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Dry Creek Greenway Trail Fluvial Audit

Prepared for:
City of Roseville
and Psomas

Prepared by:
cbec, inc.

December 2014
Project Number: 13-1041

DRY CREEK GREENWAY TRAIL FLUVIAL AUDIT
ROSEVILLE, CA

FINAL REPORT

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This report is intended solely for the use and benefit of the City of Roseville and Psomas. No other person or entity shall be entitled to rely on the details contained herein without the express written consent of cbec, inc., eco engineering, 2544 Industrial Blvd, West Sacramento, CA 95691.

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1 INTRODUCTION

1.1 PROJECT OVERVIEW

The City of Roseville is planning construction of a multi-use trail along approximately 4.5 miles of Dry, Cirby and Linda Creeks between Darling Way and Spahn Ranch Road. To assess potential risk to the trail due to the future trajectory of the creek, and to prioritize mitigative measures, cbec employed a processed-based geomorphic assessment (as per Beechie et al., 2010). This approach coupled desk-based analysis of historical aerials, LiDAR data and specific stream power with a field-based fluvial audit. The fluvial audit approach consists of characterizing various indicators of geomorphic process (e.g., channel reach type, bank erosion, depositional sedimentary bars) as well as factors influencing channel and floodplain morphology (e.g., bank protection, sediment input, large woody debris, etc). Feature locations were collected using Real Time Kinematic (RTK) Global Positioning System (GPS) and mapped with GIS software.

Field data and desk-based findings were used to characterize the channel's geomorphic regime and to develop a trail alignment risk assessment methodology with five risk classifications. An initial evaluation of risk was made on the basis of primary criteria (bank erosion and proximity of trail to the edge of the channel) which was then corroborated or modified through consideration of secondary criteria. Six trail locations with extreme or high risk were identified as well as 48 segments with moderate risk (a number which includes trail segments adjacent to higher risk areas as well as clusters of multiple areas exposed to moderate risk). To address the extreme or high levels of risk to the trail at these six sites, concept-level mitigative measures were developed and prioritized.

1.2 REPORT STRUCTURE

The report is generally divided in two sections. The first section covers both the desk-based watershed analysis and the field component of the fluvial audit. The second section details the trail erosion risk assessment and suggested measures for addressing proposed trail sections exposed to extreme, high and moderate risk. All figures are presented at the end of the report, which include site photos, maps depicting fluvial audit data and the trail risk assessment, and concept designs for select high-risk trail locations.

2 WATERSHED ANALYSIS

2.1 HISTORICAL CHANNEL ASSESSMENT

Aerial imagery dating from 1990 to 2013 was used to identify areas of significant historical channel migration and dynamic behavior. Aerials from 1990 were scanned by Roseville and georeferenced by cbec. Psomas provided aerials from 2001, 2003, 2005, 2007, 2011 and 2013 in the form of MrSID and TIF files that were already georeferenced. Given the relatively small size of the channel and presence of riparian canopy cover, discerning channel alignments was challenging or infeasible for a significant portion of the study reach. As a result of the segmented nature of this assessment, figures are not provided depicting historical channel alignments. However, the aerials did help inform historic channel behavior and the trail risk assessment in a number of locations. Notes regarding locations of historical dynamic behavior and their influence on risk assessment are included in Figures 14 through 19.

2.2 LIDAR ASSESSMENT

Inspection of LiDAR data provides a powerful tool for identifying historical channel alignments, side channels, floodplain extents and flood bypass channels that are not easily discernible in the field due to vegetation cover or the subtle relief of some features. LiDAR data provided by Psomas in the form of 2-foot contour lines was analyzed for the full length of the fluvial audit. Several observations were made using the LiDAR data that are of particular relevance to the trail:

1. Roughly 400 feet upstream of the confluence of Cirby and Dry Creeks is a high-flow side channel on the southern side of Cirby Creek's main channel (see Figure 1). At the downstream end of the side channel, the main channel has exhibited considerable dynamic behavior and bank retreat since 1990. This dynamic behavior and the presence of the side channel should be considered in assessing trail location and the design of a stream crossing and any associated bridge abutments.
2. In the open space south of Sierra Gardens Drive and Meadowlark Way, the relatively wide floodplain area shows evidence of numerous historical channel alignments (see Figure 2). While historical aerials do not indicate dramatic shifts in channel alignment since 1990, it is important to note that this section of Linda Creek and its floodplain have demonstrated significant dynamic behavior over longer historical time frames.
3. Between Rocky Ridge Drive and Champion Oaks Drive, a high-flow flood bypass channel is present in the Linda Creek floodplain (see Figure 3). This flood bypass channel interacts with the main channel in a number of locations and likely influences in-channel hydraulics and bank erosion. The proposed trail's proximity to the flood bypass channel may increase erosion risk to the path at several locations.

2.3 SPECIFIC STREAM POWER ANALYSIS

A specific stream power analysis was performed for the study reach along Dry, Cirby and Linda Creeks to quantitatively characterize the 'geomorphic energy regime' (i.e., the sediment transport capacity) of the system. Specific stream power was calculated using outputs from the HEC-RAS model developed by Psomas for the 2-year flood event[1]. Specific stream power[2] is defined as:

$$\omega = \frac{\rho g Q S}{w} \; (Watts/m^2)$$

Where:

ρ = density of water (kg/m^2)
g = gravity term (m/s^2)
Q = flow rate (m^3/s)
S = channel slope (m/m)
w = bankfull width (m)

[1] A 2-year flood event refers to a flood event that has a 50% probability of occurring during a given year.
[2] Specific stream power is typically presented in Watts/m^2. As such, calculations for this parameter are provided in metric units to facilitate meaningful comparison with relevant literature.

In the case of the specific stream power calculation for the 2-year event, the width term was the wetted width at each cross section resulting from the 2-year discharge. Similarly, the slope term was the energy grade slope computed at each cross section for the 2-year event. Specific stream power was calculated at each HEC-RAS cross section, then linearly interpolated between cross sections for display in Figures 4 and 5. Given that the stream power calculations were performed at the scale of the HEC-RAS cross section spacing, the stream power results are only meaningful at a scale larger than that spacing. In other words, stream power calculations should probably only be applied for comparison between reaches at a scale 10 times the channel width or greater as the stream power calculation does not reflect in-channel conditions at a finer resolution.

Specific stream power values for Dry, Cirby and Linda Creeks ranged from 0.17 to 87.0 Watts/m^2. Compared to the spectrum of stream power values present in the landscape, these values fall on the low end of the spectrum, thus indicating that the stream is a fairly low energy system. As a comparative example, stream power in mountain channels often exceeds 1,000 W/m^2 (Nanson and Croke,1992). Despite this, the variability in stream power offers a useful indicator of the relative differences in sediment transport capacity on a reach by reach basis. The stream power calculations informed the assessment of the channel's capacity for dynamic behavior and the degree of risk to the proposed trail.

2.4 FIELD BASED ASSESSMENTS

The field component of the fluvial audit was conducted in 2013 between October 23rd to 25th. The creeks were surveyed beginning with Dry Creek at the Darling Way bridge, heading downstream to the confluence with Cirby Creek, and then upstream along Cirby and Linda Creeks to Spahn Ranch Rd. The field assessment consisted of characterizing relevant features with written observations, photos and Real Time Kinematic (RTK) Global Positioning System (GPS) spatial location. RTK GPS was used in conjunction with California Survey and Drafting Supply (CSDS) VSN mobile base network to provide positional corrections to the Trimble R8 GNSS Receiver. The various features collected during the field survey were then mapped using ESRI's ArcMap GIS software platform. Relevant feature mapping is provided in six sheets (Figures 14 through 19). These maps also include the proposed trail alignment as well as the trail risk assessment which are described in detail in section 3.

The following is a summary of the various features of interest and how they were characterized as part of the field component of the fluvial audit:

2.4.1 Bank Erosion

Erosion severity was classified as high, moderate-high, moderate or minor. GPS positions were taken at the upstream and downstream extents to provide an estimate of length and approximate height of erosion was noted. Sections of historic or recovering bank erosion were also observed and typically classified as minor. Bank erosion was present throughout much of Dry, Cirby and Linda Creeks, with locations and severity indicated in feature mapping (see Figures 14 through 19). Figures 20 through 26 provide photographs of sites experiencing significant erosion that may affect the proposed trail. These areas are discussed in more detail later in the report.

2.4.2 Bank Protection

Observed bank protection along Dry, Cirby and Linda Creeks consisted of both hard and soft engineering measures. In this study, hard engineering refers to the use of concrete or rock protection along channel banks and this type of protection was further categorized into classes of large scale and small scale. Large scale hard engineering (HE-LS) referred to actions armoring a significant portion of the bank such as boulder rip-rap, concrete walls, and concrete lock-block. Small scale hard engineering (HE-SS) included features such as a line of small boulders at the edge of baseflow wetted channel or old concrete blocks covering only a small portion of the bank (see Figures 6 and 7 for examples). The soft engineering (SE) observed included more natural bank protection measures such as the installation of geotextile fabric, willow spiling and vegetation planting on channel banks (see Figure 8 for examples).

2.4.3 Depositional Sedimentary Features

Sediment is stored within a stream channel in depositional bar features (e.g., point bars, lateral bars[3]) as well as along the channel bed. Along the reaches of interest of Dry, Cirby and Linda Creeks, the majority of sediment storage features were lateral bars. There were also numerous instances of considerable in-channel sand storage on the stream bed, which typically occurred upstream of an artificial base level control such as a cobble weir. In addition to annotating the feature type, the sediment material (i.e. sand or gravel) and the vegetation cover, if present, were recorded. Most of the bar features observed were bare or had small amounts of young riparian vegetation, suggesting they had been recently activated during storm events (see Figure 9 for examples). However, several large bar features with mature vegetation were observed, suggesting that they had not been altered significantly in recent years. Depositional bars are classified in the report maps as either (1) bare/vegetated or (2) mature to distinguish more recently activated features from older or less regularly activated features.

2.4.4 Dominant Bed Material

During the fluvial audit, the dominant bed material was identified based on the grain size of the stream bed's sediment. The study reaches of Dry, Cirby and Linda Creeks were predominantly sand-bed channels. There were also numerous instances of "bedrock" exposure, where hydromodification of contributing watersheds had likely resulted in channel incision to the cohesive hard-pan layer (Mehrten formation) present in much of the lowland eastern slope of the Sacramento Valley region. Additionally, there were short sections of gravel beds typically associated with natural and artificial riffle features as well as what appeared to be intentionally constructed cobble, boulder and concrete sections of the channel bed. Most of these engineered sections of the channel bed were associated with bridges, pipe crossings and other grade control structures (also referred to in this study as a type of hydraulic control).

2.4.5 Reach Type Characterization

This qualitative classification is based largely on bedforms and the stream gradient or slope. The reach type was typically characterized over a section of channel at least several (if not 10 or more) channel widths in length, rather than at a specific point or individual morphological unit. The majority of Dry,

[3] Point bars and lateral bars are depositional sedimentary features typically composed of well-sorted alluvium. Point bars occur on the inside bend of a river while lateral bars typically form along the margin of relatively straight sections of channel. More detailed descriptions of these features can be found in most fluvial geomorphology text books or via an internet search.

Cirby and Linda Creeks was categorized by a slow glide (SG)[4] morphology. There were also sections of pool-riffle (P-R)[5] morphology, as well as reaches with a morphologic classification between these two channel gradients (e.g., SG/P-R). Reach types are mapped in Figures 14 through 19.

2.4.6 Hydraulic Control Points

Hydraulic control points refer to both natural features (e.g., bedrock outcrops) and manmade structures along the channel bed that control stream gradient (i.e. grade control structures). Along the study reaches of Dry, Cirby and Linda Creeks were numerous instances of natural and artificial hydraulic control points. The natural hydraulic controls consisted of "bedrock" or cohesive hard-pan. The artificial hydraulic control points consisted largely of weir structures (poured concrete, cobble, and concrete rubble) as well as several pipe crossings. A number of these weir structures appeared fairly old and may no longer be serving a necessary function (see Figures 10 and 11 for examples). The artificial grade control structures often exhibited a significant longitudinal impact on in-channel conditions, causing lengthy stretches of backwater effects which in turn influenced reach type characterization along much of the stream length. These backwater impacts were strongly apparent during base flow conditions. At higher flows, many of the grade control structures may have a significant effect on upstream water surface slope but additional quantitative assessment or hydraulic modeling would be necessary to characterize these impacts over the range of flows experienced in the system.

2.4.7 Large Woody Debris

Instances of large woody debris along Dry, Cirby and Linda Creeks were very liminted, suggesting regular maintenance activities to remove large wood from the channel. Where present, the location, general size, orientation and extent to which the feature spanned the channel were recorded as these factors determine the impact of large wood on fluvial processes.

2.4.8 In-Channel Vegetation

Sections of the channel bed exhibiting extensive macrophyte cover (i.e. emergent, submergent or floating aquatic plants growing in the channel) were recorded. There were also numerous instances of dense macrophyte cover coupled with significant in-channel sand deposition across the stream bed.

2.4.9 Stormwater Outfalls

The location, general size, associated bank armoring and severity of erosion were recorded for stormwater outfalls present along the study reaches. There were numerous stormwater outfalls observed along the study reach. Most appeared to be in fairly stable condition while a small handfull were likely eroding significant amounts of sediment during large storm events (see Figure 12 for examples).

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[4] A slow glide (SG) channel morphology is characterized by low velocity, low slope and a relatively homogenous bed morphology. Reaches exhibiting this morphology typically have low sediment transport capacity and low sediment supply.

[5] Pool-riffle (P-R) channel types are characterized by alternating sequences of pools (regions of relatively deep and slow flow with a low water surface slope) and riffles (features with relatively fast and shallow flow over a high water surface slope and coarse bed).

2.4.10 Tributary Confluences

The location of tributary confluences were noted along with their relative contribution to in-channel sediment supply. Depositional sedimentary bars located at and downstream of tributary confluences suggest that, at least in recent years, the tributaries along Cirby and Linda Creeks do not supply large volumes of sediment.

2.5 GENERAL FINDINGS REGARDING STREAM CHARACTER

The sections of Dry, Cirby and Linda Creeks surveyed as part of the fluvial audit are located in riparian corridors of varying width, typically bordered by residential, light commercial or open space land uses. Much of the reach length is fairly incised, and in many areas the channel has scoured down to the cohesive "hard-pan" or "clay-pan" (Mehrten formation) typical of the area. Fluvial processes are frequently constrained both vertically and laterally by the presence of artificial grade control structures and bank protection measures. The lower (downstream) reaches are dominated by a slow glide morphology that appears to result largely from the backwater conditions generated by grade control structures. A greater diversity in reach types exists further upstream along Linda Creek where the channel varies between a slow slide and pool-riffle morphology.

It appears that large woody material is actively removed as part of channel management as only a small number of logs were present in the channel and influencing morphology. Some lower-energy reaches exhibit dense macrophyte growth and significant sand accumulation along the bed. Tributaries appear to contribute only small to moderate amounts of sediment while several eroding stormwater outfalls appear to provide local sources of sands and smaller-grained material. Overall, the channel appears to be fairly stable and significant geomorphic change seems to be limited to fairly large flood events (we suspect events in the 5 to 10 year range, but this may vary along the channel length). However, a more detailed quantitative study and hydraulic modeling would be necessary to confirm this initial assessment of stability and the size of flood events driving significant geomorphic alterations.

3 TRAIL EROSION RISK ASSESSMENT

3.1 CRITERIA FOR ASSESSING RELATIVE RISK

A large number of criteria were integrated into the assessment of relative erosion risk to the proposed trail. These criteria were divided into two general categories (primary and secondary) based on their relative weighting or influence on the assessment. The following sections describe the primary and secondary criteria, and their utility in the risk assessment.

3.1.1 Primary Criteria

3.1.1.1 Trail proximity to edge of channel (top of bank)

The approximate location of the channel's top of bank was digitized in ArcGIS using the LiDAR-derived 2-ft contour data provided by Psomas. It is important to note that locating the top-of-bank is a subjective interpretation, and the coarseness of the contour intervals and the potential for erroneous vegetation returns (rather than true ground surface returns) in the LiDAR data may have contributed error to this exercise.

The proximity of the proposed trail to the channel's adjacent top of bank was divided into 4 categories based on distance: (1) less than 10 feet, (2) between 10 and 30 feet, (3) between 30 and 60 feet, and (4) greater than 60 feet. The specific values of 10, 30 and 60 feet are somewhat arbitrary but provide a useful framework for assessing trail proximity to the channel. Using ArcGIS, the approximate top of bank line was offset by these distances of 10, 30 and 60 feet and the proposed trail bracketed into distance classes based on the location of edge of pavement relative to these offset lines.

3.1.1.2 Presence and severity of erosion on adjacent stream bank

The presence and severity of erosion on the stream bank adjacent to the trail provided a strong indicator of the channel's potential for dynamic behavior and the likelihood of channel migration toward the trail during flood events. It is important to note that areas of historic/recovering bank erosion (which were typically classified with minor erosion severity) have the capacity to be reactivated in larger flood events (i.e. 5-yr return interval[6] or greater, though modeling would be required to more accurately assess activation thresholds) and can be the locations of considerable bank retreat. While there is a significant difference between the erosion severity classifications of minor and high, the presence of any bank erosion was considered significant as indicated by the weighting factors applied in Tables 1 and 2 (discussed in section 3.2).

3.1.2 Secondary Criteria

3.1.2.1 Nearby channel pattern/curvature

The existing curvature of the stream provided an additional indicator of the channel's potential future trajectory. Of particular relevance was whether the proposed trail was located on the outside of a meander bend.

3.1.2.2 Presence of existing bank protection measures

While bank protection is sometimes implemented as a preventative measure near key infrastructure (e.g., bridges, utility pipe crossings, stormwater culverts), it is typically located in areas historically facing bank erosion problems and is therefore indicative of sections of channel with higher potential of exhibiting dynamic behavior. Bank protection measures may also deflect bank erosion to unprotected sections of the channel bank at its upstream or downstream ends, or, in some instances, to the opposite bank .

3.1.2.3 Specific stream power

Specific stream power provided an indication of how the channel's sediment transport capacity varied from reach to reach. As a secondary criteria, stream power provided a helpful tool to qualify or modify assessments of channel dynamism and potential risk to the trail.

[6] The 5-year flood event is a flood event that has a 20% probability of occurring in a giver year

3.1.2.4 Historical channel adjustments

Specific reaches or meander bends experiencing significant channel adjustment over the last 25 years (as demonstrated in historical aerials), were considered in evaluating channel trajectory and trail risk.

3.1.2.5 Presence of historical and high-flow channel alignments

Inspection of LiDAR data revealed historical alignments, historically dynamic floodplain areas and existing high-flow channels. The location and alignment of these features informed increases in risk assessments as described in notes present in Figures 14 through 19.

3.1.2.6 Proximity to flood bypass channels

The proximity of the proposed trail to the flood bypass channel (or excavated terrace), particularly between Rocky Ridge Dr and Old Auburn Rd, poses an increased erosion risk to the trail in several locations as demonstrated in Figures 3 and 18.

3.1.2.7 Dominant bed material

The stream bed material provides an indicator of potential for channel bed erosion. The presence of sand-dominated beds in some areas provided an understanding of a reach's susceptibility to geomorphic change in the absence of grade controls and bank protection.

3.1.2.8 Presence and maturity of depositional sedimentary features

The density, maturity and size of depositional bar features informed an understanding of channel dynamism on a reach by reach scale. Furthermore, historical aerials provided a sense of changes to sedimentary bars over time and insights into geomorphic dynamism.

3.1.2.9 Reach type

Reach type classifications provided an indication of channel gradient, stream energy and the longitudinal influence of grade control structures.

3.1.2.10 Grade control structures

The presence of artificial hydraulic controls (e.g., concrete weirs, cobble weirs) strongly influences local stream gradient, hydraulics and the dissipation of stream energy. The numerous grade control structures along Dry, Cirby and Linda Creeks influence their potential for dynamic channel behavior, particularly in areas immediately upstream of the structure. However, a more detailed assessment or modeling effort would be required to determine the specific impacts of these structures on channel dynamism.

3.1.2.11 Tributaries

Tributaries supply additional flows and sediment to the main channel and can shift the channel's geomorphic equilibrium. While the tributaries along Cirby and Linda Creeks appear to supply relatively minor amounts of sediment, changes in their contributing watersheds, riparian corridor or channel sediment dynamics could alter this supply and consequently change the channel dynamics of Dry, Cirby and Linda Creeks near tributary confluences.

3.1.2.12 Stormwater outfalls

The location of stormwater outfalls experiencing significant erosion provided a sense of potential influence on local sediment supply and greater likelihood for geomorphic shifts.

3.1.2.13 Large woody debris

The location and orientation of the few large woody debris members present along the study reach were considered in assessing potential geomorphic trajectory of the channel in which they were located.

3.1.2.14 In-channel vegetation

The location of dense macrophyte growth were used as indicators of low-energy reaches and the channel's capacity to accumulate or trap sediment along the bed.

3.2 ASSIGNMENT OF RELATIVE RISK

Trail erosion risk was initially assessed using the two primary criteria: proximity to top of bank and bank erosion severity. Weighting factors were assigned to the various levels of erosion severity and trail distances from the top of bank. These factors were then combined in a matrix (see Table 1) to provide an initial predictive score of erosion risk. It is important to note that the assignment of the weighting factors was a subjective process and that the risk scores generated were intended to guide a general comparison of relative risk. Potential risk was categorized into five levels (extreme, high, moderate, minor and negligible) and each combination of erosion level and channel proximity was assigned a risk category based on the scores (see Table 2).

Table 1. Initial trail risk assessment matrix with scoring

Proximity to Stream								
	Very Close	< 10 ft	10	25	60	75	90	100
	Nearby	10 to 30 ft	7	17.5	42	52.5	63	70
	Distant	30 to 60 ft	3	7.5	18	22.5	27	30
	Very Distant	> 60 ft	1	2.5	6	7.5	9	10
		Weighting factor		2.5	6	7.5	9	10
				Negligible	**Minor**	**Moderate**	**Mod-High**	**High**
				Erosion Level				

Table 2. Initial trail risk assessment matrix with risk categorization

Proximity to Stream								
	Very Close	< 10 ft	10	Moderate	Moderate	High	Extreme	Extreme
	Nearby	10 to 30 ft	7	Minor	Moderate	Moderate	High	High
	Distant	30 to 60 ft	3	Negligible	Minor	Minor	Moderate	Moderate
	Very Distant	> 60 ft	1	Negligible	Negligible	Negligible	Minor	Minor
		Weighting factor		2.5	6	7.5	9	10
				Negligible	**Minor**	**Moderate**	**Mod-High**	**High**
				Erosion Level				

The initial risk assessment generated by the primary criteria matrix was then corroborated or modified through a reach-by-reach analysis incorporating the full suite of secondary criteria. Evaluation of the secondary criteria resulted in an increased risk assessment for a number of sections of the trail. These risk modifications are typically annotated in the Figures 14 through 19. Example situations for increases in risk assessment include high levels of historical channel adjustment, potential trail interaction with a high-flow side channel and trail location on the outside of an eroding meander bend. Furthermore, if the risk assessment for a given section of trail bordered two risk levels, the higher risk level was typically assigned.

This five-level risk assessment was applied to the entire greenway trail as shown in Figures 14 through 19. In the case of proposed pedestrian bridges, the risk assessment was typically dropped to minor (despite the relative proximity to the channel) unless there was evidence of nearby bank erosion or other indicators of higher potential for dynamic behavior. This assessment of minor risk has been made because proposed bridges and supporting abutments will be designed and constructed with scour protection meeting the 200-year flood standard.

3.3 TRAIL SECTIONS REQUIRING ACTION

There are six segments of the proposed greenway trail assessed with extreme or high erosion risk. These sites are named DRY-H1, CIRBY-H1, LINDA-H1, LINDA-H2, LINDA-H3 AND LINDA-H4 and are labeled as such in Figures 14 through 19 as well as Figures 27 through 33. While a quantitative assessment of bank retreat rates was not performed as part of this fluvial audit, the stream appears to be on a trajectory that may affect or undermine the integrity of the trail at these six sites. As indicated in Table 3, some combination of trail realignment, bank protection measures and channel modification are strongly advised for these sections of trail. Notes about the risk assessment and prioritized mitigative measures for these six locations are summarized in the subsequent sections.

Table 3. Risk levels and corresponding actions

Risk Levels	Suggested Action
Extreme	Trail realignment, bank protection and/or channel modification strongly advised
High	Trail realignment, bank protection and/or channel modification advised
Moderate	Trail realignment and/or bank protection measures encouraged
Minor	No actions suggested
Negligible	No actions suggested

It is important to note that the options specifying channel modification will require quantitative analysis (and potentially hydraulic modeling) to determine appropriate designs and to assess impacts on in-channel hydraulics and bed shear stresses. Additionally, any actions armoring a bank may change reach hydraulics and affect the erosive forces acting upstream or downstream, or on the opposite bank. The impacts and risks associated with proposed bridges and trail approaches to bridge crossings would be better assessed with more detailed quantitative analysis and two dimensional hydraulic modeling, especially given the increased complexity of flows and the significant infrastructure investments.

3.3.1 DRY-H1

This section of trail along the left-bank of Dry Creek downstream of the Darling Way bridge runs parallel to a section of moderate severity bank erosion (see Figure 20 and 27). The proposed trail is less than 10 feet from the approximate location of the top of the eroding bank. The sections of trail immediately upstream and downstream of this area were assessed with moderate risk, despite their not being adjacent to an eroding bank. However, their proximity to the channel, the nearby bank erosion and the bank protection measures in the reach that were already implemented along the opposite bank informed a moderate risk assessment. Given the relatively narrow space available between the top of bank and the private property fence line, the following actions are suggested in order of priority:

1. Eliminate the proposed trail on the eastern side of Dry Creek from the plans and construct only the proposed trail alignment on the western side of the channel.
2. If the eastern trail is to be constructed:
    a. Move the path alignment as close to the fence line (i.e. as far east) as possible.
    b. Implement bank protection measures to address existing bank protection along the high-risk section and potentially along parts or all of the moderate risk sections immediately upstream and downstream of the high risk segment.

3.3.2 CIRBY-H1

The proposed trail between I-80 and the confluence of Dry and Cirby Creeks has a segment of extreme and high erosion risk near Cirby Hills Drive and Machado Lane (see Figures 22 and 28). This section of trail along the southern side of the channel is the most concerning section of the proposed path along the entire length of the fluvial audit. The ongoing severe erosion and the limited space between the top of bank and the toe of the hill slope will likely jeopardize the integrity of the trail. The following actions are suggested in order of priority:

1. Bypass this section of the corridor altogether by connecting the trail with an existing path or sidewalk in the neighborhood to avoid constructing the trail in a highly risk-prone area. However, we understand this would not be consistent with the overall goal of the multi-use trail project to create a separate off-street Class 1 trail.
2. Realign the trail along the northern bank as indicated in Figure 28 to avoid locating the trail along the problematic southern bank although this would require construction of two additional bridge structures with associated visual impacts.
3. If the trail is to be constructed as proposed, implement a suite of measures as indicated in Figure 29:
    a. Construct a log crib wall (or similar structural measures) along the southern bank and locate the trail on top of the wall. The crib wall could be outfitted with root wads that would further protect the bank from erosion while also generating a habitat feature.
    b. Terrace the opposite floodplain to generate additional flow area and dissipate erosive energy directed at the outside bank during bankfull and larger flood events. A small backwater channel could be created near the toe of the new bank to further increase flow area and to provide a habitat feature.

c. Depending on the wall orientation and size, additional bank protection measures further upstream and downstream may be advisable.

3.3.3 LINDA-H1

LINDA-H1 is the furthest downstream segment of trail along Linda Creek with a high risk classification. The trail is located adjacent to a lengthy section of bank erosion (see Figures 23 and 30) and is positioned on the outside of a relatively large radius meander bend. The extent of bank erosion may be enhanced somewhat by a pipe crossing the channel with an angled alignment rather than one that is perpendicular to flow. The angled alignment may be directing erosive energy towards this outside bank, contributing to bank erosion at the site. Given the close proximity of the proposed trail alignment to the top of bank, the following actions are suggested in order of priority:

1. Adjust the trail alignment east to increase distance from top of bank to edge of path. It is understood, though, that an existing large sewer trunk main runs roughly parallel to the creek at this location. Moving the trail would reduce potential for erosion to the trail, however the risk to the sewer line from creek bank erosion will remain without other measures being implemented. In addition, moving the trail to the west would increase the right-of-way acquisition required of adjacent private property owners.
2. Consider a slightly narrower path width in the sections with high and moderate trail risk.
3. Implement bank protection measures along the eastern bank where there is ongoing erosion.
4. Construct a log or rock vane just downstream of the existing pipe crossing that extends from the eastern bank to a point partly or fully across the channel (as indicated by the yellow line in Figure 30). The vane may help direct erosive energy away from the outside bank to the center of the channel. More in-depth site analysis would be required to identify the ideal location and configuration of a vane structure. A curved cross vane alignment may also be appropriate.

NOTE: If a decision is made to install bank protection measures on the eastern bank and/or a vane in the channel, hydraulic modeling would be advisable to determine the effects on the opposite bank.

3.3.4 LINDA-H2

The high risk at LINDA-H2 was assessed due to the proposed trail's proximity to the outside of an actively eroding meander bend (see Figures 24 and 31). Suggested actions include slight trail adjustment, bank protection and/or channel reconfiguration. Setting the trail back may not adequately reduce risk on its own given the limited space available between the top of bank and the eastern flood wall. Suggested measures include:

1. To the extent possible, set the trail alignment further back from the channel in the direction of the floodwall.
2. Address bank erosion through one of the following sets of actions:
    a. Applying standard bank protection measures along the outside, eroding bank to protect against further erosion.
    b. Applying the suite of options indicated in Figure 32:

i. Lay back both existing banks and create an inset floodplain terrace on the inside of the bend, thereby increasing flow area and reducing erosive energy.
ii. Outfit the new toe of the bank with root wads or stone protection and willow staking to protect against future erosion.
iii. Plant the banks with native grasses (or fabric hydroseed).

NOTE: These options will require additional analysis during final engineering with consideration of available space between creek bank and floodwall, and presence of an existing sewer line. Additionally, the bank lay-back option may not be feasible due to existing storm drain infrastructure.

3.3.5 LINDA-H3

LINDA-H3 was given a high risk assessment due to the trail's proximity to the top of bank and ongoing severe erosion (see Figures 25 and 31). The suggested actions are the same as those specified in LINDA-H2 but the bank protection and channel modification measures would need to be somewhat tailored to the site-specific conditions at LINDA-H3.

3.3.6 LINDA-H4

LINDA-H4 is located on a fairly dynamic section of channel adjacent to an actively eroding bank (see Figures 26 and 33). Further upstream the channel has numerous active bar features as well as several larger bar features that appear to not have been activated since the last large flood event (i.e. likely older than 5 years). There is also a fairly significant application of bank protection further upstream. Given the dynamic nature of this reach and the presence of undeveloped property near the channel, a trail setback could be an appropriate measure to reduce risk to the trail. However, we understand trail realignment may be restricted by residential home development planned for the property. If a trail setback of 30 feet or more is not feasible, we suggest a combination of the following measures:

1. To the extent possible, adjust the trail alignment to the east to increase the distance between the edge of trail and the top of bank.
2. Apply bank protection measures to the eastern bank along the high-risk section of trail, and potentially along the moderate-risk sections upstream and downstream.

NOTE: Following field reviews, the trail alignment at LINDA-H4 has been revised to provide additional buffer space between the creek and trail.

3.3.7 Moderate Risk Sections

In addition to the 6 extreme and high risk sections of trail, 48 segments of trail were assigned moderate risk. These 48 locations included trail segments adjacent to higher risk sites as well as clusters of moderate risk segments which were given a single label (see LINDA-M3 in Figure 16 for an example). In locations where the risk assignment was increased from minor to moderate due to consideration of the secondary criteria listed in section 3.1.2, notes are provided in Figures 14 through 19 regarding the rationale. Where space is available, additional setbacks from the top of the bank may be advisable for moderate risk trail segments. Where setbacks are infeasible and ongoing erosion is present, bank protection measures may be advisable if a reduction in trail risk is desired. Some moderate risks are assigned to creek crossings or trail segments located under bridges where the higher risk is due in part to the trail's forced proximity to the channel. In these cases, appropriate bank and trail protection measures should be installed and adequate bridge abutments and foundation armoring should be constructed. Trail sections assigned moderate risk that are not adjusted or protected should be monitored routinely such that potential erosion problems can be identified and remedied before affecting the trail's integrity.

4 CONCLUSIONS

The application of cbec's fluvial audit methodology provided a process-based understanding of Dry, Cirby and Linda Creeks' current geomorphic regime and the future trajectory of their channels. A desk-based analysis of historical channel alignments, LiDAR-derived topographic contours and specific stream power was combined with a field-based geomorphic assessment. Potential risk to the proposed trail alignment was initially evaluated on the basis of two primary criteria: bank erosion severity and trail proximity to the top of the bank. Secondary criteria were used to corroborate or modify risk assessment based on their indication of the channel's capacity for dynamic behavior. Along the approximate 4.5 mile length of the proposed greenway trail, six areas of concern with extreme or high trail risk were identified. Specific mitigative measures were prioritized to address these extreme and high levels of risk. Several dozen moderate risk areas were also identified and general suggestions provided to address them. It is important to note that the mitigative actions presented represent preliminary suggestions and that more quantitative analysis (and potentially hydraulic modeling) are advisable to appropriately size, locate and design these measures.

5 REFERENCES

Beechie, T.J.; Sear, D.A.; Olden, J.D.; Pess, G.R.; Buffington, J.M.; Moir, H.J.; Roni, P.; Pollock, M.M. 2010. Process-based principles for restoring river ecosystems. BioScience 60, 209-222.

Nanson, G.C and Croke, J.C. (1992). "A genetic classification of floodplains." *Geomorphology*, 4 (6), 459-486.

6 LIST OF PREPARERS

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7 ACKNOWLEDGMENTS

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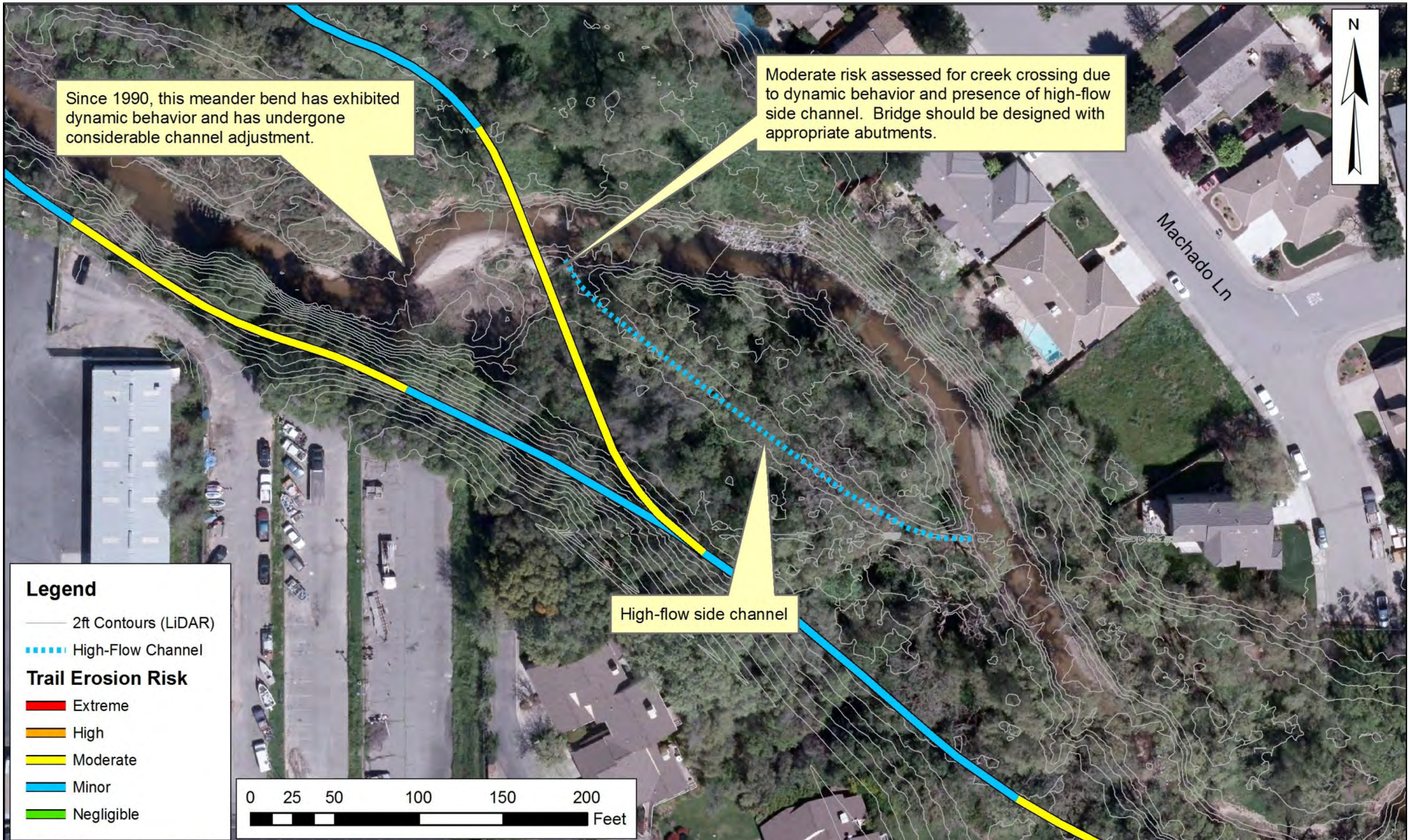


Notes: Trail width not to scale

Dry Creek Greenway Trail Fluvial Audit

LiDAR Assessment - Cirby Creek

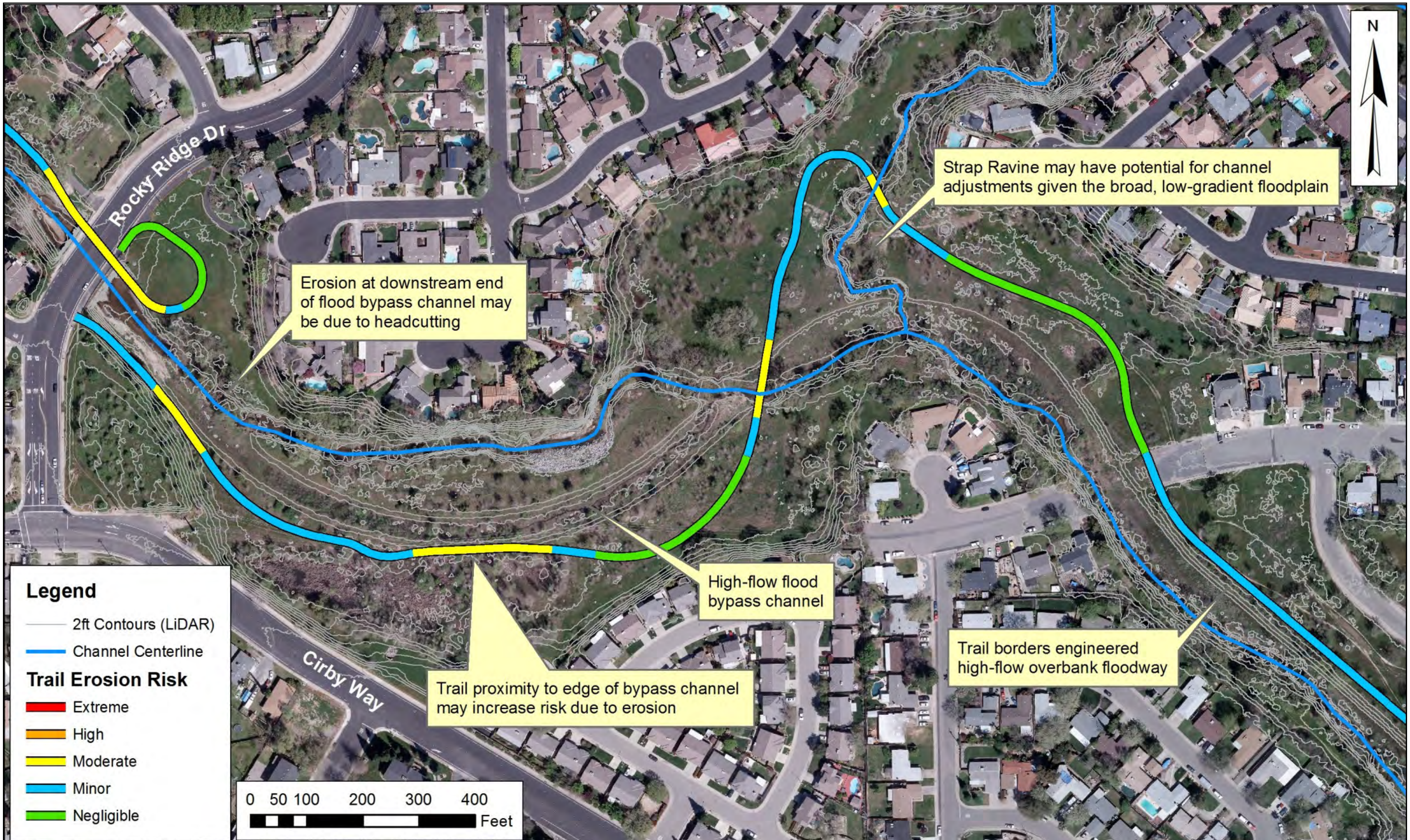
Project No. 13-1041	Created By: JDS	**Figure 1**

Notes: Trail width not to scale

Dry Creek Greenway Trail Fluvial Audit

LiDAR Assessment - Linda Creek 1

Project No. 13-1041	Created By: JDS	**Figure 2**

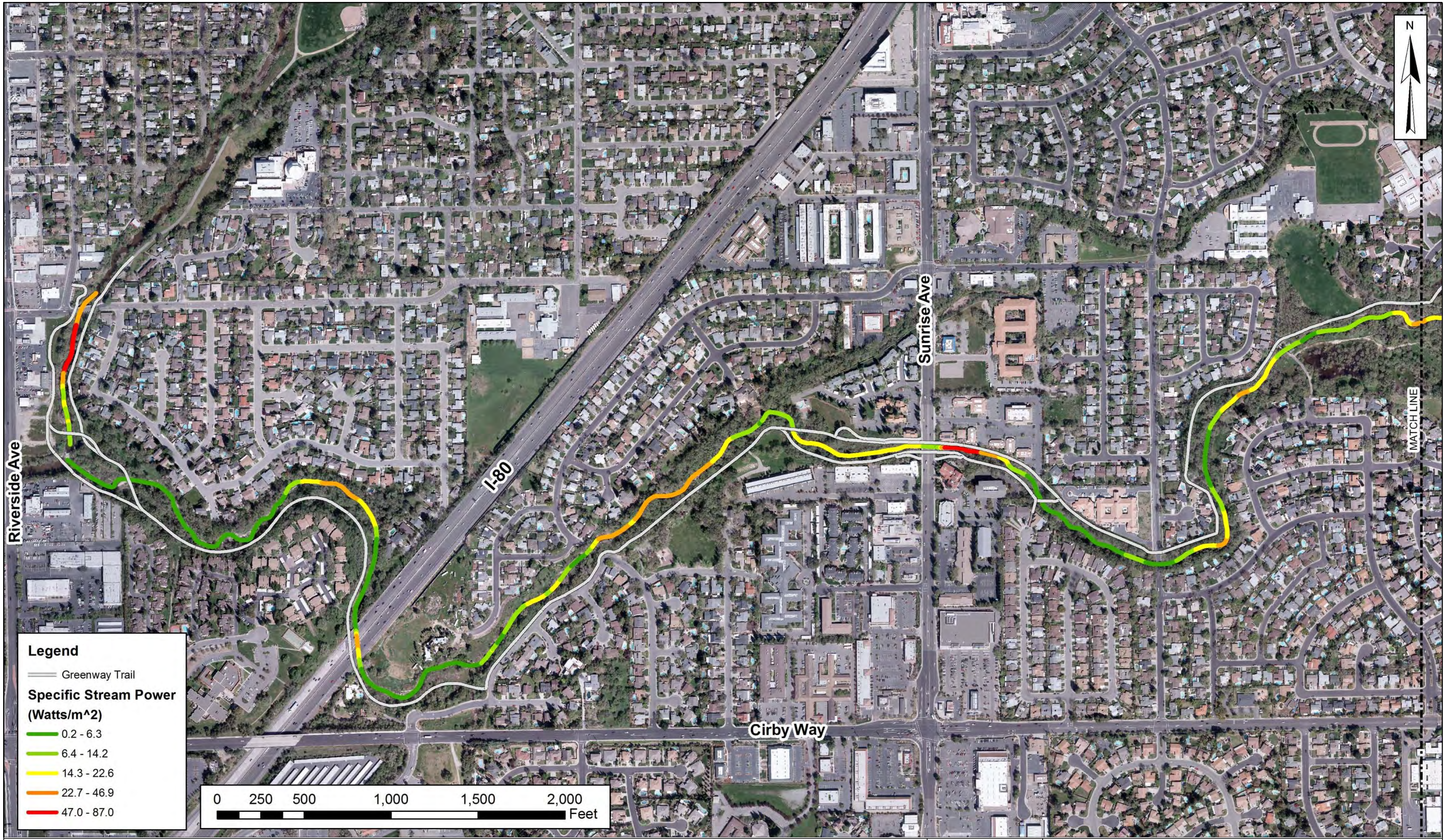


Notes: Trail width not to scale

Dry Creek Greenway Trail Fluvial Audit

LiDAR Assessment - Linda Creek 2

Project No. 13-1041	Created By: JDS	**Figure 3**



Notes: Trail width not to scale. The range of specific stream power values present in Dry, Cirby and Linda Creeks are on the lower end of the spectrum of values found in the overall landscape. For comparison, specific stream power can exceed values of 1,000 W/m^2 in mountain channels (Nanson and Croke, 1992).

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Dry Creek Greenway Trail Fluvial Audit

Specific Stream Power - Sheet 1

Project No. 13-1041 | Created By: JDS | **Figure 4**

Notes: Trail width not to scale. The range of specific stream power values present in Dry, Cirby and Linda Creeks are on the lower end of the spectrum of values found in the overall landscape. For comparison, specific stream power can exceed values of 1,000 W/m^2 in mountain channels (Nanson and Croke, 1992).

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Dry Creek Greenway Trail Fluvial Audit

Specific Stream Power - Sheet 2

Project No. 13-1041 | Created By: JDS | **Figure 5**

6A	
6B	

Notes	cbec eco engineering	*Dry Creek Greenway Trail Fluvial Audit* **Bank Protection: Hard Engineering - Large Scale**		
		Project No. 13-1041	Created By: JDS	**Figure 6**

7A

7B

Notes		*Dry Creek Greenway Trail Fluvial Audit*		
		Bank Protection: Hard Engineering - Small Scale		
		Project No. 13-1041	Created By: JDS	**Figure 7**

8A	
8B	

Notes		*Dry Creek Greenway Trail Fluvial Audit* **Bank Protection: Soft Engineering**		
	cbec eco engineering	Project No. 13-1041	Created By: JDS	**Figure 8**

9A

9B

Notes: Un-vegetated bar (top) suggests recent deposition; lightly vegetated bar (bottom)	cbec eco engineering	*Dry Creek Greenway Trail Fluvial Audit* **Depositional Sedimentary Bar Features**		
		Project No. 13-1041	Created By: JDS	**Figure 9**

10A	
10B	

Notes: Concrete-encased sewer line functions as a weir on Dry Creek at confluence with Cirby (top); I-80 culvert on Cirby Creek (bottom)	cbec eco engineering	*Dry Creek Greenway Trail Fluvial Audit* **Grade Control Structures - Updated**		
		Project No. 13-1041	Created By: JDS	**Figure 10**

11A

11B

Notes: Cobble weir on Linda (top); concrete weir (potential sewer line crossing) south of Sierra Gardens Dr (bottom)	cbec eco engineering	*Dry Creek Greenway Trail Fluvial Audit* **Grade Control Structures - Outdated**		
		Project No. 13-1041	Created By: JDS	**Figure 11**

12A	
12B	

Notes:	cbec eco engineering	*Dry Creek Greenway Trail Fluvial Audit* **Stormwater Outfalls Eroding Sediment**		
		Project No. 13-1041	Created By: JDS	**Figure 12**

Notes:

Dry Creek Greenway Trail Fluvial Audit

Fluvial Audit Data & Risk Assessment - Sheet Index

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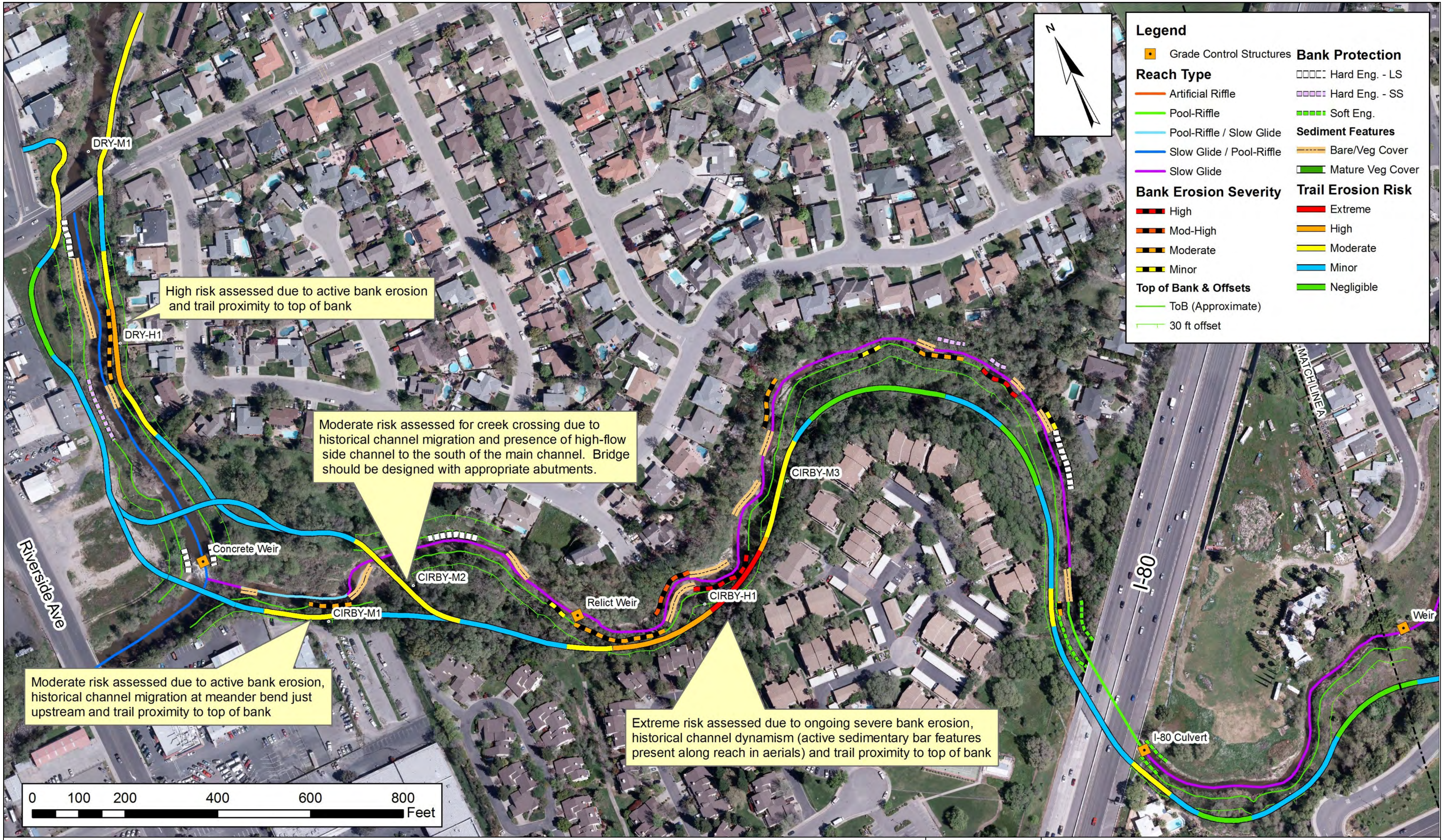
Project No. 13-1041 | Created By: JDS | **Figure 13**



Notes: Trail width not to scale. Relict weir refers to an old grade control structure.

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Dry Creek Greenway Trail Fluvial Audit

Fluvial Audit Data and Risk Assessment - Sheet 1

Project No. 13-1041 | Created By: JDS | **Figure 14**

Notes: Trail width not to scale

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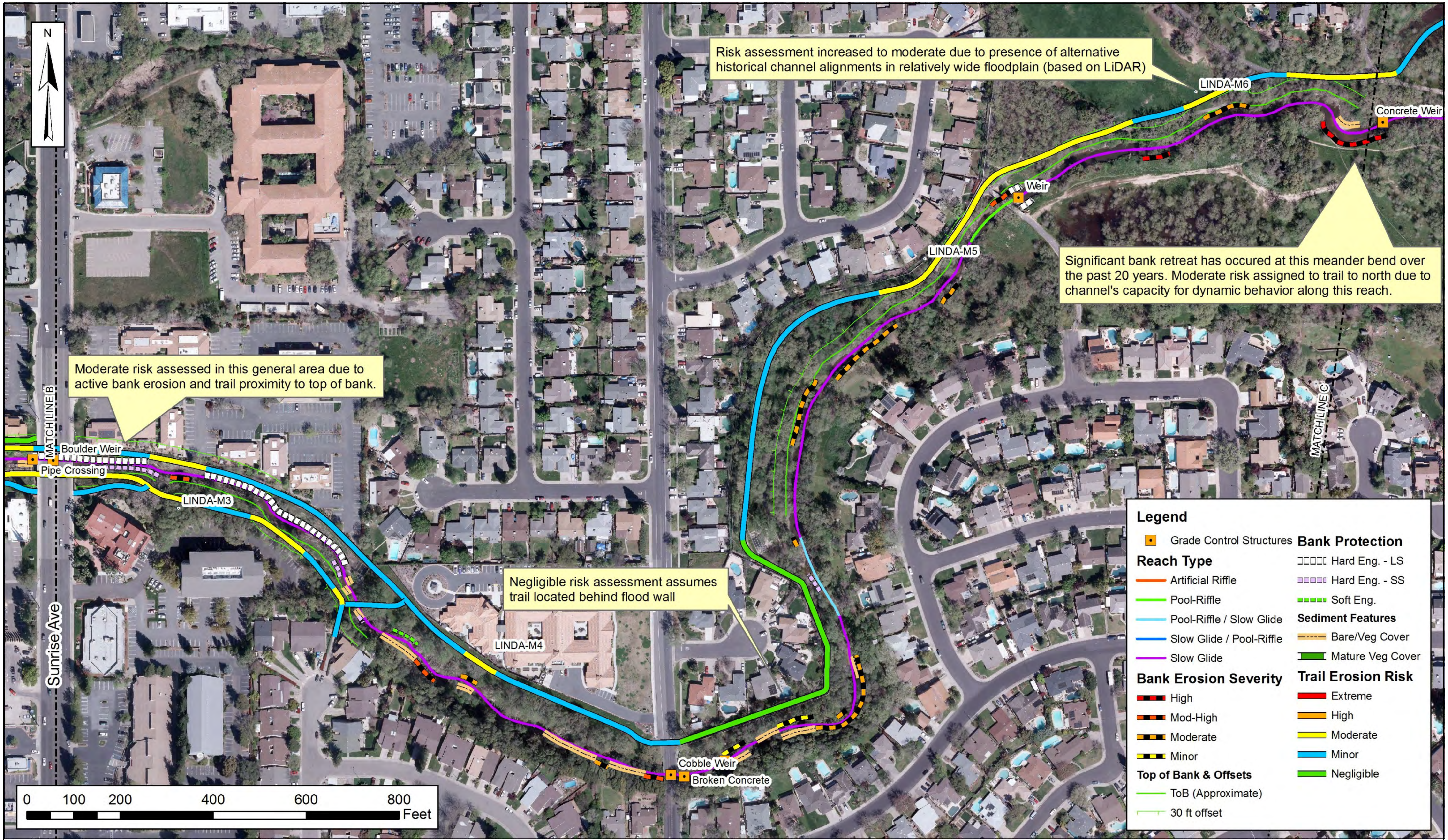
Dry Creek Greenway Trail Fluvial Audit

Fluvial Audit Data and Risk Assessment - Sheet 2

Project No. 13-1041	Created By: JDS	**Figure 15**



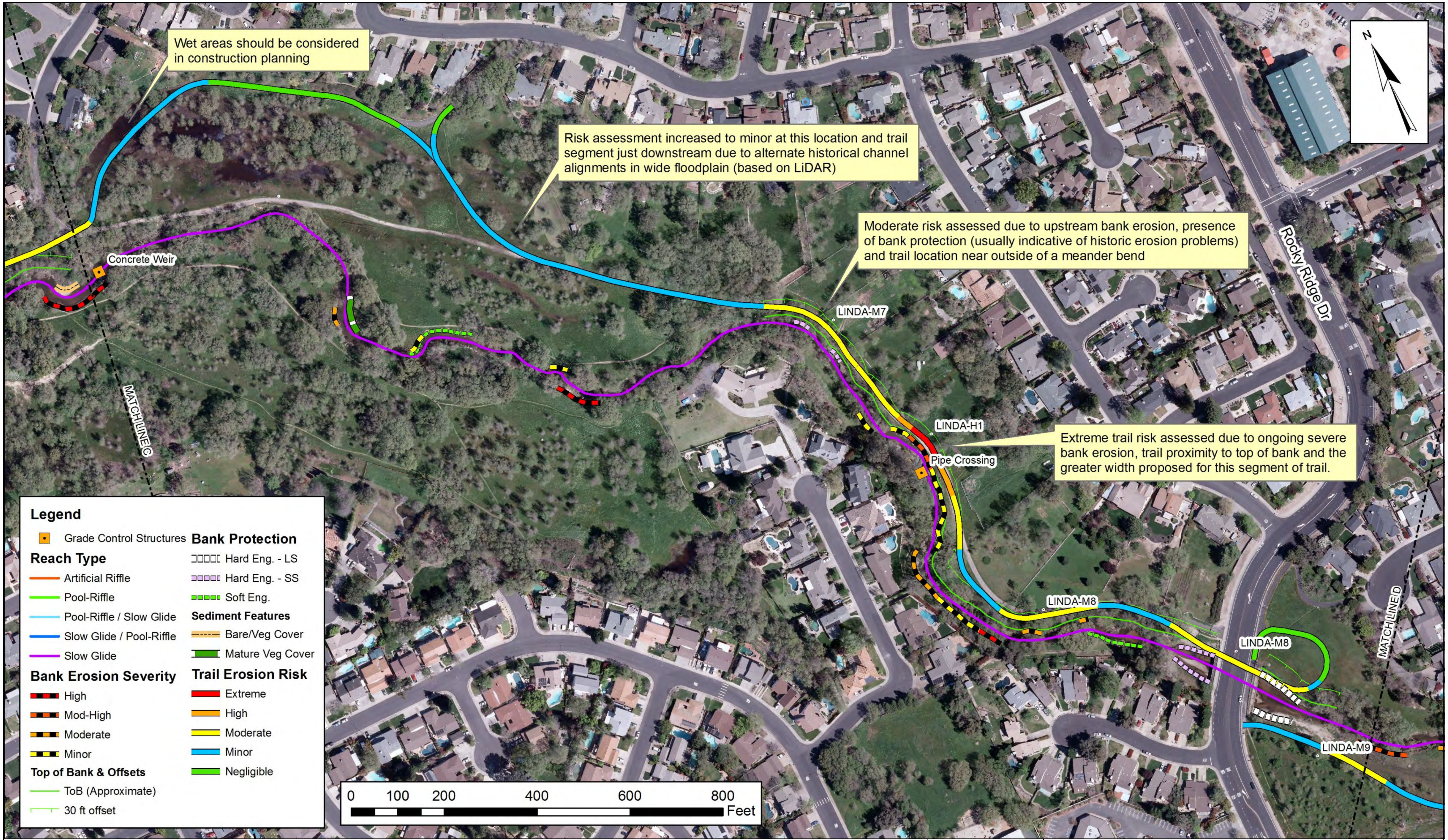
Notes: Trail width not to scale

cbec

Dry Creek Greenway Trail Fluvial Audit

Fluvial Audit Data and Risk Assessment - Sheet 3

Project No. 13-1041	Created By: JDS	**Figure 16**



Notes: Trail width not to scale

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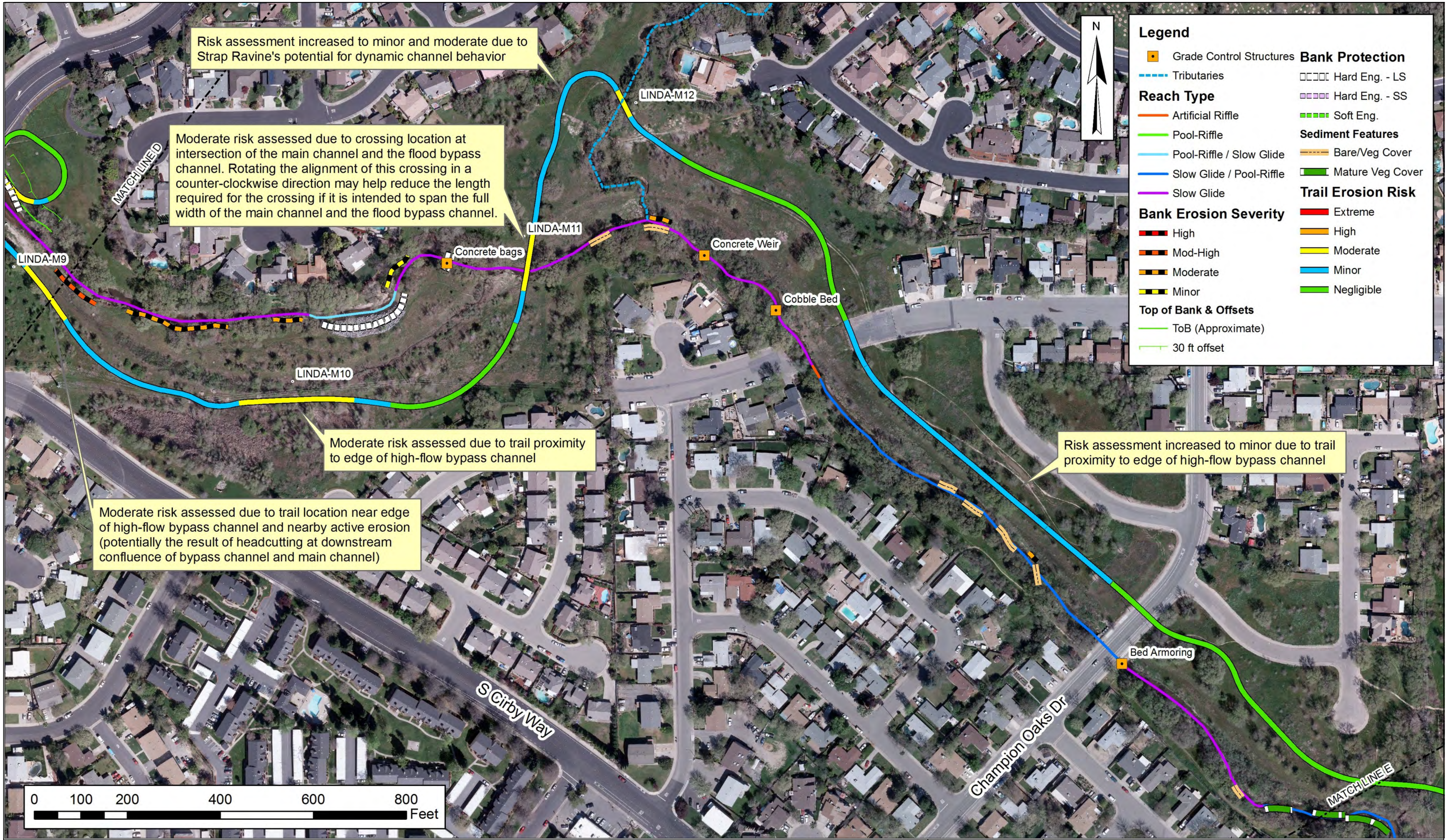
Dry Creek Greenway Trail Fluvial Audit

Fluvial Audit Data and Risk Assessment - Sheet 4

Project No. 13-1041	Created By: JDS	**Figure 17**



Notes: Trail width not to scale

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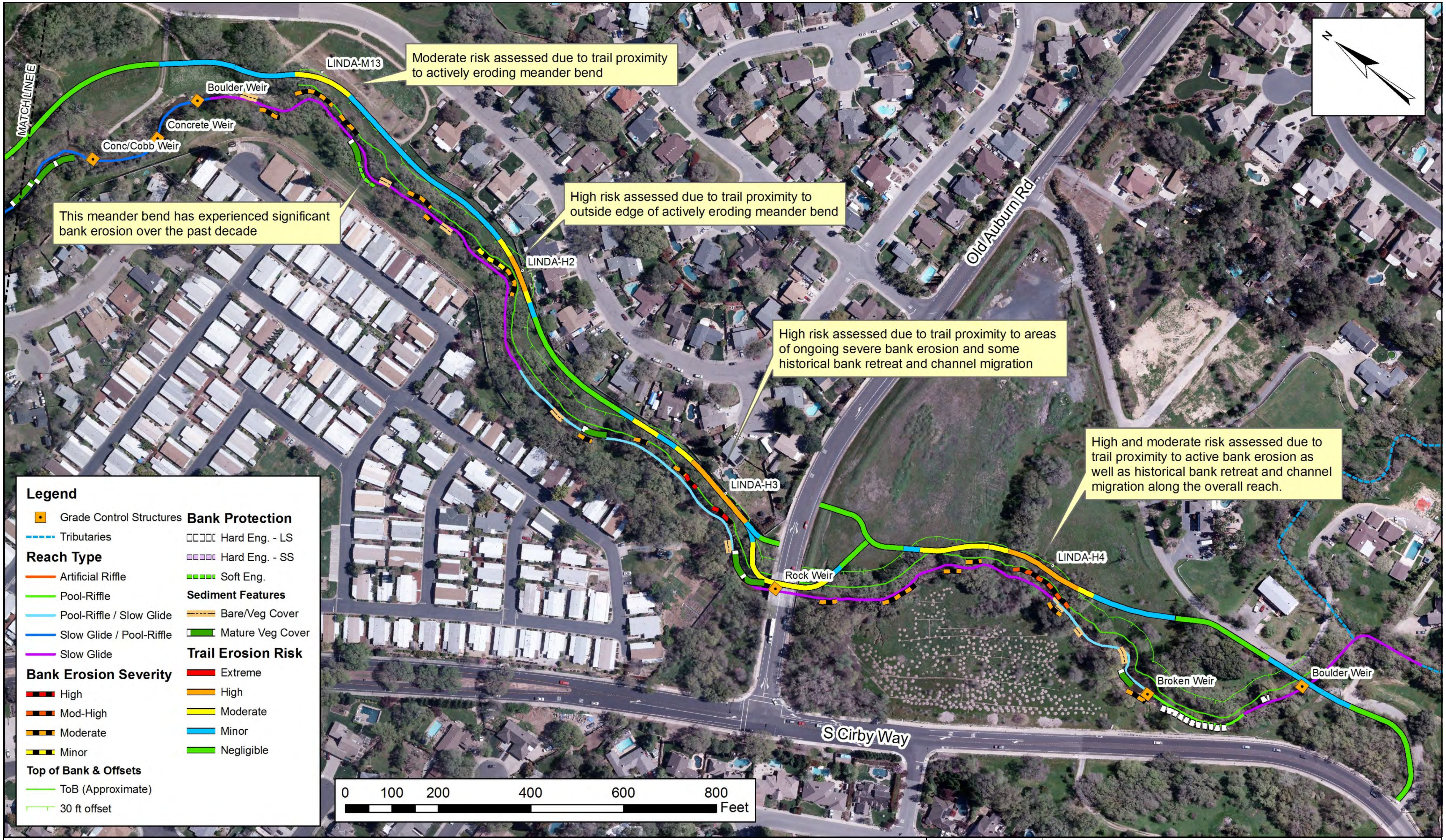
Dry Creek Greenway Trail Fluvial Audit

Fluvial Audit Data and Risk Assessment - Sheet 5

Project No. 13-1041 | Created By: JDS | **Figure 18**



Notes: Trail width not to scale

Dry Creek Greenway Trail Fluvial Audit

Fluvial Audit Data and Risk Assessment - Sheet 6

Project No. 13-1041	Created By: JDS	**Figure 19**

20A

20B

Notes:		*Dry Creek Greenway Trail Fluvial Audit* **DRY-H1 - Bank Erosion**		
		Project No. 13-1041	Created By: JDS	**Figure 20**

21A	
21B	

Notes: Top - looking upstream; bottom - looking downstream	cbec eco engineering	*Dry Creek Greenway Trail Fluvial Audit* **CIRBY-M1 - Bank Erosion**		
		Project No. 13-1041	Created By: JDS	**Figure 21**

22A

22B

Notes:		*Dry Creek Greenway Trail Fluvial Audit* **CIRBY-H1 - Bank Erosion**	
	Project No. 13-1041	Created By: JDS	**Figure 22**

23A

23B

Notes:		*Dry Creek Greenway Trail Fluvial Audit* **LINDA-H1 (Top), LINDA-M9 (Bottom)**		
		Project No. 13-1041	Created By: JDS	**Figure 23**

24A

24B

Notes: Both photos looking upstream		*Dry Creek Greenway Trail Fluvial Audit* **LINDA-H2**		
		Project No. 13-1041	Created By: JDS	**Figure 24**

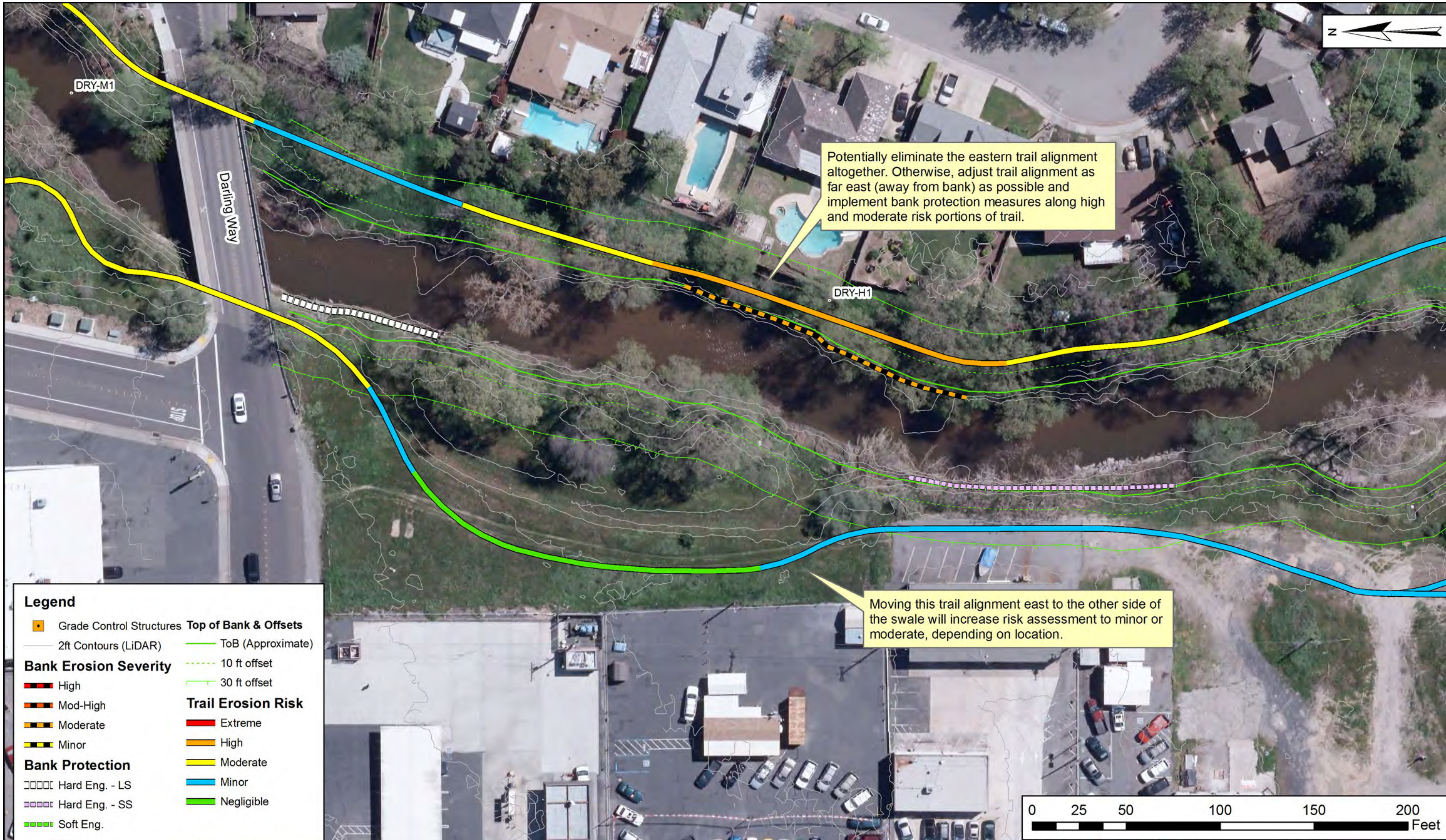
25A	
25B	

Notes: Bank erosion at downstream end (top) and upstream end (bottom) of LINDA-H3		*Dry Creek Greenway Trail Fluvial Audit* **LINDA-H3**		
		Project No. 13-1041	Created By: JDS	**Figure 25**

26A

26B

Notes: Bank erosion at downstream end (top) and continuing upstream (bottom) along LINDA-H3	cbec eco engineering	*Dry Creek Greenway Trail Fluvial Audit* **LINDA-H4**		
		Project No. 13-1041	Created By: JDS	**Figure 26**



Notes: Trail width not to scale

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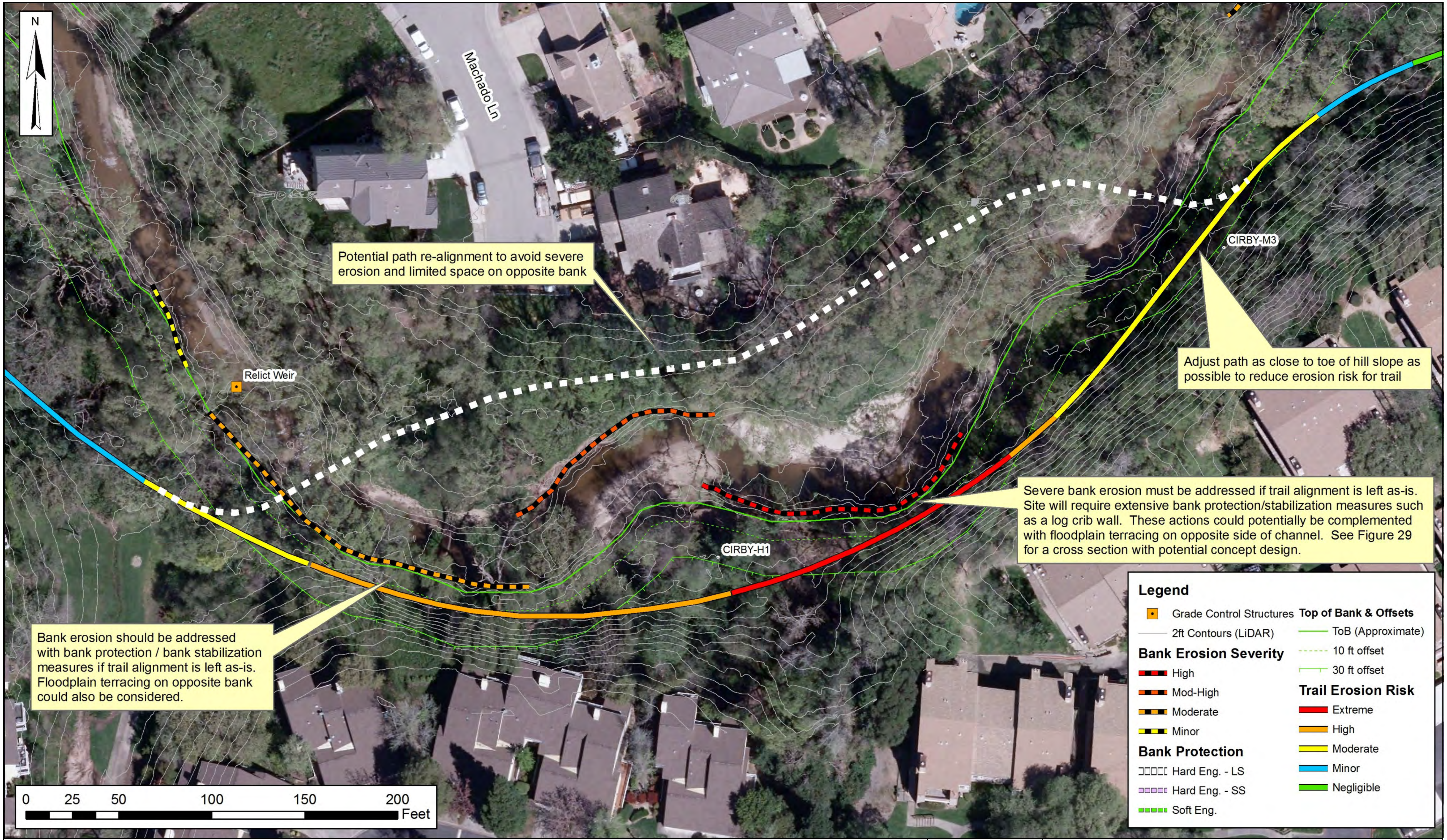
Dry Creek Greenway Trail Fluvial Audit

Risk Assessment and Suggested Actions- DRY-H1

Project No. 13-1041	Created By: JDS	**Figure 27**

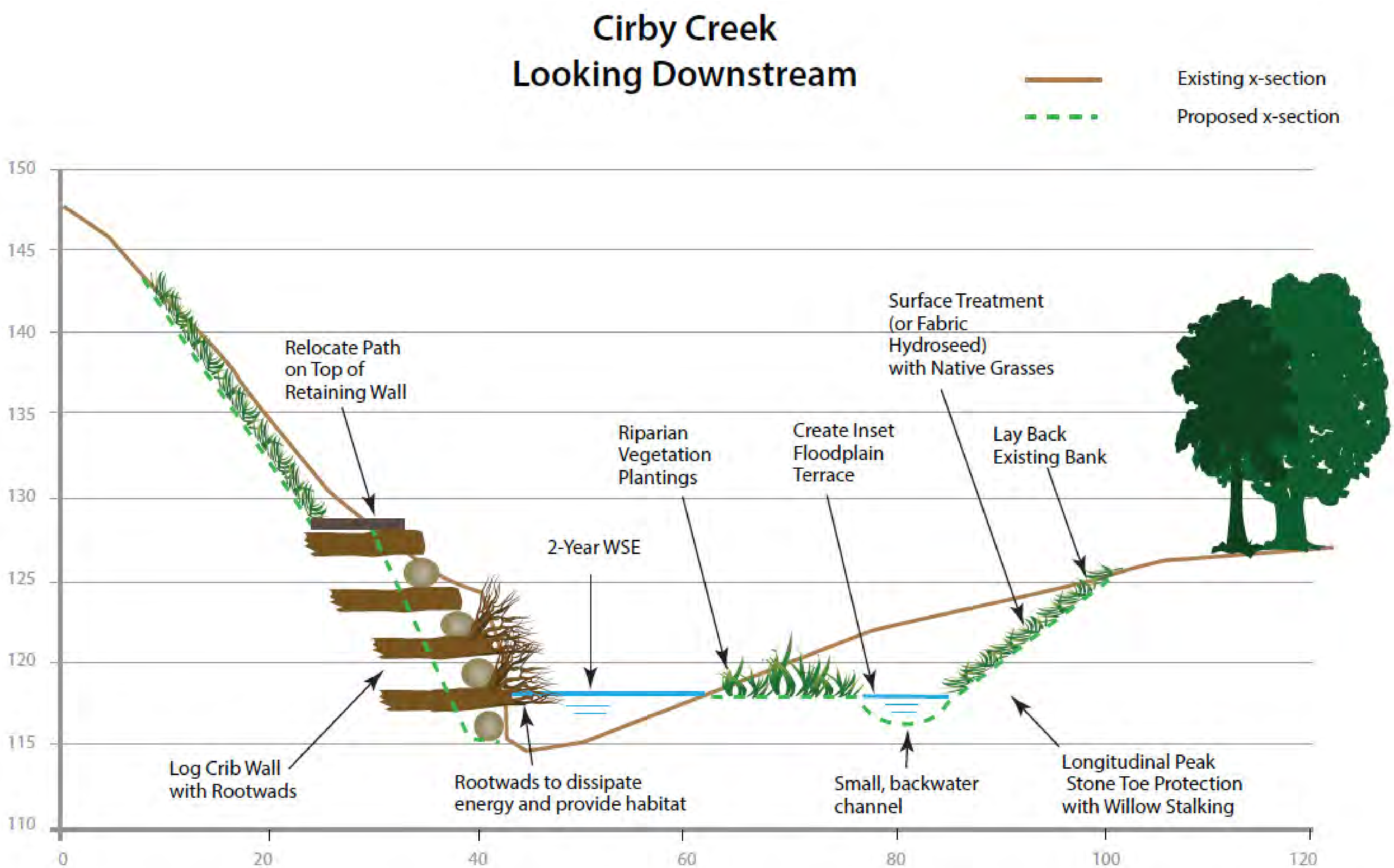


Notes: Trail width not to scale

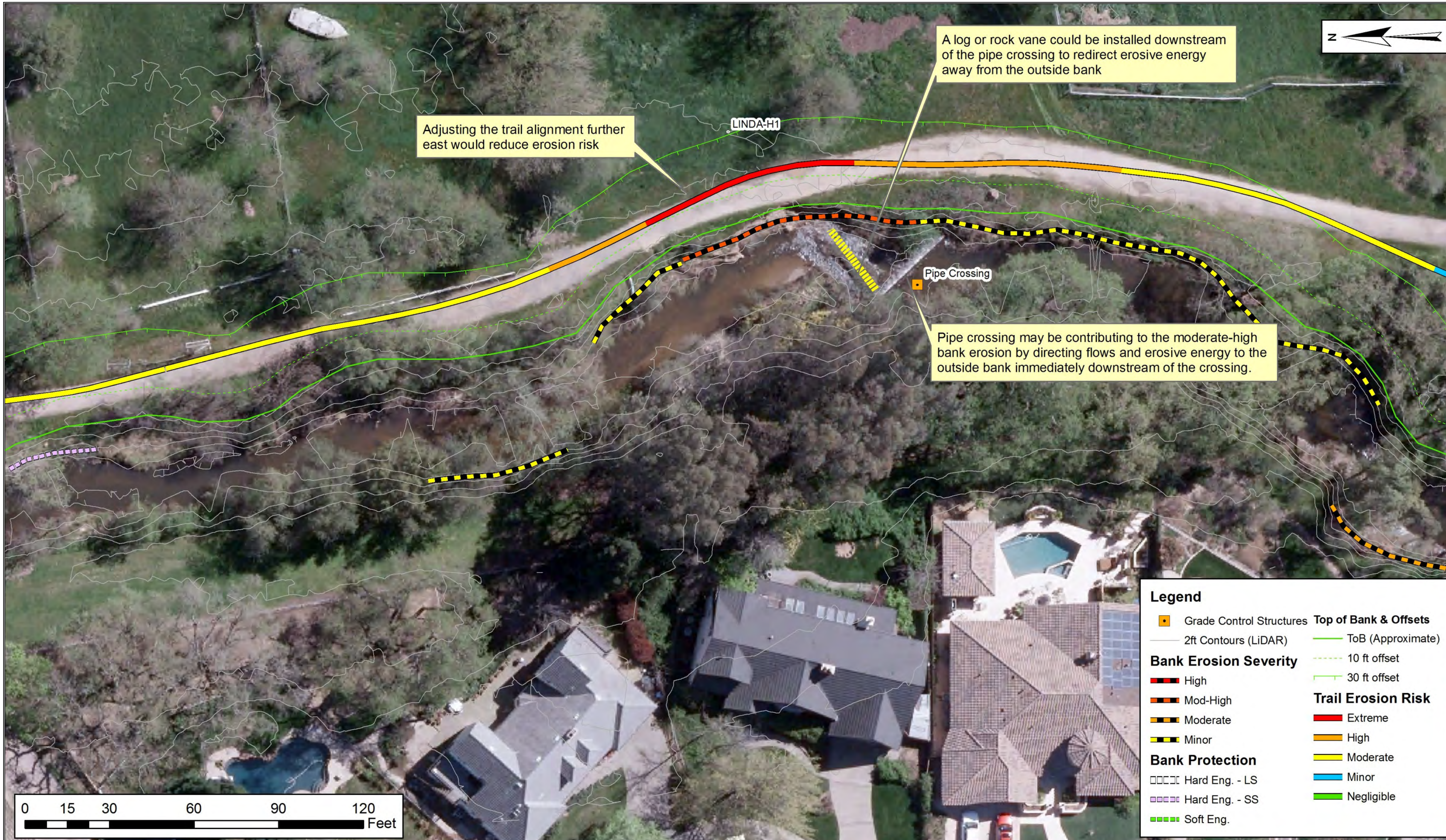
Dry Creek Greenway Trail Fluvial Audit

Risk Assessment and Suggested Actions- CIRBY-H1

Project No. 13-1041 | Created By: JDS | **Figure 28**



Notes: Apartment buildings located on top of left hill slope	cbec eco engineering	*Dry Creek Greenway Trail Fluvial Audit* **Cirby Bank Stabilization and Channel Modification**		
		Project No. 13-1041	Created By: JDS	**Figure 29**



Notes: Trail width not to scale

Dry Creek Greenway Trail Fluvial Audit

Risk Assessment and Suggested Actions- LINDA-H1

Project No. 13-1041	Created By: JDS	**Figure 30**

Notes: Trail width not to scale. The bank lay-back option may not be feasible due to existing storm drain infrastructure.

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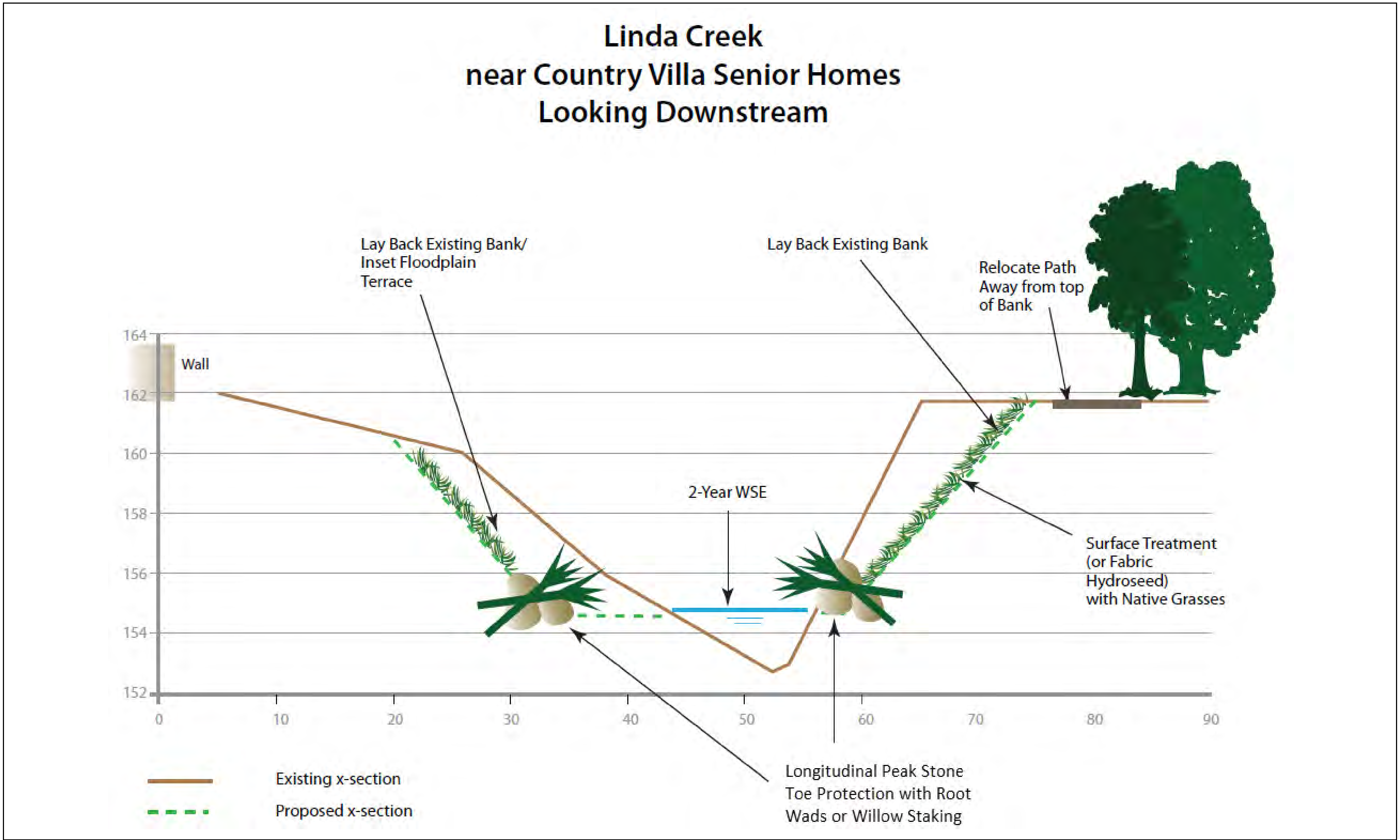
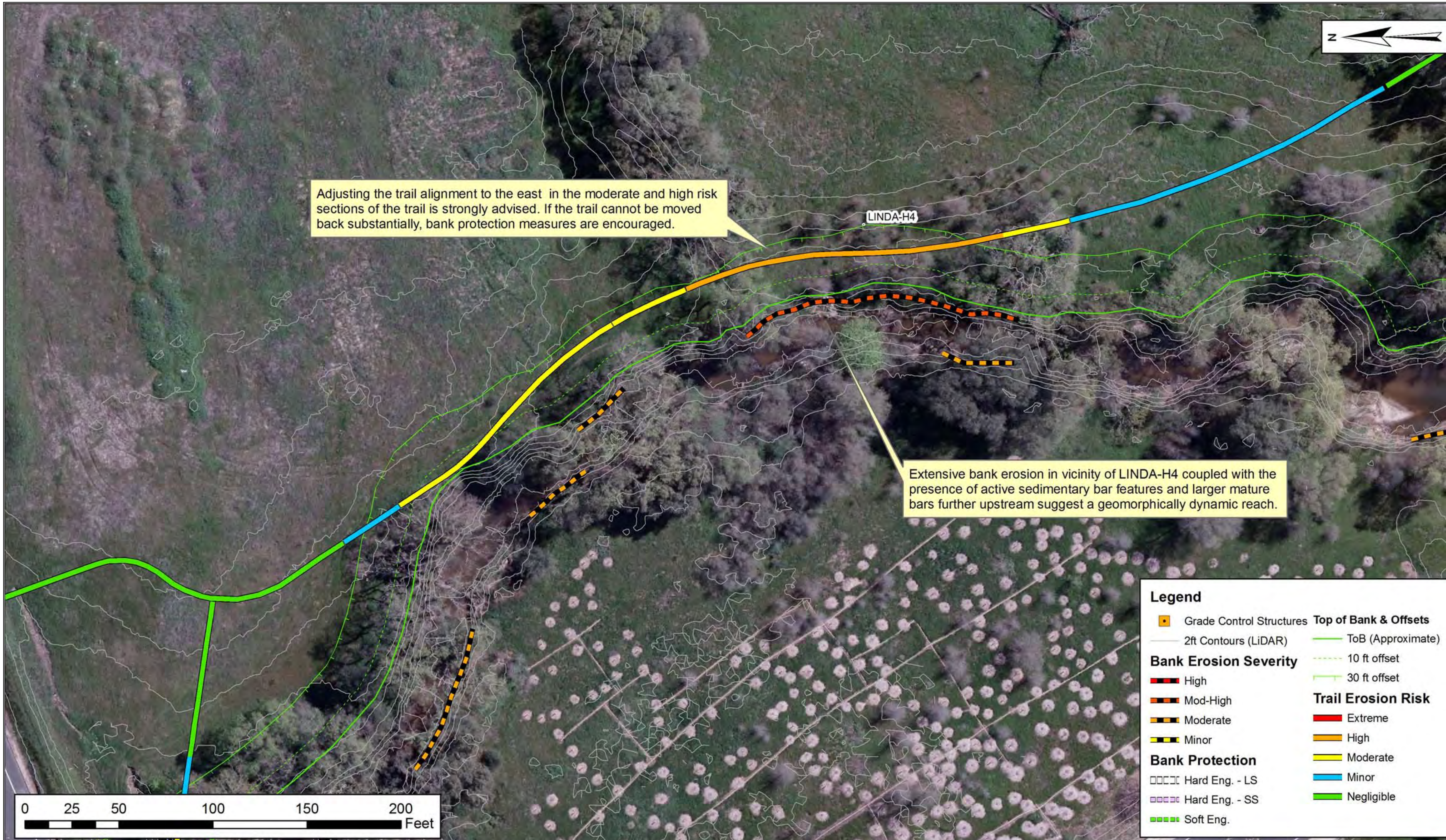
Dry Creek Greenway Trail Fluvial Audit

Risk Assessment & Suggested Actions- LINDA-H2-H3

Project No. 13-1041	Created By: JDS	**Figure 31**



Notes: The bank lay-back option may not be feasible due to existing storm drain infrastructure. A determination of the minimum trail setback distance from the top of the new bank would require a more detailed site analysis including additional field assessment (e.g., soil types, vegetation characteristics), potentially hydraulic modeling, trail design details, risk tolerance assessment and project longevity.	cbec eco engineering	*Dry Creek Greenway Trail Fluvial Audit* **Linda Bank Stabilization and Optional Channel Modification**	
		Project No. 13-1041	Created By: JDS	**Figure 32**



Notes: Trail width not to scale

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Dry Creek Greenway Trail Fluvial Audit

Risk Assessment and Suggested Actions- LINDA-H4

Project No. 13-1041	Created By: JDS	**Figure 33**

Notes: Photo location labels match labeling in figures, with exception of photos for high-risk sections of the proposed trail which are indicated by the site name (e.g., CIRBY-H1, LINDA-H4, etc.) and one moderate risk location (LINDA-M9).

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Dry Creek Greenway Trail Fluvial Audit

Fluvial Audit Photo Locations

Project No. 13-1041	Created By: JDS	**Figure 34**

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