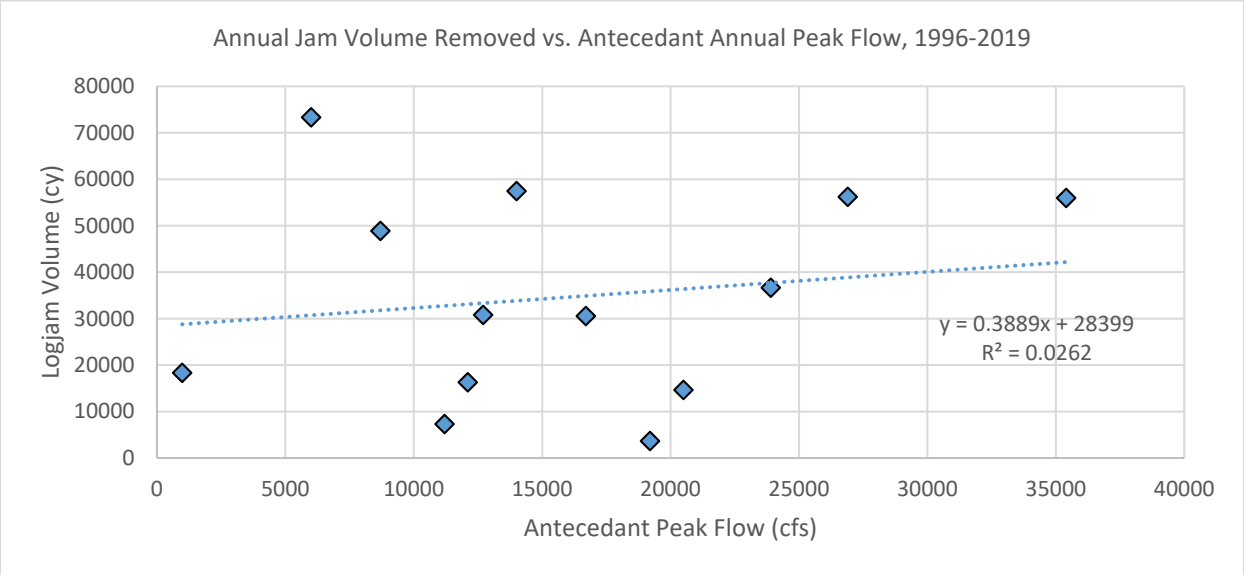

Figure 3: Flooding and logjam removal data 1996-2019

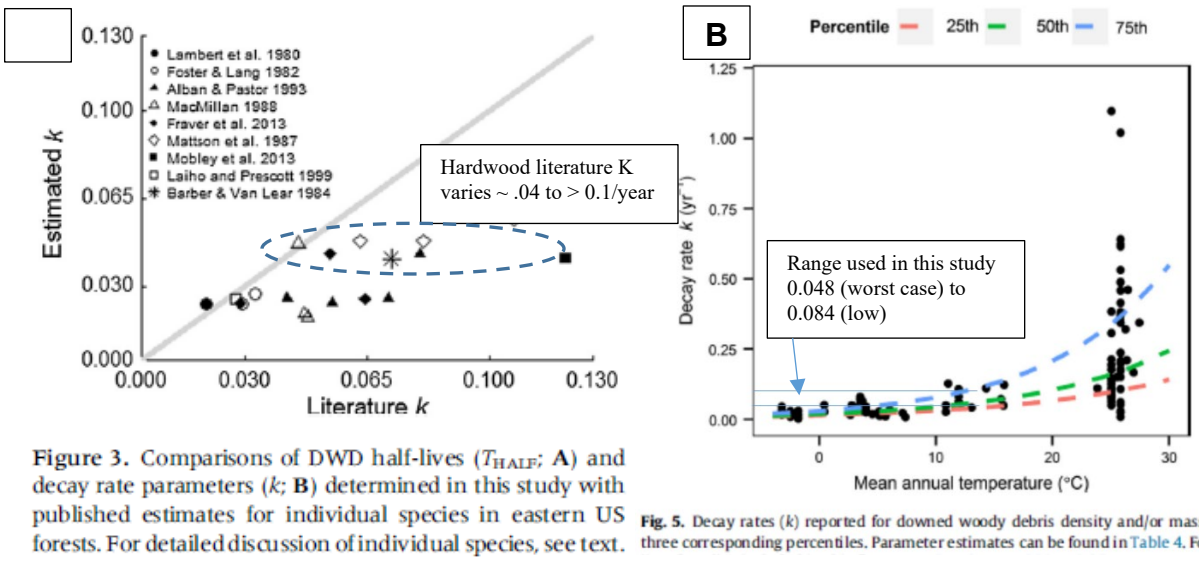

Figure 3. Comparisons of DWD half-lives (T_{HALF}; **A**) and decay rate parameters (k; **B**) determined in this study with published estimates for individual species in eastern US forests. For detailed discussion of individual species, see text.

Fig. 5. Decay rates (k) reported for downed woody debris density and/or mass at three corresponding percentiles. Parameter estimates can be found in Table 4. For a

Figure 4. (A) Exponential dead wood decay constants from Russell et al. (2014) used in this analysis compared with other values in literature. Note relationship of temperature to decay shown in (B), figure 5 from Russell et al. 2015)

Results and Discussion:

1. Volumetric loading of dead wood in the basin between 2030 and 2080 is shown below in Figure 2 and summarized in Table 2 for four scenarios described below.
2. **Low**: Uses average annualized wood load for all data, presuming decay rate similar to upper range of typical hardwood breakdown rates (~35 years max). Assumes 25% burial by sediment. Assumes most wood will float to margins of pool and break down in the dry. 33% of incoming wood either bypassed along old Locust Creek or exits basin. Nearly 90 acre-feet of basin storage capacity could be utilized by dead wood under this scenario.
3. **Medium**: Uses average annualized wood load for all data, assuming full breakdown in ~45 years due to partial burial by sediment. Assumes 25% burial by sediment. 33% of incoming wood either bypassed along old Locust Creek or exits basin. More than 290 acre-feet of basin storage capacity could be utilized by dead wood under this scenario.
4. **High**: Uses avg. annualized wood load for all data, assumes full breakdown in ~60 years due to 50% burial by sediment. All wood diverted into basin, none exiting. More than 490 acre-feet of basin storage capacity could be utilized by dead wood under this scenario.
5. **Worst case**: Uses maximum annualized wood load (downstream of Hwy 36), 1/2 life of ~60 years due to 50% sediment burial. All wood diverted into basin, none exiting. Nearly 1,100 acre-feet of basin storage capacity could be utilized by dead wood under this scenario.
6. From Figure 5 it is seen that wood storage in the basin gradually increases then approaches a steady state (steady slope/increase) condition as the deposited

material decays at a constant rate. The time to reach steady state is about 10 years under the low scenario, 20-years under the medium scenario, and greater than 30-years under the high and worst case scenario. Because wood delivery will not be steady, the real-world storage will fluctuate, but should still approach a steady state condition if most of the wood deposits along the basin margins and decays per typical rates for hardwoods.

7. Site recon data indicate wood breakdown rates near the basin are high. Material deposited in 2015 near Dobbins Notch was present during the December 2019 site visit and was found to be highly degraded. This is likely due to fact that wood entering the basin has been in the stream for several years prior to reaching site and is already in a state of decay. This indicates the worst case loading estimates are unlikely to manifest. Thus total storage volume occupied by dead wood is likely to be closer to the low, medium or high estimates.
8. The percent of wood diverted from the basin (diversion design) and percent of wood passing through the basin (wood trapping efficiency) have a strong influence on the amount of wood present in the basin over time. Design of the basin can thus influence the amount of wood stored in the basin. These estimates should be considered preliminary for sake of basin design.
9. As shown in Figure 4 above temperature increases (from climate change) may increase decay rates from those used in this analysis, which would tend to reduce the volume of dead wood present in the basin. It is likely other effects of climate change such as increased storm intensity could increase wood loading from the upper basin. Without further analysis so it is not possible to predict if dead wood loading in the basin will be higher or lower than the estimates provided. It is reasonable that the effects of climate change are captured in the high variability of the provided estimates.

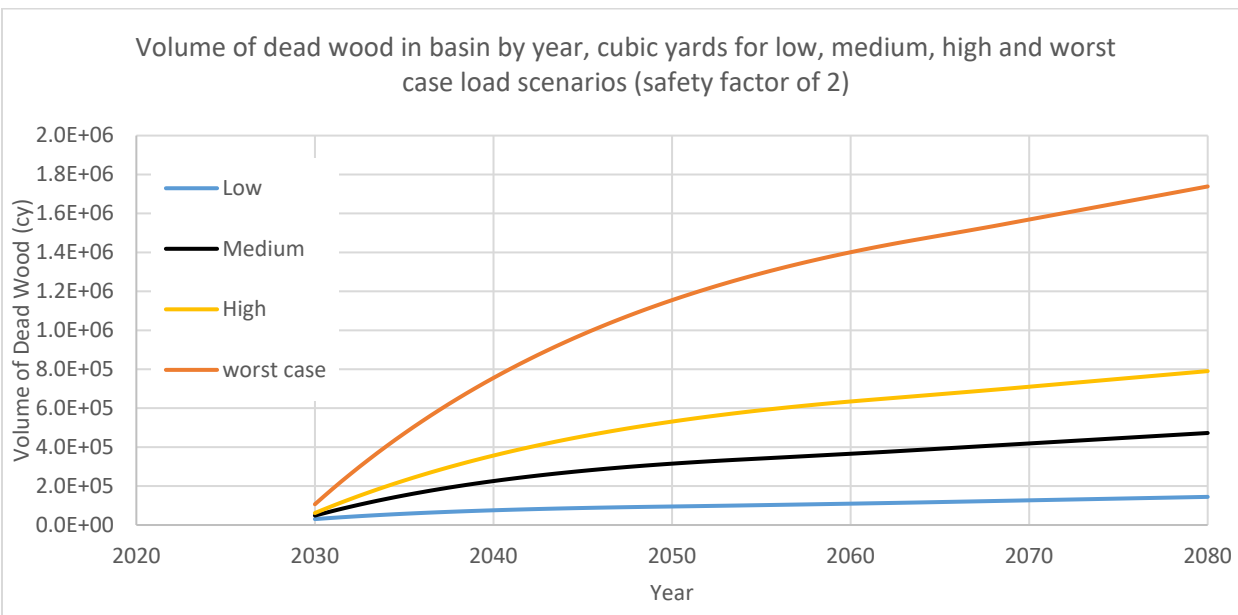

Figure 5: Locust Creek basin dead wood loading estimates

Table 2. Results summary by scenario

Scenario	Annualized Loading (cy)	Bypass %	Basin Inflow with Safety Factor (cy)	Sediment Burial %	Interval Single Piece Decay Rate (years)		End of Year 50 Storage Volume	
					50% Decay	95% Decay	cy	acre-ft
Low	6623	33%	8875	25%	8	36	1.4E+05	90
Medium	20052	33%	26870	25%	10	44	4.7E+05	293
High	20052	0%	40104	50%	13	57	7.9E+05	490
Worst Case	42480	0%	84960	50%	14	62	1.7E+06	1078

Conclusions

1. Wood loading into the Locust Creek basin depends on many stochastic input parameters, and gaps in these data preclude definitive estimates for loading. Sensitivity analysis indicates wood loading could reasonably vary by over a factor of 3 or more.
2. Site recon data indicate wood breakdown rates near the basin are high. This is likely due to fact that wood entering the Park has been in the stream for several years prior to reaching the basin and is already in a state of decay. This indicates the worst case loading estimates are unlikely to manifest. Thus total storage volume occupied by dead wood is likely to be closer to the low, medium or high estimates.
3. The percent of wood diverted from the basin (diversion design) and percent of wood passing through the basin (wood trapping efficiency) have a strong influence on the amount of wood present in the basin over time. Design of the basin influences the amount of wood in the basin. These estimates should be considered preliminary for sake of basin design.
4. Climate change effects could increase wood loading to the basin over time, however warmer temperatures should break the material down more rapidly. For the time being it is reasonable to assume the sensitivity analysis and safety factors capture climate change impacts on dead wood loading.

Critical assumptions and limitations:

For practical purposes several critical assumptions were used that impact the accuracy of the provided estimates.

1. Dead wood inputs from upstream are assumed to be wholly represented by the volume of wood contained in the Locust Creek logjams that developed in the Park during the period of time when the Park has been monitoring logjam formation and actively repositioning or removing the wood. In reality logjam removal allows for free-passage or wood for a period of time, until a new channel spanning jam forms, at which time all wood from upstream is trapped, unless an avulsion channel forms, that diverts wood away from Locust Creek. Because of ongoing flow diversion into pirate channels, loss of channel capacity, tortuous meandering, eroding streambanks, and the adjacent intact

mature riparian forest that supplies large intact trees to Locust creek capable of forming stable channel spanning logjams, Locust Creek is efficient at trapping wood in the vicinity of Highway 36, and especially so downstream of the Highway. Thus it is reasonable to assume that the jams removed within the park boundary represent a large proportion of the upper basin wood load between the intervals when jams have been removed. Because the avulsion channel to Higgins Ditch has been capable of diverting wood since 2009, and Higgins Ditch is large enough to convey wood freely to Hickory Branch, logjam data within the park after 2009 under-represents the total basin wood load. A safety factor (multiplier) should be added to wood loading estimates based on jam removal volumes. For this analysis a safety factor of 2 has been applied to dead wood loading estimate based on annualized wood volumes obtained from logjam data. No data is available at this time to assess the adequacy of this safety factor and it can be justifiably increased or decreased based in risk tolerances.

2. As shown in Figure 3 there is a weak positive relationship between flood magnitude and wood load however the largest jams formed in years when minor flooding occurred. Thus it is possible that most if not all of the wood would be diverted into the basin during frequent flood events, and a lesser proportion during very large, infrequent floods. For this analysis it is assumed that 2/3 of the incoming wood load is diverted into the basin with 1/3 bypassing the basin. Larger proportions of wood would most likely bypass the diversion during large infrequent floods. Bypass occurs either at the point of diversion, where wood is allowed to flow downstream along the old Locust Creek channel, upstream at a pirate channel, or though the basin itself. Bypass % is a design parameter. For sensitivity analysis, the high and worst case scenarios assume 0% bypass.
3. The primary mechanism for wood to exit the basin is by mechanical removal (upland stockpiling, harvest or chipping), natural decomposition and fluvial transport. In this analysis 100% of wood entering the basin is assumed to be trapped in the basin, with no fluvial transport downstream. The widespread ponding in the basin and low downstream velocities favor transport and stranding of floating wood to the margins of the basin. In this analysis natural breakdown is assumed to be the primary output mechanism. Note that sediment burial or prolonged submergence of dead wood will retard decomposition. If wood remains on the margins of the basin sediment burial of most fragments is unlikely and breakdown rates will be high. It is possible that portions of the basin could experience debris jams and sediment splays that entomb logs and retard decay. The deeper portions of the basin could trap and bury wood that sinks after it ponds and becomes super-saturated. Decomposition rates in the analysis are based on the full range of conditions that could be experienced and thus presume sediment burial of some pieces. This is approximated by using constant conservative (slow) hardwood decay rates for the proportion of wood assumed to become buried.

4. Live wood (growing vegetation) has not been included in the estimate. Thus the total volume of wood within the basin (live and dead) is greater than estimates obtained from dead wood alone. If necessary the volume of live wood can be estimated by multiplying stem density, basal area, or volume data by age-class patch. Ground surveys, first return Lidar DEMs or LAS data are very useful for this analysis.
5. The residual volume remaining after full decomposition of a wood piece is assumed to be 20% of the initial wood volume in any given year, which is likely conservative. Further literature review can be conducted to better estimate the proportion of wood that will be permanently converted to soil.
6. Future increases or decreases in basin wood loading to the site are not accounted for as these are too uncertain. Status quo wood loading is assumed for the period of analysis.

Recommendations:

1. Evaluate basin longevity for various wood loading scenarios. If the project risks posed by conservative estimates of wood inflows are manageable, no further refinement of these estimates is needed, unless significant changes in wood loading are observed in the Park.
2. If the project design appears to be at risk due to medium or high estimate wood inflows, the loading estimates should be refined based on volumetric inflow data obtained from continuous video monitoring and logjam surveys, physical measurements of decay rates of down wood in the basin, and estimation of standing live wood volumes.

If there are any questions regarding this information please don't hesitate to contact me.

Best Regards,

Zac Corum, PE

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