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Geomorphic Effects of Logging Railbeds on an Ozarks Headwater Stream, Mark Twain National Forest, Missouri

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GEOMORPHIC EFFECTS OF LOGGING RAILBEDS ON AN OZARKS HEADWATER STREAM, MARK TWAIN NATIONAL FOREST, MISSOURI

A Masters Thesis
Presented to
The Graduate College of
Missouri State University

In Partial Fulfillment
Of the Requirements for the Degree
Master of Science, Geospatial Science in Geography and Geology

By
Nickolas Bradley
May 2017

GEOMORPHIC EFFECTS OF LOGGING RAILBEDS ON AN OZARKS HEADWATER STREAM, MARK TWAIN NATIONAL FOREST, MISSOURI

Geography, Geology, and Planning

Missouri State University, May 2017

Master of Science

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ABSTRACT

Geomorphic characteristics of headwater streams draining the Missouri Ozarks have not been studied as much as larger rivers in the region. Further, while the effects of historical logging on channel form and sediment supply have been identified, no studies have investigated the effects of logging tramways constructed along Ozark headwater rivers. This study examines the geomorphic characteristics and channel disturbances of Tram Hollow (1.67 km^2) within the Mark Twain National Forest in the Ozark Highlands. The purpose of this study is to classify and quantify natural and disturbed channel morphology in Tram Hollow which has been affected by confinement, flow obstruction, and channel straightening from the construction of a historical logging tramway. The tram bed confines the valley in disturbed reaches by reducing the effective valley width to 2-3 times less than the effective valley widths in undisturbed reaches. Tram bed-affected reaches have higher incision ratios ranging from 1.1 to 1.3, higher channel enlargement ratios ranging from 1.9 to 5.4, and relatively large headcuts up to 0.6 m deep from tram bed effects. The tram bed alters the hydrology in disturbed reaches including the splitting of surface drainage and the pirating of flow from natural channels. Incised channels along tram beds cut into colluvium composed of 2-27% boulder substrates. Natural morphology at Tram Hollow has little to no incision and contains stable bed substrates. The tram bed in Tram Hollow disconnects the river system laterally through confinement, incision, headcut development, and floodplain fragmentation. Headwater streams at this scale can be sensitive to human modifications and can affect larger downstream reaches due to their positions in drainage networks.

KEYWORDS: geomorphology, headwater, logging, disturbance, Missouri

This abstract is approved as to form and content

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Robert Pavlowsky, PhD
Chairperson, Advisory Committee
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Approved:

Robert Pavlowsky, PhD

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CHAPTER 1 – INTRODUCTION

Human modifications to rivers can affect channel form and stability (Gregory, 2006). Direct human modifications to rivers include channel straightening, clearing obstructions, bank stabilization, dams and reservoir construction, and levee construction (Alexander et al., 2012). Changes in land use such as mining, urbanization, and logging indirectly affect river channel morphology by altering flow and sediment regimes. Most studies of modified channel systems occur on larger rivers since there is more incentive to study larger, downstream river channels, because these larger rivers are areas of interest for water quality projects, sediment quality, and aquatic and wildlife habitat (Alexander et al., 2007). However, headwater streams less than 1-10 square kilometers are often overlooked in studies of the effects of channel modifications in watersheds (Gomi et al., 2002; MacDonald and Coe, 2007).

The effects of some of the most influential human modifications to larger rivers including dam construction, gravel mining, and channelization have been well-documented (Brookes, 1987; Kondolf, 1997; and Graf, 2006). Dams can affect the hydrology and geomorphology of streams. Graf (2006) studied the downstream hydrologic and geomorphic effects of dams in America and found that reaches affected by the dams had 32% larger low flow channels, 50% smaller high flow channels, and 79% less active floodplain area. Kondolf (1997) also studied the geomorphic effects of dams on rivers and found that dam construction and gravel mining of rivers can lead to sediment-starved streams, leading to downcutting and channel bed and bank erosion. Channelization is another important human modification to streams. Brookes (1987) found that channelization along streams in England caused higher stream velocities, erosion, increased channel width, and enlarged cross-sectional areas up to 153%. Human modifications of river systems can negatively affect hydrologic and geomorphic regimes and the quality of aquatic and riparian habitats in smaller headwater streams as well.

Railroad effects on channel form and bed substrates have not been studied as much as other disturbances in rivers including the effects of dam construction, mining, and gravel mining. However, railroads are commonly found along rivers and in the valleys of channel networks. There are about 200,000 miles of railroads in operation in the United States today (Dobbin and Dowd, 2000). About 125,000 miles of smaller railways for temporary logging and mining use have been abandoned since 1916 (Schwieterman, 2004), but have left behind bed materials, levees, dams, and other obstacles to flow on the landscape. These rail bed features can negatively affect the hydrologic and geomorphic stability of river systems, by causing valley and channel morphology disturbance, altering drainage patterns and sediment transport processes, and by confining the river system (Magilligan, 1992; Winterbottom, 2000; Blanton and Marcus, 2009). Railroad construction represents both an historical and ongoing cause of channel disturbance.

Geomorphic Effects of Rail Roads

Geomorphic disturbance effects from rail beds can occur at both the valley and channel reach scale in river systems (McDowell, 2000, Stover and Montgomery, 2001; Blanton and Marcus, 2013). The construction can alter the relationship between valley width and channel slope in a river system and alter surface drainage patterns, leading to changes in channel planform, bed particle sizes, hydrology, stream power, and energy available for geomorphic work (Florsheim et al., 2000; Winterbottom, 2000; Adam and Spotila, 2005; Blanton and Marcus, 2013). Channel disturbance effects can be different depending on if the rail bed is filled or cut (Florsheim et al, 2000; Winterbottom, 2000). Flow and sediment can be obstructed by filled rail beds, separating surface drainage and creating multi-threaded planforms (Gilvear and Winterbottom, 1992; Winterbottom, 2000). Cut rail beds can dissect floodplains and create channels in areas that were previously unchannelized, causing flow to be pirated and concentrating stream power (Florsheim et al., 2000).

Valley Width and Slope. Rail beds can alter valley width and slope of river systems. Confining the channel planform and floodplain and narrowing effective valley widths (Wheaton et al., 2015). Effective valley width is the width of the active channel and floodplain areas between natural or anthropogenic obstacles such as valley walls or levees (Fryirs and Brierley, 2010). Narrowing the effective valley width decreases the channel's capacity to adjust laterally, and may cause an increase in channel bed slope to accommodate the concentrated stream power caused by deeper flows and straighter channels (Fryirs et al., 2016). Reaches with wide valley floors tend to have lower channel slopes and are able to dissipate their energy laterally and allow their flow to spread out (Magilligan, 1992; Lecce, 1997).

Narrow valleys have steeper channel slopes and concentrate their energy longitudinally and do not dissipate their energy laterally. Filled rail beds can confine effective valley widths by physically obstructing water and sediment, leading to alterations in valley drainage patterns and preventing the channel to dissipate its energy laterally. Cut rail beds can also confine effective valley widths by concentrating stream power in cut drainages and focusing the energy available to do geomorphic work along the channel (Florsheim et al., 2000).

Channel Planform Changes. Channel planform changes can be caused by both filled and cut rail bed construction (Florsheim et al., 2000; Winterbottom, 2000). Embankments and filled tram beds provide obstacles to flow that can lead to changes in channel planform and local slope and floodplain surface drainage patterns (Gilvear and Winterbottom, 1992). Cut tram beds can dissect the floodplain and cause channels to be created in areas where no channel previously existed (Florsheim et al., 2000).

Multi-threaded channels can coalesce to form one constrained channel along filled rail beds (Gilvear and Winterbottom, 1992; Winterbottom, 2000; and Rinaldi, 2003). Other studies found that embankments can cause single channels to divide (Bravard et al., 1986; Gurnell, 2009). Embankment construction can cause single-threaded channels to become multi-threaded in three ways: splitting surface drainage (Gurnell, 2009), breach of the embankment (Gilvear and Winterbottom, 1992), and forming secondary channels during high flows which spill out over the embankment (Bravard et al., 1986). Over-embankment flooding can occur when the valley has become constricted too much due to embankment construction, so that the flood stage rises and either overtops or erodes the embankment.

The excavation of roads or rail beds can also lead to changes in channel planform by pirating flow from the natural channel, causing incision and leading to the development of well-formed channels in areas where no channel previously existed (Florsheim et al., 2000). Piracy, or the taking of water by a channel from its natural course, can occur in small tributaries with drainage areas up to a few square kilometers, leading to significant channel deepening and widening, and creating a series of headcuts (Florsheim et al. 2000).

Headcuts. The development of headcuts is one of the most important geomorphic responses of a stream from rail beds. Headcuts are erosional features where abrupt vertical drops occur in a bed surface elevation (Alonso et al., 2002). One way for an unstable stream to return to equilibrium is to initiate a headcut. Headcutting lowers the bed elevation of streams causing a decrease in channel slope back to its equilibrium state (Lane, 1955). The decrease in channel slope also causes a decrease in flow velocity and discharge given that all the other variables remain constant. Headcuts from rail bed features can be systematic and migrate upstream in response to channel straightening, channel constriction, or water piracy and incision in cut rail beds.

Headcuts can form after channel straightening which increases channel slope. They can also form by constricting the channel enough to increase flood depths and therefore concentrate stream power and energy to cause stream bed incision. Florsheim et al. (2000) found that excavation created defined channels in the floodplain where no channel previously existed, causing headcuts to form from incision. These excavated channels were to accommodate drainage from roads but increased stream power in areas that were previously unchannelized. Headcuts from tram bed disturbances can migrate upstream (Schumm, 1979).

Non-tram headcuts tend to be localized and form sporadically due to natural variations between discharge and slope with sediment supply and particle size (Lane, 1955). Local headcuts can occur at bedrock obstacles or tributary confluences where water supply is disproportionately higher than sediment supply (Whipple et al., 2000). Headcuts increase local sediment supply by eroding into bed materials, releasing sediment downstream, and potentially mobilizing larger particles such as cobbles and boulders (Adam and Spotila, 2005; Golden and Springer, 2006).

Bed Particle Size. Rail beds and tramways can concentrate stream power and cause bed incision that increases bed particle size and channel depth. Bed substrate size does not vary systematically downstream in headwater channels. However, several studies found that larger particle sizes are typically found on channel beds with higher stream power, including where channel bed slope increases locally, transitions colluvial to fluvial conditions, and is affected by a knickpoint on a reach of higher sediment transport capacity (Adam and Spotila, 2005; Wohl and Wilcox, 2005; Golden and Springer, 2006).

Channels can incise and recruit larger substrate particles buried deeper in bed lag deposits or coarse colluvium and residuum in reaches with increased stream power or at knickpoints. This recruitment can occur along cut road and rail beds where excavation created knickpoints that migrated headward and incised upstream tributaries (Florsheim et al., 2000). Recruitment of larger particles can also occur along filled rail bed features where stream power is higher, in response to return to its equilibrium state (Lane, 1955; Schumm, 1979). Adams and Spotila (2005) found that headwater streams draining less than two km^2 are sensitive to local knickpoints and this affects downstream patterns of particle size and incision.

Floodplain Fragmentation. Floodplain fragmentation can occur from the construction of rail beds (Eitemiller et al., 2000; Snyder et al., 2003; Blanton and Marcus, 2009; Blanton and Marcus, 2013; Blanton and Marcus, 2014; Lugo et al., 2015). Roads and rail beds can cause floodplain fragmentation or disconnection by altering the natural flood and flow regimes, dissecting the floodplain by creating excavation drainages, and from the physical obstruction of the embankments. Altering the flood and flow regimes of the channel causes the channel to become constricted enough and overly sufficient at conveying floods downstream at the expense of lateral connectivity.

Floodplain pockets can form or areas that were once a particular flood zone may no longer be part of that flood zone due to the channel's inability to laterally reach those areas at particular flood magnitudes. Lateral river disconnection is measured as the ratio of the length of disconnected floodplain to total floodplain area (Snyder et al., 2003; Blanton and Marcus, 2014). Snyder et al. (2003) also found a decrease in riparian habitat quality. Several other studies found that lateral disconnection and a loss in habitat quality can also result from the physical obstruction of levees and transportation embankments along rivers (Bravard et al., 1986; Deiller et al., 2001).

Ozark Logging History

This study evaluates the present-day geomorphic influence of historical tramway construction during historical logging activities on headwater streams in the Mark Twain National Forest in the Ozark Highlands in Southeast Missouri (Figure 1). Settlement along headwater streams in the area began in 1880 at the onset of the timber boom (Guyette and Larson, 2000). Investors from other parts of the country started to build railroads to facilitate logging transportation (Guyette and Larson, 2000). Small gage tram systems were operated in Reynolds, Carter, Shannon, and Ripley Counties from 1880 to

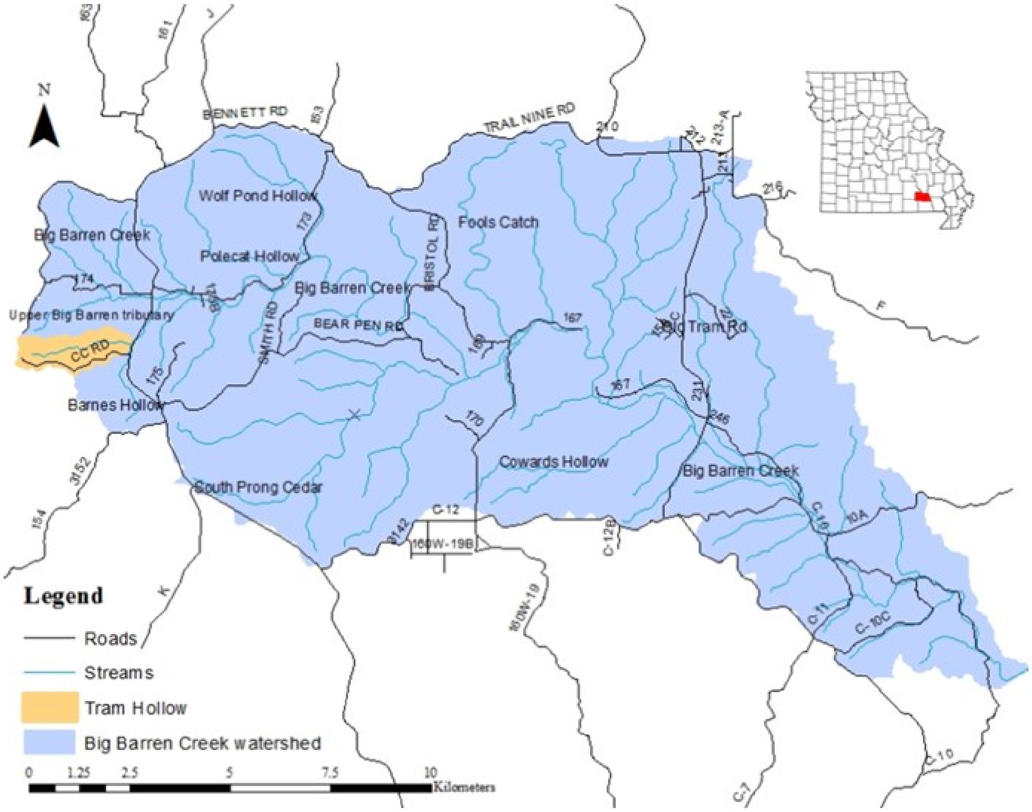


Figure 1. Location of Tram Hollow Watershed.

the mid-1940s to support logging activities (Guyette and Larsen, 2000) (Figure 2). Logging rail roads were constructed parallel to river channels, often in the floodplains, because more gradual slopes permitted easier access and transportation for the logging industry. The rail beds from this old network of logging trams still remain in several Ozark watersheds (Jacobson and Primm, 1997; Strausberg and Hough, 1997; Guyette and Larsen, 2000; Benac and Flader, 2004). Evidence includes cut tram beds, filled tram beds, boulder lines bordering filled tram beds along streams, and old bridge materials (Guyette and Larsen, 2000) (Figure 3 and Figure 4). No studies have previously evaluated the effects of these abandoned rail systems on channel disturbances such as channel straightening, flow obstruction, and valley confinement in the Ozarks. The geomorphic effects of rail beds have focused in the Pacific Northwest, and the geomorphic effects of smaller rail systems such as logging trams have not previously been studied (Blanton and Marcus, 2009). Understanding the geomorphic effects of valley and channel disturbance from tramways such as river confinement and channel straightening can answer important questions regarding the geomorphic stability of headwater streams in the Missouri Ozarks.

Tram Hollow is a small headwater watershed (1.67 km^2) located in the headwaters of Big Barren Creek Watershed in the Mark Twain National Forest of Missouri (Figure 1). Tram Hollow has been affected by confinement, flow obstruction, and channel straightening due to the construction of a logging tramway more than a century ago. Tram Hollow is typical of many low-order headwater streams in the Ozarks and offers relatively easy access. The focus of this study is on the tramway constructed along Tram Hollow. The tram bed is either filled or cut, having different affects on channel morphology. Filled tram beds are earthen embankments about 1-2 meters high and 4-5 meters wide. The tramway was built up to prevent the tramway from floods in some locations. The tramway runs parallel to the main channel for the most part and crosses the stream in several places where the channel has breached the tramway embankment (Figure 5). The tramway can be identified in some areas by observing the ages of trees, occurring in places where only younger trees are located. The tramway starts near the outlet of Tram Hollow and exits the watershed through the northwest tributary.

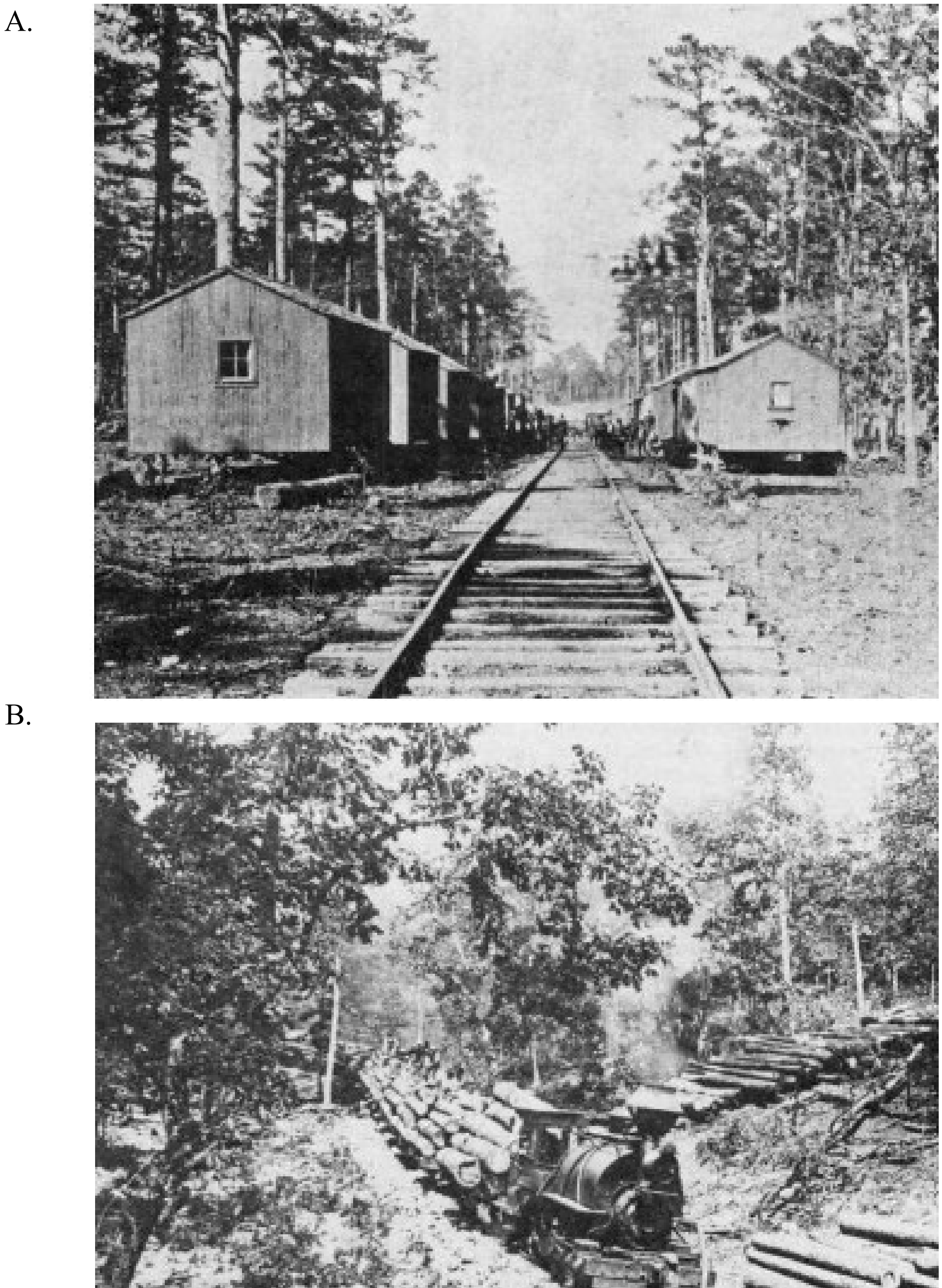


Figure 2. Logging Rail Systems in Missouri: A.) Mobile Logging Camp of the Cordz-Fisher Lumber Company, and B.) Log tram, Missouri Lumber and Mining Co., 1907. Reference: Ozarks Watch, Vol. VI., No. 1, 1992.

A.

B.

Figure 3. Filled Tram Bed Features in Tram Hollow: A.) Filled tram bed, R-km 1.17, B.) Filled tram bed, R-km 2.21. Pictures taken in December 2015 by Nick Bradley.

Figure 4. Cut Tram Bed Features in Tram Hollow A.) Cut tram bed, R-km 0.93, B.) Cut tram bed, R-km 0.60. Pictures taken in December 2015.

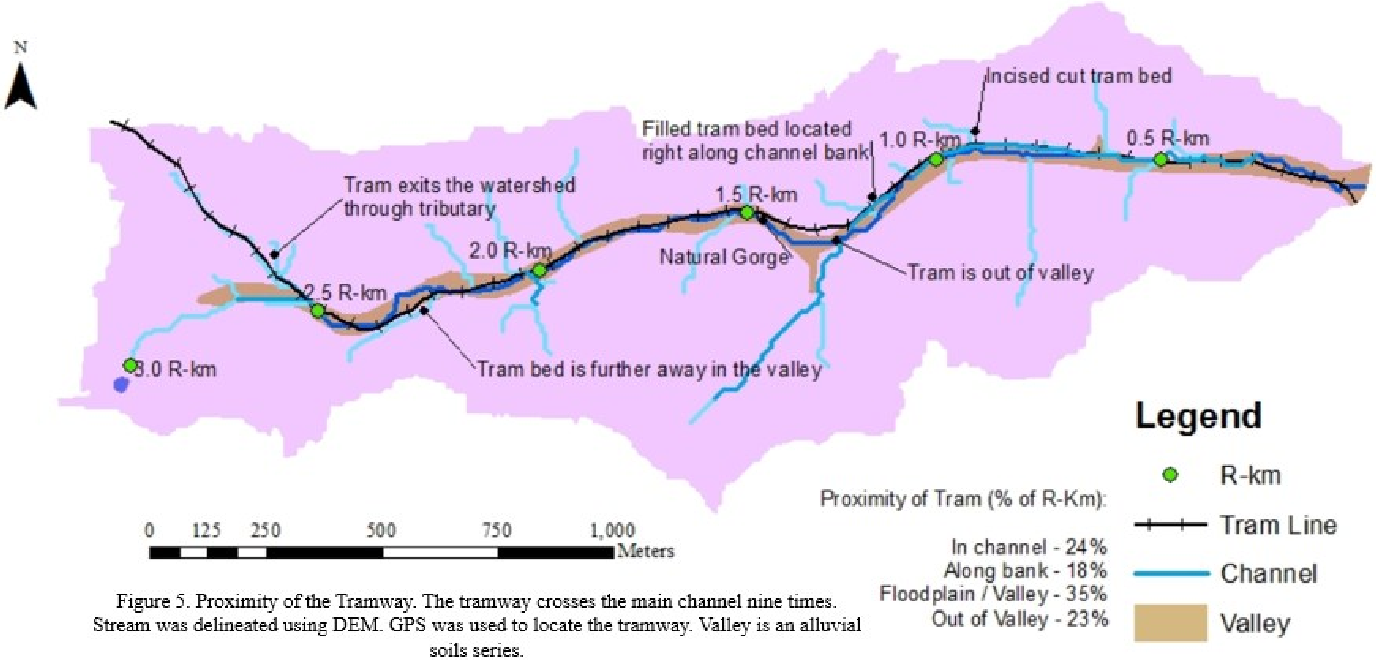


Figure 5. Proximity of the Tramway. The tramway crosses the main channel nine times. Stream was delineated using DEM. GPS was used to locate the tramway. Valley is an alluvial soils series.

Purpose and Objectives

The purpose of this study is to evaluate the geomorphic effects of disturbance from a railroad built along Tram Hollow (1.67 km²) and compare to natural headwater channel morphology in the Mark Twain National Forest of Missouri. The understanding of these effects on channel form, drainage, and sediment transport processes is important because this information can be used to identify areas of channel response to rail bed disturbance and help predict channel morphology of both undisturbed versus disturbed streams in the Ozarks in general. The three objectives of this study are to: (1) quantify the channel morphology of Tram Hollow including natural and disturbed channel reaches; (2) evaluate downstream trends and relationships in channel morphology and substrate including influence of valley and reach factors such as tram bed effects; and (3) compare the channel morphology of Tram Hollow to reference channels in order to understand how tram bed effects link to channel patterns.

Five hypotheses were developed in order to evaluate the relationships between important geomorphic variables and the influence that the tram bed may have on the channel morphology of Tram Hollow:

1. Confinement ratios of four or less will occur in channel reaches where the tram bed is present (Nagel et al. 2014). The tram bed will also lower the effective valley widths in reaches where it is present (Gilvear and Winterbottom, 1992; Lecce, 1997; Florsheim et al., 2000);
2. The tram bed will cause disturbed channel planforms that have incision ratios greater than one (Florsheim et al., 2000; Winterbottom, 2000);
3. The frequency of headcuts will be greater along reaches where the tram bed is present, because disturbed reaches will have both localized headcuts and migrating headcuts from tram bed disturbance effects (Schumm, 1979; Florsheim et al., 2000);

4. Larger bed substrates will occur along deeper, incised channel reaches due to the recruitment of larger bed particles buried deeper in coarse colluvium and residuum (Adam and Spotlia, 2005; Golden and Springer, 2006); and
5. The percentage of disconnected floodplain will be significantly greater in disturbed reaches than in natural reaches with no tram bed influence (Snyder, 2003; Blanton and Marcus; 2014).

Most studies on channel morphology in the Ozarks have focused on larger rivers. This study will be the first to evaluate the geomorphology including disturbances of Ozark headwater streams less than two square kilometers. Headwater streams comprise about 60 to 80% of the cumulative length of a drainage network (Sidle et al., 2000) and differ from downstream reaches by their close coupling to hillslope processes (Gomi et al., 2002). In addition, headwater streams are important for understanding the health of entire stream networks, such as water quality and aquatic habitat, and for understanding source and transport routes for water and sediment (Meyer and Wallace, 2001). Overall, headwater stream systems are important subjects for understanding the interactions among hydrologic, geomorphic, and biologic processes within the entire drainage network, including disturbance effects from human modifications (Gomi et al., 2002).

Benefits

The results of this study will describe the geomorphic effects of channel disturbances from rail beds and logging tramways along Ozark headwater streams. The geomorphic effects of logging have been studied for larger streams in the region, but the geomorphology of headwater streams less than two square kilometers and the geomorphic effects of rail bed and tramway construction have not yet been studied (Jacobson and Primm, 1997; Jacobson and Pugh, 1997). Oral history recalled smaller streams in the region having higher discharge from logging practices and studies have hypothesized the headward migration of channels into small valleys, but no studies have previously documented these effects in Ozark headwater channels (Jacobson and Primm, 1997). This study will be the first to evaluate geomorphology for colluvial-alluvial Ozark headwater streams, and the first to describe the geomorphic effects of disturbances from logging tram beds. Answers to important questions about natural versus disturbed headwater morphology will be addressed, and important information for management practices dealing with increased sediment supply, channel instability, and increased stream power in Ozark headwater streams will be provided. Furthermore, evaluating headwater streams is important for understanding the channel morphology, aquatic habitat quality, hydrology, and channel stability of all parts of a watershed due to their positions within the drainage network.

CHAPTER 2 – STUDY AREA

The Ozark Highlands in southeastern Missouri is an assemblage of high plateaus of variable topography and relief dissected by dendritic and radial drainages (Kabrick et al., 2000). Spring-fed streams have cut deeply into the plateaus, forming moderately rolling hills. The Current River physiographic region of the Ozark Highlands contains pine oaks forests, moderate to steep hills, and local relief ranging from 50 – 150 meters (Kabrick et al., 2000). Big Barren Creek, a tributary to the Current River, is classified as the Current River Hills land type association and contains moderately steep sideslopes with narrow and broad sinuous valleys (Kabrick et al., 2000). Tram Hollow, the focus of this study, is a small (1.67 km^2) Ozark headwater watershed and tributary to Big Barren Creek (Figure 1).

Geology

The Roubidoux geologic formation comprises the bedrock geology for the entire watershed of Tram Hollow (Orndorff, 2003). The Roubidoux Formation (lower Ordovician) is composed of chert breccia, sandstone breccia, dolomite, sandstone, and chert. Sandier textures are associated with sandstone in the Roubidoux formation and residuum have relatively high clay contents (Kabrick et al., 2000). Sinkholes are common in the Roubidoux formation where underlying dolomites are partially dissolved, allowing Roubidoux sandstone to collapse into cavity (Kabrick et al., 2000). There are no faults or sinkholes along Tram Hollow, and bedrock is only exposed locally along some parts of the channel.

Soils

The composition of the Roubidoux formation influences the character of soil parent materials, affects hillslope sediment textures, and landform shape and occurrence (Kabrick et al., 2000). The upland soils are highly weathered Utisols and Alfisols varying in texture, gravel content, and depth to bedrock, whereas most valley soils are less weathered and have formed in alluvium (Kabrick et al., 2000). There are three upland soil series at Tram Hollow: (1) Macedonia, a residuum that is moderately well drained, cherty, loamy, and occurring on hillslopes and ridgetops, (2) Coulstone, a gravelly, sandy loam on hillslopes, and (3) Clarksville, a gravelly, silty loam also occurring on hillslopes (Allgood and Persinger, 1979; National Cooperative Soil Survey, 1994).

Valley bottom soils are composed of Tilk and Secesh alluvial soil series (National Cooperative Soil Survey, 1994). These are well drained soils composed of silty and sandy loam, and rounded to subangular gravel and cobbles of sandstone, quartz, and chert (Orndorff, 2003). Tilk alluvial series is sandy and loamy alluvium with 3-inch gravel fragments increasing in quantity up to depths of 37 inches (Hansen, 2006). Secesh alluvial series is 2 feet of loamy material over gravelly residuum or alluvium, with 3-inch gravel fragments common at depths up to 80 inches (Hansen, 2006).

The National Cooperative Soil Survey (NCSS) mapped soil series in 1994 for the state of Missouri (Fortner, 2008). In 2000, the NCSS combined state databases into a national centralized database, making the spatial data available for public use (Fortner, 2008). Data from the survey was used to create a map of the soil series present in Tram Hollow (Figure 6). Natural valley bottom landforms such as floodplains and terraces are relatively wide, low, and gradual in slope at Tram Hollow, and well drained compared to upland slopes.

Climate and Hydrology

The climate of the Ozarks is humid temperate with average annual rainfall ranging from 1,000 to 1,200 millimeters and average annual temperature ranging from 15 to 18 degrees Celsius. Large floods generally are caused by intense rainfall during winter or late spring; relatively impermeable soils contribute to flashy runoff events (Jacobson and Gran, 1999). Much of the area supports a karst drainage system, and contains several karst features such as caves, springs, and sinkholes (Kabrick et al., 2000). The karst topography has resulted in some streams that are dry most of the time, whereas other streams with similar surface drainages areas have springs that provide relatively constant baseflow (Jacobson, 2004). Tram Hollow is an ephemeral stream with no springs, and only contains flow during and after rainstorm events. Tram Hollow is a third-order stream and drains 1.67 km^2 (Figure 6). The highest point of Tram Hollow is 311 meters above sea level and the outlet is 255 meters above sea level, with a maximum relief of 56 meters for the entire watershed and average slope of 1.5%.

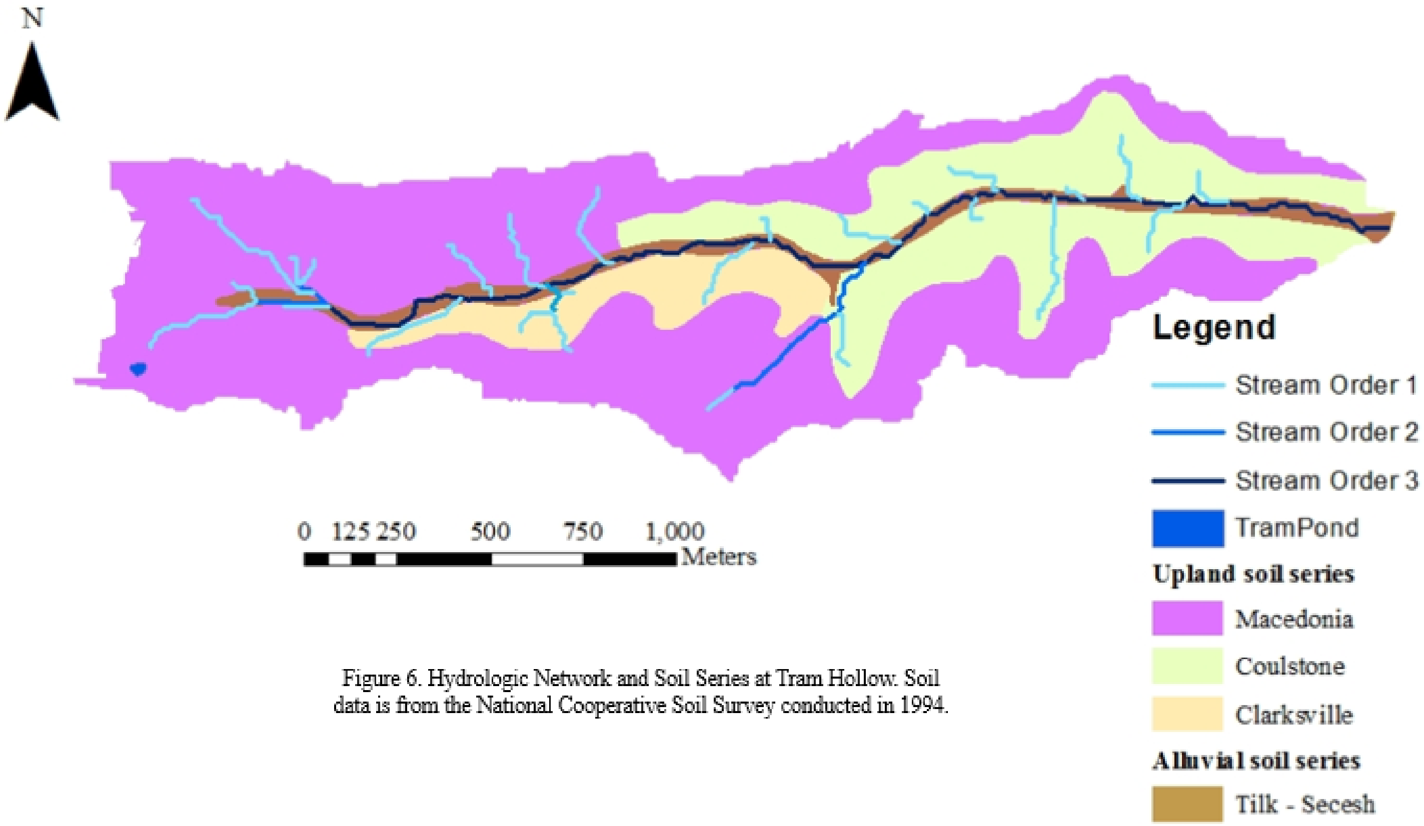


Figure 6. Hydrologic Network and Soil Series at Tram Hollow. Soil data is from the National Cooperative Soil Survey conducted in 1994.

Reference Streams

The two reference streams of this study, Upper Big Barren western tributary and Upper Barnes Hollow, contain similar characteristics to Tram Hollow (Table 1). Upper Big Barren Hollow western tributary is located just north of Tram Hollow, and Upper Barnes Hollow is located just south of Tram Hollow (Figure 7). Tram Hollow joins Upper Barnes Hollow at its outlet. Present day land use at all three watersheds comprises mainly of forest, with roads and local timber stand improvements for some patches of logging occurring along divides (Kabrick et al., 2000).

Table 1. Reference Channel Characteristics.

	Tram Hollow	Upper Big Barren western tributary	Upper Barnes Hollow
Bedrock	Roubidoux formation	Roubidoux formation	Roubidoux formation
Soil	Macedonia, Coulstone, Clarksville, Tilk-Secesh	Macedonia, Coulstone, Tilk-Secesh	Macedonia, Coulstone, Clarksville, Supplee, Tilk-Secesh
Basin slope (%)	1.5	1.8	1.3
Elevation range (m)	311 - 255	308 - 254	312 - 255
Relief (m)	56	54	57
Drainage Area (km^2)	1.67	2.13	2.77
Land Use	Forest (>99%), roads and TSI along divides	Forest (>99%), roads and TSI along divides	Forest (>99%), roads and TSI along divides

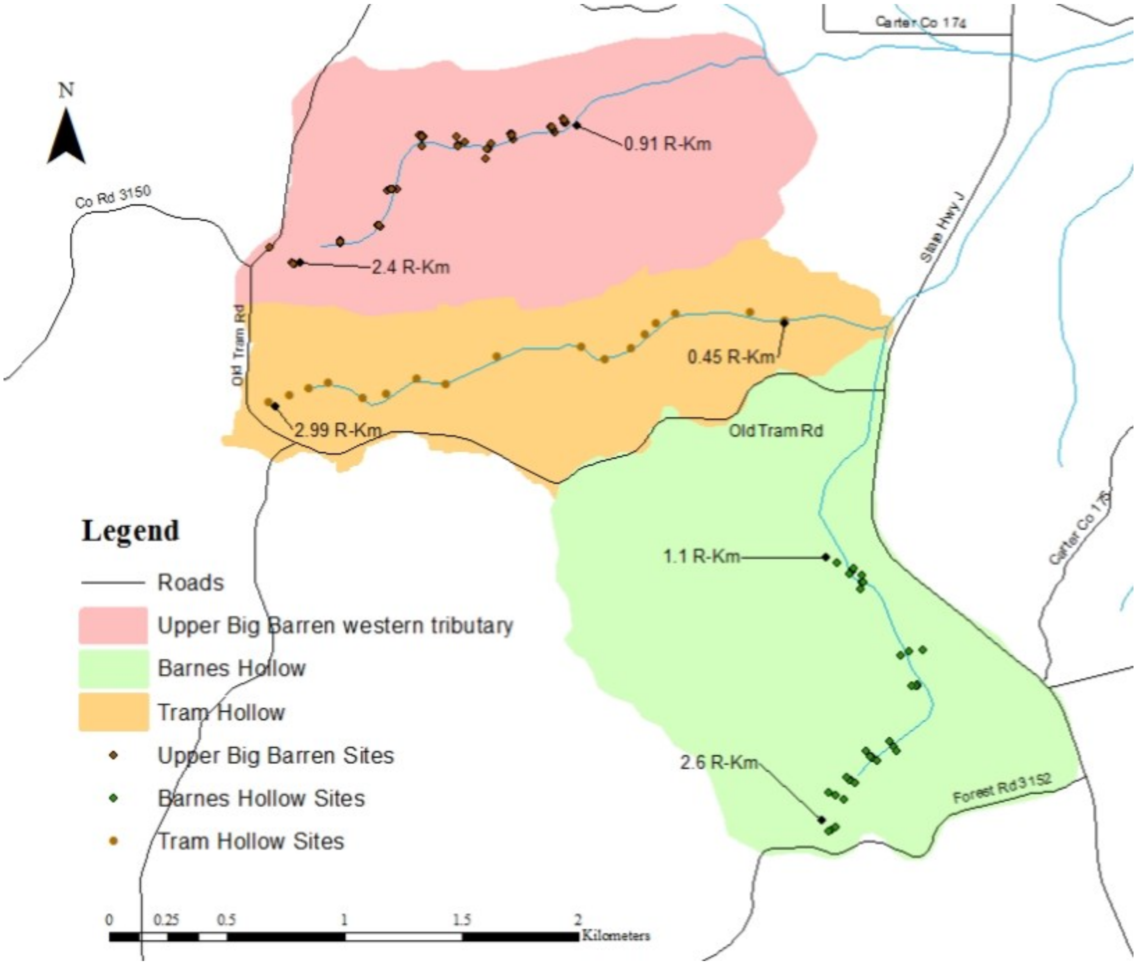


Figure 7. Tram Hollow and Reference Channels.

Land Use History

Investors moved in to Tram Hollow and the region around 1880 to build logging railroads that replaced previous transportation methods of horse pulled wagons over very poor roads and waterways (Guyette and Larson, 2000). Mobile logging camps were established along rivers where several of these railways and tramways were constructed. The tramway at Tram Hollow was probably constructed in the 1880s and was built in the valley bottom along the channel, crossing the channel in nine locations (Figure 5). Lumber exported out of Tram Hollow may have met up with the Current River Railroad, the main rail line for Carter County (Guyette and Larson, 2000). Logging operations in Tram Hollow probably ended in the 1920s, at the end of the timber boom for this area.

Much of the mobile logging camps had disappeared by the later 1920s, along with much of the state's native forests, leaving behind abandoned features of the industry including tramways (Guldin, 2008). Concern about the condition of the abandoned lands eventually led to the establishment of the Mark Twain National Forest (MTNF) in 1939, previously known as the MTNF and Clark National Forest, until combined in 1979 (Guldin, 2008). Today, the MTNF encompasses 1.5 million acres in the Ozark Highlands. Since the time of abandonment in the 1920s and due to conservation practices within the MTNF, Tram Hollow and other headwater streams have had enough time to reforest. Today, Tram Hollow is fully reforested and consists of mixed oak-pine forests (Kabrick et al., 2000). Present land use in Tram Hollow consists mainly of forest, with roads and some logging activity occurring along topographic divides. Forest management in Tram Hollow today is only local timber stand improvements for some logging along roads and assessable divides.

CHAPTER 3 – METHODS

Field, Geographic Information Systems (GIS), and Statistical Analysis methods were used to complete this study. Field methods include several geomorphic assessments (Table 2). GIS was used to map important characteristics and results of the study including hydrologic network, soil series, channel planform classification, tram bed location at Tram Hollow, headcuts, and valley confinement. Statistical analysis was used to test each of the five hypotheses of this study.

Cross-Sections

Eighteen cross-sections were completed at Tram Hollow, each one spanning across the entire valley, using a stadia rod, auto-level, and tripod to sample downstream variations in channel morphology (Harrelson, 1994). Points were collected on each important landform and at form breaks to include information on terrace, floodplain, bank, toe, and channel bed elevations (Harrelson, 1994). Cross-section widths ranged from about 10 meters at a valley gorge to about 50 meters, with about 15 – 20 points per cross-section. Notes on landform, substrate, tape distance, and stadia rod height were recorded at each point in the cross-section. GPS points and photos with the GPS camera were also taken at each cross-section site.

Table 2. Geomorphic Field Assessments.

Geomorphic Assessment	Reference	Date	Instruments	Watershed
Cross-Sectional surveys	Harrelson et al., 1994	December 14-16, 2015	Stadia rod, 50-meter tape, auto-level, tripod, Trimble GPS, field notebook.	Tram Hollow
Longitudinal profile	Harrelson et al., 1994	January 29, 2016; March 5th, 2016	Stadia rod, 100-meter tape, auto-level, tripod, Real Time Kinematic station (RTK), Trimble GPS, field notebook.	Tram Hollow
Pebble counts and substrate classification	Rosgen, 1996.	October 14, 2015; March 5-6, 2016	Gravelometer, Trimble GPS, GPS camera, field notebook.	Tram Hollow and reference channels
Modified Rapid Geomorphic Assessment (MRGA)	Barbour et al., 1999.	October 14, 2015; March 5-6, 2016	Hand level, stadia rod, 100-meter tape, Trimble GPS, GPS camera, field notebook.	Tram Hollow and reference channels
Channel planform classification	Florsheim, 2000; Winterbottom, 2000; Gilvear and Winterbottom, 1992.	December 14-16, 2015; December 16, 2016	Stadia rod, 100-meter tape, auto-level, Trimble GPS, GPS camera, field notebook.	Tram Hollow
Headcut classification	Dietrich and Dunne, 1993.	December 16, 2016	Hand level, stadia rod, 50-meter tape, Trimble GPS, GPS camera, field notebook.	Tram Hollow

Longitudinal Profiles

Eighteen longitudinal profiles (LPs) were completed at Tram Hollow at each cross-section with stadia rod, auto-level, and a real-time kinematic (RTK) device to describe variations in elevation along the channel bed and to determine channel slope (Harrelson et al., 1994; Krahulik et al, 2011). The length of each LP was determined by measuring five channel widths up and five channel widths down from each cross-section site (Harrelson et al., 1994). Each profile was about 60-100 meters long, depending on channel width, with each one having 15 – 20 points. A real-time kinematic device was used to measure the first 200 meters of the channel starting from the top of the watershed at the pond by Old Tram Road, but could not be used for LPs further downstream because of poor reception of the RTK base from canopy cover. Auto-level and stadia rod were used to complete the rest of the LPs further downstream.

Pebble Counts and Substrate Classification

Pebble counts and qualitative bed and bank substrate classifications were recorded for each of the 18 cross-section sites with a gravelometer. (Rosgen, 1996). The composition of bed and banks is important geomorphic variable influencing channel form, hydraulics, erosion rates, and sediment supply (Rosgen, 1996). Pebbles counts were completed in 7 by 5 transects with 35 pebbles per site. Transect spacing was determined by measuring 3 channel widths upstream and 3 channel widths downstream from each cross-section, with 5 pebbles recorded across the channel for each transect. Notes on channel bed substrate were recorded at each site, classifying each particle size as silt, sand, gravel, cobble, boulder, soil, scour soil, cut-earth residuum, or moss (Table 3).

Table 3. Channel Bed Substrates. Descriptions are based on definitions from USDA Soil Survey Manuel and Wolman (1954).

Type	Name	Description
Alluvial		
	Silt	< 0.062 mm
	Sand	0.062 - 2 mm
	Gravel	2 - 64 mm
	Cobble	64 - 256 mm
	Boulder	> 256 mm
Colluvial		
	Soil	Intact O-horizon containing leaf litter and organic materials
	Scour Soil	O-horizon has been partially or completely eroded
	Cut-earth residuum	Subsoil exposed by erosion

Modified Rapid Geomorphic Assessment

A modified EPA rapid geomorphic assessment of physical stream characteristics including channel width, depth, valley width, bed and bank substrates, bank conditions, large woody debris, and channel planform was completed at Tram Hollow and two reference streams to compare channel morphology and evaluate tram bed disturbances (Barbour et al., 1999). Ten sites were assessed at the Upper Big Barren Hollow reference stream and nine sites were assessed at Upper Barnes Hollow reference stream to sample downstream variations in channel morphology (Figure 7). Channel width, depth, and bank heights were measured at each site with a stadia rod and hand level. Valley width was measured with a 100-meter tape and points were taken with the GPS. Notes on substrate, bank conditions, headcuts, boulder obstacles, and channel planform were recorded for each site.

Channel Planform Classification

There are three main classes of channel morphology at Tram Hollow: natural, confined, and tram bed-forced channel morphology. There are seven planform sub-classes at Tram Hollow: two natural, three confined, and two tram bed-forced sub-classes (Table 4). Natural morphology reflects undisturbed conditions with no tram bed influence. There is little to no incision in natural reaches with low banks. The first natural planform sub-class is a sinuous pool riffle channel with relatively low width:depth (w:d) ratios (Table 4; Figure 8; Figure 11). Natural channel morphology can include colluvial or alluvial channels with high w:d ratios that sometimes may contain a secondary channel separated by a low floodplain (Table 4; Figure 8).

Confined morphology occurs where the tram bed provides an obstacle for valley confinement with little direct influence on the channel. The location of tram beds in floodplains may be related to hydraulic effects including increased stream power and higher bed shear stress during floods. Channels can straighten, incise, or possibly head-cut (Gilvear and Winterbottom, 1992; Florsheim et al., 2000; Winterbottom, 2000). There are three confined morphology sub-classes: (1) natural channels that are constricted by the tram bed, (2) natural or tram drain channels with beds that are perched above the current channel, and (3) side flow channels that are cut off from reaching the natural channel by the filled tram bed (Table 4; Figure 9; Figure 12). Confined morphology typically occurs in valleys where the tram bed is further away in the valley or right along the channel bank.

Table 4. Channel Planform Classification.

Class	Description	Sub-classes	Reference
1. Natural	Reflects undisturbed condition with no tram bed influence. Little to no incision, with low banks.	A. Colluvial or alluvial channels with low floodplains and high w:d. B. Pool riffle channel with lower w:d ratio.	Kabrick et al., 2000
2. Confined	Tram bed provides an obstacle for valley confinement with little direct influence on the channel. The tram bed can also cause channels to straighten, incise, or possibly head-cut.	A. Natural channels or tram drain channels that are either incised or perched. They are indirectly affected by the tram bed due to channel confinement. B. Side flow channel between valley wall and tram bed that is cut off from the natural channel.	Bravard et al., 1986; Gilvear and Winterbottom, 2002; Gurnell, 2009
3. Tram Bed forced	Tram bed directly forces a disturbed morphology on the channel system.	A. Incised and coalesced channels that contain series of headcuts from incision along filled tram beds. B. Incised cut tram beds that contain headcuts from incision, and pirate flow from the natural channel, increasing stream power.	Bravard et al., 1986; Florsheim et al., 2000; Gilvear and Winterbottom, 2002; Gurnell, 2009

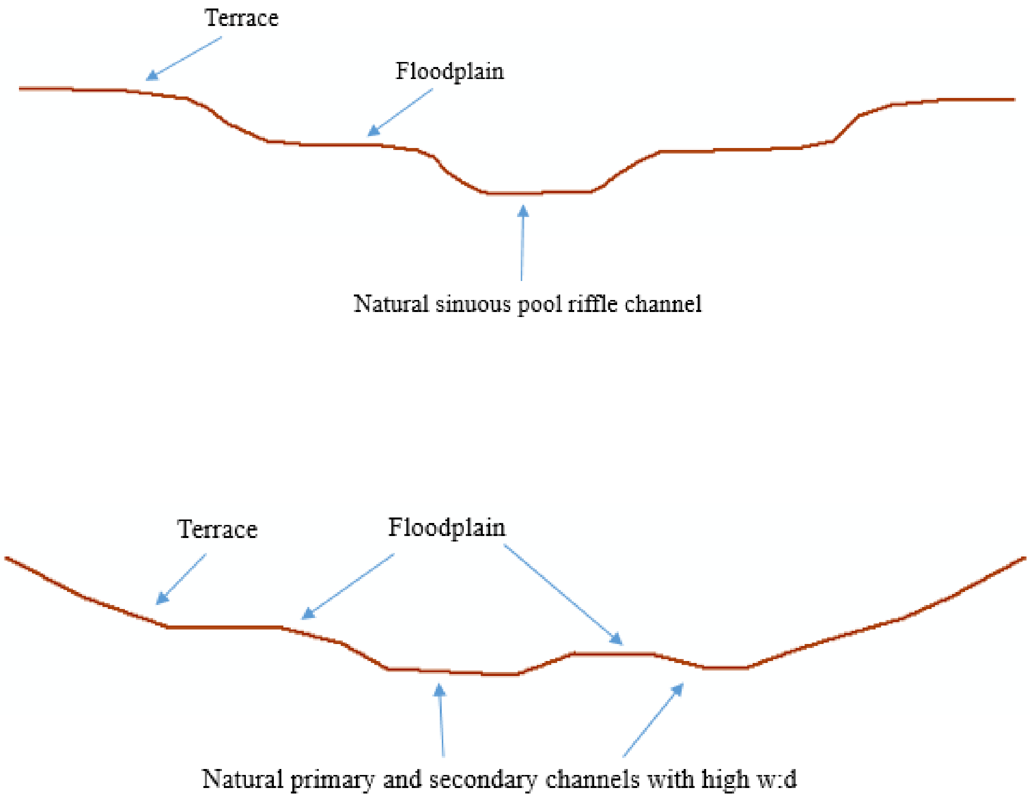


Figure 8. Natural Morphology. Natural morphology reflects undisturbed conditions with no tram bed influence. There are two types, pool riffle channels, and colluvial or alluvial channels with high w:d and sometimes containing secondary channels.

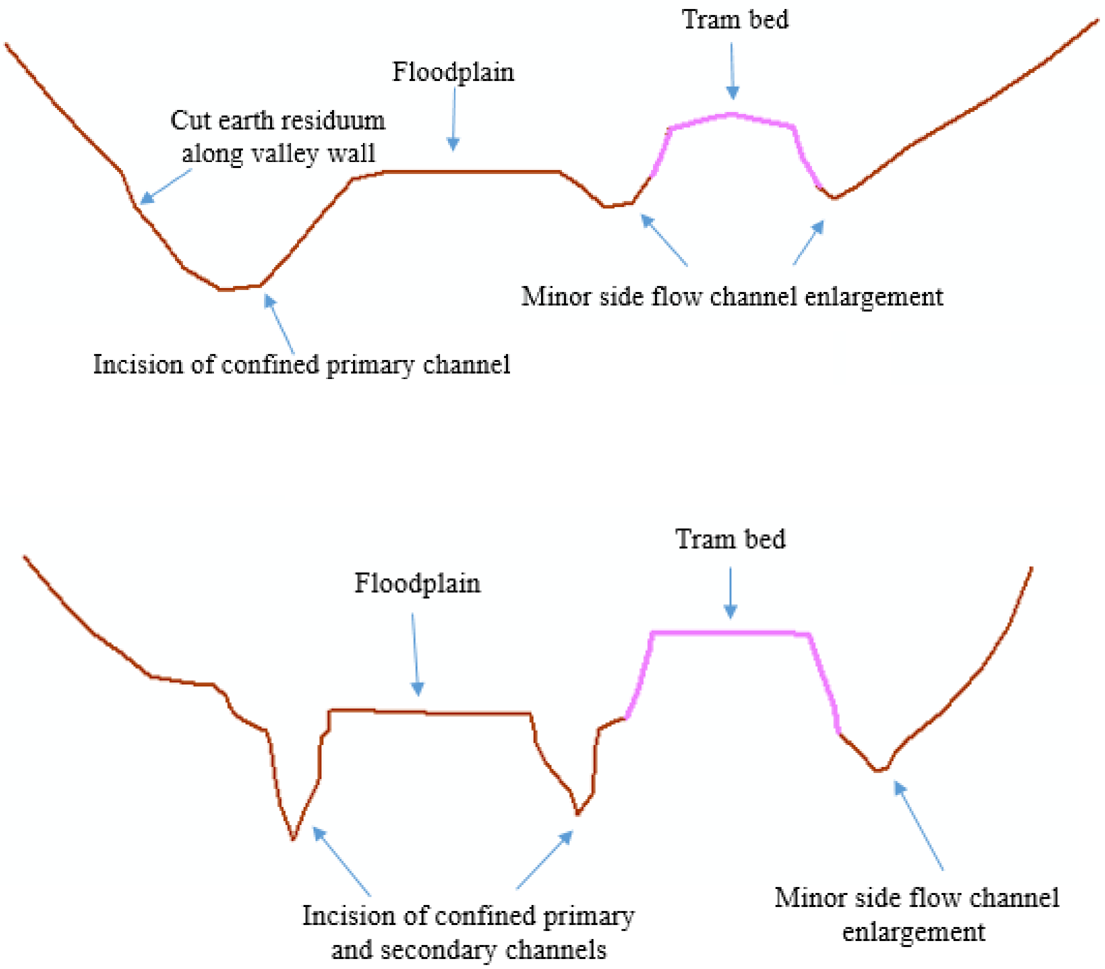


Figure 9. Confined Morphology. The tram bed provides an obstacle for valley confinement with little to direct influence on the channel. The diagram further above depicts confinement for natural pool riffle channels, and channels with secondary channels directly above.

Tram bed-forced morphology occurs where the tram bed has direct effects on channel morphology, including channel incision, piracy of flow from the natural channel, and causing channels to be located in new locations within the valley (Florsheim et al., 2000; Gilvear and Winterbottom, 1992; Winterbottom, 2000). The tram bed forms a boundary or obstacle within the channel. There are two tram bed-forced sub-classes: (1) natural and tram drain channels coalesce into a single planform along filled tram beds, and (2) incised cut tram beds that pirate flow from the natural channel with increases in stream power (Table 4; Figure 10; Figure 13).

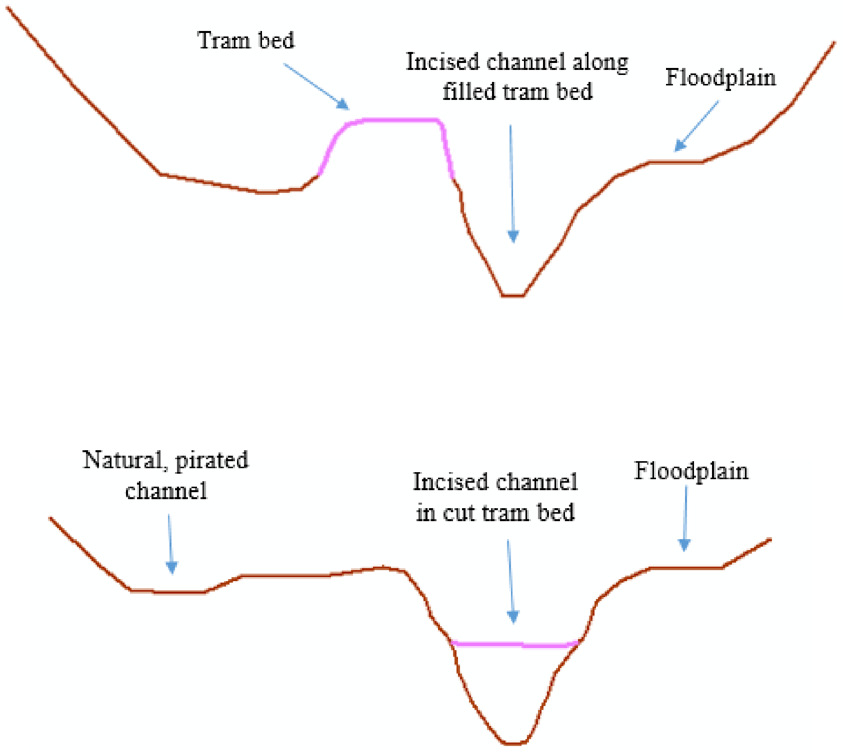


Figure 10. Tram Bed Forced Morphology. The tram bed directly forces a disturbed morphology on the channel system. The diagram further above depicts incision along a filled tram bed, and the diagram directly above depicts incision in a cut tram bed.

A.

B.

Figure 11. Natural Morphology Photos. A) Sinuous Pool Riffle, R-km 2.99, B) Colluvial channel with high w:d ratio, R-km 2.78. Photos taken in December 2015.

A.

B.

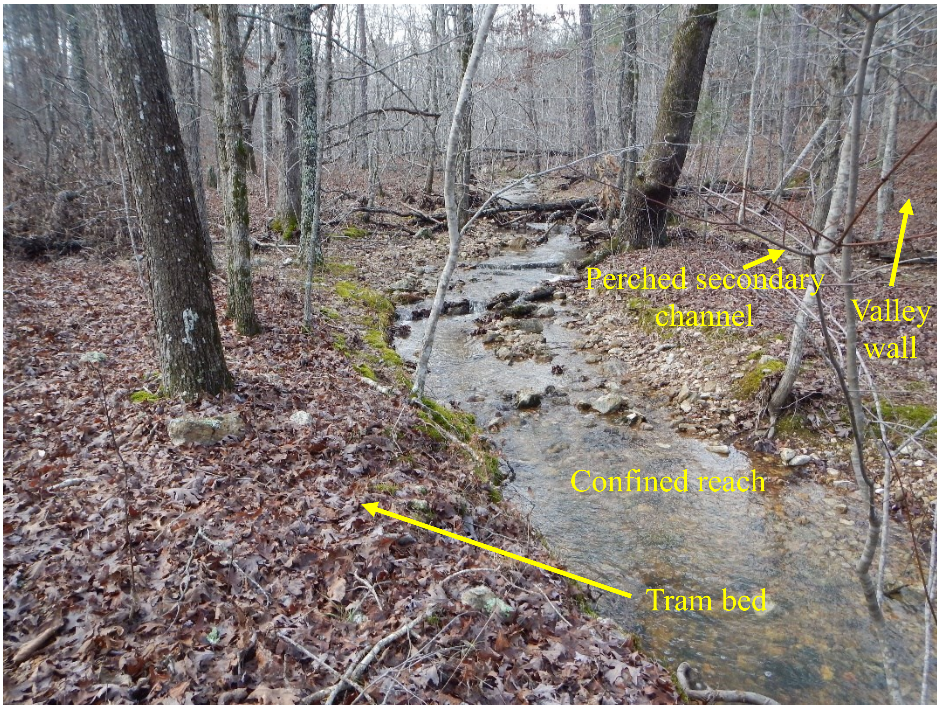


Figure 12. Confined Morphology Photos. A) Confined pool riffle channel along valley wall, R-km 2.36, B) Confined alluvial channel that had high w:d and low banks prior to tram construction, R-km 1.90. Photos taken in December 2015.

Figure 13. Tram Bed Forced Morphology Photos. A) Incised channel along filled tram bed, R-km 1.17, B) Incised channel in cut tram bed, R-km 0.93. Photos taken Dec. 2015.

Headcut Classification

The headcuts along Tram Hollow were classified by location and scale to compare how the channel responds to tram and non-tram disturbances (Figures 14-17; Dietrich and Dunne, 1993). Headcut width and depth were measured with a stadia rod and hand level. Notes were taken on headcut location and were marked with a GPS (Table 5). Headcuts located in cut tram drainages or along filled tram beds were expected to migrate upstream and have more geomorphic influence than local, non-tram affected headcuts (Schumm, 1979; Temple and Moore, 1997; Florsheim et al., 2000). Tram headcuts can occur in two ways, from channel confinement by the tram bed, and from incision in cut tram beds and where the tram bed forms an embankment (Figure 14 and Figure 16). Non-tram headcuts are local and do not migrate upstream, and occur in three locations: below tributary confluences, at bedrock obstacles, and at local bends and pools (Figure 15 and Figure 17). Headcuts in disturbed reaches were predicted to occur more frequently than in natural reaches, because disturbed reaches can have both tram headcuts and locals headcuts.

Hydraflow, Channel Incision, and Channel Enlargement Ratios

The software Hydraflow Express (2006) was used to verify cross-sectional data recorded in the field. The cross-section data for all of the sites was put into Hydraflow. A regional regression equation computed by the USGS for streams in the Ozark Plateau physiographic province was used to calculate 2-year bankfull discharges for Tram Hollow (Alexander and Wilson, 1995). Two-year bankfull flood depths were computed

Table 5. Headcut Classification (Modified from Dietrich and Dunne, 1993).

	Location	Reason	Local or Confined	Scale
Tram Headcuts	1. Filled tram beds and cut tram beds	Incision and piracy of flow	Confined	0.1 - 0.6 m deep and 1 - 4.5 m wide
	2. Confined reaches	Channel confinement	Confined	0.1 - 0.6 m deep and 1 to 4.5 m wide
Local Headcuts	1. Below tributary confluences	Disproportion in sediment supply versus water	Local	0.1 to 0.4 m deep and 0.5 to 6 m wide
	2. Bedrock obstacles	Bedrock-forced morphology	Local	0.1 to 0.4 m deep and 0.5 to 6 m wide
	3. Bends and pools	Bend/pool-forced morphology	Local	0.1 to 0.4 m deep and 0.5 to 6 m wide

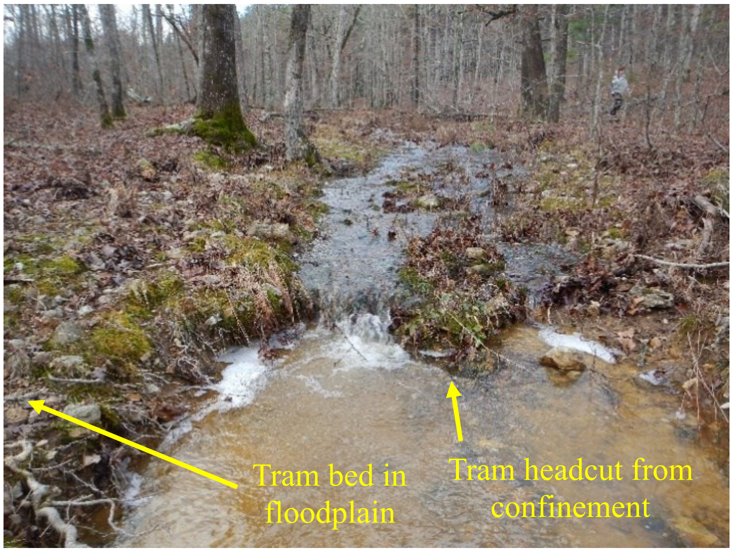


Figure 14. Tram Headcut from Channel Confinement. R-km 2.10, Photo taken in March 2016.

Figure 15. Local Headcut below Tributary Junction. R-km 2.70, December 2016.

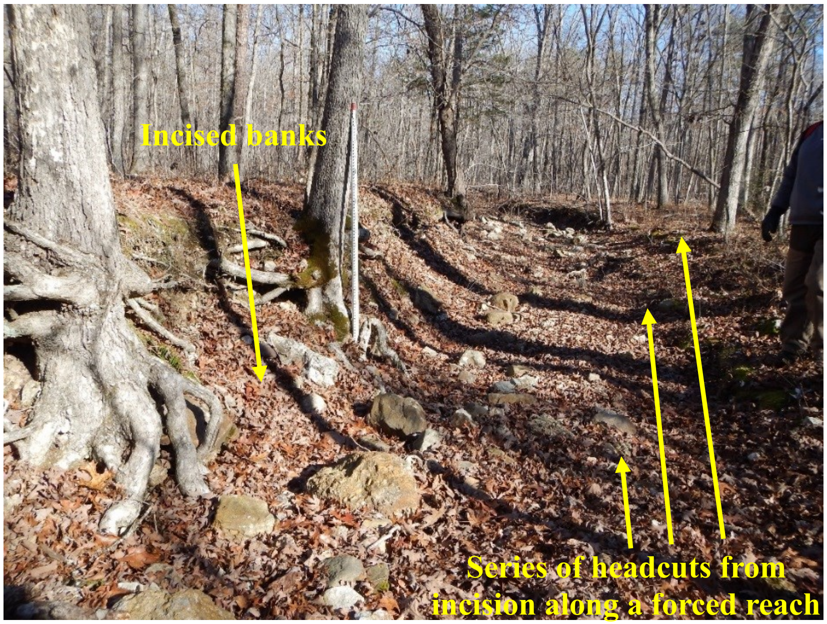


Figure 16. Headcuts from Incision along Filled Tram Bed. R-km 1.17, December 2016.

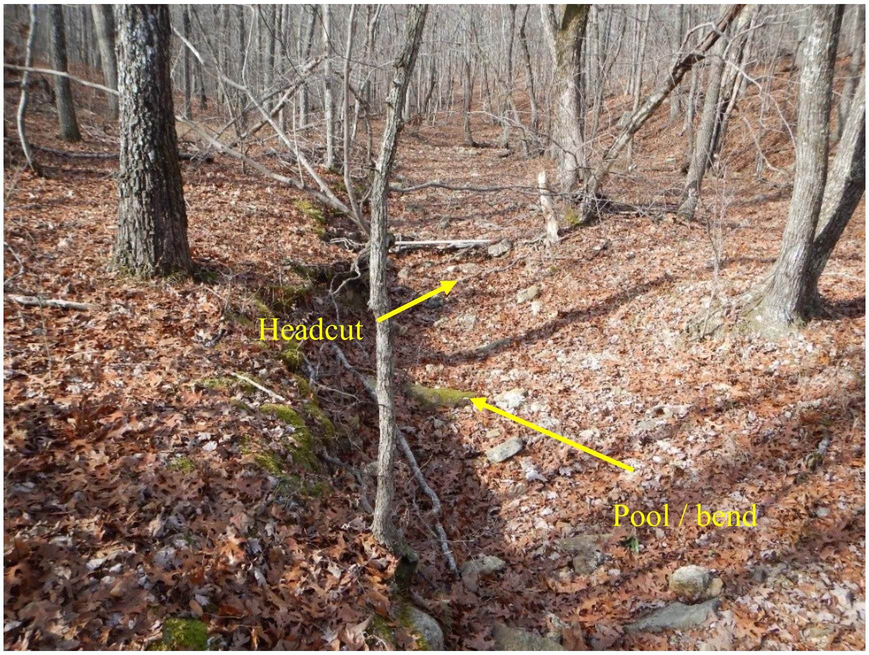


Figure 17. Local Headcut along Pool / Bend. R-km 2.05, December 2016.

in Hydraflow by using the calculated discharges and cross-section data for each site. Channel incision and channel enlargement were also computed in Hydraflow to determine if sites affected by the tram bed are larger and more incised than sites not affected by the tram bed. Channel incision can be calculated as the ratio of depth at total channel capacity to bankfull flood stage (Starr, 2009). Channel enlargement ratios, area of total channel capacity to bankfull area, is a more comprehensive measure than incision because it is a two-dimensional indicator of channel equilibrium (Hammer, 1972).

GIS Analysis

ArcGIS 10.4 and GPS locations taken from the field were used to produce maps of Tram Hollow to display important characteristics of the study area and results of this study. Data for maps of headcut locations, tram line, valley width, and channel width were collected in the field with GPS. Data from the National Cooperative Soil Survey

(1994) was used to create a soil series map of Tram Hollow. The hydrology of Tram Hollow including stream order, tributaries, and watershed delineation was mapped using standard watershed delineation methods and hydrology tools in the Spatial Analyst extension of ArcGIS 10.4 (Wu et al., 2008).

Statistical Analysis

Statistical Package for the Social Sciences (SPSS) Statistical software program version 24 was used to conduct three statistical analyses: Analysis of Variation (ANOVA), chi-square, and linear regression (Rogerson, 2014). ANOVA, chi-square, and linear regression tests were completed in SPSS using standard SPSS methods and limitations outlined by Rogerson (2014). ANOVA was performed using the One-Way ANOVA application in SPSS on the first, second, and fifth hypotheses to determine if there was significance between the means of confinement ratios, incision ratios, and floodplain disconnection. Chi-square was performed on the third hypothesis in SPSS to determine if there was significance in the frequency of headcuts in disturbed planforms versusnatural reaches. The fourth hypothesis was tested using Linear Regression in SPSS to determine the correlation between channel depth and bed particle size.

CHAPTER 4 – RESULTS AND DISCUSSION

The results of this study are divided into ten sections: (1) valley width and channel slope; (2) channel planform classification; (3) longitudinal profiles and headcut classification; (4) cross-sections; (5) incision an enlargement ratios; (6) channel substrates; (7) reference channel comparison; (8) summary of tram bed disturbance effects; (9) floodplain fragmentation; and (10) statistical analysis. Tram Hollow has natural, confined, and tram bed forced morphology. The tram bed confines the valley and forces disturbed channel morphologies, leading to headcuts, changes to surface hydrology, and larger bed particles. Confined channels occur where the tram bed indirectly affects channel morphology. Tram bed forced reaches are incised channels that are directly affected by the tram bed, causing migrating headcuts to form, and piracy of flow from the natural channel. The natural, confined, and tram bed forced morphology classifications reveal the geomorphic effects of historical logging tram beds along Tram Hollow.

Valley Width and Channel Slope

Valley width was measured at Tram Hollow to determine if the tram bed influences the effective valley width, the area where most of the energy available for geomorphic work is located in a river system. At Tram Hollow, valley width ranges from 20 meters at the natural gorge to 107 meters in the headwaters (Figure 18). Effective valley width, the width of the channels and floodplains, ranges from 10 to 107 meters at Tram Hollow (Figure 18). Total valley width and effective valley width is the same for natural reaches (Figure 18), however effective valley width is about half of total valley

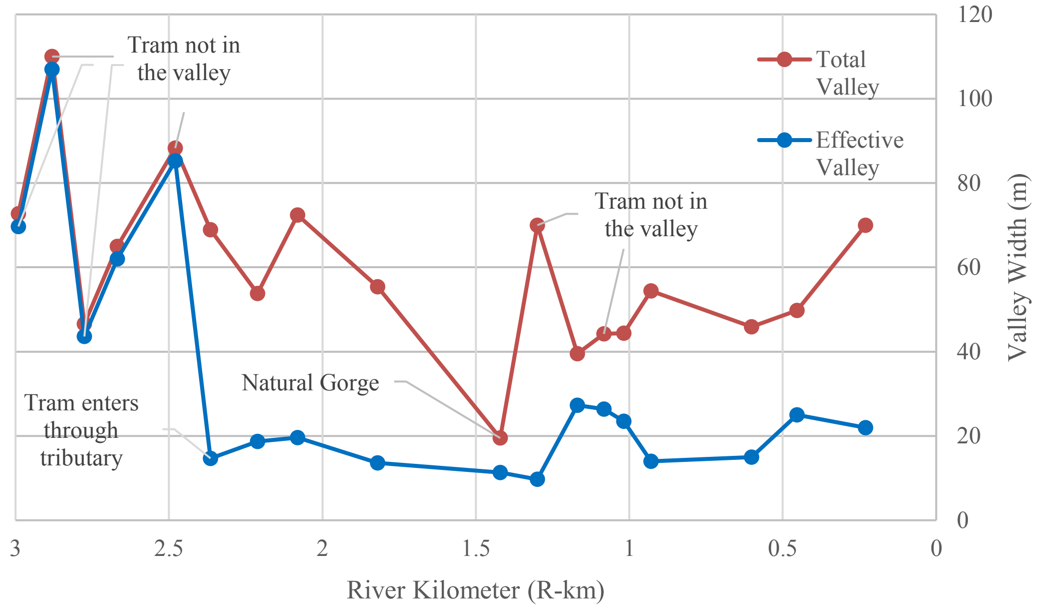


Figure 18. Total Valley Width and Effective Valley Width. The tram bed decreases the effective valley width.

width in downstream parts of the watershed that are confined and have forced disturbed morphologies. In confined and tram bed forced morphologies, effective valley width ranges from 10 meters to 27 meters (Figure 18). The decrease in effective valley width is due to valley confinement caused by the tram bed (Figure 18). The tram bed at Tram Hollow confines the effective valley width by obstructing water and sediment in channel segments with filled tram beds and by concentrating stream power in channels with cut tram beds (Florsheim et al, 2000). Effective valley width is an important measure of valley confinement as opposed to total valley width, because it reflects the energy available for geomorphic work, whereas total valley margins along hillslopes reflect the geology of a valley (Wheaton et al., 2015).

Channel slope was quantified at all cross-sections sites at Tram Hollow to determine if the tram bed influences slope at the reach scale. At Tram Hollow, channel slopes range from 0.5 to 3.1% with an average basin slope of 1.5%. Channel slope at Tram Hollow is typical of Ozark headwater streams in the Current River Hills land type association that have Tilk-Secesh alluvium in river valleys with slopes ranging from 0 to 3% (Hansen, 2006). The tram bed does not affect channel slope at the reach scale and channel slopes at Tram Hollow do not respond much to confinement, because effective valley width remains relatively constant around 20 m, but channel slopes range from 1 to 3% (Figure 19 and Figure 20). For reaches with effective valley widths greater than 30 m, channel slopes decrease exponentially to 0.5% (Figure 20). Channels can be straightened in tram bed forced morphologies, but the channel slopes in straightened reaches range from 1 to 1.8%, within the range of slopes for natural and confined channel reaches.

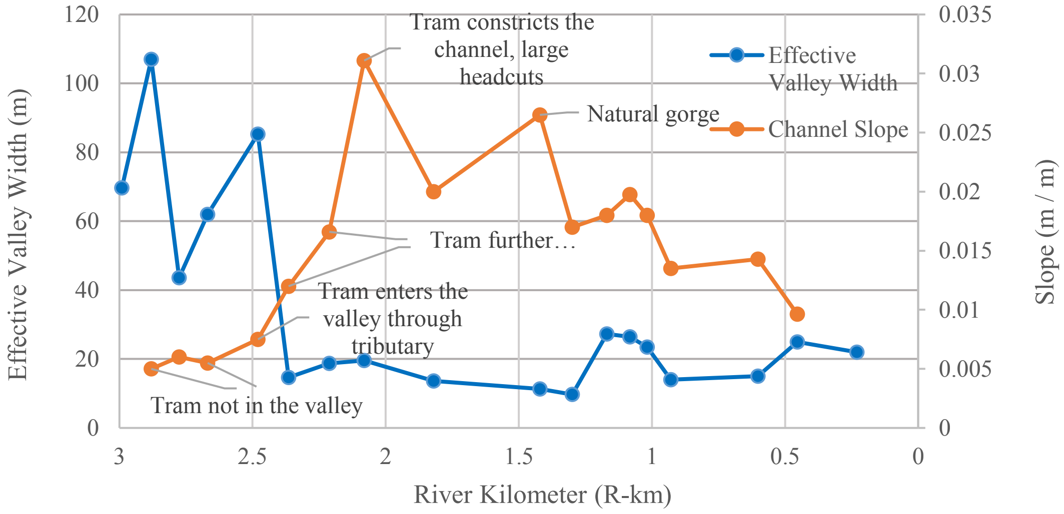


Figure 19. Longitudinal Trends of Effective Valley Width and Channel Slope. The tram bed confines the effective valley width.

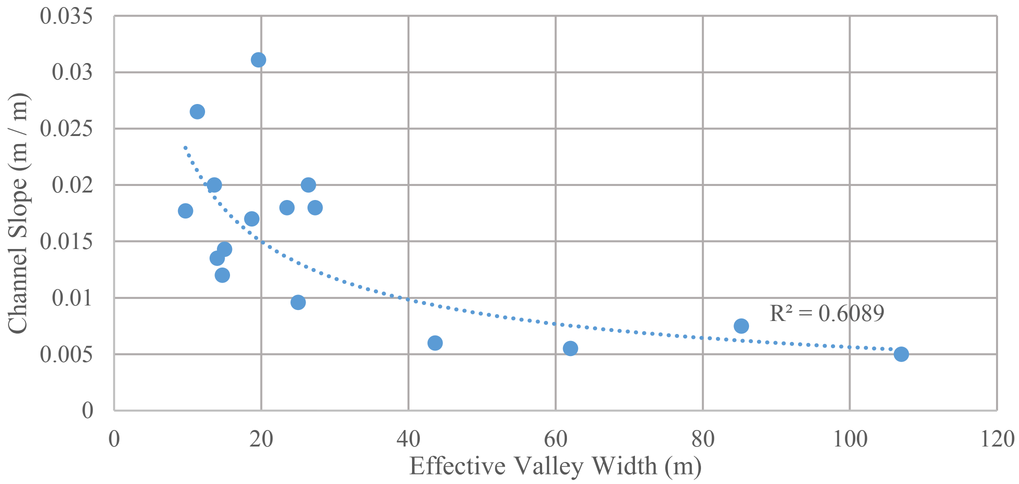


Figure 20. Effective Valley Width versus Channel Slope.

Longitudinal Profiles and Headcut Classification

Longitudinal profiles and headcuts were quantified at Tram Hollow to determine if the tram bed influences patterns of bed elevation changes and to determine if the tram bed influences the frequency of headcut development. The tram bed does not affect channel slope at the reach scale, although its disturbance effects such as confinement and incision can create migrating headcuts that locally affect slope and cause more variable bedforms. There are 36 headcuts at Tram Hollow. Both migrating tram headcuts and local headcuts are found in Tram Hollow. There is no statistical difference between headcut depths and width for tram headcuts and local headcuts, but there is significant difference in the frequency in which headcuts occur for natural and disturbed reaches. Natural reaches had three local headcuts, whereas disturbed reaches had 33 tram and non-tram, local headcuts. All three channel planforms, natural reaches and the two types of disturbed morphologies, confined and tram bed forced morphology, were mapped for the entire main channel at Tram Hollow (Figure 21).

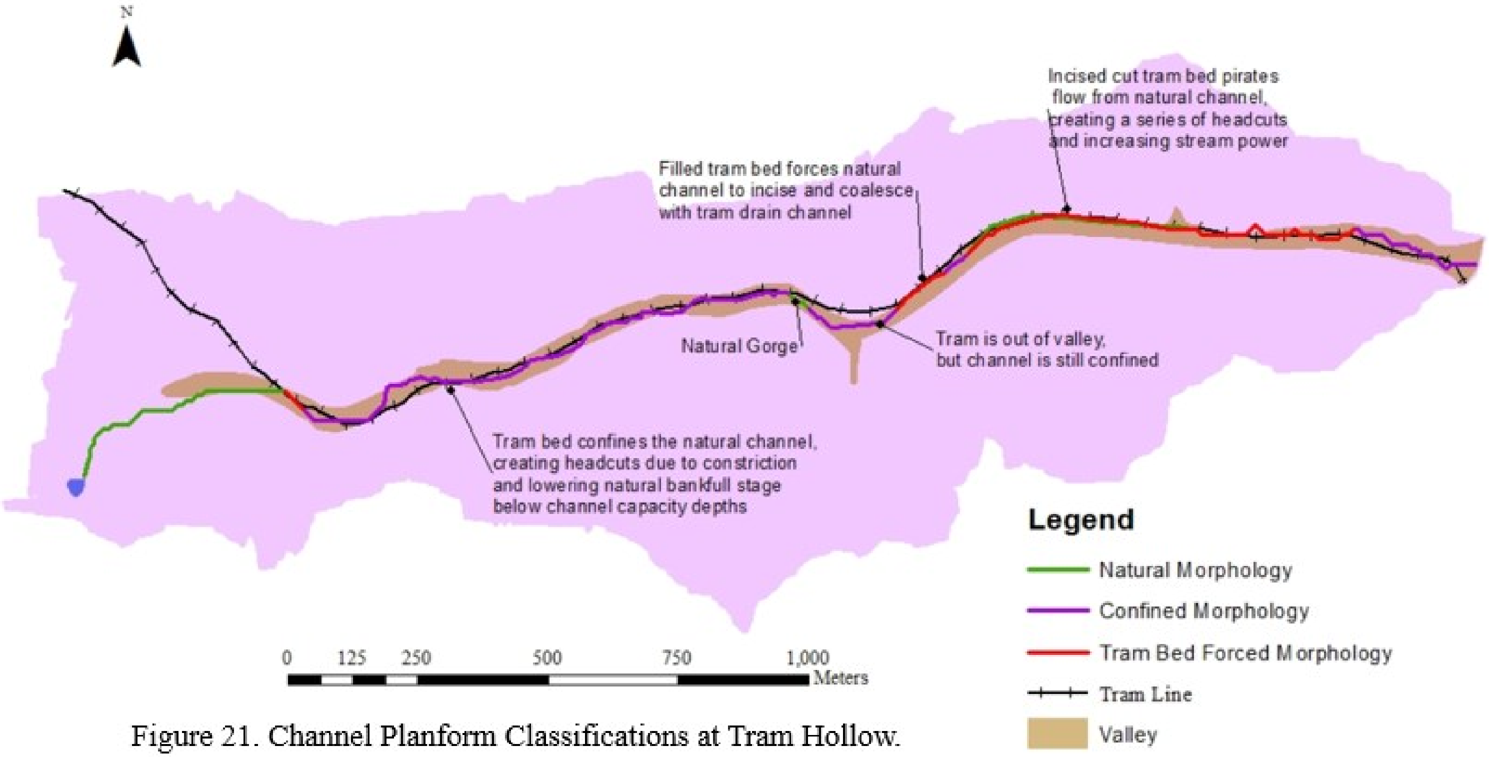
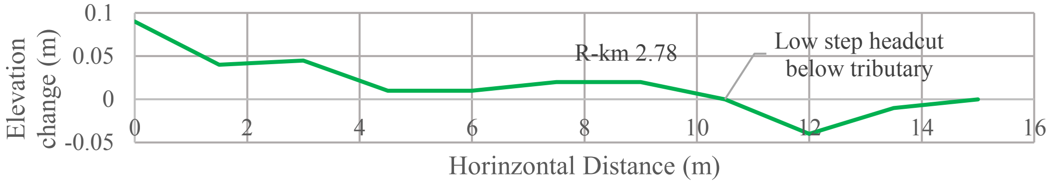


Figure 21. Channel Planform Classifications at Tram Hollow.

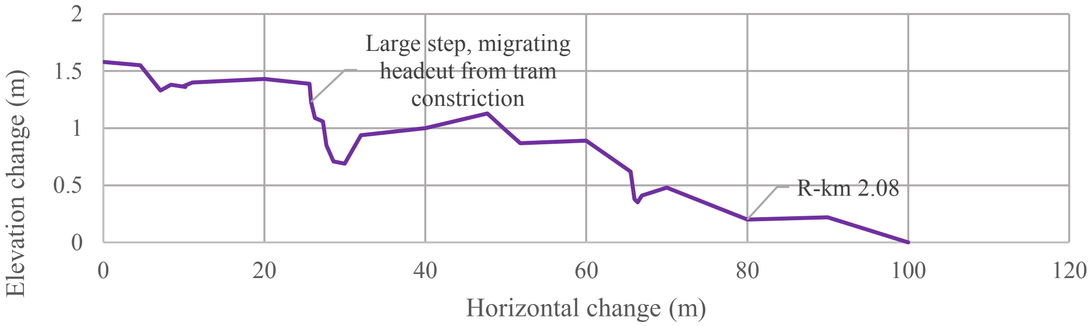
Natural morphology has the most gradual bed elevation changes compared to confined and tram bed forced morphology (Figure 22; Figure 23; Appendix A-1). Channel slopes in natural reaches ranged from 0.5% to 1%, with the natural gorge having a relatively steep slope of 2.7%. In natural reaches, headcuts are shallow, local, and located below tributary confluences, bedrock obstacles, and along bends / pools (Table 6 and Figures 24 and 25). Local headcuts in natural reaches had depths ranging from 0.1 to 0.15 meters and widths of 0.5 meters. These local headcuts occur where there is a disproportionate balance between sediment supply and size, and discharge and slope, such as at tributaries with higher discharge and lower sediment supply (Lane 1955).

Confined channel morphology has more variable bedforms than natural reaches (Figure 22; Figure 23; Appendix A-2). Slopes in confined reaches ranged from 1.2% to 3.1%. Confined reaches contain a combination of both local headcuts and tram headcuts from confinement. Headcuts in confined reaches are steeper and migrate upstream at relatively fast rates (Schumm, 1979). Confined reaches had headcuts with depths ranging from 0.1 to 0.6 meters deep, and widths ranging from 0.5 to 5 meters. (Table 6).

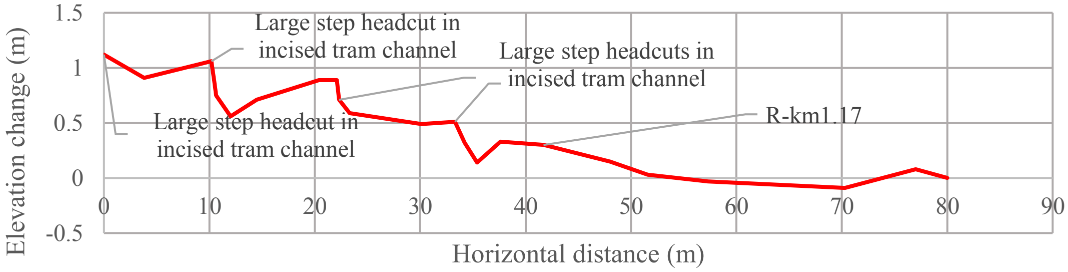
Channel slopes in tram bed forced reaches ranged from 1 to 1.8%. Tram bed forced morphology also had larger and migrating headcuts from tram bed disturbance effects. Depths of headcuts ranged from 0.2 to 0.5 meters and widths ranged from 2 to 6 meters (Table 6). In forced morphologies, headcuts were from channel incision along filled tram bed embankments and in cut tram beds (Florsheim et al, 2000). Headcuts in incised reaches were concentrated and often occurred in series (Figure 22; Appendix A-3). Tram headcuts migrate upstream as they recruit substrates and lower bed elevations in an attempt to return to its equilibrium state (Lane 1955; Schumm, 1979).



A. Natural Channel Morphology. Measurements taken with stadia rod and auto-level.



B. Confined Morphology. The filled tram bed constricts the channel, causing large step headcuts to form and migrate upstream.



C. Tram Bed Forced Morphology. Series of large step headcuts in an incised channel along a filled tram bed.

Figure 22. Longitudinal Profiles at Tram Hollow. A) Natural morphology, B) Confined morphology, and C) Tram Bed Forced Morphology.

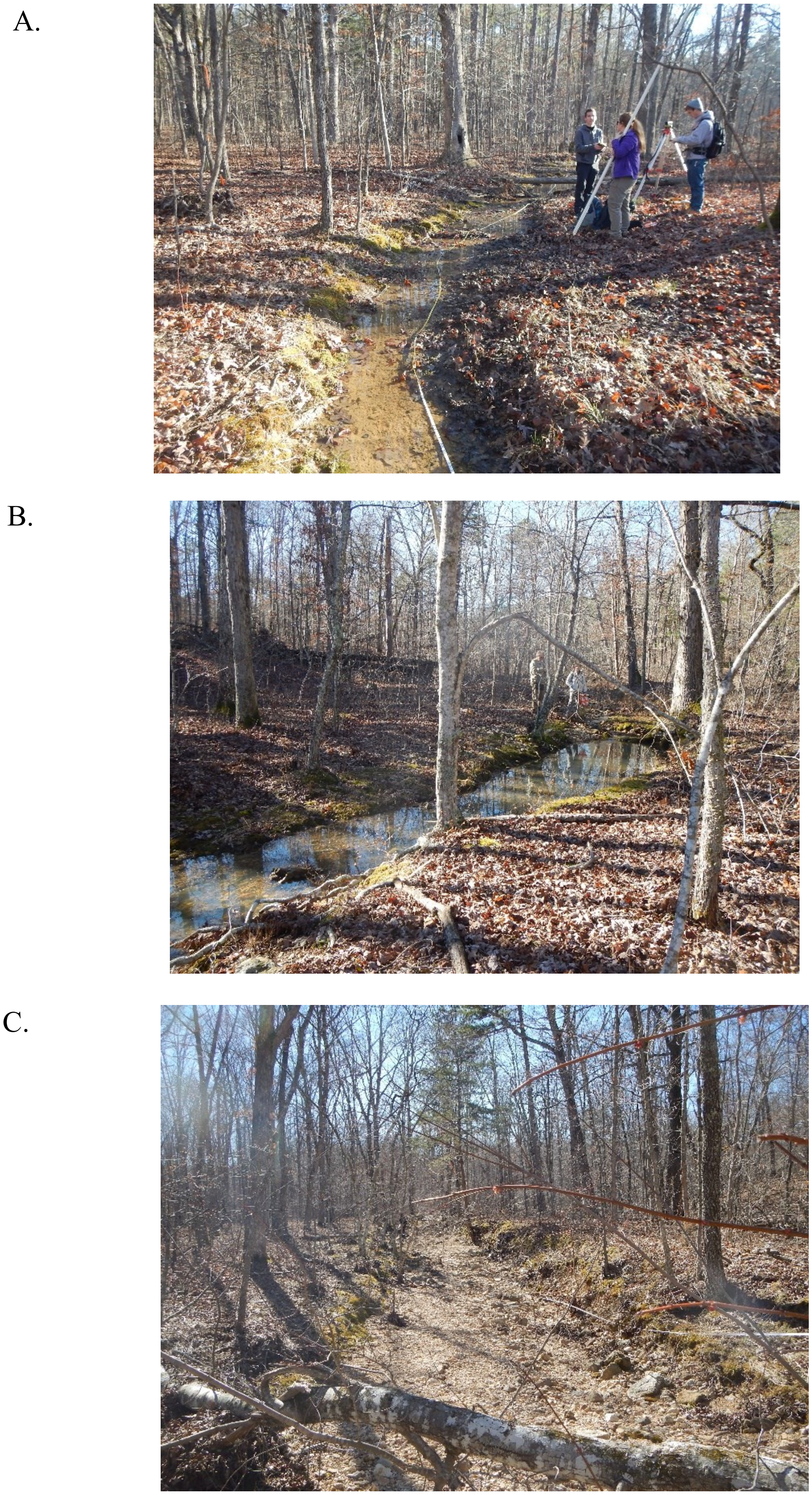


Figure 23. Longitudinal Profile Sites. A) R-km 2.78, B) R-km 2.08, and C) R-km 1.17. Photos taken in March 2016.

Table 6. Headcuts in Tram Hollow.

	Migrating tram headcuts from channel confinement and tram bed incision.			Local headcuts below tributaries, bedrock obstacles, and bends / pools.	
R-km	Height (m)	Width (m)	R-km	Height (m)	Width (m)
2.55	0.1	1	2.78	0.15	0.5
2.3	0.5	1.4	2.65	0.1	0.5
2.25	0.4	2.3	2.25	0.2	0.5
2.15	0.5	2.4	2.21	0.4	2.3
2.10	0.6	2.5	2.10	0.4	2.5
1.9	0.3	2.2	1.85	0.2	2.5
1.85	0.4	1.5	1.82	0.3	4
1.85	0.4	3	1.82	0.3	3
1.17	0.4	3	1.45	0.4	2
1.17	0.5	2	1.30	0.2	2
1.16	0.3	4.5	1.20	0.3	5
1.16	0.3	2	0.75	0.2	2
1.16	0.2	3	0.7	0.3	1.5
1.10	0.3	2	0.60	0.2	6
1.08	0.3	2			
0.85	0.3	2			
0.08	0.2	2			
0.40	0.3	2			
0.40	0.3	1.5			
0.38	0.2	1			
Average	0.34	2.17		0.26	2.45
Range	0.1 – 0.6	1 – 4.5		0.1 – 0.4	0.5 - 6
Standard Deviation	0.12	0.80		0.10	1.64
C.V. (%)	36.21	36.87		36.99	66.74

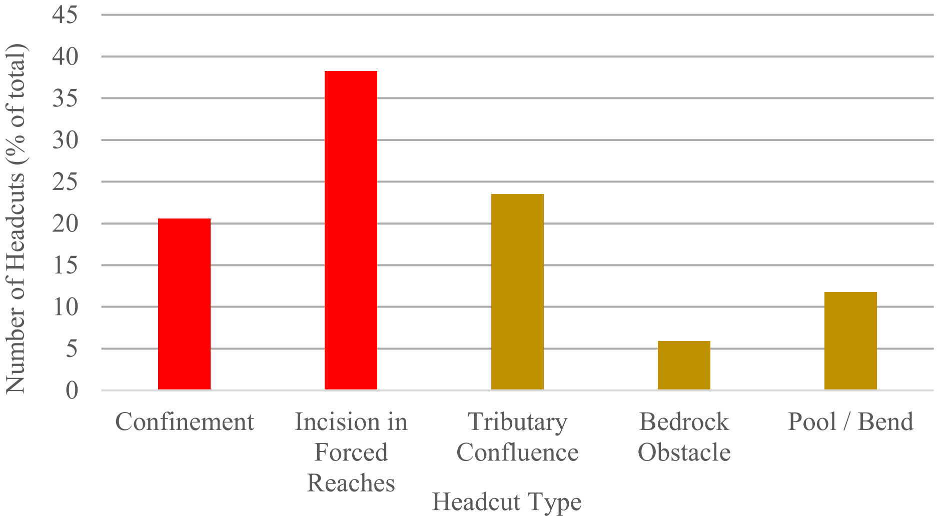


Figure 24. Headcut Count. Red indicates tram headcuts, and brown indicates localized headcuts.

Cross-Sections

Cross-sections were quantified at Tram Hollow to determine if the tram bed influences the patterns of elevation changes in valley landforms. There are five natural and twelve disturbed channel reaches at Tram Hollow. Four of the five single-threaded planforms at Tram Hollow occur in natural reaches, and the twelve multi-threaded planforms occur in both natural and disturbed planforms. Cross-sections at Tram Hollow range from single-threaded sinuous pool riffle channels with low banks less than 0.1 m to tram bed forced morphology with incision up to 2 meters in cut tram beds that pirate flow from natural channels. Disturbed morphology at Tram Hollow includes confined reaches where the tram bed does not directly affect the channel and tram bed forced morphology where the tram bed forces new planforms to occur.

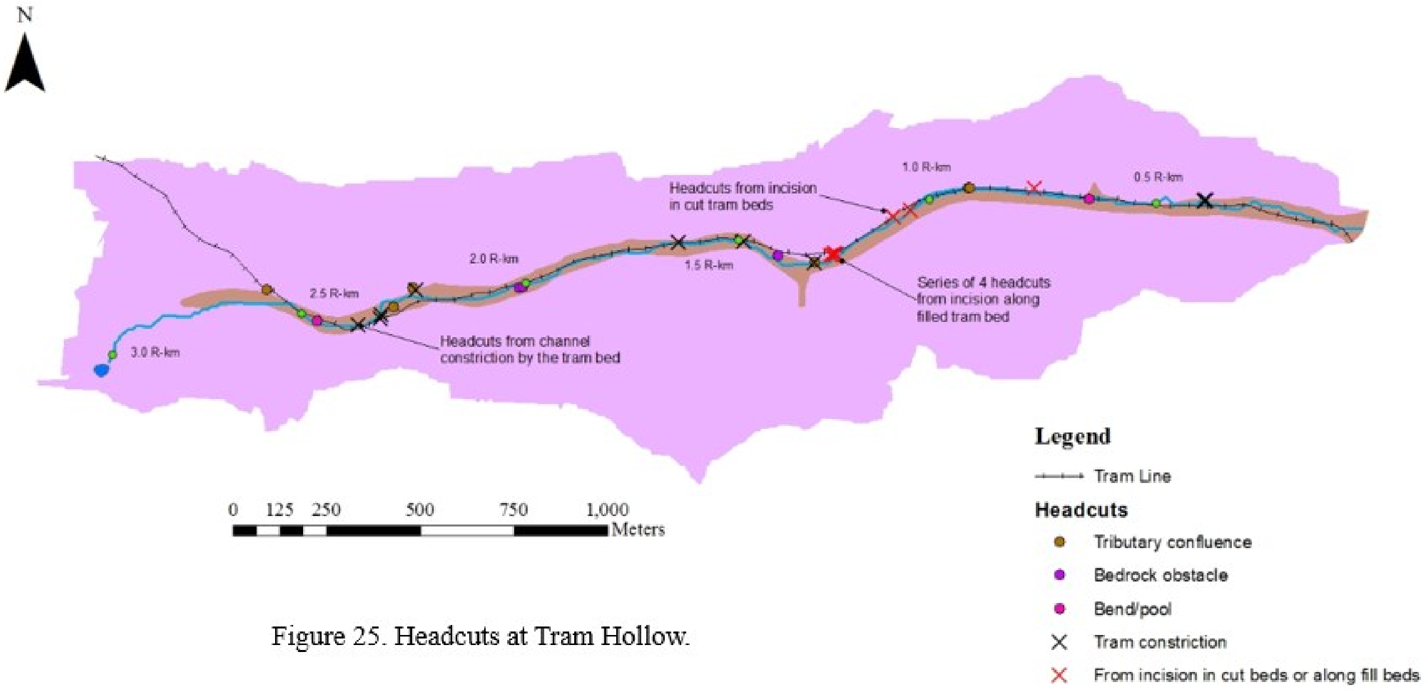


Figure 25. Headcuts at Tram Hollow.

Natural channels are typically colluvial or alluvial channels that sometimes contain secondary channels separated by low floodplain bank heights less 0.3 meters on elevations above the channel bed (Figure 8; Figure 26; Appendix B-1). At Tram Hollow, natural reaches have relatively gradual changes in landform elevation across the valley compared to confined and tram bed forced morphology (Figures 26). The tram bed is absent from the valley in natural reaches. The valley landforms reflect much of the natural morphology of other Ozark headwater streams that are low and gradual in slope changes across the valley (Kabrick et al., 2000).

The tram bed is located in the valley for most of the confined channel reaches, and reaches heights up to 0.5 m above floodplains (Figure 26; Appendix B-2). Two confined reaches do not have the tram bed, but are located below other disturbed reaches where the tram bed is present. Channels with confined morphology have much more variation in valley landform elevation compared to natural reaches (Figure 26). Filled tram beds constrict channels, causing natural bankfull stages to be below total channel capacity. Filled tram beds also cause alterations to surface hydrology such as splitting of drainage on opposite sides of the tram bed, separating side flows from reaching the main channel, and causing headcuts to form due to constriction (Figure 9 and Figure 26).

Floodplain heights in tram bed forced morphologies range from 0.46 m to 1.9 meters (Figure 26; Appendix B-3) The cross-sections of tram bed forced morphologies have more variation in landform elevation compared to natural reaches due to incised channel beds along filled tram beds and in incised cut tram beds that pirate flow from the natural channel (Figure 10, and Figure 26). Cut tram beds can concentrate flow and can incise to form channels deeper than natural beds (Florsheim et al., 2000).

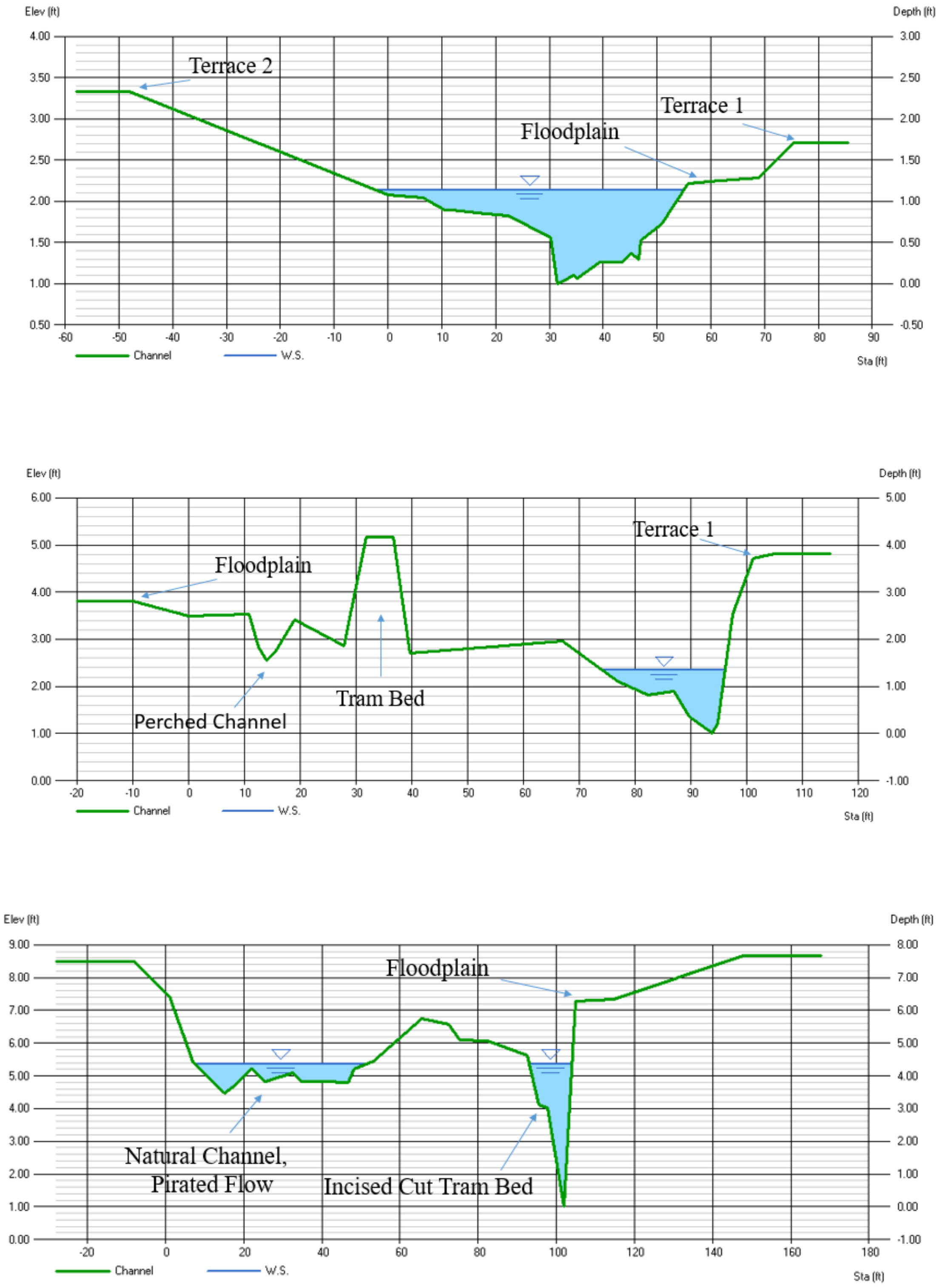


Figure 26. Cross-Sections. A.) Natural morphology, B.) Confined morphology, and C.) Tram Bed-Forced Morphology**.**

Incision and Channel Enlargement Ratios

Channel incision and channel enlargement was measured at Tram Hollow to determine if the tram bed causes higher rates of channel incision and enlargement. At Tram Hollow, channel incision ratios range from 1 to 3, with an average of 1.6 (Figure 27). An incision ratio is the measure of channel depth at total capacity divided by the depth of the channel at the bankfull two-year flood stage (Starr, 2009). Starr (2009) classifies incision ratios of 1 as no incision, 1.1 to 1.2 as low incision, 1.3 to 1.4 as moderate incision, 1.5 to 1.6 as high incision, and 1.7 or greater as very high incision. Incision ratios in all of the natural reaches was one, except at the natural gorge that had an incision ratio of 2.8 (Figure 27). Disturbed channel reaches had higher incision ratios than natural reaches with a range from 1 to 3, and an average of 1.8 (Figure 27). One confined channel reach had relatively low banks due to local aggradation below a series of headcuts in an incised tram bed forced morphology (Figure 27).

Channel enlargement at Tram Hollow ranges from 1 to 5.4, with an average of 2.9 (Figure 28). A channel enlargement ratio is the measure of the area at total channel area divided by the channel area of the bankfull two-year flood (Hammer, 1972). Natural reaches all had channel enlargement ratios of one, except at the natural gorge that had an enlargement ratio of 3.9 (Figure 28). Disturbed reaches had channel enlargement ratios that ranged from 1.9 to 5.4, with an average of 3.5 (Figure 28). Channel areas in disturbed reaches were at least twice as much as their natural counterparts due to confinement and incision by the tram bed (Figure 28). Both natural and disturbed reaches had multi-threaded planforms, but multi-threaded planforms in natural reaches were not enlarged, unlike multi-threaded planforms in disturbed reaches (Figure 28).

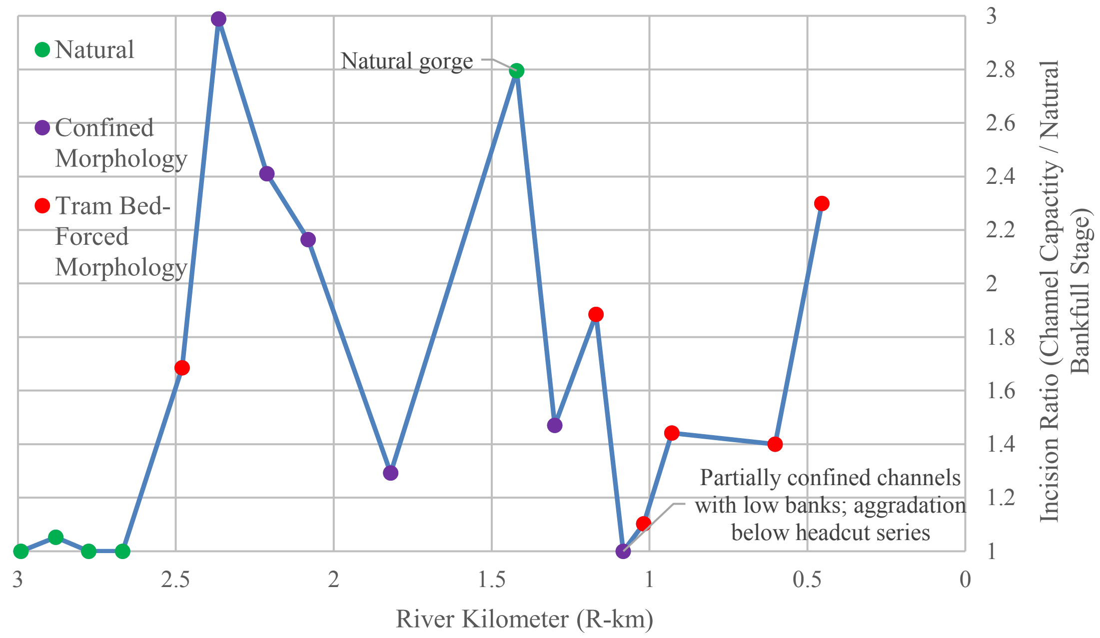


Figure 27. Incision Ratio. Channel capacity depth / natural bankfull stage (Starr, 2009).

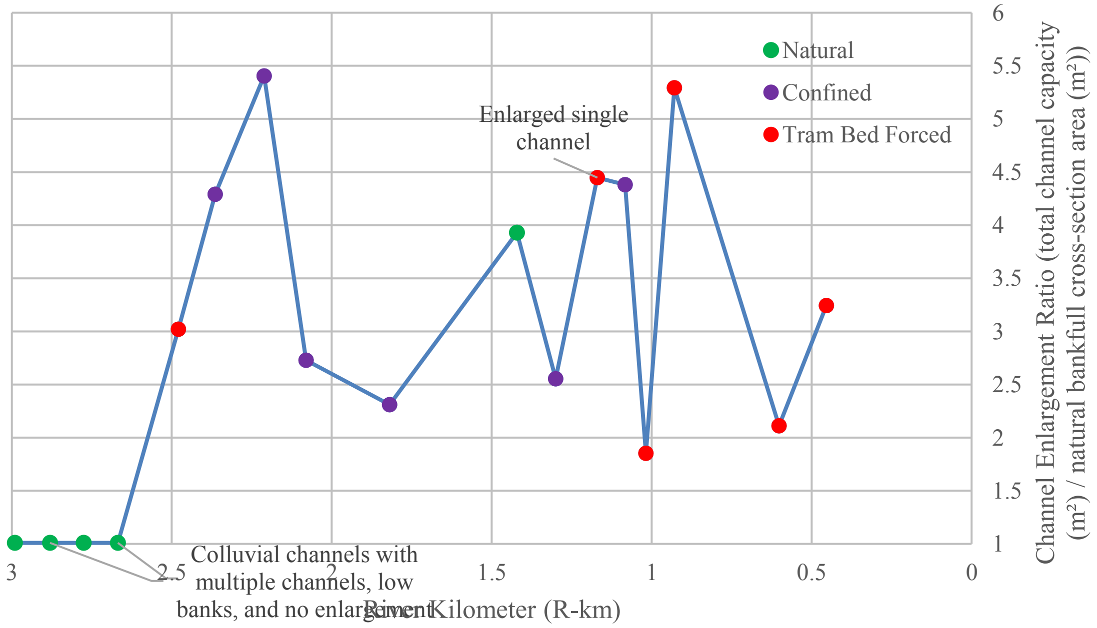


Figure 28. Channel Enlargement Ratio. Total channel capacity / natural bankfull cross-section area (Hammer, 1972). Multiple planforms for natural reaches are not enlarged, whereas multiple planforms for disturbed reaches are enlarged.

Channels affected by the tram bed have higher incision ratios and higher channel enlargement ratios than natural reaches (Figure 27 and Figure 28). The tram bed causes channel incision and channel enlargement directly by forcing channel morphologies and indirectly by confining channels. Incision and confinement cause natural bankfull stages to be lower than the heights of total channel capacity. Incision is a one-dimensional indicator of channel disturbance, because it a ratio of the depth at total channel capacity divided by natural bankfull stage (Starr. 2009). Channel enlargement ratio is a more comprehensive measure of incision and confinement because it is two-dimensional, the ratio of total channel area capacity divided by natural bankfull cross-section area (Hammer, 1972). These incised and enlarged channels have higher percentages of boulders and higher d50 particles sizes. Bed shear stress and stream power is higher in these incised and enlarged reaches due to concentrated flow and the system's inability to dissipate energy laterally across the valley at a given discharge.

Channel Substrates

Channel bed substrates were quantified at Tram Hollow to determine if the tram bed affects bed particle sizes. Median d50 particle sizes for all channel reaches at Tram Hollow range from 2 mm to 60 mm with an average of 21 mm. At Tram Hollow, channel bed substrates range from fines and stable soil substrates less than 2 mm in diameter, to boulders more than 200 mm in forced morphologies and boulders more than 1820 mm in diameter in the natural gorge. Natural reaches had smaller bed substrates compared to confined and tram bed forced reaches, with average particle sizes being less than 2 mm, except at the natural gorge with a d50 particle size of 60 mm. Confined channel reaches have median particle sizes ranging from 2 mm to 30 mm, and have higher percentages of gravel, cobble, and boulders compared to natural reaches. Boulders comprise 2-6% of total bed substrates in confined reaches compared to 0% in natural reaches. Tram bed forced reaches have median d50 particle sizes ranging from nine to 45 mm, with one site in the headwaters having a d50 particle size of 2 mm. Boulders comprise 10 to 27% of total bed substrates in tram bed forced reaches.

Colluvial bed substrates at Tram Hollow indicate channel stability and larger bed particles such as boulders indicate instability (Montgomery and Buffington, 1993). Higher percentages of colluvial bed substrates are located in natural reaches further up in the watershed, before the tram enters the system at river kilometer 2.5 (Figure 29). Stable colluvial bed substrates have higher percentages of vegetation including moss and grass and have little bed changes (Montgomery and Buffington, 1993). Moss decreases downstream along with other colluvial bed substrates, but then increases again further downstream at R-km 1.4, which may be due to increased connection with groundwater further down the channel network or increased shading (Figure 29). Some headcuts are located along natural reaches, but are relatively shallow and local (Table 6). Higher percentages of alluvial bed substrates are located in confined and tram bed forced reaches (Figure 30). Larger bed particles indicate channel instability (Montgomery and Buffington, 1997). Bed particle size increases dramatically once the tram enters the system. Larger and deeper headcuts are in disturbed reaches and have larger bed particles and are continuing to incise into colluvium (Figure 25). Percentages of boulders and median particle size (d50) are both positively correlated with deeper channel reaches (Figure 31). Stable substrates such as soil, moss, and fines are negatively correlated with channel depth, with higher percentages located along shallow reaches (Figure 31).

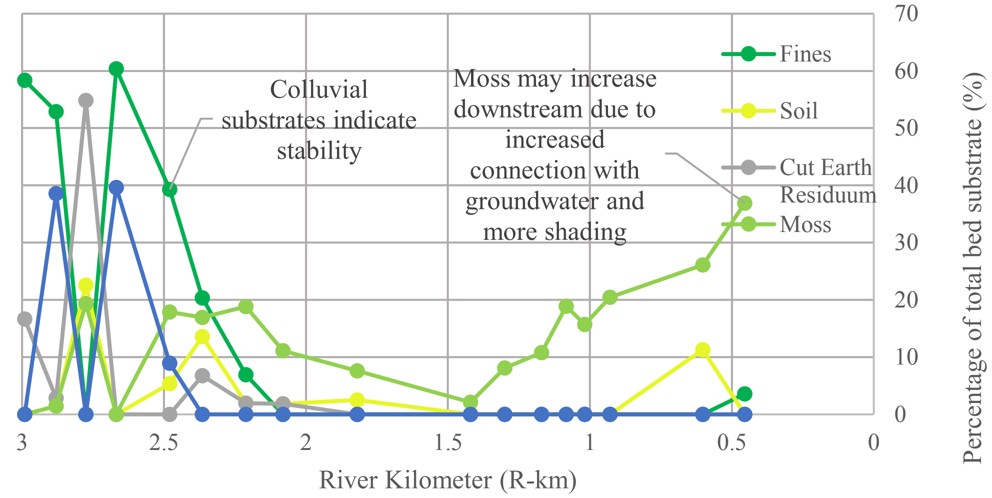


Figure 29. Colluvial Channel Substrates at Tram Hollow. Colluvial substrates indicate stability. The natural reaches have the highest percentages of colluvial substrate.

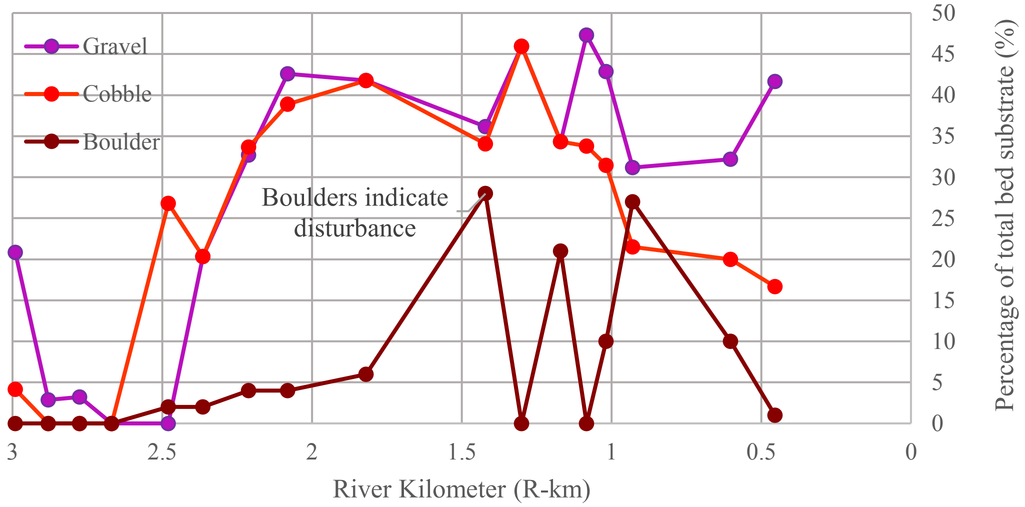
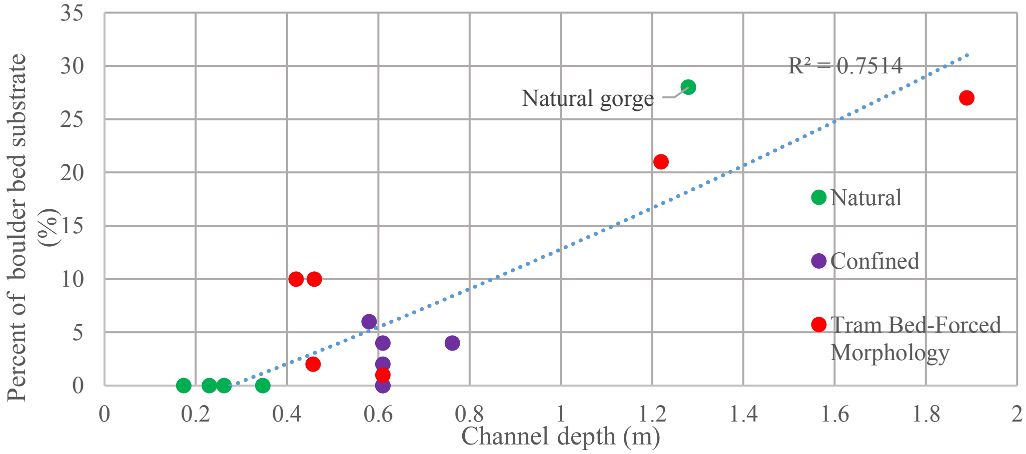
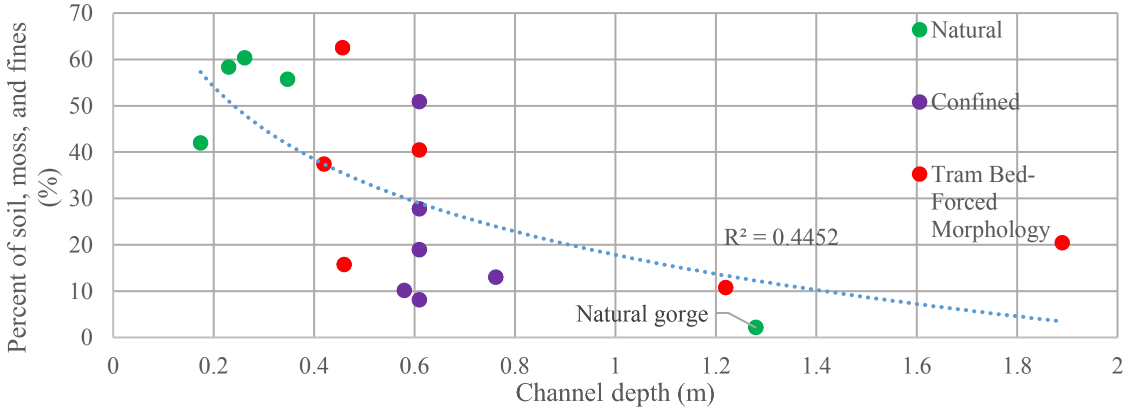


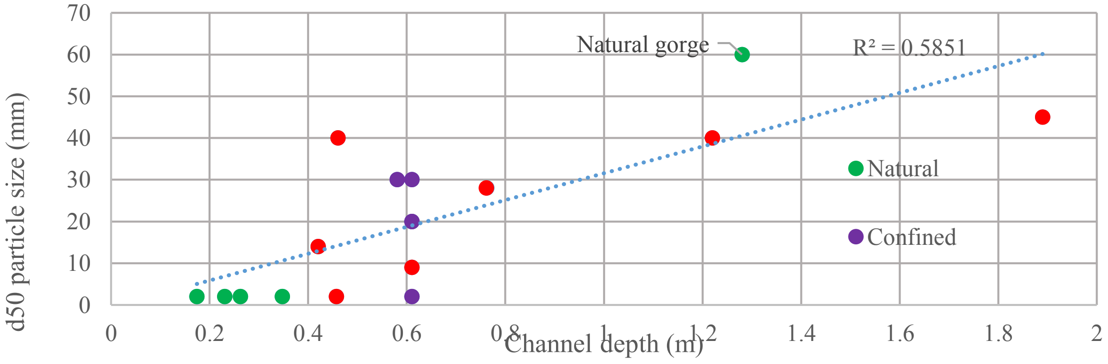
Figure 30. Alluvial Channel Substrates at Tram Hollow. Boulders indicate disturbance at Tram Hollow with high percentages being located along cut tram beds and constricted channels. No boulders were found in the natural reaches.



A. Channel Depth versus Boulders. The channel incises into colluvium lag deposits and residuum, recruiting larger substrates. Depth is measured at channel capacity.



B. Channel Depth versus Soils, Moss, and Fines. Confined and Forced reaches were deeper and had lower percentages of stable substrates such as soil, moss, and fines.



C. Channel Depth versus Median Particle Size (d50).

Figure 31(A-C). Channel Depth versus Bed Substrates. Depth is measured at channel capacity, since it is the height that is able to mobilize the largest particles.

Reference Channel Comparison

Effective valley width, total channel width, and confinement (effective valley width / channel width) were quantified for Tram Hollow and two reference streams (Figures 32-34). Tram Hollow had relatively low effective valley widths compared to the two reference streams (Figure 32). The lowest effective valley width at Tram Hollow was 10 meters in the natural gorge and the highest was 107 meters in the relatively wide colluvial channels in the upper parts of the watershed (Figure 32). Barnes Hollow had effective valley widths that ranged from 10 meters in the headwaters to 61 meters. Upper Big Barren tributary had effective valley widths that ranged from 30 meters in the headwaters to 60 meters. Total channel width ranged from 10 to 22 meters at Tram Hollow, 0.7 to 6 meters at Barnes Hollow, and 2 to 10 meters at Upper Big Barren tributary (Figure 33). Confinement ratios ranged from 1 to 13 at Tram Hollow, 8.5 to 24 at Barnes Hollow, and 5.6 to 23 at Upper Big Barren tributary (Figure 34). The USFS defines confined channels as having confinement ratios of four or lower (Nagel et al., 2014). Almost all of the valleys with the tram bed had confinement ratios less than 4 (Figure 34 and Figure 35). Natural reaches with no tram bed influence had the highest confinement ratios, with all of them above four and ranging from 6.2 to 13.4.

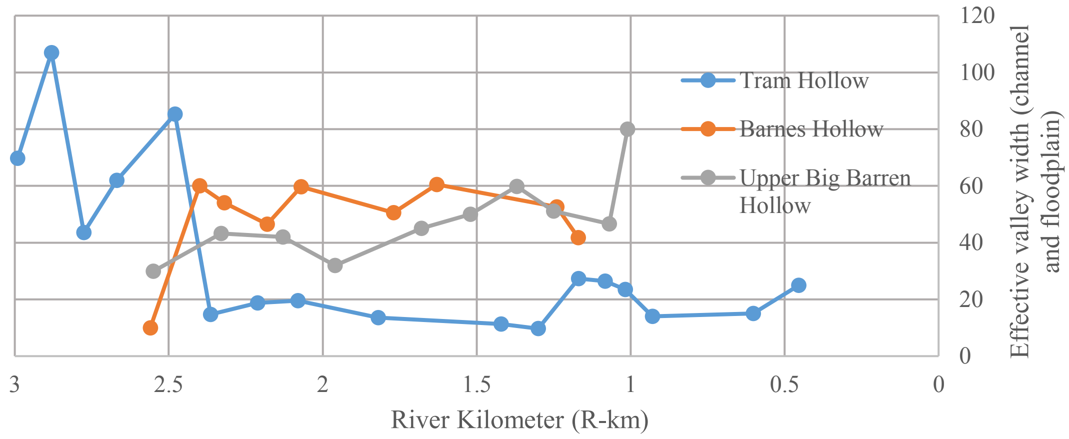


Figure 32. Effective Valley Width at Tram Hollow and Reference Channels.

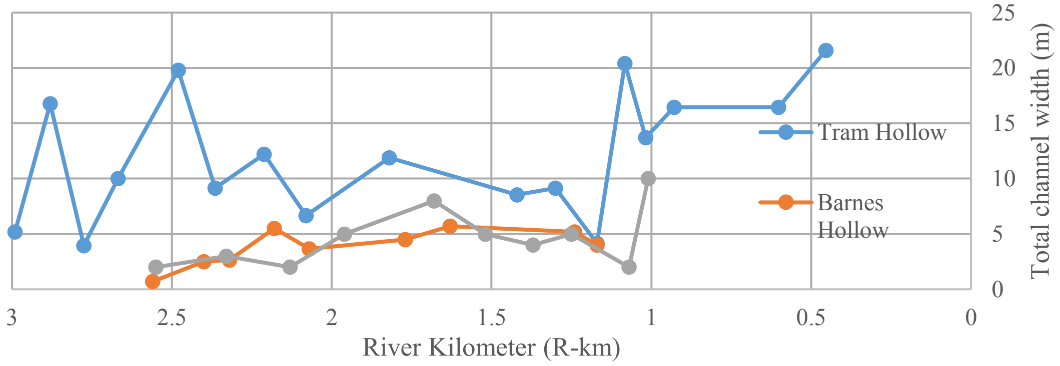


Figure 33. Total Channel Width at Natural Bankfull Discharge.

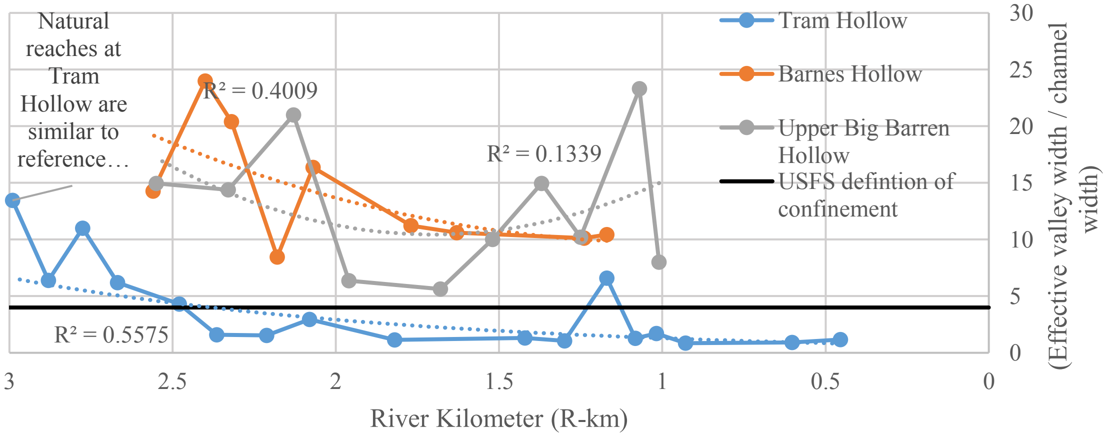


Figure 34. Confinement Ratio at Tram Hollow and Reference Channels.

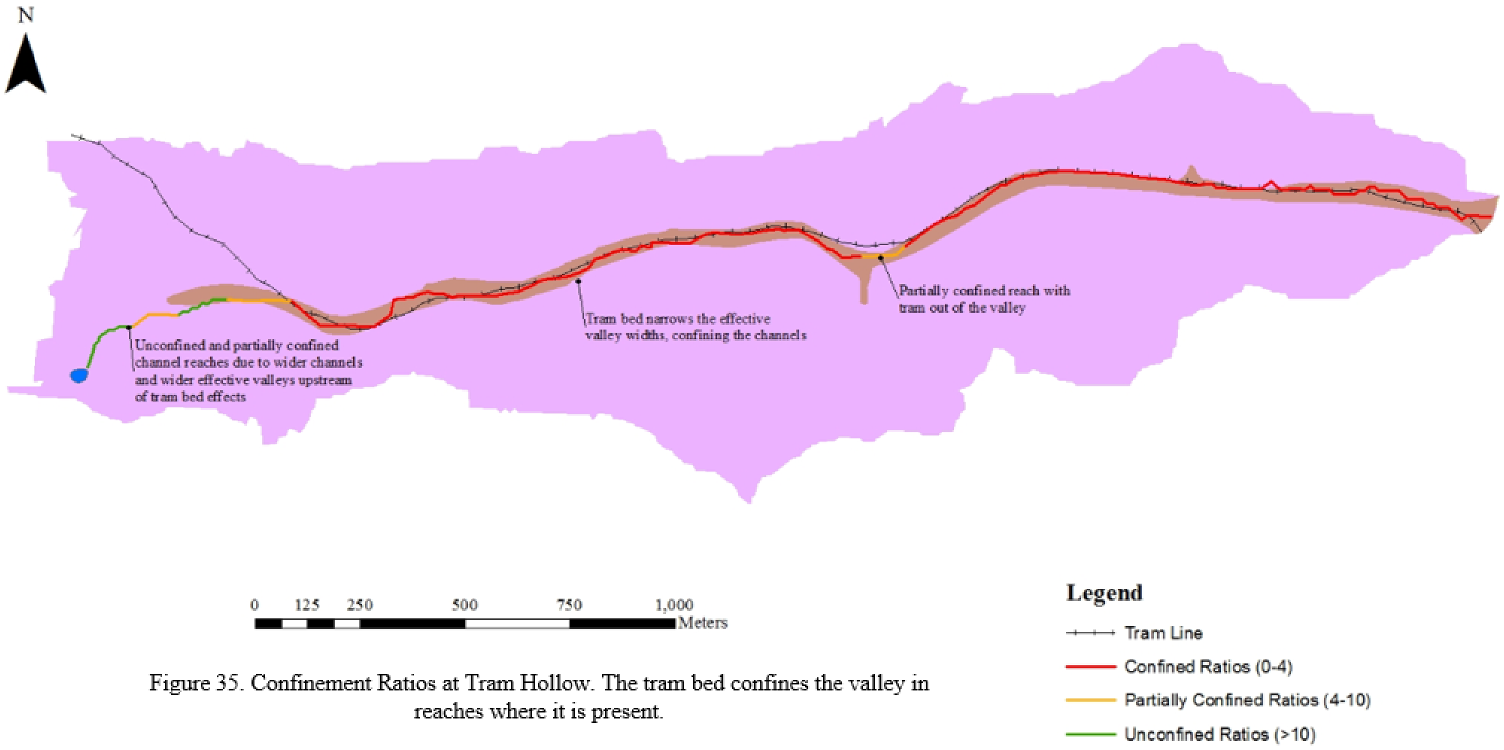


Figure 35. Confinement Ratios at Tram Hollow. The tram bed confines the valley in reaches where it is present.

Summary of Tram Bed Disturbance Effects

There are three channel planform classes at Tram Hollow: natural morphology, confined morphology, and tram bed forced morphology. Natural reaches reflect undisturbed conditions with no tram bed influence. Tram beds can cause channel disturbance indirectly by confining channels and directly by forcing particular disturbed morphologies that cause incision. Natural morphology at Tram Hollow had higher confinement ratios ranging from 6.2 and 13.4, had little to no incision with incision ratios less than 1.05, and contained stable bed substrates with average bed particles about 2 mm in diameter and no boulders (Table 7).

Disturbed channel morphology had lower confinement ratios, higher incision and channel enlargement ratios, higher frequency of headcuts, and larger and unstable bed particles. Confinement ratios in disturbed planforms ranged from 1.1 to 6.6 (Table 7). Incision ratios and channel enlargement ratios ranged from 1.1 to 3 and 1.9 to 5.4 (Table 7). Headcuts were more frequent in disturbed reaches with thirty-three tram and non-tram headcuts, whereas natural reaches had only three headcuts. Larger bed particles up to 200 mm comprised 2 to 27% of total bed substrates in disturbed reaches, whereas no boulders were found in natural reaches.

Table 7. Summary of Channel Morphology at Tram Hollow

	Natural	Confined	Tram Bed Forced
Valley confinement	Ratios between 6.2 and 13.4.	Ratios between 1.1 and 2.9.	Ratios between 1 and 6.6.
Headcuts	Only small, local, non-tram headcuts. Heights range from 0.1 to 0.15 m and widths are all about 0.5 m.	Large and migrating headcuts from confinement by tram bed. Heights range from 0.1 to 0.6 m. Widths range from 1.0 to 2.5 m.	Large and migrating headcuts in incised channels, often occurring in series. Heights range from 0.2 to 0.5 m. Widths range from 1.5 to 4.5 m.
Channel capacity	In equilibrium with bankfull discharge. Incision ratios range from 1 to 1.05, and 2.8 at the natural gorge. Enlargement ratios are all 1, with 3.9 at the natural gorge.	Natural bankfull discharge is below channel capacity heights, surface drainage is often split. Incision ratios range from 1.3 to 3, with an area of local aggradation having 1. Enlargement ratios range from 2.3 to 5.4.	Natural bankfull discharge is below channel capacity heights, pirates flow from natural channel, increases in stream power. Incision ratios range from 1.1 to 2.3. Enlargement ratios range from 1.9 to 5.3.
Bed substrates	Most stable, mainly colluvial. No boulders, except at the natural gorge.	Unstable, higher percentages of boulders and cobbles. Boulders range from 2 to 6% of total bed substrates, with 0% occurring in areas of local aggradation.	Most unstable, highest percentages of boulders and cobbles. Boulders range from 10 – 27% of total bed substrates with one site having 1 % due to higher percentage of moss in secondary channel.

Floodplain Fragmentation

The metric of lateral floodplain disconnection is the ratio of the area of the disconnected floodplain to the total floodplain area (Snyder et al., 2003; Blanton and Marcus, 2014). The boundary of disconnected floodplain is the distance from the active channel edge to the transportation line on the same side of the channel (Blanton and Marcus, 2014). The connected floodplain is the floodplain inside the transportation line, and the disconnected floodplain is the remainder of the floodplain (Figure 36). Floodplain fragmentation was calculated for all cross-sections at Tram Hollow (Table 8). Eight of the ten channel reaches where the tram bed was present had fragmented floodplains. Disturbed channel reaches had a range of floodplain fragmentation from 0% to 67% and had an average of 33%. In confined reaches, floodplain fragmentation ranged from 0% to 67% and had an average of 34.5%. In tram bed forced reaches, floodplain fragmentation ranged from 0% to 62% and had an average of 32.2%. All natural channel reaches had 0% floodplain fragmentation.

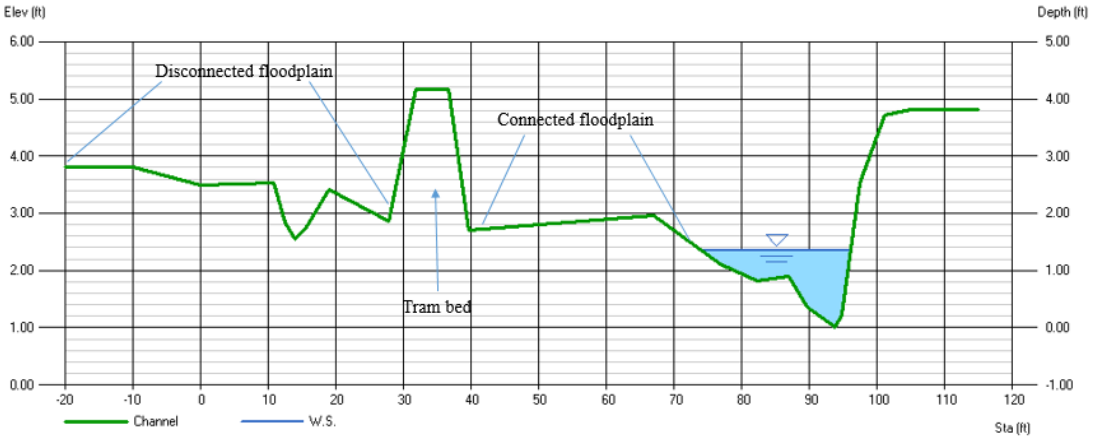


Figure 36. Floodplain Fragmentation.

Table 8. Floodplain Fragmentation.

R-km	Main	Secondary	Forced	Perched	Planform	Length of Disconnected floodplain (%)	Tram present
2.99	1	1			Natural	0	No
2.88	1				Natural	0	No
2.78	1				Natural	0	No
2.67	1	1			Natural	0	No
2.48	1		1		Forced	32	Yes
2.36	1			1 (Natural)	Confined	33	Yes
2.21	1			1 (Tram drain)	Confined	50	Yes
2.08	1			1 (Tram drain)	Confined	57	Yes
1.82	1	1		1 (Side channel)	Confined	67	Yes
1.42	1				Natural	0	No
1.30	1	1			Confined	0	No
1.17			1		Forced	41	Yes
1.08	1	1			Confined	0	No
1.02	1		1		Forced	62	Yes
0.93	1		1		Forced	58	Yes
0.60	1		1		Forced	0	Yes
0.45	1		1		Forced	0	Yes

Statistical Analysis

ANOVA, chi-square, and linear regression analyses were performed to test the five hypotheses of this study. The results of each test show that each hypothesis is statistically significant with all p-values less than the alpha value of 0.05 (Appendix C). The alternative hypotheses that the tram bed has significant influence on the channel geomorphology of Tram Hollow is accepted for each case.

For the first hypothesis, ANOVA was used to determine if the confinement ratios in natural versus disturbed channel reaches at Tram Hollow are statically significant. One of the most important disturbance effects by the tram bed is channel confinement. The p-value for the first hypothesis was 0.011 and confinement ratios in natural reaches were statically higher than confinement ratios in disturbed reaches (Appendix C-1). The mean for confinement ratios in natural reaches was 7.67 and 2.11 in disturbed reaches (Appendix C-1). The range of confinement ratios at the 95% confidence interval was 1.82 to 13.52 for natural reaches and from 1.02 to 3.20 in disturbed reaches.

The second hypothesis was also tested with ANOVA to determine if incision ratios were statically significant in natural versus disturbed reaches. Channel reaches affected by the tram bed can affected by incision and channel enlargement. Incision ratios in disturbed reaches is statically greater than incision ratios in natural reaches, with the results of the test having a p-value of 0.017 (Appendix C-2). The mean for incision ratios in natural reaches was 1.01 and 1.67 in disturbed reaches. The range of incision ratios at the 95% confidence interval was 1 to 1.05 for natural reaches, showing little to no incision, and from 1.37 to 1.97 in disturbed reaches.

Chi-square analysis was used to test the third hypothesis to determine if there was significant differences in the frequency of headucts in disturbed reaches versus the frequency of headcuts in natural reaches. Chi-square was used to test this variable since the data is count / frequency data. Headcuts can occur from tram bed disturbance effects such as confinement and incision. The test results show that there is statistically more headcuts occurring in disturbed reaches, with a p-value of 0.032 (Appendix C-3). There were 33 headcuts in disturbed reaches and 3 headcuts in natural reaches. Disturbed reaches had more headcuts, because they had both headcuts from tram bed disturbance effects and local headcuts, whereas natural reaches just had local headcuts.

Linear regression was used on the fourth hypothesis to test the relationship between channel depth and percentage of boulder bed substrates. The tram bed can concentrate stream power affecting depth and the size of bed particles. The results of the test show that channel depth and percentage of boulders have a positive correlation with a p-value of zero and adjusted r-square value of 0.733 (Appendix C-4). Larger particles are being recruited into the river in deeper reaches that incise into colluvium and residuum.

ANOVA was used to test the fifth hypothesis to determine if there was significant difference in the percent length of disconnected floodplain in natural reaches versus disturbed reaches. Higher percentages of disconnected floodplain was hypothesized to occur in disturbed reaches from the presence of the tram bed. The test results show that disconnected floodplains significantly occur more in disturbed reaches than in natural reaches with a p-value of 0.016 (Appendix C-5). All natural reaches had 0% disconnected floodplains and disturbed reaches ranged from 16.3% to 50.4% in the 95% confidence interval with an average of 33.3% (Appendix C-5).

CHAPTER 5 – CONCLUSIONS

Historical logging tram beds along headwater streams provide past and ongoing sources of channel disturbance to Tram Hollow. Abandoned tram beds are still present along several Ozark headwater streams (Guyette and Larsen, 2000). The abandoned logging tram constructed along Tram Hollow over a hundred years ago continues to affect the hydrology, surface drainage patterns, and geomorphology of the channel. Tram Hollow (1.67 km²) served to be an accessible and valuable location to study the geomorphic effects of rail beds along headwater streams, due to a combination in both filled and cut rail beds, and variations in the proximity of the rail bed to the channel.

Key Findings

The key findings of this study include:

1. There are two types of disturbed planforms at Tram Hollow, six confined reaches where the tram bed obstructs flow and sediment, and six forced reaches where the tram bed directly forces a disturbed morphology. Confined planforms can incise and develop headcuts from channel confinement (Magilligan, 1992; Lecce, 1997). Forced reaches occur where the tram forms a bank forcing the channel to occur along it or in cut tram beds that pirate flow from natural channels and can contain a series of headcuts from incision (Florsheim et al., 2000; Winterbottom, 2000). Disturbed planforms alter the hydrology of channels including cutting of side flow channels from main channels and concentrating stream power in incised channels;

2. Disturbed channel reaches were more confined due to the reducing of effective valley widths by the tram bed. Confinement ratios ranged from 1 to 6.6 in disturbed channel reaches, while natural reaches had ratios that ranged from 6.2 to 13.4. Effective valley widths ranged from 10 to 27 m in the most disturbed reaches, and natural reaches had effective valley widths that ranged from 43 to 107 m. The tram bed reduces the effective valley width, an important measure of confinement where most of the energy available for geomorphic work is located, by obstructing water and sediment and by concentrating stream power (Florsheim et al, 2000; Wheaton et al., 2015);

3. Incision ratios and channel enlargement ratios are higher in disturbed reaches at Tram Hollow compared to natural reaches. In confined and forced reaches, incision ratios range from 1.3 to 3 and 1.1 to 2.3, whereas incision ratios in natural reaches ranged from 1.0 to 1.05 (Starr, 2009). Enlargement ratios in confined and forced reaches ranged from 2.3 to 5.4 and 1.9 to 5.3, whereas natural reaches had ratios of 1.0 (Hammer, 1972). Natural reaches with secondary channels were not enlarged, indicating that enlargement results from confinement and incision and not from a greater number of channels;

4. Headcuts occurred more frequently at disturbed channel reaches than natural reaches, because disturbed reaches had both tram headcuts and local headcuts. Disturbed reaches had thirty-three headcuts, whereas natural reaches had three local headcuts. Tram headcuts occured from confinement and incision, and migrate upstream and range from 0.1 m to 0.6 m deep and 1 to 4.5 m wide. Local headcuts occur below tributary confluences, bedrock obstacles, and pools / bends and range from 0.1 to 0.4 m deep and 0.5 to 6.0 m wide. Channels affected by confinement and incision develop headcuts in an attempt to return back to the channel's equilibrium state (Schumm, 1979; Florsheim et al., 2000). Local headcuts at Tram Hollow and in other Ozark headwater streams have less pronounced disturbance and result from a disproportionate balance between sediment size and supply, and discharge and channel slope at channel bends and tributary junctions (Lane, 1955);

5. Larger bed substrates occur along disturbed reaches with average particles ranging from 2 to 30 mm in confined reaches, and 9 to 45 mm in forced reaches. Natural reaches have average particle sizes of 2 mm or less, and 60 mm at the natural gorge. Boulders up to 200 mm in diameter comprised 2 to 6% of total bed substrates in confined reaches, 10 to 27% in forced reaches, and 0% in natural reaches. Larger bed particles such as boulders indicate channel instability, and colluvial channels with smaller particles, more vegetation, and little bed changes indicate stability (Montgomery and Buffington, 1993); and

6. Eight of the ten channel reaches where the tram bed was present had fragmented floodplains. Disturbed channel reaches had a range of floodplain fragmentation from 0% to 67% and had an average of 33%. In confined reaches, floodplain fragmentation ranged from 0% to 67% and had an average of 34.5%. In tram bed forced reaches, floodplain fragmentation ranged from 0% to 62% and had an average of 32.2%. All natural channel reaches had 0% floodplain fragmentation. The metric of lateral floodplain disconnection is the ratio of the area of the disconnected floodplain to the total floodplain area (Blanton and Marcus, 2014). The boundary of disconnected floodplain is the distance from the active channel edge to the tram bed on the same side of the channel. Floodplain fragmentation decreases lateral river connectivity and the quality of riparian habitat in channel networks (Marcus and Blanton, 2009).

Future Work

Future work should perform the geomorphic assessments of this study in reaches further down the channel network in order to determine if the tram bed disturbance effects are connected to downstream reaches. A comparison of downstream reaches affected by the tram bed with downstream reaches with no tram bed influence can be performed. Current management problems in larger Ozark streams include larger bed particles, increased sediment supply, and concentrated stream power. The results of this study provide a potential source of disturbance for these problems occurring along larger valley bottoms. Management and future studies should focus on determining if the current management problems that occur further downstream may in part be attributed to these disturbances in the headwaters.

The results of this study address a gap in knowledge on the geomorphology of alluvial and colluvial Ozark headwater streams less than two square kilometers, and the geomorphic effects of historical logging rail beds. The geomorphic effects of rail beds was previously studied in the Pacific Northwest of the United States, and the geomorphic effects of smaller rail beds such as tramways were not previously studied (Blanton and Marcus, 2013). The tram bed in Tram Hollow disconnects the river system laterally through confinement, incision, headcut development, and floodplain fragmentation. Headwater streams at this scale can be sensitive to human modifications and can affect larger downstream reaches due to their positions in drainage networks.

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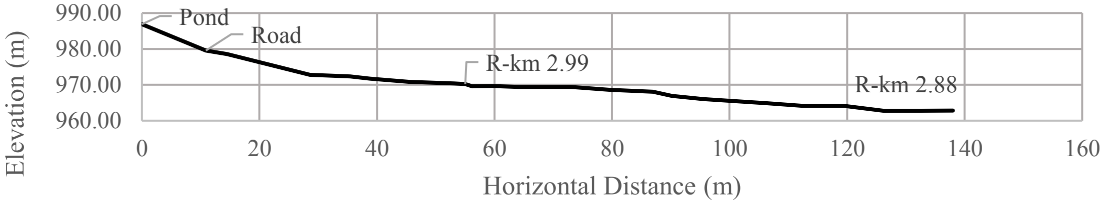
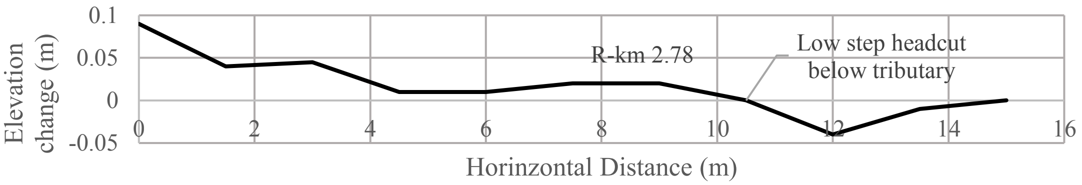
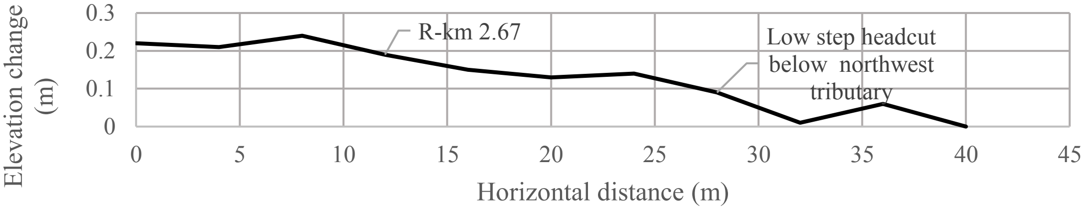
APPENDICES

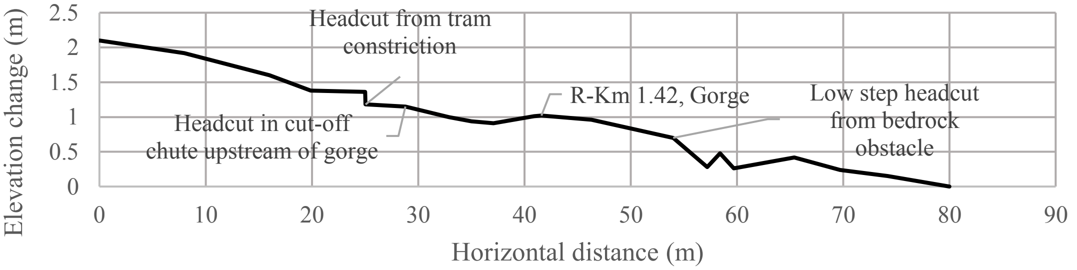
Appendix A – Longitudinal Profiles

Appendix A-1 - Longitudinal Profiles of Natural Morphology.

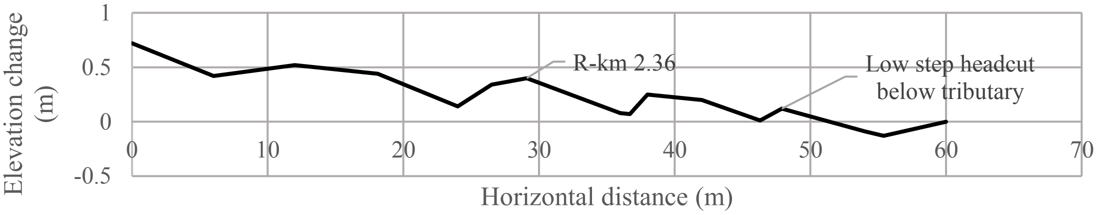


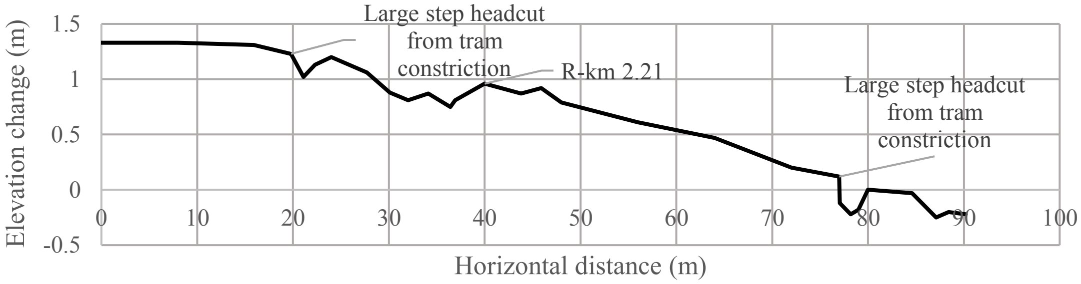


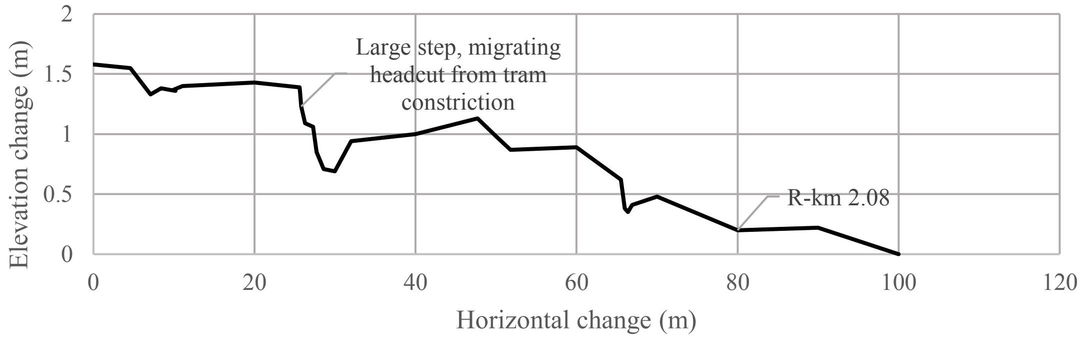


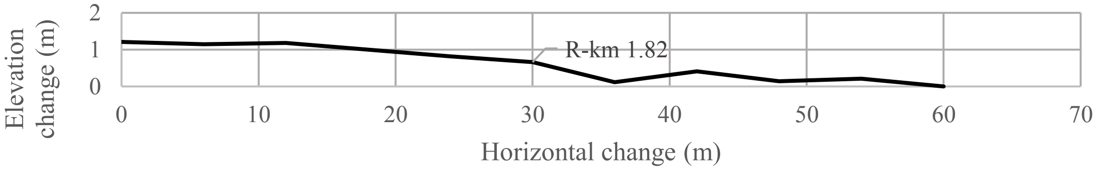


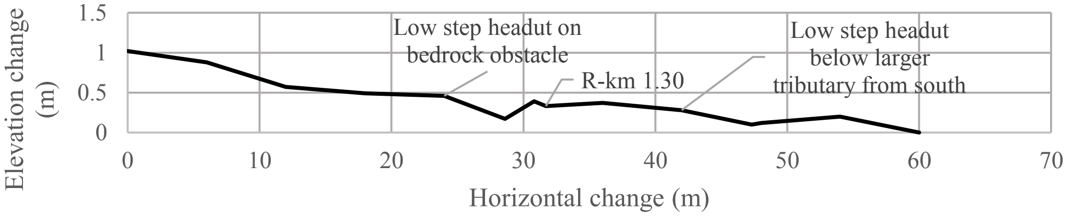
Appendix A-2 - Longitudinal Profiles of Confined Morphology.

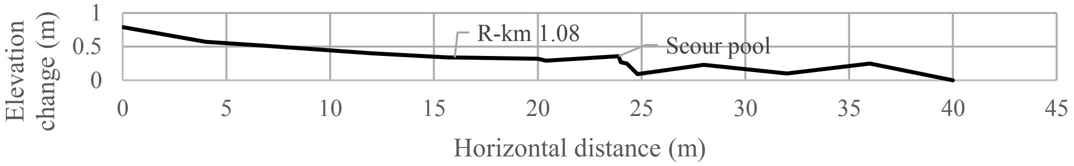




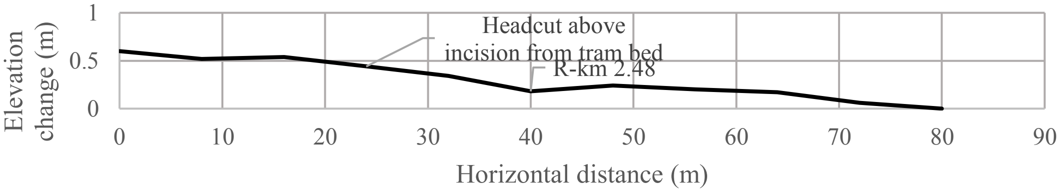


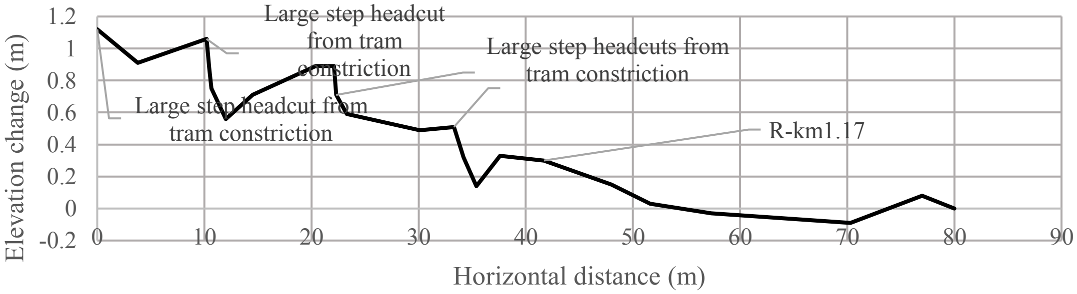


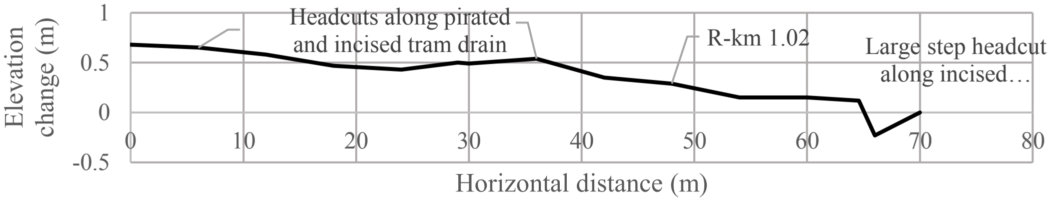


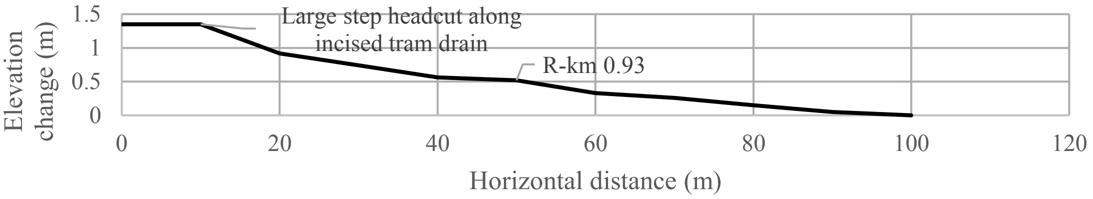


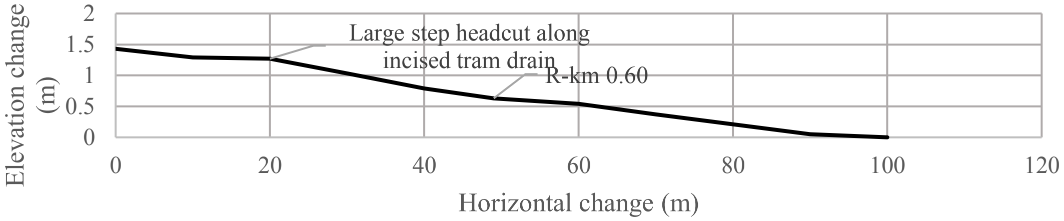
Appendix A-3 - Longitudinal Profiles of Tram Bed Forced Morphology.

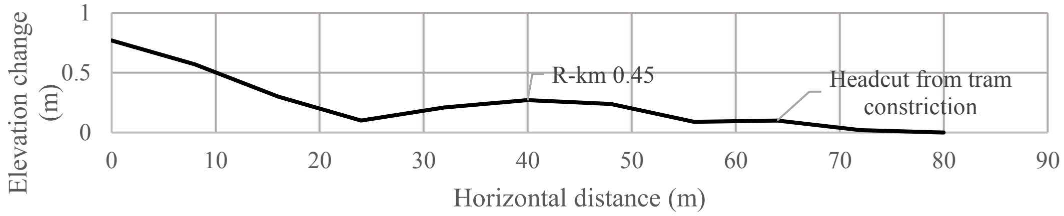







1.5
1
0.5
0
Elevation change (m)
0
20
40
60
80
100
120
Horizontal distance (m)
Large step headcut along incised tram drain
R-km 0.93

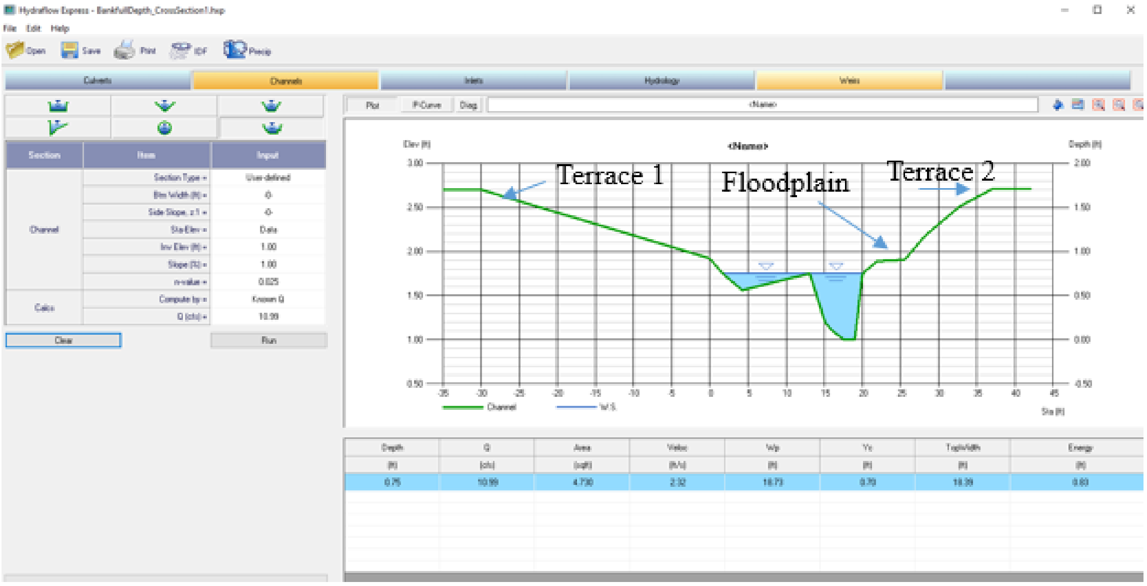

2
1.5
1
0.5
0
Elevation change (m)
0
20
40
60
80
100
120
Horizontal change (m)
Large step headcut along incised tram drain
R-km 0.60


1
0.5
0
Elevation change (m)
0
10
20
30
40
50
60
70
80
90
Horizontal distance (m)
R-km 0.45
Headcut from tram constriction

Appendix B – Cross-Sections.

Appendix B-1 - Natural Morphology Cross-Sections.

R-km 2.99, 2 Year Flood.



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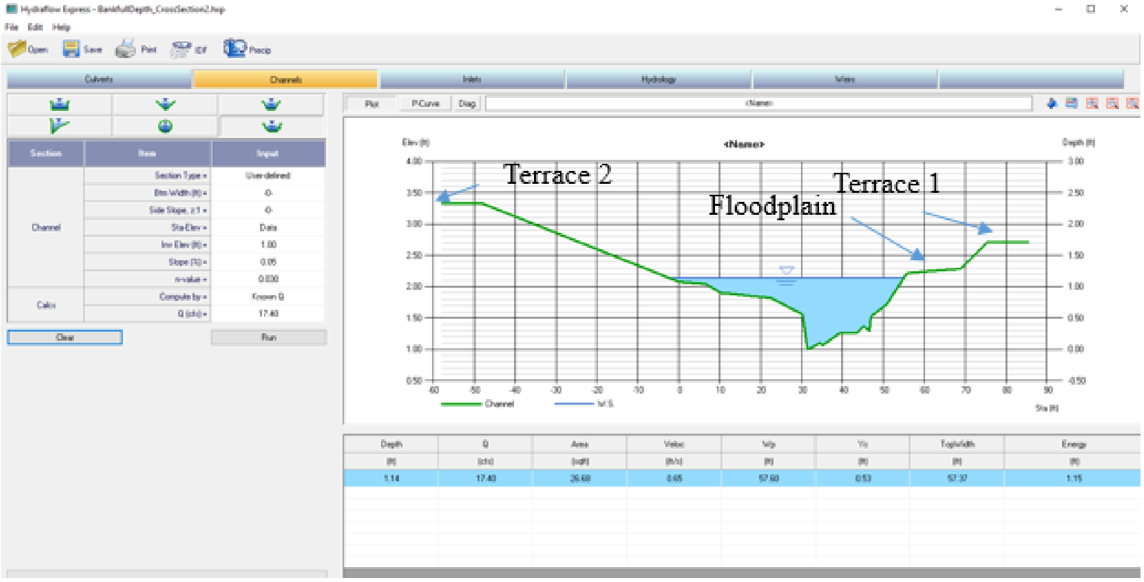
	Side Slope, z:1 =	-0-
	Sta-Elev =	Data
	Inv Elev (ft) =	1.00
	Slope (%) =	1.00
	n-value =	0.025
Calcs	Compute by =	Known Q
	Q (cfs) =	10.99

Depth	Q	Area	Veloc	Wp	Yc	TopWidth	Energy
(ft)	(cfs)	(sqft)	(ft/s)	(ft)	(ft)	(ft)	(ft)
0.75	10.99	4.730	2.32	18.73	0.70	18.39	0.83

R-km 2.88, 2 Year Flood.



Section	Item	Input
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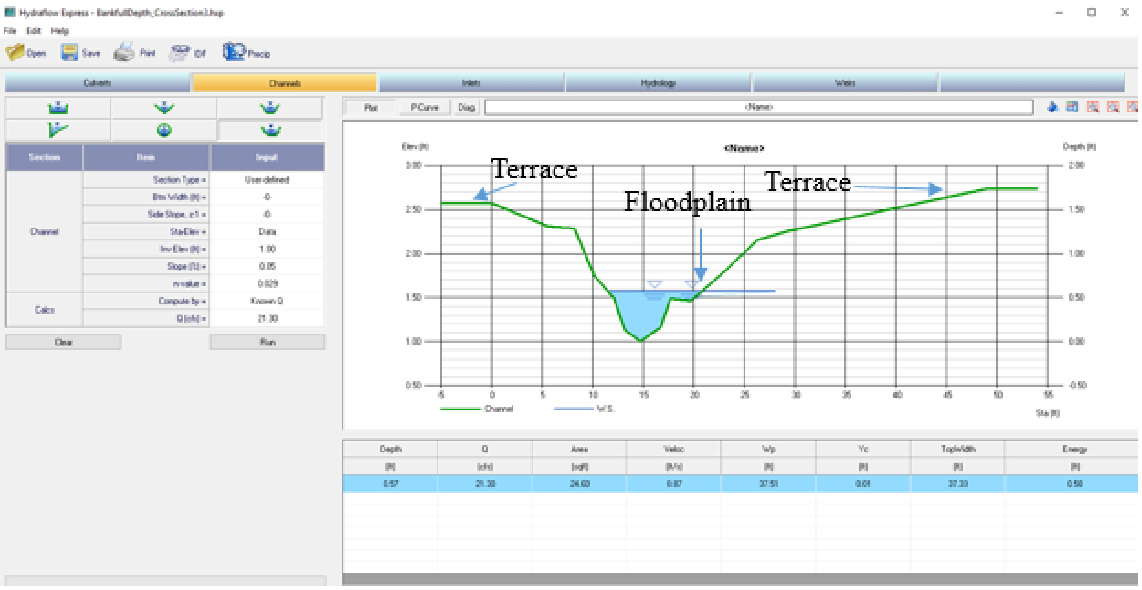
	Btm Width (ft) =	-0-
	Side Slope, z:1 =	-0-
	Sta-Elev =	Data
	Inv Elev (ft) =	1.00
	Slope (%) =	0.05
	n-value =	0.030
Calcs	Compute by =	Known Q
	Q (cfs) =	17.40

Depth	Q	Area	Veloc	Wp	Yc	TopWidth	Energy
(ft)	(cfs)	(sqft)	(ft/s)	(ft)	(ft)	(ft)	(ft)
1.14	17.40	26.69	0.65	57.60	0.53	57.37	1.15

R-km 2.78, 2 Year Flood.



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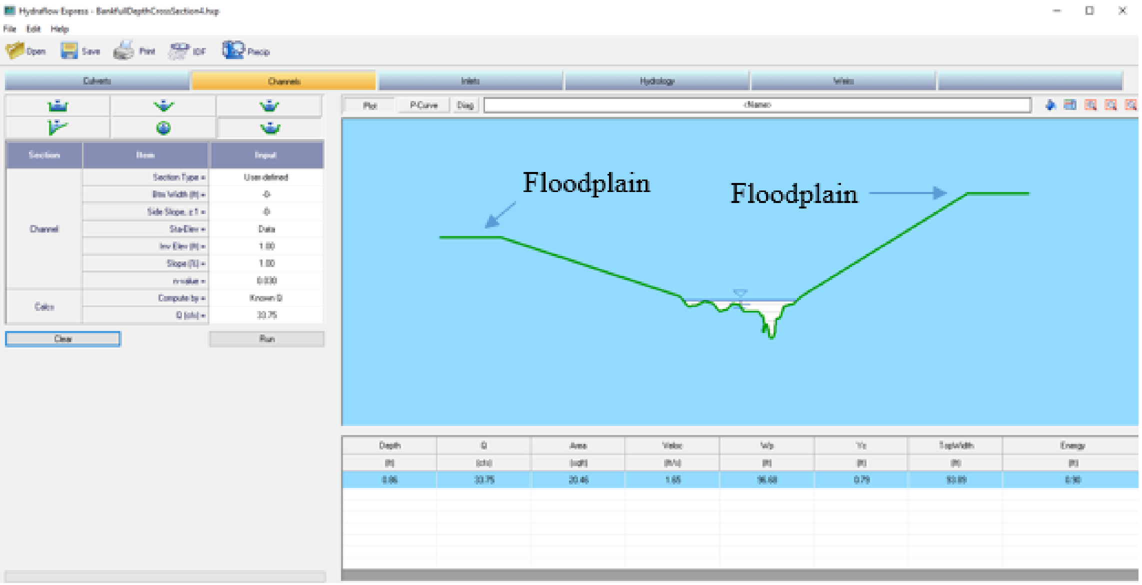
	Inv Elev (ft) =	1.00
	Slope (%) =	0.05
	n-value =	0.029
Calcs	Compute by =	Known Q
	Q (cfs) =	21.30

Depth	Q	Area	Veloc	Wp	Yc	TopWidth	Energy
(ft)	(cfs)	(sqft)	(ft/s)	(ft)	(ft)	(ft)	(ft)
0.57	21.30	24.60	0.87	37.51	0.01	37.33	0.58

R-km 2.69, 2 Year Flood.



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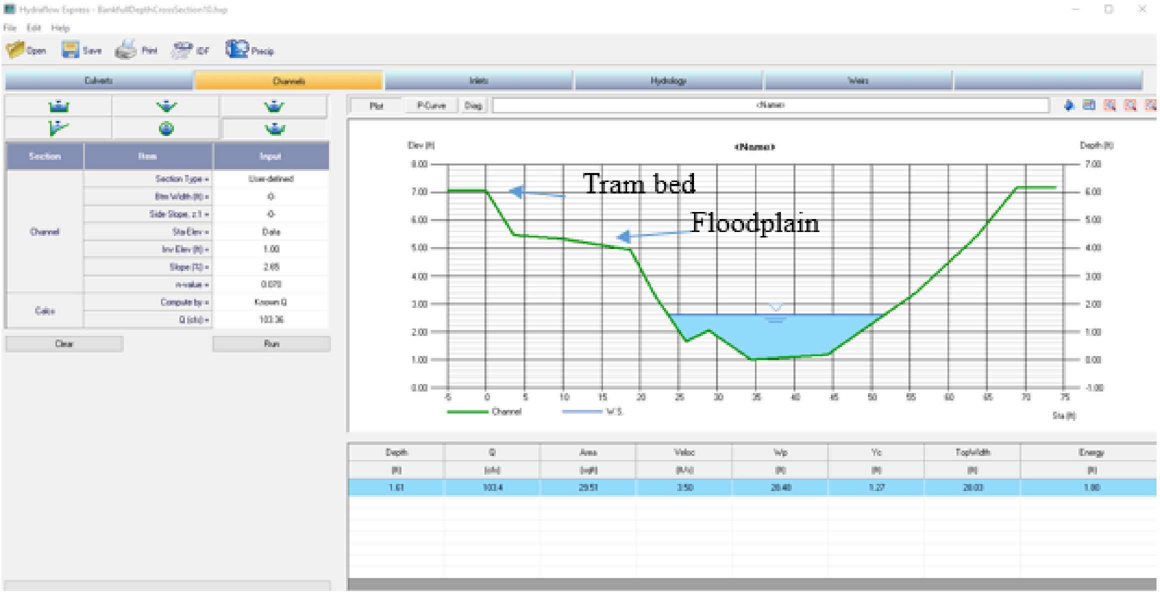
	Side Slope, z:1 =	-0-
	Sta-Elev =	Data
	Inv Elev (ft) =	1.00
	Slope (%) =	1.00
	n-value =	0.030
Calcs	Compute by =	Known Q
	Q (cfs) =	33.75

Depth	Q	Area	Veloc	Wp	Yc	TopWidth	Energy
(ft)	(cfs)	(sqft)	(ft/s)	(ft)	(ft)	(ft)	(ft)
0.86	33.75	20.46	1.65	96.68	0.79	93.89	0.90

R-km 1.42, Natural Gorge, 2 Year Flood.



Section	Item	Input
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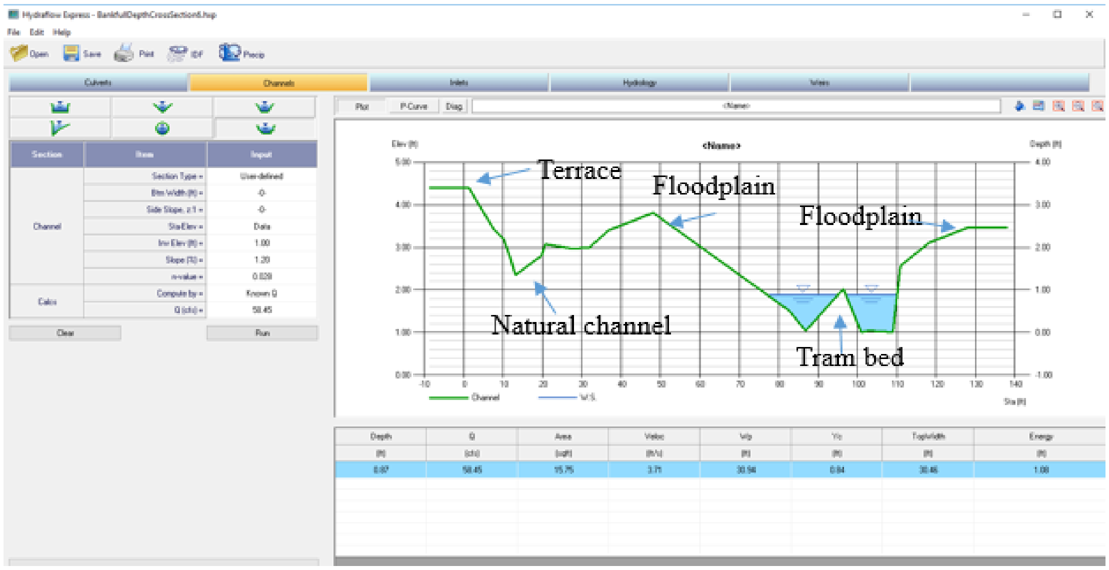
	Sta/Elev =	Data
	Inv Elev (ft) =	1.00
	Slope (%) =	2.65
	n-value =	0.070
Calcs	Compute by =	Known Q
	Q (cfs) =	103.36

Depth	Q	Area	Veloc	Wp	Yc	TopWidth	Energy
(ft)	(cfs)	(sqft)	(ft/s)	(ft)	(ft)	(ft)	(ft)
1.61	103.4	29.51	3.50	28.40	1.27	28.03	1.80

Appendix B-2 - Confined Morphology Cross-Sections.

R-km 2.36, 2 Year Flood.



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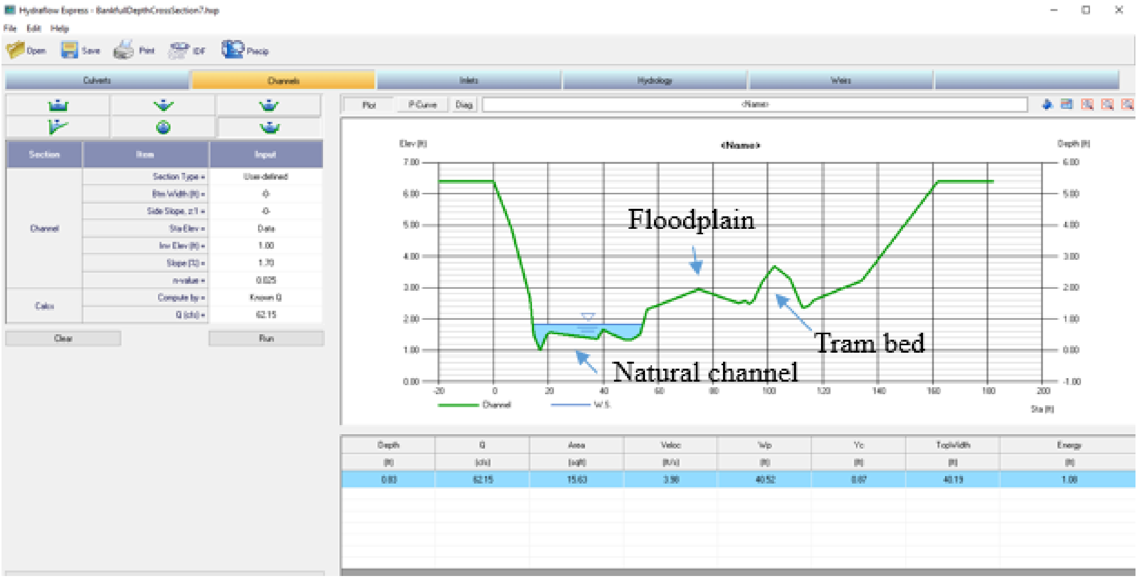
	Inv Elev (ft) =	1.00
	Slope (%) =	1.20
	n-value =	0.028
Calcs	Compute by =	Known Q
	Q (cfs) =	58.45

Depth	Q	Area	Veloc	Wp	Yc	TopWidth	Energy
(ft)	(cfs)	(sqft)	(ft/s)	(ft)	(ft)	(ft)	(ft)
0.87	58.45	15.75	3.71	30.94	0.84	30.46	1.08

R-km 2.21, 2 Year Flood



Section	Item	Input
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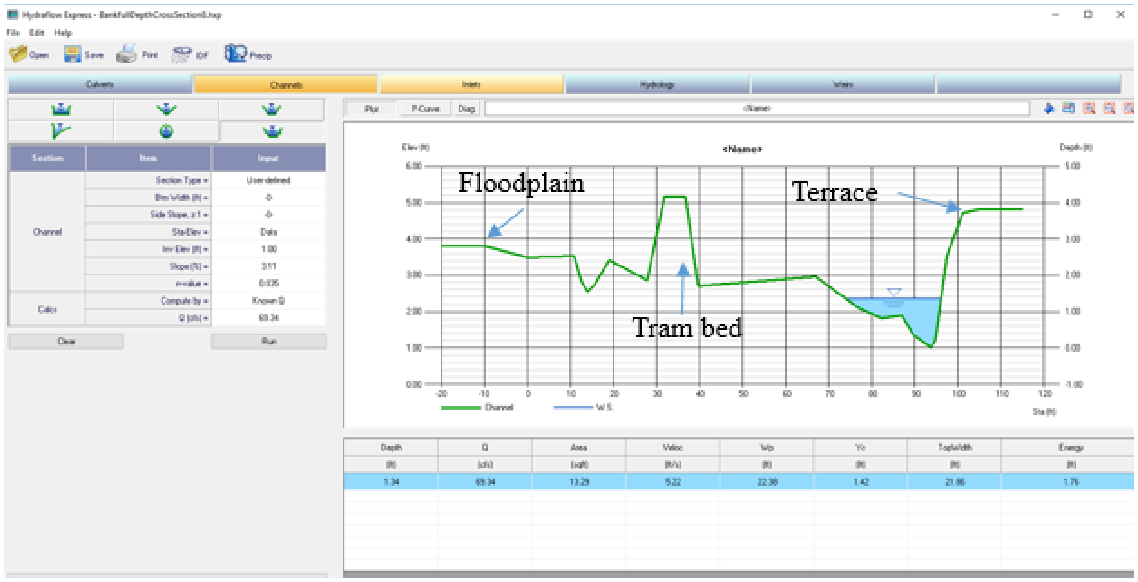
	Sta/Elev =	Data
	Inv Elev (ft) =	1.00
	Slope (%) =	1.70
	n-value =	0.025
Calcs	Compute by =	Known Q
	Q (cfs) =	62.15

Depth	Q	Area	Veloc	Wp	Yc	TopWidth	Energy
(ft)	(cfs)	(sqft)	(ft/s)	(ft)	(ft)	(ft)	(ft)
0.83	62.15	15.63	3.98	40.52	0.87	40.19	1.08

R-km 2.08, 2 Year Flood.



Section	Item	Input
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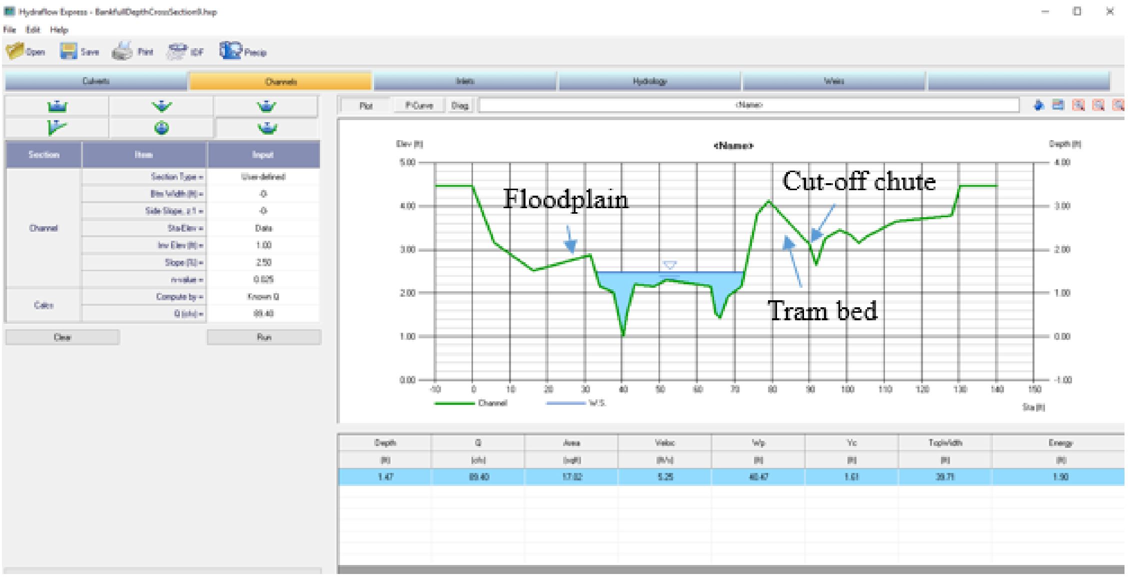
	Btm Width (ft) =	-0-
	Side Slope, z:1 =	-0-
	Sta/Elev =	Data
	Inv Elev (ft) =	1.00
	Slope (%) =	3.11
	n-value =	0.035
Calcs	Compute by =	Known Q
	Q (cfs) =	69.34

Depth	Q	Area	Veloc	Wp	Yc	TopWidth	Energy
(ft)	(cfs)	(sqft)	(ft/s)	(ft)	(ft)	(ft)	(ft)
1.34	69.34	13.29	5.22	22.38	1.42	21.86	1.76

R-km 1.82, 2 Year Flood.



Section	Item	Input
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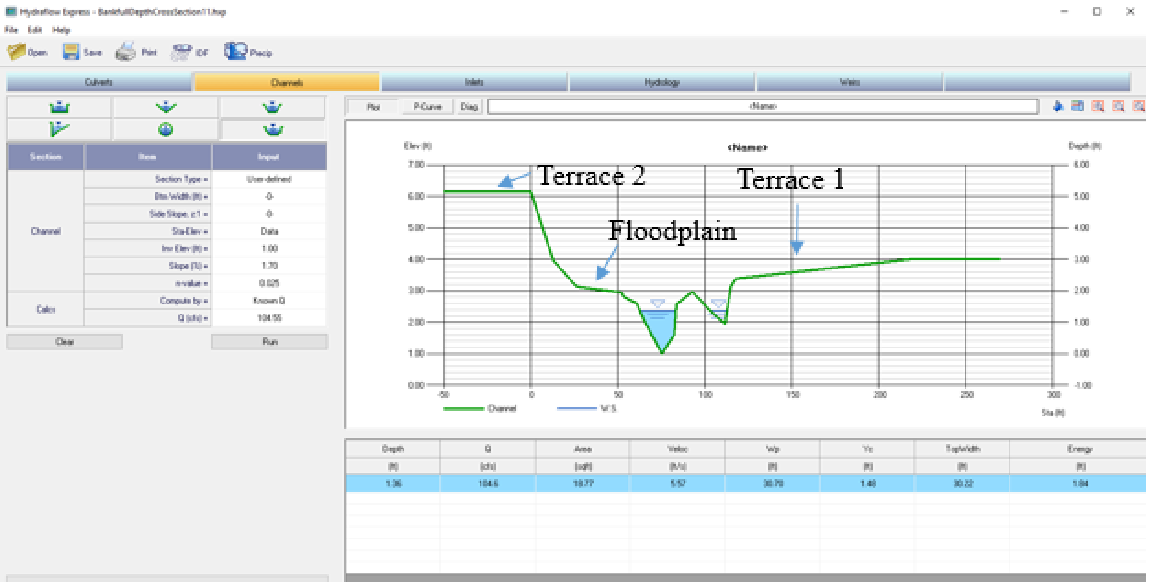
	Side Slope, z:1 =	-0-
	Sta-Elev =	Data
	Inv Elev (ft) =	1.00
	Slope (%) =	2.50
	n-value =	0.025
Calcs	Compute by =	Known Q
	Q (cfs) =	89.40

Depth	Q	Area	Veloc	Wp	Yc	TopWidth	Energy
(ft)	(cfs)	(sqft)	(ft/s)	(ft)	(ft)	(ft)	(ft)
1.47	89.40	17.02	5.25	40.47	1.61	39.71	1.90

R-km 1.30, 2 Year Flood.



Section	Item	Input
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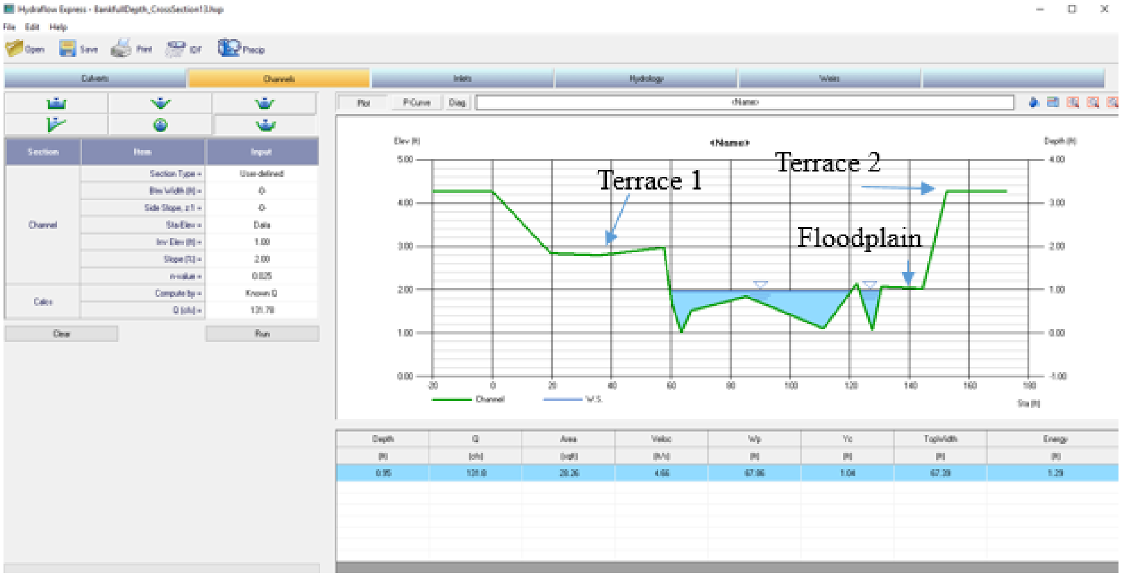
	Side Slope, z:1 =	-0-
	Sta-Elev =	Data
	Inv Elev (ft) =	1.00
	Slope (%) =	1.70
	n-value =	0.025
Calcs	Compute by =	Known Q
	Q (cfs) =	104.55

Depth	Q	Area	Veloc	Wp	Yc	TopWidth	Energy
(ft)	(cfs)	(sqft)	(ft/s)	(ft)	(ft)	(ft)	(ft)
1.36	104.6	18.77	5.57	30.79	1.48	30.22	1.84

R-km 1.08, 2 Year Flood.



Section	Item	Input
Channel	Section Type =	User-defined
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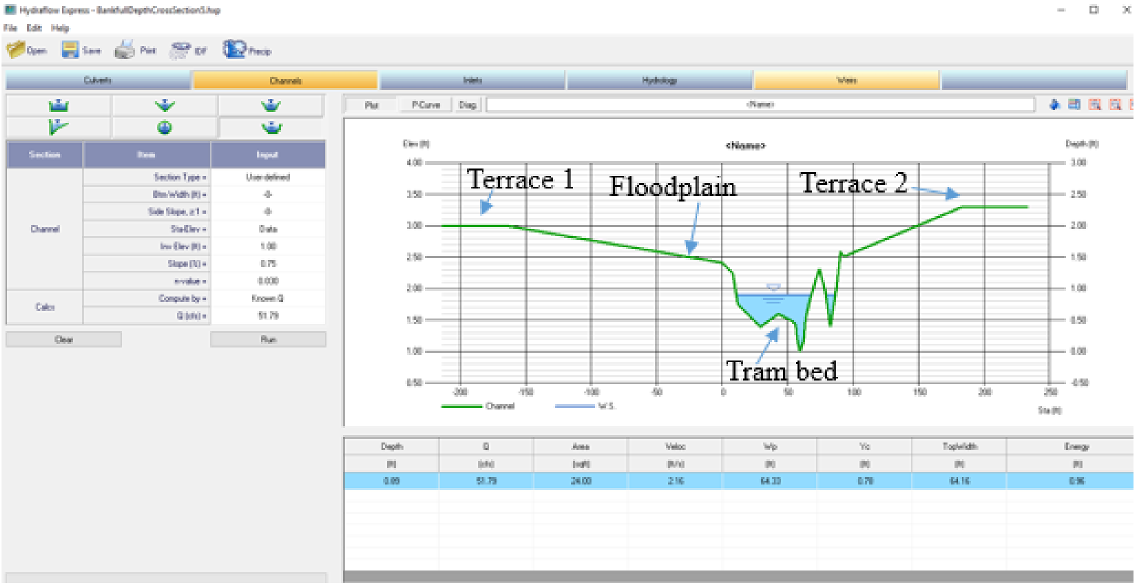
	Side Slope, z:1 =	-0-
	Sta/Elev =	Data
	Inv Elev (ft) =	1.00
	Slope (%) =	2.00
	n-value =	0.025
Calcs	Compute by =	Known Q
	Q (cfs) =	131.78

Depth	Q	Area	Veloc	Wp	Yc	TopWidth	Energy
(ft)	(cfs)	(sqft)	(ft/s)	(ft)	(ft)	(ft)	(ft)
0.95	131.8	28.26	4.66	67.86	1.04	67.39	1.29

Appendix B-3 - Tram Bed Forced Cross-Sections.

R-km 2.48, 2 Year Flood.



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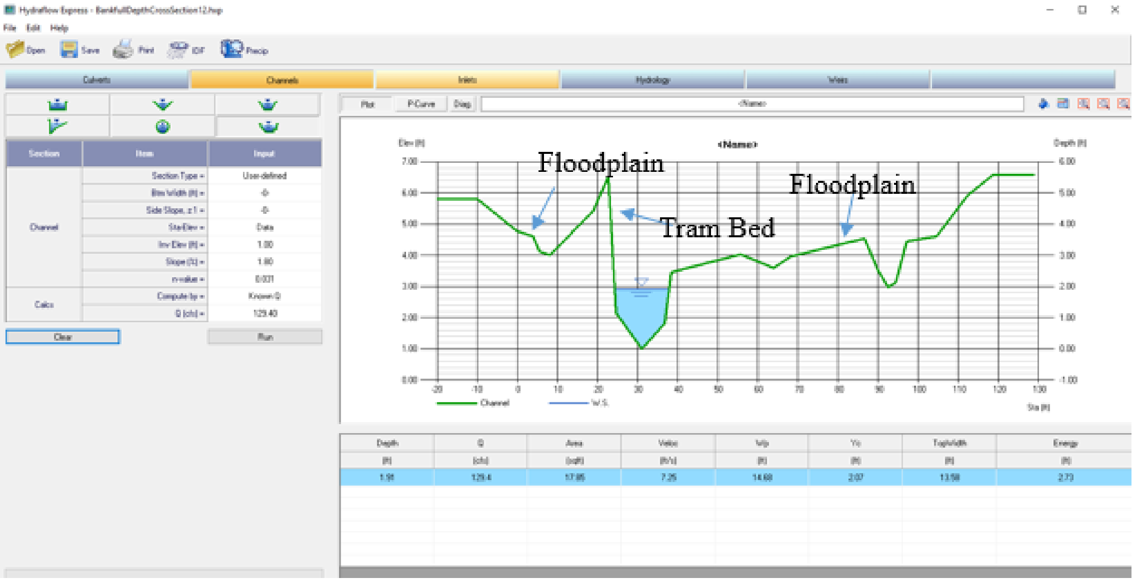
	Side Slope, z:1 =	-0-
	Sta/Elev =	Data
	Inv Elev (ft) =	1.00
	Slope (%) =	0.75
	n-value =	0.030
Calcs	Compute by =	Known Q
	Q (cfs) =	51.79

Depth	Q	Area	Veloc	Wp	Yc	TopWidth	Energy
(ft)	(cfs)	(sqft)	(ft/s)	(ft)	(ft)	(ft)	(ft)
0.89	51.79	24.00	2.16	64.33	0.78	64.16	0.96

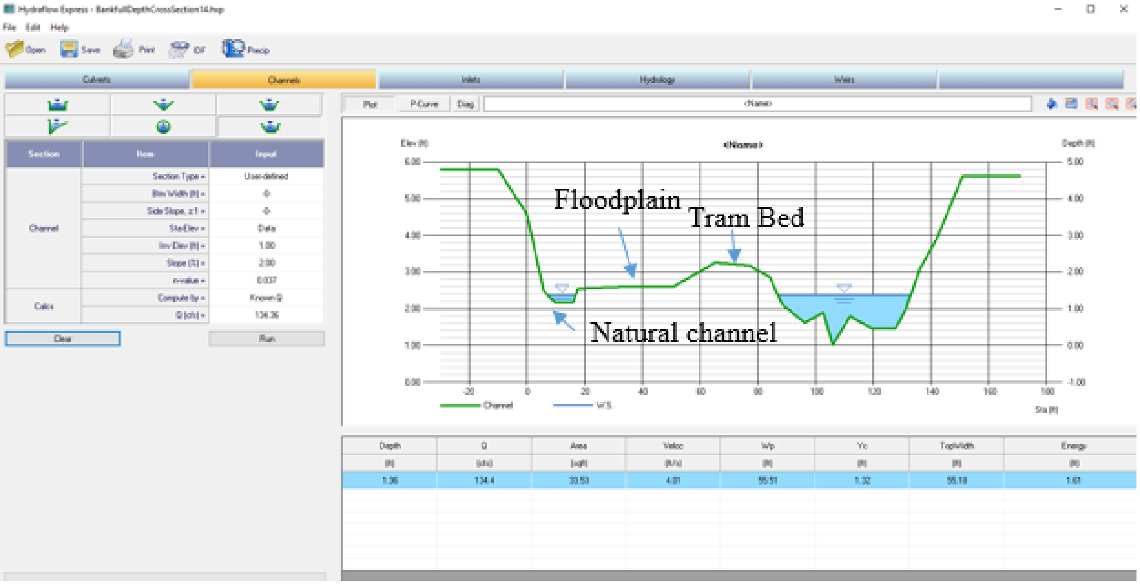
R-km 1.17, 2 Year Flood.



Section	Item	Input
Channel	Section Type =	User-defined
	Btm Width (ft) =	-0-
	Side Slope, z:1 =	-0-
	Sta/Elev =	Data
	Inv Elev (ft) =	1.00
	Slope (%) =	1.80
	n-value =	0.031
Calcs	Compute by =	Known Q
	Q (cfs) =	129.40

Depth	Q	Area	Veloc	Wp	Yc	TopWidth	Energy
(ft)	(cfs)	(sqft)	(ft/s)	(ft)	(ft)	(ft)	(ft)
1.91	129.4	17.85	7.25	14.68	2.07	13.58	2.73

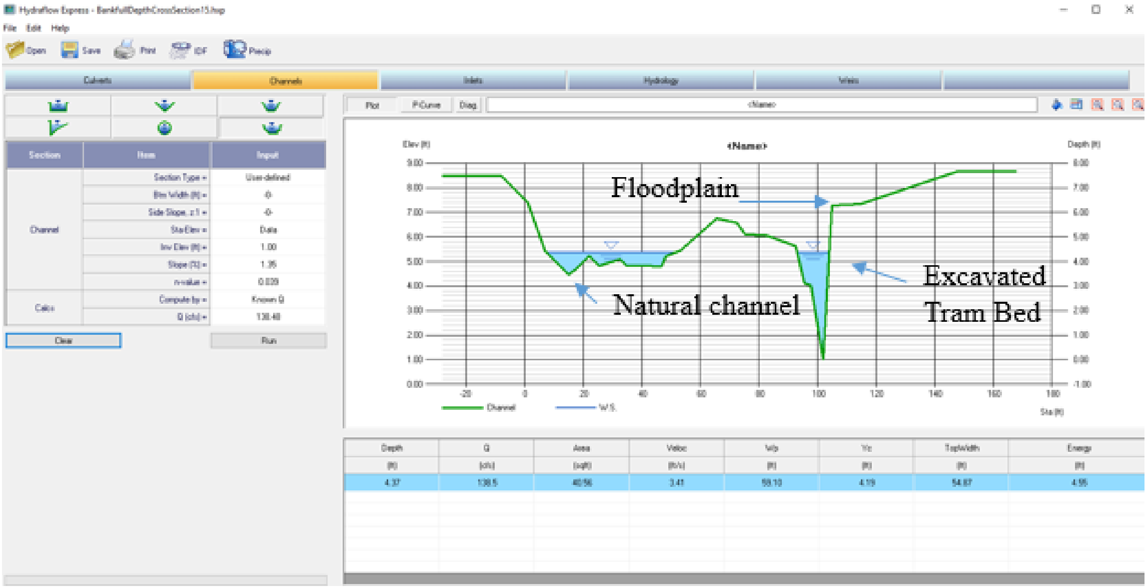
R-km 1.02, 2 Year Flood.



Section	Item	Input
Channel	Section Type =	User-defined
	Btm Width (ft) =	-0-
	Side Slope, z:1 =	-0-
	Sta/Elev =	Data
	Inv Elev (ft) =	1.00
	Slope (%) =	2.00
	n-value =	0.037
Calcs	Compute by =	Known Q
	Q (cfs) =	134.36

Depth	Q	Area	Veloc	Wp	Yc	TopWidth	Energy
(ft)	(cfs)	(sqft)	(ft/s)	(ft)	(ft)	(ft)	(ft)
1.36	134.4	33.53	4.01	55.51	1.32	55.18	1.61

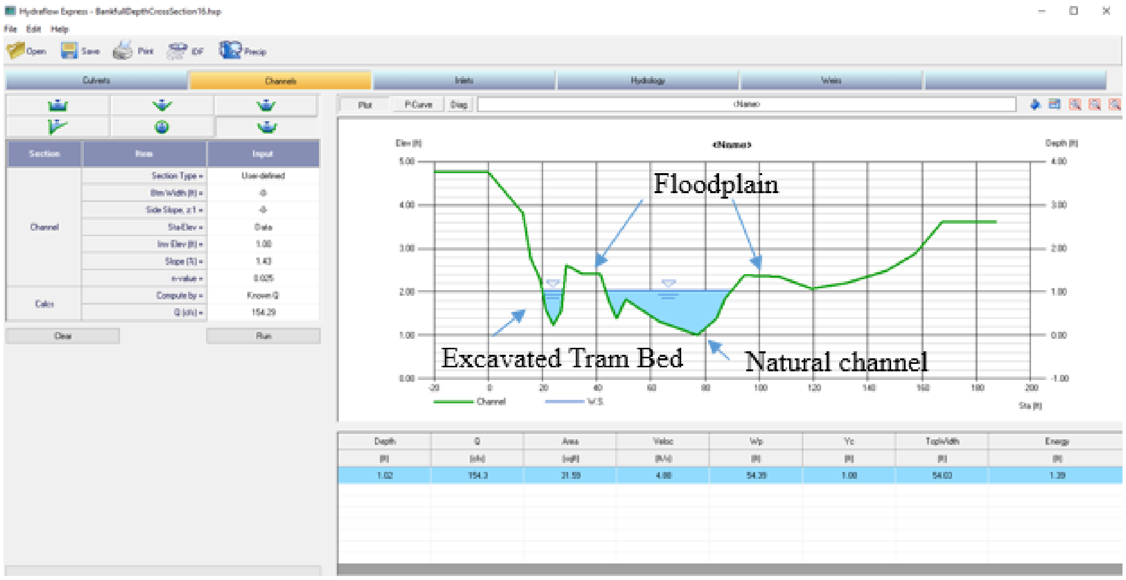
R-km 0.93, 2 Year Flood.



Section	Item	Input
Channel	Section Type =	User-defined
	Btm Width (ft) =	-0-
	Side Slope, z:1 =	-0-
	Sta/Elev =	Data
	Inv Elev (ft) =	1.00
	Slope (%) =	1.35
	n-value =	0.039
Calcs	Compute by =	Known Q
	Q (cfs) =	138.48

Depth	Q	Area	Veloc	Wp	Yc	TopWidth	Energy
(ft)	(cfs)	(sqft)	(ft/s)	(ft)	(ft)	(ft)	(ft)
4.37	138.5	40.56	3.41	59.10	4.19	54.87	4.55

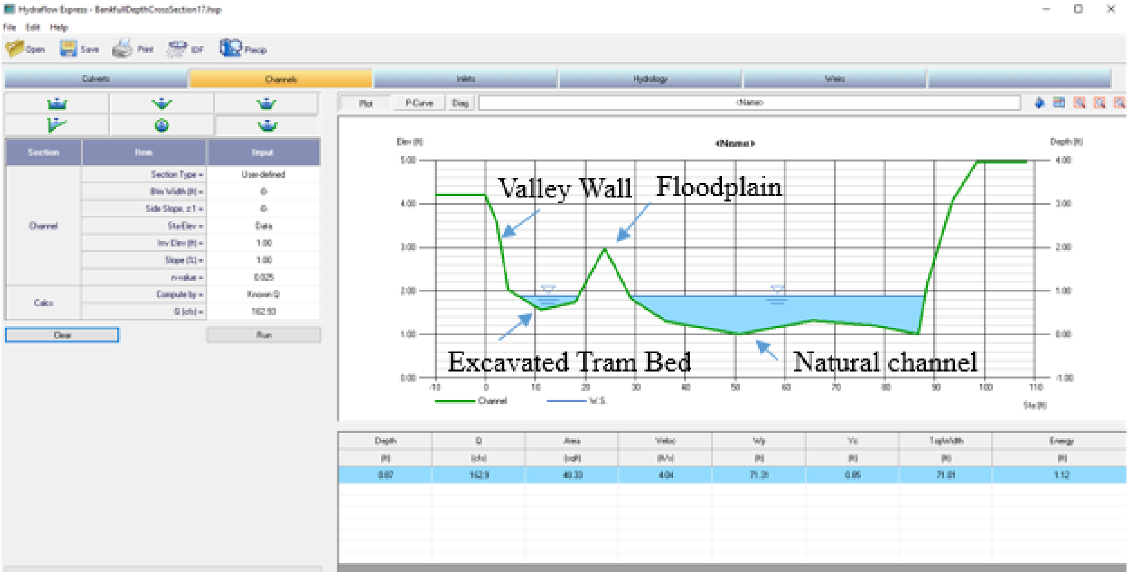
R-km 0.602, 2 Year Flood.



Section	Item	Input
Channel	Section Type =	User-defined
	Btm Width (ft) =	-0-
	Side Slope, z:1 =	-0-
	Sta/Elev =	Data
	Inv Elev (ft) =	1.00
	Slope (%) =	1.43
	n-value =	0.025
Calcs	Compute by =	Known Q
	Q (cfs) =	154.29

Depth	Q	Area	Veloc	Wp	Yc	TopWidth	Energy
(ft)	(cfs)	(sqft)	(ft/s)	(ft)	(ft)	(ft)	(ft)
1.02	154.3	31.59	4.88	54.39	1.00	54.03	1.39

R-km 0.454, 2 Year Flood.



Section	Item	Input
Channel	Section Type =	User-defined
	Btm Width (ft) =	-0-
	Side Slope, z:1 =	-0-
	Sta-Elev =	Data
	Inv Elev (ft) =	1.00
	Slope (%) =	1.00
	n-value =	0.025
Calcs	Compute by =	Known Q
	Q (cfs) =	162.90

Depth (ft)	Q (cfs)	Area (sqft)	Veloc (ft/s)	Wp (ft)	Yc (ft)	TopWidth (ft)	Energy (ft)
0.87	162.9	40.33	4.04	71.31	0.85	71.01	1.12

Appendix C - Statistical Analysis

Appendix C-1 – ANOVA Results on Confinement Ratios.

Descriptives

VAR00002

					95% Confidence Interval for Mean		
	N	Mean	Std. Deviation	Std. Error	Lower Bound	Upper Bound	Minimum
1.00	5	7.6720	4.71064	2.10666	1.8230	13.5210	1.32
2.00	12	2.1100	1.71613	.49540	1.0196	3.2004	1.00
Total	17	3.7459	3.79425	.92024	1.7951	5.6967	1.00

Descriptives

VAR00002

	Maximum
1.00	13.46
2.00	6.59
Total	13.46

Test of Homogeneity of Variances

VAR00002

Levene Statistic	df1	df2	Sig.
8.463	1	15	.011

ANOVA

VAR00002

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	109.185	1	109.185	13.518	.002
Within Groups	121.156	15	8.077		
Total	230.342	16			

Appendix C-2 – ANOVA Results on Incision Ratios.

Descriptives

VAR00002

	N	Mean	Std. Deviation	Std. Error	95% Confidence Interval for Mean		Minimum
					Lower Bound	Upper Bound	
1.00	4	1.0125	.02500	.01250	.9727	1.0523	1.00
2.00	12	1.6708	.47659	.13758	1.3680	1.9736	1.00
Total	16	1.5063	.50336	.12584	1.2380	1.7745	1.00

Descriptives

VAR00002

	Maximum
1.00	1.05
2.00	2.41
Total	2.41

Test of Homogeneity of Variances

VAR00002

Levene Statistic	df1	df2	Sig.
11.147	1	14	.005

ANOVA

VAR00002

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	1.300	1	1.300	7.280	.017
Within Groups	2.500	14	.179		
Total	3.801	15			

Appendix C-3 – Chi-Square Results on Frequency of Headcuts in Disturbed Reaches versus Frequency of Headcuts in Natural Reaches.

Case Processing Summary

	Cases					
	Valid		Missing		Total	
	N	Percent	N	Percent	N	Percent
VAR00001 * VAR00002	23	100.0%	0	0.0%	23	100.0%

VAR00001 * VAR00002 Crosstabulation

			VAR00002				
			.00	1.00	2.00	3.00	4.00
VAR00001	1.00	Count	6	3	0	0	0
		Expected Count	2.7	3.9	1.2	.8	.4
	2.00	Count	1	7	3	2	1
		Expected Count	4.3	6.1	1.8	1.2	.6
Total		Count	7	10	3	2	1
		Expected Count	7.0	10.0	3.0	2.0	1.0

VAR00001 * VAR00002 Crosstabulation

			Total
VAR00001	1.00	Count	9
		Expected Count	9.0
	2.00	Count	14
		Expected Count	14.0
Total		Count	23
		Expected Count	23.0

Symmetric Measures

		Value	Approximate Significance
Nominal by Nominal	Contingency Coefficient	.561	.032
N of Valid Cases		23	

Appendix C-4 - Regression between Channel Depth and Percentage of Boulders.

Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.866[a]	.750	.733	4.92438

a. Predictors: (Constant), Depth

ANOVA[a]

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	1089.316	1	1089.316	44.921	.000[b]
	Residual	363.743	15	24.250		
	Total	1453.059	16			

a. Dependent Variable: Boulders

b. Predictors: (Constant), Depth

Coefficients[a]

		Unstandardized Coefficients		Standardized Coefficients		
Model		B	Std. Error	Beta	t	Sig.
1	(Constant)	-5.598	2.197		-2.548	.022
	Depth	18.880	2.817	.866	6.702	.000

a. Dependent Variable: Boulders

Appendix C-5 – ANOVA Results on Percent Length of Disconnected Floodplains.

Descriptives

VAR00002

					95% Confidence Interval for Mean		
	N	Mean	Std. Deviation	Std. Error	Lower Bound	Upper Bound	Minimum
1.00	5	.0000	.00000	.00000	.0000	.0000	.00
2.00	12	33.3333	26.81022	7.73944	16.2989	50.3677	.00
Total	17	23.5294	27.18942	6.59440	9.5499	37.5089	.00

Descriptives

VAR00002

	Maximum
1.00	.00
2.00	67.00
Total	67.00

Test of Homogeneity of Variances

VAR00002

Levene Statistic	df1	df2	Sig.
14.632	1	15	.002

ANOVA

VAR00002

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	3921.569	1	3921.569	7.440	.016
Within Groups	7906.667	15	527.111		
Total	11828.235	16			