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Factors for Improved Fish Passage Waterway Construction

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RESEARCH

FACTORS FOR IMPROVED FISH PASSAGE WATERWAY CONSTRUCTION

Final Report

SPR 654
OTREC-RR-11-19

ODOT/OTREC

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16. Abstract

Streambeds are important fish passageways in Oregon; they provide for the necessary habitats and spawning cycles of a healthy fish population. Oregon state law requires that hydraulic structures located in water properly provide fish passage. Increasingly stringent state and federal regulations apply to these fish passageways, and designers must become more cognizant of conditions over a range of flows to accommodate fish movement and avoid expensive structural failure of these passageways. Fish passage structures are built when roads cross streambeds and may include culverts, or bridges. When these structures are built, the streambeds are re-created using a technique called "roughened channels". Roughened channels are man-made stream channels utilized for re-creating the hydraulics necessary for adequate stream passage, and this may include new constructions or retrofits of older, inadequate structures. Mixtures of materials are used to construct the bed of roughened channels, ranging from fines such as sand, silt and gravel to coarse elements like cobbles and boulders. Fines are a critical element in limiting permeability of the constructed bed thus keeping stream flow at the surface of the roughened channel during low flow periods. This report discusses work of a research project designed to discover factors that are key to successful long-term implementation of fish passageways, especially focused on the construction process.

Areas of inquiry postulated in this study are that failures experienced in actual installations may be due to inadequate range and/or mix of soil and rock material gradation; unexpected water velocity, especially during high flows; inadequate mixing of rock and soil materials during construction; and inadequate compaction of rock and soil materials during construction. This report suggests that several factors may be especially important considerations in fish passage success. These factors are the relationship of downstream slope to structure slope, well-graded fine soil materials in the channel fill (improved by choice of fill source), and frequent site visits. Improving fish passages for cost-efficient fish movement is a priority for government agencies such as Oregon Department of Transportation (ODOT) and Oregon Transportation Research and Education Consortium (OTREC).

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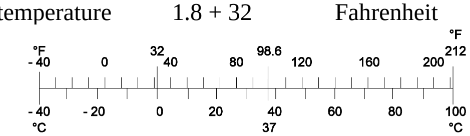
SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	millimeters squared	mm^2
ft^2	square feet	0.093	meters squared	m^2
yd^2	square yards	0.836	meters squared	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	kilometers squared	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	meters cubed	m^3
yd^3	cubic yards	0.765	meters cubed	m^3
NOTE: Volumes greater than 1000 L shall be shown in m^3.				
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams	Mg
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5(F-32)/9	Celsius temperature	°C

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	millimeters squared	0.0016	square inches	in^2
m^2	meters squared	10.764	square feet	ft^2
ha	hectares	2.47	acres	ac
km^2	kilometers squared	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	meters cubed	35.315	cubic feet	ft^3
m^3	meters cubed	1.308	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.205	pounds	lb
Mg	megagrams	1.102	short tons (2000 lb)	T
		TEMPERATURE (exact)		
°C	Celsius temperature	1.8 + 32	Fahrenheit	°F



* SI is the symbol for the International System of Measurement

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DISCLAIMER

FACTORS FOR IMPROVED FISH PASSAGE WATERWAY CONSTRUCTION

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES AND PHOTOS

1.0 SUMMARY

This report discusses the results of field investigation of 19 fish passageways constructed by the Oregon Department of Transportation (ODOT). The purpose of this field investigation was to explore and discover factors that may provide insight into more reliable and sustainable solutions to the problem of reconstructing fish passageways when highway crossings disturb natural waterways. The focus of this study is whether construction practices may play a significant role in the long-term success of these passageways. The investigation measured the physical channel characteristics of seasoned fish passageways and developed a rating—a Success Index—to measure how these channels behaved as successful fish passageways. The researchers additionally collected measurement information including slopes, channel configurations, crossing structure characteristics, and streambed soil characteristics. These physical metrics of the sites were correlated against the Success Index and other important fish passageway factors, and the results are presented here. Important findings include a relationship between downstream slope and scour, as well as an assessment that subsurface flow may be related to construction technique factors such as material source.

2.0 WATERWAY CROSSINGS

Waterway crossings such as bridges and culverts play a critical role in the U.S. transportation network. When properly designed, constructed, and maintained, bridges and culverts provide safe passage across all sizes of streams and rivers, estuaries, bays, reservoirs, and lakes. Waterway crossings represent a key and expensive element in the overall transportation system. While ubiquitous in urban areas, there are thousands of bridges and culverts that also service untold miles of remote roads in forests, national parks, and other environmentally sensitive areas (*Frei et al. 2005*).

Highway waterway crossings create stress on the natural environment. Fish and other aquatic wildlife depend on these waterways for passage to undertake natural processes, such as spawning. To address this issue, design methods have developed to serve the needs of both highway crossings and fish passage. The integral relationship between roadway stream crossings and fish passage creates a need to understand the basic characteristics of both culverts and bridges.

2.1 CULVERTS

There are more than 10,000 culverts on Forest Service and Bureau of Land Management Lands in Washington and Oregon alone, and more than 5,500 have been classified as impassable for fish. It has been estimated that it will take decades and may cost as much as $375 million to properly respond to these deficiencies (*General Accounting Office 2001*). There are likely thousands more crossings on city, county, state, and federal highways that are also impassable (*Frei et al. 2005*).

Culverts are used to convey water under road embankments. Smaller culverts are commonly circular. As culvert size increases other cross-sectional shapes such as elliptical, rectangular, or pipe arch become increasingly common. Culvert diameters can vary from inches to several feet. Even though culverts commonly have a length of about 100 feet (~30 m), culverts with lengths exceeding 300 feet (>90 m) are not uncommon. The longitudinal slope of culverts generally ranges from zero to about 5% (*Ead et al. 2002*).

A culvert is a rigid body that is set into an ever-changing stream environment. Even if originally designed to provide successful hydraulics, changes in land use due to urbanization or other factors can create an unstable watershed. As runoff volume increases, the streams actively degrade in order to accommodate higher flows. The inverts (bottoms) of culverts are unable to adapt to the degrading streams and thus may become barriers to fish movement. The most common reasons culverts become barriers are excessive outlet drops, high water velocity within the culvert, turbulence within the culvert, accumulation of sediment and debris, and an inadequate water depth within the culvert (*Bates 2003*). In addition to these barriers, the absence of refuge pools at either end of the culvert prevents fish from acquiring the rest necessary to traverse the obstacle. Scour pools located at the culvert outlet and mid-channel bars upstream of the culvert can also be signs of velocity barriers within the culvert. Some culverts are only seasonal barriers, acting as barriers during periods of low flow (*Bates 2003*).

The interior surface of a culvert is usually designed to optimize water passage; it does not have the roughness and complexity needed to slow down the water flow that a streambed does. Instead, the culvert concentrates and then dissipates energy in the form of increased velocity or turbulence downstream; channel scour creates the most prevalent impediment to passage at locations with culvert structures (*Bates 2003*).

Existing culverts may be altered or retrofitted to improve fish passage. Such efforts usually focus on reducing the height fish are required to leap in order to enter the culvert or on improving flow conditions within the culvert barrel through the use of baffles *(Frei et al. 2005)*. Existing culverts are oftentimes modified to meet fish passage requirements, creating retrofitted culvert fishways. A common modification is to divide the culvert into cells or bays, where fish can rest. The velocity barriers are known as baffles, an example of which is shown in Figure 2.1. Fish and wildlife agencies of Oregon, Washington, Maryland, and Virginia all state that the use of baffles on newly installed culverts should be discouraged, and cement aprons should not be used on culverts (*Gardner 2006*).

Figure 2.1: Example of Baffles in a Box Culvert

If a culvert is required to pass fish, then conventional hydraulic design procedures may have to be modified to consider fish passage (*Ead et al. 2002*). It is assumed that fish will use their burst speed to get past the velocity barriers, and then use their prolonged speed to travel in the pools along the areas of lower velocity. The advantages of a baffle system are that they require less over sizing than buried culverts and are less expensive than bridges and large, open-bottomed culverts (*Gardner 2006*).

Ead et al. (*2002*) performed a global analysis of the available experimental data on discharge and depth of flow and the velocity fields in these culvert fishways. The results of this study may facilitate the design and building of successful culvert fishways.

2.2 BRIDGES

Robinson et al. (*1999*) define a bridge as a structure spanning the entire width of a stream, which sits on abutments and/or piers. Regarding fish passage, bridges are generally considered as the best design alternative. They change the stream habitat and flow regime the least, and bridges are preferred in regards to natural resource protection. Bridges do not tend to create the same flow problems that culverts do, or at least not to the same extent. However, bridges are much more expensive to build and maintain than culverts.

The amount of money budgeted for resolving fish passage problems is limited. Constructing new bridges or converting a culvert to a bridge at an existing crossing would greatly increase the cost of waterway crossings and reduce the number of projects that could be accomplished. (*Robinson 1999*). In choosing between a bridge and a culvert for a specific site it is important to consider the geometry of the stream and other topographical features. Channel slope can play a major role in choosing a culvert or a bridge. Culverts are best used when they can be installed at the slope of the streambed or at less than 3% (*Fitch 1996*). When the stream gradient ranges from 5-8% ,the cost of the culvert becomes comparable to the cost of a bridge for that stream (*Robinson 1999*). In general, bridges become economical as the stream size increases. In *The Design of Road Culverts for Fish Passage*, Bates (*2003*) suggests that when a stream width exceeds 20 feet (6.1 m) or there is frequent movement of large debris, a bridge is the best design alternative. Another source suggests that culverts should only be used on small streams with a channel width of less than 10 feet (3.05 m) (*Robinson 1999*).

Most research articles and state design manuals list their order of preference for stream crossing options in the same order. The Oregon restoration guide has the following design table with advantages and disadvantages to fish passage for each crossing type, listed in descending order of preference.

Table 2.1: Advantages and disadvantages for crossing types. Source: (*Robinson 1999*)

Type	Advantage	Disadvantage
Bridge	Best alternative (for minimum ecological impact)	Most Costly alternative
Open Bottom Culvert	Good Alternative if properly sized	Expensive and difficult to install with a potential for scour and instability
Sunken and Embedded Culverts	Same slope as stream and same stream characteristics	Reported as difficult to install compared to non-buried culvert but ODOT hasn’t had difficulties
Flat Culverts	Least cost alternative	Difficult to get this passage flat and limited to <0.5% slope
Outlet Backwater Culvert	Low cost alterative (≤4% slope)	Installation of effective, stable weirs for passage can be tricky
Weir/baffle Culverts	Less expensive compared to bridges and open bottom culverts	Have a legacy of failure due to debris and sediment clogging and securing baffles
Fords	Low cost (limited use)	Can only be used for low traffic areas and large gravel apron needed on both sides of stream

2.3 ROUGHENED CHANNELS

Roughened channels refer to a method of design that strives to simulate a stream-like condition that will facilitate fish passage. This design consists of a graded mix of rock and sediment in an open channel that creates enough roughness and diversity to facilitate fish passage. The increased roughness aspect controls the velocity and patterns of flow, water depth, and the diversity aspect provides migration paths and resting areas for a variety of fish species and sizes (*Bates 2003*).

According to Bates (*2003*), the application of roughened channels might occur in the following situations:

- replacement culvert installations;
- moderate to high culvert slopes;
- over-steepened channel sections;
- where target species are identified for passage;
- where there is limited work area, e.g., limited to right-of-way; or
- where special design expertise, hydrology and survey information is available.

Roughened channels may be located inside of culverts, upstream and downstream. Installations of roughened channels inside of culverts have had mixed results with regard to fish passage and stability. Because of this, culverts designed as roughened channels are viewed as experimental at this time (*Bates 2003*). ODOT often designs culverts to retain bed material on the invert. The purpose of this is to provide resting and refuge for fish, not to dissipate energy as is the objective for a roughened channel.

When applied downstream of a fixed culvert structure, a roughened channel should be designed cautiously, since any degrading of the channel will result in conditions that degrade fish passage (*Bates 2003*). The design should be very conservative for steepened channels downstream of culverts or other fixed structures where any degrading of the channel may result in the culvert countersink or velocity criteria to be exceeded.

2.4 DESIGN AND CONSTRUCTION CONSIDERATIONS

2.4.1 Hydraulics

Three regimes of flow exist within highway crossings—flow upstream of the crossing itself, flow at the point of crossing (called here the “structure channel”), and flow downstream of the crossing; these three comprise the fish passage “system”. While these three regimes are clearly evident in culvert installations, they may or may not be clearly evident in bridge crossings. The configuration of the bridge, especially placement of the bridge abutments, significantly influence whether bridge crossings exhibit three flow regimes or merely one continuous channel. These crossings are designed to have sufficient capacity to pass a wide variety of stream flows without threatening the structural integrity of the highway and are also designed to avoid significant erosion of the upstream, structure, and downstream channels.

According to Bates (*2003*), most states practice one of two general design approaches; stream bed simulation and/or hydraulic design. According to the Oregon Department of Fish and Wildlife (ODFW), for road crossings (i.e., culverts or bridges), either of the two design and installation methods (or both) may be used as long as the respective criteria are met for that method; however, the stream bed simulation method is preferred by ODFW (*2004*). The decision of method depends upon many factors, including site configuration, existing obstructions, right-of-way availability, and available funds.

This research assumes that the original hydraulic design of the waterway crossings was sufficient for the purposes of capacity and integrity; therefore, the reader is referred to existing literature for discussion of hydraulic design.

2.4.2 Erosion

One of the main design considerations for roughened channels is to preserve stream bed stability. Erosion impacts the stability of roughened channel materials and therefore it is important to discuss erosion in more detail. Designers of stabilization or restoration projects must ensure that the materials placed within the channel or on the banks will be stable for the full range of conditions expected during the design life of the project (*Fischenich 2001*).

Erosion is attributed to many causes. Some of the factors that influence bank erosion were identified by Fischenich (*2001*) and they are listed below in Table 2.1. Many of these same factors apply to channel erosion generally.

Table 2.2: Factors that influence bank erosion

Factor	Description
Flow Properties	Magnitude of flow, Frequency and variability of stream discharge, Magnitude and distribution of velocity and shear stress. Degree of turbulence
Sediment composition	Sediment, Size gradation, Cohesion. Stratification
Climate	Rainfall Amount, Intensity and duration, Frequency and duration of freezing
Subsurface conditions	Seepage Forces, Piping, Soil moisture levels
Channel geometry	Width and depth of channel, Height and angle of bank, Bend curvature
Biology	Vegetation type, Density and root character, Burrows
Anthropogenic factors	Urbanization, Flow control, Boating. Irrigation

2.4.3 Fish Passage

Since August 2001, the owner or operator of an artificial obstruction located in Oregon waters in which native migratory fish are currently or were historically present must address fish passage requirements prior to installation, major replacement, fundamental change in permit status (e.g., new water right, renewed hydroelectric license), or abandonment of the artificial obstruction (*ODFW 2004*).

Most bridges and culverts contract the flow area at the crossing location because it has traditionally been considered uneconomical to span the entire channel and floodplain width. Such contractions, or encroachments, constrict and narrow the channel through the bridge opening or culvert barrel. The constricted reach changes the characteristics of water flow near and through the hydraulic structure. Typically, the water depth will be increased upstream of the structure. The water velocity inside the structure is increased, relative to the upstream, natural channel. A hydraulic jump can form at the entrance with a resulting decrease in the water depth in the culvert barrel.

A culvert is a rigid boundary set into a dynamic stream environment. As the natural stream channel changes, especially with changes in hydrology due to land use changes, culverts often are not able to accommodate those changes. Instead, they become barriers to fish passage. Fish-passage barriers at culverts can be the result of improper design or installation factors, or they may be the result of subsequent changes to the channel. Fish-passage barriers are very often the result of degrading channels, creating scour pools and leaving the culvert perched above the downstream channel. The scour pool may be good habitat in itself but it moves the backwater control of the downstream channel further downstream and creates a drop at the outlet. The presence of large scour pools at a culvert outlet and/or mid-channel gravel bars upstream of the culvert are often indicators that a velocity barrier for fish exists inside the culvert at high flows (*Bates 2003*). Impacts on the river environment are common and include scour of the streambed through and downstream from the structure, and upstream channel incision. As a result, many bridges and culverts act as stream barriers to juvenile and adult fish passage. Higher velocities may exceed fish swimming ability and scour at culvert outlets may create jump heights too large for fish to leap into the structure (*Frei et al. 2005*).

Barriers block the use of the upper watershed, which is often the most productive spawning habitat, defined by channel size, substrate and available rearing habitats. Fish access to upper portions of the watershed is important; fry produced there then have access to the entire downstream watershed for rearing. Complete barriers block all fish migration at all flows. Temporal barriers block migration some of the time and result in loss of production by the delay they cause. Partial barriers block smaller or weaker fish within a species and limit the genetic diversity that is essential for a robust population (*Bates 2003*). Many fish-passage barriers that occur at high stream flows are not apparent during low and normal stream flows (*Bates 2003*). Fish-passage criteria accommodate weaker individuals of target species including, in some cases, juvenile fish.

Solutions to fish passage depend upon whether the installation is new or a retrofit of an existing structure. New, fish-friendly, installations often use culverts spanning more than twenty feet, technically classifying them as bridges for inspection purposes. In the State of Washington, for example, simulating the natural stream and streambed is a popular design approach, followed by a more traditional hydraulic design procedure (*Bates 2003*).

Culverts become velocity barriers to fish passage by reducing the cross-sectional area of flow, reducing roughness, decreasing the flow path length and increasing the gradient by straightening the stream channel and presenting a uniform velocity distribution with a lack of resting areas. Placing a culvert at too steep of a gradient is a common cause of excessive velocities though even moderate velocities can be a barrier if the culvert length is beyond the endurance of the fish. Sudden changes in velocity at the culvert inlet, outlet or within the barrel due to debris or culvert design can also be barriers to fish (*Robinson et al. 1999*).

There are five common conditions at culverts that create migration barriers:

- Excess drop at the culvert outlet,
- High velocity within the culvert barrel,
- Inadequate depth within the culvert barrel,
- Turbulence within the culvert, and
- Debris and sediment accumulation at the culvert inlet or internally.

All fish-passage structures require some level of maintenance. Adult fish typically migrate during the high flow seasons and in response to freshets. Timely inspections and maintenance during inclement weather are necessary at all facilities. When culverts are not adequately inspected and maintained, fish-passage barriers can form. The maintenance done at a culvert for the purpose of high-flow capacity is often different than what is required for fish passage. For example, debris that is plugging slots in baffles for example may not affect the flow capacity of a culvert, but it may block fish from passing through (*Bates 2003*).

2.4.3.1 Height between the culvert outlet and the water surface

Fish have been observed to jump considerable heights and distances to clear obstacles. Few studies of the ability of fish to jump have actually been conducted however, and this is especially true for young and small fish. From laboratory studies, Stuart (*1962*) determined that ideal jumping conditions for fish occur when the ratio of the jump height to the depth of the pool below the jump is 1:1.25. Culverts placed at too small of a slope as compared to the stream gradient can result in impassable jumps to the culvert outlet as well as designs that did not adequately account for the potential of the streambed to degrade below the culvert. The lack of a resting pool below the outlet can also prevent fish passage. Even a small jump with a resting pool can be a barrier if velocities within the culvert are too great or the water too shallow (*Robinson et al. 1999*).

2.4.3.2 Bed Porosity

The gradation of the mix used for the streambed should have enough fine materials to seal the bed and provide the variety of particle sizes that are present in natural channels. Even after years of seasoning, some channels have experienced loss of surface flow into the bed. Specifying a well-graded mix reduces permeability but may reduce stability if the voids are overfilled and rock-to-rock contact is lost. The mix must be designed to limit the reduction of stability and the risk of failure (*Bates 2003*).

ODFW indicates that the following mix of fill/bed material provides a well-functioning streambed and, thus, fish passage:

- 30% fines (dirt or silt; this allows the new bed to “seal” and water to remain in the channel rather than sub-surface);
- 30% small rock (½-6” (1-15 cm) diameter);

- 30% large rock (6 inch (15 cm)-D100); and
- 10% "shadow" rock (D150-D200 (these simulate undercut banks, large wood, and boulders and should remain in place during flood events)).
  (Note: in the above usage D_{100} is the average diameter of the 10 largest, naturally-occurring rocks in the stream reach; $D_{150} = D_{100} \times 1.5$, or 1.5 times the value of D_{100}; $D_{200} = D_{100} \times 2$, or 2.0 times the value of D_{200})

2.4.4 Construction

2.4.4.1 Bed-Material Placement

Bates (*2003*) describes a process of streambed material placement. While the description is in the context of building a streambed within a culvert, similar principles would apply to any streambed construction. As described, the culvert fill material is loaded into the pipe with a small Bobcat-style front-end loader, a small bulldozer, a gravel conveyor belt or a rail-mounted cart, or it is pushed into the culvert with a log manipulated by an excavator. In order to achieve stream simulation, fill materials must be arranged to mimic channel conditions, avoiding grid patterns or flat, paved beds made of the largest rocks. A low-flow channel and secondary high-flow bench on either side should be created in the culvert. A step-pool profile generally occurs in the 3 to 10% slope range. The spacing of steps is somewhat variable, but one to four channel widths with a maximum 0.8 foot (0.24 m) drop between successive crests is recommended. This type of channel ensures that stream energy is dissipated in pool turbulence, creating better fish passage and more stable channels. Segregating a portion of the coarsest fraction into bands can encourage this pattern. The steepest channels (greater than 10% grade) are cascades with large roughness elements protruding into the channel. The same material comprises the whole depth of fill.

At ODOT, the construction of roughened channels and stream simulation generally consists of using equipment to mechanically mix and place the streambed materials into the stream channel or culvert. Water is then used to wash fine sediment materials into streambed voids until water briefly pools at the surface. In open channel situations, this water compaction method is used in conjunction with bucket and track (using the wheels and tracks of equipment) compaction techniques. Some variance of these methods occurs, as indicated in Subsection 6.2.3.

2.4.4.2 Bank Stabilization Measures

To prevent toe scour and surface erosion at the disturbed stream banks in the project area, the following structural and bioengineering measures are often included:

- large woody debris toe protection;
- rock toe protection;
- fabric-encapsulated soils (FESs); and
- coir fabric slope protection.

Bank protection measures are selected based on integration with the proposed in-channel structure and by relating estimated channel shear stress values to published allowable values for channel and bank protection (*Herrera 2007*).

2.4.4.3 Criteria for Construction (ODFW 2004)

In 2004, the Oregon Department of Fish and Wildlife defined certain criteria to apply to the structural construction of fish passageways (*ODFW 2004*), among which are:

- disturbance of the bed and banks should be limited to that necessary to place the structure;
- all disturbed areas should be protected from immediate erosion using vegetation or other means; and
- in the long-term, the banks should be re-vegetated.

More specific construction criteria are developed on a site-specific basis. Usually these are included in the design plans and specifications for each site.

3.0 PROBLEM STATEMENT AND RESEARCH PLAN

3.1 INITIAL SITE INVESTIGATION

Five fish passageway sites were preliminarily examined to evaluate reported problems with the sites' stability and fish passage performance. The five sites, Chenoweth Creek, Bateman Creek, Miller Creek, Tryon Creek and Perham Creek, are located in northwest Oregon as shown in Figure 3.1.

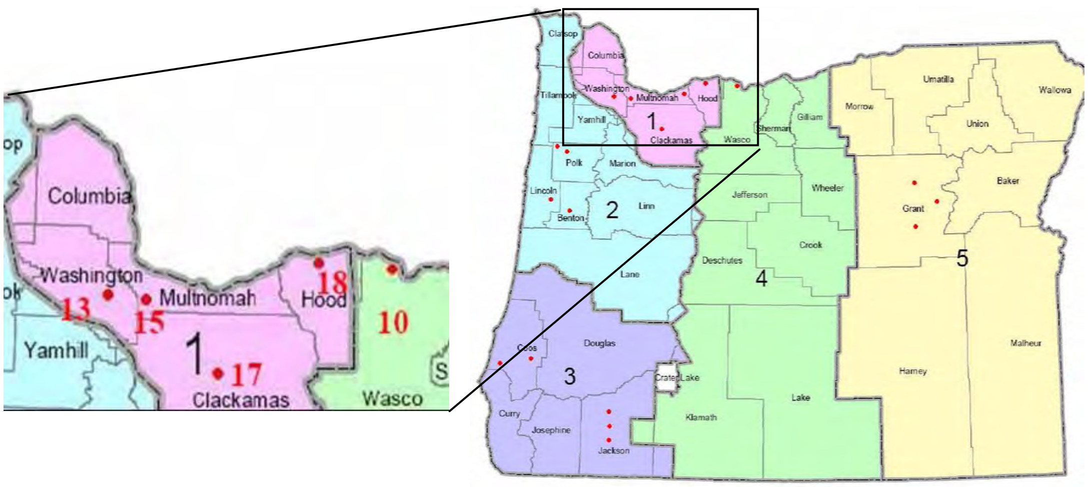

Figure 3.1: Location of five study sites evaluated in the initial examination

These preliminary investigations provided insight into the field conditions that exist after varying durations of operation. Significant findings included evidence of large amounts of downstream material migration, increased porosity of the streambed (resulting in subterranean flow) and scouring at the downstream side of the crossings. Degradation of the downstream channel appears to be the prevalent failure mode when these waterways show signs of failure; this observation is consistent with the impressions of members of the Technical Advisory Committee that are familiar with the sites. The results of the literature review and of the preliminary field investigation informed the problem statement and research plan development. It is the intent of this research to discover factors that create the observed failure conditions, especially focused on the downstream channel. These efforts are intended to provide ODOT with information for adjusting guidelines for constructing more reliable and durable fish passages.

3.2 PROBLEM STATEMENT

ODOT has experienced both successful and unsuccessful performance from its constructed fish passage waterways. The reasons for this varying performance are not fully understood, although degradation of the downstream side of the waterway system is a prevalent failure mode.

Discovery of methods used for constructing the fish passage waterways, and discovery of factors that correlate with ODOT's occasional poor fish passageway performance may provide opportunity for change in future design and construction methods, ultimately resulting in more successful performance of constructed fish passage waterways.

The focus of this investigation is the construction process—whether factors occur during construction of these roughened channels that affect successful performance. Implicit in this study is that the original designs are sufficient from both a hydraulic and a habitat perspective. Therefore, as indicated in Figure 3.2, a base assumption is that at the stage of design completion, the installation is successful, and it is changes forward of the design which create the failure. Roughened channels are expected to undergo change, similar to a natural streambed. However, these changes are expected to be benign, or slow and gradual, causing little or no effect on both hydraulic capacity and habitat (other than would naturally occur). The focus of this study is to identify post-design factors that are malignant—causing deleterious effects to either hydraulic capacity or habitat.

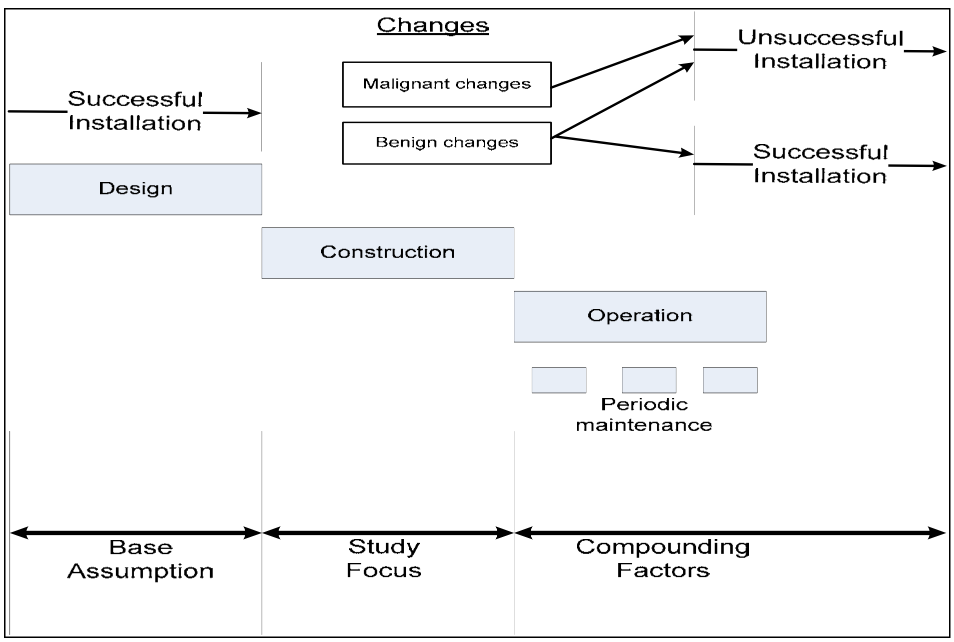

Figure 3.2: Study Limitations

In evaluation of mature channels that have reached a state of equilibrium with their environments, it is recognized that changes may have occurred after completion of construction. Therefore, the field investigation will look for the compounding effect of potential changes, such as the impact of unexpected water flows.

It is the hypothesis of this report that failure of fish passageways at structured highway stream crossings is largely the result of migration of constructed streambed materials on the downstream side of the highway crossing structure. Factors affecting this material migration may include:

- Construction Factors:
    - Inadequate range of soil and rock material gradation;
    - Inadequate mixing of rock and soil materials during construction;
    - Inadequate compaction of rock and soil materials during construction; and
- Compounding Factors:
    - High water velocity, especially during peak flows.

3.3 RESEARCH PLAN

The research plan consisted of the research tasks described in the following subsections.

3.3.1 Data gathering plan

Based on the information collected in this report and the proposed hypotheses, the research team determined which key factors to investigate on the existing sites. Key in this determination was the definition of *success*; i.e., what characteristics evidence a successful implementation? Factors investigated in the field and through contact with project-based individuals included physical site features, material composition, construction methods, and other data determined to be likely factors in fish passage failure, including the natural streambed condition, upstream and downstream of the structure.

3.3.2 Field data collection

A field investigation was undertaken on all of the identified sites, collecting data and populating a database. Observation of ongoing construction of roughened channels was made where available. Observations were recorded in written and photographic form.

3.3.3 Data analysis, conclusions, and recommendations

Using statistical techniques, the collected field data were evaluated, correlating fish passage performance with observational data. Conclusions are drawn as to the importance of the various factors in fish passage failure.

3.3.4 Construction methods investigation

A survey of construction methods for the various sites was conducted. Analysis was made, correlating construction method with passageway success.

3.3.5 Conclusions and recommendations

Recommendations are provided regarding changes to the fish passage development process, changes to construction-phase work actions, and potential future research. In addition, recommendations are provided for further monitoring of sites.

4.0 FIELD INVESTIGATION

4.1 EXISTING ODOT ROUGHENED CHANNELS

ODOT's history with roughened channels is not highly documented. Information provided here was gained through discussions with current and previous ODOT employees and discovery of limited documents in ODOT archives. Reportedly, prior to the early 1960s, culvert selection was based largely on simple design methods including judgment-based size selection and was made primarily by those skilled in roadway design. After this period, culvert design became the province of a newly-created hydraulics design department at the agency. The focus of culvert design was largely hydraulic capacity—moving water effectively to avoid threatening the roadway. The effect on habitat was perhaps a consideration, but not evaluated in a formal manner.

In the late 1990s, waterways received increasing attention for their ecosystem functions, specifically as a means of fish passage for spawning. While it was recognized in the agency that bridges are usually the better choice for re-creating natural passageways, economics prevented wholesale replacement of proposed or existing culverts with bridges. Existing culvert installations, then, became the focus of potential retrofits. Furthermore, in some situations of small stream flow, installations of culverts remain the economical method of choice for waterway crossings.

In total, 22 sites with roughened channels constructed in the last five years were identified by ODOT and a search for available records on the construction and design parameters was undertaken from the agency archives for examination. These sites are listed in Table 4.1.

Table 4.1: ODOT Roughened Channels

Site No.	Site Name	County	Road	Hwy. Mile Post	Stream Name
1	Gooseneck Creek	Polk	Hwy 22	3.97	Gooseneck Creek
2	Mill Creek	Lincoln	Hwy 229	25.16	Mill Creek
3	King Creek	Coos	Hwy 42	Below town of Bridge	King Creek
4	Oak Creek	Benton	Hwy 20	55.16	Oak Creek
5	Wahkeena Creek	Multnomah Cr	Hwy 84		Wahkeena Creek
6	Griffin Creek	Jackson	I-5		Griffin
7	Jackson Creek #1	Jackson	Hwy 99	1.09	Jackson Cr
8	Jackson Creek #2	Jackson	I-5	35.24	Jackson Cr
9	Wiley Creek	Grant	Hwy 395	101.8	Wiley Cr
10	Cheneoweth Creek	Wasco	Old Hwy 30	72.1	Chenoweth Cr
11	Cottonwood Creek	Grant	Hwy 395	106.35	Cottonwood Cr.
12	Beech Creek (5 Locations)	Grant	Hwy 395	106.99-108.0	Beech Creek @ 5 locations

Table 4.1 Continued: ODOT Roughened Channels

13	Bateman Creek (Channel Reconstruct)	Washington	Hwy 6	40.89	Bateman Cr
14	Bethel Creek (Channel Reconstruct)	Coos	Hwy 101	284.79	Bethel Cr
15	Miller Creek (Channel Reconstruct)	Multnomah	hwy 30	10	Miller Cr
16	Jackass Creek (Channel Reconstruct)	Polk	Hwy 18	19.16	Jackass Cr
17	Tryon Creek 2007 Hybrid Roughened Channel	Clackamas	OR 43	5.8	Tryon Cr
18	Perham Creek (Channel Reconstruct)	Hood	Hwy 84	57.67	Perham Cr
19	Three mile Creek	Wasco	Hwy 30/97 Int.	?	Three mile Cr
20	Tickle Creek	Clackamas	Hwy 26	21.89	Tickle Cr
21	Porter Creek	Wheeler	Hwy 207	?	Porter Cr
22	Stuart Creek	Umatilla	Hwy 395	12.93	Stuart Cr

A summary of the investigations of archived information is shown in 0. As may be seen, there are few remaining records from the roughened channel projects, except for those constructed in recent years. Limited detailed information such as plans or drawings exists for 35% of the sites. Existing information, including actual dates of construction, are difficult to obtain and the researchers had to rely on the memories of individuals; in many cases individuals have changed employment and therefore the information is scant.

4.2 METHODS

4.2.1 Objective

The objective of the site visits was to gather information regarding the existing site conditions at which ODOT performed or commissioned roughened channel work. These sites included both culverts and bridges.

The information that was collected included many physical characteristics of the channel system. Primarily, the investigators looked at any visual problems in the flow, such as scour and subsurface flow. The slopes of the river bed were also measured; measurements were recorded at several sections along the river bed, the culvert structure and underneath the bridges. In addition, soil conditions were investigated and recorded at several points along the channel.

A visual documentation of the vicinity of the sites was recorded as well, through the use of video, pictures, and sketches.

4.2.2 Investigation process

At each site, an exploration of the area was performed before investigating the streams in order to find the best method to approach them. Once that was decided, all the necessary equipment was unloaded and carried close to the area to be investigated.

A surveyor's level was set up first at a point where culvert inflow and outflow could be observed simultaneously. In the case of bridges, the level was placed at a point where most of the flow could be observed. Notes and sketches of observed flow conditions and vegetation were recorded. In addition, the structure (culvert or bridge) was described, measured and recorded. Recorded culvert dimensions included structure cross-sections, length, slope, and the existence of cement aprons. For bridges, the span of the bridge was measured as well as the distance the streams travel underneath the bridge. The slope of the stream underneath the bridge was also measured.

Upstream and downstream slopes were calculated over a distance of 7 to 10 culvert diameters. In some cases, the terrain did not allow the investigators to reach the required distance, and the slopes were measured up to the point that was accessible.

Streambed soil composition was recorded at three points along the flow; within 7-10 culvert diameters upstream and downstream, as well as under the structures (bridges). The amount of boulder material was estimated first by observation as a percentage of the total amount of soil. When that was recorded, the amount of fine particles was estimated. A sample of the soil was picked up and an estimation of the amount of fine particles and sand was obtained, and then converted as a percentage of the total soil present. The amount of cobble was estimated by observation and recorded as a percentage of the total amount of soil. The percentage that remained was recorded as gravel.

If the location had a scour pool, then the characteristics of the pool were measured. This included the plan dimensions of the scour pool, as well as the depth of the water.

In the case of culverts, the existence of any baffles and weirs was documented, as well as the average distance between them.

Finally, video and still photography were used to document the sites visually. Particular attention was paid to the details such as flow of water, scour, soil conditions and structure characteristics.

When each site investigation was completed, the investigators attempted to rate each stream according to six characteristics; 1) jumps in the flow, 2) surface flow, 3) scouring, 4) debris blockage, and 5) aggradation using the Success Index Score Card shown in 0 (the Success Index is discussed in detail in Sub-section 5.2.1.).

4.2.3 Investigation notes

The majority of the sites were investigated without problems. Several, though, were inaccessible due to vegetation and steep approaches.

For future investigations to the sites, it would best if the exact location of the sites was predetermined by an ODOT employee. The investigators spent some inefficient time trying to find the location from the simple mile post descriptions; in some cases, the difference from the mile post description was significant and dense vegetation hampered efforts at the site location. In addition, since some of the sites were inaccessible due to vegetation, more complete information on those few inaccessible sites could have been more readily obtained. Observation of the continued condition of those sites may be improved with selected brush clearing.

Care was taken to avoid disturbance of the stream beds and not disrupt the natural balance. While the methods used for streambed gradation estimation were considered sufficient for the purposes of this research, future site visits might obtain a better soil measurement by taking deep soil samples and performing a complete soil sieve analysis.

4.3 SUMMARY SITE STATISTICS

The total number of locations that were visited was 22, shown in Table 4.1. Of these 22 locations only 19 were investigated in detail, since some of the sites were inaccessible due to overgrowth of vegetation or steep approaches. Of the visited sites, 13 were culverts and 6 were bridges. See Figure 4.1.

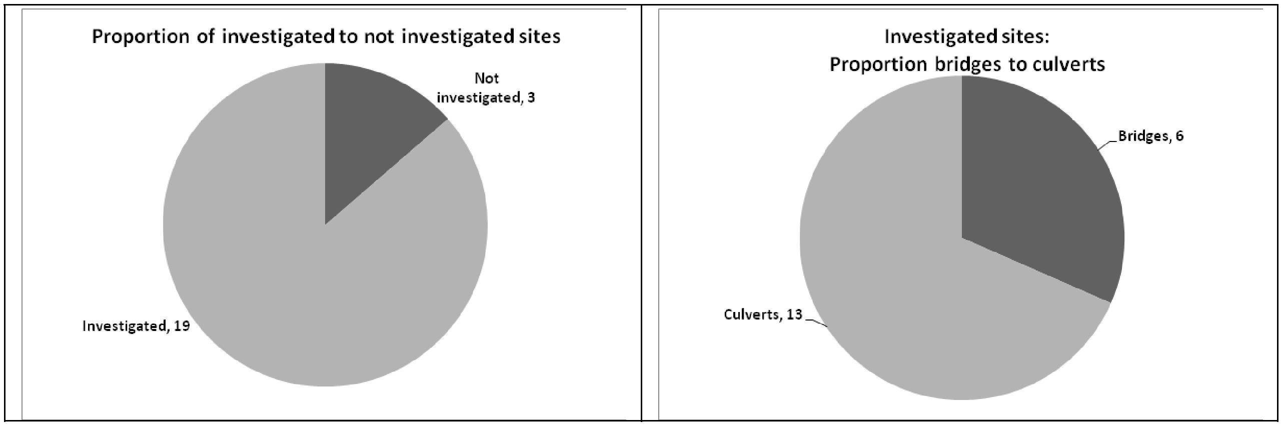

Figure 4.1: Site Characteristics

The culverts investigated had a variety of configurations and materials. Specifically, of the 13 culverts that were investigated, eight were box culverts made of concrete, one culvert was made of corrugated steel with a concrete bed, two were made of corrugated steel, while two more were made of smooth steel and had a roughened channel constructed in them along their length. Eleven had baffles or weirs while two had neither. See Figure 4.2.

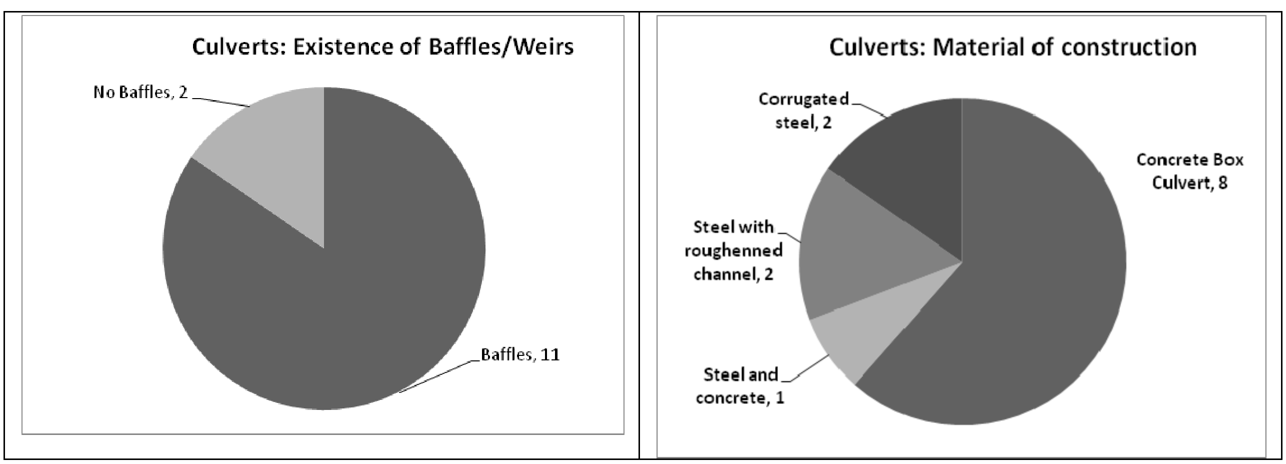

Figure 4.2: Culvert Characteristics

The channels exhibited several adverse characteristics. These included, scour, subsurface flow and jumps greater than 12 inches (30 cm). Of the investigated sites, 14 did not show any scour, but five did. Of the five sites that had scour, one site was a bridge, while the other four were culverts. Some sites had subsurface flow. Four sites had partial subsurface flow, while two had complete subsurface flow. Two sites that were visited did not have any flow and that was due to seasonal reasons. In addition to scour and subsurface flow, some sites also exhibited jumps in the flow greater than 12 inches (30 cm). In total, six sites had jumps in their flow. See Figure 4.3.

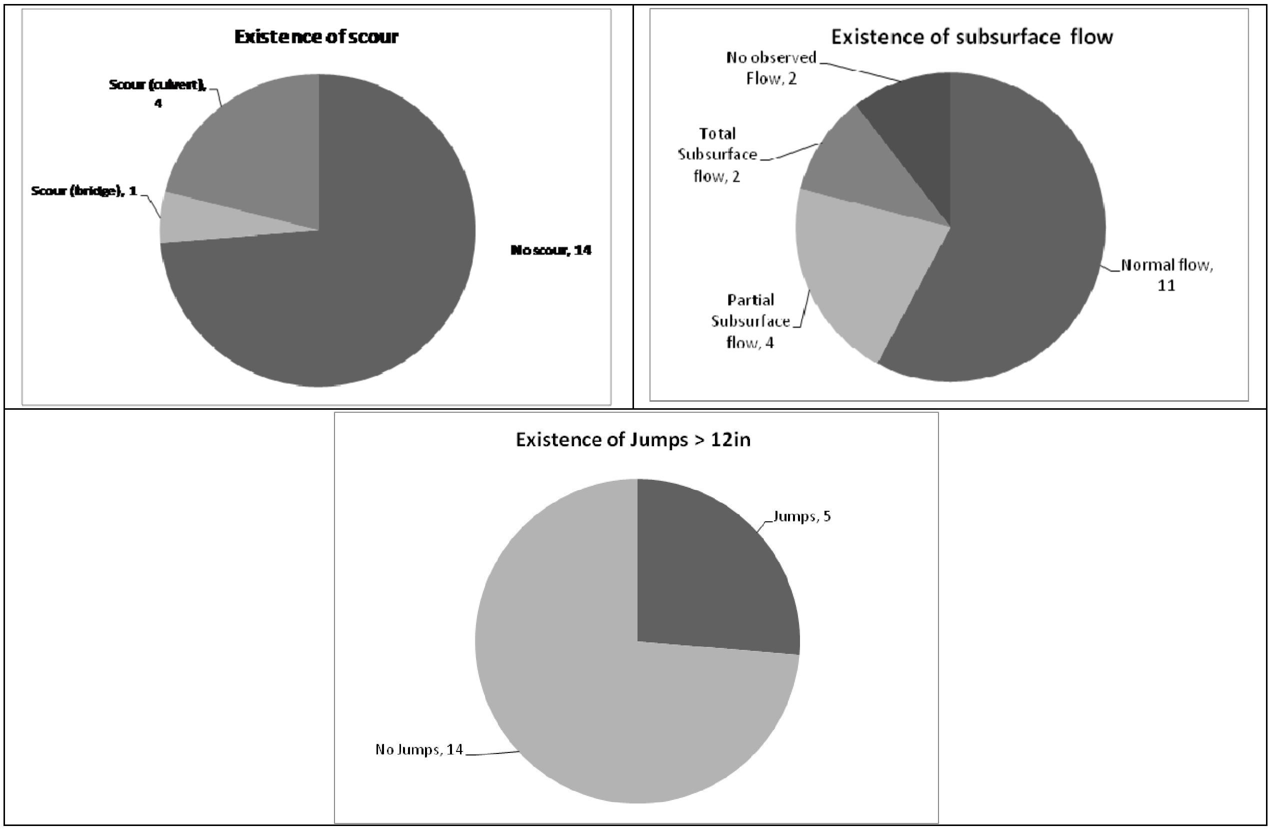

Figure 4.3: Channel Characteristics

4.4 SITE SPECIFIC NOTES

This section of the report includes general information and site visit notes regarding each individual site. More detailed information from the field investigation may be found in 0, and analysis of the field findings is discussed in Section **Error! Reference source not found.**.

4.4.1 Site 01 – Gooseneck Creek

Gooseneck Creek is located in Polk County; it is a roughened channel under a bridge carrying Highway 22 at Mile Post (MP) 3.97. The area under the bridge is concrete, embedded with boulders. The concrete seems to have been cast in two sections since there are two jumps created at the end of the concrete bed downstream. The downstream and upstream channels have a large accumulation of gravel and cobble (Figure 4.4).

The creek was accessible from the road, and the observers reached the roughened channel from the downstream side.

Figure 4.4: Site 01 – Gooseneck Creek upstream and downstream

4.4.2 Site 02 – Mill Creek

Mill Creek is located in Lincoln County and consists of a roughened channel downstream from a circular culvert as shown in Figure 4.5. The culvert is underneath Highway 229 at MP 25.16. The location is not visible from the road, and was only reached after finding the guardrails next to the road and hiking several hundred feet through the woods. The access was from the downstream side of the creek. Due to the high amount of vegetation it was very difficult to obtain cross-sections of the river flow. There was a large amount of boulder material placed downstream. At some points along the downstream side the water was flowing on solid rock.

The upstream side was only accessible after walking through the culvert. There was an accumulation of sand and gravel at the upstream channel.

Figure 4.5: Site 02 – Mill Creek downstream and upstream

4.4.3 Site 03 – King Creek

King creek is located in Coos County and crosses Highway 42. The river was not accessible from the road. The observers tried to reach the creek from the downstream site, but the grade was too steep. The upstream side of the creek was inaccessible due to neighboring private property.

4.4.4 Site 04 – Oak Creek

Oak Creek was conveniently located within the city of Corvallis in Benton County, and it crosses Highway 20 at MP 55.16. Access to the creek is not very obvious, since the upstream side is steep, while the downstream side is covered by blackberry bushes. The upstream side has an accumulation of silt and was very deep. It was very difficult to measure depth and cross-sections upstream with the available field equipment. The structure consists of two rectangular culverts, one with baffles. Cross-sections could not be measured at the downstream side due to vegetation. Photos of the Oak Creek site are shown in Figure 4.6.

Figure 4.6: Site 04 – Oak Creek downstream and structure

4.4.5 Site 05 – Wahkeena Creek

Wahkeena Creek is located in Multnomah County and it crosses under Interstate 84. The creek was visible at a nearby park site, but it disappears into blackberry bushes as it approaches the Interstate. The observers walked along the Interstate to try and find the point where the creek crosses the road, but the extensive vegetation made discovery impossible. The creek was also inaccessible from the downstream side.

4.4.6 Site 06 – Griffin Creek

Griffin creek is located in Jackson County. Griffin Creek is reached by following an exit from the interstate towards Blackwell Road and then following an unnamed gravel road. The local authorities blocked the road in order to clear the area of transients; for that reason, the only way the investigators could access the road was from Interstate 5, and only after crossing the protective fence separating the Interstate from the surrounding area. The site had a large amount of vegetation and the cross-sections could not be measured. The structure consisted of two culverts, one of which had baffles and weirs, while the other had no flow due to gravel and sand accumulation in the culvert. Accumulation of gravel and sand was evident in the culvert that was carrying water also. Photos of the Griffin Creek site are shown below in figures 4.7 and 4.8.

Figure 4.7: Site 06 – Griffin Creek downstream and structure

Figure 4.8: Site 06 – Roughened channel at Griffin Creek

4.4.7 Site 07 – Jackson Creek (1)

Jackson Creek (1) is in Jackson County and crosses Highway 99 at a location close to Central Point. The structure is approachable from the downstream side after going over a fence. The upstream site is not accessible from the road, because of the steep banks and deep water (Figure 4.9). The creek is fast flowing, making in-water access very difficult.

There are three culverts in parallel at the site. There was a lot of gravel accumulation and in all three culverts. All the weirs in the middle culvert were covered by this accumulation.

 

Figure 4.9: Site 07 - Jackson Creek (1) downstream and upstream

4.4.8 Site 08 – Jackson Creek (2)

Jackson Creek (2) is in Jackson County and crosses Interstate 5 at a location close to Central Point. The creek is accessible from the downstream side after following an exit from the interstate towards Blackwell Road and then following an unnamed gravel road. The upstream side is not accessible from the road, and was accessed after walking through the culvert. The investigators had to clear the area of some vegetation in order to perform some measurements. The structure consisted of three culverts side by side. One of the culverts had a water pump close to it that was used by a local farmer to pump water for the fields. Cross-sections of the flow were not possible due to vegetation. Photos of the site appear below in Figure 4.10.

 

Figure 4.10: Site 08 - Jackson Creek downstream and upstream

4.4.9 Site 09 – Wiley Creek

Wiley Creek is located in Grant County and crosses Highway 395 at MP 101.8. The culvert is easily accessible from both sides of the road and the investigators had no problem performing measurements, except for cross-sections of the river could not be performed due to heavy bank vegetation. As can be seen in Figure 4.11, the river was dry.

Figure 4.11: Site 09 - Wiley Creek downstream and upstream

4.4.10 Site 10 – Chenoweth Creek

Chenoweth Creek is located in Wasco County and crosses old highway 30 at MP 72.1 in the Middle Columbia – Hood River sub-basin. It is close to The Dalles and it is easily accessible from the downstream side. The area under the bridge was recently upgraded, and the concrete river bed was broken and improved (work was performed in 2007). The creek had partial sub-surface flow. There was a large accumulation of cobble and gravel along the creek (Figure 4.12).

Some history was available for this structure: Repairs to the channel located under the remnant bridge were performed in September of 2006 by applying concrete to the eroded streambed and placement of compacted streambed materials over the concrete base to provide fish passage to steelhead and salmon. Chenoweth Creek had exceptional winter flows in 2006 just after the concrete bed was installed. This resulted in structural failure of the concrete, extensive streambed material movement and loss of fines. In August 2007, subsurface flow was observed under the concrete channel liner and remaining streambed material immediately downstream of the structure as shown in Figure 4.13. Large boulders served to concentrate stream flow, created backwater and flow vortexes in the channel. In September 2007, ODOT made further repairs to this passage by removing the mid portion of the concrete bed and replacing streambed materials (*NMFS Washington 2008*).

Figure 4.12: Site 10 - Chenoweth Creek downstream and upstream

Figure 4.13: Site 10 – Chenoweth Creek failed under-structure concrete lining

4.4.11 Site 11 – Cottonwood Creek

Cottonwood Creek is located in Grant County and crosses Highway 395 at MP 106.35. The culvert is easily accessible and the investigators had no problem accessing the culvert; however, due to heavy bank vegetation, cross-sections of the creek could not be obtained.

The structure consisted of one culvert, which had baffles and weirs. There was no water flowing in the creek. Photos of Cottonwood Creek are shown in Figure 4.14 below.

Figure 4.14: Site 11 - Cottonwood Creek upstream and downstream

4.4.12 Site 12 – Beech Creek

Beech creek consists of five locations all crossing Highway 395 between mileposts 106.99 – 108. The area is heavily wooded and access to the creeks was very treacherous and steep. None of the five culverts were investigated.

4.4.13 Site 13 – Bateman Creek

Bateman creek was the first site visited in this series of investigations. It is located in Washington County near the town of Gales Creek and it crosses Highway 6 at MP 40.89. The site has an easy access from the road. Cross sections of the flow were produced, and the slopes were easily measured. A photo of the downstream side of the culvert is shown in Figure 4.15.

Some history of this site was available: The slope of Bateman Creek is 4 to 6%. In summer 2006 the culvert at the site was replaced by a roughened channel and a bridge. At this site bed slope was reduced from 6% to 4.3% by introducing sinuosity to the channel. Grade control structures were buried in the streambed to prevent the stream from head-cutting. The banks of the stream were armored with large rocks to prevent erosion. ODOT used a 50 yr event as their design flow for this installation (*HDR 2004*).

Figure 4.15: Site 13 - Bateman Creek downstream

4.4.14 Site 14 – Bethel Creek

Bethel creek is located in Coos County and crosses highway 101 at MP 284.79. The site was easily accessible, but the investigators had to jump the protecting fence separating the highway from the surrounding area. Access to the creek was from upstream. There were no major concerns about the area and river cross-sections were taken. Views of the structure are shown below in Figure 4.16.

Figure 4.16: Site 14 - Bethel Creek under structure and downstream

4.4.15 Site 15 – Miller Creek

Miller Creek is located in Multnomah County, and crosses Highway 30 at MP 10. It consists of a channel reconstruction and was the second site visited by the investigating team. Access to the river bed was from upstream of the creek and was very steep (Figure 4.17). Measurements were taken for slope and cross-sections. The creek had very few fines, and all the flow was subsurface.

Some history of the site was available: Miller Creek is located in NW Portland in the Willamette watershed and drains into the Multnomah Channel. The site is located 720 feet (220 m) from the intersection of Miller Creek and the Multnomah Channel. The land use surrounding Miller Creek is predominantly forested. In 2003, ODOT restored the viaduct located under the highway to a natural streambed when the existing hydraulic structure was replaced by a bridge. The slope of the channel at the site is 6.0%. Large boulders were scattered around the site channel bed to produce low velocity pools. Weirs were also installed in an existing culvert further downstream as part of the improvement of the complex of fish passages. The 50-year flood event had been used by ODOT as its design flow (*Clark 2002*).

Figure 4.17: Site 15 - Miller Creek upstream

4.4.16 Site 16 – Jackass Creek

Jackass Creek is located in Polk County and crosses highway 18 at MP 19.16. Access to the creek was from the downstream side (Figure 4.18 left) and was not particularly difficult. There were no problems in gathering any of the information and slopes and cross-sections were obtained easily. The upstream side of the creek (Figure 4.18 right) had an artificial block that created a small pool. In addition, the upstream channel had several high jumps (greater than 12 inches (30 cm)).

Figure 4.18: Site 16 - Jackass Creek downstream and upstream

4.4.17 Site 17 – Tryon Creek

Tryon Creek is located in Clackamas County and it crosses OR 43 at MP 5.8. The creek is accessible from the downstream site. There is a large scour pool at the mouth of the culvert and that did not allow the investigators to access the culvert itself. Access from the upstream site was very steep. All measurements were taken from the downstream site (Figure 4.19 right).

Some history of the site was available: Tryon Creek is the only site to be found with a stream gage. Average discharge recorded by the U.S. Geological Survey (*2008*) since 2001 is 8.5 cfs (0.24 cms) with a high flow of 520 cfs (15 cms) in 2003. Tryon Creek watershed is 4,200 acres (1700 hectares) with 21% development. The stream runs through the 645 acre (261 hectare) Tryon Creek Natural Area before emptying into the Willamette River. The riparian areas are mostly natural but the steep (30%) slopes result in an unstable channel with frequent mass wasting events and erosion. Tryon Creek has a low slope of two to four percent. The hydraulic structure in place at the site is an 8 foot by 8 foot (2.4 m by 2.4 m) box culvert that is 400 feet (122 m) long. The culvert has been in place since 1920 and supports Highway 43 and two railroads *(Herrera 2007; DJWarrenAssociatesINC 2007)*. The City of Portland and ODOT had scheduled work to be done Fall 2007 to repair the culvert baffles and restore the streambed materials below the culvert. According to a study by DJ Warren Associates (2007), the Cities of Lake Oswego and Portland both agreed the culvert is in need of replacement and at the time of the study were currently contemplating alternatives such as a concrete span bridge, steel span bridge or a concrete arch to support the highway and railways (*Herrera 2007*).

Figure 4.19: Site 17 - Tryon Creek outlet and downstream

4.4.18 Site 18 – Perham Creek

Perham Creek is located in Hood River County and crosses Interstate 84 at MP 57.67. It has a relatively easy access from the upstream side of the river (Figure 4.20 right). Due to increased vegetation, the slopes and the river cross-sections could not be measured. The outlet of the culvert is located in the south bank of the Columbia River. Fish passage through the culvert, and up into the creek drainage, depends on the stage of the Columbia River being high enough to backwater the culvert outlet.

Some history of this site was available: The stream has a slope of 2% where it intersects with Interstate 84. In the summer of 2003, a completely impassible standpipe culvert was removed from service and a 12 foot (3.7 m) culvert was constructed nearby. The stream flow was shifted from the old streambed to a newly constructed roughened channel that extends through the new culvert (Figure 4.20 left). ODOT used a 50-year event as their design flow for this installation. Perham Creek is unusual because of the orientation of the baffles installed in the culvert to provide low velocity pools for fish to use as resting areas. The baffles are mounted vertically and extend from the bottom to the top of the culvert to ensure they withstand the high bedload accumulation expected inside the culvert (*Bryson 2000*).

Figure 4.20: Site 18 - Perham Creek structure and upstream

4.4.19 Site 19 – Three Mile Creek

Three Mile creek is located in Wasco County on the East side of The Dalles, and crosses Highway 30/197 at three locations. At the time of the investigation only the northernmost site was modified with a roughened channel. The roughened channel was inside the culvert and the water was flowing normally. There was no evidence of scour. There were some locations inside the culvert with jumps greater than 12 inches. The creek was accessible from downstream, through the property of a private business. After asking for permission, the owner allowed the investigators to approach the creek.

The upstream side was not accessible from the road, since the approach was very steep. There were no measurements taken for the upstream side of the culvert due to the large amount of vegetation that was present. Photos of the inside of the culvert are shown below in Figure 4.21.

Figure 4.21: Site 19 - Three Mile Creek structure looking downstream and upstream

The other two sites of Three Mile creek were improved in August, and the sites were investigated in September. Since these two sites had only functioned for one month, they are not used in this study for the purposes of assessing performance over time.

4.4.20 Site 20 – Tickle Creek

Tickle creek is located in Clackamas County and crosses Highway 26 at MP 21.89. Access to the culvert is not obvious from the highway, and the researchers spent some time trying to find an alternative access; the sides of the highway have steep banks and the creek is at a much lower elevation. The great amount of vegetation did not allow visual observation of the creek from the highway. The creek was finally accessed from upstream (Figure 4.22 right) after asking for permission for a resident to pass through his land. Elevations and measurements were taken for the upstream side. The downstream (Figure 4.22 left) was accessed through the culvert, which was 477 feet (145 m) long. Cross-sections were not possible due to heavy bank vegetation.

Figure 4.22: Site 20 - Tickle Creek downstream and upstream

4.4.21 Site 21 – Porter Creek

Porter Creek is located in Wheeler County and intersects Highway 207 at the county border line. Access to the creek was easier from the downstream side and it was a little steep. There was no water flowing and the slopes could be measured easily. The culvert, which was made of corrugated metal, had no baffles or weirs inside. The downstream side (Figure 4.23 right) had a large accumulation of boulders, which seems to have been placed intentionally. There were no obvious water marks for estimating the high flow elevations of the water in the downstream side of the culvert, while the upstream side (Figure 4.23 left) had a lot of vegetation.

Figure 4.23: Site 21 - Porter Creek downstream and upstream

4.4.22 Site 22 – Stewart Creek

Stewart Creek is located in Umatilla County and crosses both the current highway 395 at MP 12.93 as well as the old highway 395. The creek is easily accessible from the highway. Access to the river bed only requires jumping the guardrails and climbing down a few feet. The creek crosses beneath the old highway in a small box culvert and under the current highway through a much wider culvert (see Figure 4.24). There was a lot of accumulation of fines in the smaller culvert and the water carved its path in the mud. Slopes were easily measured. There was evidence of baffles and weirs in the culvert but a large portion of these was covered by the accumulation of fines. Inside the larger culvert, there was no accumulation of fines and water was flowing normally.

Figure 4.24: Site 22 - Stewart Creek – Culverts under new and old highways

5.0 ANALYSIS OF FIELD DATA

An analysis of the field data was conducted to discover the existence of any strong relationships among the physical channel characteristics themselves, including peak stream velocity and flow rates, as well as relationships between the physical characteristics and a Success Index (described in 5.2.1). The focus of these analyses was the structural stability of the downstream channel, since it was found in the preliminary investigation that the downstream channel was the most often distressed portion of the waterway system. Many such relationships were explored; reported here are the more noteworthy that were found. The field data comprised both bridge and culvert structures. In many cases the data were considered for both structure types together, and in others they were considered separately. The decision to combine or separate was based on assessment of the analyzed data and of the physical traits of the relationship explored. Unless otherwise indicated, data presented in the report represent the combined condition. The relationships reported are shaded in the matrix of Table 5.1. The numbers indicated in the matrix refer to the subsections where the relationships are discussed in this report.

Table 5.1: Analyzed field relationships

The effect of this ↓ on this →	Soil Gradation Ratio (downstream)	Soil Gradation Ratio (structure)	Jumps	Scour pools	Success Index
Soil Gradation Ratio (downstream)			5.1.4		5.2.2
Structure slope	5.1.3	5.1.3	5.1.4	5.1.5	5.2.2
Downstream slope	5.1.3		5.1.4	5.1.5	5.2.2
System slope			5.1.4		
Slope differentials				5.1.5	5.2.2
Flow rate	5.1.6				
Velocity	5.1.6				5.2.2

5.1 STRUCTURAL SITE RELATIONSHIPS

Structural site characteristics, i.e. physical properties of the channel structure, were measured in the field investigation. Of interest in this project is whether there appear to be relationships among these characteristics. Many of these interrelationships were explored; the more noteworthy are reported here, including relationships among streambed soil composition, channel slopes, and the existence of features such as jumps and scour, etc.

5.1.1 Streambed soil gradation

The streambed soil composition was estimated in the field in terms of groupings of soil particle sizes, which was measured in percentages. The literature review indicated that such gradation is an important factor in the health of streambeds. For example, a basic comparison that shows a clear difference between the streams of this study that have subsurface and surface flow is observed by taking the average of the components that make up the soil at the roughened waterway downstream. That comparison is shown in Figure 5.1. As observed, streams that had surface flow showed a sand percentage that was double that of the streams that had subsurface flow. In total, the finer particles – sand and fines – made up 19.52% of the soil in streams that had subsurface flow, while in streams that had surface flow; the streams had an average of 30.83% of these materials. Figure 5.1 suggests that streams that had subsurface flow were importantly lacking finer particles, especially sand.

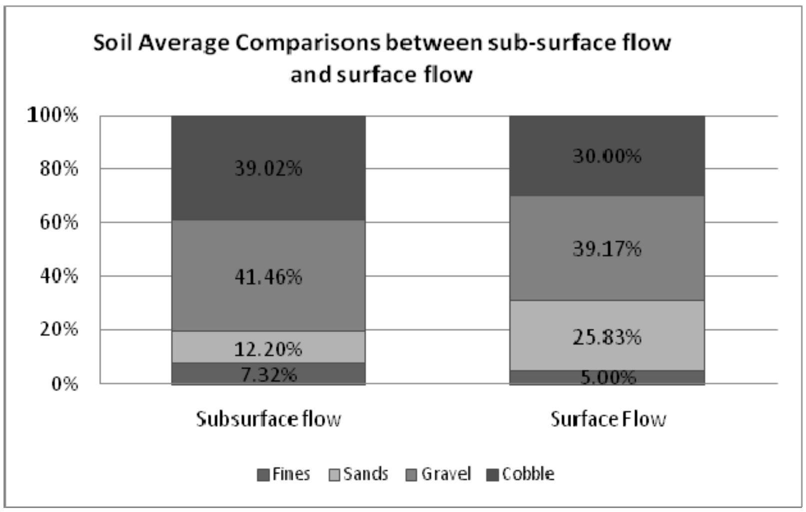

Figure 5.1: Soil Average Comparisons between sub-surface flow and surface flow

It was found, however, that this raw percentage data was not very practical when making comparisons among the various factors, largely because it did not intuitively capture the impact of larger particle sizes vs. smaller particle sizes. For that reason, a ratio was developed that compared the amount of finer material (fines and sands) to the coarser material (gravel and cobble), and that value was used in the statistical analyses. The ratio is called the "Gradation Ratio" and it was calculated using the following formula:

$$Gradation\ Ratio = \frac{(\%\ of\ fines + \%\ of\ sand)}{(\%\ of\ gravel + \%\ of\ cobble)}$$

5.1.2 Slope differentials

The slope for each waterway was measured for three waterway system segments—upstream, within the structure, and downstream. Through field observation and discussion with the expert panel of Technical Advisory Committee members, it was suspected that the relationship among these segment slopes may be contributing factors in the performance of the waterway. In particular, two such relationships were modeled:

- The difference between the upstream slope and the downstream slope.
- The difference between the structure slope and the downstream slope.

These calculations are herein called Slope Differentials, and are calculated as follows:

$$\text{Slope Differential} = \text{upper slope} - \text{lower slope}$$

Note that the lower slope is always the Downstream Slope of the waterway system, and the upper slope may be either the Upstream Slope or the Structure Slope (either culvert or under bridge); the individual analyses indicate which is under consideration. Further note that a positive value indicates a downstream slope that is less steep, while a negative value indicates a downstream slope that is steeper (see Figure 5.2).

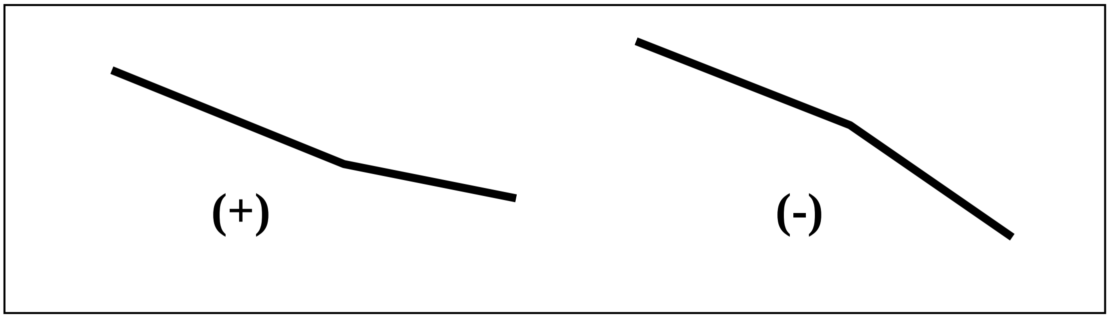

Figure 5.2: Slope Differential sign indications

5.1.3 Soil Gradation Ratio and Slopes

Several analyses regarding the relationships of Soil Gradation Ratio vs. structure slopes (under bridge and/or culvert slope) and vs. downstream slope were explored. The following regressions are reported in detail in 0:

- Gradation Ratio Downstream and Slope Downstream (combined and individual);
- Gradation Ratio under Bridges and Slope under Bridges; and
- Gradation Ratio Downstream and Slope of Culverts.

These regressions produced r^2 values ranging from 0.002 to 0.205 which clearly indicates that the regressions are explaining little of the variation in the data. The fact that the P-values for these regressions ranged from 0.161 to 0.943 indicates that the slopes of none of these regressions is statistically different from zero. Figure 5.3 shows the scatter of the data for Soil Gradation Ratio plotted versus downstream slope. The regression of the data with no hydraulic jump demonstrated the best of these poor fits. The r^2 for this case was 0.205 and the P-value was 0.161. Clearly the Soil Gradation Ratio is being controlled by something other than the channel slope.

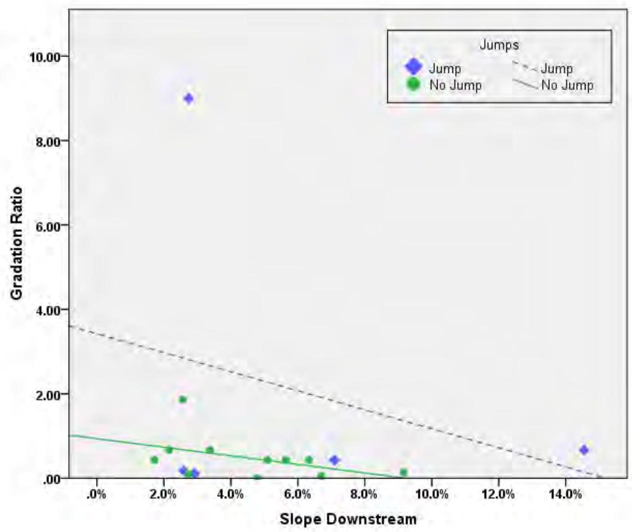

Figure 5.3: Gradation Ratio vs. slope (downstream) with and without jumps.

5.1.4 Channel characteristics and the existence of jumps

Jumps in the flow greater than 12 inches (30 cm) have been shown to be significant barriers to fish passage. Factors affecting the development of such jumps were explored; reported here are:

- Jumps and downstream slopes;
- Jumps and structure slopes;
- Jumps and overall system slopes;
- Jumps and differential slopes; and
- Jumps and downstream gradation ratio.

In order to examine if the streams with jumps greater than 12 inches (30 cm) had any correlation with the slopes in the streams, several sets of data were evaluated. These are shown in Figure 5.4.

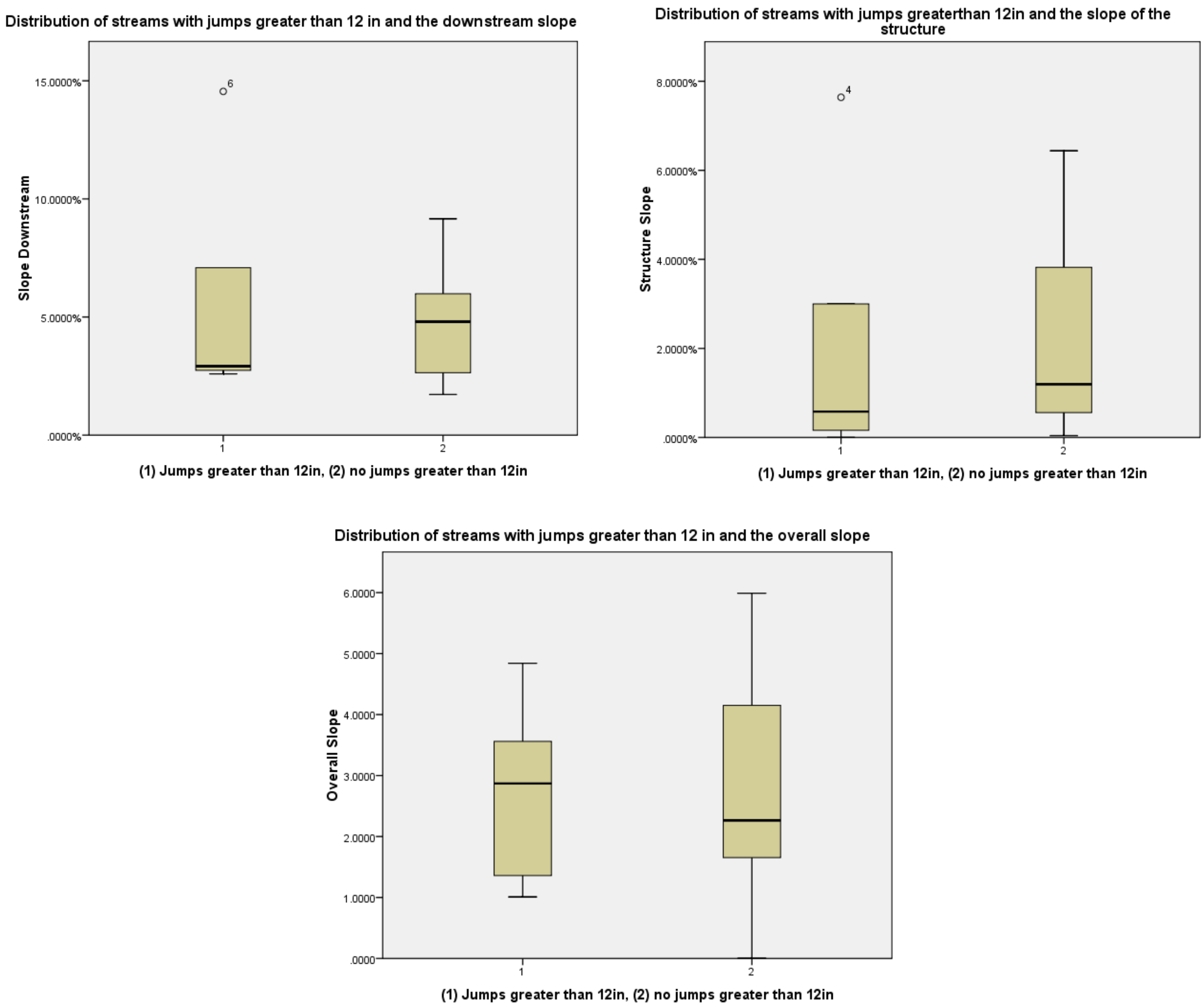

Figure 5.4: Slope relationships with the presence of jumps greater than 12 in.

As observed in Figure 5.4, the presence of jumps in the flow does not appear to be significantly related to any of the slope conditions with the amount of data that were available for the study. For this reason, the relationship between the slopes and the jumps is inconclusive.

Similar to the observations of the relationship between absolute slopes and jumps, there is no evidence to indicate a relationship between slope differentials and the existence of jumps, as observed in Figure 5.5.

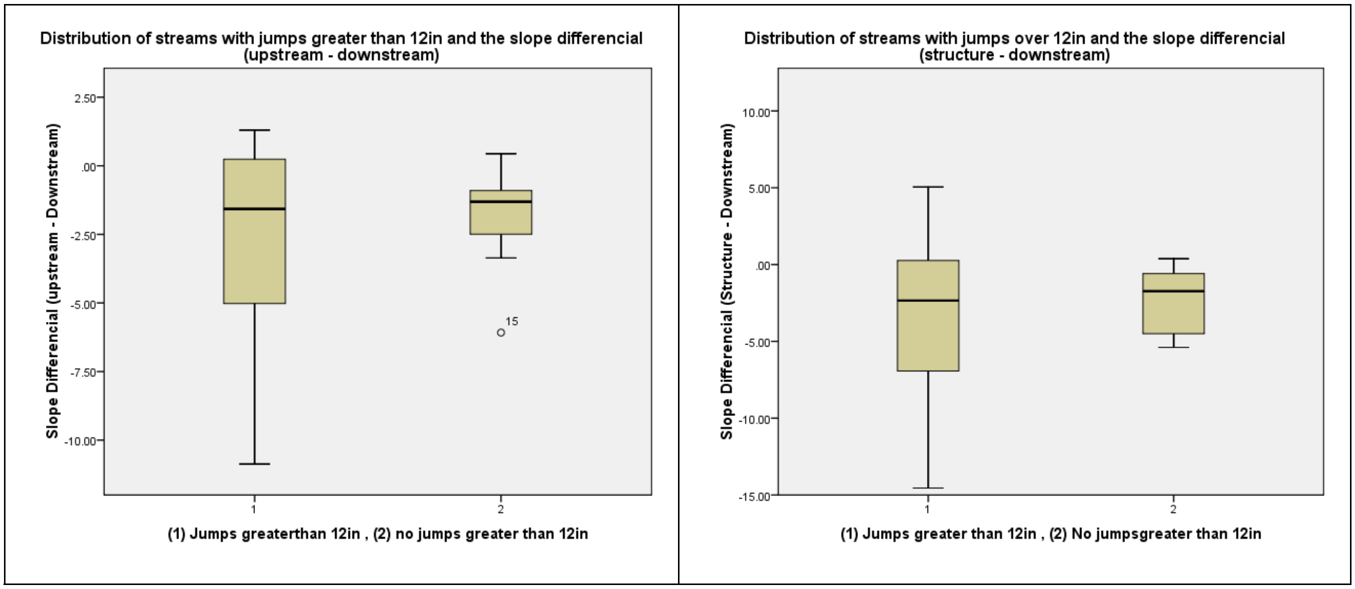

Figure 5.5: Differential Slopes vs. jumps

The presence of jumps in the flow was then plotted against the Gradation Ratio downstream. That is shown in Figure 5.6. Once again the results were inconclusive since there was no clear relationship between the gradation ratio and the presence of jumps.

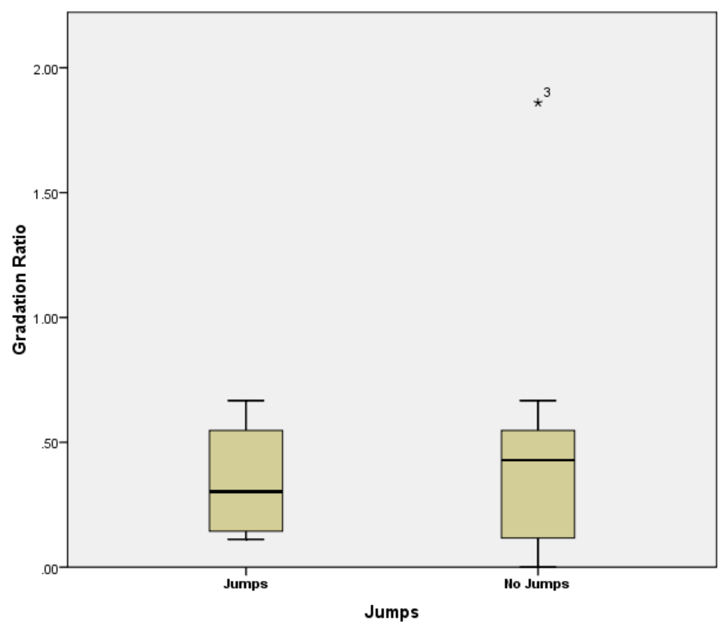

Figure 5.6: Downstream gradation ratio vs. jumps

5.1.5 Slope and scour pools

With the exception of Gooseneck Creek, scour was only observed in locations with culverts. Box plots were developed to determine how the existence of scour differs against various waterway system slopes and differential slopes. The following comparisons were performed to investigate the relationships:

- Downstream slope and scour;
- Structure slope (culvert) and scour; and
- Slope Differentials and scour.

As observed in Figure 5.7, when the downstream slope is high, scour pools were less likely to be observed. Scour pools were only observed when the downstream slopes were low; ranging between 2.15% and 2.74%. This may be an indication that low slopes streambeds must absorb high velocity flows and for that reason turbulent conditions exist at the culvert outlets, which cause scour.

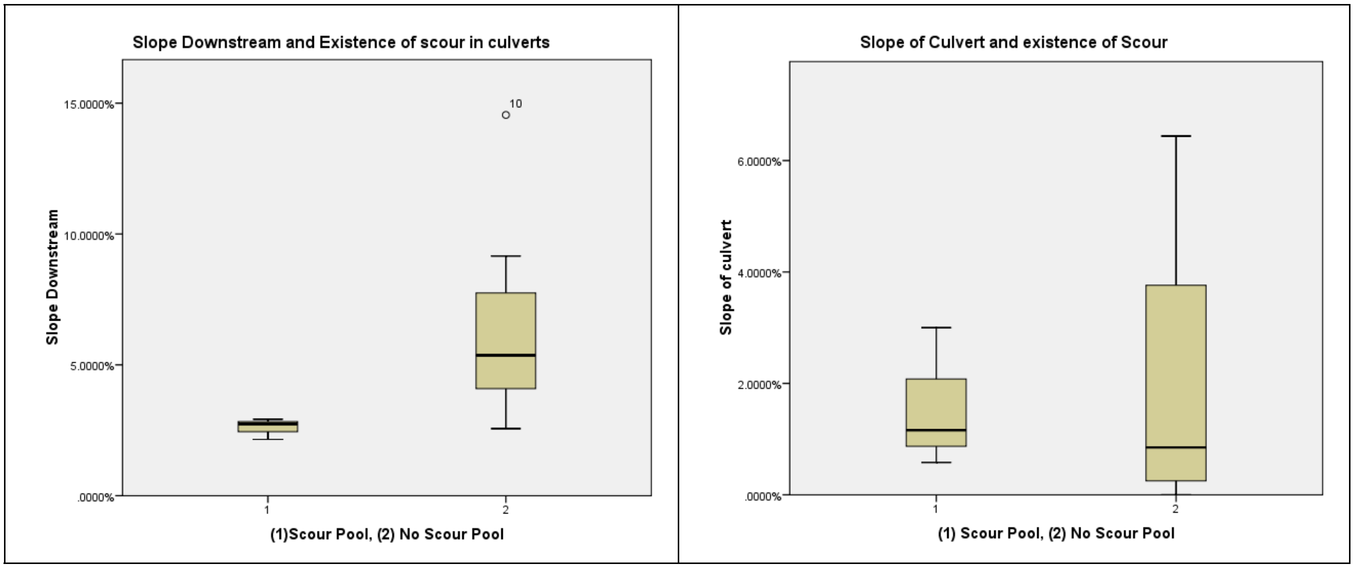

Figure 5.7: Waterway system slopes vs. scour

The slope of the culvert by itself does not appear to be a factor in the existence of scour, since scour occurred at various culvert slopes. Streambeds that did not have scour had culverts that had a wider range of slopes.

The first Slope Differential relationship with scour reported here is the difference between the slopes of the culvert and the downstream sections of the stream. It is observed in Figure 5.8 that scour was present when there was very little difference in slope between the structure and the downstream. All the sites that had experienced scour were within the range of slope difference between -2.34% and 0.26%. Structures that did not have scour had a range of slope differentials from -14.55% to 0.38%. This suggests that there is a lower likelihood for scour to exist when the slope of the downstream portion is greater than the slope of the culvert.

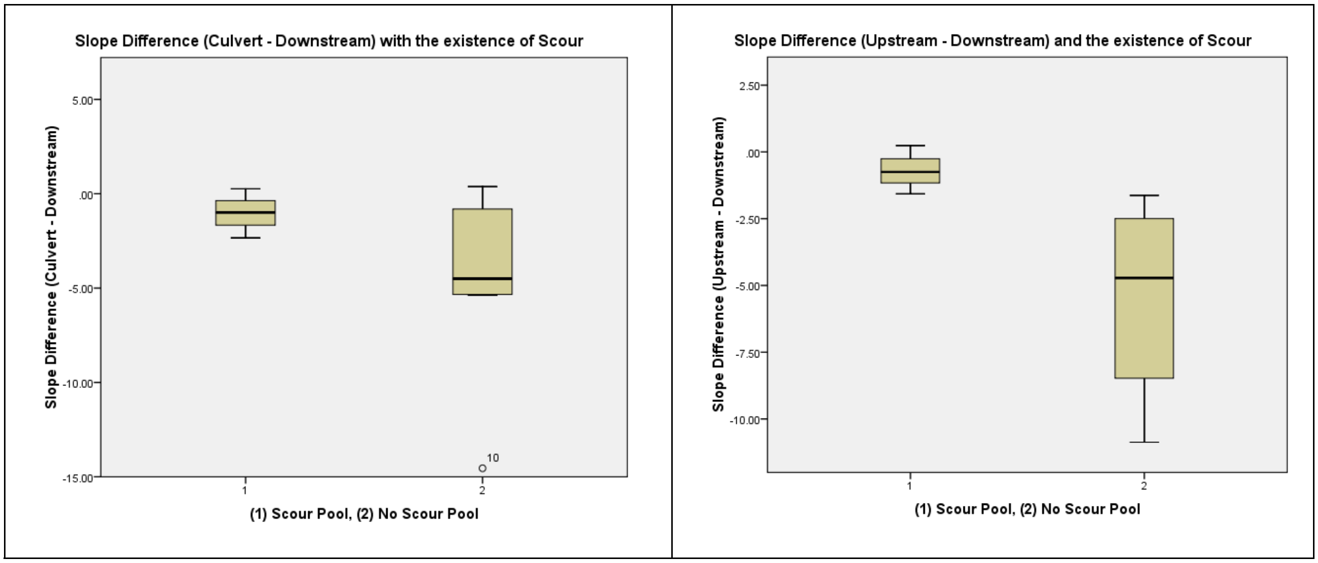

Figure 5.8: Slope Differentials vs. scour

One additional differential that was examined is the difference between the upstream and the downstream portions of the stream beds. It was observed that in streams where the upstream and downstream slopes were almost the same (range -1.57% to 0.24%), there was a scour pool created. In the other stream channels with culverts, where the downstream slope was greater there was no evidence of a scour pool. This appears to be an indication that steeper downstream slopes are not faced with absorbing the energy of high velocity upper flows, lessening the incidence of scour.

5.1.6 Flow Rate/Velocity and Soil Gradation Ratio

Flow rates and velocities at the structures (either under bridge or in culvert) during peak flows were calculated for all sites where sufficient field data existed. The flow rate analysis consisted of calculating the estimated peak flow wetted perimeter of the streambed/culvert, calculating the cross-sectional area of flow, calculating the slope of the streambed/culvert, and estimating an appropriate Manning's Roughness Coefficient. Roughness coefficients were chosen with the use of pictures of individual sites and gradation analysis. The flow rate at the structure (under bridge or in the culvert) was calculated with the Manning Equation:

$$Q = \frac{1.49}{n} A R_h^{\frac{2}{3}} S_0^{\frac{1}{2}}$$

where Q is the estimated flow rate, n is the roughness coefficient, A is the cross-sectional area of flow, R_h is the hydraulic radius and S_0 is the slope of the streambed.

Velocity for each site was calculated by dividing the flow by the cross-sectional area. Estimated flow rate and velocity was successfully calculated for 10 of the 22 sites. The r^2 values ranged from 0.016 to 0.452 while the P-values ranged from 0.213 to 0.9. These results clearly indicate that there is little relationship between the downstream Soil Gradation Ratio and either the calculated flow or the calculated velocity in the streams. The full results of regression analysis of this data can be found in 0.

5.2 FISH PASSAGE SUCCESS RELATIONSHIPS

A Success Index was developed, and the Index was used to rate each location that was investigated. The components that were used to develop the Success Index and the rating for each location are described in this section.

5.2.1 Success Index – development and components description

The Technical Advisory Committee for this project provided a list of important factors that largely indicate a structurally successful fish passage waterway. These factors include six characteristics; 1) Jumps in the flow, 2) Surface flow, 3) Scouring, 4) Debris blockage and 5) Aggradation.

For the item "Jumps in the flow", the streams were examined and noted for the presence of vertical changes in the flow of the water that would cause the fish to jump a height of 12 inches or more (>30 cm). A value of '0' was given to the streams that exhibited such a characteristic, while a value of '10' was given to streams that did not have any jumps in the flow. If jumps in the flow of water were between 0 and 12 inches, then the rating was interpolated.

"Surface Flow" reflects the existence of surface/subsurface flow in the streams. If there was total subsurface flow through a portion of the stream, then a value of '0' was given. If no subsurface flow was observed, then the streams were given a value of '10'. In streams where some subsurface flow was observed, an intermediate value was given.

Scouring (the creation of scour pools) downstream of the structure, especially in culverts, was examined. If the scour created a jump greater than 12 inches, then the stream was rated with a value of '0'. If there was no scour or if the scour pool did not create a jump in the flow, then a value of '10' was given for that portion of the success index. Intermediate values between 0 and 10 were obtained by interpolation if the jumps in the flow were less than 12 inches (<30 cm).

For the rating of debris blockage, the amount of debris was observed. If debris was seen to be obstructing the passage of fish, then the stream was rated with a value of '0'. If there was no debris blocking the passage of fish, then a value of '10' was given to the stream. Intermediate values were given to streams that had some debris blockage.

Aggradation is present when a particular size of sediment is accumulated in large quantity in sections of the streams. If sediment was accumulated in an area representing more than 20% of the area of the downstream bed, then a rating of '0' was given. If no aggradation was observed, then a rating of '10' was assigned. Intermediate values were given to streams that had some aggradation.

As is clear from the description above, and as was confirmed by a Spearman method bivariate correlation test, a strong correlation between the variables "Jumps" and "Scour" exists; therefore, these two variables were combined into a single variable, by taking the average of the two for each individual observation.

The rating results and total Success Index are shown in Table 5.2. Note that the higher the Success Index (to a maximum of 40), the better is the waterway performance. The rating instrument is included in 0.

Table 5.2: Success Index factors and ranking

Site No	Name	Visit date	Surf. Flow	Debris Block	Aggr.	Jump/ Scour	Total Success Index	Rank
1	Gooseneck	29-Jul-08	7	10	5	0	22	17
2	Mill	14-Aug-08	10	10	5	7.5	32.5	9
4	Oak	14-Aug-08	10	2	5	10	27	15
6	Griffin	27-Aug-08	10	2	10	7.5	29.5	12
7	Jackson (1)	16-Jun-09	10	10	0	9	29	14
8	Jackson (2)	27-Aug-08	10	2	10	9	31	11
9	Wiley	3-Sep-08	8	10	6	10	34	7
10	Chenoweth	12-Aug-08	2	10	10	10	32	10
11	Cottonwood	3-Sep-08	9	8	10	10	37	6
13	Bateman	13-Jul-08	10	10	10	10	40	1
14	Bethel	26-Aug-08	10	10	10	10	40	1
15	Miller	23-Jul-08	0	10	10	0	20	18
16	Jackass	29-Jul-08	10	3	10	6.5	29.5	12
17	Tryon	11-Sep-08	10	8	8	8	34	7
18	Perham	11-Sep-08	10	10	10	10	40	1
19	Three Mile C	12-Aug-08	10	10	10	10	40	1
20	Tickle	5-Aug-08	5	10	2	1	18	19
21	Porter	3-Sep-08	9	10	10	10	39	5
22	Stewart	2-Sep-08	0	10	5	8.5	23.5	16

The above ranking closely matches field observations. For example, Miller Creek is ranked least successful, and that location had almost complete subsurface flow and total absence of fines. Tickle Creek came second to last, and that location had a scour pool jump at the end of the culvert and severe aggradation downstream. Gooseneck Creek was ranked 17th and that location also had a scour pool, and jumps greater than 12 in. downstream. The one area of concern is that the debris factor seems to be lowering the factor of some sites that are qualitatively viewed as doing well.

In contrast, the higher ranked creeks showed a healthy flow. Three Mile Creek was a successful site with no subsurface flow and no jumps in the channel. Bethel Creek was also a site that did not show any sign of concern. Two other sites that showed healthy flow and were also ranked high were Bateman Creek and Perham Creek. Both of these creeks had surface flow and no sudden jumps nor scour pools.

Overall, the streams investigated evidenced a wide range of success according to the index described here. A distribution of that success is shown below in Figure 5.9.

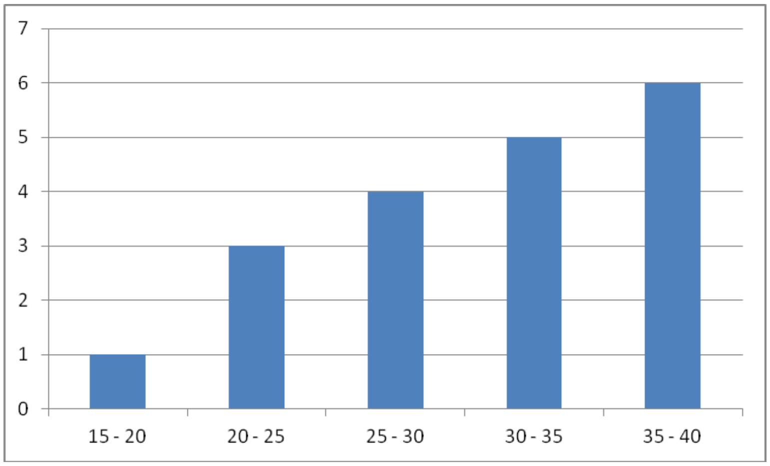

Figure 5.9: Success Index histogram

5.2.2 The Success Index and site characteristics

The Success Index was regressed on several of the fundamental field measurements in order to determine if the success of the streams is directly related to any of them:

- Success Index and downstream slope
- Success Index and structure slope
- Success Index and Slope Differentials
- Success Index and downstream Gradation Ratio
- Success Index and structure velocity

These regressions produced r^2 values ranging from essentially zero to a high of 0.483 while the P-values ranged from 0.215 to 0.929. Once again, based on these high P-values, all of the slopes could have values of zero. The r^2 values show that little of the variation is being explained by the regression equations. Details of the regression analyses can be found in 0

5.3 FIELD DATA ANALYSIS SUMMARY

As expressed earlier, there were limited locations available for investigation and as a result the statistical analysis that was performed is subject to large margins of error, and tendencies in the results are often influenced by data points that appear to lie outside of the bounds of the bulk of the data; where reasonable, accommodations have been made for many of these circumstances. As a result, conclusions must be drawn by using judgment that cautiously considers the data analysis, and that also considers anecdotal information from the Technical Advisory Committee and is tempered with field observation. Some conclusions have been developed that are based on this judgment and they are as follows:

5.3.1 Gradation considerations

The results in the field investigation did not find a strong relationship between field conditions of slope and soil gradation. This may indicate that the factors that lead to subsurface flow are due to influences beyond slope. Construction techniques used to source, mix, and install the original roughened channel streambed may be a strong factor.

5.3.2 Scour and slope considerations

It appears that the downstream slope of the roughened channel system is related to the development of scour. Specifically, where downstream slopes are steeper than upstream slopes, especially than upstream culvert slopes, there is less likelihood of scour. Configuring fish passageways thus may lead to a situation that successfully sustains fish passage, by avoiding the development of scour pools that in turn create large and difficult jumps in the waterway.

5.3.3 Velocity considerations

The analysis shows a mild relationship between velocity and success—higher velocities tend toward lower success and lower Gradation Ratios (an important factor in subsurface flow). This indicates that a special design and construction awareness should occur under high velocity conditions.

6.0 CONSTRUCTION HISTORY

Choices made during construction of the fish passageways may have an effect on successful long-term performance (refer to Figure 3.2). This proposition was explored through discovery and analysis of historical information of the fish passage locations. Some of the information was gathered through existing documents; other was gathered through a survey of ODOT personnel involved in the design, construction, and maintenance phases.

Once the historical information was collected, it was analyzed and compared to the existence of various conditions at the sites, such as scour, jumps, and subsurface flow. In addition, the relationship between the collected data and the Success Index was also examined. The relationships analyzed are shown in Table 6.1. The numbers indicated in the matrix refer to the subsections where the relationships are discussed in this report.

Table 6.1: Analyzed construction history relationships

The effect of this ↓ on this →	**Success Index**	**Jumps**	**Surface Flow**	**Scour pools**
Year improved for fish passage	6.3.1			
Design focus	6.3.3	6.4.1	6.4.1	6.4.1
Specified channel fill mix	6.3.4	6.4.2	6.4.2	6.4.2
Construction entity	6.3.5	6.4.3	6.4.3	6.4.3
Fill source	6.3.6	6.4.4	6.4.4	6.4.4
Fill mixing method	6.3.7	6.4.5	6.4.5	6.4.5
Placement and consolidation method	6.3.8	6.4.6	6.4.6	6.4.6
Frequency of biologist visit	6.3.9			

6.1 INVESTIGATION METHODS

A survey was prepared to gather information in the following areas: 1) Background Information, 2) Design Process, 3) Construction Process, and 4) Post Construction Process. The survey is shown in 0.

Three groups were targeted for information:

- Hydraulic engineers are responsible for designing the channel for hydraulic and/or fish passage purposes. These engineers are either employed by ODOT or independent design firms. They generally do not regularly return to the site after the construction is complete. Seven individuals responded.

- Regional ODOT personnel, with primary responsibility for the construction, inspection and maintenance of all the fish passage sites. Thirteen individuals, representing all five ODOT regions, responded to the request for information.

- Biologists, who are employed by ODOT and in general answer to the Environmental Manager for each region. They are in charge of evaluating the passages for healthy fish passage. They also do most of the monitoring after the facility is complete. Seven biologists responded with information.

An initial survey to solicit design and construction detail was sent to the hydraulic engineers involved in the development of the fish passage projects. They were first contacted with a phone call and the survey was sent to them by e-mail. They were asked to complete the survey and send the survey back electronically. A follow up phone call was also made in case there were any questions. The initial survey was instrumental in identifying other key project personnel and important site factors. Where other personnel were identified, they were contacted by phone. These phone conversations improved on the information obtained through the survey. The additional information expanded on the type of maintenance and environmental monitoring that is performed. Further information concerning the design of the various locations was also collected from the ODOT archives in Salem.

The "Background Information" section of the survey sought to identify the key players in the design and construction of the project. Additional identified key players included the ODOT Project supervisor/inspector, private designers, and private construction contractors. Questions in this section also sought to identify whether the design or construction was performed internally by ODOT or externally by a private firm.

The "Design Process" portion of the survey solicited the focus of the design that was performed. This included questions that asked whether hydraulic design was performed at the bridge or culvert structure and whether hydraulic design was performed for the roughened channel associated with the structure. Whenever possible, the hydraulic engineers were asked to provide a copy of their design. In some cases, the designs were obtained from ODOT archives. The respondents were also asked to characterize whether design considered hydraulics, fish passage or both—or any other requirements.

In the "Construction Process" section of the questionnaire, the respondents were asked to provide information concerning events that took place during the construction of the roughened channels. Some of this information included identifying the source of the fill material that was used, the methods that were used to mix it, the fill proportions, placement methods and methods of consolidation. In addition, construction photos were provided for several of the projects either by the maintenance managers or the hydraulic engineers.

The "Post-Construction Process" section of the questionnaire concentrated on any maintenance work that has been performed at the fish passage sites. The maintenance managers were asked to identify any work they perform at the sites, as well as identify the frequency that these sites are inspected. In addition, the biologists at the different regions were asked to identify the frequency with which they visit and inspect the sites for fish passage requirements. Whenever possible, the fish passage monitoring reports were obtained either from the region biologists or from ODOT main offices.

6.2 INVESTIGATION RESULTS

Attempts were made to contact personnel that were involved in all of the projects. Of the 22 projects that are included in the study, hydraulic engineers from 18 of them responded. For the remaining four, contact was not possible either due to retirement or transfer of these individuals. All the hydraulic engineers that were contacted replied to the survey that was sent to them. Information regarding aspects of the design and the work that took place during construction proved useful and was augmented by other sources such as ODOT archives.

6.2.1 Design and construction entities

The large majority of the design work was performed by ODOT personnel. In total, the design of 19 of the 22 sites was identified as performed by ODOT. At one site, Bateman Creek, design was performed by the private firm, HDR in 2004. Information was not available for two sites. The above information is summarized in Figure 6.1.

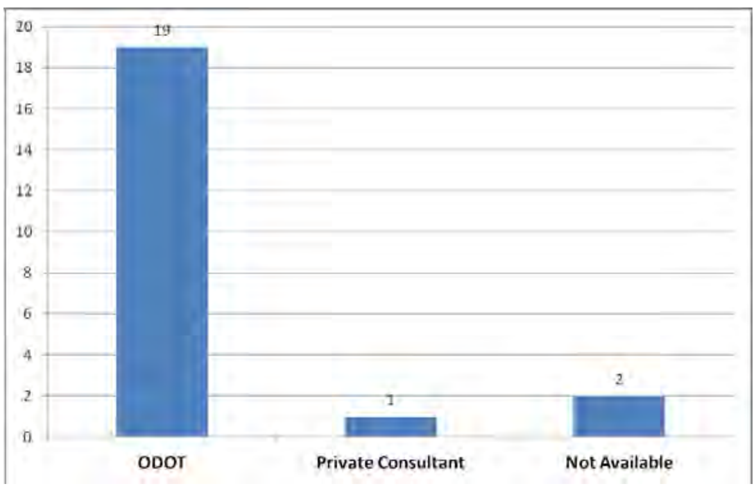

Figure 6.1: Design entity histogram

Construction of the fish passage projects was performed by both ODOT maintenance crews and private contractors. Specifically, the survey revealed that ten of the projects were constructed by ODOT, while eight were constructed by private contractors. Information on the construction of four of the projects was not obtained. This information is summarized in Figure 6.2.

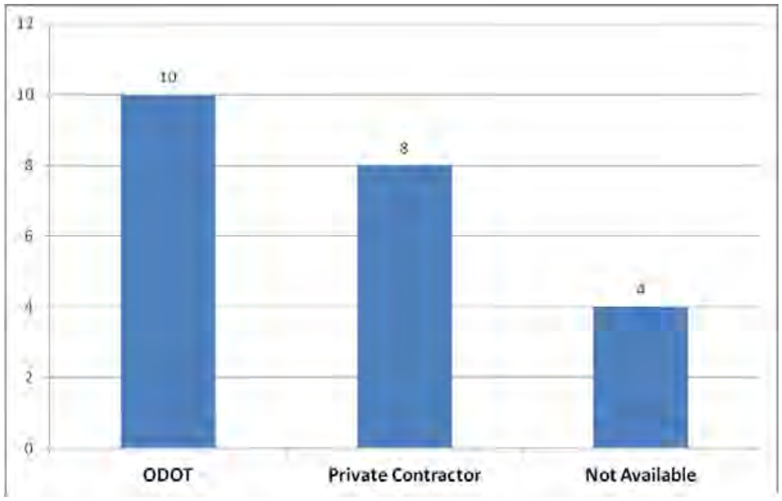

Figure 6.2: Construction entity histogram

6.2.2 Design focus and specified channel fill mixes

At the structure portion of the system, hydraulic design regularly occurred. For new bridges and culverts, complete hydraulic design occurred for the structure portion. When older culverts were retrofitted, partial structure hydraulic design was performed on added weirs, or other similar improvements that were put in place. For older bridges, hydraulic design was performed for the roughened channel that was put in place under the bridge. Information was not obtained for two of the sites.

At the downstream portion of the system, channel design (meaning either hydraulic or roughened channel design) was performed on most of the sites. Information could not be obtained for two of the sites, but from the remaining project locations, sixteen projects had full channel designs performed. At three of the sites, only a preliminary design was performed, and one site did not have any design for the downstream channel. This information is summarized in Figure 6.3.

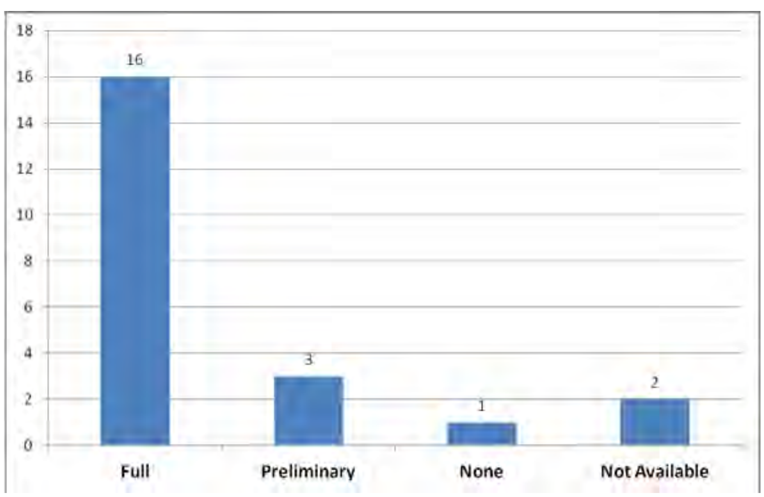

Figure 6.3: Design effort at downstream channel

When the hydraulic engineers were asked to characterize the design of the downstream channel, their responses indicated that fish passage alone was the reason for the design at 12 of the sites (recalling that only 18 of the 22 sites had survey responses from a design engineer). At three of the sites, the downstream channel design was performed for hydraulic and fish passage reasons. Each of the three remaining sites had a unique design reason in addition to fish passage. These unique reasons were: in the case of Goose Creek "the protection of the bridge from the channel cutting down" was needed; in the case of Wahkeena Creek "repair of culvert" was the reason; and in the case of Bateman Creek a "no rise certification required for Washington county." (This "No rise certification" refers to FEMA prohibiting new construction from increasing the "flood height" levels of the community in which a project is constructed (FEMA 2009)). The above results are summarized in Figure 6.4.

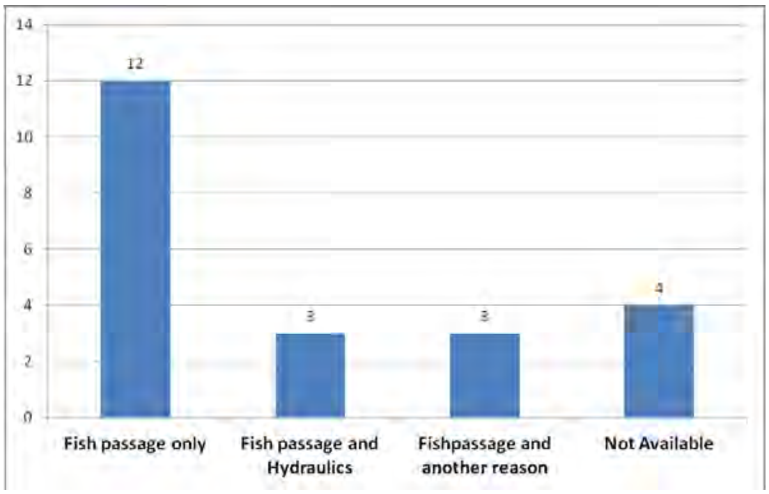

Figure 6.4: Design focus at downstream channel

Specified channel fill mixes varied among the different locations. In all of the sites, riprap was added to some extent; which according to the ASCE "Nomenclature for Hydraulics" is "broken stone or boulders placed compactly or irregularly … for the protection of earth surface against the action of waves or currents" (ASCE 1962). In this case, rip rap was specified for placement at the river bed of the streams, as well as at the banks of the streams where it was necessary according to the design requirements of each site.

In summary, five categories of fill mixtures were specified:

A. At one site, the ratio of soils to riprap was 50% by volume. The soils were generally mixed at a ratio of 2:1 (cobble and gravel : sand and fines) by volume;
B. At seven of the sites, the ratio of soils to rip-rap was 30% by volume;
C. At two of the sites, the ratio of soils to riprap was 25% by volume;
D. At one site, imported large rock mixed, or embedded, in place with the fine-grained bed material; and
E. At five locations, the channel fill mix was not specified, but rather was determined in the field, the details of which are unavailable.

The information regarding specified channel fill mix was not available for six of the sites. The information is summarized in Figure 6.5.

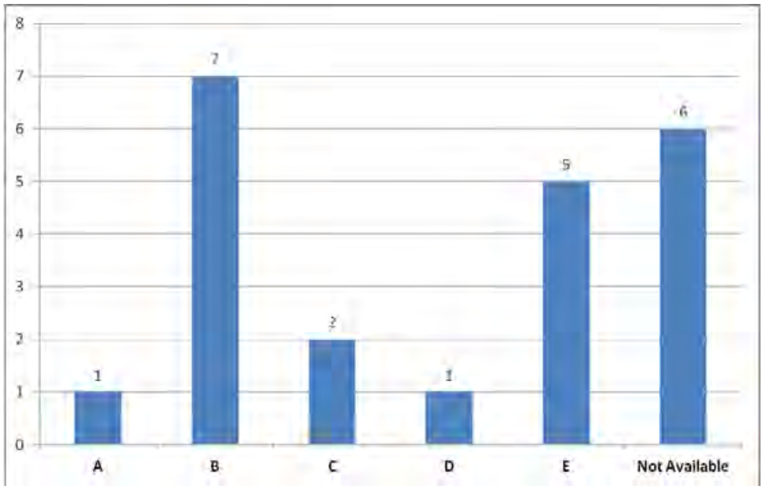

Figure 6.5: Specified channel fill mixes

There is indication that the specified channel fill mixes were achieved using the combined judgment of the construction and supervising personnel at the site. Because no instrumented post-placement measurement system was used, the actual fills may have varied from the targets.

6.2.3 Construction process

The investigation indicated that the fill material was frequently obtained through locally available sources with limited gradations. Often, the hydraulic engineers specified a well-distributed channel fill mix for the projects but the installed gradation was limited by the source from local quarries, the existing riverbed, or soil material that was originally set aside for other uses. A graphical representation of the various sources is shown in Figure 6.6. As can be observed, the majority of the time the source of the soil material was from a combination of local quarries and existing soil at the site. Soil obtained from quarries was always larger material such as boulders, cobble, and gravel.

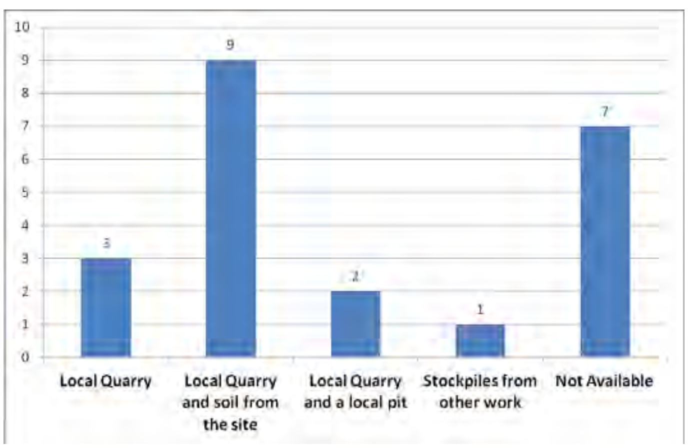

Figure 6.6: Source of fill material

The respondents were asked to indicate whether and how the fill material was mixed. At two of the sites, the fill was mixed on site prior to placement. At eleven of the sites, the fill was mixed on site during placement. The mixing was done using the equipment on site, such as skip loaders, and the material was always hosed down with water. At one of the sites, large rock fill material was placed into fine-grained streambed material with no additional fine grained material being used. This was technically mixing in place, but might better be described as embedding large material into fine-grained material. At two of the sites, mixing occurred prior and during placement using a skip loader. For five of the sites, no information was available regarding the mixing of the fill material. The above information is shown in Figure 6.7.

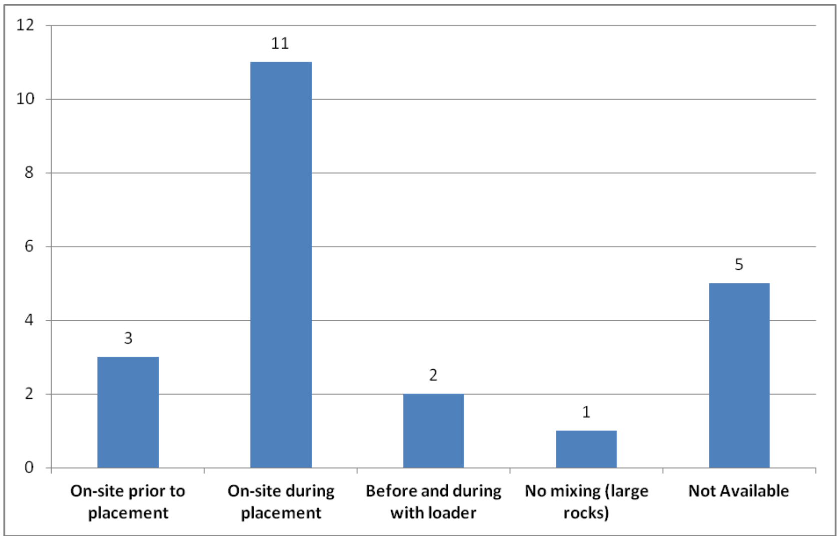

Figure 6.7: Mixing of fill material

The fill material was placed and consolidated using several methods:

A. In a few cases, the placement and consolidation method was placement of riprap in a layer, then additional soil material, which included cobbles, gravel sand and fines placed above each layer of riprap and mixed into the riprap by hose-applied water to fill the voids, then the protruding large riprap was shaken with a skip loader in order to facilitate the filling of the voids. The process was repeated to achieve the level and slope required by the design.

B. The most frequent method involved the layering of materials as described above, without the mechanical shaking.

C. At one of the sites, large material only was specified and this was mixed, or embedded, into fine-grained streambed material by pushing it down with the excavator bucket.

The information is summarized in Figure 6.8.

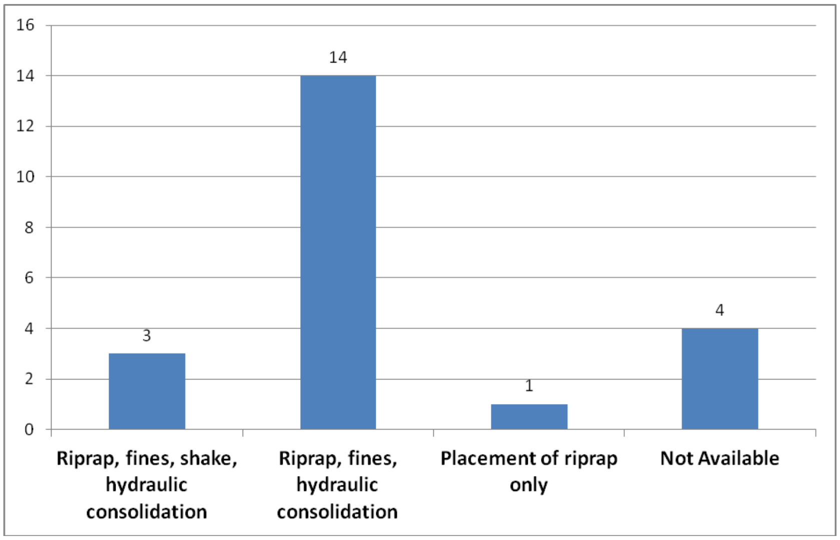

Figure 6.8: Placement and consolidation of fill material

There was no vibratory or similar compaction performed in any of the sites. Hydraulic consolidation was performed to the point that the water was ponding.

6.2.4 Post Construction

Information regarding site visits by the biologists was obtained for all 22 sites. The biologists were contacted by phone and were asked about the frequency with which they visit the sites, as well as the monitoring reports they produce. Many of the sites have passed the required annual monitoring period that is specified by NOAA or the USFWS, and annual reports are no longer prepared. Also, it is very difficult for the biologists to perform annual visits due to the large number of sites that fall under their jurisdiction, and as a result site visits are often opportunistic. Whenever possible though, biologists in the different regions pass by the sites and do a visual inspection of the fish passage structures. The frequency with which the sites are visited is summarized in Figure 6.9.

Biologist monitoring reports were only obtained for 12 of the investigated sites. This is because written monitoring reports were not always required for the different sites. In addition, the amount of monitoring depends on the permit requirements ODOT has with the different resource agencies such as NOAA or ODFW.

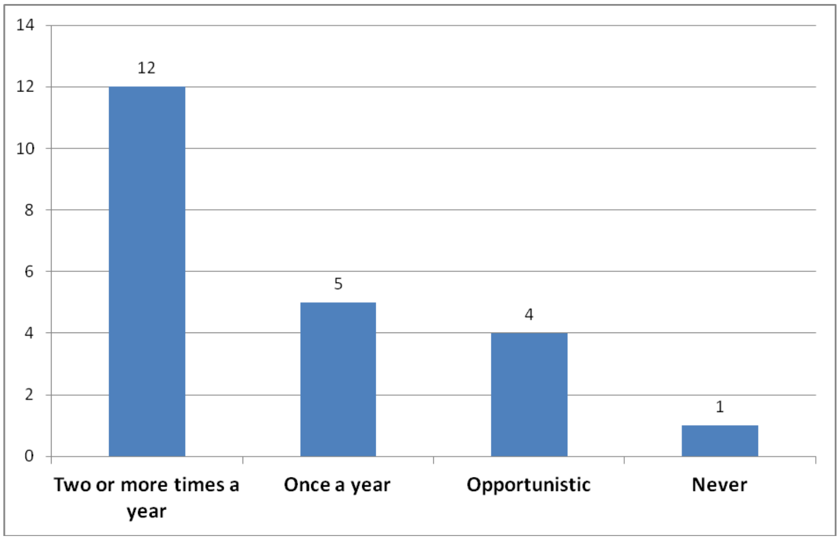

Figure 6.9: Frequency of visits to sites by biologists

All of the sites are visited occasionally by maintenance supervisors to check for any debris that may be blocking the culvert or the bridges. No maintenance is taking place at any of the sites on a regular basis, except for work that is carried out after a problem is observed or after the biologists notify that there is a problem with the fish passageway, such as excessive amount of debris blocking the flow of water, etc.

6.3 SUCCESS INDEX RELATIONSHIPS

To find out how the Success Index, which was discussed in the previous section, relates to the information that was gathered from the survey, several comparisons were produced. These include year of construction, design focus, specified channel fill mix, construction entity, material source, mixing methods, placement and consolidation, and frequency of site visits.

6.3.1 Year of construction

The year of fish passage construction was compared with the Success Index, in an attempt to discover if when the work was performed has had any effect on the performance. The Success Index was plotted against the construction year, as shown in Figure 6.10. It is clear that the lower bound of success has increased significantly over time. This is to be expected as successive episodes of high discharge degrade some sites over time. Further, it is observed that there have been many sites that continue to merit high-scores over the years. This suggests that while there has not been any consistent improvement in the design and construction over the years, it is possible to construct resilient waterway enhancements that show limited deterioration over as much as a decade.

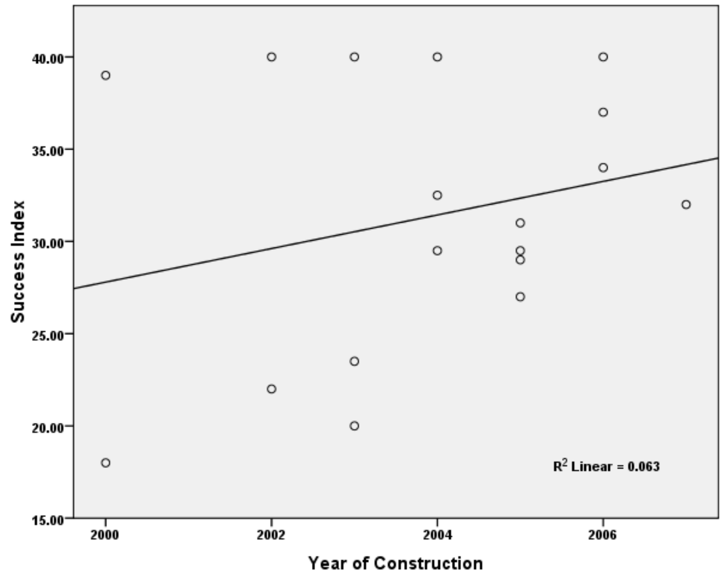

Figure 6.10: Success Index vs. year of construction

6.3.2 Highly successful sites

The sites that scored high – 39 and 40 in the Success Index – are compared in Table 6.2. Three of the sites are culverts while two are bridges. Design and construction information for Porter Creek could not be obtained. Three of the sites were designed by ODOT personnel, while one was designed by a private consultant. Three of the sites were constructed by private contractors. Two of the sites were designed for fish passage reasons, while one was designed for fish passage and channel degradation/incision, as indicated earlier. The fill that was used for two of these sites came from nearby quarries.

In addition, soil that existed at the site was also used as a component of the fill material. Information on the source of the soil was not obtained for three of the sites. Information on fill mix specifications was only obtained for two of the top rated sites. At the Perham Creek location, the fill mix that was specified consisted of a 30% ratio of soils to rip rap, while at Bateman Creek the specified mix ratio was 25%. Mixing was performed during placement at Perham Creek and prior to placement at Bateman Creek. Information on channel fill mix and mixing of the soil was not available for the other sites.

The method of placement of the fill was the same for the three sites for which information was obtained. In all three, the large rock material – riprap – was placed first and the finer material was placed above it and spread with the equipment that was available. The placed material was then flooded by hose until water was ponding at the surface. The process was repeated until the required soil level and slopes were achieved. Periodic biologist monitoring takes place at these sites except at Porter Creek. Bethel Creek is visited once a year by biologists, while the other three are visited two or more times a year.

Table 6.2: Comparison of highly successful fish passage sites

	Porter Creek	Perham Creek	Bethel Creek	3 Mile Creek	Bateman Creek
Construction year	2000	2002	2003	2004	2006
Structure type	Culvert	Culvert	Bridge	Culvert	Bridge
Success Index	39	40	40	40	40
Design entity	NA	ODOT	ODOT	ODOT	Private
Channel design effort	NA	Full	Full	NA	None
Construction entity	NA	Private	Private	NA	Private
Design focus	NA	Fish Passage	Fish Passage	NA	F.P.+Other
Fill Source	NA	Quarry + Site	Quarry +Site	NA	NA
Specified channel fill mix (soils:rip-rap)	NA	30%	NA	NA	25%
Mixing	NA	During	NA	NA	Prior
Placement and consolidation method	NA	riprap-fines-power wash	riprap-fines-power wash	NA	riprap-fines-power wash
Freq. of biologist visit	Never	2 or more	Once a year	2 or more	2 or more

It is difficult to draw firm conclusions regarding these highly successful sites based on the information available (or lack thereof) in Table 6.2. However, it is worthy to note that there is consistency with the fill source, and placement and consolidation methods.

6.3.3 Design focus

The Success Index was compared to design focus, as shown in Figure 6.11. The results are unexpected; when the design was described as being performed for fish passage reasons alone, the median Success Index is higher than when the design was performed for fish passage and hydraulic reasons. The spread of the Success Index is very wide when the design was performed for fish passage and another reason, and the median was higher than the median of the streams that were designed for fish passage and hydraulic reasons. Compounding factors, such as the requirement to perform hydraulic design on historically challenging sites may cause these curious results.

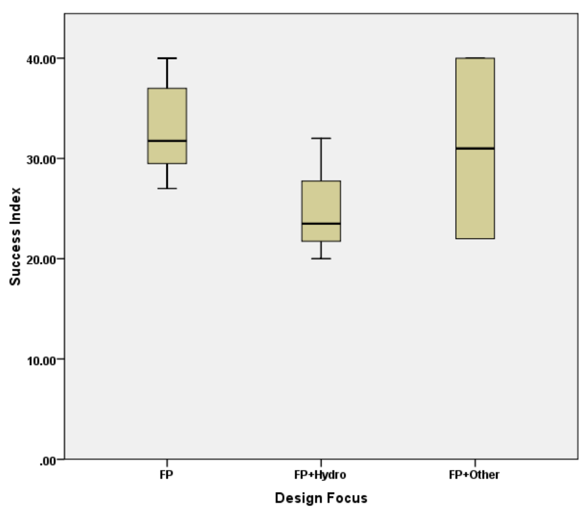

Figure 6.11: Success Index vs. design focus

6.3.4 Specified channel fill mix

Channel fill mix that was specified by the hydraulic engineers was plotted against the Success Index. That information is shown in Figure 6.12.

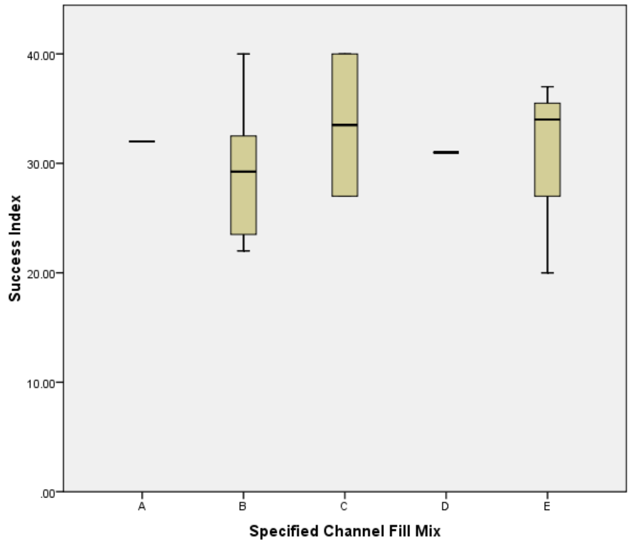

Figure 6.12: Success Index vs. specified channel fill mix

Five soil types were compared:

A. At one site, the ratio of soils to riprap was 50% by volume. The soils were generally mixed at a ratio of 2:1 (cobble and gravel : sand and fines) by volume;

B. At seven of the sites, the ratio of soils to rip-rap was 30% by volume;

C. At two of the sites, the ratio of soils to riprap was 25% by volume;

D. At one site, rip-rap was mixed in place with the existing fine-grained bed material so the ratio is unknown; and

E. At five locations, the channel fill mix was not specified, but rather was determined in the field, the detail of which is unavailable.

It is not possible to draw clear conclusions regarding the channel fill mix specified since there is a lot of overlap between the Success Index ranges of the different treatments.

6.3.5 Construction entity

The comparison of the Success Index with the construction entity is shown in Figure 6.13. It is observed that the median value of both the ODOT constructed projects and the private contractor constructed projects is about the same. The spread of the Success Index is far less for the ODOT constructed projects. These results do not support a conclusion that choice of contracting entity plays a strong role in success.

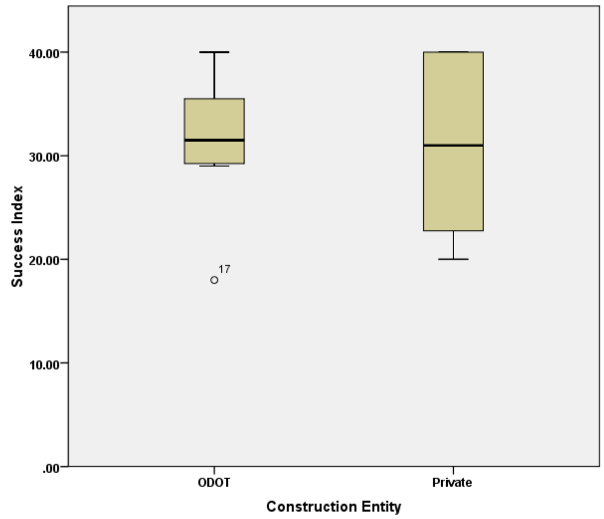

Figure 6.13: Success Index vs. construction entity

6.3.6 Material source

When the Success Index is compared with the source of the soil material (Figure 6.14), it is observed that the sites that exhibited the best success had a combination of large quarry material – riprap and boulders –mixed with soils obtained from the site. When the soil material was obtained from a quarry alone, the fish passage sites had the lowest Success Index. Similarly, when the source of material was from a quarry and a pit, or from stockpiles, the Success Index was lower than when the source was from a quarry and the site itself.

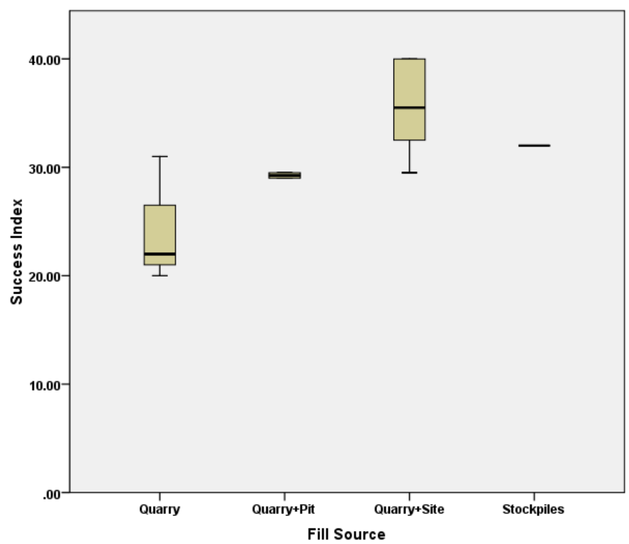

Figure 6.14: Success Index vs. source of fill material

Due to the small number of sites that are included in each category – two for quarry and pit and one for stockpiles – it is very difficult to make strong conclusions; however, there appears to be more success achieved when site soils are used as fillers in the rip-rap/soil mixture. This may be due to the naturally well-graded composition of site soils.

6.3.7 Mixing methods

Mixing of the fill material was performed for most of the sites, either before placement or during or both. The relationship between mixing method and the Success Index is shown in Figure 6.15.

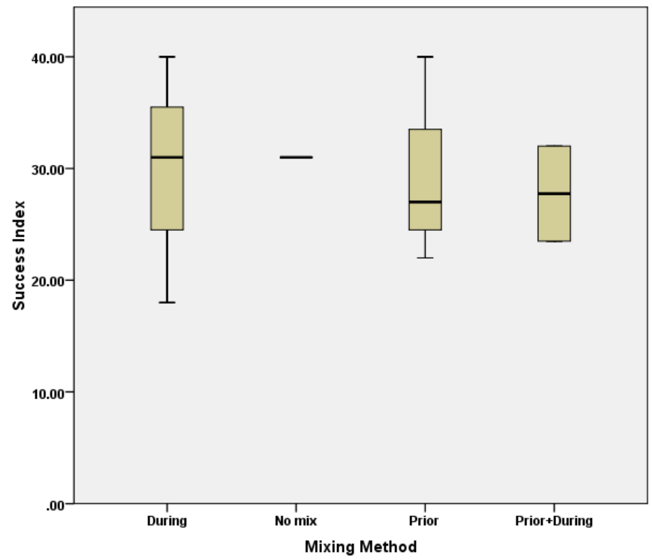

Figure 6.15: Success Index vs. mixing of soil material

As observed, the sites that had the soil material mixed only during placement had the higher spread of success. The median of that range is higher than the median of the other two methods, but it is not substantial enough to make any concrete assumptions. One site did not have true mixing as only large material was placed and this was more embedded into in situ material rather than truly mixed.

These results do not indicate a strong relationship that mixing prior to or during construction (or both) leads to more successful passageways.

6.3.8 Placement and consolidation

The next comparison that was considered was between the Success Index and the method of placement and consolidation. The results of this comparison are shown in Figure 6.16.

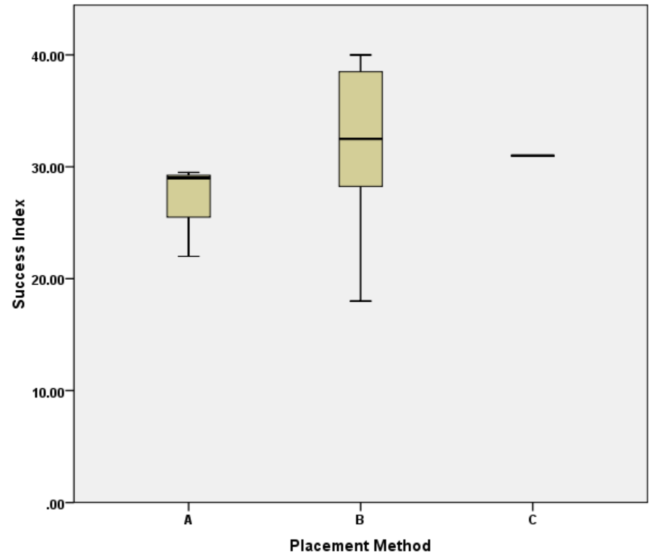

Figure 6.16: Success Index vs. placement method

Three placement and consolidation methods were considered:

A. In placement method A, first large material (riprap) was placed in the streambed. Next, the finer (cobble, gravel, sand, fines) material was placed over and around the riprap. The protruding large material was then shaken to allow the finer material to fill the voids. Finally, the material was hydraulically compacted until ponding of water was occurring at the surface. This process of placing the material was repeated until the design ground elevation was reached.
B. Placement method B is the same as method A without the shaking of the protruding rocks.
C. Placement method C consisted of working large material (riprap) into the finer grained in-situ material occurring naturally at the site.

Interestingly, method B—layering and hydraulic consolidation without shaking—appears to show better performance than when shaking is introduced. Although the sample sizes are small, this result may be worth further investigation.

6.3.9 Site visits

One final comparison that was performed was the relationship between success and the frequency of visits by the biologist. These results are shown in Figure 6.17.

Interestingly, the one site that is never visited showed a high value of success. The term opportunistic refers to sites that have visits by biologists that do not occur at a regular schedule and not on an annual basis. ‘2 or more’ refers to sites that have visits two or more times per year. Because of the high spread of the Success Index between the groups of sites, it is very difficult to conclude that frequency of visits has a significant effect on success, although it would be expected that increased visits should identify potential problems before they become actual barriers to fish passage.

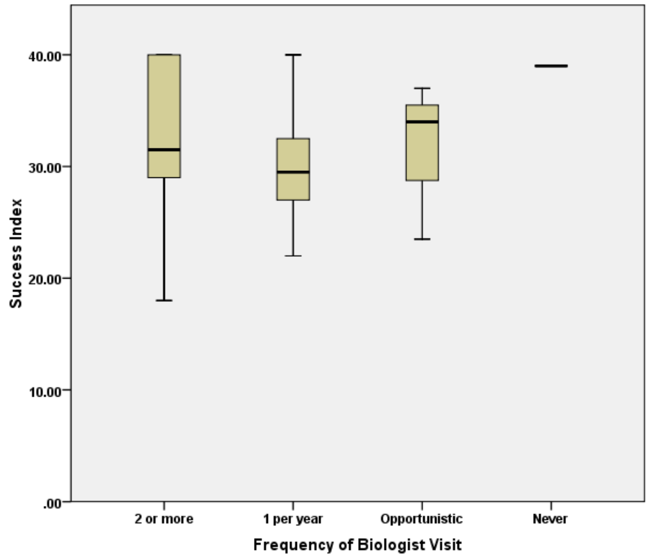

Figure 6.17: Success Index vs. frequency of visits by biologists

6.4 SPECIFIC SUCCESS FACTOR RELATIONSHIPS

The Success Index is a combination of many factors that measures overall waterway success, as explored in Section **Error! Reference source not found.**. However, exploration of some of the individual components of the Success Index may reveal relationships not evident in the earlier Success Index analysis. In this section, the historical data is compared to the specific success factors of jumps, scour, and surface flow. Design focus, specified channel fill mix, fill source, mixing method, and placement method are compared against these factors.

6.4.1 Design focus relationships

As described in Section 6.2.2, the design focus of the downstream channels was for hydraulics, fish passage, or both simultaneously. In this section, design focus is compared with specific success factors.

The existence of scour vs. design focus is plotted in Figure 6.18; jumps vs. design focus is plotted in Figure 6.19; and surface flow type (surface or subsurface) vs. design focus is shown in Figure 6.20.

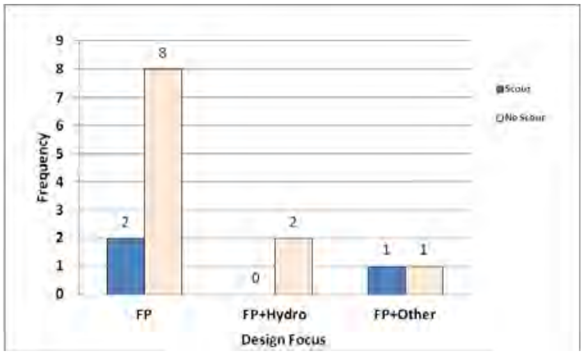

Figure 6.18: Scour vs. design focus

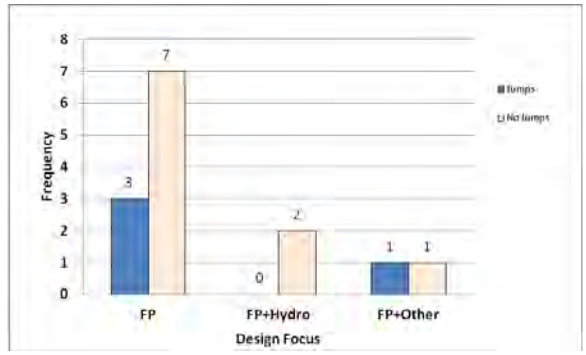

Figure 6.19: Jumps vs. design focus

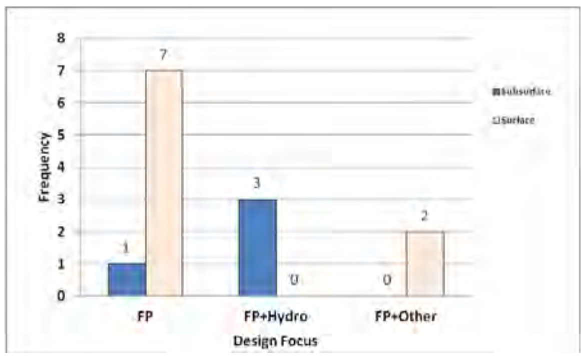

Figure 6.20: Surface Flow vs. design focus

As observed, at the sites where the design was performed for fish passage reasons alone, scour appeared at two of the sites. Scour also appeared at one site (Gooseneck Creek) that the design was performed for Fish passage and to address the channel degradation/incision described earlier. Similar jumps occurred at three of the sites that were designed for fish passage alone, while one site (Gooseneck Creek) that was designed for fish passage and to address the channel degradation/incision described earlier had jumps in the flow.

As may be observed in Figure 6.20, subsurface flow was present at all the sites where the design of the roughened channel was performed for fish passage and hydrologic reasons (Stewart, Miller and Chenoweth Creeks).

It was noted earlier that the Success Index was lower for those sites for which hydraulic design was a component of downstream channel design. These results indicate that the lower Success Index in those cases is driven by the existence of subsurface flow. The mechanism causing these results is not understood, but should be further explored.

6.4.2 Specified channel fill mix relationships

In this section, the specified channel fill mix is compared against the success factors. The existence of scour vs. specified channel fill mix is shown in Figure 6.21. The existence of jumps vs. specified channel fill mix is shown in Figure 6.22. The flow type (surface or subsurface) vs. specified channel fill mix is shown in Figure 6.23

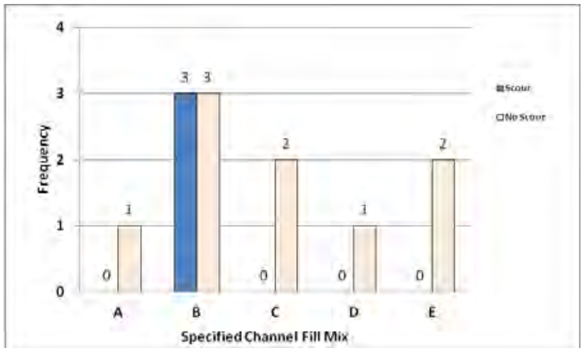

Figure 6.21: Scour vs. specified Channel fill mix

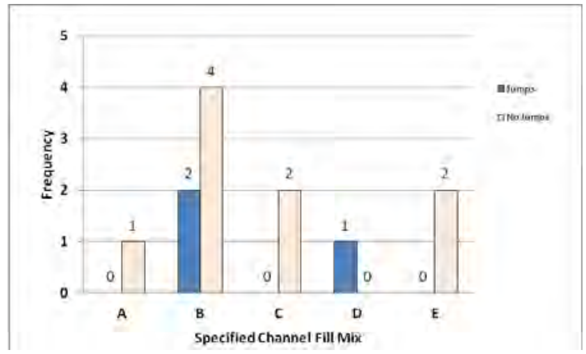

Figure 6.22: Jumps vs. specified Channel fill mix

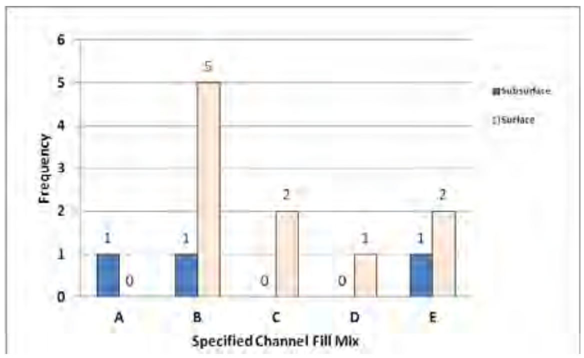

Figure 6.23: Surface flow vs. specified Channel fill mix

For the explanation of the specified channel fill mixes A through E refer to Section 6.3.4, where the design channel fill mix is compared with the Success Index.

As observed in the figure above, scour occurred in situations where the fill material ratio was 30% (type B). These three sites were Gooseneck Creek, Mill Creek and Griffin Creek.

As observed in Figure 6.22, jumps occurred at three locations. Two of the locations were built with a fill material ratio (type B). These sites were Gooseneck Creek and Griffin Creek. One site (Jackson I-5) that exhibited jumps in the flow had a specified fill of large rock only with the fine grained material being provided by the existing stream bed.(type D).

As observed in Figure 6.23, three instances of subsurface flow occurred in three sites that all had different specified channel fill mixes. Specifically, one site with a specified 50% fill material ratio (type A) showed subsurface flow (Chenoweth Creek); one site with a 30% fill material ratio (type B) showed subsurface flow (Stewart Creek); and lastly, one site with field-determined fill ratios (type E) showed subsurface flow (Miller Creek).

These results do not lead to a strong conclusion that the fill mix ratio is significant in the development of these success factors. The fact that the type C mix experienced none of the three problems is noteworthy.

6.4.3 Construction entity relationships

Success factors were compared to the construction entity information in the form of column charts, indicating the frequency of occurrence against the construction entity of these projects.

The existence of scour vs. construction entity is plotted in Figure 6.24. The existence of jumps vs. construction entity is plotted in Figure 6.25. Surface flow vs. construction entity is shown in Figure 6.26.

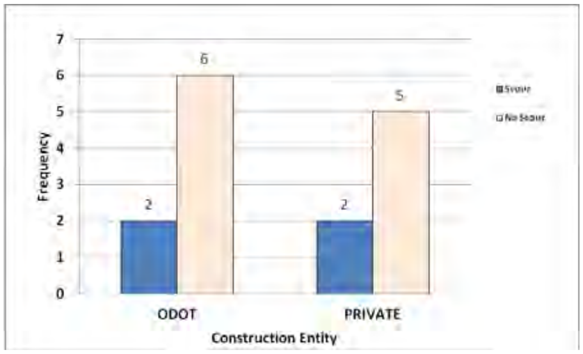

Figure 6.24: Scour vs. construction entity

Figure 6.25: Jumps vs. construction entity

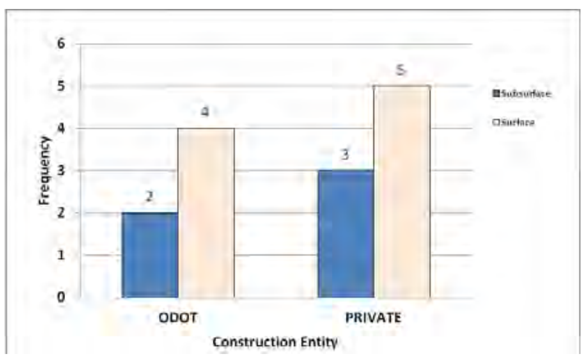

Figure 6.26: Surface flow vs. construction entity

As observed from the bar graphs, the existence of adverse success factors does appear more predominant in any one of the construction entity groups, ODOT or private. As a result, it cannot be concluded here that choice of construction entity has a significant role in these factors of success.

6.4.4 Fill source relationships

In this section, the source of the soil material is compared against the success factors. The existence of scour vs. fill source is plotted in Figure 6.27. The existence of jumps vs. fill source is plotted in Figure 6.28. Surface flow vs. fill source is shown in Figure 6.29.

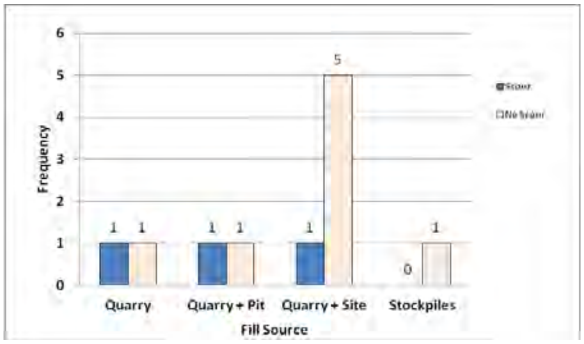

Figure 6.27: Scour vs. fill source

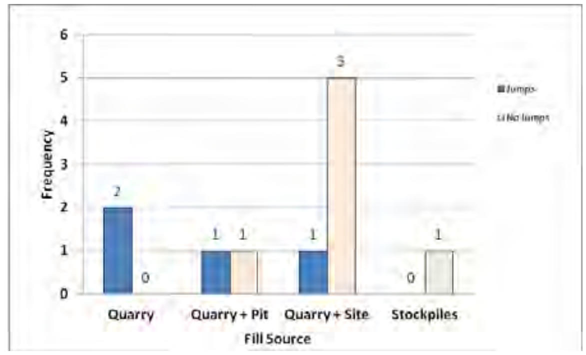

Figure 6.28: Jumps vs. fill source

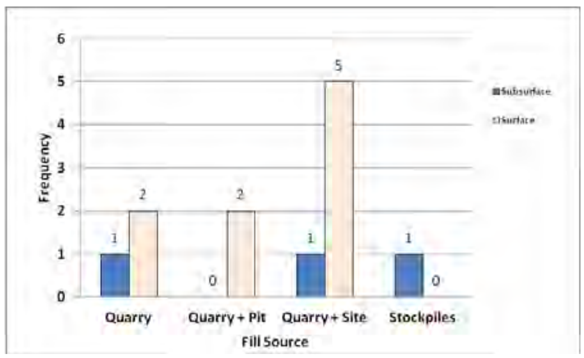

Figure 6.29: Surface flow vs. fill source

As indicated, scour occurred in varying cases of fill sources. Specifically one observation of scour occurred in each of the sites that had soil obtained from a quarry (Gooseneck), a quarry and a pit (Griffin), and a quarry and the site itself (Mill).

Jumps also occurred in sites that had a variety of fill sources. Specifically, jumps occurred in the two sites that had a source from a quarry (Gooseneck, Jackson I-5), a quarry and a pit (Griffin), and a quarry and the site itself (Jackass).

Subsurface flow also occurred in a variety of fill source conditions. In detail, subsurface flow occurred in one site that had its source from a quarry (Miller), one site that had its source from a quarry and the site (Bethel) and the site that had its source from stockpiles (Chenoweth).

Within the limitations of these small sample sizes, there appears to be a stronger likelihood of success where fill material sources includes a combination of site-obtained soils mixed with quarry-obtained rip-rap. This may be due to the naturally-occurring well-graded nature of the soil materials in the site-excavated soils.

6.4.5 Mixing method relationships

In this section, the mixing method is compared against the success factors. The existence of scour vs. mixing method is shown in Figure 6.30. The existence of jumps vs. mixing method is shown in Figure 6.31. Surface flow vs. mixing method is shown in Figure 6.32.

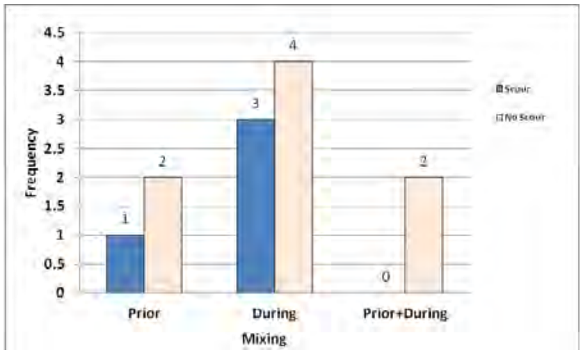

Figure 6.30: Scour vs. mixing method

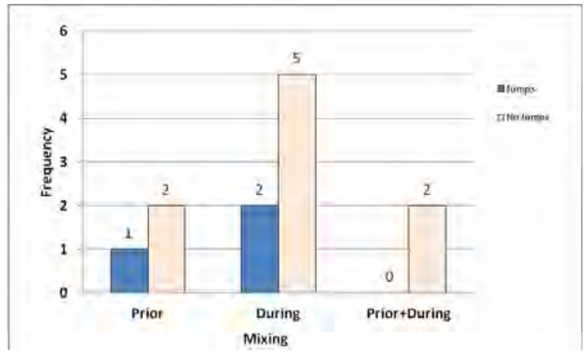

Figure 6.31: Jumps vs. mixing method

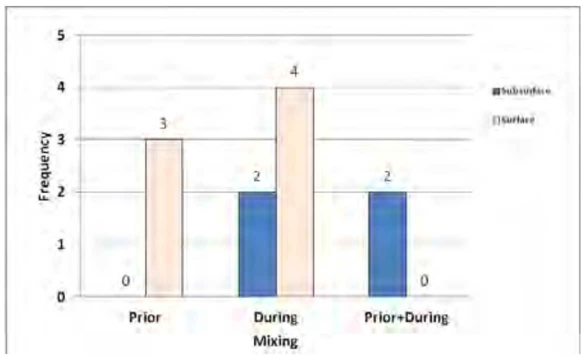

Figure 6.32: Surface flow vs. mixing method

As observed in Figure 6.30, scour occurred in situations where the soil placed was mixed before placement alone (Gooseneck Creek), as well as in situations where the soil was mixed during placement (Mill Creek, Griffin Creek, Tickle Creek).

Jumps occurred in the same two mixing methods, prior only and during only. Jumps occurred in one location where mixing was done prior to placement and that was Gooseneck Creek. At sites where mixing was done during placement, jumps occurred at Tickle Creek and Griffin Creek.

Subsurface flow occurred in only four streams. Two of these (Tickle and Miller) had their soil material mixed during placement alone. The two streams that had their soil material mixed prior and during placement were Chenoweth and Stewart Creek also exhibited subsurface flow.

The case of Gooseneck Creek which was the only location that had both jumps and scour, is a unique case, since both of these observations are attributed to stream's the channel degradation/incision and not to the fish passage improvement.

No strong conclusions result from these comparisons.

6.4.6 Placement and consolidation method relationships

In this section, the placement and consolidation method (indicated in the graphs below as simple "placement method") is compared against the success factors. The existence of scour vs. placement method is shown in Figure 6.32. The existence of jumps vs. placement method is shown in Figure 6.33. Surface flow vs. placement method is shown in Figure 6.34.

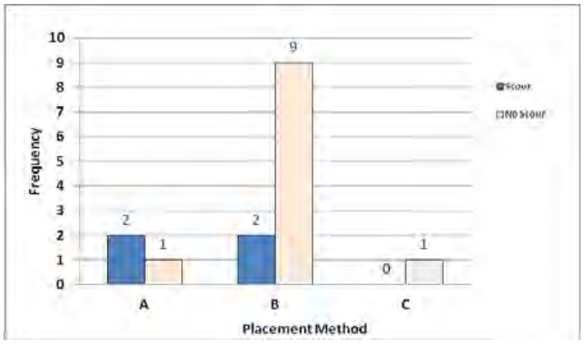

Figure 6.32: Scour vs. placement method

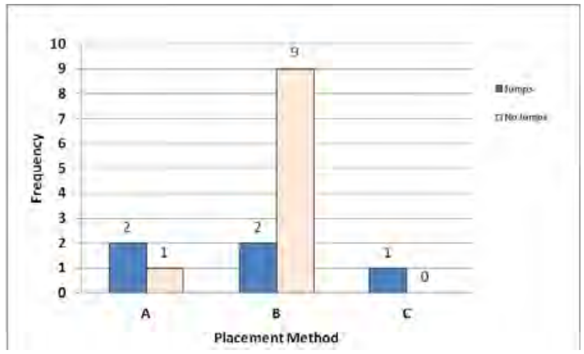

Figure 6.33: Jumps vs. placement method

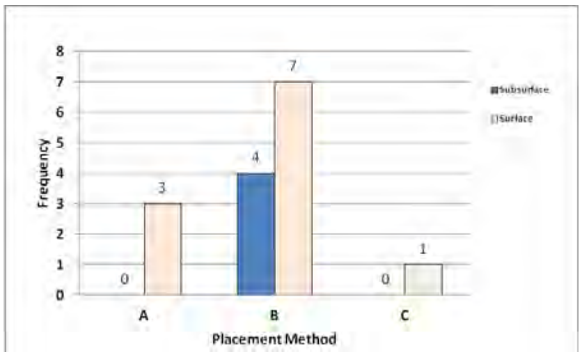

Figure 6.34: Surface flow vs. placement method

As observed in figure 6.32 above, scour only occurred in situations where soil placement was performed by methods A and B. Gooseneck Creek and Griffin Creek, placed by method A, and Mill Creek and Tickle Creek, place by method B, were the four sites that experienced scour.

The only site using placement method C did not experience scour.

As observed in Figure 6.33, jumps occurred at five locations. Two of the locations were built with placement method A. These two sites were Gooseneck Creek and Griffin Creek. Two sites placed by method B also exhibited jumps. These sites were Jackass Creek and Tickle Creek. The only site that used placement method C also exhibited jumps. That site was Jackson Creek at I-5.

Subsurface flow was unique to sites that used placement method B. These sites were Chenoweth Creek, Bethel Creek, Tickle Creek, and Stewart Creek. This observation would suggest that the additional shaking of the protruding large material, that this method omits, helps to inhibit the development of subsurface flow at the various sites. Note that earlier, however, in Subsection 6.3.8, there was slight indication that in cases where shaking occurred the overall Success Index tended to be lower. There may be undiscovered compound effects that require further investigation.

6.5 CONSTRUCTION HISTORY SUMMARY

After the analysis of the results of the investigation into construction history, one thing that can be concluded by looking at Figure 6.10—some fish passage sites seems to degrade over time while others do not.

Only one site was not designed by ODOT personnel, and as a result no inferences can be made regarding design entity and the effect on the success of the fish passage site.

The construction of the sites was undertaken by both private companies and ODOT crews. The projects that were constructed by private contractors showed the highest spread in their Success Index, while the range of the ODOT constructed project was more confined. The median value of the Success Index, however, for both groups of projects was the same.

Hydraulic design was almost always performed at the structure to some extent for the fish passage projects. For the downstream channel portion, fish passage design was always a focus, sometimes combined with hydraulic design. Although lower success appears to be related to the existence of downstream hydraulic design, compounding factors may be the cause of this result; therefore, no conclusions were formed regarding the relationship between these design focuses and success.

Channel fill mix for the construction of the fish passage projects was always specified in the hydraulic design, including 50%, 30%, and 25% mixtures of soils to rip-rap. The source of these materials was from a variety of quarries and pits, existing stockpiles, or was excavated from natural soils at the site. The more successful sites, according to the Success Index, were the sites that used large rock material from a quarry and finer material that was present at the site as opposed to imported material. This can be observed in Figure 6.14. There is no clear indication whether one type of channel fill mix specified is more successful than others, as observed in Figure 6.12 It is noteworthy that mix type C had a slightly higher median Success Index than types A, B, or D while not experiencing jumps, scour, or subsurface flow. It is speculated that the soil that is present at the various sites is already well graded and that is a better fill material compared to imported soil material.

When the construction methods were compared with the success factors that occur at the streams (scour, jumps, subsurface flow) it was observed that certain construction processes may affect surface flow conditions. The information of Subsections 6.4.4, 6.4.5, and 6.4.6 indicates that more failures occur when fill materials do not include site soils, when fills are mixed in the channel, and when the practice of shaking the larger rip-rap material to improve consolidation does not occur.

These sites should be monitored frequently. As observed in Figure 6.17, the sites that had more frequent visits by the regional biologists, had a slightly better Success Index. This is because the biologists' observations can trigger a conclusion by hydraulic engineers that improvement and maintenance work might be required at the sites.

7.0 CONCLUSIONS AND RECOMMENDATIONS

Fish passageways are designed to provide stream-like conditions that give fish the variety of stream currents and pools necessary for their migration to upstream spawning areas. These passageways must be created after disturbance of the natural streambed due to the construction of roadway crossings, such as bridges or culverts. In the case of bridge construction, a continuous channel reconstruction is possible and reportedly often successful. However, in the case of culverts, the reconstructed waterways exhibit several differing channel surfaces—from upstream channel, to culvert chute, to downstream channel. These changes provide many challenges in design of successful fish passageways, especially at the interface of each of these different surfaces.

Investigation of culvert and bridge placements in the Oregon Department of Transportation highway system has found that there is a widely varying record of success in constructing sustainable fish passageways. The field investigation of these passageways has developed conclusions regarding several important factors related to fish passage success – scour, streambed soil gradation, construction methods and monitoring.

It is important to note that the number of facilities investigated was small, and many factors were investigated among this group, creating even smaller samples that defy highly conclusive statistical analysis. Therefore, conclusions drawn are developed using a case-study style of objective and subjective observation, bolstered by the data analysis of field measurements contained herein and intuitive advice provided by the expert members of this project's Technical Advisory Committee.

7.1 SUCCESS FACTOR CONSIDERATIONS AND RECOMMENDATIONS

7.1.1 Overall success

The success of the fish passage sites seems to follow one of two paths. This is shown in Figure 6.10, where the success index of one group of sites stays high over time while another group's seem to degrade over time.

The paucity of data available about the design, and construction of many of the sites investigated inhibited the ability of this research to draw firm conclusions. More closely documenting future design and construction work may both inform future evaluations as well as impose a degree of rigor to the process that may produce more reliably positive results.

7.1.2 Scour

As noted in Figure 5.7, scour was present when the downstream portion of the streams had low slopes. Scour occurred in a number of locations where the downstream slope is very low; ranging between 2.15% and 2.74%. The streambed downstream at low slopes needs to absorb a lot of energy from the upstream flow and this may be a leading cause of scour. In addition, the existence of scour can lead to the creation of jumps and therefore another obstacle for fish passage.

A further comparison of the slopes, using the slope differentials at the various sites, showed that when the downstream slope is steeper than the upstream slope, scour was less likely to occur. So it is further suggested that the slopes downstream be at a higher slope than the upstream sections of the waterway system.

One design adjustment that might be tried is to insure that the channel immediately down stream has a roughened channel steeper than the culvert to dissipate energy before transitioning to the natural stream gradient.

7.1.3 Surface flow

Surface flow is a significant factor in success of fish passage, and it is found to be related to a lack of fines and sands in the stream channel. While no conclusive information was presented that related field factors, such as slope, with a lack of fines and sand, it was observed that certain construction processes may affect surface flow conditions. The information of Subsections 6.4.4, 6.4.5, and 6.4.6 indicates that more failures occur when fill materials do not include site soils, when fills are mixed in the channel, and when the practice of shaking the larger rip-rap material to improve consolidation does not occur.

An additional, not unexpected, result indicates a mild relationship between velocity and gradation ratio—higher velocities tend to indicate lower gradation ratios. Lower gradation ratios are, in turn, related to subsurface flow. Therefore, where higher velocities are indicated, special attention should be paid to those factors that will improve surface flow, as indicated above.

One design adjustment that might be tried is to include more and better graded sand and smaller material (more like the type C) in the construction mix to try and inhibit subsurface flow. Also layering exclusively fine grained material with the mix that includes gravel material would tend to emulate the stratification that occurs in natural stream beds.

7.2 MONITORING

The fish passage sites need to be constantly monitored, even beyond the period that is demanded by the environmental organizations. Frequent site visits can catch any problems that might arise, and corrective action be taken sooner. As observed in Figure 6.17, the sites that had visits by biologists twice or more times per year had a higher success than the sites that were only visited once a year.

In addition, development of a more rigorous method of capturing key indicators of project construction and performance would facilitate the development of future success analyses—these indicators could include such observations as actual soil gradations, in-place fill mix ratios, better documentation and standardization of placement and consolidation methods, and the use of a measuring system, such as the Success Index, to monitor longitudinal performance of the fish passageway sites, possible indicating an early-warning system of sites that may exhibit degradation over time.

7.3 FUTURE RESEARCH

Of course, the single most important expansion of this research would be the inclusion of additional data to allow for more certainty in an objective, data-based analysis. Perhaps such an expansion could include additional sites on Federal or local roadway systems, or additional ODOT sites that are constructed in the future. Greater effort should also be made to collect the complete suite of data for all of the sites that are addressed in this report.

Further investigation could also try to resolve results that were inconclusive in this investigation. Specifically, it is not understood why downstream channels that underwent hydraulic design exhibited less success than those which did not; compounding factors are suspected, but further investigation may reveal areas of interest. Additionally, actual monitoring of several cases, including detailed capture of design, construction, and performance information may provide further insight into the actual mechanisms behind the "before-and-after" conclusions of this report.

The appropriateness and manner of use of the debris component of the success index merits further investigation. Some sites, which are viewed by ODOT staff as performing well, received average scores due to this factor. The basis for the factor is clear, but its roll and value in the Success Index is less clear.

To capture the performance of these sites over time, they should be revisited in 2 to 3 years and their Success Index re-scored. This would give direct information about the rate of degradation at all the sites.

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APPENDIX A: ODOT RECORDS

Site Name	Gooseneck	Mill	King	Oak	Wahkeena	Griffin	Jackson (1)
Site Number	1	2	3	4	5	6	7
County	Polk	Lincoln	Coos	Benton	Multnomah	Jackson	Jackson
Road	Hwy 22	Hwy 229	Hwy 42	Hwy 20	Interstate 84	Interstate 5	Hwy 238
Mile Post	3.97	25.16	Below town of Bridge	55.16			1.09
Date Site Visited	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Site Visit Photos	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Before Photos (ODOT)	Yes	No	No	No	No	Yes	No
After Photos (ODOT)	Yes	No	Yes	No	Yes	Yes	No
Hydrological Report (ODOT)	Yes	No	No	No	Yes	No	No
Site Plans (ODOT)	Yes	No	No	No	Yes	No	No
Site Drawings (ODOT)	Yes (MS)	No	Yes (MS)	No	Yes	Yes	No
Design Package (ODOT)	No	No	No	No	No	No	No
Design Package	No	No	No	No	No	No	No
Design Memos/Notes (ODOT)	Yes	No	Yes	No	Yes	Yes	No
ODOT Emails	Yes	No	Yes	No	Yes	Yes	No
ODOT Permit Applications	No	No	Yes	No	Yes	Yes	No
Biological Reports (ODOT)	Yes	No	No	No	Yes	No	No
Installed	Summer 2002						
Channel Slope (%)							
Gauged							
Subsurface Flow							
Scour Pool							
Notes							

Site Name	Jackson (2)	Wiley	Chenoweth	Cottonwood	Beech	Bateman	Bethel	Miller
Site Number	8	9	10	11	12	13	14	15
County	Jackson	Grant	Wasco	Grant	Grant	Washington	Coos	Multnomah
Road	Interstate 5	Hwy 395	Old Hwy 30	Hwy 395	Hwy 395	Hwy 6	Hwy 101	Hwy 30
Mile Post	35.24	101.8	72.1	106.35	106.99-108	40.89	284.79	10
Date Site Visited	N/A	N/A	8/27/07	N/A	N/A	9/27/07	N/A	9/27/07
Site Visit Photos	N/A	N/A	Yes	N/A	N/A	Yes	N/A	Yes
Before Photos (ODOT)	No	No	No	No	No	No	No	Yes
After Photos (ODOT)	No	No	No	No	No	No	Yes	Yes
Hydrological Report (ODOT)	No	No	No	No	No	Yes	No	Yes
Site Plans (ODOT)	No	No	No	No	No	Yes	No	No
Site Drawings (ODOT)	No	No	No	No	No	Yes (MS)	No	Yes (MS)
Design Package (ODOT)	No	No	No	No	No	Yes	No	No
Design Package	No	No	No	No	No	No	No	No
Design Memos/Notes (ODOT)	No	No	No	No	No	Yes	No	Yes
ODOT Emails	No	No	No	No	No	Yes	No	Yes
ODOT Permit Applications	No	No	Yes	No	No	No	No	No
Biological Reports (ODOT)	No	No	Yes	No	No	No	No	No
Installed			Fall 2006			Summer 2006		Spring 2003
Channel Slope (%)			6.75			~4.3		5.4
Gauged			No			No		No
Subsurface Flow			Present					Present
Scour Pool			Present			Absent		Absent
Notes			Repaired Fall 2007					

Site Name	Jackass	Tryon	Perham	Three mile	Tickle	Porter	Stuart	Mail
Site Number	16	17	18	19	20	21	22	23
County	Polk	Clackamas	Hood	Wasco	Clackamas	Wheeler	Umatilla	
Road	Hwy 18	Hwy 43	Interstate 84	Hwy 30/97	Hwy 26	Hwy 207	Hwy 395	
Mile Post	19.16	5.8	57.67		21.89		12.93	
Date Site Visited	N/A	8/27/07	8/27/07	N/A	N/A	N/A	N/A	N/A
Site Visit Photos	N/A	Yes	Yes	N/A	N/A	N/A	N/A	N/A
Before Photos (ODOT)	No	No	Yes					Yes
After Photos (ODOT)	Yes	No	Yes					Yes
Hydrological Report (ODOT)	No	No	Yes					No
Site Plans (ODOT)	No	No	Yes					Yes
Site Drawings (ODOT)	No	No	No					Yes (MS)
Design Package (ODOT)	No	No	No					No
Design Package	No	Yes	No					No
Design Memos/Notes (ODOT)	No	No	Yes					Yes
ODOT Emails	No	No	Yes					Yes
ODOT Permit Applications	No	No	No					Yes
Biological Reports (ODOT)	No	No	Yes					No
Installed			Winter 2002					
Channel Slope (%)		2.9	1.8					
Gauged		Yes	No					
Subsurface Flow		Absent	Absent					
Scour Pool		Present	Absent					
Notes		Repaired Fall 2007?						

APPENDIX B: FIELD DATA

Site No	Name	Visit date	County	ODOT Region	Type	Culv No	Year Built	Year Imp	Add'l Work	BR Length	CULV Length
1	Gooseneck	29-Jul-08	Polk	2	1		1934	2002		45	
2	Mill	14-Aug-08	Lincoln	2	2	1					181
4	Oak	14-Aug-08	Benton	2	2	2					103
6	Griffin	27-Aug-08	Jackson	3	2	2					230
7	Jackson	16-Jun-09	Jackson	3	2	3		2005			154
8	Jackson	27-Aug-08	Jackson	3	2	3					353
9	Wiley	3-Sep-08	Grant	5	2	2					50.5
10	Chenoweth	12-Aug-08	Wasco	4	1			2006	Fall 2007	24	
11	Cottonwood	3-Sep-08	Grant	5	2	1					51
13	Bateman	13-Jul-08	Washington	1	1			2006		45	
14	Bethel	26-Aug-08	Coos	3	1					56	
15	Miller	23-Jul-08	Multnomah	1	1			2003		62	
16	Jackass	29-Jul-08	Polk	2	1					38.5	
17	Tryon	11-Sep-08	Clackamas	1	2	1					
18	Perham	11-Sep-08	Hood	1	2	1		2002			224
19	Three Mile C	12-Aug-08	Wasco	4	2	1					175
20	Tickle	5-Aug-08	Clackamas	1	2	1					477
21	Porter	3-Sep-08	Wheeler	4	2	1					124
22	Stuart	2-Sep-08	Umatilla	5	2	1					98.5

SiteNo	Name	CULV Length	CULV SHP	CULV MAT	CULV SURF	Culv Base	Culv Ht	Culv Diam	Baffles _y_n
1	Gooseneck								
2	Mill	181	2	1	2			12	1
4	Oak	103	1	2	2	12	11.5		1
6	Griffin	230	1	2	2	12	5.33		1
7	Jackson	154	1	2	2	9	5		
8	Jackson	353	1	2	2	14.5	7		1
9	Wiley	50.5	1	2	2	4	4		1
10	Chenoweth								
11	Cottonwood	51	1	2	2	6	4		1
13	Bateman								
14	Bethel								
15	Miller								
16	Jackass								
17	Tryon		1	2					1
18	Perham	224	2	1	2			12	1
19	Three Mile C	175	2	1	1			21	
20	Tickle	477	2	1	1			8	1
21	Porter	124	3	1	1	7.75	8.75		
22	Stuart	98.5	1	2	2	10	8		1

SiteNo	Name	RoughCulv	RoughChannelDS?	CemApron	ApronLength
1	Gooseneck		1	1	12.3
2	Mill	2	1	2	
4	Oak	2	1	1	16
6	Griffin	2	1	2	
7	Jackson	2	1	2	
8	Jackson	2	1	1	9
9	Wiley	2	1	1	4.3
10	Chenoweth		1	2	
11	Cottonwood	2	1	1	4
13	Bateman		1	2	
14	Bethel		1	2	
15	Miller		1	2	
16	Jackass		1	2	
17	Tryon	2	1	2	
18	Perham	1	2	2	
19	Three Mile C	1	1	2	
20	Tickle	2	1	2	
21	Porter	2	1	2	
22	Stuart	2	1	2	

SiteNo	Name	RestPool_y_n	RestPoolDist	Jumps_y_n	Jumps_gr_12	Sub_Flow
1	Gooseneck	2		1	1	0
2	Mill	1	20	1	2	0
4	Oak	1	17	2	2	0
6	Griffin	1	15	1	1	0
7	Jackson	1		2	2	0
8	Jackson	1	35	1	1	0
9	Wiley	1	9	2	2	
10	Chenoweth	1		2	2	1
11	Cottonwood	1	10	2	2	
13	Bateman	1		2	2	0
14	Bethel	1		2	2	1
15	Miller					1
16	Jackass	1		1	1	0
17	Tryon	1				0
18	Perham	1		2	2	0
19	Three Mile C	1		2	2	0
20	Tickle	1	18	1	1	1
21	Porter	1		1	2	
22	Stuart	1		2	2	1

SiteNo	Name	ScourP_y_n	ScourPJump	Debris _Block	Debr_type	Aggradation	Aggr _type	Trash_ Racks
1	Gooseneck	1	33.6	0		1	2	2
2	Mill	1		0		1	1,2	2
4	Oak	2		2	2,3,5,7	1	1	2
6	Griffin	1	4.2	2	2	2		2
7	Jackson	2		0		1	2	2
8	Jackson	2		2	2,3	2		2
9	Wiley	2		2	2,7	2		2
10	Chenoweth	2		0		2		2
11	Cottonwood	2		1	2,3,7	2		2
13	Bateman	2		0		2		2
14	Bethel	2		0		2		2
15	Miller			0		2		2
16	Jackass	2		2	1,5,6	2		2
17	Tryon	1		0		2		2
18	Perham	2		0		2		2
19	Three Mile C	2		0		2		2
20	Tickle	1	11	0		1	1	2
21	Porter	2		2	1,2,3	2		2
22	Stuart	2		2	3,4	1	1	2

SiteNo	Name	SLUp	SLMid	SLDown
1	Gooseneck	2.07%	0.16%	7.09%
2	Mill	1.40%	1.16%	2.15%
4	Oak		0.83%	2.56%
6	Griffin	3.16%	0.58%	2.92%
7	Jackson		0.25%	5.64%
8	Jackson	3.68%	0.009%	14.55%
9	Wiley	1.75%	3.76%	3.38%
10	Chenoweth	1.41%	0.29%	2.72%
11	Cottonwood	3.08%	3.88%	9.16%
13	Bateman	5.64%	6.02%	6.70%
14	Bethel	2.16%	1.23%	1.72%
15	Miller		6.69%	
16	Jackass	3.89%	7.64%	2.59%
17	Tryon			
18	Perham		1.86%	
19	Three Mile C		6.44%	6.33%
20	Tickle	1.17%	3%	2.74%
21	Porter		0.85%	4.80%
22	Stuart	1.73%	0.04%	5.09%

SiteNo	Name	SoilDistUp	UPLFBoulder	UPLFFines	UPLFSand	UPLFGravel	UPLFCobb
1	Gooseneck	41		5%	5%	85%	5%
2	Mill	20		5%	20%	45%	30%
4	Oak		0				
6	Griffin	30	0%	5%	35%	60%	0%
7	Jackson						
8	Jackson	26	0%	40%	40%	20%	0%
9	Wiley	10	20%	10%	20%	20%	50%
10	Chenoweth	70	20%	10%	10%	20%	60%
11	Cottonwood	20	50%	5%	10%	35%	50%
13	Bateman	50		5%	15%	25%	55%
14	Bethel	50	5%	5%	25%	65%	5%
15	Miller						
16	Jackass	13	60%	10%	10%	20%	60%
17	Tryon						
18	Perham	20	20%	5%	5%	40%	50%
19	Three Mile C	10	70%	0%	15%	40%	45%
20	Tickle	30	10%	5%	15%	30%	50%
21	Porter	29	30%	20%	20%	20%	40%
22	Stuart	15	5%	60%	30%	5%	5%

SiteNo	Name	UPHFBould	UPHFFines	UPHFSand	UPHFGravel	UPHFCobb
1	Gooseneck		5%	10%	50%	35%
2	Mill		10%	20%	60%	10%
4	Oak	0%				
6	Griffin	0%				
7	Jackson					
8	Jackson					
9	Wiley	10%	20%	25%	25%	30%
10	Chenoweth	20%	10%	20%	40%	30%
11	Cottonwood	40%	5%	10%	40%	45%
13	Bateman		0%	10%	20%	70%
14	Bethel		0%	15%	80%	5%
15	Miller					
16	Jackass		0%	10%	30%	50%
17	Tryon					
18	Perham	40%	10%	10%	40%	40%
19	Three Mile C					
20	Tickle	10%	15%	15%	20%	50%
21	Porter					
22	Stuart					

SiteNo	Name	MidLFBould	MidLFFines	MidLFSand	MidLFGrav	MIDLFCobb
1	Gooseneck					
2	Mill	0%	10%	30%	60%	0%
4	Oak	0%	25%	25%	40%	10%
6	Griffin	0%	<5%	40%	60%	0%
7	Jackson					
8	Jackson					
9	Wiley	10%	10%	50%	20%	20%
10	Chenoweth	60%	10%	10%	30%	50%
11	Cottonwood	0%	0%	0%	50%	50%
13	Bateman		5%	25%	30%	40%
14	Bethel	50%	5%	15%	60%	20%
15	Miller	20%	0%	5%	25%	50%
16	Jackass	40%	15%	5%	20%	60%
17	Tryon					
18	Perham	20%	0%	0%	50%	50%
19	Three Mile C	40%	5%	15%	30%	50%
20	Tickle					
21	Porter	50%	5%	10%	20%	65%
22	Stuart	0%	50%	50%	0%	0%

SiteNo	Name	MidHFBould	MidHFFines	MidHFSand	MidHFGrav	MIDHFCobb
1	Gooseneck					
2	Mill					
4	Oak					
6	Griffin					
7	Jackson					
8	Jackson					
9	Wiley					
10	Chenoweth	60%	10%	20%	40%	30%
11	Cottonwood					
13	Bateman	0%	0%	30%	20%	50%
14	Bethel	0%	0%	5%	75%	20%
15	Miller	60%	0%	0%	50%	50%
16	Jackass		0%	15%	35%	50%
17	Tryon					
18	Perham	20%	0%	0%	50%	50%
19	Three Mile C	0%	0%	20%	35%	45%
20	Tickle					
21	Porter					
22	Stuart	0%	50%	50%	0%	0%

SiteNo	Name	SoilDistDown	DSLFBould	DSLFFines	DSLFSand	DSLFGrav	DSLFCobb
1	Gooseneck	36	60%	10%	20%	60%	10%
2	Mill	36	50%	5%	35%	30%	30%
4	Oak	30	60%	20%	45%	20%	15%
6	Griffin	10	50%	5%	5%	40%	50%
7	Jackson	20	80%	0%	30%	50%	20%
8	Jackson	16	40%	0%	40%	60%	0%
9	Wiley	20	0%	20%	20%	50%	10%
10	Chenoweth	36	40%	5%	5%	20%	80%
11	Cottonwood	20	70%	6%	6%	30%	60%
13	Bateman	20	0%	0%	5%	40%	55%
14	Bethel	20	30%	15%	15%	50%	20%
15	Miller		0%	0%	10%	80%	10%
16	Jackass	36	30%	5%	10%	35%	50%
17	Tryon	70	20%	5%	10%	40%	45%
18	Perham						
19	Three Mile C	49	30%	5%	25%	30%	40%
20	Tickle	36	10%	60%	30%	5%	5%
21	Porter	30	60%	0%	0%	50%	50%
22	Stuart	45	30%	10%	20%	20%	50%

SiteNo	Name	DSHFBould	DSHFFines	DSHFSand	DSHFGrav	DSHFCobb
1	Gooseneck	0%	5%	15%	70%	10%
2	Mill	30%	10%	45%	40%	5%
4	Oak	60%	20%	45%	20%	15%
6	Griffin					
7	Jackson	60%	30%	60%	10%	0%
8	Jackson					
9	Wiley	10%	20%	40%	40%	0%
10	Chenoweth	40%	0%	0%	20%	80%
11	Cottonwood	50%	5%	5%	40%	50%
13	Bateman	0%	0%	10%	40%	50%
14	Bethel	0%	0%	20%	60%	20%
15	Miller	0%	0%	5%	60%	35%
16	Jackass	0%	0%	10%	50%	4%
17	Tryon	20%	5%	10%	40%	45%
18	Perham					
19	Three Mile C	0%	5%	15%	20%	60%
20	Tickle	30%	40%	40%	10%	10%
21	Porter	70%	0%	0%	40%	60%
22	Stuart	40%	15%	5%	20%	60%

APPENDIX C: SUCCESS INDEX SCORE CARD

Fish Passage Success Rating

Date: ________________ Location: ________________

	Description	Rating
1	**Jumps in the flow –** If a cross-section of the fish passage forces the fish to jump for more than 12 inches, then a value of ‘0’ should be given. If there are no fish obstructions and there are no jumps in the flow, a value of ‘10’ should be given. If the obstruction is between 0” and 12”, the value given should be interpolated.	0 1 2 3 4 5 6 7 8 9 10
2	**Surface Flow –** If there is subsurface flow then a value of ‘0’ should be given. If no subsurface flow is observed, then a value of ‘10’ should be given. Intermediate values should be assigned if some loss in surface flow is observed	0 1 2 3 4 5 6 7 8 9 10
3	**Scouring –** If a scour pool at the outlet creates a jump of 12” or more a value of ‘0’ should be given. If the scour pool creates no jump, then a value of ‘10’ should be given. If the jump is between 0” and 12”, the value given should be interpolated	0 1 2 3 4 5 6 7 8 9 10
4	**Debris Blockage –** if no blockage is present due to debris, a value of ‘10’ should be given. If debris completely blocks fish passage, a value of ‘0’ should be given. Intermediate values according to the amount of debris present	0 1 2 3 4 5 6 7 8 9 10
5	**Aggradation –** if sediment is accumulated in more than 20% of the downstream bed of the roughened channel or culvert, then a value of ‘0’ should be given. If aggradation does not occur a value of ‘10’ should be given.	0 1 2 3 4 5 6 7 8 9 10

APPENDIX D: FISH PASSAGE QUESTIONNAIRE

FISH PASSAGE QUESTIONNAIRE

Location Number: ______

Stream Name:

____

ODOT REGION: _______

COUNTY:

____

Structure Construction Year: _______

Fish passage Construction Year: _______

Preliminary information

Who performed the Fish Passage Hydraulic Design? (ODOT or Private)
Who constructed the Fish Passage work? (ODOT or Private)
Who was the project Engineer?
Who were the key players involved in the design and construction? Hydraulic Engineer ODOT Project Supervisor/ Inspector Private Designer/ Consultant Private Contractor Etc.

Design process

Was there a hydraulic design performed for the Structure (Culvert or Bridge)? If yes, who performed it? When was the design performed? Is it possible to get a copy of the design?
Was there a hydraulic design performed for the roughened channel downstream/upstream? If yes, who performed it? When was the design performed? Is it possible to get a copy of the design?

Characterize the design. Was it done just for hydraulics, fish passage or any other design requirements?

Construction process

What was the source of the soil material that was used for the creation of the roughened channel?
Was the soil material mixed (before or during placement) and if so, how?
What was the gradation for each soil type? How was that determined?
What proportions were used for each material type?

How was the soil material placed?
Was there compaction performed on the soil material after placement in the roughened channel? If compaction was performed, how was it performed?
What was done in order to ensure that the fines remained in place?

Post - Construction process

Was there any maintenance work performed after the initial construction for the roughened channel?
How often is the culvert/bridge inspected, for fish passage requirements?
Is maintenance work performed on the structure (Culvert or bridge)? If that is the case, how often and what were the dates that maintenance work was performed?

Information that we are seeking regarding the construction date

When was the culvert or bridge constructed?

When was the structure improved for fish passage?
Was there additional work performed to improve fish passage, or to stabilize structure? If that was the case **when** was that performed and **what** was performed?
What photographs / or other records are available?

APPENDIX E:
REGRESSIONS OF SOIL GRADATION AND THE SUCCESS INDEX ON VARIOUS SITE CHARACTERISTICS

Soil Gradation Ratio and Slopes

Several analyses regarding the relationships of Soil Gradation Ratio vs. structure slopes (under bridge and/or culvert slope) and vs. downstream slope were explored. The following are reported here:

- Gradation Ratio Downstream and Slope Downstream (combined and individual);
- Gradation Ratio under Bridges and Slope under Bridges; and
- Gradation Ratio Downstream and Slope of Culverts.

The first comparison that was considered was the relationship of the downstream slope to the Gradation Ratio downstream. The field information was analyzed for culverts and bridges combined and then separately for the two types of structures. From the graphs shown in Figure E-1, it can be observed that there is very little relationship between the slope downstream and the downstream gradation ratio. The r2 values for the graph that shows the bridges and culverts together is 0.009. When the bridges and culverts were plotted separately, the r2 values were 0.002 for bridges and 0.039 for culverts. The P values for the regression lines shown in Figure E-1 are 0.734 for the regression of the bridges and culverts combined, 0.943 for bridges alone, and 0.586 for culverts alone.

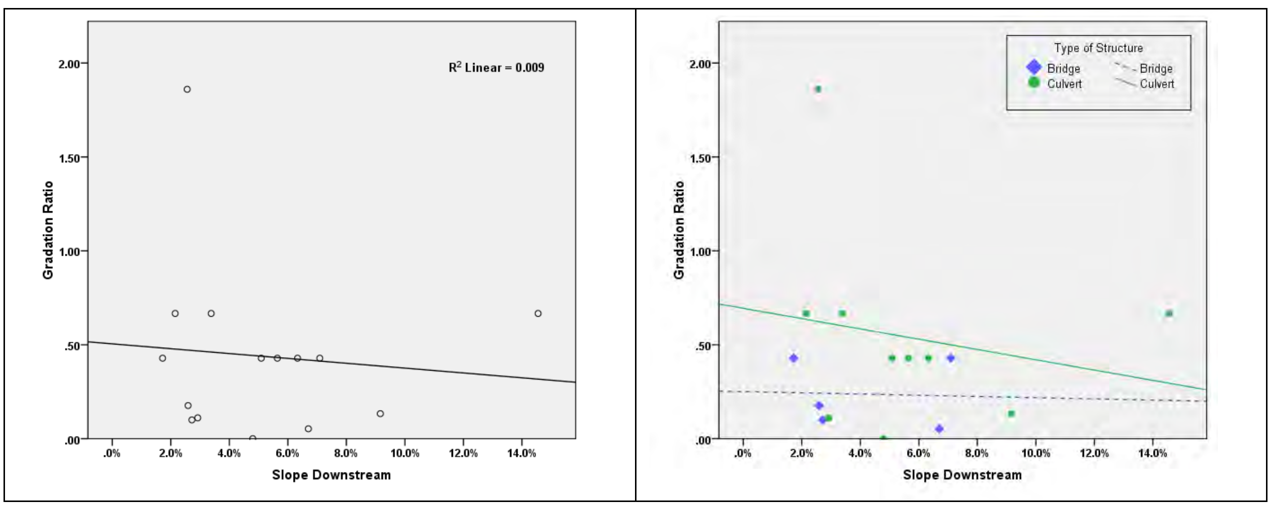


Figure E-1 – Downstream Gradation Ratio vs. slope downstream, by structure type

A graph of the effect of slope downstream on the Gradation Ratio compared against surface or subsurface flow is shown on the left in Figure E-2.

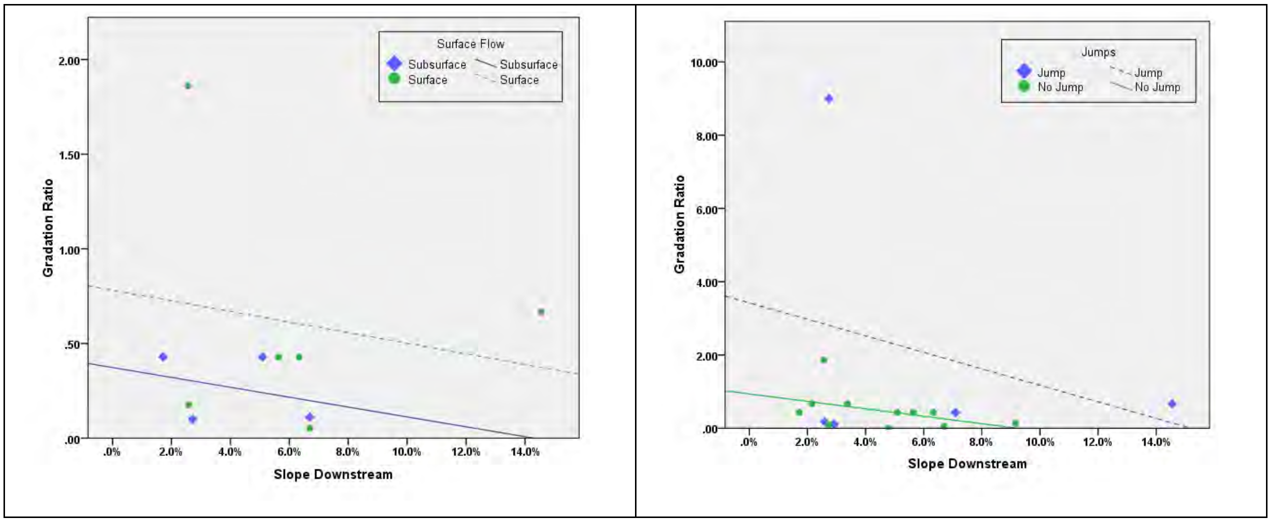


Figure E-2 – Gradation Ratio vs. slope (downstream) by surface flow, and jumps.

Figure E-2 shows that the Gradation Ratio decreases with increasing downstream slope, for both surface flow streams (the broken line) and subsurface flow streams (the solid line). Surface flow streams, though, have a higher Gradation Ratio than the subsurface flow streams. The results are not very conclusive since the R2 values are very small; 0.035 for the surface flow streams and 0.099 for the subsurface flow streams. The P values are also very high: 0.721 for the surface flow streams, and 0.685 for the subsurface flow streams.

As also observed on the right in Figure E-2, the r^2 values for this relationship, when segregated by the existence of jumps > 12”, are not very encouraging. They are 0.09 for the case where jumps greater than 12” existed along the stream (the solid line) and 0.205 for the streams that did not have any jumps (the broken line). The p values were 0.625 for the streams with jumps and 0.161 for the streams without jumps.

A similar relationship was examined for the Gradation Ratio under bridges against the slope under the bridge. This relationship is shown in Figure E-3. Again there does not seem to be any relationship between the slope under the bridge and the Gradation Ratio under the bridge. This is evident by the r^2 value which is 0.006, and the p value which is 0.904.

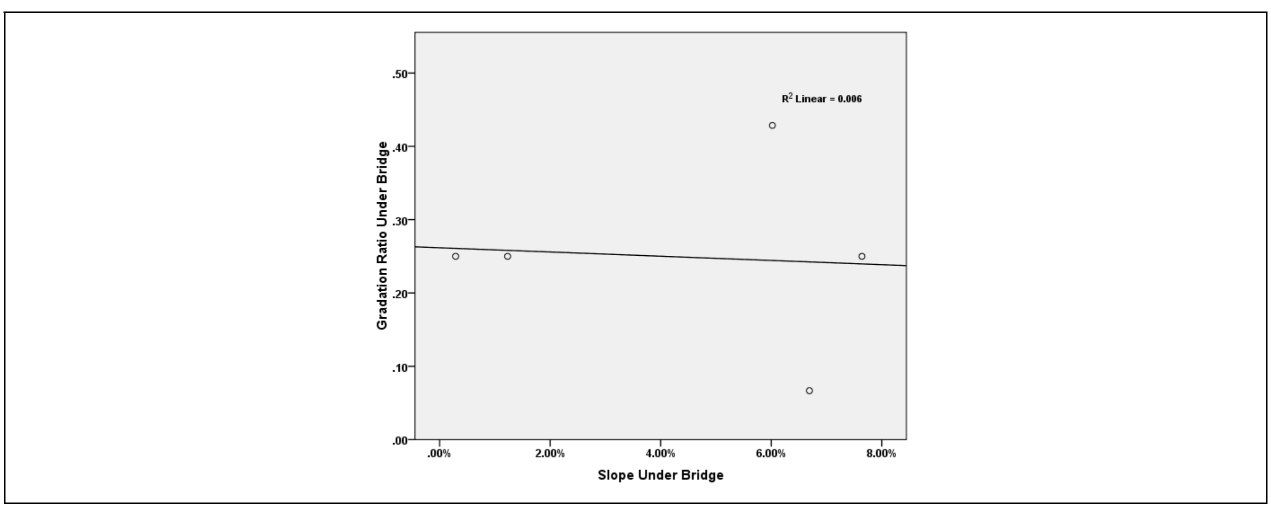


Figure E-3 – Gradation Ratio under bridge vs. slope under Bridge

A final similar comparison reported here is the relationship between the Gradation Ratio downstream and the slope of the culverts. That relationship is shown in Figure E-4. Again, there seems to be very little correlation between these two variables, since the r^2 value is only 0.016 and the p value for the slope is 0.725.

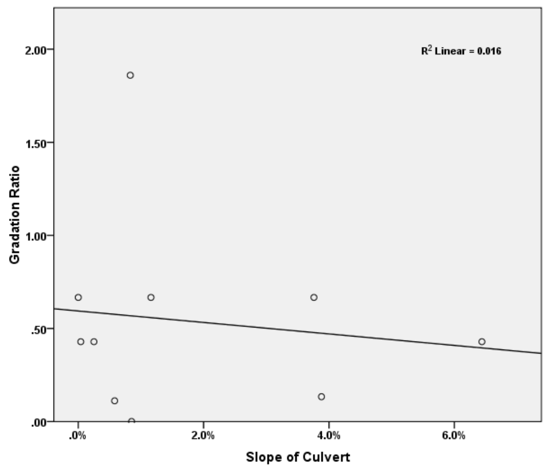


Figure E-4 – Gradation Ratio downstream vs. slope of culvert

These results do not indicate a relationship between slope and Gradation Ratio. In other words, a lack of fines may likely be the result of factors other than slope.

Slope and scour pools

Flow rates and velocities at the structures (either under bridge or in culvert) during peak flows were calculated for all sites where sufficient field data existed. The flow rate analysis consisted of calculating the estimated peak flow wetted perimeter of the streambed/culvert, calculating the cross-sectional area of flow, calculating the slope of the streambed/culvert, and estimating an appropriate Manning's Roughness Coefficient. Roughness Coefficients were chosen with the use of pictures of individual sites and gradation analysis. The flow rate at the structure (under bridge or in the culvert) was calculated with the Manning Equation:

$$Q = \frac{1.49}{n} A R_h^{\frac{2}{3}} S_0^{\frac{1}{2}}$$

where Q is the estimated flow rate, n is the roughness coefficient, A is the cross-sectional area of flow, R_h is the hydraulic radius and S_0 is the slope of the streambed.

Velocity for each site was calculated by dividing the flow by the cross-sectional area. Estimated flow rate and velocity was successfully calculated for 10 of the 22 sites.

The flow rates and velocities that were estimated for each site were compared to the corresponding downstream Gradation Ratios. The comparison between the flow rate and the downstream Gradation Ratio is shown in Figure E-5, while the comparison between the velocity and the downstream Gradation Ratio is shown in Figure E-6.

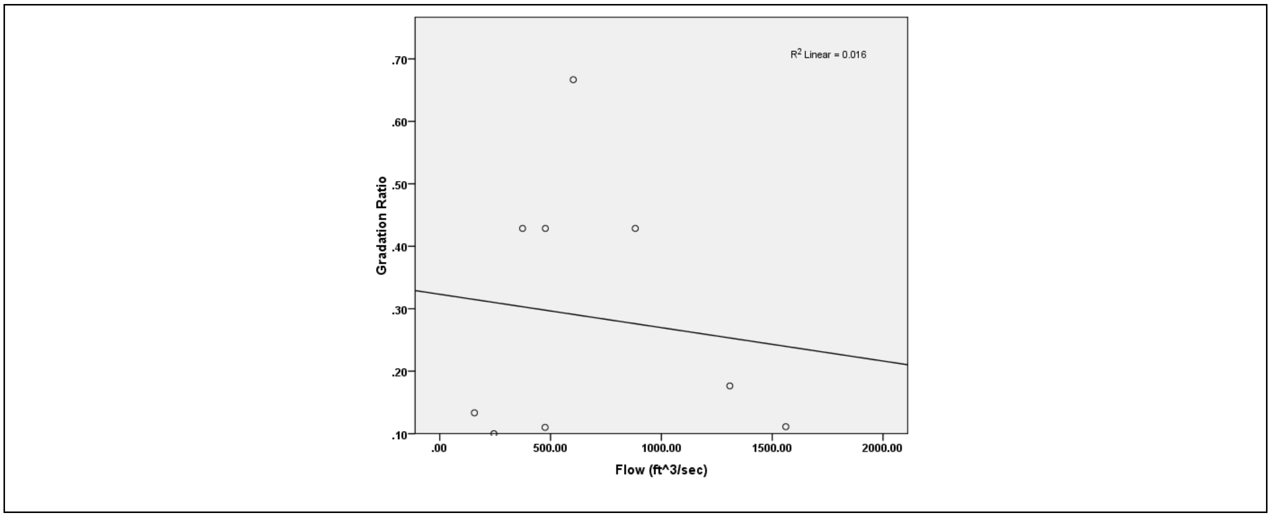


Figure E-5 – Downstream Gradation Ratio vs. flow rate

The r^2 value of the relationship between the downstream Gradation Ratio and the flow was 0.016 while the p value for that relationship is 0.747, indicating a weak relationship.

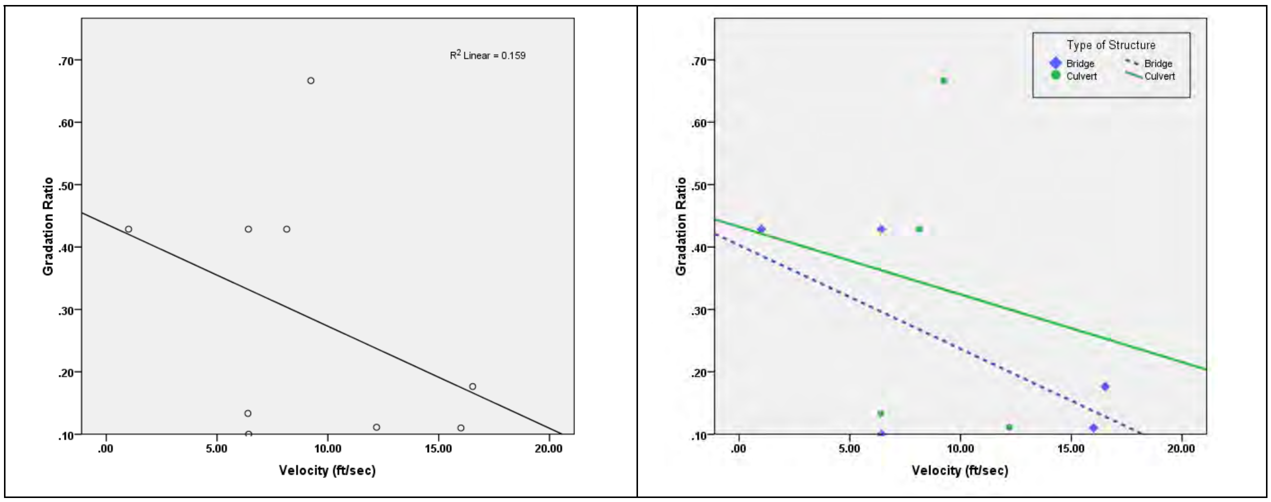


Figure E-6 – Downstream Gradation Ratio vs. velocity, and by structure type

When the downstream Gradation Ratio was assessed against structure velocity, the r^2 value of the relationship between the downstream Gradation Ratio and the velocity calculated at 0.159 and the p value was 0.288. Separately, the r^2 value for the locations with bridges was 0.452 and the p value was 0.213. Similarly for culverts, the r^2 value was 0.01 and the p value was 0.9.

The above information suggests that there is little relationship between the downstream gradation ratio and the calculated flow in the streams, and a mild relationship between velocity and Gradation Ratio, where a higher velocity indicates a lower Gradation Ratio.

The Success Index and site characteristics

The Success Index was plotted against several of the fundamental field measurements in order to determine if the success of the streams is directly related to any of them. Noteworthy comparisons include:

- Success Index and downstream slope;
- Success Index and structure slope;
- Success Index and Slope Differentials;
- Success Index and downstream Gradation Ratio; and
- Success Index and structure velocity.

The Success Index was plotted against the downstream slopes and structure slopes. In this comparison, it is evident that there is virtually no relationship between them as observed in Figure E-7. When compared with all the streams, the r^2 value was 0.011. The p value for that linear regression was 0.704. When the streams were separated according to structure type (culvert or bridges), the r^2 values were 0.102 for streams with bridges and 0.075 for streams with culverts. The p values for these relationships were 0.6 and 0.416 respectively.

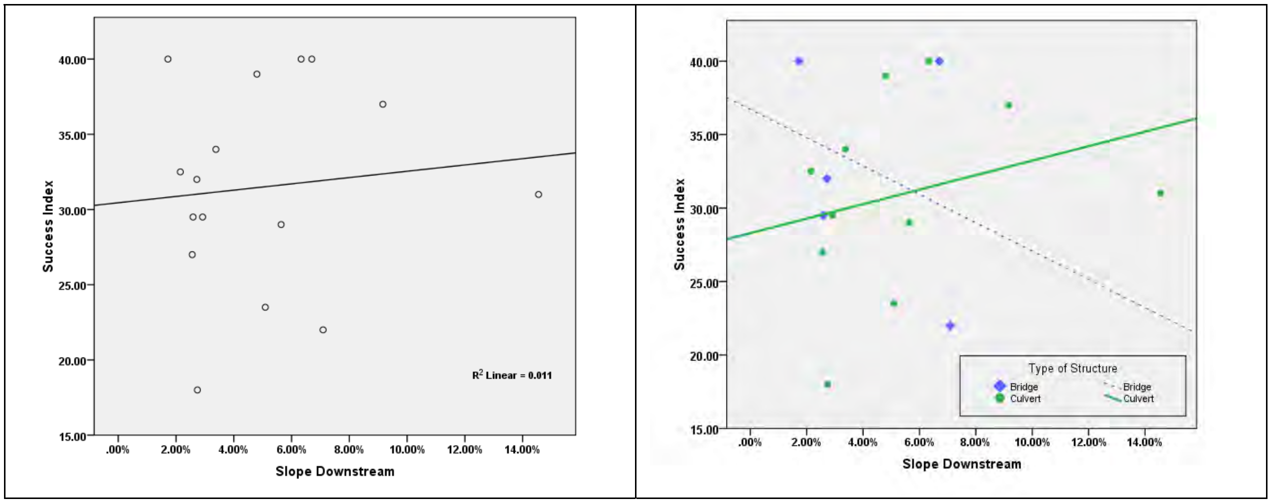


Figure E-7 – Success Index vs. downstream slope, and by structure type

Because the channel conditions for culverts are substantially different than bridges, the success index was plotted against the structure slope separately for bridges and culverts. That information is shown in Figure E-8.

From that relationship it is observed that the r^2 values were 0.006 for streams with bridges and 0.149 for streams with culverts. The p values were 0.881 and 0.215 respectively. This suggests that there is very little relationship between the Success Index and the slope under the bridge. On the contrary, there appears to be some relationship between the slope of the culvert and the Success Index. Figure E-8 suggests that culverts with a higher slope have a higher Success Index.

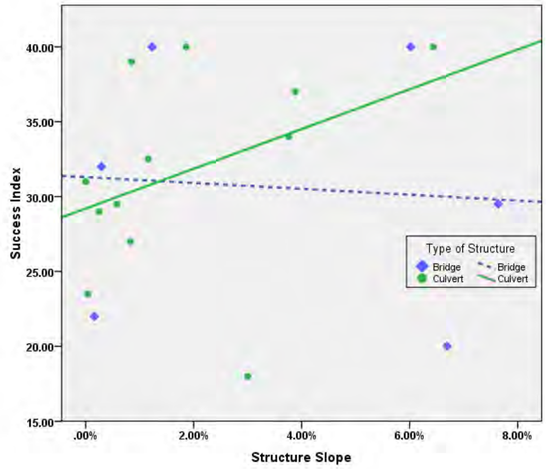


Figure E-8 – Success Index vs. structure slope

The Success Index was also plotted against the slope differentials in order to explore any possible relationships between them. Two conditions – the difference between structure and downstream slopes and the difference between upstream and downstream slopes – was plotted and analyzed as seen in Figure E-9. (Note that the calculated Slope Differential is such that a negative value indicates a steeper downstream slope, while a positive value indicates a less steep downstream slope.) In both cases of structure/downstream and upstream/downstream Slope Differentials there is a mild tendency for steeper downstream slopes to correlate with a higher success index. The r^2 values for the two relationships are 0.017 for the structure/downstream and 0.015 for the upstream/downstream. The p values for the relationships are 0.630 and 0.705 respectively.

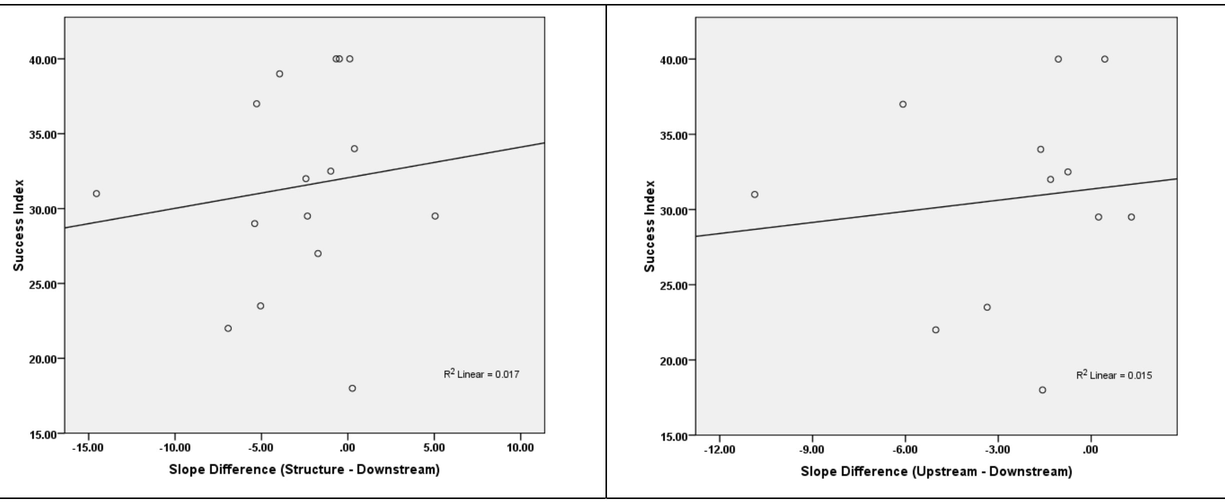


Figure E-9 – Success Index vs. Slope Differentials

The Success Index was then assessed against the slope differentials with bridges and culverts considered separately. The results are shown in Figure E-10. As observed, when bridges are compared, there is a stronger indication for a higher Success Index when there is a steeper upstream slope. In the case of Structure/Downstream, the r^2 value was 0.152 and the p value was 0.516. In the case of Upstream/Downstream, the r^2 value was 0.367 and the p value was 0.263.

For culverts, on the other hand, the results have a reverse tendency. There is some indication that a lower upstream slope is best. For the Structure/Downstream case, the r^2 value was very close to 0 and the p value was 0.929. For the Upstream/Downstream comparison, the r^2 value was 0.069 and the p value was 0.601.

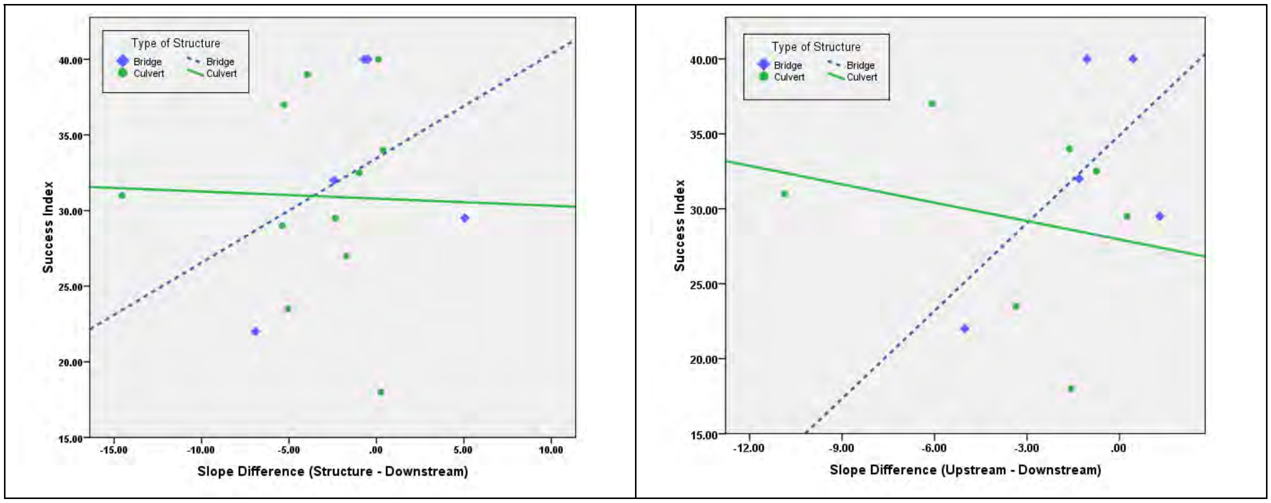


Figure E-10 – Success Index vs. Slope Differentials, by structure type

The Success Index was also plotted against the downstream Gradation Ratio. The results are shown in Figure E-11.

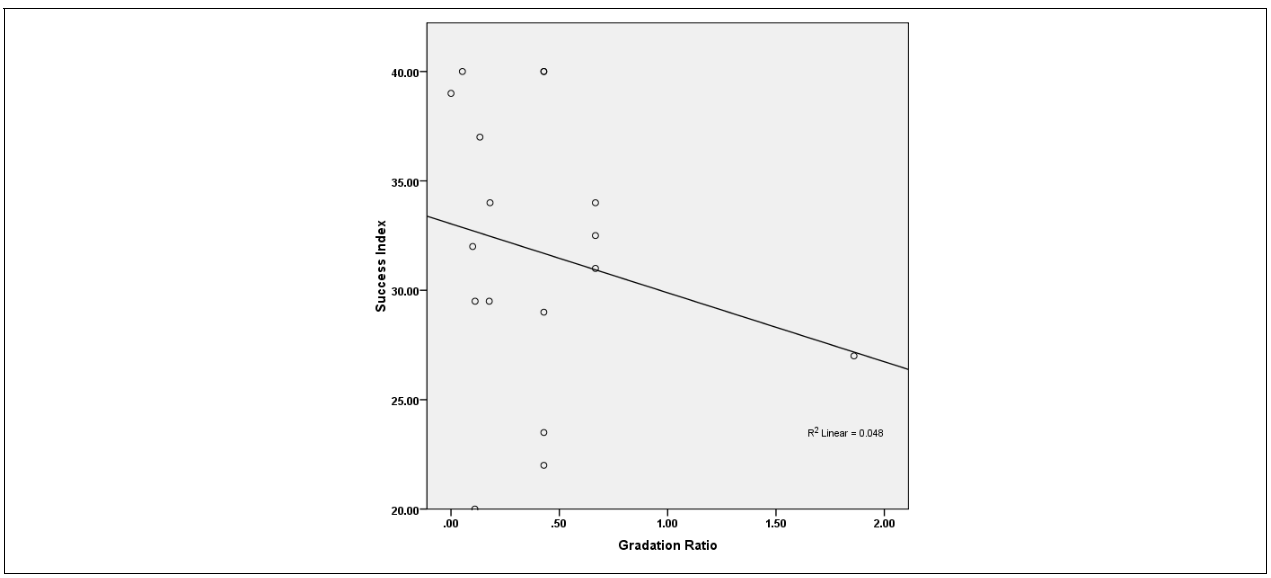
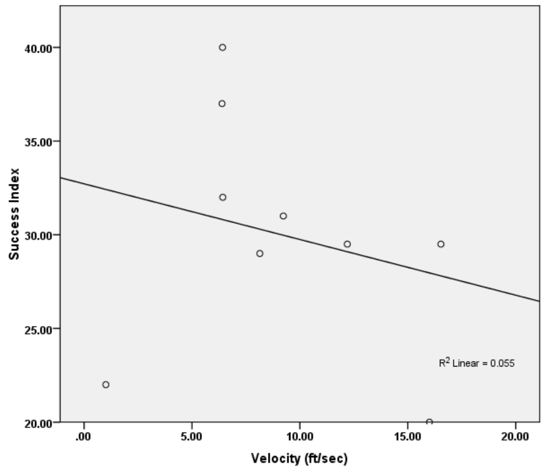


Figure E-11 – Success Index vs. downstream Gradation Ratio

Figure E-11 shows that there is some correlation between the Success Index and Gradation Ratio, with an r^2 value of 0.048. However, this is a mild relationship and by observation is strongly influenced by one atypical data point with a Gradation Ratio of nearly 2.0; if considered without that point, the r^2 value drops to 0.011—indicating a very weak relationship.

An additional noteworthy comparison was the relationship between the Success Index and the peak velocity in the streams. The results are shown in Figure E-12.



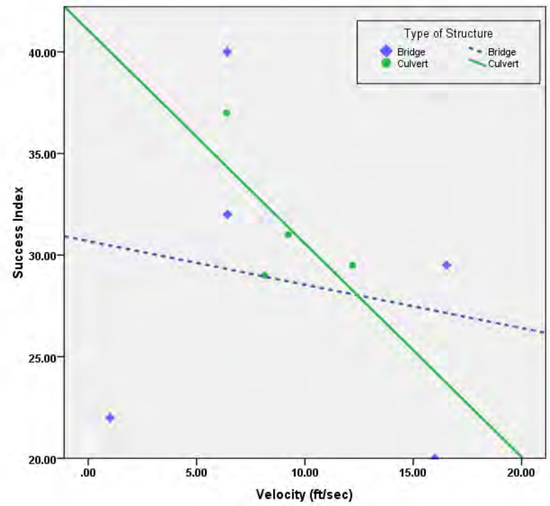


Figure E-12 – Success Index vs. velocity of middle section, and by structure type

When the locations with bridges and the culverts were compared together, the r^2 value of the relationship between the success index and the velocity was 0.055 and the p value was 0.542. Separately, the r^2 value for the locations with bridges was 0.032 and the p value was 0.773. Similarly for culverts, the r^2 value was 0.483 and the p value was 0.305.

Similar to earlier results, a mild relationship is noted that indicates higher velocities tend toward lower success.