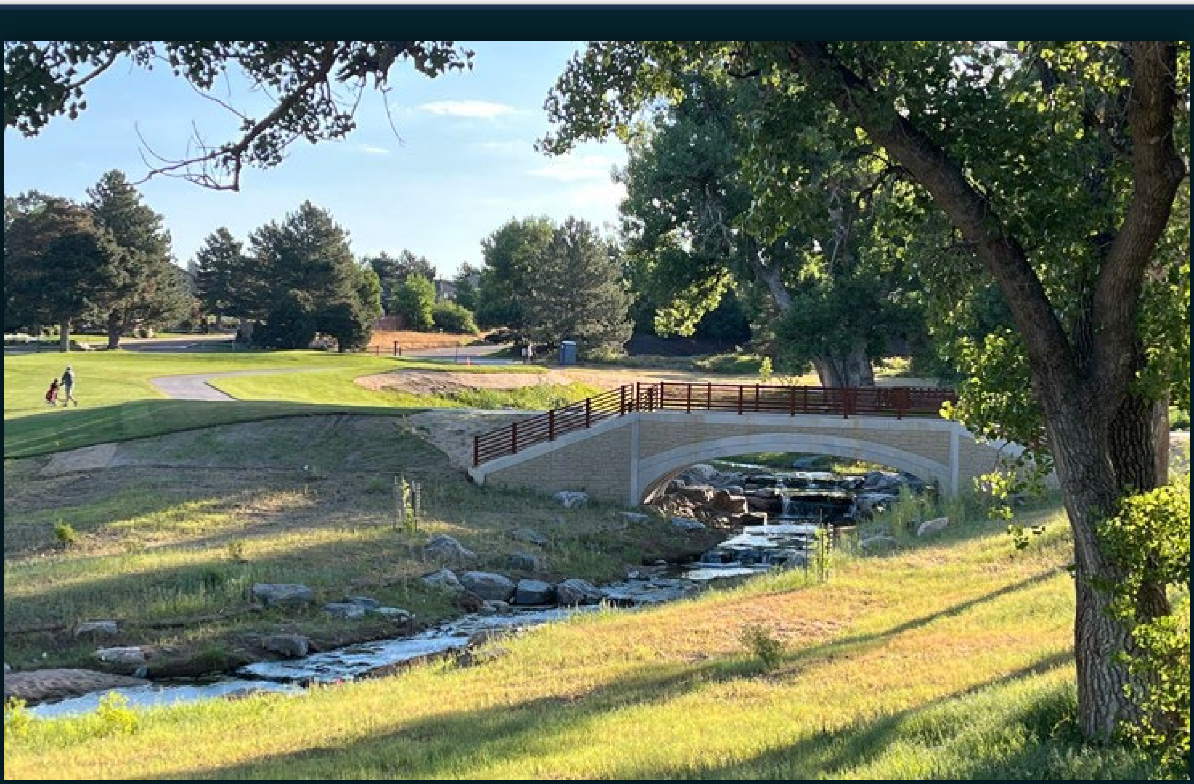

Geomorphically Informed Stream Crossing Structures

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Prepared For: MHFD

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Table of Contents

Table of Figures

SECTION 0 - ACKNOWLEDGEMENTS

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And many others who spoke to us in support of this report including individuals at:

- Colorado Department of Transportation
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- Massachusetts Department of Fish and Game
- Connecticut Department of Environmental Protection
- Vermont Fish and Wildlife Department
- U.S. Forest Service

SECTION 1 - INTRODUCTION

1.1 Purpose

The purpose of this paper is to explore the use of principles from fluvial geomorphology to inform the design of stream crossing structures. This approach is referred to in this paper as geomorphically informed stream crossing structures (GISCS). This paper presents geomorphic principles that can complement traditional hydraulic sizing in the design of stream crossings. Roadway crossings that incorporate these principles are safer, more resilient to large flood events, better convey sediment and debris, require less maintenance over time, and provide better conditions for aquatic passage compared to traditionally designed crossings. The Mile High Flood District (MHFD) supports this concept, acknowledging that site-specific conditions may, in some cases, limit its application.

This paper is the result of a literature review that included academic journals, technical presentations, and stream crossing guidance documents from various state transportation, wildlife, and environmental protection agencies. Additionally, phone interviews were conducted with many of the authors. We would like to thank those who took the time to speak with us and share their insights. Your contributions are greatly appreciated.

1.2 Usage

For new stream crossings in developing areas, and for the replacement of old structures at already established crossings, geomorphically informed design practices should be considered in addition to more traditional design methods. Section 5 of this document outlines key geomorphic design criteria that should be followed to the greatest extent possible. It is also recognized that geomorphic design may not be feasible for all stream crossing situations. Economically, GISCS are typically more expensive initially than traditional designs. Additionally, GISCSs generally require more space than traditional crossings. In some cases, these or other constraints may limit the feasibility of geomorphic design. When this occurs, the reasons why a GISCS design is not viable at a particular site should be clearly demonstrated before pursuing an alternative design approach.

SECTION 2 - STREAM PRINCIPLES

2.1 Stream Input and Function

Streams are a fundamental part of the natural environment. Streams act as agents of erosion, moving water and sediment from the land to the ocean (Knighton, 1998). Figure 1 depicts the longitudinal zones of sediment source, transfer, and deposition within a mountain to ocean river system. In the Colorado Front Range, the river systems exhibit characteristics of all three zones.

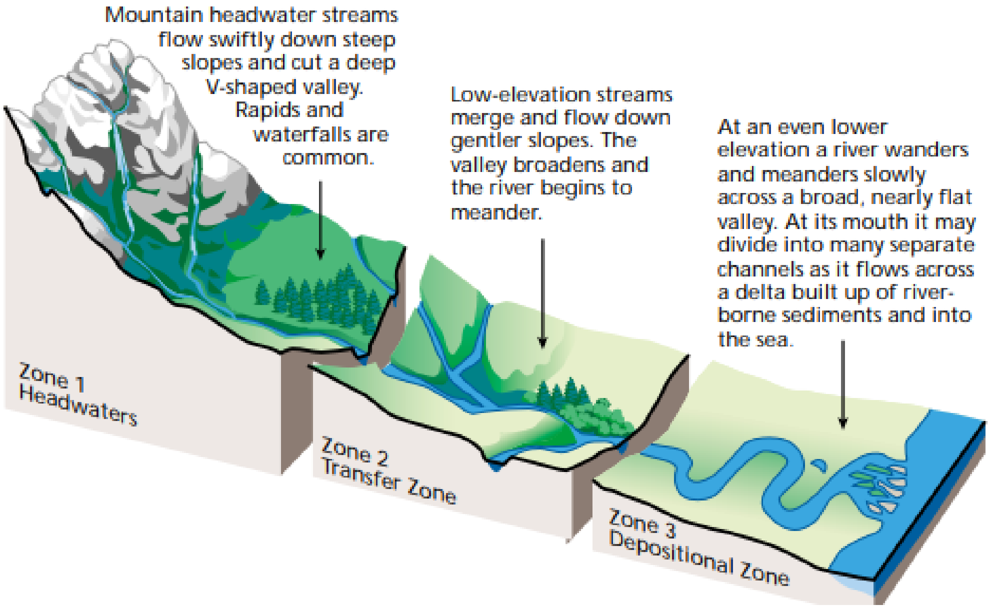

Figure 1: Longitudinal Profile Zones (Federal Interagency Stream Restoration Working Group, 1998)

There are many variables influenced by climate and geology that interact to create the form of a stream channel. These variables include: discharge, sediment supply, sediment size, vegetation, longitudinal slope, and channel roughness (Leopold, 1994).

2.2 Stream Adjustments and Stability

Streams are dynamic systems that change their form over time in response to changing inputs and anthropogenic constraints. Characteristics of a stream can change in response to fluctuations in input including, but are not limited to: width, depth, slope, sediment gradation, planform and bedforms. Commonly, aggradation (the deposition of sediment) and degradation (the erosion of sediment) are two responses a stream may have to changing flow and sediment regimes. A common depiction of this relationship is known as Lane’s Balance (Figure 2). Lane (1955) conceptualized this relationship in an easy-to-understand manner.

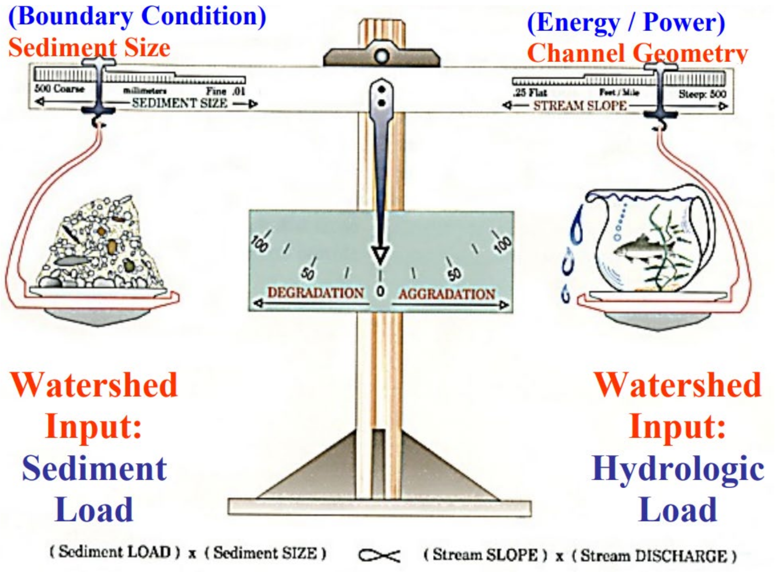

Figure 2: Lane's Balance (1955) from Rosgen 1996

Lane’s balance is very useful, but inherently limited because it does not account for changes in cross sectional geometry, bedforms, or planform (Wohl, 2014). A more detailed look at the complex response has been provided by others (Dust and Wohl, 2012; Schumm, 1973).

From a geomorphic perspective, a stable stream is one that has adjusted its width, depth, and slope such that there is no significant aggradation or degradation of the stream bed, nor any major planform changes (e.g., meandering to braided) within the typical engineering time frame, which is generally about 50 years (Biedenharn et al., 1997). The goal of GISCS design is to apply this sense of stability to the road-stream intersection to increase flood resiliency and minimize maintenance at the crossing.

SECTION 3 - TRADITIONAL SIZING OF STREAM CROSSINGS

3.1 Traditional Hydraulic Design

Engineers have traditionally designed stream crossings with the primary objective of accommodating a specified design discharge, either without overtopping the roadway, with a pre-determined freeboard to prevent overtopping, or with an acceptable depth of overtopping. Often the design discharge may be the estimated 100-, 50-, or 25-year discharge depending on the level of service of the roadway. Perhaps second only to the goal of accommodating the design discharge, is minimizing the construction cost of the crossing. These objectives have historically led engineers to design roadway crossings that efficiently convey large peak flow rates through the smallest possible structure. This often results in crossings with a high headwater depth to depth of structure (Hw/D) ratio. High headwater depth ratios generate pressures that push large volumes of water through the crossing structure at a high velocity. While these structures may be hydraulically efficient, focusing solely on the hydraulic performance of a stream crossing alone can be detrimental to the stability of both the upstream and downstream portions of the stream system. For this reason, several regulatory bodies have established maximum headwater depth ratios to guide the design and construction of new stream crossing structures.

3.2 Stream Crossing Structure Problems

3.2.1 Problems Resulting from Undersized Crossings

Crossing designs that utilize high headwater depth ratios often minimize construction cost by sizing the crossing structure small. This type of design can be very efficient from a hydraulic perspective. However, to achieve this efficiency, water velocity and pressure are often increased beyond natural levels found in the stream. Excessive stream velocity and pressure within a culvert can cause scour and erosion problems at the downstream end (Furniss et al., 1998) while simultaneously causing sediment deposition at the upstream end.

Undersized culverts are also prone to collecting debris that can't pass through or fit into the culvert (Minnesota Department of Transportation, 2014). Large pieces of wood and other floatable debris can accumulate at the entrance to the culvert, reducing the structure's efficiency and increasing the risk of overtopping, which can ultimately lead to roadway failure. High stream velocity and pressure within a culvert during periods of high flow can also cause a temporary barrier to aquatic organisms.

Figure 3: Debris Accumulation at the Entrance to Undersized Trail Crossing Resulting from Storm Event

3.2.2 Problems Resulting from Over Widened Crossings

To achieve the desired hydraulic capacity, it may be necessary to widen a single culvert or bridge beyond the natural width of the upstream channel. Or similarly, the hydraulic design may require placing multiple culverts at the same elevation across the channel width. In these situations, the increased active flow width (relative to the upstream channel) can lead to a reduction in flow depth, velocity, and shear stress resulting in sediment deposition. The sediment buildup within the culvert, which must be removed to maintain the required hydraulic capacity (Figure 4), crossing can become a costly and ongoing maintenance challenge.

Figure 4: Sediment Deposition at Over Widened Box Culvert

Sediment deposition with a stream crossing structure doesn't only occur when the crossing structure is overly wide. It can also result from various factors including structure slope and downstream tailwater conditions. Therefore, conducting thorough hydraulic analysis is essential to understand all contributing factors.

3.2.3 Inhibition of Organism Passage

Aquatic organisms living in streams and rivers rely on access to spawning, feeding, and shelter zones for survival. When roads cross these waterways, habitat fragmentation can occur, potentially impacting populations of various aquatic species (USFS, 2008). Fragmentation happens when conditions created by the stream crossing structure hinder the movement or passage of an aquatic organism. Common factors contributing to this inhibition include elevation barriers, depth barriers, and velocity barriers.

Elevation barriers may restrict aquatic organisms, requiring them to jump from the water’s surface to enter a culvert. Culverts with this type of elevation differential at their downstream end are often referred to as perched (Figure 5). Perched crossings present a significant physical barrier to aquatic organism movement (Connecticut Department of Environmental Protection, 2008). Even a small amount of perching at a roadway crossing can entirely segment a stream for fish and amphibians preventing them from accessing different parts of their environment. Perched crossings are commonly associated with undersized crossings and the increased velocity through the culvert creates a scour hole on the downstream side, often results in perching.

Figure 5: Culvert Perched Approximately 18 Inches

Depth barriers occur when there is insufficient flow depth through the culvert to allow aquatic organisms to pass (Bates et al., 2003). Many species of aquatic organisms require a specific flow depth for movement and survival. Insufficient depth barriers often occur when the flow depth through a crossing is lower than that of the stream outside of the crossing. Depth barriers often form in overly wide structures that disperse low flows, reducing the flow depth to a level inadequate for passage.

Velocity barriers occur when the speed of water moving through the crossing exceeds the swimming or movement ability of aquatic organisms. A velocity barrier may completely inhibit passage or only restrict it at times when the flow rate is high. Velocity barriers are more common in overly steep culverts or those with low hydraulic roughness. Mitigating velocity barriers to aquatic organism passage can involve increasing the structure size, reducing the gradient, or adding hydraulic roughness or refugia zones within the culvert.

SECTION 4 - GEOMORPHICALLY-INFORMED STREAM CROSSING STRUCTURES (GISCS)

4.1 Principles of Geomorphic Sizing

The key principle of GISCS is that, rather than being sized primarily based on hydraulic considerations with the goal of passing a design discharge, the crossing is sized according to the dimensions and geomorphic characteristics of the upstream and downstream channel and floodplain. Multiple overlapping approaches to GISCS design exist.

4.1.1 Stream Simulation

The stream simulation approach for design culverts was developed by the United States Forest Service. The methodology was pioneered and developed by engineers and biologists in Alaska and the Pacific Northwest who were concerned about barriers to anadromous fish. Stream simulation aims to create a structure that that closely resembles the natural channel. This method assumes that when crossing structure parameters—such as width, depth, gradient and roughness—match those of the upstream and downstream open channel, the hydraulic conditions will also be similar. Thus, the simulated channel will not pose more of an obstacle to aquatic organisms than the natural channel (USDA Forest Service, 2008).

4.1.2 MESBOAC

‘MESBOAC’ is a stream crossing design methodology developed by University of Minnesota (UMN) researchers with joint input from the Minnesota Department of Transportation (MnDOT) and a technical advisory panel that included the Minnesota Department of Natural Resources (MN DNR), the USFS, and independent aquatic organism passage and geomorphology experts. MESBOAC is based on the principles of fluvial geomorphology and aims to allow geomorphic processes to function naturally through a stream crossing. While aquatic passage is a specific goal of the stream simulation methodology, MESBOAC simply assumes that aquatic passage will occur as a byproduct of successful geomorphic design (Minnesota Department of Natural Resources, 2014).

MESBOAC stands for:

Match culvert width to bankfull stream width.
Extend culvert length through the side slope toe of the road.
Set culvert slope the same as stream slope.
Bury the culvert.
Offset multiple culverts.
Align the culvert with the stream channel.
Consider headcuts and cutoffs.

4.2 Continuum of Connectivity

Each stream crossing design and its associated methodology offer a distinct level of connectivity. Depending on the crossing design, the level of connectivity can vary along a continuum as depicted in Figure 6. At the lower end of the continuum is traditional hydraulic design for flood capacity. While traditional hydraulic design may meet hydraulic goals for peak flow passage, it can restrict the movement of aquatic organisms, sediment, debris, and may also encroach on the floodplain.

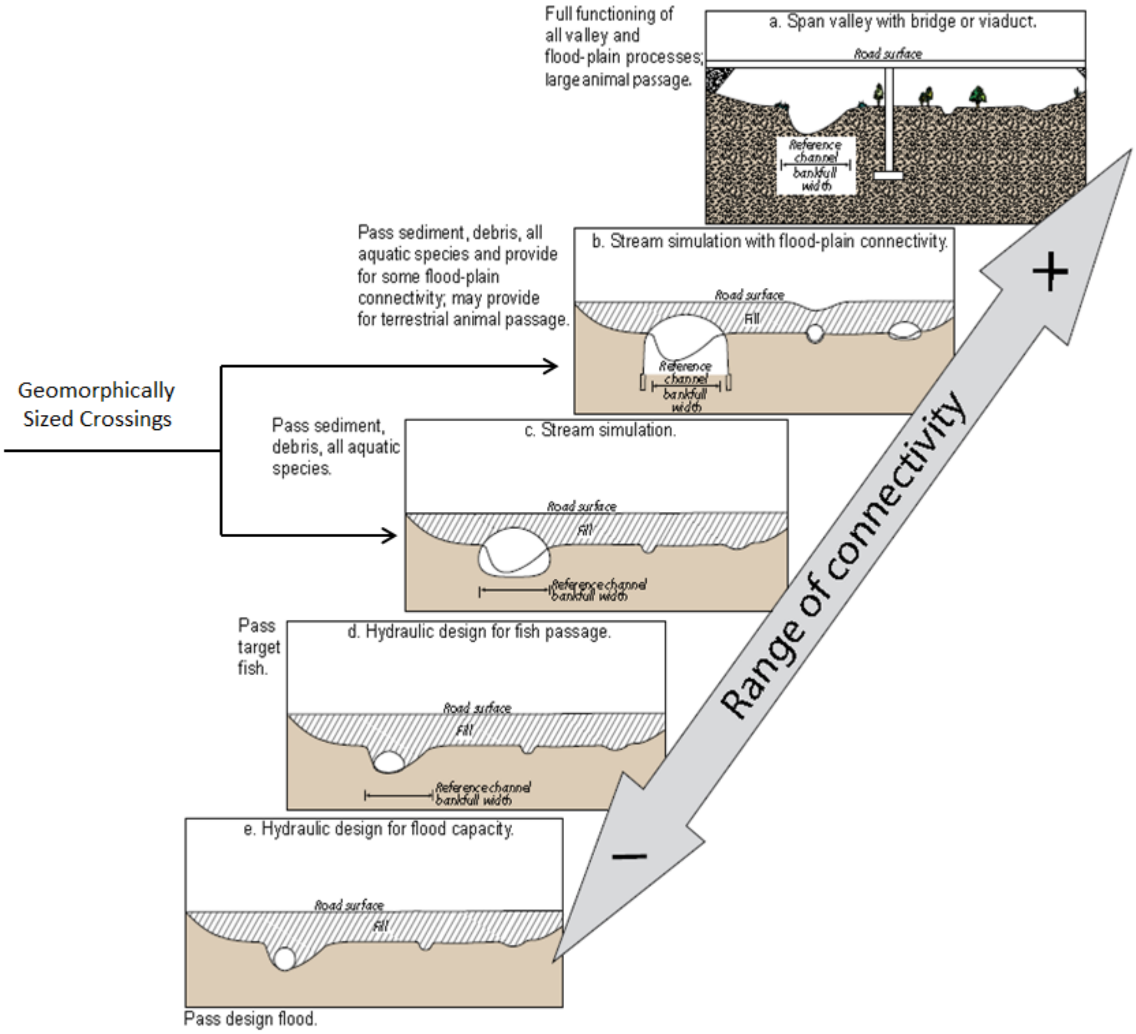

Figure 6: Stream Crossing Design Continuum of Connectivity (Adapted From: Forest Service, 2008)

Hydraulic design for fish passage improves upon traditional hydraulic design by limiting velocity within the crossing to levels that target species can withstand. This allows the target species to be able to traverse the crossing during the design discharge. However, crossings designed for fish passage may still restrict the movement of other aquatic organisms, sediment, or debris as they generally do not accommodate the bankfull width. As a result, these designs may still encroach on the floodplain.

Geomorphic sizing improves the hydraulic design for fish passage by providing a bankfull width passage through the road. By mimicking the upstream characteristics of the bankfull channel, the crossing ensures the same level of sediment transport, debris conveyance, and aquatic passage as the natural channel. To further enhance floodplain connectivity, smaller, auxiliary culverts can be placed within the floodplain. These auxiliary culverts encourage natural floodplain functions while increasing the overall hydraulic capacity of the crossing. The level of connectivity provided by GISCS is a great improvement on hydraulic design methodologies.

The highest level of connectivity is provided by a valley-spanning bridge. These bridges allow the passage of floodwaters, sediment, debris, aquatic organisms, and even large animals. While they offer excellent functionality, valley spanning bridges are cost prohibitive or impractical for many small to mid-size rivers.

4.3 Benefits of Geomorphic Sizing

4.3.1 Economic

Replacing conventional culverts with GISCS yields positive economic benefits. Although GISCS have higher initial construction costs (FHWA, 2011), GISCS are also more resilient to floods and catastrophic failure, require less maintenance, and are more durable (Christiansen et. al., 2014). The long lifespan and reduced maintenance requirements provide a net fiscal benefit (Christiansen et. al., 2014).

Typical service lifetimes for conventionally designed galvanized steel culverts range from 25 to 50 years, while similar galvanized steel culverts with geomorphically informed designs can achieve lifetimes of 50 to 75 years (Gillespie et al., 2014). GISCSs culverts have a longer lifetime primarily because:

1. their increased size results in less likelihood of catastrophic failure during large flood events (O'Shaughnessy et al., 2016);
2. they transport sediment more efficiently reducing scour and abrasion which can damage the culvert (Christiansen et. al., 2014).

The lifecycle of three different culverts for a theoretical watershed is conceptualized in Figure 7 below. In this figure, traditional culverts are depicted with blue and orange lines, while a GISCS design (Stream Simulation) is shown as a range of costs between two green lines. Although the GISCS design has the highest initial construction cost, it has the lowest lifecycle cost due to its resilience during large flood events and minimal to no maintenance requirements.

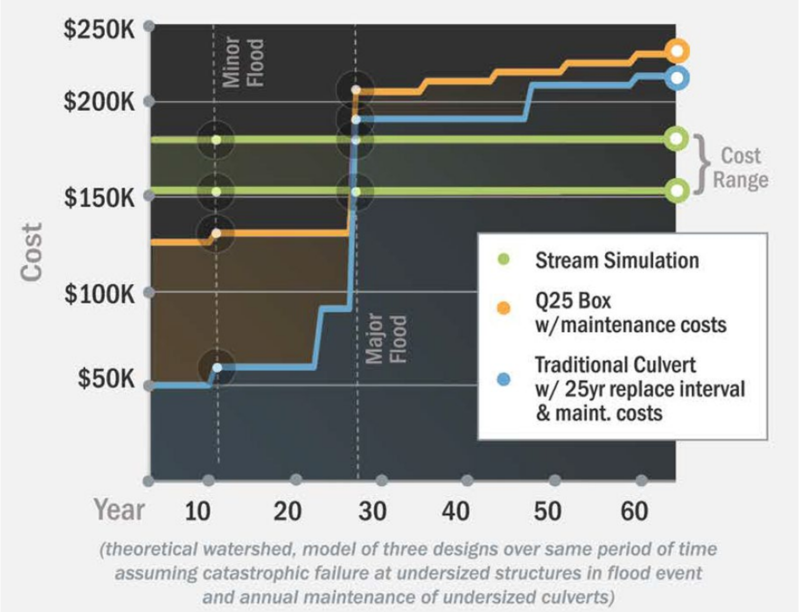

Figure 7: Theoretical stream crossing cost over time (Trout Unlimited, 2018)

4.3.2 Safety

During flooding events, overtopped roadways and washed-out road crossings pose significant dangers. Vehicles attempting to drive through floodwater can be swept away. In the United States, most flooding-related deaths involve drivers and passengers who become trapped in their vehicles (Yale et al., 2010).

Creating a more resilient road system will help keep people safer during floods. GISCSs are less likely to clog with debris, overtop, or catastrophically fail compared to traditional crossings (O'Shaughnessy et al., 2016). GISCSs are one tool that can enhance human safety during floods.

4.3.3 Environmental

Traditional road crossing culverts present barriers to the passage of aquatic organisms, leading to fragmented ecosystems. This fragmentation limits aquatic species' access to critical spawning habitats and reduces aquatic populations (Fausch et al., 2002; Letcher at al., 2007). Other methods of culvert design that incorporate geomorphic sizing criteria (USFS Stream Simulation, MESBOAC) have been shown to greatly improve aquatic passage at road crossings for multiple species (Rathburn, 2015).

4.4 Geomorphic Sizing Constraints

While there are many potential benefits to using GISCSs, their implementation may be challenging due to a variety of constraints. Common constraints include economic factors, right of way issues, utilities, lack of information, and general unfamiliarity with the concept.

State highway departments and local municipalities often operate on fixed budgets, making it hard to justify the higher up front construction and installation costs for GISCSs, especially when multiple culvert replacements are being considered. In urban areas, right-of-way constraints and the presence of utilities can further complicate the design process. Existing utilities can impact the elevation and slope of GISCS designs unless additional costs are incurred to relocate them. Lastly, the lack of suitable geomorphic data or knowledge of how to apply such information can limit the ability to implement GISCS designs effectively.

4.5 Usage of Geomorphic Sizing Concepts in Crossing Design

Stream simulation stream crossing design was pioneered by engineers and biologists in Alaska and the Pacific Northwest, who were concerned about barriers to anadromous fish. Today, Washington, Alaska, Oregon, California all require stream simulation design elements to be incorporated into culvert design. The United States Forest Service also applies stream simulation design criteria whenever possible to facilitate aquatic passage through road crossings on National Forests. Additionally, the state of Minnesota uses geomorphic sizing criteria in the stream crossings design though on a limited basis.

In the northeastern United States, geomorphic sizing parameters have been incorporated into standard criteria and best management practices in many states. Massachusetts, Vermont, and

Connecticut have geomorphic sizing procedures statewide. For some of these Northeastern states, the turning point came with Hurricane Irene in 2011. The hurricane produced massive runoff that damaged or destroyed thousands of stream crossings across multiple states. In Vermont, where the storm caused severe damage, a few stream simulation culverts installed in 2006 remained largely undamaged from Hurricane Irene. This resilience prompted Vermont to adopt stream simulation design principles statewide to improve flood resiliency and safety (Kirn, 2018).

SECTION 5 - DESIGN GUIDANCE FOR GEOMORPHICALLY INFORMED STREAM CROSSING STRUCTURES (GISCS)

5.1 Site Reconnaissance

Before beginning the design, visit your project site and conduct a field reconnaissance with a multi-disciplinary team of experts. Your team's expertise will vary depending on the project type and needs but may include professionals with expertise in engineering, construction, geomorphology, ecology, biology, and urban planning.

Begin by walking the channel at least 30-50 channel widths upstream and downstream of the crossing. Extend it further if the streambed is more mobile (Forest Service, 2008). Look for instabilities such as headcuts, knickpoints, eroding streambanks, areas of aggradation, and debris jams. Unstable reaches upstream of your project site could dramatically increase sediment or debris loading to your site. Be mindful of recent floods that may influence your interpretation of the channel (Forest Service, 2008). Take note of the channel's condition and function. The goal of this site reconnaissance is to gain an understanding of the broader context in which you are working.

5.2 Geomorphic Analysis

5.2.1 Selection of Reference Reach

A "reference reach" is a natural channel near the project site that can serve as a real-world model for the designing the channel through the road crossings (CalTrans, 2007). Selecting an appropriate reference reach for your stream crossing location is crucial. Suitable reference reaches should be in a state of dynamic equilibrium, where they are actively adjusting their size and form to inputs of sediment and water within their surrounding geologic and vegetative setting.

Ideally, a suitable reference reach is located immediately upstream of your project. However, this is not always the case, and sometimes it may be necessary to look at more distant sections of the same stream, or even a different stream to find a suitable reference reach. Ideal reference reaches share the following similarities with the design site (Bledsoe et al., 2017):

- Location (ideally the same river)
- Flow and sediment regime (absence of dams, tributaries, flow extractions in between reference and design site)
- Valley energy (driven by valley slope)
- Lateral constraints (dikes, roads, urban encroachment)
- Land use (urban, rural, agricultural)
- Geology and stream bed material

Once you have selected the reference reach location using the guidance provided above, a more detailed approach can be followed (Harrelson et al., 1994).

1. Choose sites with evident natural features, such as floodplains, terraces, bars, and natural vegetation.
2. Look for signs of physical impact on the stream from roads, bridges, buildings, and diversions. Ideally, your reference reach should be free of such disturbances.
3. The reference reach should, if possible, encompass an entire meander (two bends). The length should be at least 20 times the bankfull width of the channel.

5.2.2 Observations of Reference Reach

Once you have selected your reference reach, there are several observations that need to be made. These observations will inform the design of your stream crossing structure.

(i) Bankfull Stage

The term “bankfull stage” was coined by Wolman and Leopold (1957) to describe the elevation at which flow begins to leave the channel banks and enter the floodplain. Bankfull discharge is one of the most important and influential terms in fluvial geomorphology because it is widely considered the key flow magnitude controlling channel process and form (Wolman and Miller, 1960; Dunne and Leopold, 1978). Bankfull discharge is typically associated with a recurrence interval of 1-2 years for most channels (Leopold et al., 1964, Castro and Jackson, 2001).

Identifying the bankfull stage and associated geometry of your stream is a critical component to designing GISCS. Active floodplains are the best indicator of bankfull stage and are seen as flat, depositional surfaces (Harrelson et al., 1994). Other indicators of bankfull elevation are (Harrelson et al., 1994):

- a change in vegetation (especially the lower limit of perennial species);
- slope breaks along the bank;
- a change in the particle size of bank material, such as the boundary between coarse cobble or gravel with fine-grained sand or silt;
- undercuts in the bank, which usually reach an elevation slightly below bankfull stage.

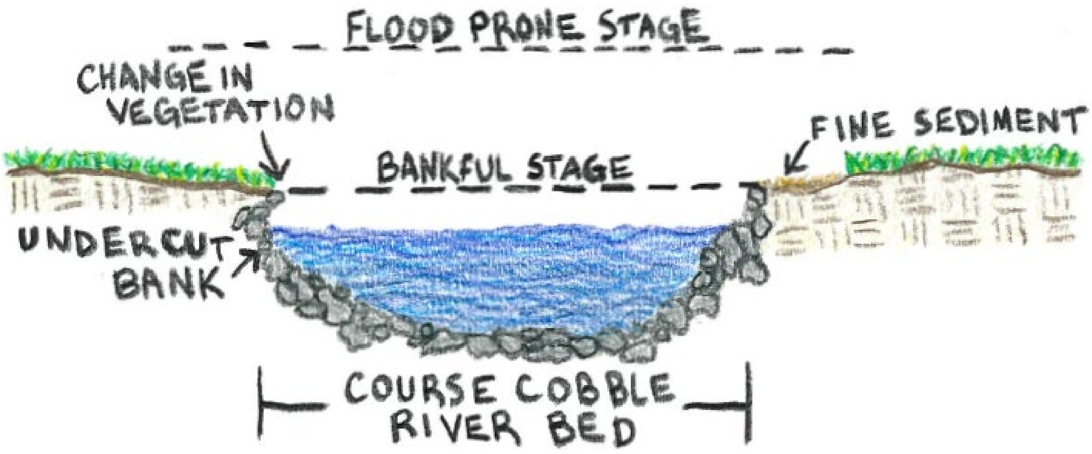

Figure 8: Measurement of Bankfull Stage (Natural Resource Conservation Service, 2009)

For more information on identifying the bankfull stage, and the processes that create these indicators see: Dunne and Leopold (1978), Harrelson et. al. (1994), and Rosgen (1996).

(ii) Longitudinal Profile

The longitudinal profile of the stream should be surveyed during the field visit to the reference reach. The profile should extend at least 20 times the bankfull channel width. While measuring the profile, the elevation of the channel thalweg, water surface, and bankfull elevation should be recorded (Harrelson et. al., 1994).

(iii) Characterization of Bed Material

The composition of the stream bed and banks is an important aspect of stream character, influencing channel form and hydraulics, erosion rates, sediment supply, and other parameters (Harrelson et. al., 1994). Understanding the sediment gradation of the channel bed is a necessary component of geomorphic crossing design. For streams with gravel sized sediment or larger, the Wolman Pebble Count (1954) is the most efficient and simple technique for characterizing the bed sediment size. The Wolman Pebble Count involves traversing a stream riffle and randomly selecting 100 pieces of sediment. The intermediate axis of each piece of sediment should be measured and recorded. This data can then be organized to obtain a representative sediment gradation (Harrelson et. al., 1994).

For streams with finer sediment, a sieve analysis is required. For more information on this procedure, consult the U.S. Soil Conservation Service, Soil Survey Handbook (1982).

5.3 Alignment

Establishing the crossing alignment is one of the first steps in GISCS design. The crossing alignment represents the two-dimensional plan view that connects the channel upstream and downstream. The crossing profile, which is designed next, is a longitudinal view showing the elevation change of the crossing from upstream to downstream. The alignment and profile of the crossing must be considered together, as they are interdependent.

Historically, culverts were aligned perpendicular to the road to minimize culvert length and reduce cost. However, in some cases, perpendicular alignments can create instabilities in the upstream and downstream channels by shortening the channel length, thereby increasing the slope and stream power. Additionally, forcing a perpendicular alignment creates unnatural bends (MDNR, 2008).

Considerations for selection of design alignment:

- Consider the natural channel location through the crossing. Ideally, the culvert should be parallel to the upstream channel as much as is possible without overlengthening the culvert (Forest Service, 2008).

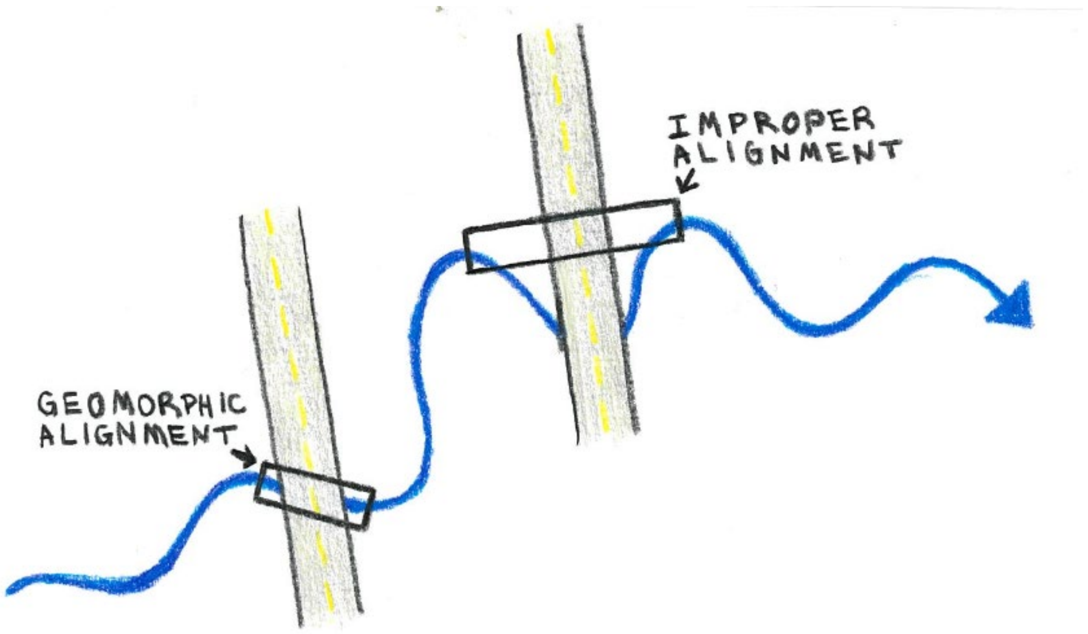

Figure 9: Improper and Geomorphic Crossing Alignment

- Shorter culverts are preferable to longer culverts. Longer culverts carry a greater risk that hydraulic energy is not adequately dissipated within the culvert. Additionally, longer culverts on meandering streams may be more likely to cutoff channel bends and steepen the channel (Forest Service, 2008). To reduce the total length of the culvert, the use of vertical headwalls rather than fill slopes is recommended (Connecticut Department of Environmental Protection, 2008).
- Where it is not possible to match the culvert alignment with the upstream alignment without significantly lengthening the culvert, consider over widening the culvert to reduce

the risk of failure (Forest Service, 2008). Also, consider using headwalls in conjunction with an overwide culvert (Figure 10).

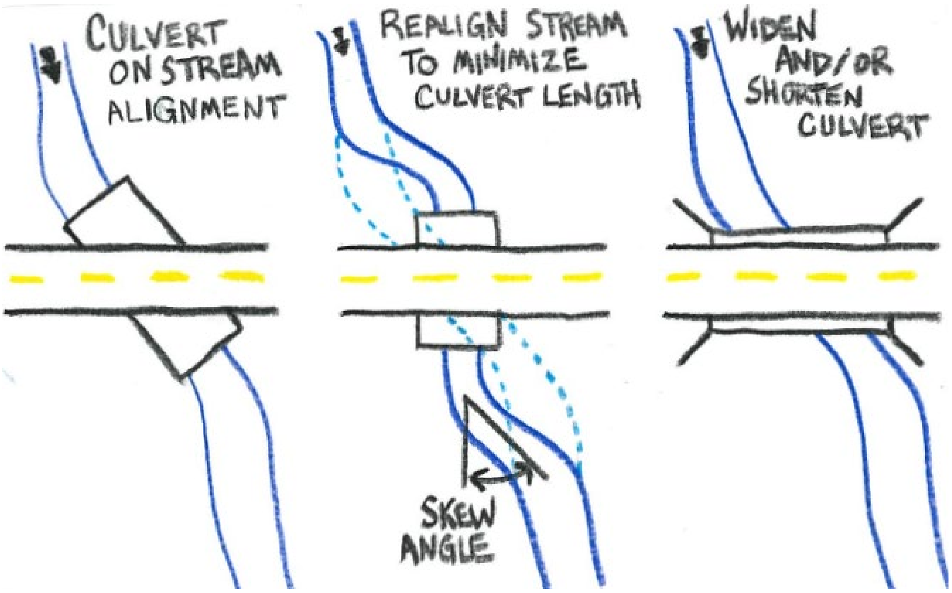

Figure 10: Alignment Options for Skewed Culvert

- The relationship between the radius of curvature (R_c) of the upstream bend and bankfull width is an indicator of the level of the risk posed by a skewed alignment. When R_c is greater than 5 times the bankfull width, sediment and debris transport are essentially the same as in a straight channel. However, as R_c decreases to a point where it is equal or less than 2 times bankfull width, the risk of impeding sediment and debris transport is substantial (Forest Service, 2008). Avoid placing the culvert crossing downstream of a meander bend with a R_c less than 2 times the bankfull width.

5.4 Profile

Because the crossing alignment and profile are interdependent, designing these components is an iterative process.

Considerations for selection of design profile:

- Use the survey of the longitudinal profile of the reference reach to ensure the culvert matches the slope of the reference reach. The slope should be based on stable grade control features, such as bedrock outcrops, highly stable step drops, or riffle crests (Forest Service, 2008).

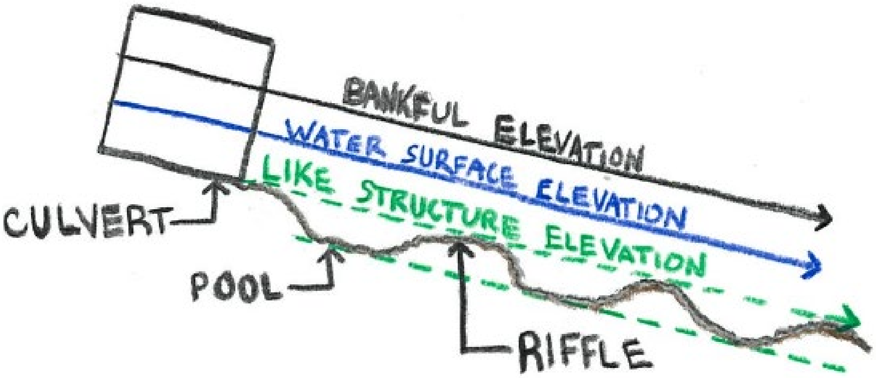

Figure 11: Set Culvert Slope to Match Riffle Slope

- The culvert gradient should be no steeper than the streambed gradient upstream or downstream of the culvert and should match the overall stream gradient as closely as possible. For sunken culverts, the gradient should not exceed 3%. Bottomless arch culverts or clear span bridges should be used when the gradient exceeds 3% (Connecticut Department of Environmental Protection, 2008).

5.5 Design of the Channel Bed

Bed material inside the stream crossing is crucial for maintaining flow resistance, bed forms, and cross-sectional shape similar to the upstream and downstream channels. From a hydraulic perspective, this helps prevent aggradation or degradation, which can lead to costly maintenance issues, within the culvert. Placing bed material within the stream crossing also allows a range of flow depths and velocities, providing optimal conditions for aquatic passage (Forest Service, 2008). For these reasons, spans (bridges, 3-sided box culverts, open arches) are strongly preferred (Jackson et. al., 2011) stream crossing alternatives. However, in enclosed stream crossings, the channel bed can be simulated by placing material on the bottom.

Considerations for creation of channel bed within culvert:

- When placing the channel bed, it is best to use material of a similar origin and gradation to the upstream channel bed material.
- For buried culverts:
    - The culvert should be buried at a depth of 1/6th the bankfull width (up to 2 feet), 1/5th for steeper streams with larger cobble substrate (MDNR, 2014).
    - The minimum bury depth for box culverts shall be 2 feet, for circular culverts the minimum bury depth shall be 25 percent of the pipe diameter (Jackson et. al., 2011).
- The minimum thickness of the channel bed over the culvert should be 1.5 times the diameter of the largest immobile particles or four times the size of the largest mobile particle, whichever is greater (Bates and Kirn, 2009).
- Material placed within the crossing should be shaped into a cross section resembling the bankfull channel. The banks of the bankfull channel should be constructed with immobile material. To achieve this, you may need to use material up to twice the size of the D95 of the reference reach. Gaps in the larger bank material should be filled with smaller material (Forest Service, 2008).
- For very mobile bed streams, such as sand beds, the initial channel can be a simple V-shaped section with a 5:1 (H:V) slope. This design will prevent the thalweg from contacting the culvert walls until a bankfull channel can form (Forest Service, 2008).
- For crossings located in watersheds with a disrupted, or severely reduced sediment supply (urban watershed, upstream reservoir) the bed material shall be sized so that the D_{50} is immobile during the design flood.

5.6 Structure Width and Height

Only after the crossing alignment, profile, and bed have been determined should the crossing designer consider the dimensions and elevation of the structure itself. The recommendations listed below focus solely on geomorphic sizing. These recommendations are designed to reduce channel instabilities related to sediment transport, improve the passage of debris, reduce risk of clogging, and enhance maintenance needs and overall structure lifespan. Separate analyses must be conducted to assess the hydraulic capacity, water surface elevations, and flood risk associated with the culvert design.

5.6.1 Structure Width

The initial estimate of the structure width can be estimated by adding the bankfull width to the size of the largest rocks used to construct the channel banks within the crossing. This ensures that channel-forming flows can pass through the culvert without being constricted. Wider structures can be used if a floodplain bench is desired through the culvert (Forest Service, 2008). Other guidelines suggest that culverts should span a distance at least 1.2 times the bankfull width of the stream (Connecticut Department of Environmental Protection, 2008).

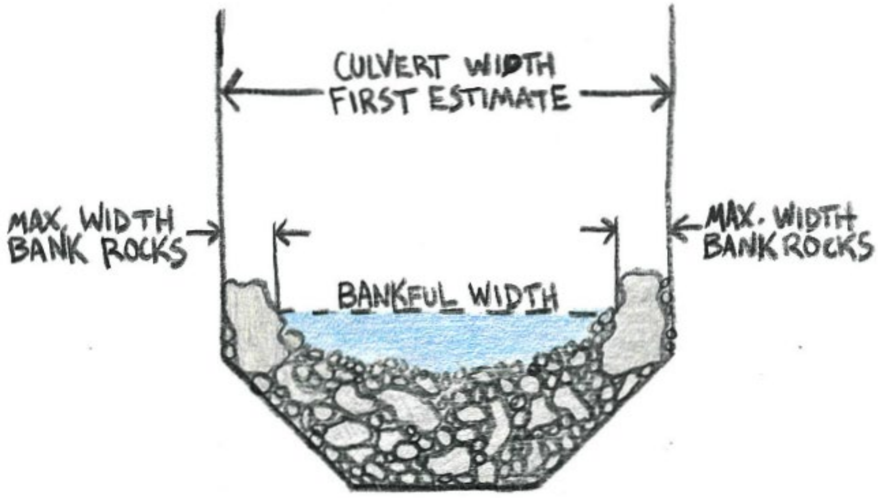

Figure 12: Estimate of Crossing Width

5.6.2 Structure Height

Determining the culvert height can be a challenging aspect of the design process. The Forest Service (2008) recommends first determining the bed-design flow, which is the highest flow that immobile bed particles can sustain without moving. To determine the bed-design flow, an incipient motion analysis needs to be performed on the D_{84} of the channel bed material to identify the discharge rate that entrains the D_{84}. The discharge is considered the bed-design flow. The structure height should accommodate the bed-design flow without exceeding 80% submergence of the structure, or 67% submergence if woody debris is a significant concern (Forest Service, 2008). This requirement helps prevent wash out of the simulated streambed during high flow events.

Other guidance documents don’t require an incipient motion analysis, instead providing general recommendations for the minimum culvert height. In these cases, the culvert height is set to provide flood conveyance, ensuring the structure is not undersized. For example, the state of Minnesota recommends a minimum culvert height of at least 1/3 the bankfull width (MDNR, 2014), while Massachusetts suggests a minimum height of 6 feet (Jackson et. al., 2011).

In general, designers should ensure that the structure height accommodates the design flow (Ex: 50- or 100-year) with at least 1 foot of freeboard. If the system includes significant in-stream wood or ice flows, additional freeboard (up to 3’ feet) may be necessary to account for these factors.

5.6.3 Openness Ratio

The openness ratio is an important factor in assessing the cross-sectional area of your culvert. It is calculated by dividing a culvert’s cross-sectional area (ft^2) by its length (ft). The resulting value is expressed in feet. For embedded culverts, only the cross-sectional area that is open to flow conveyance should be used in the calculations.

Different agencies have varying recommendations for the minimum openness ratio. For example, the State of Connecticut recommends an openness ratio of at least 0.25 feet for passage of aquatic organisms (Connecticut Department of Environmental Protection, 2008). In wildlife corridors, where passage of terrestrial animals is a concern, a ratio of at least 1.0 is preferred (Brudin, 2003). Other states, such as Massachusetts recommend a minimum of 0.82 feet (Jackson et. al., 2011) with 1.64 being the preferred value. In Colorado, the Mile High Flood District (MHFD) recommends a minimum openness ratio of 0.82 for stream crossings.

5.6.4 Multiple Culvert Crossings

Multiple culvert crossings are a common solution when design discharges exceed the capacity of a single culvert but do not warrant a bridge. Typically, the culverts are installed side by side and at the same invert elevation, as shown in Figure 13. However, this configuration can lead to an over-widened active channel, resulting in sediment deposition (see Section 3.2.2). The accumulation of sediment may require regular maintenance to preserve hydraulic capacity. Additionally, this design may reduce flow depths during dry conditions, potentially hindering aquatic organism passage (see 3.2.3).

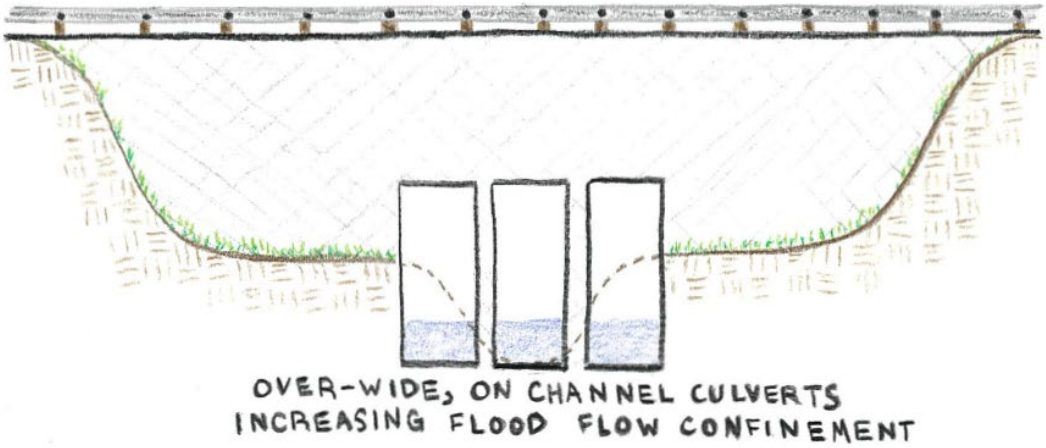

Figure 13: Conventional Configuration of Multi-Box Culvert Crossing

To address these issues, the elevation and orientation of the culverts should be carefully considered during the design process to better align with the shape of the bankfull channel and floodplain, as shown in Figure 14. The idealized scenario illustrated in Figure 14 uses the primary culvert to match the elevation and width of the bankfull channel. Secondary and tertiary culverts, necessary to meet flood capacity requirements, can be set at higher elevations to more closely match the natural floodplain. This adjustment in elevation and orientation of the secondary and tertiary culverts helps reduce concerns about over widening and improves floodplain connectivity.

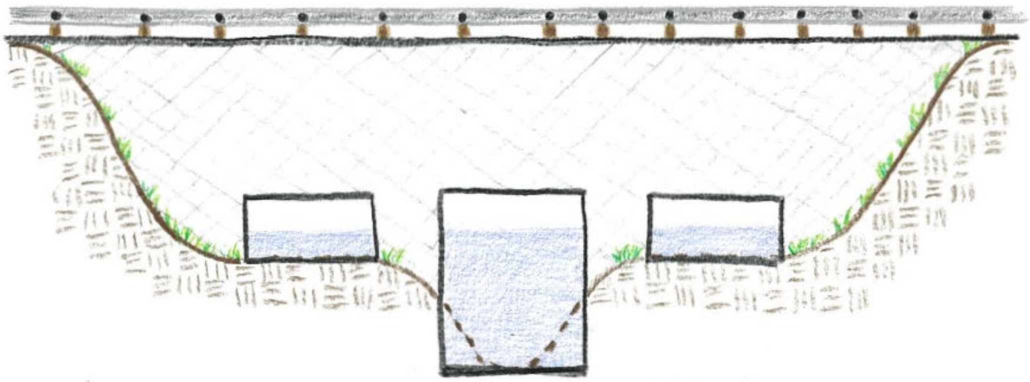

Figure 14: GISC Multi-Box Crossing

5.6.5 Floodplain Relief Culverts

Floodplain relief culverts (FRCs) are auxiliary culvert crossings placed adjacent to the stream within the floodplain (Figure 15). FRCs are particularly useful for maintaining ecological connectivity and reducing the hydraulic conveyance demands of the primary crossing structure. The use of FRCs may be necessary when the crossing spans multi-thread or anastomosing[1] channels. These types of channels have multiple flow paths, which require multiple crossing structures to prevent disruption of channel-forming processes.

FRCs may also be considered in situations where the stream system has a high entrenchment ratio (greater than 2.5). In these broad, well-connected floodplain environments, relying only one crossing structure will force all floodplain conveyance to contract upstream of the road

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[1] Describes a river system with multiple interconnecting channels separated by stable or semi-stable islands.

crossing as it enters the structure and expands downstream. This significant contraction and expansion of floodplain conveyance may create destabilizing forces and may also disconnect habitats.

FRCs are a useful solution for meeting flood conveyance targets without exceeding freeboard goals for the primary bankfull crossing. They also provide an effective means for terrestrial animals to safely cross road systems. Since floodplain culverts are primarily designed to increase hydraulic capacity and floodplain connectivity, they do not need to adhere to geomorphic sizing criteria or feature a natural bed.

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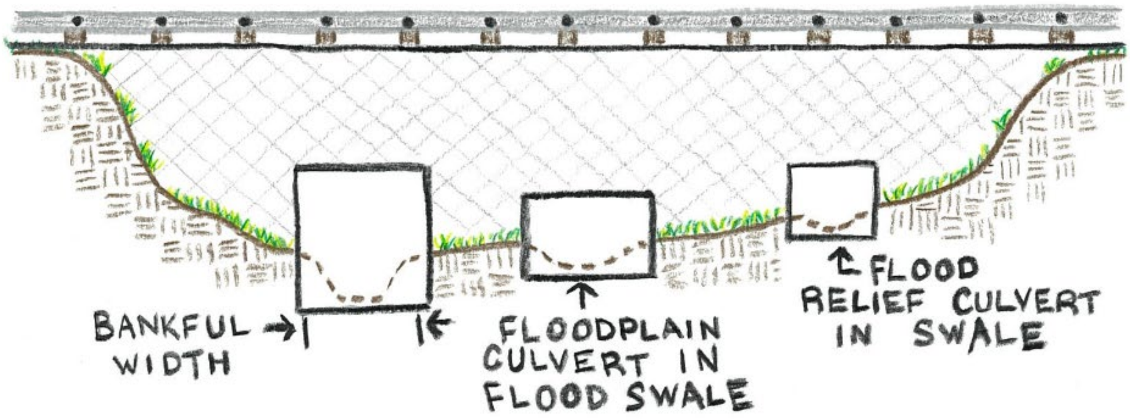

Figure 15: Geomorphically Sized Crossing with Floodplain Relief Culverts

Considerations for creation of floodplain relief culverts:

- Floodplain culvert should be located at, or above, bankfull elevation (Zytkovicz and Murtada, 2013).
- Floodplain culverts should be sized large enough to allow for maintenance as needed.
- From a floodplain function perspective, many small floodplain culverts are better than just one large floodplain culvert (Zytkovicz and Murtada, 2013).

- Designers should consider the ease of maintaining floodplain culverts. Larger culverts are generally easier to maintain than smaller ones, and rectangular culverts are typically more maintainable than circular ones.

SECTION 6 - EXAMPLE

6.1 First Creek at E. 26th Avenue – Aurora, Colorado

6.1.1 Site Context

First Creek at East 26th Avenue in Aurora, Colorado, is situated within the South Platte River Watershed. The site is characterized by a semi-arid climate with precipitation occurring as short-duration high intensity storms during the summer months and occasional snowfall in the winter. The watershed upstream of East26th Avenue is approximately 13.9 square miles and includes a mix of urban, suburban, industrial, and undeveloped land. In recent years, the watershed has seen rapid development, with large areas of undeveloped agricultural and grazing land being converted to suburban and industrial land uses. This urbanization has lead to reduced infiltration, increased surface runoff, and elevated flood peak flows and volumes. This trend is expected to continue as Aurora continues to grow.

The expansion of 26th Avenue was necessary to accommodate increased traffic volumes and support adjacent land uses. The existing two-lane roadway is planned to be expanded to six lanes over several years. To facilitate this change, the stream crossing structure over First Creek needed to be reconfigured. Before reconstruction, the crossing consisted of two, 36-inch reinforced concrete pipes (RCPs) (Figure 16) with the following hydraulic inadequacies:

- The pre-project crossing structure was severely undersized for the watershed's hydrology. Hydraulic modeling demonstrated that the roadway would overtop during a 10-year flood event, while 100-year capacity under future conditions hydrology was desired.
- During flow events associated with the 10-year return period, the crossing was found to generate extremely high flow velocities due to its undersized design. Additionally, the crossing configuration led to headwater depths up to three times the structure's height (HW/D > 3). These factors contributed to scour on the downstream side of the roadway and aggradation on the upstream side.

- The pre-project existing crossing was at risk of failure due to frequent overtopping flows and a high potential for clogging.

Figure 16: Pre-project photo of First Creek Crossing Structure at E. 26th Avenue in Aurora, Colorado

6.1.2 Project Goals

The design team defined key goals and metrics for the new stream crossing structure at E. 26th Avenue.

- The crossing configuration should accommodate the future roadway expansion, ensuring traffic demands are able to be met.
- The project should increase the hydraulic capacity of the crossing to convey 100-year flood events without overtopping.
- The crossing should promote stable stream conditions upstream and downstream of the roadway, minimizing erosion and aggradation.
- The project should be low-maintenance and require infrequent sediment and debris removal.
- The project should enhance floodplain connectivity and support ecological health.

6.1.3 Project Design

The multi-disciplinary team determined that a 61-foot span by 12.8-foot rise concrete arch bridge best met the project goals for the proposed crossing (Figure 17). The design was intended to provide 100-year capacity with approximately 1.3 feet of freeboard within the arch.

The concrete arch featured an open bottom wide enough to accommodate the estimated 30-foot bankfull top width. The wide span allowed for placement of shallow spread footings outside the active channel, providing a buffer for minor channel adjustments over time. Void-filled riprap was implemented in the channel section beneath the arch to mimic a natural riffle, providing roughness and scour protection. The void-filled riprap was sized to prevent mobilization during the 100-year flow event. Additionally, the proposed channel dimensions upstream and downstream of the roadway were maintained through the crossing to avoid expansion or contraction in lower flow events.

Floodplain relief culverts (FRCs) were incorporated into the proposed design to enhance floodplain connectivity through the crossing and reduce the hydraulic conveyance demands on the primary structure. On each side of the channel, one 10-foot wide and 8-foot high reinforced concrete box culvert was installed at the bankfull elevation within the stream's flood-prone width. The large size of the FRCs ensures that maintenance access can be easily provided using medium-duty equipment (i.e. skid steer) if sediment or debris removal becomes necessary.

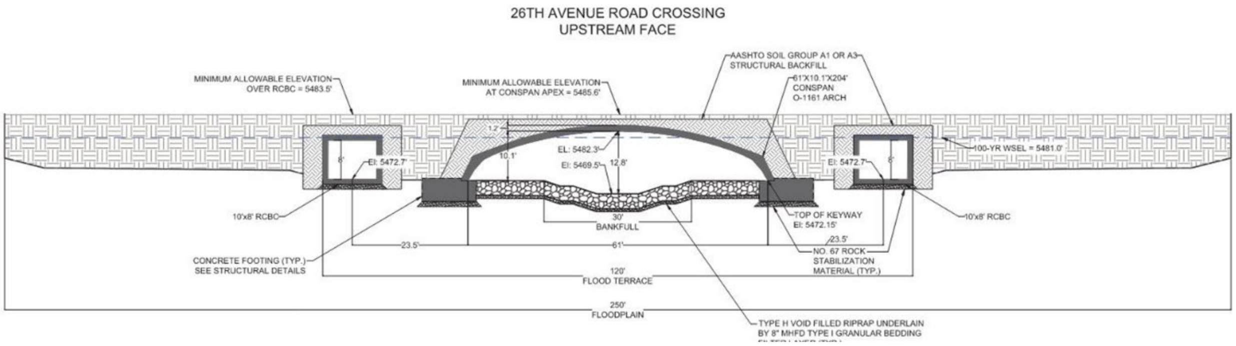

Figure 17: Proposed 26th Avenue Stream Crossing Structure over First Creek

6.1.4 Project Results

The construction of the First Creek at E. 26th Avenue crossing project was completed in April 2022 and has met the goals set for the project to date (Figure 18). The project will continue to be monitored and maintained by the MHFD to ensure it performs as intended and to facilitate ongoing research into Geomorphically Informed Stream Crossing Structures (GISCS).

Figure 18: Constructed Crossing of First Creek at E. 26th Avenue in Aurora, Colorado

Figure 19: Primary Crossing of First Creek at E. 26th Avenue

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