# Abstract

Historically culverts were placed in streams with little or no consideration for effects on the stream channel or for aquatic organisms. Perched culvert outlets, excessive water velocities, constricted stream channels, debris plugged culverts or culverts with inadequate water depth often impact fish passage by delaying or impeding fish movements. Stream simulation culverts (also known as Aquatic Organism Passage or embedded culverts) are channel spanning structures designed to replace traditional culverts with a structure that mimics a bridge and has similar passage conditions to the adjacent channel. The assumption is that any aquatic organism that can move in the natural stream channel should also be able to move up and downstream through a well designed and constructed stream simulation culvert. Stream simulation culverts are widely accepted both in Alaska and elsewhere as the preferred method in constructing small road-stream culvert crossings. Over 300 stream simulation type fish passage culverts have been installed in Alaska since 2005 with approximately 160 of those projects located in the study area of the Matanuska Susitna (Mat-Su) Borough, Municipality of Anchorage, and West Cook Inlet.

# Background

Historically culverts were placed in streams with little or no consideration for effects on the stream channel or for aquatic organisms. Perched culvert outlets, excessive water velocities, constricted stream channels, debris plugged culverts or culverts with inadequate water depth often impact fish passage by delaying or impeding fish movements (Goodrich et al.,2018; MacPherson et al.,2012.) Unrestricted access via stream corridors to spawning, rearing, and overwintering habitats is essential to maintaining salmonid production as well as healthy populations of resident trout and other fish (Jackson 2003). Movement of juvenile salmon and resident trout has been observed in response to a variety of environmental factors, including high and low flow events, changes in stream temperature, predation pressure, population densities and the availability of food or shelter (Gowan et al. 1994; Robison et al. 1999; Kahler and Quinn 1998). Due to the architecture of rivers as networks, stream bar-riers have potential to impede access to large swaths of upstream aquatic habitat when positioned lower in drain-ages (Cote et al.,2009; Kemp & O’Hanley,2010).

Sethi et al (2022) studied the movement of juvenile coho salmon (*Oncorhynchus kisutch*) in the Big Lake drainage, Alaska, USA between 2012–2013 and found that “Juvenile coho salmon that moved seasonally to lake overwintering habitats grew faster and were significantly larger as smolts compared to their counterparts who remained in streams exclusively (spring Age 1 fish: 18% larger by weight, 9% faster growth rate; spring Age 2+ fish: 26% heavier, 11% faster growth)” and that juvenile coho that were blocked from accessing a potential overwinter headwater lake by a culvert had lowest body condition among study groups”.

# Stream Simulation Culverts

Stream simulation culverts (also known as Aquatic Organism Passage, embedded culverts, fish-friendly culverts etc.) are channel spanning structures designed to replace traditional culverts with a structure that mimics a bridge and has similar passage conditions to the adjacent channel. The assumption is that any aquatic organism that can move in the natural stream channel should also be able to move up and downstream through a well designed and constructed stream simulation culvert. Stream simulation culverts are widely accepted both in Alaska and elsewhere as the preferred method in constructing small road-stream culvert crossings for aquatic organism passage (McKinnon and Hyntka, 1985, Browning, 1990, Municipality of Anchorage 2007, CDFG 2002, Taylor and Love 2003, USFS 2008).

Over 300 stream simulation type fish passage culverts have been installed in Alaska since 2005 with approximately 160 of those projects located in the study area of the Matanuska Susitna (Mat-Su) Borough, Municipality of Anchorage, and West Cook Inlet.

Although each site is different and requires a specific design solution in general ADFG Fish passage program recognizes that stream simulation designs should conform to the following guidelines:

* Size – the diameter of the culvert will be at least 20% greater than the stream’s natural active channel width in an alluvial system and will be equal or greater than the streams active channel width in a wetland or low gradient system.
  + For narrow channels with wide floodplains, streams with multiple channels or streams with high seasonal variation in flows additional or overflow culverts are considered.
* Gradient – the culvert gradient will be +/- 1% of the average natural stream gradient.
* Embeddedness – culverts will be embedded no less than 20% below the naturally projected bed scour depth and no more than 40% the overall diameter of the culvert.
* Substrate – culverts will be back-filled with the same size and size fraction of sediment as the naturally occurring stream sediment but be dynamically stable up to the 50-year event.
* Low Flow Channel – care should be given to mimic stream conditions during low flow conditions such that the thalweg within the culvert has similar depth and velocity to the natural stream. Often this requires utilizing substrate to mimic the stream bank lines or creating another type of forcing structure.
* Capacity- the culverts will pass a 100-year storm flow at less than 100 percent of the culvert’s height. This allows for passage of other watershed products (large wood, debris, and substrate) during extremely high flows.
* Channel- the project will maintain or construct stable stream banks upstream and downstream of the crossing in the transition zone that tie into the natural banks to prevent either scour or sedimentation.
* Revegetation- the disturbed area will be re-vegetated with native riparian and upland vegetation.

The goal of a stream simulation culvert is to move water, sediment and debris at the same rate the adjacent natural channel does by maintaining the same physical dimensions throughout. Outside of a culvert, reconstructed channels are stabilized to the desired dimensions using large rock and bank bioengineering and will become more stable over time as revegetation takes place. As no plants will grow inside a culvert, maintaining desired channel width and depth relies solely on the design and construction of the stream beds and banks. Stream beds are typically defined with both large rock designed to be immobile at the largest anticipated flows and the rest of the channel consists of a mix of smaller material down to very small sand and silt. At the highest flows when the stream flows are able to mobilize the bedload it is assumed that any sediment washed out of the culvert will be replaced by sediment of a similar size and composition washing in from upstream. If there is concern about sediment stability, for example in high gradient systems, sub-surface sills or baffles may be installed to help retain sediment.

If there is concern about high bedload filling the structure banks made of large immobile rock or other forcing features (created meander bends, rock weirs) to encourage scouring of gravel and fines within the active channel.

Structures may be undersized, estimating flows is difficult in Alaska where there are few gages of record and many watershed with unusual hydrology or geology. Ice jam related flooding, beaver dams, extensive wetlands and porous watershed boundaries where water may flow into one of two or more channels in any given water year can complicate flow estimation. Most failures of the undersized structures would involve sediment being moved downstream out of the structure or the aggradation of sediment within the structure. The former are typically related to an undersized structure which concentrates flow and creates more scour than is present in the adjacent channel. Once substrate has been removed from the pipe it will not typically refill naturally with stream sediment.

Conversely failures due to aggradation are typically due to the constructed channel being oversized in relation to the natural channel and to a lack of banks or other forcing structures to concentrate flow on the falling hydrograph. A plane bed will form inside the culvert and will persist indefinitely in the absence of plant growth and other natural channel forming processes. In some cases this can block all fish passage but this more typically a low flow barrier, therefore the impacts to fish will depend on the migratory habits of individual species at that site.

Correctly sized structures may fail if the substrate is not correctly sized or installed. A well designed and densely packed substrate should be watertight and flow should not scour down into the channel or wash out more small cobbles, gravel and fines than are replaced by bedload coming in from upstream. When the installed substrate is not watertight flow will go subsurface in extreme cases the channel inside the culvert will be dry despite flow up and downstream. Where too many fines wash out the channel becomes “bony” or composed only of large rocks with no smaller substrate and in extreme cases can block fish from passing, especially larger fish and at lower flows. If the channel is installed at too high or low an elevation in relation to the natural stream channel it will not function as designed, common complications in this case are sub-surface flow due to a lack of stream armoring or the formation of a plane bed due to aggradation as forcing structures are buried during bedload transportation into the structure.

An additional common point of failure is constructed grade control structures. These are full or partial channel spanning structures that are designed to retain bedload and maintain a given channel bed elevation that is required to prevent large drops in the water surface over a reach or to prevent a headcut in the upstream reach. Constructed grade control can be difficult to construct and may be damaged when hit by debris, in ice jams or even when being walked on. When grade control structures fail large drops or headcuts can develop.

Bioengineering and re-vegetating the disturbed are critical to the success of stream simulation type fish passage projects. Bioengineering structures are used to re-create the bank and channel profile, to ensure the up and downstream reconstructed reaches are similar to the natural channel, and to prevent bank erosion due to riverine or overland flooding. Rapid revegetation of natural species provides habitat and resting areas for fish and ensures there are no behavioral barriers to fish approaching the structure.

# Objectives

Over 300 stream simulation type fish passage culverts have been installed in Alaska since 2005 and at the time of this study approximately 150 of those projects located in the study area of the Mat-Su Borough and Municipality of Anchorage. This study sought to evaluate the stability of these stream simulation type fish passage culverts and associated channel and bank reconstruction and revegetation over time in order to better inform future design and construction of fish passage projects. Physical assessments of these culverts and the constructed stream simulation channels and associated bank engineering and re-vegetation efforts were conducted and the results compared to the original project designs and adjacent reaches in order to determine whether the design performs as intended and whether constructed channels and features have remained functional.

The objectives of this project were to

1. Evaluate the stability of constructed channels and banks inside and adjacent to the culvert with respect to the original design parameters.
2. Evaluate the stability of bioengineered banks and the success of re-vegetation efforts.
3. Develop a standardized data collection protocol that can be used for long term monitoring.
4. Make recommendations to better inform future design and construction of fish passage projects in Alaska and beyond.

Hypothesis to be tested:

1. Culverts must have a minimum construction ratio of 1:1.20 to maintain a stable channel, this ratio was chosen as it is used in regulation in regions outside Alaska.
2. Stability will decline as you move away from that ideal range in either direction, but loss of stability will be greater in magnitude where the CR decreases vs increases.
3. Stability in reconstructed reaches outside the culvert will be greater than inside at the same site due to the stabilizing effects of vegetation on the bank and channel dimensions.

# Methods

## Site Selection

The Study Area encompasses the Mat-Su Borough and the Municipality of Anchorage. This area was chosen for its proximity to Anchorage and the density of fish passage projects (Figure 1).

All known “fish passage” culvert replacement, including Tier I projects constructed under the MOU between ADF&G, were located using records from the ADF&G Fish Passage Improvement Database, ADF&G Habitat Section permitting records, the U.S. Fish and Wildlife Service (USFWS) Fish Passage program, the Mat-Su Borough (MSB) Public Works and the Alaska Department of Transportation and Public Facilities (AKDOT). Replacement projects not already in the DF&G Fish Passage Improvement Database as fish passage sites were entered during this study.

All sites were evaluated for the availability of design, as-built drawing and/or permit information and at a minimum information on the culvert dimensions, design slope and design channel dimensions and substrate size were required for inclusion. 147 suitable stream simulation projects were identified, installed between 2004 and 2020. All 147 sites were visited and 69 were found to fit the criteria for this study: replacement accurately reported, availability of design data, accessible from the road system or with permission from the landowner, and large enough for the survey crew to take the required measurements inside.

The breakdown of those sites by size and gradient is shown in Table 1. These categories were chosen as representative of two of the major drivers of design: stream size and gradient. Stream size drives design in terms of constructability while stream gradient is a major driver of the natural forming channel bed type which the constructed stream simulation channels are mimicking. 8’ was chosen as it approximates the width separating designs based on circular culverts and rectangular or box culverts. 1.5% gradient was chosen as it is the gradient that typically separates the most prevalent stream types in the project area. Streams less than 1.5% in gradient are typically low gradient streams with few bed features and sediment composed of sand, small gravels and silt or organic materials while streams between 1.5% and 4% gradient represent pool-riffle and step pool channels with bed material composed primarily of gravel or cobble.

Table 1.- Breakdown of selected sites by size and gradient

|  |  |
| --- | --- |
| **Streams less than 8' in width** | **Number of Sites** |
| 0-1.5 % gradient | 48 |
| >1.5 % | 30 |
| **Streams greater than 8' in width** |  |
| 0-1.5 gradient | 41 |
| >1.5 | 36 |
| **Total Number of Sites** | **155** |

At each site 5 reaches were identified as follows moving from downstream to upstream (Figure 12.) Example of numbered survey reaches to be designated at each site.

1. Existing channel downstream of the disturbed area for 50’
2. Reconstructed channel extending from the edge of the disturbed area to the culvert outlet.
3. Interior of culvert; which will be divided into three evenly spaced lengths designated 3a (downstream), 3b (middle) and 3c (upstream)
4. Reconstructed channel extending from the culvert inlet to the edge of the disturbed area.
5. Existing channel downstream of the disturbed area to 50’

Diagram, engineering drawing

Description automatically generated

1

2

3

4

5

Figure 1.–Example of numbered survey reaches to be designated at each site.

## Pre Survey Data

For all selected sites a standard set of information (Table 2.–Pre-Survey Data Collection.) was taken from the final stamped PS&E or designs prior to data collection in the field. Where a range of data was provided, typically in case of Channel Width the median value was used. In some cases red lines or construction notes were provided and that information was used and recorded in the study dataset.

Additional data identified in the Operational Plan was not available for any or the majority of sites including: Designer, Contractor, Channel Depth, Water depth, OHW Depth, Date of Completion with more accuracy than the year, Date of Planting, Floods of Record Since Construction and are not included in this study.

Table 2.–Pre-Survey Data Collection.

|  |  |  |
| --- | --- | --- |
| Variable Name | Recording Format | Source |
| Year of construction | 4-digit Year | ADFG FPID, Road Owner or Project Manager |
| Design Stream Slope | Number in %.. If up and downstream slopes differ the slope chosen for the constructed reach was used (Reaches 2,3 and 4) | Final Design Materials |
| Design Channel Width | Number in decimal feet. Maybe be a range in which case record range and median width  Note whether: Ordinary High Water, Bankfull and Active Channel width. If more than one, all were recorded. | Final Design Materials |
| Structure Width and Height (effective opening) | Height from top of structure to thalweg and widest width of opening at inlet and outlet. | Final Design Materials or As-Builts |
| Number of Typical Cross Sections | Count of typical cross sections from plans, typically: upstream reconstructed reach, downstream reconstructed reach and one or two interior typical cross sections | Final Design Materials |
| Bank Design Type | None, Same as Stream Bed or Larger than Stream Bed | Final Design Materials |
| Channel Design Type | Step Pool, Pool-riffle, Rocky Riffle, Plane Bed, Other | Final Design Materials |
| Channel Plan | Straight, Meandering | Final Design Materials |
| Grade Control Structures | Type and Count  Types: Fully channel-spanning, partially channel spanning, above or below channel bed elevation. | Final Design Materials or As-Builts |

### Field Data Collection

Fieldwork was carried out between August and October of 2021 by a crew consisting of two field technician and one biologist from the Sport Fish Passage Program. During this period the water levels remained visibly at or within 1-2” of OHW throughout the study area due to persistent rainfall in the MSB and Anchorage.

Each located site was visited by the field crew and it was determined if it was safe and accessible to survey. If a site was safe and accessible a standard set of measurements, visual observations, photographs and survey data was collected (tables 4-6). Data collection took, on average, between one and two hours per site.

Where possible all data collection has been made consistent with either the ADFG Fish Passage Assessment Protocols (Eisenman and O’Doherty 2014) or the Draft ADF&G Streambank Rapid Monitoring Protocols. Measurements were all recorded in decimal feet and will be recorded to the nearest 1/10th foot, except any elevations which will be recorded to the nearest 1/100th foot.

Table 3.–Measured variables.

|  |  |  |
| --- | --- | --- |
| Location Measured | Name | Description |
| 1,2,3,4,5 | Reach Length | Reach length was measured by running a tape measure along the left bank outside the culvert and by running the tape long the top or side of the culvert inside the structure. |
| 1,2,3,4,5 | Channel Width | The average of three measurements taken in straight or riffle sections. Measured from top of bank to top of bank (distinct break above OHW where substrate transitioned from primarily vertical to primarily horizontal.) |
| 1,2,3,4,5 | Average Water Depth in Thalweg | Measured at three or more locations in the thalweg and averaged. Measured with a pocket rod or survey rod. |
| 1,2,3,4,5 | Water Surface Gradient | The difference in elevation between the water surface at the upstream end of the reach and the downstream end. Elevations will be taken at the stream margin or in a pool where water surface is smooth and unbroken. |
| 1,2,3,4,5 | D100 | The median diameter of the visually estimated largest rock in the selected area will be measured in decimal feet using a tape measure or pocket rod. |
| 1,2,3,4,5 | D50 | The median diameter of the visually estimated median sized rock material in the selected area will be measured in decimal feet using a tape measure of pocket rod. |
| 2,3,4 | Bank Height | Measured from the toe of the bank to the top of the bank using a tape measure or pocket rod where bank is placed or natural occurring substrate with elevation greater than OHW. |
| 3 | Bank Width | Measured from the top of the bank to the edge of the culvert using a tape measure or pocket rod where bank is placed or natural occurring substrate with elevation greater than OHW. Only taken inside culverts with placed or naturally occurring banks. |
| 3 | Interior Bank Length (inside culvert only) | Length of visible bank where bank is placed or natural occurring substrate with elevation greater than OHW. |
| 2,4 | Exterior (Reconstructed Reach) Bank Length | The total length of reconstructed bank for each type of bank reconstruction categorized by the technique used closest to the water line: riprap, rootwads, toewood, brushlayers, coir logs, trenched willows, brush matrix. |

Crews visually estimated the following variables using the guidelines provided for the Reaches indicated in Column 1.

Table 4.–Categorical variables.

|  |  |  |
| --- | --- | --- |
| Reaches | Variable Name | Recording Options |
| 1,2,3,4,5 | Overall Channel Stability | Severe Downcutting, Moderate Downcutting, Stable, Moderate Aggradation, Severe Aggradation |
| 1,2,3,4,5 | Geomorphic Channel Type | Cascade, Step-pool, Pool-riffle, Unbroken Riffle, Plane-bed, Sand (dune-ripple), Braided, Multiple Stable Channels, Wetland, Other. |
| 1,2,3,4,5 | Flow Type | Broken Waves, Unbroken Waves, Rippled, Smooth, No Visible Flow, Intermittent Sub-surface Flow, Dry. |
| 1,2,3,4,5 | Dominant Channel Bed Substrate | Bedrock, Boulder, Cobble, Gravel, Sand, Silt, Clay, Organics, None. |
| 1,2,3,4,5 | Depositional Feature Type | Point bar, Side-bar, Mid-Channel Bar, Confluence Bar, other |
| 2,3,4 | Constructed Grade Control visible? | Rock Weir, Rock Weir , Riffle, Other  Count |
| 2,3,4 | Any Channel Spanning Drops | Number, Description and photo |
| 1,5 | Natural Channel? | Mostly Natural, Mostly Altered |
| 2,4 | Bioengineering Structure Condition | 1= failed or imminent failure, 2=poor >50% failure of structures and/or <50% plant survival along length of structure, 3=fair condition between 2 and 4, 4= good < 5% failure of structures and continuous plant survival through length of structure 5= no failures, excellent plant survival |
| 2,4 | Bioengineering Structure Breakdown | 1= Total or near total breakdown of structures such as coir logs or disappearance/ incorporation of rock/ wood into natural vegetation, 2= >50%, 3= between 2% and 50%, 4= less than 2%, 5 = none, structures are all as installed. |
| 2,4 | Estimated total vegetated cover of disturbed area | Estimated percent cover of any kind of vegetation in disturbed area above OHW elevation. |
| 2,4 | Bank or adjacent upland vegetation loss? | Bank, Riparian, Upland, None. |
| 3 | Concentrated flow along edge? | No, Right, Left, Both alternating, (Both culvert filled with water) |
| 3 | Channel form | Straight, Meandering, Braided |
| 3 | Structure Condition | 1-5 as described below.  1. Defective: culvert is in dire need of prompt repair or replacement; flaws threaten to disrupt or are hindering traffic, 2. Poor: culvert is in need of repair and shows potential for further deterioration, 3. Fair: culvert is operational but may need maintenance to restore function to full potential; distinct rust line and/or abraded bottom present; adverse conditions could lead to major problems. 4. Good: culvert shows minor deficiencies; beginning of rust line formation may be visible; with continued maintenance culvert should be trouble free. 5. Excellent: culvert shows no signs of problems or rust; could allow flow at full capacity without disrupting fish passage. |

Crews also carried out additional visual observations with a simple Y/N answer.

Table 5.–List of other data collected.

|  |  |  |
| --- | --- | --- |
| Reaches | Variable | Recording Options |
| 1,2,3,4,5 | Continuous Thalweg? | Yes, No |
| 1,2,3,4,5 | Beaver Dam? | Yes, No |
| 1,2,3,4,5 | Depositional Features present? | Yes, No |
| 2,3,4 | Scour pool or scoured banks at inlet/ outlet? | Yes, No |
| 2,3,4 | Evidence of bank instability? | Yes, No |
| 2,3,4 | Failed Grade Control | Count |
| 1,5 | Pond or Lake? | Yes. No |
| 1,5 | Confluence or Ditch? | Yes, No |
| 2,4 | Collar Armor Collapsing into channel? | Yes, No |
| 2,4 | Natural vegetation recruitment occurring? | Yes, No |
| 2,4 | Invasive Plant Species present? | Yes or No. |
| 3 | Water surface drop at outlet? | Yes, No  Measure and photograph. |
| 3 | Woody debris present in culvert? | Yes, No |
| 3 | Fish holding in culvert? | Yes, No |
| 3 | Fish spawning in culvert? | Yes, No |
| 3 | Undermined footing? (open bottom arch culverts only) | Yes, No |
| 3 | Culvert bottom visible | Yes, No |
| 3 | Observed interior Banks | Yes, No |
| 3 | Evidence of banks collapsing (paint lines, missing sections etc) | Yes, No |
| 3 | Evidence of banks buried in sediment | Yes, No |
| Site | Any Potential Fish Passage Barriers? | Yes, No  Description and Photograph |
|  |  |  |

### Channel Width

Prior to commencing field data collection we carried out repeated measurements at one site on Pacer Street in Anchorage to determine the most replicable method for measuring bank width. 8 staff took part in this exercise: 2 field technicians, 2 fish passage biologists with experience carrying out fish passage assessments and other monitoring activities at culverts, two fisheries biologists with limited experience taking stream measurements and 2 stream bank restoration staff with experience carrying out measurements on streams but not inside culverts. We also had data from a previous professional survey of the site carried out licensed surveyors and a design sheets and accompanying documents prepared by an experienced licensed fish passage PE.

Typical measurements are bankfull width and ordinary high water (OHW). During this exercise we found that OHW could not be measured consistently or at all inside the culvert and was not a useful metric. Similarly bankfull is a measurement that relies on natural channel forming processes which were not present in a culvert or the adjacent armored banks. The only consistent measurements of channel width amongst participants and designer was top-width- the widest point of the channel measured perpendicularly to the break in gradient where a vertical bank becomes horizontal. With minimal instruction, similar to what a monitoring crews of seasonal technicians might receive in the future, all participants were able to consistently measure channel width this way both inside and outside the culvert and in the adjacent natural reach.

This is also typically how channel width is indicated on engineered drawings and if not, it can be reliably calculated. The majority of the designs we used in this study did not include OHW width. The top-width was indicated on all of them, although under various labels including “Channel Width”, “Bankfull Width”, “Top of Bank Width”, “Bank to Bank” “Width” etc.

### Bank Dimensions

Many AOP culverts are constructed with artificial banks throughout all or part of the interior. These interior “banks” are constructed by installing substrate along one or both side of the culvert that projects above the projected ordinary high water or bankfull water elevation. Interior banks may be constructed of substrate that is the same size and mixture to the channel bed or, more typically, of larger substrate, often large riprap. In some culverts sediment transport has caused the deposition of substrate that mimics these constructed banks. Interior banks cannot be stabilized with vegetation and are frequently limited in height by the overall structure size. Interior banks may function more like unvegetated bars or like bedrock chutes, depending on the design and construction methods. There are various reasons to install interior banks but the most common is to maintain the cross sectional area of the stream through the structure at most flows while still providing additional capacity during high flows.

During the field portion of this study we found that interior banks had formed inside culverts where they were not designed through the natural movement of sediment. For the pusposes of this study inside the culvert any sediment, placed or naturally accumulated, that was above the estimated OHW level was called an interior bank and measured and recorded as such.

Throughout this study both interior banks and streambank heights were measured from the bottom of the streambed at the toe of the bank vertically to the elevation corresponding to the “top” of the bank, or the location that we took the top-width channel measurement. The width of interior banks was measured from the edge of the structure (inside the corrugations where applicable) to the same location at the top of the bank.

### Channel Features and Grade Control Structures

Designers used a variety of channel forming features and grade control structures and also various names for those features and structures. We assigned each structure to one of three categories as follows:

1. Channel Spanning (CS)- a structure designed to extend vertically above the stream bed into the flow of water and span the entire channel, e.g. rock and log weirs, steps and some cross-vanes.
2. Partially Channel Spanning (PA)- a structure designed to extend vertically above the stream bed into the flow of water but not span the channel, e.g. rock clusters, J-hook, some cross-vanes.
3. Subsurface (US): a structure designed to be entirely below the channel bed or at the channel bed elevation and not extend vertically into the flow of water, e.g. rock banks and sediment retention sills.

### Visual Observations of Sediment Transport

Visual Observations were made in accordance with draft monitoring plans for the ADF&G bioengineering program as follows:

* Severe Erosion: Downcutting of channel bed, collapsing banks, vegetation collapsing into channel sediment absent from inside culvert or footings exposed in open bottom
* Moderate Erosion: Little to no smaller material/ bars. Exposed riprap/ grade control in constructed reaches or inside culvert. Bed deep and narrow. Some bank instability.
* Stable: Bed consolidated and armored, often algae covered. Bed and bar material equal in size, Banks stable.
* Moderate Aggradation: Moderately large bars often with siltation. Bed wide and flat but with defined continuous thalweg. Bioengineering or grade control features installed at OHW buried. Siltation on top of banks.
* Severe Aggradation: Flat bed, channel filled in with sediment. Undefined or discontinuous thalweg. Bars covering most of channel. Sediment loose and unconsolidated. Gravel deposited on top of banks.

### Flow Types

Flow types were categorized visually as follows:

* BW: Broken standing waves; white-water; tumbling associated with rapids
* UW: Unbroken standing waves upstream facing wavelets which are not broken ~ mostly associated with riffles
* RP: Rippled no waves, but general flow direction is downstream with disturbed rippled surface ~ mostly associated with runs
* SM: Smooth perceptible downstream movement is smooth~ mostly associated with glides
* NP: No perceptible flow no net downstream flow ~ associated with pools, ponded reaches

### Cross-Sectional Area

Cross sections were collected at a typical location inside the culvert and at the up and downstream reconstructed reaches to replicate cross sections available on the designs. Measurements were made to an accuracy of 1/100th of a foot using a high precision altimeter which was chosen for ease of use inside the structures. The altimeter was tested against the an optical level prior to the commencement of field work.

Elevations were taken at as many of the following locations that are present at each side: Top of bank, Bank Culvert Interface, Ordinary High Water, Toe of Bank, Edge of Water, Edge of Low Flow Channel, Thalweg. Additional elevations may be taken at points on the Streambed, Bank, and any stream features such as bars or large rocks.

Cross-sections were collected during the field portion of this study however comparison to designs was problematic as many designs did not contain cross sections or they were not sufficiently labeled to calculate the cross sectional area and therefore no broad comparison to the designs was possible.

### Bioengineering and revegetation

It became apparent during the data collection period that bioengineering, bank reconstruction and revegetation outside the culvert (reaches 2 and 4) were often not drawn with sufficient detail or were altered during construction to better match existing conditions or because the disturbed area was smaller than planned. Bioengineering data was collected as planned however it was not analyzed against the designs and was instead used to evaluate the success of bioengineering as a whole.

Bioengineering assessments were made using the following guidelines:

* Structure Condition Score:1= failed or imminent failure, 2=poor >50% failure of structures + poor plant survival, 3=fair condition, 4= good < 5% failure of structures and good plants survival 5= no failures, excellent plant survival
* Breakdown Score: 1= Total or near total breakdown of structures such as coir logs or disappearance/ incorporation of rock/ wood into natural vegetation, 2= >50%, 3= between 2% and 50%, 4= less than 2%, 5 = none, structures are all as installed.

## Data Recording

Crews entered all measured or observed values into field forms and notebooks and later transcribed to a laptop computer. All data entry and calculations were checked by another crew member and later by fish passage program staff. A series of error checks was carried out and corrections made as needed. During analysis additional error checks were made to verify outlying values or results. Digital photographs were taken with one of two waterproof Olympus cameras and backed up each day onto a laptop computer and external hard drive.

## Data Analysis

For each of the variables we calculated a stability metric as follows:

Stability V = Measured Dimension / Design Dimension

|  |
| --- |
| Metrics |
| Channel Width |
| Water Surface Gradient  Interior Culvert Height |
| Interior Bank Length |
| Bank Height |
| Interior Bank Width |

Topic of discussion……….

# Results

## Designs

The major site considerations and design choices identified in the designs are shown in Table 6.

Table 6.- Major design considerations and choices taken from design materials and sheets.

|  |  |
| --- | --- |
| **Lake Outlet** | **No of Sites** |
| Lake Outlet | 6 |
| Lake Outlet with metal weir | 2 |
| **Structure Type** |  |
| Bottomless Structure | 9 |
| Closed bottom structure | 57 |
| **Channel Form** |  |
| Straight | 54 |
| Meandering | 12 |
| **Banks** |  |
| With Banks | 26 |
| Without Banks | 40 |
| **Grade Control** |  |
| Constructed grade control | 35 |
| Constructed grade control visible above substrate | 22 |
| No grade control | 31 |
| **Substrate** |  |
| Bank Material larger than Bed Materials | 19 |
| Bank and Bed same material | 22 |
| More than one mix or substrate size used for bed or banks | 43 |
| Only one substrate mix on designs | 22 |
| **Other** |  |
| Overflow pipe within banks | 2 |

## Outcomes of Field Surveys

Overall the surveyed sites were functioning well with only one site deemed unpassable, which was due to a large fallen tree on the upstream side of the road. A report was made to the maintenance staff and it is anticipated there will be no long term impacts at the site. All other sites appeared to be in passable condition and fish of several species were visually observed to hold inside or pass through the majority of measured culverts.

## Data Summary

Table 7.- Measured and Observed conditions at Culverts

|  |  |
| --- | --- |
| **Measured and Observed conditions at Culverts** | **No of Sites** |
| **Length of Culvert (ft)** |  |
| 25-75 | 49 |
| 75-125 | 14 |
| 125-175 | 3 |
| **Average Channel Width in Reach 3 (Culvert)** |  |
| 0-10 | 26 |
| 10-20 | 37 |
| 20-30 | 3 |
| **Average Water Depth in thalweg in center of Culvert (ft)** | |
| 0-1 | 26 |
| 1-2 | 15 |
| 2-3 | 2 |
| **Lake Outlet Y or N** |  |
| Y | 10 |
| **Channel Form in Reach 3 (Culvert)** |  |
| Straight | 61 |
| Meandering | 5 |
| **Interior Banks** |  |
| With Banks | 36 |
| Without Banks | 30 |
| **Grade Control or Channel Forming Feature Count Reach 3** |  |
| Total number of features or structures | 18 |
| Total number of features or structures | 65 at 18 sites |
| Observed failed features or structures | 6 |
| **Grade Control or Channel Forming Feature Type Reach 3** |  |
| Channel Spanning | 8 |
| Partially Channel Spanning | 10 |
| **WS Gradient through Culvert (%)** |  |
| 0-1.5 | 33 |
| >1.5 | 31 |
| unmeasured | 2 |
| **Observed Damage in Reach 3 (Culvert)** |  |
| N | 59 |
| Y | 7 |
| **Beaver Dam observed in Reach 3 (Culvert)** |  |
| N | 66 |
| Y | 0 |
| **Woody Debris Observed Inside Culvert** |  |
| N | 43 |
| Y | 23 |

Table 8.- Observed changes from major design considerations and choices at culverts.

|  |  |  |
| --- | --- | --- |
| **Lake Outlet** | **No of Sites Design** | **No of Sites Measured** |
| Lake Outlet | 6 | 10 |
| **Channel Form Inside Culvert** |  |  |
| Straight | 54 | 61 |
| Meandering | 12 | 5 |
| **Banks?** |  |  |
| With Banks | 26 | 36 |
| Without Banks | 40 | 30 |
| **Grade Control** |  |  |
| Constructed grade control visible above substrate | 22 | 18 |

Table 9.- Measured and Observed Conditions at Reaches 2 and 4, up and downstream reconstructed reaches located within the disturbed area.

|  |  |
| --- | --- |
| **Measured and Observed conditions at reconstructed stream reaches outside the culvert** | **No of Sites** |
| **Length of reconstructed reach at Reach 2 downstream (ft)** |  |
| 10-35 | 33 |
| 35-60 | 17 |
| 60-85 | 11 |
| 85-110 | 3 |
| 160-185 | 1 |
| **Length of reconstructed reach at Reach 4 upstream (ft)** |  |
| 0-25 | 22 |
| 25-50 | 26 |
| 50-75 | 7 |
| 75-100 | 7 |
| 100-125 | 2 |
| 125-150 | 1 |
| **Visually Estimated Vegetation Cover in downstream disturbed area** |  |
| <20% | 4 |
| 20%-40% | 1 |
| 40%-60% | 4 |
| 60%-80% | 5 |
| 80%-100% | 51 |
| **Visually Estimated Vegetation Cover in downstream disturbed area** |  |
| <20% | 5 |
| 20%-40% | 3 |
| 40%-60% | 1 |
| 60%-80% | 5 |
| 80%-100% | 46 |

Table 10.- Measured and Observed Conditions at Reaches 1 and 5, up and downstream natural reaches located outside but adjacent to the disturbed area. All reaches 1 and 5 are 50' in length.

|  |  |
| --- | --- |
| **Measured and Observed conditions at Adjacent Natural Reaches** | **No of Sites** |
| **Downstream Channel Visibly Altered or Modified** |  |
| N | 55 |
| Y | 8 |
| **Upstream Channel Visibly Altered or Modified** |  |
| N | 53 |
| Y | 9 |
| **Downstream Average Water Depth in thalweg** |  |
| 0-1 | 28 |
| 1-2 | 24 |
| 2-3 | 3 |
| 4-5 | 1 |
| **Upstream Average Depth in thalweg** |  |
| 0-1 | 22 |
| 1-2 | 24 |
| 2-3 | 2 |

## Measured vs Design Construction Ratios

Constriction Ratio is typically defined as the width of the structure divided by the upstream bankfull, active channel or OHW width. However the majority of designs and design documentation did not include a calculate CR value. Instead the design CR was calculated by taking the upstream measured width and dividing it by the structure width. When comparing the design CR to the measured construction ratio acting on flows entering the culvert , ie the ratio of the culvert structure to the measured top-width of the immediate upstream reach (Reach 4) discrepancies were found at the majority of sites. A variety of causes were directly observed for these discrepancies: different measurement techniques, incorrect installation of the culvert or the upstream reach, vertical adjustment of the streambed where a culvert had angled sides. At other sites the source of the discrepancy was not clear. Figure 2 shows the range of differences observed.

Figure 2.- Difference between calculated and measured CR at the inlet of each site. Each vertical line represents a site and the two colored points represent the measured and design CR.

## Visual Observations of Sediment Transport

319 of 452 visual observations or 71% judged the channel to show no signs of active or past aggradation or loss of sediment or vertical movement of the channel bed (Table 7). Only 10.5% of observations were judged “severe” with the majority being severe aggregation inside the culvert. Overall aggradation (19%) was more commonly observed than channel degradation or downcutting (10%). The combined up and downstream constructed and natural reaches (4 observations per site) had a higher rate of Stable observations at 70% than the reaches inside the culvert (3 observations per site) where the rate was 44%.

Focus here will be on

Table 11.- Breakdown of Visual Assessment of vertical channel stability.

|  |  |  |
| --- | --- | --- |
| Visual Assessment of Channel | No. Of Observations | No of Observations inside culvert |
| Severe Degradation | 3 | 3 |
| Moderate Degradation | 40 | 27 |
| Stable | 310 | 88 |
| Moderate Aggradation | 43 | 41 |
| Severe Aggradation | 43 | 39 |
| **Total** | **439** | **198** |

### Evaluating the stability of constructed channels and banks inside and adjacent to the culvert with respect to the original designs

For each of the variables we calculated a stability metric as follows:

Stability V = Measured Dimension / Design Dimension

The Design width, measured width and Vstability score for each site are shown in Table 7- See Tab “Vtable” in Excel spreadsheet for this data.

Figure 3.- VChannel Width absolute deviation from 1 plotted against the Design CR

## Comparing Vstability to Categorical Values

Categorical Values were compared to the Vstability Score to determine how closely they correlate and if some may have utility as a more rapid assessment method.

Changes from up to downstream through the 5 reaches are compared to the Vstability score to see if there is utility in using visually discontinuous sites as a more rapid assessment method

## Bank construction and bioengineering in Reaches 2 and 4

# Discussion and Recommendations

1. Overall the projects are successful and no fish passage issues were noted related to design (one had damage and one had a large tree blocking in the inlet)
2. Culvert designs are more imprecise than anticipated, it was relatively difficult to extract standardized data. On several design the width of the channel + banks did not fit inside the structure or could not be constructed using the size of rock specified (ie Class 3 riprap and 1’ bank width)
3. A lack of consistency in how CR are defined, measured, calculated, recorded and verified is a major issue that is clearly leading to some inconsistent results. It is likely impossible to designate a single method of measuring the CR that will work at the variety of stream types in Alaska. Instead care should be taken to reach agreement on the methods used and those should be verified between all members of the project team and the reasoning recorded in writing.
4. The culvert width on quite a few designs did not take into account the width of the culvert walls (9- 16” on large corrugated structures) in the designs leaving the channel/ banks unable to be constructed as designed. And/or the internal and external width were used interchangeably or it was not clear which was referred to. Recommend always using the internal width going forward.
5. The design of the channel up and downstream was not well defined on many plans or was significantly different in some dimension than the culvert channel width or in what was actually constructed. This dimension was often height but sometimes width.
6. Bioengineering weas very successful and often hard to even find. Designs for bioengineering were vague, absent or altered onsite at the majority of sites so real analysis from design not possible. However it works so not a real issue.
7. Channel “banks” inside the culverts act more like bars in reality due to the lack of vegetation.
8. The most instability was seen in very small culverts that are not included in this study because we could not walk through them. We still visited and observed them and noted that several had been affected by head cutting/ channel adjustment or what appeared to be high flows and had lost substrate to some extent or developed a scour pool or even the beginning of a small perch at the outlet. The majority of these culverts were approx 4’ round, several were smaller. It is difficult to place substrate in such small culverts and due to the shallow depth of substrate it is more prone to instability due to channel incision of even a small amount. Very small creeks were visually judge to have seen more adjustment post replacement as a percentage of their overall depth. Very small creeks with pipe arches were thought o look better (no actual data on this) than round pipes.
9. Where multiple small culverts on one creek have been replaced in a small area (for ex at an intersection, or under multiple driveways) the affects of channel adjustment were typically greatest at the upstream most culvert in the series.
10. We did not survey the very long culvert under the New Seward Highway installed in ?? (the long Campbell Creek one) but we did walk through it and the constructed meandering channel appeared very stable and there were a number of good sized rainbow trout in there.

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