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Natural Channel Design for Degraded Streams in Robinson County, TN

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ENGR 491 – Senior Design
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Acknowledgements

We would like to thank Jason Hill (Ph.D.,P.E.) for all his assistance through this project. He has helped us to stay on track with our design and guided us through the tasks we were unfamiliar with. Vince Wilhelmus and Tony Yeatman began the project in the Fall of 2023 and passed on their information and design details. They had begun acquiring some of the plan form geometry which was used to begin the design. Between their work and Dr. Jason Hill's work, we had a great starting point for this design.

Abstract

This project involves design of a restoration plan for over 5000 feet of degraded streams located in Cedar Hill, Tennessee. The existing streams are highly incised due to agricultural activities and judged to be poorly functioning. Incised streams are typically deep and narrow and disconnected from the adjacent floodplain. Natural streams have features such as riffles and pools as well as a meandering pattern in plan form. These features sustain a diverse aquatic habitat by creating variable hydraulic conditions in the stream. A comprehensive redesign of the streams was performed that included a meandering planform and design of the longitudinal profile and cross section geometry. A hydrologic analysis was completed to determine the range of flow rates expected in the stream. The software package Autodesk Civil 3d was used to generate a design plan set. A hydraulic analysis of the final design was conducted using the model HEC-RAS (Hydrologic Engineering Center – River Analysis System). The hydraulic model was used to refine the design.

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1. Introduction

This project is a redesign and restoration of streams in Robinson County, TN. It consists of over 5,000 feet of stream including the main reach, Chambers Branch and three unnamed tributaries. The land was formerly used for agricultural farming but will no longer serve that purpose. The field and tributaries are shown below in Figure 1. A natural channel design for degraded streams is often needed due to poorly functioning streams destroying the environment. This will lead to bad drainage, deterioration of land, and possible ecosystem destruction. The existing stream is being incised by rapid flow rates. This is largely due to the use of drainage tiles by the farmers of the field. The degradation of the existing channel is resulting in a deep and narrow channel. A stream mitigation bank is the restoration of these poorly functioning streams to provide compensation for unavoidable impacts to other aquatic resources. These benefit the landowner, property, environment, and ecosystem. A third party designs and restores the stream in order to sell credits. These credits can be purchased by anyone who plans to complete construction on or near a stream resulting in damage to that stream. This process is done to ensure there is no net loss to the environment. There are many characteristics of a highly functioning stream that are considered when designing which will be discussed later.

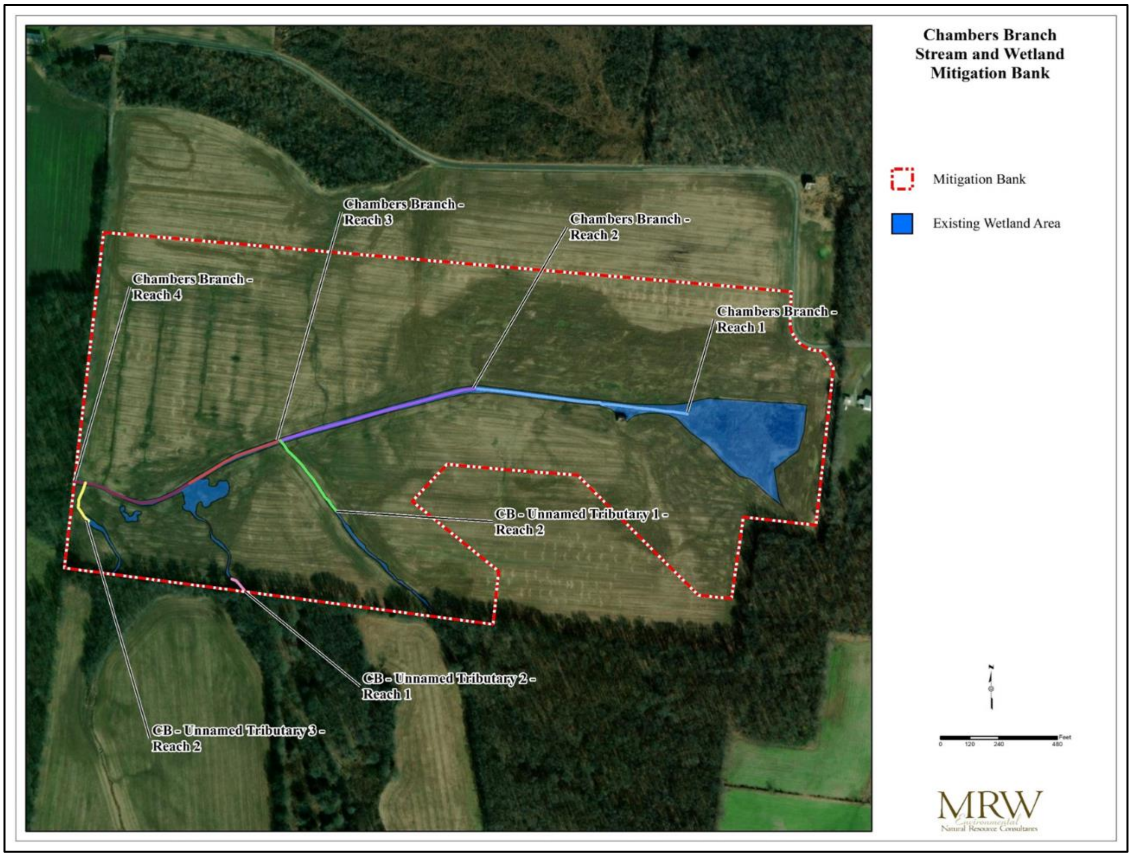

Figure 1: Chambers Branch Aerial View

2. Scope of Work

The primary objective of this project is to design a restoration plan for over 5000 feet of degraded streams shown in Figure 1. This includes the main channel of Chambers Branch and three unnamed tributaries. The restoration plan includes planform design, cross-section sizing, and design of the vertical profile geometry.

3. Attributes of Highly Functioning Natural Streams

There are certain attributes of a stream that characterizes it as highly functioning. Studies have been conducted on streams across the state of Tennessee and 36 of them have been classified as highly functioning streams, or reference streams. Jennings Environmental, LLC has completed a study for the Tennessee Department of Environment and Conservation and provided a vast spread of information on these reference streams. Reference streams have characteristics such as little to no incision and require a miniscule amount of maintenance. These streams are also well-connected to alluvial floodplains. These characteristics include a meandering plan form with a riffle and pool sequence. The meandering plan form with riffle/pool sequence allows the stream to flow rapidly with an increase of oxygenation in straight sections while the pool areas have a slow velocity around the bends in order to limit erosion in the banks. The vegetation benefits the surrounding ecosystem and enhances the floodplain. Another characteristic of a highly functioning stream is having the channel dimensions that holds water inside its banks for a 2-year rainfall event and leaves its banks during a 100-year rainfall event. Lastly, upstream watersheds consist of rural areas with a majority of forest and agricultural land use. This project will have all of these characteristics after the stream has been fully restored.

4. Hydrologic Analysis

A hydrologic analysis determines a point of focus and calculates the total drainage area. This helps understand the amount of water and actual drainage area that is entering a stream. It is crucial to determine the initial hydrological data to know the guidelines when designing the stream. A USGS application, Stream Stats, was used to delineate the watershed boundaries and to determine the discharges of a two-year and one-hundred-year rainfall event. Figure 2, shown below, is an example of the delineation of the watershed.

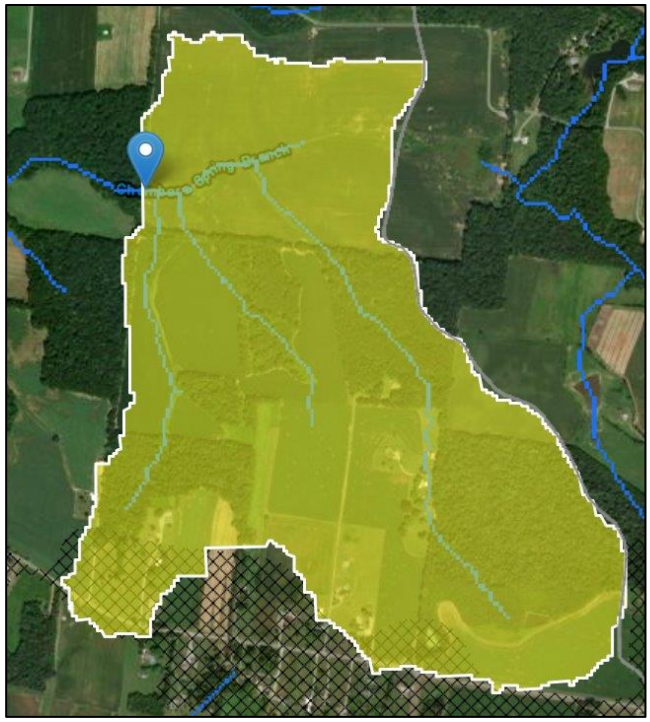

Figure 2: Watershed Boundary Delineation

A hydrologic analysis using Stream Stats was conducted for each reach and unnamed tributary in Chamber's Branch. Table 1, shown below, is all data collected from Stream Stats that was used in determining channel sizing.

Table 1: Estimates of 2-year and 100-year Frequency Stream Discharges Estimated with StreamStats

Stream Stats		
Stream ID	**Q 2-year (cfs)**	**Q 100-year (cfs)**
Reach 1	5.42	22.9
Reach 2	65.4	257
Reach 3	67.9	267
Reach 4	104	418
Tributary 1	56.2	222
Tributary 2	30.8	124
Tributary 3	30	121

5. Stream Design

The design of this stream focusses on four main components; the plan form geometry, channel geometry, riffles and pools, and the vertical profile geometry. The software programs used to complete this design and analysis process were Autodesk Civil 3D and HEC-RAS (Hydrologic Engineering Center-River Analysis System).

5.1 Plan Form Geometry

The plan form geometry is the design in arial view. Many features are included in this as in the following: of sinuosity, radius of curvature, belt width, and meander length. Figure 3 illustrates all these characteristics which will be further explained below. These characteristics were acquired from "Morphological Stream Design and Assessment Tools for the Interior Plateau (Ecoregion 71) of Tennessee". These characteristics were directly correlated with the drainage area into each reach and tributary. All of the values determined were directly correlated with drainage areas from the Ecoregion 71 study.

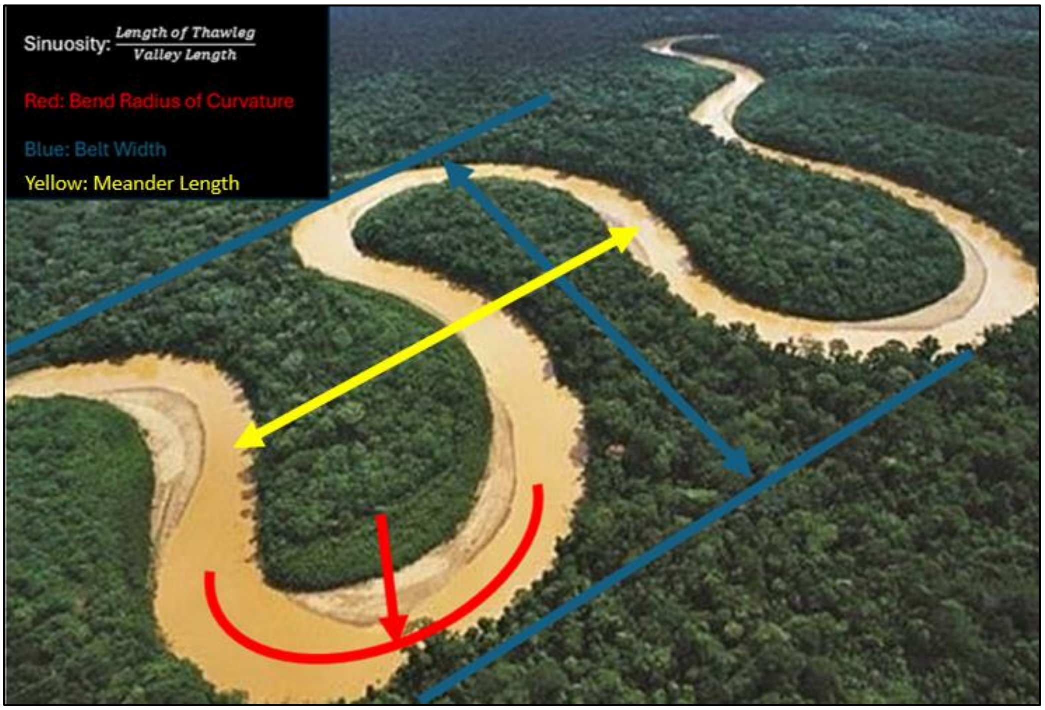

Figure 3: Plan Form Geometry Characteristics

Sinuosity is a very important characteristic of these streams. The sinuosity is the ratio between the length along the thalweg to the length of the valley in a straight line, starting and ending at the same points. The required ratio for this project was 1.2 and these were checked using Autodesk Civil 3D. The value of 1.2 came directly from the Ecoregion 71 document. Shown in 'Table 2', the sinuosity for reaches 1 through 4 and tributaries 1 through 3 were all within 0.4 percent of the desired value.

Table 2: Sinuosity Design Results

	R1	R2	R3	R4	T1	T2	T3
Desired Stream Length (Feet)	1,058.8	1,049.2	481.0	535.4	1,205.0	608.0	459.3
Actual Stream Length (Feet)	1,059.1	1,050.9	481.5	535.4	1,202.9	605.4	459.6
Sinuosity	1.200	1.202	1.201	1.200	1.198	1.195	1.201

The next characteristic is radius of curvature, which is the rate of how quickly each bend turns through the meandering plan form. An illustration of this is shown as the red in 'Figure 3'. The way this was measured using Civil 3D was by measuring the radius of each arc. The average radius for each reach or tributary was taken over the bankfull width to get the ratios as shown in 'Table 3' below. The designs were altered multiple times to get close to the desired average curvatures. These were found to be successful for the design constraints.

Table 3: Radius of Curvature Design Results

	R1	R2	R3	R4	T1	T2	T3
Average R Curvature (Feet)	33.0	32.8	34.8	39.7	20.7	15.2	15.0
Desired R Curvature (Feet)	25.8	39.4	40.8	44.7	21.4	15.3	16.3

Belt width is the straight-line distance between two bends as illustrated in 'Figure 3'. The way this constraint was controlled was by drawing construction lines before using a polyline to create the thalweg. The desired value for the belt width for this calculation varied with each reach or tributary as shown in 'Table 4' below. Meander length is also shown in 'Table 3' with the desired values. Meander length is the straight-line distance between one full sinuous bend.

Table 4: Belt Width and Meander Length Design Results

	R1	R2	R3	R4	T1	T2	T3
Meander Length (Feet)	71.9	108.0	111.4	120.4	59.1	42.6	47.1
Belt Width (Feet)	25.9	39.9	41.3	45.7	21.5	15.3	16.9

Shown in 'Figure 4', is the completed thalweg on Autodesk Civil 3D. The red line is the thalweg of the existing stream, and the purple is the thalweg of the designed stream. The designed streams were placed away from the existing streams for construction purposes. The bottom right tributary shows a different case where the stream is designed on top of the existing due to the large slope in elevation on each side of the valley. This does not allow for the designed stream to be moved.

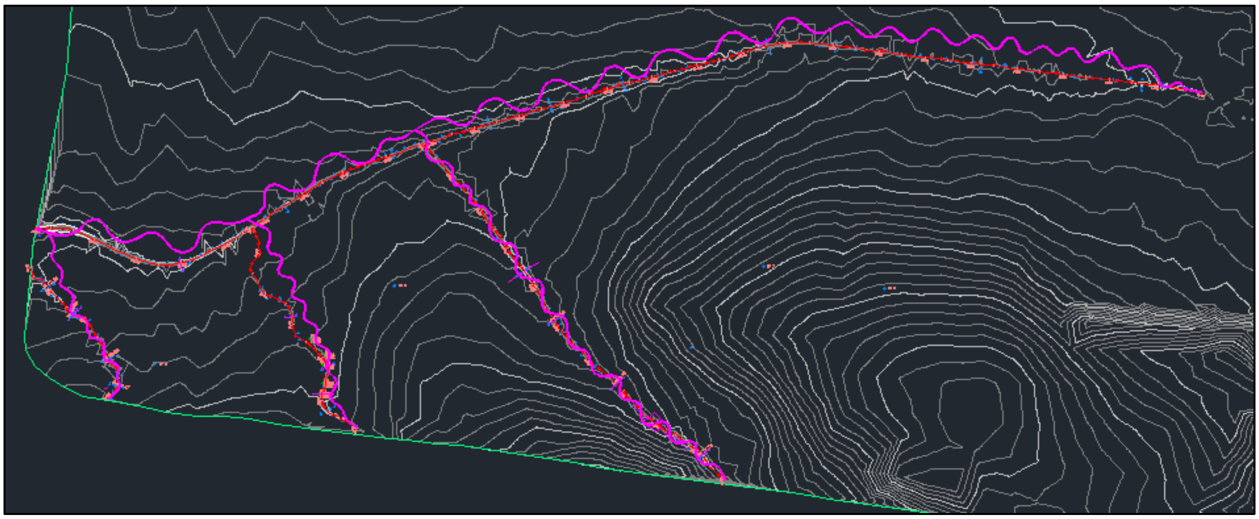

Figure 4: Plan Form Design with Complete Thalweg

5.2 Channel Geometry

The channel geometry in this project represents the preliminary channel dimensions. These channel dimensions are found using the equations from Ecoregion 71 of Tennessee. The equations are formed from a study with field measurements from 36 highly functioning streams in Tennessee. The streams in this study have a drainage area from 0.2 square miles to 107 square miles. Figure 5, shown below, shows the graph made from stream data in calculating the bankfull width.

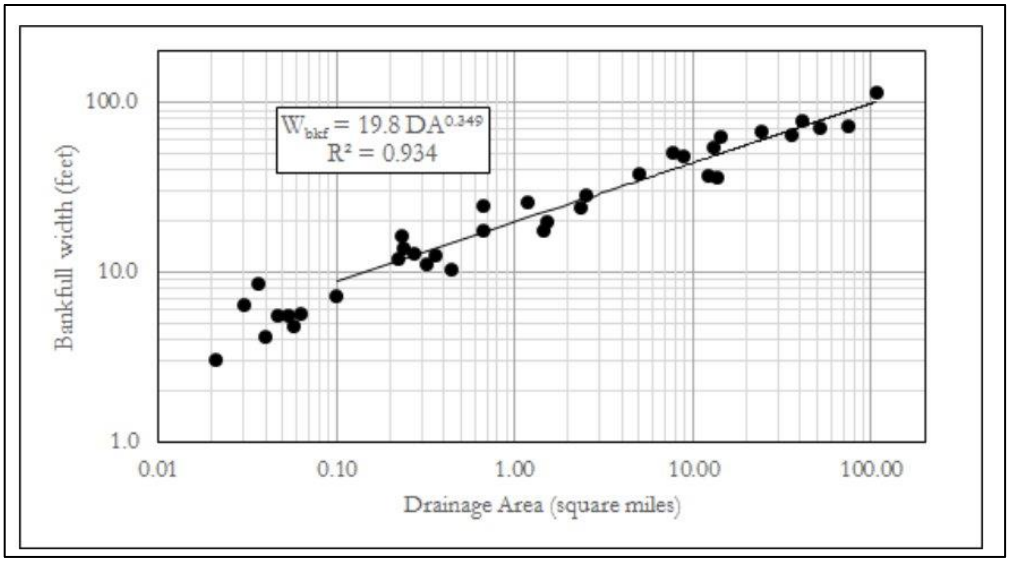

Figure 5: Ecoregion 71 of Tennessee Bankful Width Graph

Preliminary channel dimensions are crucial in having a solid foundation in doing the final channel geometry. Multiple equations from Ecoregion 71 of Tennessee are used to find the bankfull width, bankfull depth, bankfull area, and bankfull flow rate. All that is needed to generate the channel geometry is the drainage area of the stream. Figure 6, shown below, is the equations used from Ecoregion 71 of Tennessee to find the preliminary channel dimensions for Chamber's Branch.

$$A_{bkf} = 24.6\ DA^{0.658} \qquad R^2 = 0.976$$

$$W_{bkf} = 19.8\ DA^{0.349} \qquad R^2 = 0.934$$

$$d_{bkf} = 1.25\ DA^{0.307} \qquad R^2 = 0.931$$

$$Q_{bkf} = 91.2\ DA^{0.687} \qquad R^2 = 0.925$$

Figure 6: Ecoregion 71 Regression Equations

In this project's case, preliminary channel dimensions were found for all four reaches and all three tributaries. Table 5, shown below, shows all drainage areas and preliminary channel dimensions for the reaches and tributaries. The dimensions shown are not the final channel sizing, but a great understanding of how large the channel needs to be.

Table 5: Preliminary Channel Sizes by Regression Equations

		Ecoregion 71 Regression Equations			
Stream ID	DA (mi^2)	A_{bkf} (ft^2)	W_{bkf} (ft)	d_{bkf} (ft)	Q_{bkf} (cfs)
Reach 1	0.09	5.0	8.5	0.6	17.4
Reach 2	0.35	12.3	13.7	0.9	44.3
Reach 3	0.39	13.2	14.3	0.9	47.8
Reach 4	0.57	17.0	16.3	1.1	62.0
Tributary 1	0.24	9.6	12.0	0.8	34.2
Tributary 2	0.09	5.0	8.5	0.6	17.4
Tributary 3	0.12	6.1	9.4	0.7	21.3

The channel geometry is the viewing of a final channel design in the cross-sectional view. The channel geometry would include the following: bankfull width, bankfull depth, entrenchment ratio, channel slope, floodplain slope, and roughness coefficients. Figure 7 shows the bankfull geometry and flood-prone width. The entrenchment ratio is another term that becomes important when determining the channel dimensions. The entrenchment ratio is the flood-prone width divided by the bankfull width. This ratio determines the sizing of the flood-prone channel dimensions and the capacity for large flood events. Maintaining the flow during large flooding events is crucial to not deteriorating the land or harming other environment. The target ratio for this project was four to five. A universal entrenchment ratio of 4.5 was chosen for all reaches and tributaries.

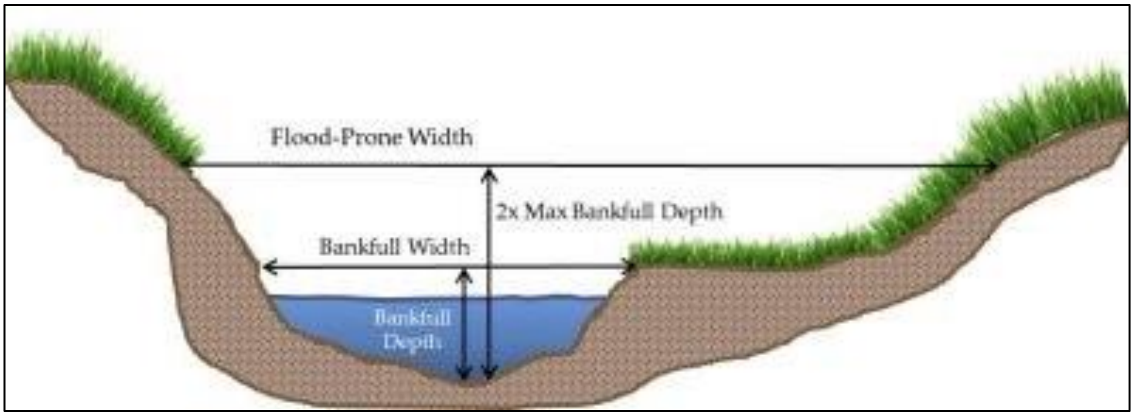

Figure 7: Channel Cross-Section with Bankfull

The bankfull geometry is the dimensions of the main channel. This portion will control the regular water flow as well with the short year flooding. The bankfull geometry also includes the channel slope, which was chosen to be two. This slope controls how steep the bank of the channel is. An important criterion for designing the reaches and tributaries is for a bankfull width to depth ratio to be twelve or greater. The ratio is the width divided by the depth. Table 6, shown below, shows the final bankfull geometry dimensions for all reaches and tributaries and the width to depth ratios.

Table 6: Final Channel Dimension and Width to Depth Ratio

Final Channel Dimensions			
Stream ID	W_{bkf} (ft)	d_{bkf} (ft)	W/D Ratio
Reach 1	8.5	0.60	14.2
Reach 2	13.7	1.10	12.5
Reach 3	14.3	1.15	12.4
Reach 4	16.3	1.10	14.8
Tributary 1	12.0	0.95	12.6
Tributary 2	8.5	0.7	12.1
Tributary 3	9.4	0.75	12.5

Roughness coefficients are important to consider when designing a channel due to different textures affecting the water flow. Two coefficients were needed, one for the channel and one for the floodplain. The channel slope will be of a smaller value due to it being a smoother surface, so the water does not become disturbed while flowing. The floodplain will be rougher because tree roots, vegetation, and other debris being embedded into the embankment. The coefficient for the channel chosen was 0.04 and for the floodplain 0.08. These were more adequate and provided a better design.

After the bankfull width dimensions were completed, it was implemented into Civil 3D. The thalweg remained the same as shown in 'Figure 8'. The bankfull widths varied for each reach which meant the junction of these reaches needed to have a varying width between the two. The ratio we used to increase the width downstream was five feet in length to one foot in width. This created a gradual transition between each reach which was adequate. The figure below shows the completed plan form design before the implementation of riffles and soil lifts.

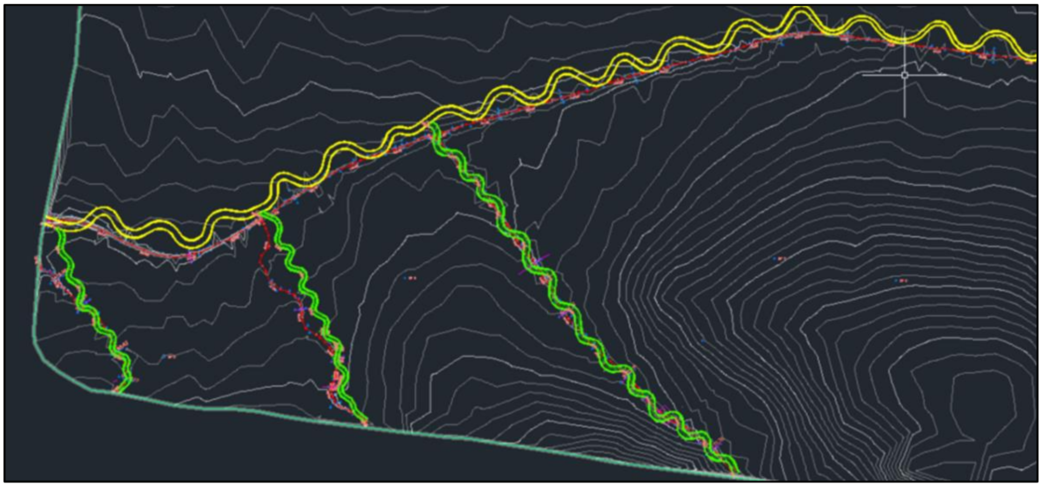

Figure 8: Bankfull Width Implementation, Plan Form Design

5.3 Riffles and Pools

Riffles and pools are extremely important to a highly functioning stream. They are also greatly beneficial to the environment. Riffles create oxygenation in the water. Oxygen helps to break down toxins in the water and creates an environment for fish and invertebrates to flourish in. The riffle and pool sequence creates a variation in flow velocity. This variation is beneficial to wildlife as well as the stream. The slow velocity around bends helps to decrease the impact of erosion.

Two kinds of riffles were used in this project, including an enhanced riffle and a brush riffle. An enhanced riffle is a straight section of the stream that is made to be high velocity with shallow depth due to a decrease in cross-sectional area by the implementation of rocks. This type of riffle is displayed in 'Figure 9'. A brush riffle is similar to the enhanced riffle although it implements rock and wood. This type of riffle is displayed in 'Figure 10'. Riffles create a large amount of energy dissipation which is beneficial before reaching a bend in the stream. These were applied into the design using the hatching tool on Civil 3D. The riffles elongated the total of each straight.

Figure 9: Enhanced Riffle

(StreamHandbook.org)

Figure 10: Brush Riffle

(StreamHandbook.org)

Soil lifts were also used in this design. A soil lift is wrapped layers of soil and vegetation in geotextile fabric. These are placed around the outer bank of each bend in order to eliminate or decrease the occurrence of erosion. These were placed around the outer bank of each bend. The image in 'Figure 11' shows a soil lift when it is first placed during construction.

Figure 11: Soil Lifts

(StreamHandbook.org)

After all of the riffles and soil lifts had been implemented in to Civil 3D, the final plan form was completed. Figure 12 displays the full-scale image of the drawing. At this point the streams were fully designed and checked to be fully functioning.

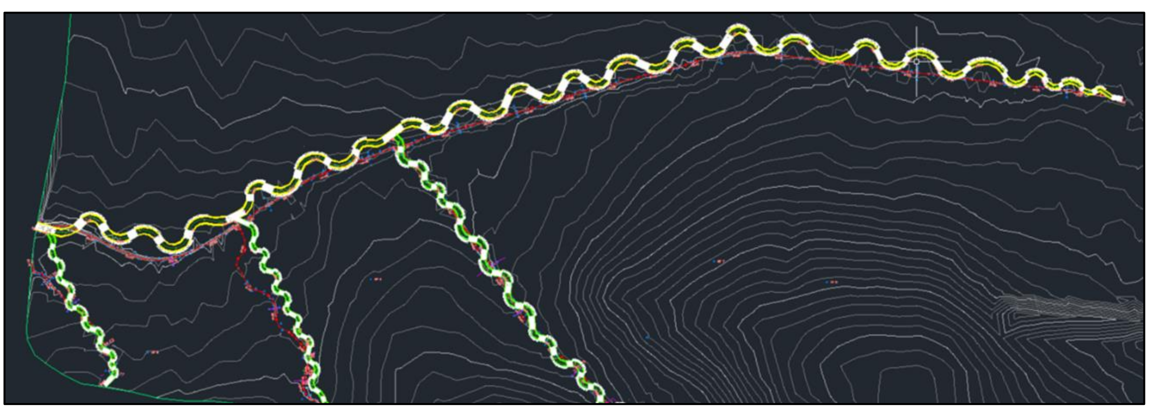

Figure 12: Riffles and Pools, Final Plan Form

After the riffles and pools were implemented into the Civil 3D drawing, a check was performed on the spacing. The riffle/pool stationing was checked by measuring the distance from the start of a riffle through the pool to the start of the next riffle. An example of how this was measured is shown below in 'Figure 13'.

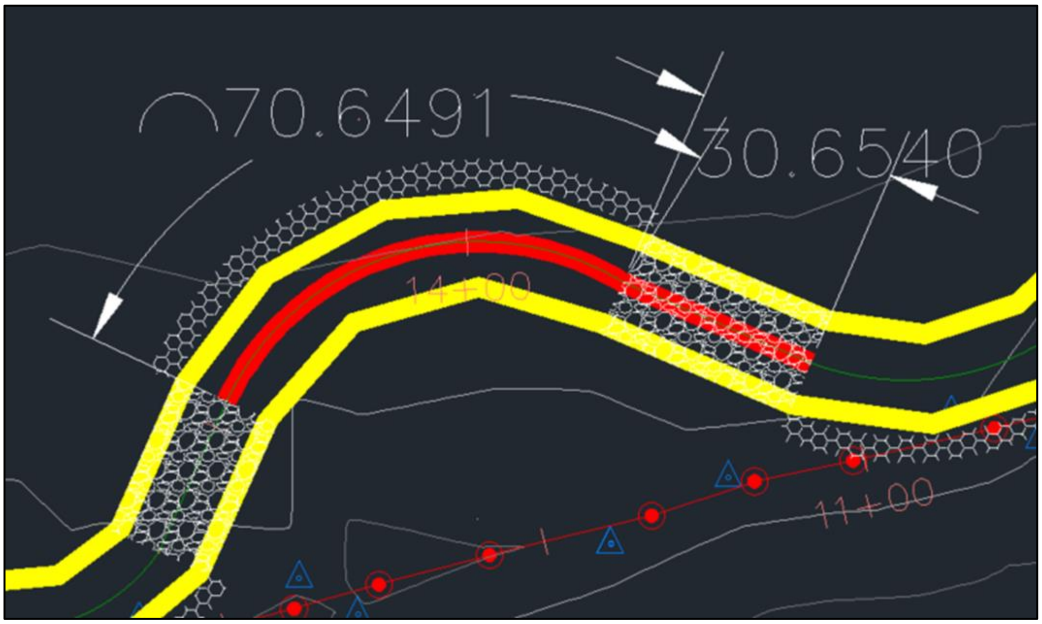

Figure 13: Riffle/Pool Spacing

The ratio between the riffle spacing and bankfull width for each reach and tributary was used for this check. As shown in the table below, each riffle/pool spacing was within the range of where it needed to be besides reach 1. The goal for the reaches were between five and six. The goal for the tributaries was between three and four. These values were able to be altered to fit the design.

Table 7: Riffle/Pool Spacing Results

	Reach 1	Reach 2	Reach 3	Reach 4	Tributary 1	Tributary 2	Tributary 3
Bankfull Width (Feet)	8.50	13.70	14.30	16.30	12.00	8.50	9.40
Average Spacing	**8.65**	**5.80**	**5.95**	**5.32**	**3.98**	**4.16**	**3.61**

5.4 Vertical Profile Design

The vertical profile design first consisted of determining what slope would be applicable to each reach and tributary. The existing grade had to be used unless a large amount of cut and fill would occur which was not ideal. The longitudinal slope was calculated for each reach and tributary using the difference in elevation at the start point and end point. The length for this calculation was found using only the distance of the riffles. The reason for this is because the pools have no slope or if there is a slope it is small enough to be considered negligible. As shown below in 'Figure 14', is a representation of how the riffle and pool sequence is applied in the vertical profile.

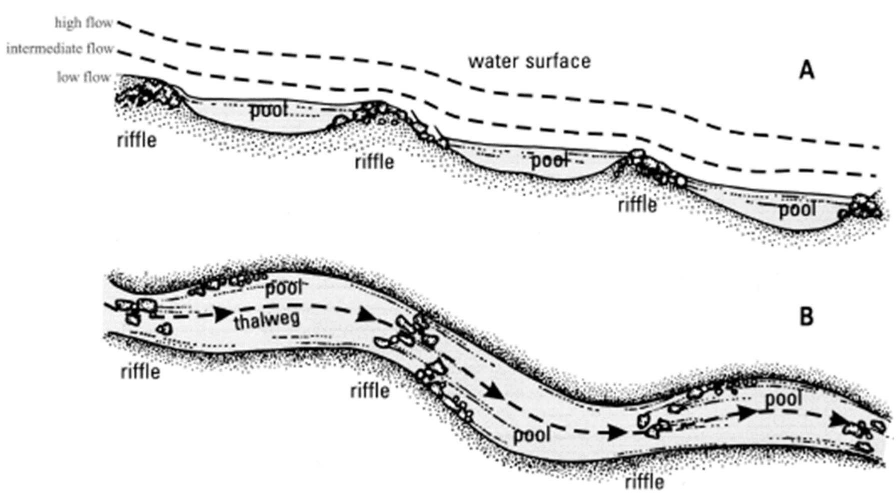

Figure 14: Riffle/Pool Diagram of Longitudinal Slope

(https://content.ces.ncsu.edu/natural-stream-processes)

The vertical profile design consists of the stream's riffle/pool profile. An analysis of the existing grade was conducted to determine the allowable slope for each reach and tributary. Shown below, in 'Figure 15', is the vertical profile design for tributary 3. The depth of the pools was set to be twice the bankfull depth of the riffles. The slope for each riffle was close to the total slope in order to keep the riffles consistent down the stream.

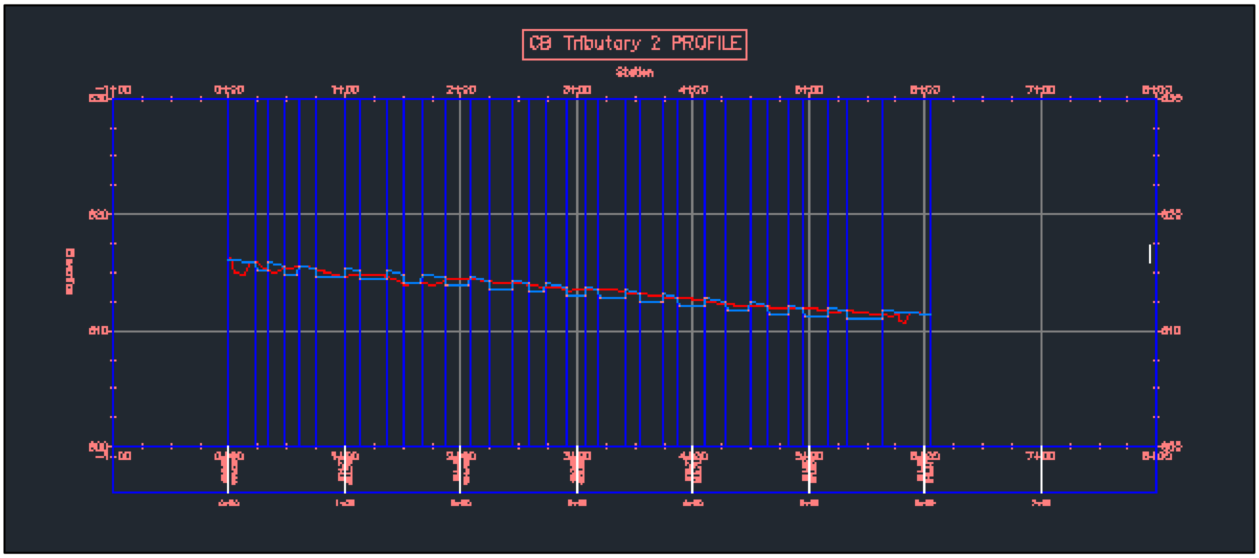

Figure 15: Vertical Profile with Riffle/Pool Sequence

5.5 Hydraulic Analysis

A HEC-RAS model was developed for each reach and tributary. It allowed all data to be inputted for a two-year and one-hundred-year flood simulation to be run. The simulations resulted in a flow then compared to the Stream Stats hydrologic analysis flows. The HEC-RAS calculated flow needed to be close to the Stream Stats flow to check that the final designed dimensions would withstand the flooding. Table 7, shown below, shows all data collected from HEC-RAS. All flows were within an acceptable range from the hydrologic analysis.

Table 8: HEC-RAS 2-Year and 100-Year Flow Rates

HEC-RAS		
Stream ID	Q 2-year (cfs)	Q 100-year (cfs)
Reach 1	11	43
Reach 2	58	232
Reach 3	60	241
Reach 4	87	349
Tributary 1	11	43
Tributary 2	58	232
Tributary 3	60	241

6. Distribution of Workload within the Team

The workload for this project was pretty evenly distributed throughout the team. We completed the plan form design together. Tanner completed the hydrologic analysis, channel sizing, and hydraulic analysis, while James completed the implementation of riffles, pools, and soil lifts and the vertical profile design. We feel we worked very well as a team in this project. The ability for each of us to overcome struggles with software or design constraints was fully a team effort.

7. Conclusion and Recommendations

The degraded stream now has a highly functioning design that will greatly benefit the environment and the surrounding community. The design eliminated the rapid flow rates causing instability in the stream caused by the agricultural uses. Throughout this project many skills and thought processes were learned. Many challenges and obstacles were identified throughout the project and we worked as a team to solve them. A degraded, poorly functioning stream was given to improve, and a successful redesign of a highly functioning stream was created that will be a great benefit to the surrounding ecosystem and environment as a whole. After the construction has been completed trees and vegetation will be planted in the floodplain to further improve the surrounding ecosystem. There are a few steps left to complete this design before construction. These include the development of a corridor in Autodesk Civil 3D and a final check of channel stability using HEC-RAS. When these steps are completed and pass the checks, the plans will be ready to submit.

8. References

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9. Appendix

9.1 ABET Outcome 2, Design Factor Considerations

Design Factor	Page number, or reason not applicable
Public health safety, and welfare	There are no homes in this area that will be affected by flooding or the degraded stream therefore, there is no effect on public health safety, and welfare.
Global	This design has no global impact due to total project area being relatively small.
Cultural	There were no cultural considerations for this design due to the restoration not having any effect on cultural standards.
Social	The stream is on private property and will not be accessible for the public and will have no social factors.
Environmental	20, 26, 27
Economic	9, 10
Ethical & Professional	27, 28
Reference for Standards	'Tennessee Reference Stream Morphology and Large Woody Debris Assessment'

9.2 Channel Dimmensions

Figure 16: Channel Cross Section, Reach 1

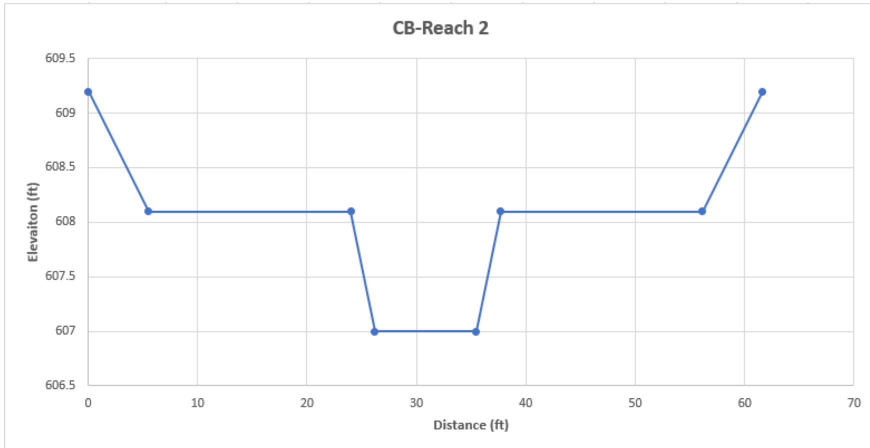

Figure 17: Channel Cross Section, Reach 2

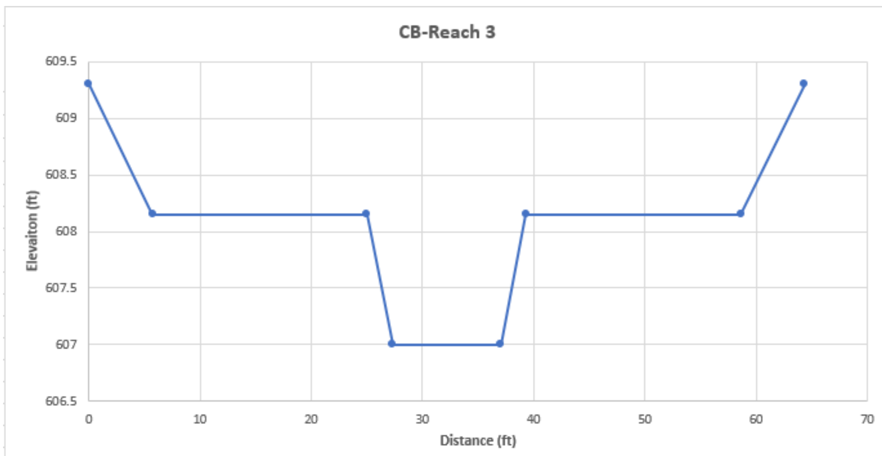

Figure 18: Channel Cross Section, Reach 3

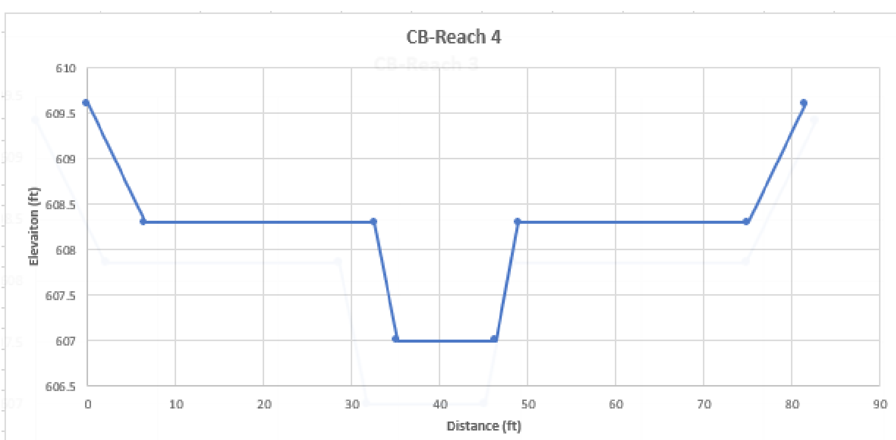

Figure 19: Channel Cross Section, Reach 4

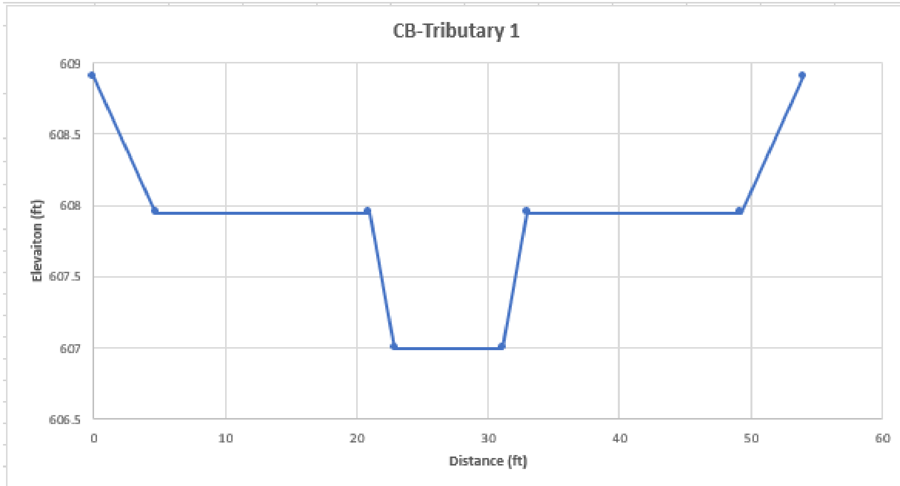

Figure 20: Channel Cross Section, Tributary 1

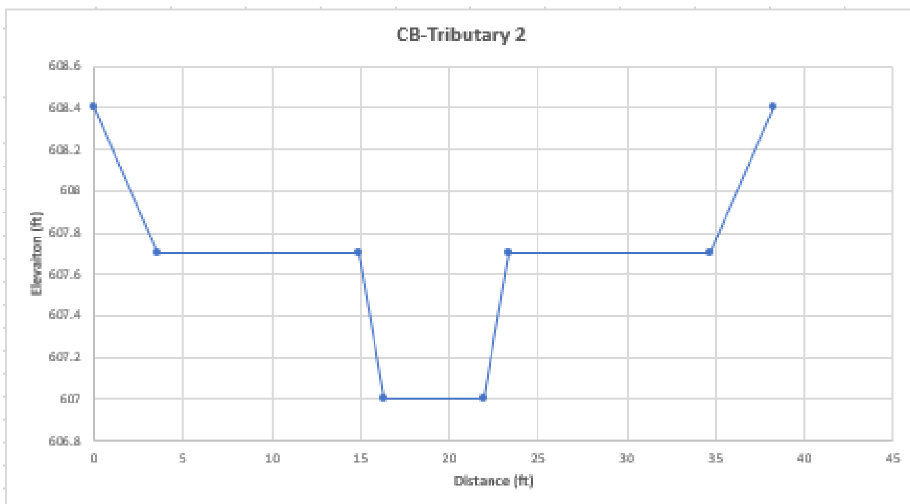

Figure 21: Channel Cross Section, Tributary 2

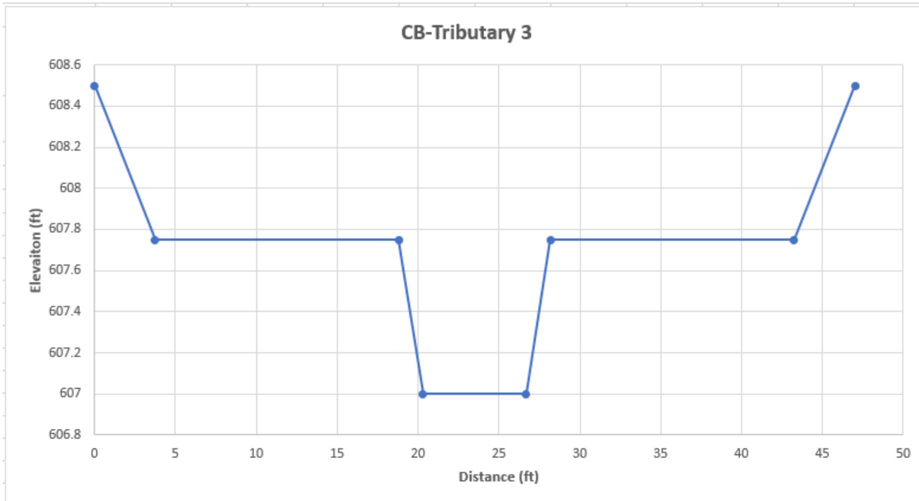

Figure 22: Channel Cross Section, Tributary 3

9.3 Longitudinal Slope Results

Reach 1		
Elevation 1	620.006	ft
Elevation 2	617.080	ft
ΔZ	2.926	ft
Length of Riffle	267.208	ft
Slope	**0.011**	**ft/ft**
Design Slope	**0.011**	**ft/ft**

Table 9: Longitudinal Slope, Reach 1

Reach 2		
Elevation 1	617.080	ft
Elevation 2	613.665	ft
ΔZ	3.415	ft
Length of Riffle	349.151	ft
Slope	**0.010**	**ft/ft**
Design Slope	**0.0175**	**ft/ft**

Table 10: Longitudinal Slope, Reach 2

Reach 3		
Elevation 1	613.665	ft
Elevation 2	611.344	ft
ΔZ	2.321	ft
Length of Riffle	143.895	ft
Slope	**0.016**	**ft/ft**
Design Slope	**0.015**	**ft/ft**

Table 11: Longitudinal Slope, Reach 3

Reach 4		
Elevation 1	611.344	ft
Elevation 2	606.013	ft
ΔZ	5.332	ft
Length of Riffle	267.208	ft
Slope	**0.020**	**ft/ft**
Design Slope	**0.016**	**ft/ft**

Table 12: Longitudinal Slope, Reach 4

Tributary 1		
Elevation 1	620.327	ft
Elevation 2	614.065	ft
ΔZ	6.262	ft
Length of Riffle	403.277	ft
Slope	**0.0155**	**ft/ft**
Design Slope	**0.020**	**ft/ft**

Table 13: Longitudinal Slope, Tributary 1

Tributary 2		
Elevation 1	616.004	ft
Elevation 2	611.378	ft
ΔZ	4.626	ft
Length of Riffle	286.753	ft
Slope	**0.0161**	**ft/ft**
Design Slope	**0.020**	**ft/ft**

Table 14: Longitudinal Slope, Tributary 2

Tributary 3		
Elevation 1	613.135	ft
Elevation 2	608.299	ft
ΔZ	4.836	ft
Length of Riffle	189.842	ft
Slope	**0.0255**	**ft/ft**
Design Slope	**0.020**	**ft/ft**

Table 15: Longitudinal Slope, Tributary 3

9.4 Vertical Profile with Riffle/Pool Sequence

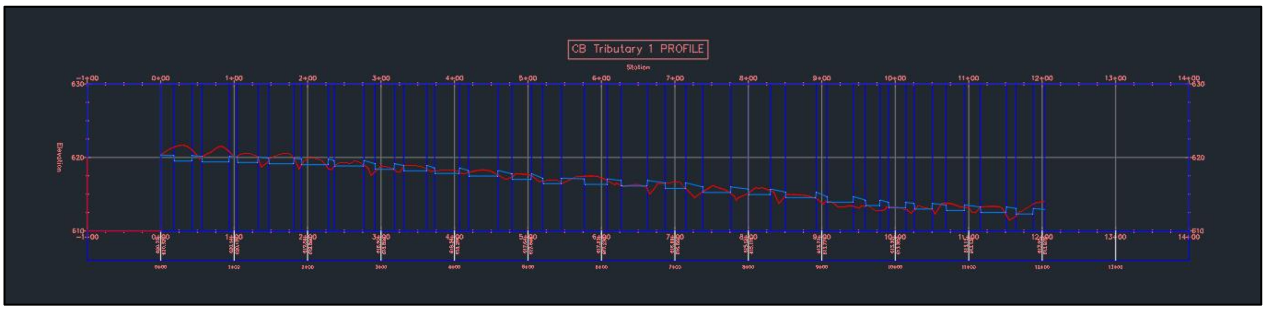

Figure 23: Vertical Profile with Riffle/Pool Sequence, Tributary 1

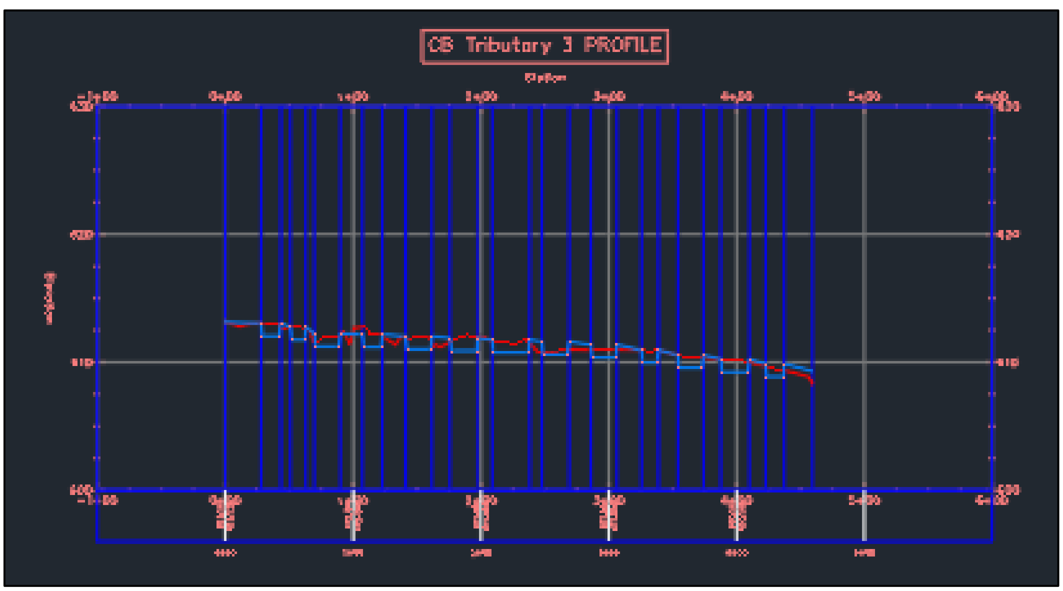

Figure 24: Vertical Profile with Riffle/Pool Sequence, Tributary 3