

ABSTRACT

MERRILL, MAXIMILIAN ATLAS. The Effects of Culverts and Bridges on Stream Geomorphology. (Under the direction of Dr. James D. Gregory.)

Culverts and bridges are necessary in order to cross waterways during road construction. However, these structures have detrimental affects on the hydrology and ecology of the streams they cross. The objective of this study was to investigate how these bridges and culverts alter stream hydrology and geomorphology by determining the effects on the upstream and downstream reaches of a road crossing on the cross sectional area, the hyporheic depth, on riffle habitat, and substrate types. Three types of culverts (arch, box, and pipe) and small bridges were evaluated. All four types of stream crossings were determined to increase the cross sectional area downstream of the structure. Crossing structures also affected hyporheic zone depths by decreasing average depths downstream of the structure. Finally, most mussels seemed to occur in substrates that were dominated by relatively large particles (gravel and cobble) that were less movable by sheer stress during higher flows. Each of the problems discovered with these structures is a result of the channel restriction and the increased flow velocity and turbulence scour that it creates. These detrimental conditions can be mitigated by providing for floodplain access for higher flows. It is recommended that culverts be designed for low flows and high flows. Oversizing culverts, compared to current design criteria will allow floodplain access and build bankfull benches in the extra openings to restrict low flows to a few openings. The use of bridges that span across the valley limiting fill and allowing floodplain access may even be more beneficial. When valley fill is necessary, then side culverts in the floodplain may alleviate degradation and allow more natural floodplain hydrology.

**THE EFFECTS OF CULVERTS AND BRIDGES ON
STREAM GEOMORPHOLOGY**

by
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DEDICATION

To my mother and father who have always been supportive while helping me strive towards my goals.

BIOGRAPHY

I grew up in the mountains of western Pennsylvania in the small town of Ligonier an hour outside Pittsburgh. I attended Mercersburg Academy for my high school years and came to North Carolina to attend North Carolina State University. After completing a B.S. in Natural Resources, Ecosystem Assessment, I began work in February 2001, for a local land trust north of Charlotte, North Carolina. After two years I came back to North Carolina State University to attend the masters program in Natural Resources, Hydrology. During my undergraduate and graduate years, I have increased my knowledge about our natural resources and plan to return to the fight for conservation.

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INTRODUCTION

Over the past decade, questions have been raised by the staff of the North Carolina Department of Transportation (NCDOT) and staff of other agencies concerned with stream resources about the possible detrimental effects of road crossings on those resources. Now that many of these crossing are getting older and degrading it is time to replace these culverts and bridges with structures that will have less effect on the hydrology and ecology of the stream ecosystems. When roads cross waterways, culverts or bridges are used to allow for the waterway to travel under the road during all flows so that passengers may safely cross and that the structure is never compromised (Hamill, 1999).

However, culverts and bridges can have a negative affect on the hydrology and ecology of the waterway (Wellman et al., 2000); (Gilvear et al., 2002; Gregory and Brookes, 1983). Culverts and bridges may cause increased velocities and turbulence of flow, aggradation, scour, and bank erosion downstream of the crossing structure (Richardson and Richardson, 1999). Changes in flow velocities and channel geomorphology may, in turn, result in stream habitat alteration and adverse effects on the stream biota. Channel hydraulic alterations can also cause channel incision which disconnects the waterway from its floodplain, compounding the degradation of the ecology of the stream and riparian corridor (Philippi, 1996).

The Piedmont of North Carolina holds thousands of these stream crossing structures that vary in age, type, and impact on the stream channel. Many of the older culverts and small bridges across the state are being replaced. In some instances, where it is feasible, NCDOT construction engineers wish to replace small bridges with culverts to

reduce costs. Natural resources and regulatory agencies have raised questions about the impacts of current bridge and culvert design and installation practices on stream channel biota and aquatic habitat quality.

Reported here is a preliminary study of many culverts where mussel populations are more present in the stream and a more detailed investigation of 14 of these road crossings to determine how they alter stream geomorphology. Stream cross sectional areas, hyporheic depths, and habitat types of the stream reaches upstream and downstream of the road crossings were measured and compared.

This work is a component of a larger master study that is evaluating the impact of stream road crossings on mussel populations (Levine et al., 2003). Mussels are of concern because many of the species that may be affected by these crossing are endangered. Also mussels are considered to be excellent indicators of water quality. Other components of the master study are investigating mussel toxicology in the vicinity of stream road crossings and the effects of culverts and bridges on fish movement. The master study of mussel populations is headed by Dr. Jay Levine, North Carolina State University College of Veterinary Medicine (CVM). Each component of the study is also comparing the upstream reach with the downstream reach, and all these parts will combine to give a complete analysis of how these bridges and culverts are affecting the stream ecosystems. Each component will tell a story.

LITERATURE REVIEW

Bridges and Culverts and their Effects on Stream Morphology

In order for a road to cross a stream, engineers must design and construct a culvert or bridge. However, it is well known that these crossings adversely affect stream habitat, hydrology, and floodplain connectivity. Fish are known to be adversely affected due to resulting habitat degradation and higher flow velocities that control fish passage (Gilvear et al., 2002; Yanes et al., 1995). Fish are host species for mussels; a main concern of the master study and NCDOT.

Channel scour is one of the main issues to be addressed when a bridge or culvert is designed and constructed for a road crossing. Boulders and woody debris can alter a channel by causing turbulent flows that create scour (McKenney et al., 1995; Robert, 2003). In the same way, bridges and culverts can have an impact on channel scour and bed degradation. Several different types of scour can occur around culverts and bridges during high flows. Local scour effects the bridge abutments and piers. Flow eddies and turbulent flow erosion can happen at these locations. Contraction scour occurs when the natural cross sectional flow area of a stream channel is reduced or constricted. As this area is reduced, water velocities increase. Increased velocity adds to the shear stress and thus exacerbates bed degradation at that site (Hamill, 1999; Richardson and Richardson, 1999; Simon and Johnson, 1999; Umbrell et al., 1998). Therefore the cross sectional area is expanded by scour and bank degradation to handle these flows as the stream tries to reach equilibrium. Furthermore, as the channel adjusts towards a lower state of energy by lowering bed elevation and channel widening, the bridge structure is compromised

(Simon and Johnson, 1999). When the bridge is submerged by even greater flows, then this pressurized flow increases shear stress and creates scour (Jones et al., 1999).

Contraction scour can be further split into two types of scour. The first, live bed scour, occurs when sediment transported into the bridge area scours the stream bed. Secondly, clear water scour occurs during clear water stages and the increased flow velocities create higher shear stresses and thus scour the stream bed (Richardson and Richardson, 1999).

Scour can have a long term impact on bed degradation and affect entire channel reaches (Simon and Johnson, 1999). During high flows it has been recorded that bed degradation of 6 m can occur as a result of this contraction scour (Richardson and Richardson, 1999). These major channel scours are usually downstream of major channel constrictions, such as crossings, and check dams (Hooke and Mant, 2000). The narrow section at a bridge can cause backwater and a hydraulic jump through the bridge opening eventually causing the development of enormous scour holes just downstream. These scour holes ultimately migrate upstream through the bridge opening, posing a threat to the stability of the bridge (Darby, 1999). At some bridge sites, aggradation can occur that raises bed elevation and may bury macro fauna. Such aggradation will also increase the backwater effect and affect the pressure on the structure and passability of the bridge (Johnson et al., 2002). Bridges seem to more readily allow sediment transport than culverts and therefore have less accumulation up stream of the crossing (Wellman et al., 2000).

Culverts have similar effects on stream geomorphology and hydrology, but since most have artificial bottoms their bed effects usually stop at the structure. However these

effects can have a greater impact on fish and other mobile aquatic species than bridges since they disconnect the upstream channel from the downstream channel once the culvert becomes perched from the degradation caused by increased velocities and turbulence (Hendrickson, 1964). A perched culvert has its downstream invert elevated above the channel bottom. Severely perched culverts have been especially problematic for anadromous fish, resident fish, and terrestrial species because they disrupt the connectiveness of the stream channel (Castro, 2003). Severe erosion of the channel bottom is often the cause for culvert crossing failures. Culverts can also cause sediment accumulation in the channel upstream of their position. In the Wellman et al. (2000) study, they found that box culverts caused the most sediment accumulation (Wellman et al., 2000). However it is noted that the degradation from culverts has a limited scope downstream (Corry et al., 1975).

Culvert design has usually focused on the criterion of passing normal to flood flows through a limited cross sectional space. Many adverse geomorphological effects have resulted including plugging of the culvert, aggradation, and the high flow velocities which have contributed to the channel bottom scour that elevates the downstream end of the culvert (Gregory and Brookes, 1983). Culverts that are undersized can be overtopped by high flows, resulting in erosion of the road surface and road fill. Culverts installed at an excessive gradient can also create downstream erosion by increasing flow velocities and turbulence at the culvert outlet (Adair et al., 2002). Culvert construction handbooks even state that in higher gradient streams, providing for a spillway into a pool at the culvert outlet will reduce velocities and dissipate energy (American Concrete Pipe Association, 1964; Hendrickson, 1964).

In an effort to minimize costs and maintain flow velocity in the culvert, engineers sometimes, decrease stream sinuosity, divert flows, straighten reaches at the crossing, or perch culverts above the stream bed. Purposefully perching of a culvert and establishing a plunge pool at the end during installation is stated to sometimes be “beneficial, for the sediment will settle out” (American Concrete Pipe Association, 1964). Corrective measures are usually taken by engineers to maintain stream velocity; in some cases by removing rocks, or by armoring or shaping the channel (American Concrete Pipe Association, 1964).

Many of the standard culvert installation practices have deleterious effects on stream habitat and stream hydrology. In the past, the only factors considered when a project was designed were structure cost, structure safety, flow capacity, and any economic disasters that may come about from excessive ponding or flooding, usually pertaining to businesses or crops in the adjacent floodplain (American Concrete Pipe Association, 1964; Hamill, 1999; Hendrickson, 1964).

Incision and Stream Morphology

The formation of a stream channel is on a long (cyclic) or long (graded) time scale and is dependent on a complex set of variables. Isolation of the effect of one of these variables can be difficult. On the short time scale, channel morphology may be regarded as controlled by the physical characteristics of the system and quantities of water and sediment supplied (Schumm et al., 1987). Most of the investigated streams in our study have been channelized or incised at the crossing site and or beyond. Such channel alterations have led to incision that disconnects the stream from its floodplain,

and this instability can migrate through the whole system (Johnson et al., 2001).

Channelization and incision removes habitat and leads to an unstable channel ecosystem that will continuously erode until it reaches a new equilibrium (Darby, 1999; Gregory and Walling, 1987). The scour that the culverts and bridges cause only compounds channel incision and habitat degradation problems. Channel degradation is a response to a disturbance in which there is an excess of flow energy, shear stress or stream power relative to the amount of sediment supplied to the stream (Darby, 1999). Gilvear et al. (2002) state that: “A river channel’s geometry, planform, bed material size and levels of bed and bank stability are all controlled by river flow regime, both in terms of overall water yield, and the frequency and magnitude of flood events”.

Incised streams are disturbed ecosystems. Since these streams are incised by the local scour and channelization, the response of these streams will begin with deepening and then transition to widening as bank undercutting and slumping occur (Darby, 1999). The increased cross sectional area creates reduced velocities, reducing the channel’s sediment transport capacity and allowing sediment to settle out. Increased sedimentation rates can bury aquatic life and lead to mid channel bar formation, which can deflect flows towards the banks causing further bank erosion (Frizzell et al., 2004). Basically, any alteration or control on a natural stream system can modify channel size and shape and induce a range of geomorphological problems (Gilvear et al., 2002). Previous studies have shown that bridges have caused increased cross-sectional areas by two times or more up to 85 m downstream of a crossing (Gregory and Brookes, 1983). This widening process and bank erosion can cause large amounts of sediment to enter the system that can also bury any aquatic life downstream, and cause macroinvertebrate mortality.

However, these instances of increased bank erosion and sediment movement are related to the type of structure at the crossing.

Floodplain Importance

In North America, up to 90% of floodplains may be in agricultural use and therefore some of the floodplain functions are lost. When developed or used in agriculture the natural hydrology is altered and natural forest ecosystems are lost (Tockner and Stanford, 2002). The ecological services that floodplains provide and the threats upon them make them one of the most endangered landscapes. The hydrology of a floodplain is the single most important aspect controlling the ecological functions of this ecosystem. The dense vegetation in these riparian areas increases Manning's "n" and retards flow and thus causes slower velocities of flood flows (Rodzenko et al., 1988). When high flows enter the floodplain, the travel time of the flood waves moving downstream are increased, and reduced peak flood flows result (Rodzenko et al., 1988). These slower controlled flood flows allow sediments to fall out into the floodplain.

Construction projects that alter the floodplain hydrology, may degrade or lead to the destruction of such ecosystems (Philippi, 1996). Structures that deprive floodplains of the flood pulse generate the most damage to the health of the riparian ecosystem (Philippi, 1996). Clearing, development, and channelization of floodplain ecosystems have adversely effected the wildlife habitat within them (Lovell et al., 1988). The Army Corps of Engineers found that in some areas, development encroachments of more than 15% of the natural floodplain resulted in more than a one foot rise in flood elevation; more than allowed by FEMA (Rodzenko et al., 1988). Bridge and culvert embankments

that constrict flow may result in backwater upstream and thus alter floodplain functionality (Gilbert and Schnuck-Kolben, 1987).

The Hyporheic Zone and Mussel Habitat

“The hyporheic zone is composed of the shallow, saturated sediment below and to the sides of the stream bottom” (Schindler and Krabbenhoft, 1998). Its importance and influence is regulated by water movement, permeability, substrate particle size, resident biota, and physiochemical features (Boulton et al., 1998; Olsen and Townsend, 2003). River regulation, agriculture, urban, and industrial activities all have the potential to impair interstitial bacteria and invertebrate biota and disrupt the hydrological connections between the hyporheic zone and the stream, groundwater, riparian, and floodplain ecosystems (Hancock, 2002; Marshall and Hall Jr, 2004). The hyporheic zone is a key hydrological and biological component of most sand bed and gravel streams. Impacts on the hyporheic zone potentially jeopardize the water quality of streams and groundwater.

The hyporheic zone acts as a biological filter that is a refuge from the shear stress of the surface for macro and micro invertebrate fauna (Boulton et al., 1998; Hancock, 2002). An important interface hydrologically, chemically, and biologically for streams, the hyporheic zone can also act as a refuge for biota during dryer periods (Schindler and Krabbenhoft, 1998); (Del Rosario and Resh, 2000). However all these ecological functions of the hyporheic zone can change due to channel degradation.

In streams where there has been incision or scour, the biochemical processes of the hyporheic zone can change. Ammonification, nitrification and denitrification often occur in the hyporheic zones of shallow streams. Near the surface of the bottom substrate,

constant mixing of interstitial water with the flowing aerated stream water maintains an aerated zone where ammonification and nitrification can occur. Deeper in the sediments is an anaerobic zone where denitrification can occur. (Shibato et al., 2004); (Boulton et al., 1998; Hinkle et al., 2001). The deeper parts of hyporheic zones can be a sink for dissolved organic carbon and organic nitrogen, as well as nitrate (Shibato et al., 2004), but shallow disturbed hyporheic zones can be a source of dissolved organic carbon, organic nitrogen, and nitrate (Schindler and Krabbenhoft, 1998).

The deeper the hyporheic zone, the larger the biochemical and ecological role it will have, especially where bedrock is farther below the channel bottom surface (Boulton et al., 1998). Where there is exposed bedrock from scour, mussels can not burrow into the hyporheic zone to flee from shear stress during higher flows (Frizzell et al., 2004). The hyporheos consists of fauna that reside in this ecosystem and is composed of surface and subsurface species (Boulton et al., 1998; Schindler and Krabbenhoft, 1998). Sediment composition and vertical hydrological exchange determine the composition, populations, and distribution of the hyporheos (Boulton et al., 1998; Olsen and Townsend, 2003). Hyporheic zone development and importance is greatest in intermediate stream reaches and less important in lowland rivers and headwater streams (Boulton et al., 1998; Hancock, 2002). Ultimately the significance of the hyporheic zone to the stream is a function of its activity, health, and extent of connectivity (Boulton et al., 1998). Because of its ecological importance, managers must recognize the importance of links between the hyporheic zone and the surrounding habitats and incorporate hyporheic zone restoration or enhancement into their restoration and management plans (Hancock, 2002).

Mussels are part of this hyporheic zone but more related to the top layers. Research has pointed to the importance of the stability of substrate rather than the type of substrate that a stream contains for maintenance of mussel habitat. Streams with a good riparian zone and equal fractions of fine sediments, sands, gravels, and cobble seem to maintain normal mussel numbers (Poole and Downing, 2004). Some studies relate this provision of good mussel habitat to the larger substrate types and the resistance to movement of the larger particles by the shear stress generated by high flows (Strayer, 1999; Vannote and Minshall, 1982). Therefore mussel beds can be safely established in these “refuges” from shear stress and bed transport. In a study of mussels in the Salmon river Canyon in Idaho, mussel beds were mostly found in areas with cobble filled with gravel, or pockets of gravel behind boulders (Vannote and Minshall, 1982). These “refuge areas” are formed from local fluvial geomorphological processes.

Bridges and culverts can drastically affect the stable equilibrium of localized stream bottom areas that provide good mussel habitat. When scour or aggradation occurs from the road crossing affecting the local hydrologic processes, it can lead to mussel mortality (Box and Mossa, 1999; Vannote and Minshall, 1982). Mussel mortality rates reached over 90% for all species in one study when a silt layer began to cover the sand or gravel (Box and Mossa, 1999). These “refuge populations” are important for the long term recruitment in establishing populations in other parts of the channel (Vannote and Minshall, 1982).

MASTER STUDY OBJECTIVES

The overall goal of this study was to determine how culverts and bridges affect water resources. Specific objectives were to determine if bridge or culvert road crossings have an impact upstream or downstream on:

1. Mussel populations,
2. Environmental toxicology,
3. Fish passage, and
4. Stream geomorphology.

STREAM GEOMORPHOLOGY STUDY OBJECTIVES

The goal of this study was to determine how culverts and bridges affect stream geomorphology. Specific objectives were to determine if bridge or culvert road crossings have an impact upstream or downstream on:

1. Stream cross sectional area,
2. Hyporheic zone depth,
3. Riffle habitat or
4. Substrate types.

METHODS

Experimental Design and Study Site Selection

The ideal experimental design would have been to have a stratified random sample of culverts throughout the state. Comparison of the effects of culverts and bridges on stream channels to natural reference stream reaches may be a more statistically powerful design. In addition the upstream reach from a crossing may not be necessarily a good control. Since this study of channel geomorphology was a part of the master study on mussel populations, other factors dictated the selection of sites to investigate. The initial population of potential study sites was selected by The College of Veterinary Medicine (CVM) research team in the previous bridge study and the current culvert study of road crossing impacts on mussel populations. The choice of study sites was limited to those within 50 miles of Raleigh and that had mussel populations upstream of the road crossing. Most were in the Piedmont with a limited number in the Coastal Plain. Given this limited site database, we decided to limit our focus to one soil system in a single geologic region in order to minimize the natural variability among stream channels.

A preliminary study was conducted to investigate the condition of each road crossing included in the master studies and the land use around it. We measured bankfull widths, thalweg depths at first riffle above crossing, took pictures, and recorded dominant substrates. During this investigation we noticed a wide variation of stream widths, adjacent land uses, and substrate types, all of which can affect the hydrologic functions of a stream. We further noted many crossings had beaver dams or old mill dams that can also affect the hydrologic functions of a stream, especially stream gradient. Therefore we

needed to minimize variability among stream crossing environments from this population in order to make it possible to detect significant impacts of the culverts and bridges on stream geomorphology.

A total of 14 stream crossing sites (six bridges and eight culverts) were selected for more intensive study. These sites are dispersed across seven Piedmont counties (See Table 1). These sites were selected with the following parameters in order to control the environment around the area and to minimize impacts on stream channel geomorphology from factors other than the road crossing itself.

Foremost, only culverts or bridges that were in the soil system, the Carolina Slate Belt, were selected in order to control soil erodibility factors and stream substrate materials.

Secondly, active agricultural areas and/or cattle pastures around potential sites that allowed cattle access to streams were omitted because of sedimentation and erodibility effects that can cause channel incision and degradation of aquatic habitats and hydrology (Schumm et al., 1987). Where erosion rates are high, these agricultural lands can cause severe stream aggradation that could not be attributed to the constructed structure this study investigated (Johnson et al., 2001).

Potential study streams that had a stream confluence within the 70 m reach upstream or the 70 m reach downstream of the road crossing were omitted because of the resulting dynamic turbulent flows that create scour holes. This scour has an effect on the hyporheic zone and would cause an inconsistency in measurements (Robert, 2003).

Streams that had control devices such as dams or sills, man-made, by beavers, or natural, in the vicinity of the road crossing were omitted because of their adverse effects on free

flow and stream gradient. Larger rivers with bridges that had bankfull widths greater than the streams with culverts were also removed. Also, larger rivers or streams seemed to have bridges that allowed great amounts of floodplain access and thus were not comparable to the restricted flows of smaller bridges and culverts.

Potential study sites with relatively high proportions of urbanization in the watersheds were omitted because urbanization can have negative impacts on the physical, chemical, and biological character of the streams (Henshaw and Booth, 2000); (Finkenbine et al., 2000). Finally, sites without owner granted access were omitted.

Table 1. Study Sites List

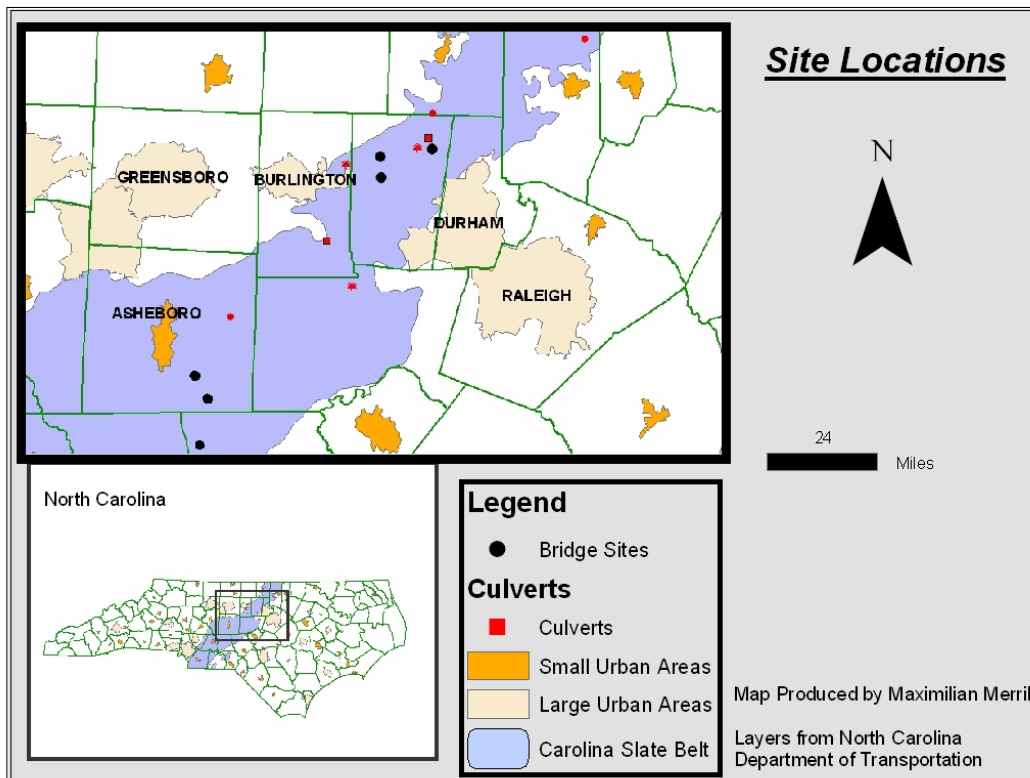
County and Site #	Type
Alamance 20	Box
Alamance 29	Arch
Chatham 12	Arch
Granville 217	Pipe
Moore 173	Bridge
Orange 13	Arch
Orange 30	Box
Orange 4	Bridge
Orange 55	Bridge
Orange 67	Bridge
Person 38	Pipe
Randolph 220	Bridge
Randolph 349	Bridge
Randolph 459	Pipe

This study was designed to compare the channel geomorphology upstream and downstream of culvert or bridge road crossings on streams with current mussel populations. We measured four factors: habitat areas (riffles, substrate types), hyporheic layer depths, channel gradient, and cross sectional areas. The channel section upstream of the road crossing is the control site for each comparison to downstream impacts. The purpose of this study is to provide information on how the road crossing is affecting stream geomorphology and how that may relate to mussel habitat near the crossing.

Geographic Location

All of the stream study sites are located in the Cape Fear and Neuse River Basins of North Carolina. The stream networks commonly have a dendritic drainage pattern and the study streams are all at least 2nd order and no greater than 4th order at the crossing (Thorne et al., 1997). The study sites are in Alamance, Chatham, Granville, Orange, Moore, Person, and Randolph counties, all which are in the Carolina Slate Belt soil system (Figure 1). This soil system has a longitudinal axis that is aligned in a northeast to southwest direction, from north of Raleigh to south of Asheboro. Topography in this part of the Piedmont in North Carolina is characterized by moderate to severe slopes. The valley sides can be very narrow. First and second order streams are common but very short in length (Daniels et al., 1999).

Figure 1. Site Location Map



Climate

The study area has a sub-humid and temperate climate with an average rainfall of 45.5 inches per year. The average high temperature is 70.0 degrees while the average low temperature is 47.0. The mean temperature is 58.6 degrees.

Geology and Soils

Study sites were chosen in one geological region with a limited range of soil types to limit the natural geomorphic variability among the study streams. Different soil types can produce different effects from disturbance (Schumm et al., 1987). Both large scale and local effects on movement of surface water exists because of geologic structure (Viessman et al., 1989). All soils in the Carolina Slate Belt system are formed from parent materials of gneiss, schist, phyllite, and volcanic igneous rocks along with slates. The less eroded soils are at least 30 percent silt plus very fine sand in the B horizon with silt surfaces. This high silt content separates these slate belt soils from those in other soils systems in North Carolina. Saprolite or bedrock is usually at the base of these shallow soils (Table 2). In our research area, which is mostly in the northern portion of the slate belt region; Georgeville and Herndon soils usually occur on the ridge tops while Nason and Tatum occur in the valleys. Georgeville and Badin are the most common soils in the study area and all soils in the region generally are moderately permeable (Daniels et al., 1999).

Land Use

Historically, a relatively high percentage of the forests in this region were clear cut for pasture or for row crop agriculture. Since the industrial revolution and immigration of the textile industry to North Carolina, many of the fields and pastures became fallow and now the region is mostly forested. Forests in these areas are dominated by hardwood, hardwood-pine mixed forests, or pine plantations, with agriculture lands sporadically placed along the hillsides and in the valleys

Table 2. Major Soils in the Carolina Slate Belt System (Daniels 1999)

Soil Series	B horizon color	B horizon texture	Major slope range (%)	Thickness >1 meter	Thickness < 1 meter	Comments
Herndon ²	YR-YB	Clay	2-15	X		
Nason ³	YR	Clay	2-15		X	
Misenheimer ^{2,4,5}	YB	Loamy	0-5		X	Level bedded slates
Goldston ²	YB	Loamy	4-25		X	40-60% slate fragments
Georgeville ²	R	Clay	6-12	X		
Tatum ³	R	Clay	4-15		X	15-40% slate fragments
Badin ^{3,4}	R	Clay	4-25		X	10-35% slate fragments
Orange ⁵	YB	Clay	0-7		X	Smectitic; Subsoil>35% base saturated
Lignum ³	YB	Clay	2-7		X	Somewhat poorly drained

1. YR=Yellowish red; YB=Yellowish brown; R= Red

2. Kaolinitic clay mineralogy

3. Mixed clay mineralogy (more than 10% expanding 2:1 clays)

4. Less than 1 m to hard rock

5. Moderately well drained

Stream Geomorphology Measurements

All stream channel measurements were made with a Sokkia SET 30R total station using a prism reflector and 7.62m (25ft) long survey rod. Cross sections were surveyed both upstream and downstream of each stream crossing at 1, 5, 10, 20, and 50 m distances from the bridge or culvert along the thalweg (Castro, 2003; Gregory and Brookes, 1983; Hadley and Emmett, 1998). The cross sections were established from the structure edge with a 100 m tape. Survey pins were set at each cross section and a

measuring tape was strung across the stream perpendicular to the flow. Permanent pins of rebar were set beside the survey pins in case a return visit was needed.

Between cross sections, the stream channel was surveyed to gain a planar image of the stream channel and how it ties into the crossing. Location measurements were made at points along bankfull, top of bank, water surface, thalweg, and across the upstream and downstream ends of the culvert and bridge (Castro, 2003). The stream points were measured to 70 m upstream and downstream of each culvert and bridge.

Hyporheic Zone Depth Measurements

At each channel cross section a piece of rebar was driven into the hyporheic zone in order to record the depth at 5 equal intervals from the left water surface edge to the right water surface edge (Wellman et al., 2000). Once bedrock or saprolite was reached the depth was recorded to the nearest 0.5 cm.

Habitat Measurements

Box stated that a simple ordinal index ranking average sediment sizes may be a useful substrate assessment approach for drawing inferences between mussel density and substrate composition (Box and Mossa, 1999). To measure substrate types upstream and downstream of the crossing, the dominant textural character of the substrate was evaluated at each point where there was a change of substrate in the stream channel. This study used substrate texture classes to characterize these substrate measurements (Table 3). Determination of substrate was from previous training using the USDA size classification (Table 4). One person did the ocular substrate analysis part on each site to

establish continuity among measurements. Sands and silts (particles less than 2 mm) were grouped into the *sand* class. Pebbles and all sizes of gravels were grouped into one *gravel* class. Cobbles and boulders were grouped into one *cobble* class. Bedrock and saprolite were classified into one *bedrock* class.

Table 3. Substrate Classes

Class	Label
Predominately Bedrock	b
Predominately Bedrock w/ Cobble	b/c
Predominately Bedrock w/ Gravel	b/g
Predominately Bedrock w/ Sand	b/s
Predominately Cobble	c
Predominately Cobble w/ Bedrock	c/b
Predominately Cobble w/ Gravel	c/g
Predominately Cobble w/ Sand	c/s
Predominately Gravel	g
Predominately Gravel w/ Bedrock	g/b
Predominately Gravel w/ Cobble	g/c
Predominately Gravel w/ Sand	g/s
Predominately Sand	s
Predominately Sand w/ Bedrock	s/b
Predominately Sand w/ Cobble	s/c
Predominately Sand w/ Gravel	s/g

Riffle habitat locations and endpoints were also measured using the total station. These measurements established an area of riffles upstream and downstream of each crossing. The stream substrate habitats were measured to 70 m upstream and downstream of each culvert and bridge.

Table 4. USDA Particle Size Classes

Material	Size (mm)
Clay, total	<0.002
Silt, total	0.002 - 0.05
Silt, fine	0.002 - 0.02
Silt, coarse	0.02 - 0.05
Sand, total	0.05 - 2.00
Very fine sand	0.05 - 0.10
Fine sand	0.10 - 0.25
Medium sand	0.25 - 0.50
Coarse sand	0.50 - 1.00
Very coarse sand	1.00 - 2.00

Statistical Analysis

Each relationship measured was evaluated using the statistical package: JMP 5.1.1. Each of the upstream measurements was paired with its downstream location counterpart and compared using analysis of covariance (ANCOVA: multiple factors) because of the four crossing types studied. An initial full model was used to analyze the culvert sites by location of cross section and hyporheic depth, but was found not to be significant. All interaction terms were dropped because none were significant. Therefore the model used was:

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2$$

where;

Y= Predicted Downstream
X1= Actual Upstream Measurement
X2= Type of Crossing.

This reduced model is the reason for the parallel regression lines for each type of crossing measured. All measurements were finally analyzed using this model. On each graph one should pay attention to the regression lines and where they cross the 1:1 slope line. When the regression line crosses the 1:1 line the effects of the crossing structure change.

Detection of statistical differences was an issue because of the small sample size and the high variability in channel characteristics among the study sites. Sample size could be increased by loosening the selection parameters and examining streams that did not have mussel populations. This would allow for more sites to be studied. However adjusting the selection parameters may increase variability and decrease R²-values. Also future studies of this type should separate small bridges with wingwalls from the newer longer spanning cement bridges and try to select sufficient examples of each to provide a sound comparison.

RESULTS AND DISCUSSIONS

General Description of Sites

During the preliminary study of culvert sites, it was noted that many channel characteristics in the vicinity of the culvert may have resulted from the impacts of the stream crossing structures. Notes were taken at each culvert site in order to guide selection of parameters to be used to select the final intensive study sites (Table 5).

First and foremost, all culvert crossings were restricting the floodplain width to a narrow portion under the crossing. This constriction of the floodplain is probably the most important impact of these culvert crossings, thus affecting flow velocity, sediment transport, and channel erosion/sedimentation processes at high flows. At a majority of the culvert crossings, the stream appeared to be enlarged and incised downstream of the crossing compared to the upstream channel reach. Hupp and Simon (1991) would define these streams in stage IV of the evolution process. Thus these streams will continue to widen and degrade until aggradation starts and they form a new but smaller floodplain. Many trees were overhanging banks and the banks were slumping more often downstream of the crossing structure (Figure 2).

Figure 2. Photographs of Channel Widening, Incision, and Overhanging Trees (looking downstream from culvert).



Table 5. Short Note Database for Potential Culvert Sites

ID #	Type	Year Built	Basin	County	Field Notes
4	Box	1934	Cape Fear	Alamance	water using 2 out of three boxes, slow water flow, ferry control devise downstream, small creek, downstream
20	Box	1930	Cape Fear	Alamance	incised below and above
29	Arch	1935	Cape Fear	Alamance	Highly incised, beaver dam, large amounts of debris downstream, narrow buffer
74	Pipe (Arch)	1997	Cape Fear	Alamance	braided up stream, deep pool below, incised more
158	Box	1997	Cape Fear	Alamance	slightly entrenched above, acting like a bridge, 1 box used, grass and shrubs on shoulder
204	Pipe	1978	Cape Fear	Alamance	slightly entrenched, bars upstream and down, deep pool below
338	Box	1960	Cape Fear	Alamance	slightly entrenched, 2 sides used third directly to floodplain
62	Box	1984	Dan	Caswell	greatly incised, slow moving, beaver activity
12	Arch	1933	Cape Fear	Chatham	bank protection needs minor repairs
18	Box	1968	Cape Fear	Chatham	incised more below, culvert in large pool
464	Box	1970	Cape Fear	Chatham	long pool after culvert, cows in creek above with bank erosion, very deep
470	Pipe	1971	Cape Fear	Chatham	culvert much wider than bankfull width, small creek
16	Box	1941	Tar	Franklin	deep hyporheic zone, more incised below but banks seem stable
62	Box	1973	Tar	Franklin	greatly incised, straightened, very deep could not get in
9	Pipe (Arch)	1989	Tar	Granville	slightly incised below less above, foot bridge above, almost flow to floodplain
28	Box	1931	Tar	Granville	greatly incised above and below, large water flow?, large log jam, large pool after culvert
29	Box	1950	Tar	Granville	greatly incised, straightened, 2 boxes only used
46	Box	1934	Dan	Granville	incised below less above, does not seem straightened
116	Pipe	1975	Dan	Granville	Slightly incised below less above, log jam.
217	Pipe (Arch)	1990	Dan	Granville	slightly incised below less above, more eroded downstream
254	Box	1960	Tar	Granville	Medium incised above with long rip rap, below highly incised, sand bar, exposed trees and roots.
268	Box	1991	Tar	Granville	slightly to medium incised
190	Arch	1930	Cape Fear	Guilford	deep pool below, beaver dam below
257	Pipe	1988	Cape Fear	Guilford	silt in pipes, more incised below, large pools above and below, culvert wider than BFW
608	Box	1938	Cape Fear	Guilford	Small creek, highly incised. 1 side used
26	Box	1991	Cape Fear	Harnett	incised downstream, sand in culvert, some scour downstream
2052	Box	1947	Neuse	Johnston	deep pool below, may be straightened, beaver dams up and down stream
27	Box	1967	Pee Dee	Montgomery	seems straightened above till rock face
44	Box	1931	Cape Fear	Montgomery	medium incised, deep pool above and below
12	Box	1931	Cape Fear	Moore	slightly incised, no cement floor
212	Pipe	1970	Cape Fear	Moore	slightly incised
220	Pipe (Arch)	1995	Cape Fear	Moore	highly incised, old bridge acting as deflector
225	Pipe (Arch)	1975	Cape Fear	Moore	slightly incised, not straightened, side culvert for swamp, 2 sides used
13	Arch	1941	Cape Fear	Orange	little influence, low incision, seemed to be normal riffle pool sequence, on bridge embankments in stream
30	Box	1941	Cape Fear	Orange	slightly incised above but less below, two sides used of box
242	Box	1950	Cape Fear	Orange	beaver activity
251	Box	1950	Cape Fear	Orange	banks beginning to slump, debris restrict channel slightly
263	Box	1986	Cape Fear	Orange	very long culvert, floodplain on each side
?	Arch	?	Cape Fear	Orange	highly incised below
22	Pipe (Arch)	1985	Cape Fear	Person	slightly incised , beaver dam upstream and maybe down, slow moving water
38	Pipe	1991	Cape Fear	Person	slightly incised , gravel bar below
211	Pipe	1994	Cape Fear	Person	banks slightly entrenched but stable
339	Box	2000	Cape Fear	Randolph	more incised below, new culvert, different than the rest
459	Pipe	1955	Cape Fear	Randolph	2 pipes being used, highly incised above and below
463	Box	1968	Cape Fear	Randolph	old cow fence above, maybe old pasture, 2 boxes used, 90 degree incision on banks, trib connection below
49	Box	1968	Cape Fear	Wake	incised banks 90 degrees, but stable
134	Box	1992	Cape Fear	Wake	greatly incised, bedrock and sediment in pools
135	Arch	1988	Cape Fear	Wake	slightly incised
372	Pipe	1993	Cape Fear	Wake	incised banks but vegetated, new culvert
561	Box	1926	Cape Fear	Wake	sinuous upstream and straight below, more entrenched downstream, sand in culvert

Because some of the culverts are oversized for low flows, mid-channel bars have formed (Figure 3). This is a definite sign that the channel cross section is too large and therefore normal sediment transport is not taking place. Furthermore it seems that over time some of these oversized culverts are forming bankfull benches in the culvert openings not readily used during low flows. These culverts with bankfull benches established inside, seemed to have the least impact on downstream conditions, and resulted in a more stable channel environment (Figure 4). In effect, where ample cross sectional flow area is available in a multi-opening box culvert, the stream has re-established a low flow channel in one or more openings and using the remaining openings as the bankfull channel. The larger multi-opening box culverts exhibited little perching (Figure 3 &4). However, relatively small pipe culverts that severely restricted high flows often had an incised pool downstream of the culvert resulting in perching of the downstream end of the culvert. (Figure 5).

Figure 3. Photograph of Mid-Channel Bar Forming.



Figure 4. Bankfull Bench Forming in Culvert.



Figure 5. Perched Pipe Culvert.



Minimum Impact Example

Certain sites seemed to have the least amount of impacts on stream geomorphology. The Randolph 220 Bridge site was one of the crossings that had the least amount of impact on cross sectional areas, hyporheic depths, riffle habitat, and longitudinal profiles. The survey data illustrates that this crossing does not greatly increase cross sectional area downstream nor does it decrease hyporheic or riffle habitat downstream (Figure 6 and Table 6). The total change in riffle habitat came to about 15 m² which was the least amount of change measured (Appendix D). These results probably stem from the fact that this bridge allows larger flows to access the floodplain, thus minimizing the energy through the river channel. However other crossing types have a great impact on the stream geomorphology.

Table 6. Cross Section Areas and Hyporheic Depths of Randolph 220

Site Name		Ave Depth (cm)	Ave Depth (cm)	
		UpStrm	Dwn Strm	Difference
Rand 220 Bridge	X1	21.10	9.42	-11.68
	X5	19.16	9.81	-9.35
	X10	3.94	10.06	6.13
	X20	11.03	12.45	1.42
	X50	8.77	20.19	11.42
		X-Area (m²)	X-Area (m²)	
		UpStrm	Dwn Strm	Difference
	X1	6.41	2.41	-4
	X5	6.51	4.03	-2.48
	X10	5.51	5.3	-0.21
	X20	6.77	7.51	0.74
	X50	5.2	6.43	1.23

Figure 6. Cross Section Areas at 10m from crossing Randolph 220
(.21 m² difference)

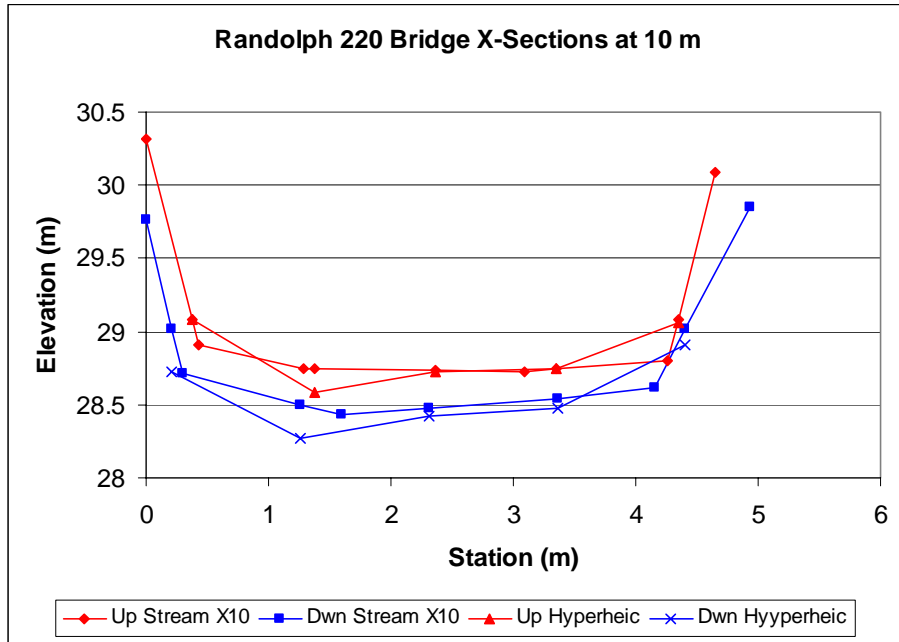
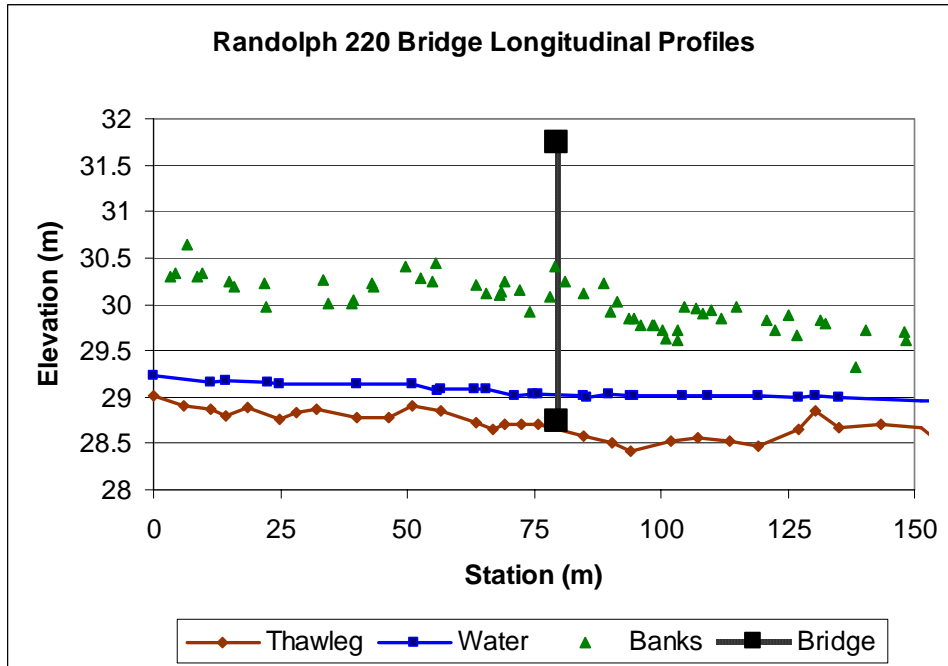


Figure 7. Longitudinal Profile with Very Little Change after Crossing Structure



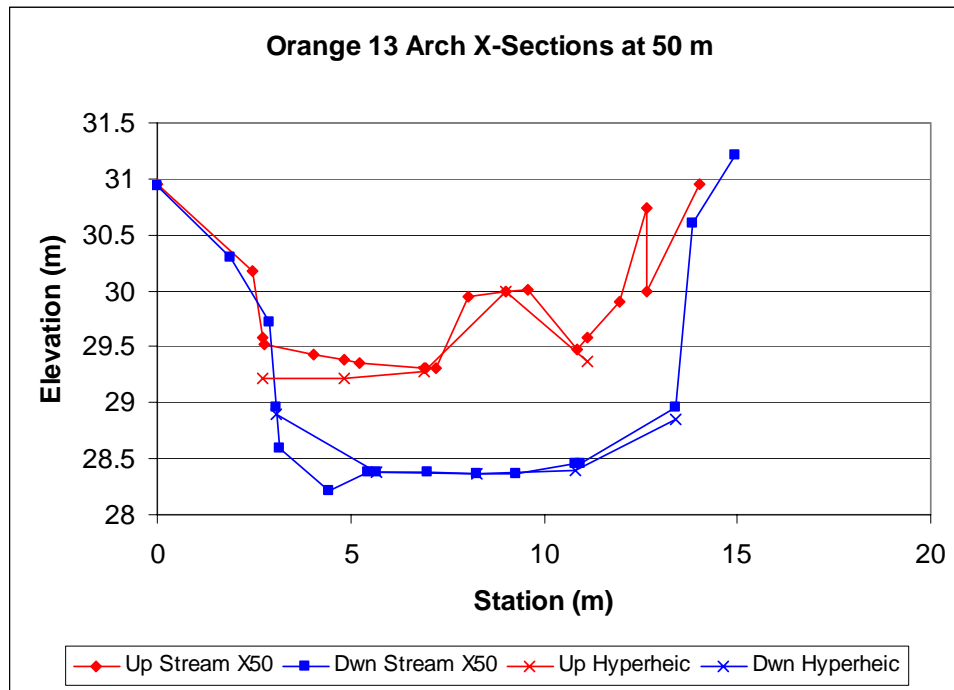
Maximum Impact Example

Arch culverts seem to have a great impact on stream geomorphology. Even though they may be good for fish passage other hydrology factors are being affected. The data for the cross sectional analysis and hyporheic zone analysis points to a decreasing or hyporheic zone depths downstream and an increase of cross sectional area in the same sections (Table 7 and Figure 8). This is probably due to the channel constriction of the floodplain. This arch culvert spans from bank to bank and fill is placed up to the culvert. Therefore absolutely no floodplain access is allowed. This site is especially sensitive to culvert effects because it is one of the streams in a high relief region and therefore the narrow floodplain present is even more valuable to slow and dissipate higher flows.

Table 7. Cross Section Areas and Hyporheic Depths of Orange 13

<u>Site Name</u>	Ave Depth (cm)	Ave Depth (cm)	<i>Difference</i>
	<i>UpStrm</i>	<i>Dwn Strm</i>	
X1	10.52	9.42	14.19
X5	30.32	8.26	-11.48
X10	38.13	24.77	20.90
X20	11.68	45.48	29.87
X50	15.35	4.97	-13.10
Rand 220 Bridge	X-Are (m²)	X-Area (m²)	
	<i>UpStrm</i>	<i>Dwn Strm</i>	<i>Difference</i>
X1	13.71	4.93	-8.77
X5	19.94	25.30	5.36
X10	23.56	23.94	0.38
X20	20.09	34.49	14.40
X50	14.86	27.92	13.06

Figure 8. Cross Section Areas at 50m from Crossing Orange 13
(13.06 m² difference)



Cross Section Area Effects

A total of 140 cross sections were measured at the 14 intensively studied culvert and bridge sites. The cross sectional areas ranged from 1.85 m² to 34.29 m². When comparing downstream segments with their upstream counterparts, most of the culverts and bridges seemed to increase downstream cross sectional area. In Figure 9 is an example where the channel has significantly widened downstream of a stream crossing. Analysis of the 140 cross sections shows that there is a difference between box culverts and arch culverts in their downstream impacts on cross sectional area (Figure 10). The regression lines of upstream cross sectional area versus downstream cross sectional area have a slightly positive y intercept, meaning that the channels of the smaller streams are slightly greater in size downstream of the crossing than upstream.

All regression lines of upstream versus downstream cross-sectional areas for the different types of crossings have a slope at .861 and the overall R^2 -value is .538. Cross section location was not a significant factor. There was also no statistical difference between regression lines when the data from all culvert types were pooled and compared to the bridges (Appendix D).

The statistical comparison of downstream versus upstream cross sections show that box culverts have less effect on increasing downstream cross sectional area than the other crossing types. This is concurrent with the observations in the field. While doing the preliminary study, it was noted that box culverts seemed to be often oversized compared to the other types. Box culverts do not restrict high flows as severely as do smaller culvert types that can create a back water affect. Many of these box culverts only used a few of the openings during low flows while bankfull benches were formed or forming in the other openings (Figure 4). This allowed for sediment transport during low flows and floodplain access during higher flows. All crossings seem to have increased cross section areas downstream, except for the larger streams where the regression line crosses the 1:1 slope line, at which point the larger streams seem not have increased in cross sectional area downstream. This is probably due to the fact that the larger streams are crossed with large box culverts or bridges which have less effect on the downstream cross sectional area (Figure 10). These culverts and small bridges restrict the floodplain hydrology causing channel scour and bank erosion that increases downstream cross sectional area and degrades mussel habitat.

Figure 9. Example of Upstream Cross Section VS Downstream Cross Section

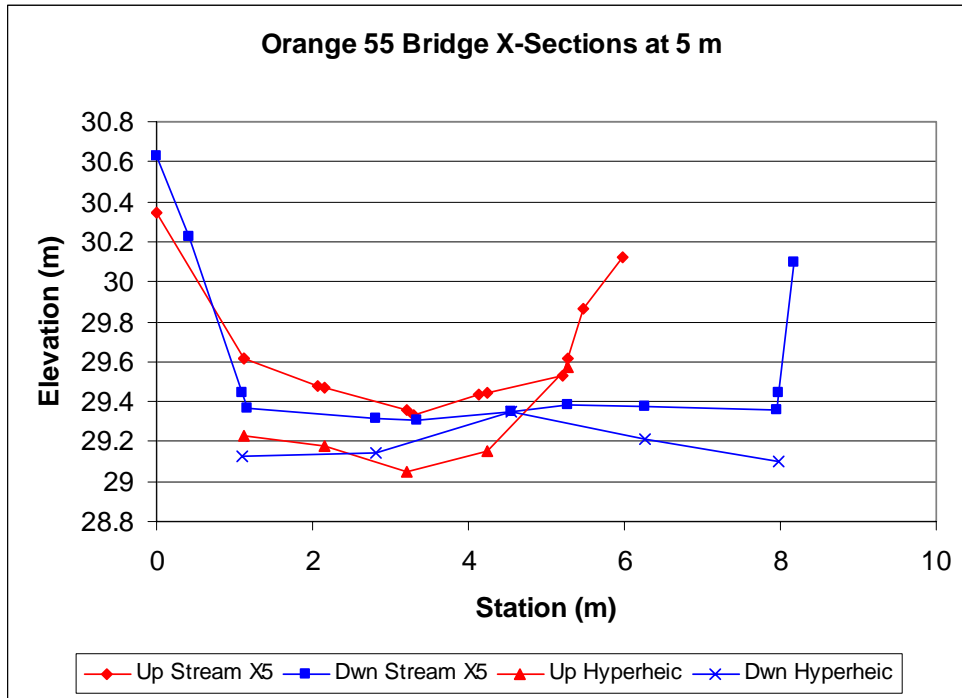
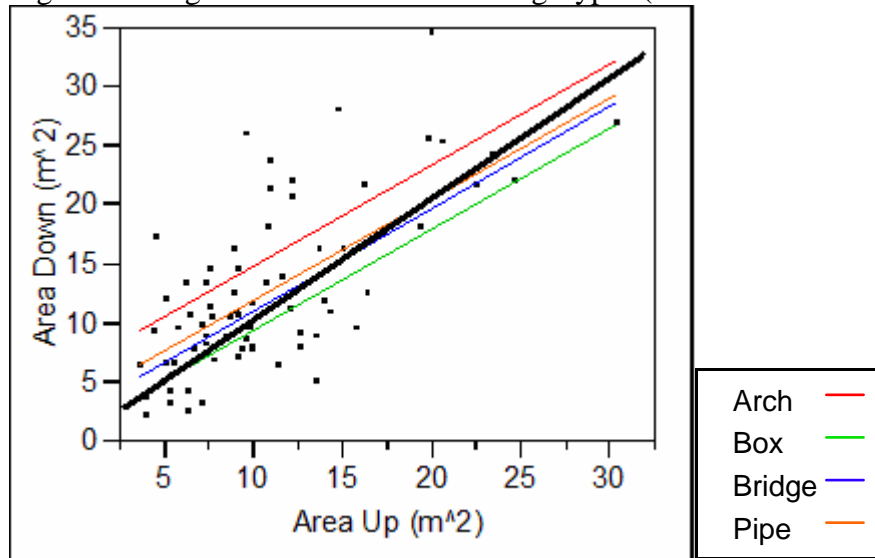


Figure 10. Regression Plot of all Crossing Types (Cross Section Areas)



*Black line shows 1:1 slope line

Level	Least Sq Mean
Arch A	15.595120
Pipe A B	12.530572
Bridge A B	11.800844
Box B	10.148930

Levels not connected by same letter are significantly different

Hyporheic Zone Depth Effects

The average hyporheic zone depth for each cross section was determined from the five measurements made at each cross section location. Regression comparisons of upstream versus downstream depths were performed on the average hyporheic zone depths at the cross sections. Initial hyporheic zone depths ranged from 0 to 62.13 cm. The high variability among the study streams in types and depths of hyporheic zones resulted in regression equations that explained only about 30 % of that variation.

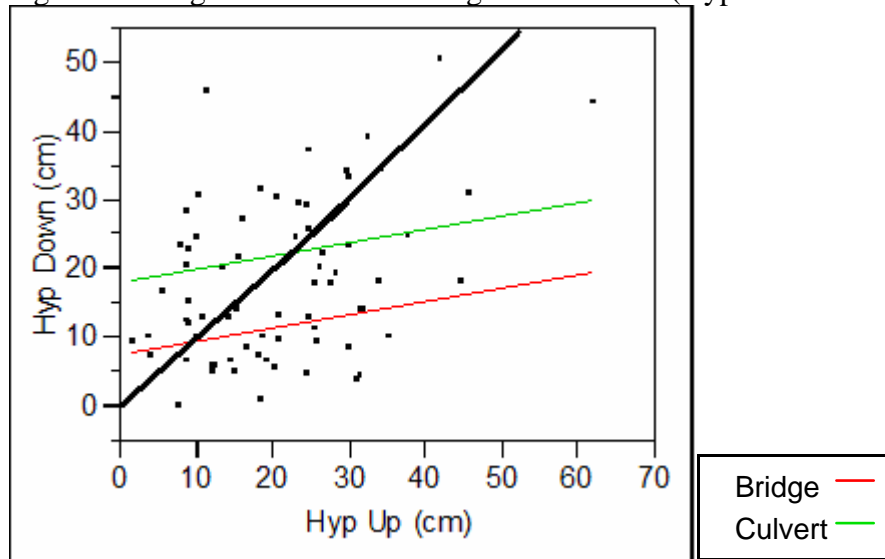
For the regression of bridges compared to the pooled culvert data, R^2 -values are around 0.32 with the slopes of the regression lines at 0.19 (Figure 11).

Comparing the regression lines for all four different types of crossings, the regression for bridges was similar to arch culverts but significantly different from pipe culverts and box culverts. These slopes are .10 and the overall R^2 values are .345. No statistical difference was detected when comparing different cross section locations (Appendix D). However there seemed to be the least amount of change when comparing cross sections at 5m and a greater effect when comparing 1m locations.

All types of road crossings seem to have an effect on decreasing hyporheic zone depth downstream though the impact of the crossing bucked that trend at certain sites (Figure 12). Note the table of hyporheic zone depths in Appendix E. Of the 3 arch culverts, there was a definite decrease in hyporheic zone depths downstream of the culvert at Alamance 29, a definite increase in hyporheic zone depths downstream of the culvert at Chatham 12 and a mixed bag of effects at Orange 13. The general trend for decreased hyporheic zone depths downstream of the crossing is probably due to the scour that occurs as high velocity restricted flow is released into the channel. However, this

trend for decreased hyporheic zone depths downstream of the crossings is only true for the larger depths. For the streams with shallow hyporheic depths, this trend is not as clear. Each regression line crosses the 1:1 slope line between 10 and 20 cm of hyporheic zone depth, showing that these effects are not as significant with streams that have shallow hyporheic zone depths. This is intuitive because if the stream is already degraded or has scoured the bottom sediments down close to a restrictive layer with very shallow hyporheic depths the scour will have less effect downstream. If the stream flows on bedrock upstream then it can not get much shallower in depth downstream.

Figure 11. Regression Plot for Bridges vs Culverts (Hyporheic Zone Depths).

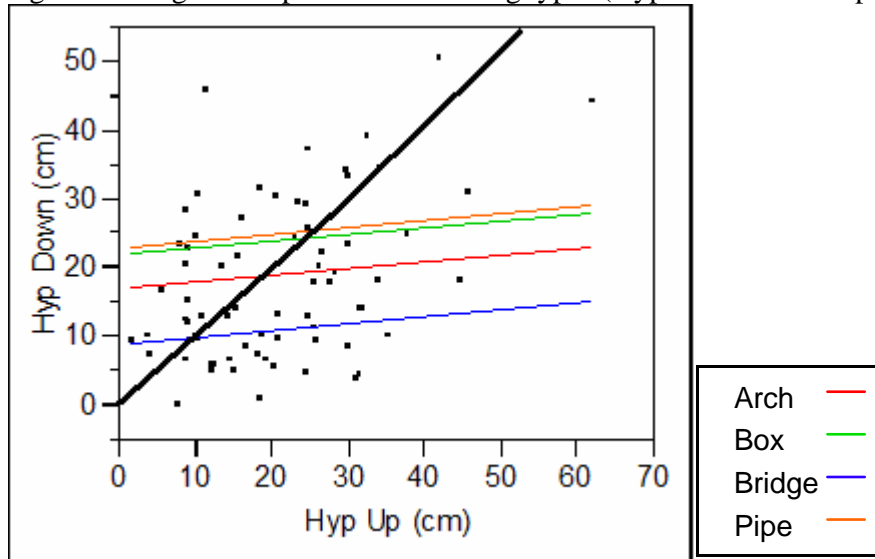


*Black line shows 1:1 slope line

Level		Least Sq Mean
Culvert	A	22.136122
Bridge	B	11.774505

Levels not connected by same letter are significantly different

Figure 12. Regression plot for all crossing types (Hyporheic Zone Depths)



*Black line shows 1:1 slope line

Level		Least Sq Mean
Pipe	A	25.076814
Box	A	24.040801
Arch	A B	19.023061
Bridge	B	11.225796

Levels not connected by same letter are significantly different

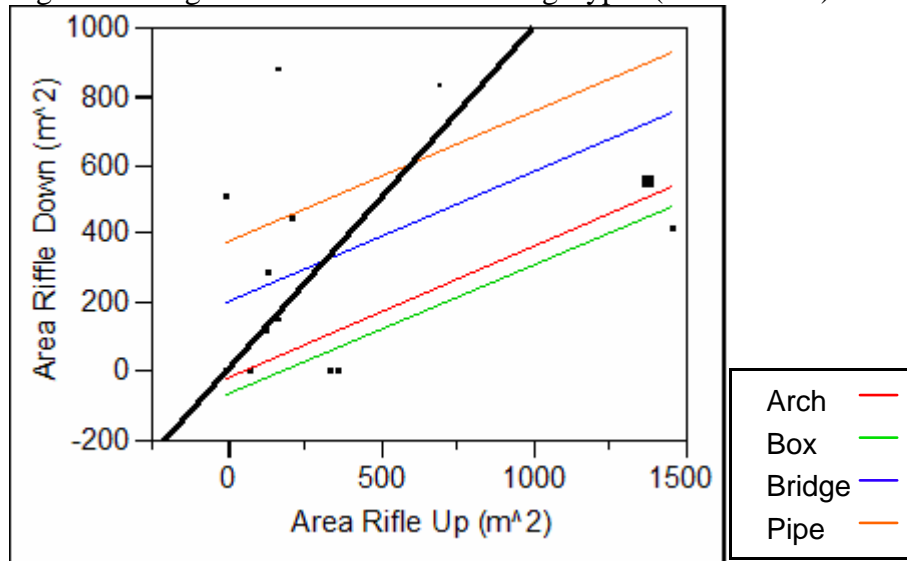
The results show that bridges have the greatest effect on hyporheic zone depths while pipes and box culverts have the least effect. This may be due to the fact that cross sectional areas at the pipes and boxes (with bankfull benches) allow for sediment transport in low flows because they keep their velocities. The other crossings are wider and thus create slower flow velocities upstream of the culvert. Therefore they settle out sediments and do not allow for as much sediment transport at these low flows. This causes downstream sections to be sediment starved. Scour may control the bed gradient but it seems that low flow transport may control hyporheic zone depth.

Riffle Area Effects

Each of the 14 sites was measured for area of riffles upstream of the culvert and downstream. The range of riffle areas was 0 to 1377.83 m². There was no significant difference in the regressions between the types of crossings or when bridges were compared with all culverts pooled. Each regression line in a reduced model had a slope of .37 and an overall R² value of .37 (Figure 13). The regression lines show a pattern that may point to arch and box culverts having a greater effect on downstream riffle areas than bridges or pipe culverts. However all crossing structures seem to reduce riffle area downstream within the study reach. Again better detection of statistical differences was an issue because of the lack of sample size. Sample size could be increased by limiting the selection parameters and examining streams that did not have mussel populations. This would allow for more sites to be studied. However adjusting the selection parameters may increase variability and decrease R² values. Also future studies of this type should separate small bridges with wingwalls from the newer longer spanning cement bridges.

Because the sample size for comparing the impact of the crossings on riffle areas is so small, we can not draw any firm conclusions about crossing effects. However, if the data for all the crossings are pooled, the slope of the regression line is less than 1, thus pointing to an effect of structures on reducing area of downstream riffle habitat (See Appendix D). Therefore, there may be some sort of effect that the crossing has on downstream riffle habitats but more research will be needed to determine whether such an effect exists.

Figure 13. Regression Plot for all Crossing Types (Riffle Areas)



*Black line shows 1:1 slope line

Level		Least Sq Mean
Pipe	A	517.55005
Bridge	A	342.36685
Arch	A	122.10017
Box	A	74.48411

Levels not connected by same letter are significantly different

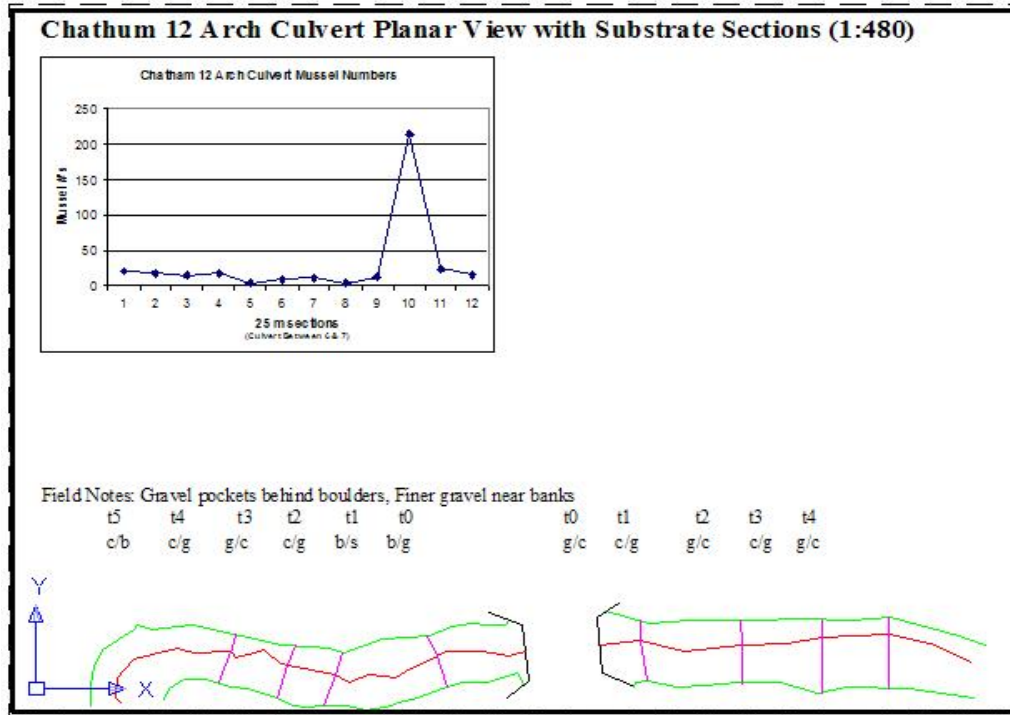
Substrate Type Area Effects

All 14 study sites were surveyed for substrate type changes upstream and downstream of the crossing. Compare the mussel graph in the upper corner with the substrate zones segregated by a line on the planar graphs (Figure 4 and Appendix C). Take notice that each section in the mussel graphs are 25 m long stream channel sections. The substrate zones in the planar graph are not regular rather the exact placement where there was a change in the stream substrate.

A few spatial relationships are apparent when comparing the planar graphs with their corresponding mussel numbers graphs. It seems that the spikes in number of mussel individuals occur where there are stable substrate classes: cobble/gravel, cobble, and gravel/cobble. Decline in number of mussels occurs when the substrate class is sand

especially, in front of a culvert where aggradation can occur. Areas dominated by bedrock obviously have small counts of mussel individuals because of the inhospitable habitat (Figure 14 and Appendix C).

Figure 14. Planar Graph with Mussel Numbers Graph (not to scale)



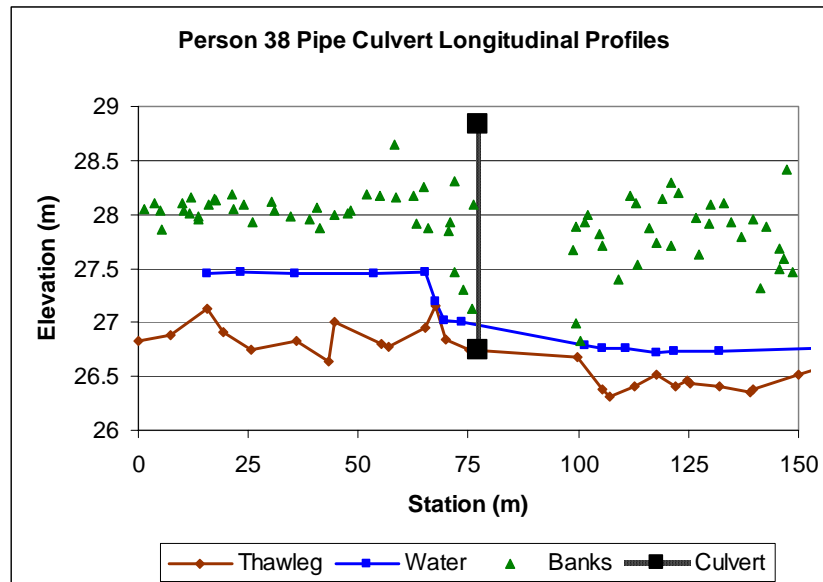
*Stream Flow from left to right
 **change in t# is change in substrate section
 ***for better resolution please see Appendix C

The substrate analysis points to the fact that mussels do seem to prefer more stable substrates and can be affected by sedimentation and scour. Therefore the stream degradation and cross section expansion downstream of these crossings can have a negative effect on mussel numbers. Since bank erosion is occurring downstream mussels can be buried by these extra sediments entering the system.

Longitudinal Profiles Effects

All sites were surveyed along the thalweg, banks, and water surface to determine the longitudinal channel gradients through these stream reaches with crossings. The longitudinal profiles show that pipe culverts and one bridge (Orange 67) had the most influence on stream gradient below the crossing (Figure 15). Most bridges, arch culverts and box culverts seem not to cause a significant change in the stream elevation (See Appendix C).

Figure 15. Longitudinal Profile of Steep Gradient after Crossing Structure



Contraction scour is the factor that appears to cause the decrease in channel elevation along the thalweg downstream of the crossing. The longitudinal profiles of all the pipe culverts and Orange 67 bridge show a significant drop in bed elevation downstream of the crossing. This contraction creates scour and degrades bed levels. Even though these pipe culverts may be allowing low flow sediment transport, at higher

flows they are causing scouring of bed levels. This is directly related to the floodplain restriction and thus all of the water's energy is focused through those pipes, when its energy would otherwise be dissipated in the floodplain. The Orange 67 bridge also had this same effect of a drop in bed elevation downstream of the structure because it is one of the smaller bridges with wingwalls in the study that is constricting higher flows and also scouring the downstream section.

CONCLUSIONS AND RECOMMENDATIONS

In review, the impacts of bridge and culverts on stream channels are that they:

1. increase channel cross sectional area downstream
2. decrease hyporheic zone depths downstream and
3. may decrease riffle habitat downstream.

The key to minimize adverse impacts on the stream channel in culvert and bridge design is to allow the stream to dissipate its energy into the floodplain during high flows. To counteract the typical flow restriction and scouring effects, it is recommended that culverts be designed to accommodate both low flows and high flows. Large multi-opening box culverts that are forming bankfull benches are mimicking the natural processes of sediment transport and deposition during high flows. Such large culverts allow for sediment transport during low flows and energy dissipation into the flood plain during higher flows. Also bridges that span across the valley limiting fill and allowing floodplain access have the same effect of providing for flow energy dissipation during high flows. When valley fill is necessary, then side culverts in the floodplain may

provide for additional flood flow capacity and energy dissipation, thus alleviating degradation and allowing for more natural floodplain hydrology.

These design suggestions will allow for sediment transport during low flow and thus minimizing impacts on downstream hyporheic zone depths. Furthermore they will allow for maximum energy dissipation during higher flows that seem to degrade the banks and habitat downstream of the crossing.

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Appendix A: Preliminary Study Data Sheets and Photos

This list of definitions will help you understand each site.

Site : My ID #

BR# : DOT database #

CO : County

BASIN : River Basin

BFW= Bankfull width at first riffle above culvert

THD= Thawleg depth from top of bankfull

CW= Width of culvert from one side of the road to the next

CT= Culvert type

Built= Year culvert was built

Substrate= stream bottom material seen at visit

Channel cond= DOT database information on channel see
table on next page

Scour status= DOT database information on scour around
culvert see table on next page

Conditions= My notes of stream condition during each visit

Opinion= My opinion of site due to conditions

Site 11
BR#12
CO Chatham
BASIN Cape Fear



BFW= '
THD= '
CW= 45'
CT= Single 38'18' RC Arch
Built=1933
Substrate= cobble, gravel, bedrock
Channel cond= bank protection needs minor repairs
Scour Status= scour above top of footing

Conditions= slightly incised
both up and downstream,
much more downstream,
more rocky upstream
Land Use= Wooded?
Opinion= OK Site



* Pic 1 of arch culvert looking upstream
**Pic 2 looking upstream from top of culvert

Site 36
BR#38
CO Person
BASIN Neuse



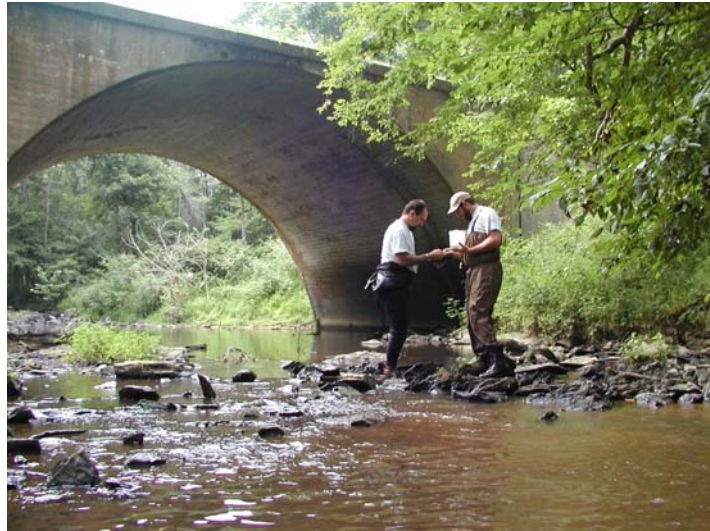
BFW=25'
THD= 2'5"
CW= '80
CT= Double 117"x79" corrugated pipe
Built= 1991
Substrate= rocky and sandy pools,
Channel cond=banks well protected or well
vegetated, no control devise needed
Scour status= scour above top of footing

Conditions= slightly incised , gravel bar below
Land Use= wooded?
Opinion=Ok site



***Pic 1 looking upstream into arch culvert**
****Pic 2 looking upstream from top of culvert**

Site 34
BR#13
CO Orange
BASIN Neuse



BFW=28'5"

THD= 2'2"

CW= 37'7"

CT= 51'4" Cement Arch

Built =1941

Substrate= rocky, sandy pools

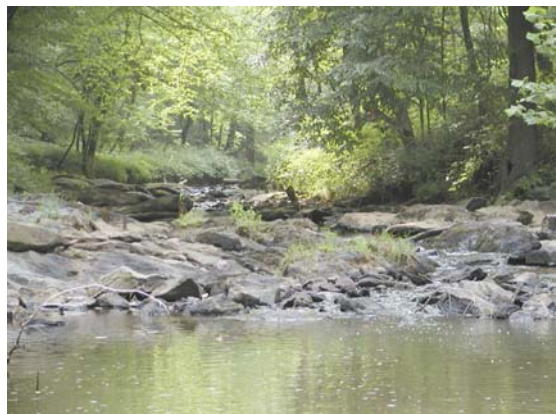
Channel cond= banks beginning to slump, debris restricting channel slightly

Scour status= scour above top of footing

Conditions= little influence, low incision, seemed to be normal riffle pool sequence, on bridge embankments in stream

Land Use= wooded?

Opinion= Good site because of substrate bottom



***Pic 1 looking upstream at culvert**

****Pic 2 looking upstream from culvert**

Site 02
BR#20
CO Alamance
BASIN Cape Fear



BFW=23.6'
THD= 2.4'
CW= 58. 6'
CT= Quadruple 8x9 RC box
Built=1930
Substrate= sand and gravel
Channel cond= bank beginning to slump , debris
restrict channel
Scour Status= scour above top of footing

Condition notes= incised below and above
Land Use= Wooded, grassy bank
Opinion= not a good site



***Pic 1 looking downstream at the culvert**
****Pic 2 looking upstream from culvert**

Site 23
BR#459
CO Randolph
BASIN Cape Fear



BFW=17.2'

THD=1.3'

CW=54'6"

CT= Triple 120" Corrugated Pipe

Built 1955

Substrate= rock above, sand and gravel bars below

Channel Cond= bank beginning to slump, debris
restricts channel slightly

Scour Status= scour above top of footing

Conditions= 2 pipes being used, highly incised above
and below

Land Use= pasture above and below

Opinion= not a good site..cows



***Pic 1 looking downstream at culvert**

****Pic 2 looking upstream at culvert**

Site 28
BR#217
CO Granville
BASIN Dan



BFW=17.2'

THD=1.0'

CW= 92'6"

CT= Triple 142x 91 Corrugated Pipe arch

Built= 1990

Substrate= rocky

Channel cond= bank protection needs minor repairs

Scour status= scour above top of footing

Conditions= slightly incised below less above, more eroded downstream

Land Use= Wooded

Opinion= Ok site!



***Pic 1 looking downstream at culvert**

****Pic 2 looking upstream from culvert**

Site 03
BR#29
CO Alamance
BASIN Cape Fear

BFW=25' 6"
THD= 4'6"
CW= 37' 3"
CT= Single RC 39'6"x20 Arch
Built= 1935
Substrate= Sandy
Channel cond= bank protection needs repairs
Scour status= scour above top of footing

Conditions= Highly incised, beaver dam, large amounts of debris downstream, narrow buffer

Land use= New golf course upstream

Opinion= Not a good site because of constricted flow by dam and golf course.



***Pic 1 looking upstream from bank near culvert**

****Pic 2 looking downstream through culvert**

Site 03
BR#67
CO Orange
BASIN Neuse



BFW= 12.2'
THD= 1.2'
CW=
CT=
Built= 1953
Substrate= Cobble and gravel
Channel cond= unknown
Scour status= unknown
Conditions= Extreme erosion on banks
 downstream
Land use= Wooded some nearby
 houses
Opinion= OK site



***Pic 1 looking upstream at bridge**
****Pic 2 looking downstream from bridge**

Site 03

BR#4

CO Orange

BASIN Neuse

BFW=19.7'

THD= .9'

BW=

BT= Cement and Metal

Built= 1949

Substrate= Sand and Cobble

Channel cond=unknown

Scour status=unknown

Conditions=Incision upstream and downstream

Land use= Wooded, past farmland

Opinion= Larger site but OK



***Pic 1 looking up stream at bridge**

****Pic 2 looking upstream from under the bridge**

Site 03
BR#55
CO Orange
BASIN Neuse

BFW=16.7'

THD=1.2'

BW=

BT= Metal and wood

Built=1964

Substrate= Cobble and gravel

Channel cond=unknown

Scour status=unknown

Conditions=slight incision upstream, one side
being used during low flows

Land use= Wooded but a pasture near stream

Opinion= Good Site!



***Pic 1 looking up stream at bridge**

****Pic 2 looking upstream from bridge**

Site 03
BR#30
CO Orange
BASIN Neuse



BFW=24.8'

THD=1.6'

CW= 24'

CT= Triple Box

Built=1941

Substrate= Cobble and Sand

Channel cond=unknown

Scour status=unknown

Conditions=Bankfull forming in one side, Incision upstream
and down

Land use= Wooded but a
lawn near stream

Opinion= Good Site!



*Pic 1 looking upstream from culvert

**Pc 2 looking upstream at culvert

Site 10
BR#12010
CO Randolph
BASIN Cape Fear
WB= BACHELOR CREEK
BFW=15'9"
THD= 2'7"
BW= 159
BT= Wood and Metal
Built= 1954
Substrate=Sand and
Gravel, bedrock below
Channel cond= stable
banks
Conditions= Wooded w Ag

Opinion= half a wing wall
on each side



***Pic 1 looking downstream at bridge**

****Pic 2 looking downstream from under the bridge**

Site 22

BR#12032

CO Randolph

BASIN Cape Fear

WB= LITTLE CREEK

BFW=25'1"

THD= 3'1"

BW= 220

BT= Metal

Built= 1955

Substrate= cobble,
gravel, sand

Channel cond=
downstream
straightened

Conditions= Wooded
and Ag

Opinion= OK site!



***Pic 1 looking downstream at bridge**

****Pic 2 looking upstream from bridge**

Site 25

BR#173

CO Moore

BASIN Cape Fear

WB=WILLIAMS CREEK

BFW=14'3

THD= 3'4"

BW= 193

BT= Wood w/wingwalls

Built= 1955

Substrate= cobble, gravel,
bedrock

Channel cond= highly
incised

Conditions= Old Ag

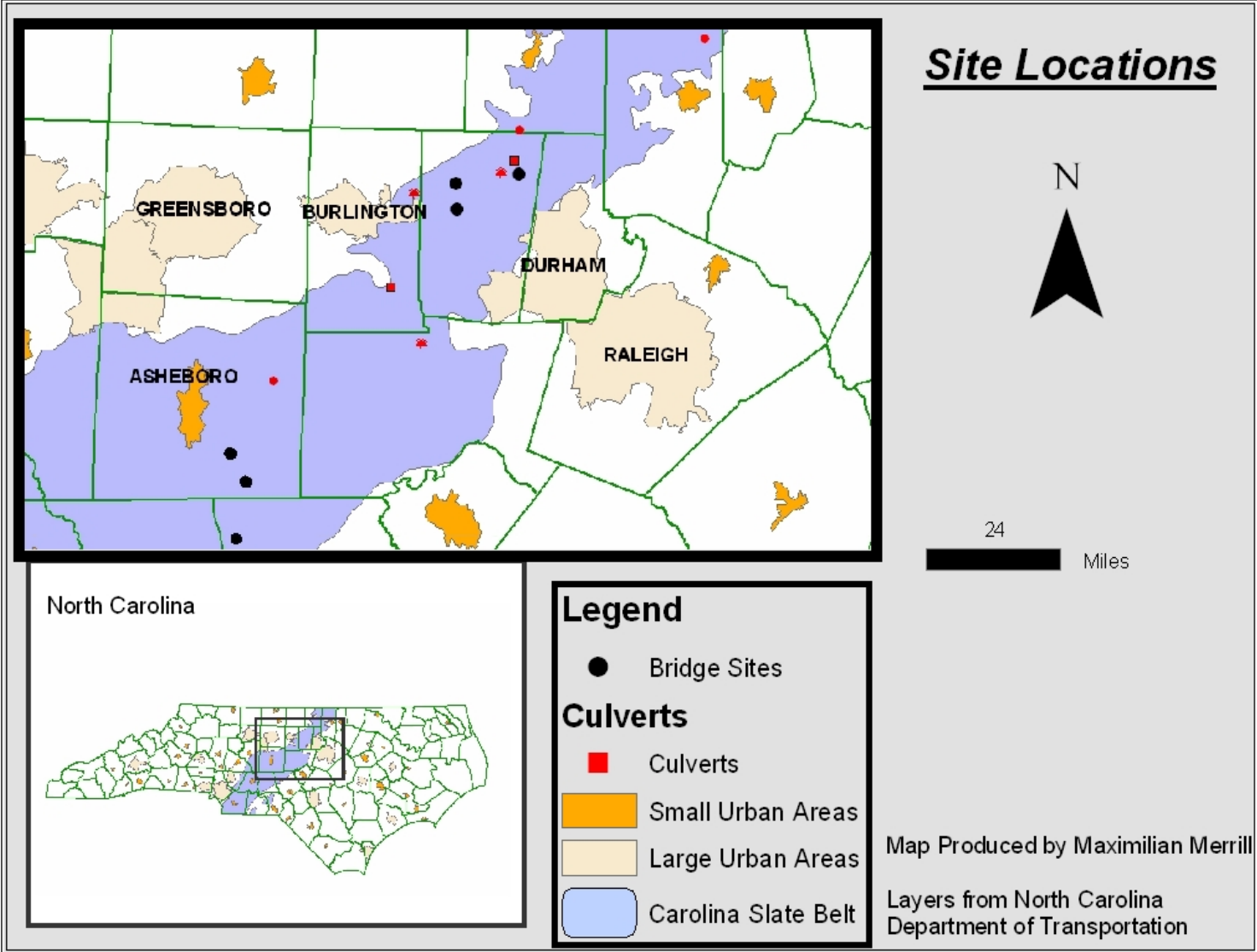
Opinion= Good Site



***Pic 1 looking at bridge abutment**

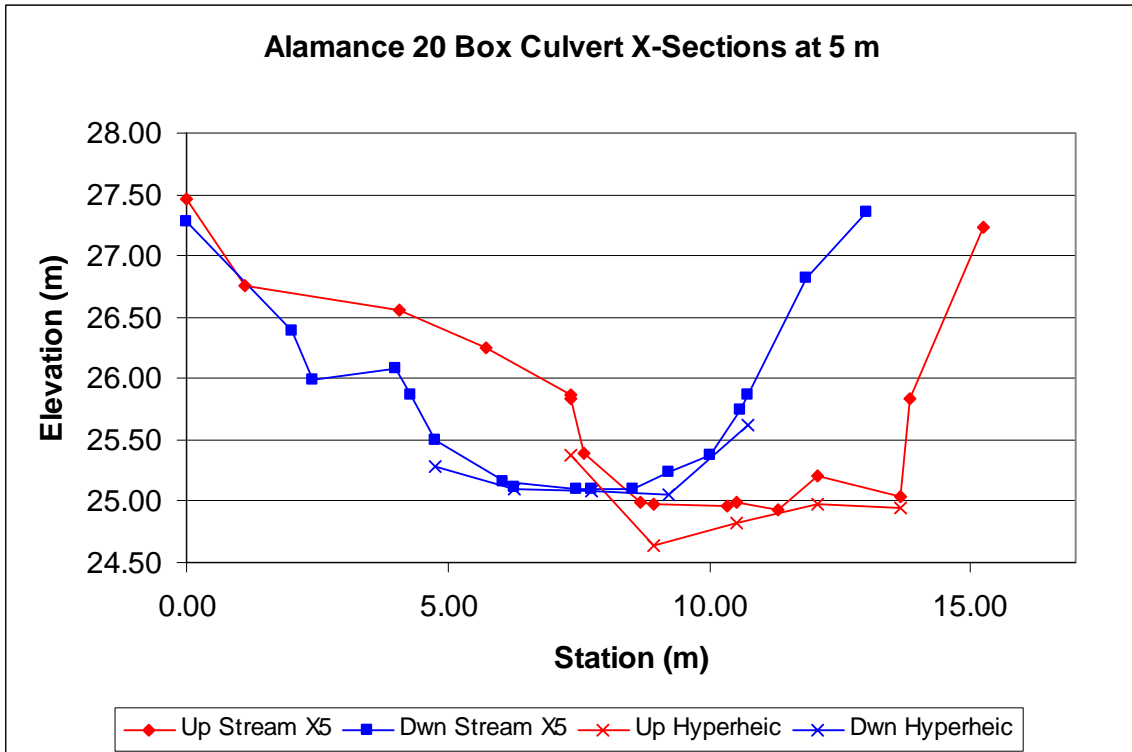
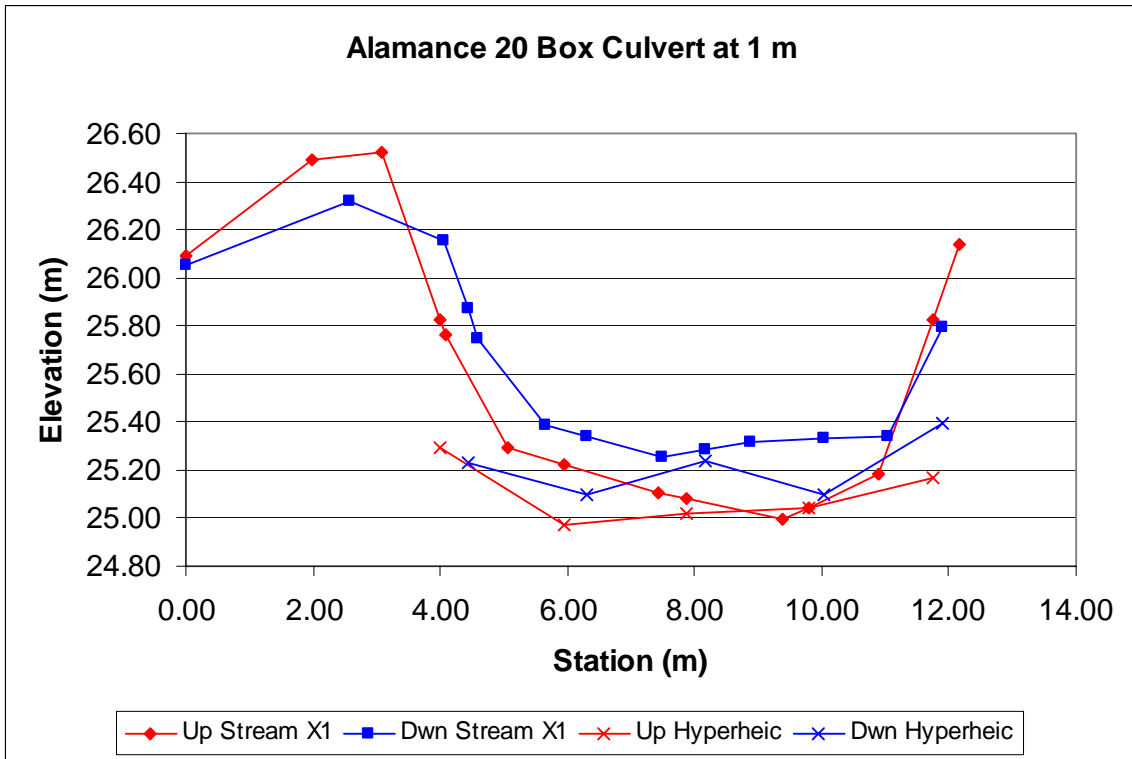
****Pic 2 looking upstream from bridge**

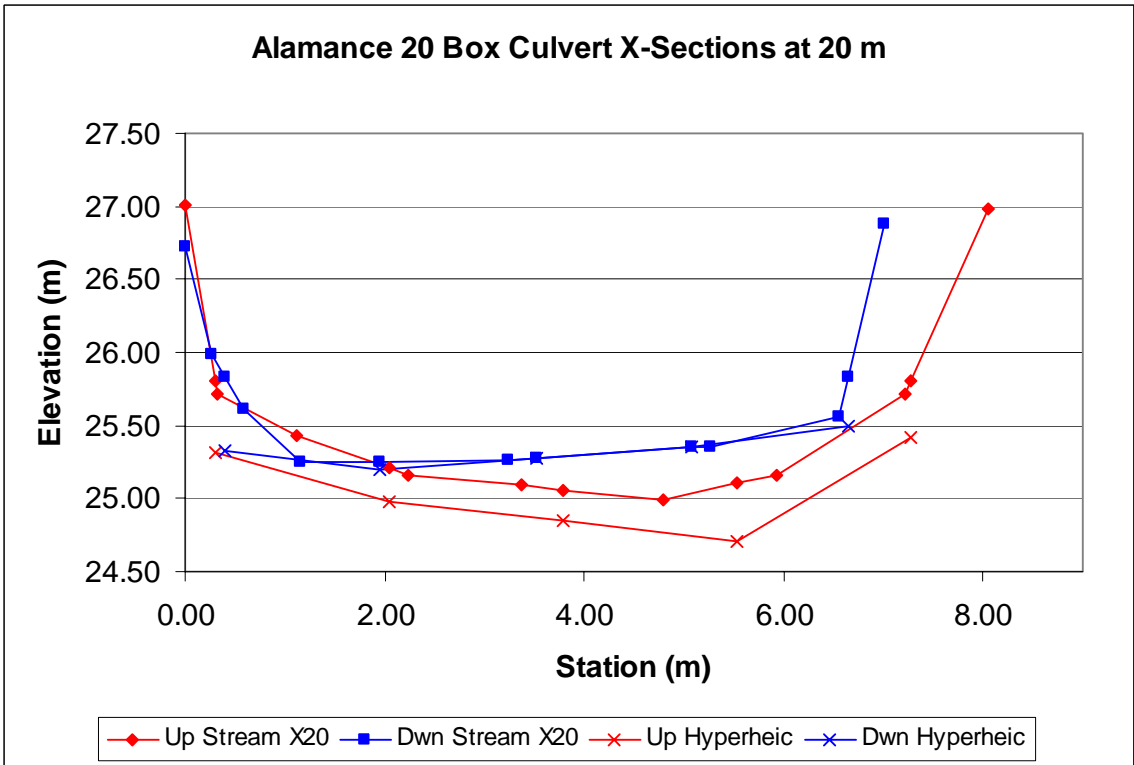
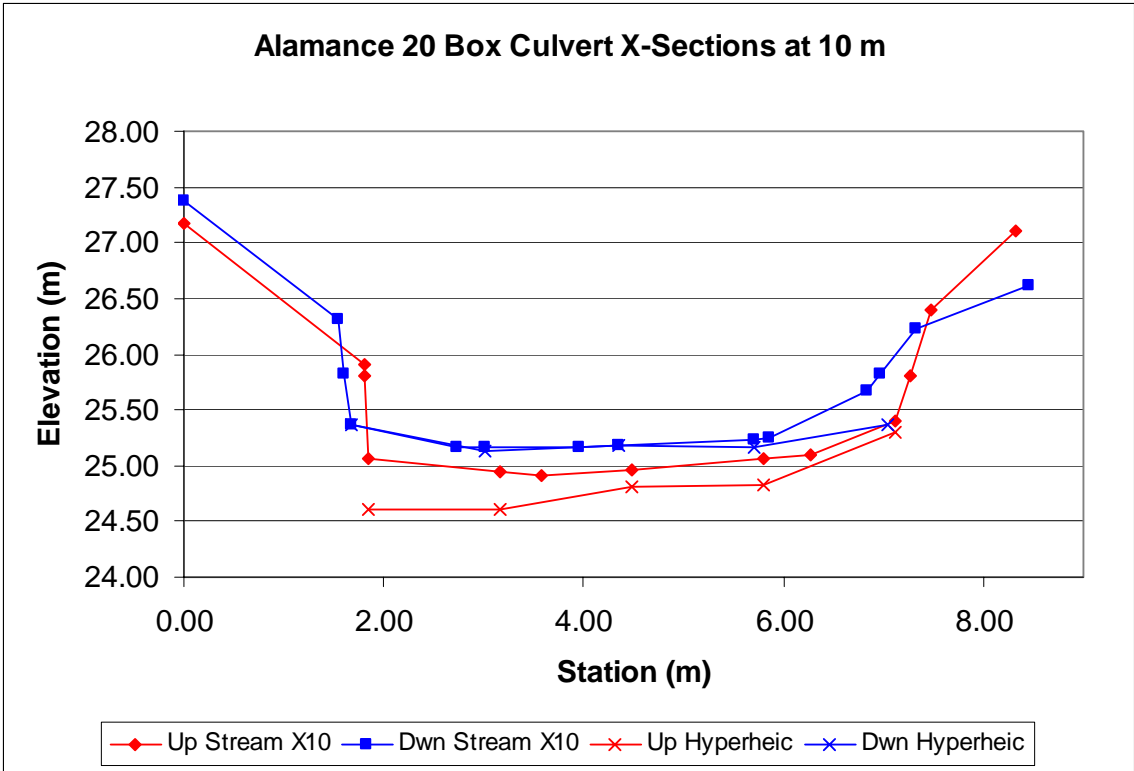
Appendix B: Site Location Map

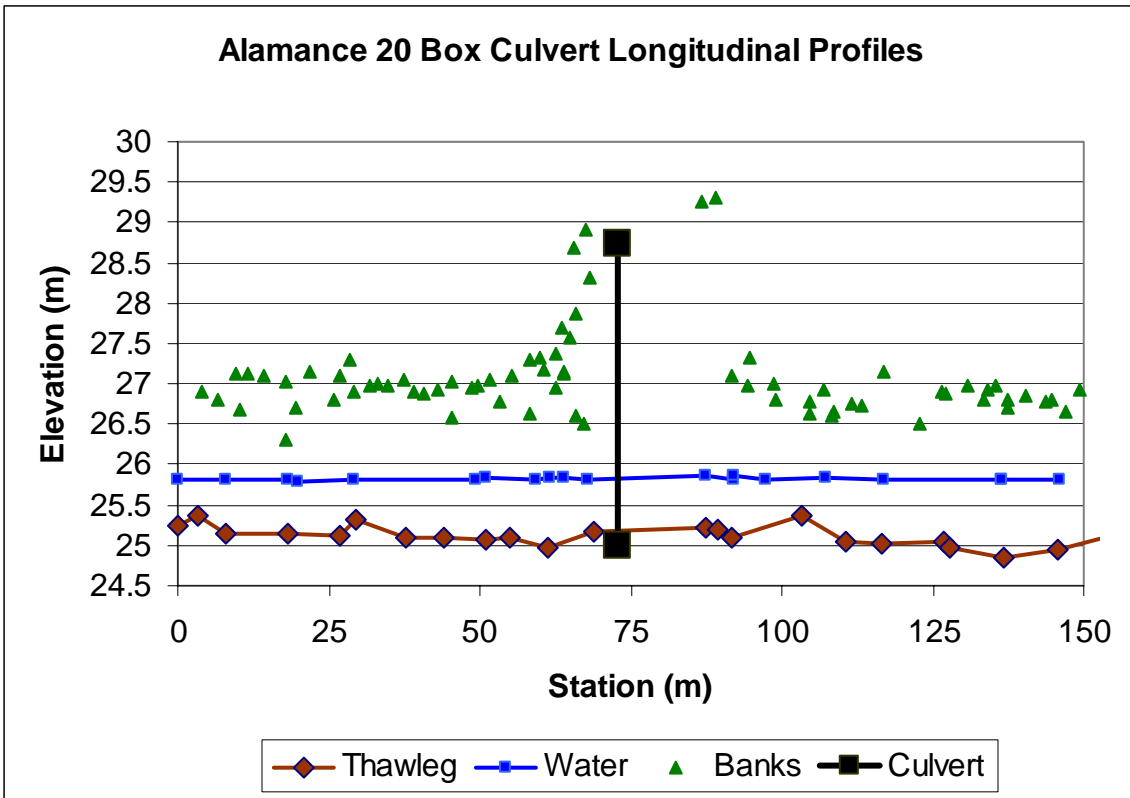
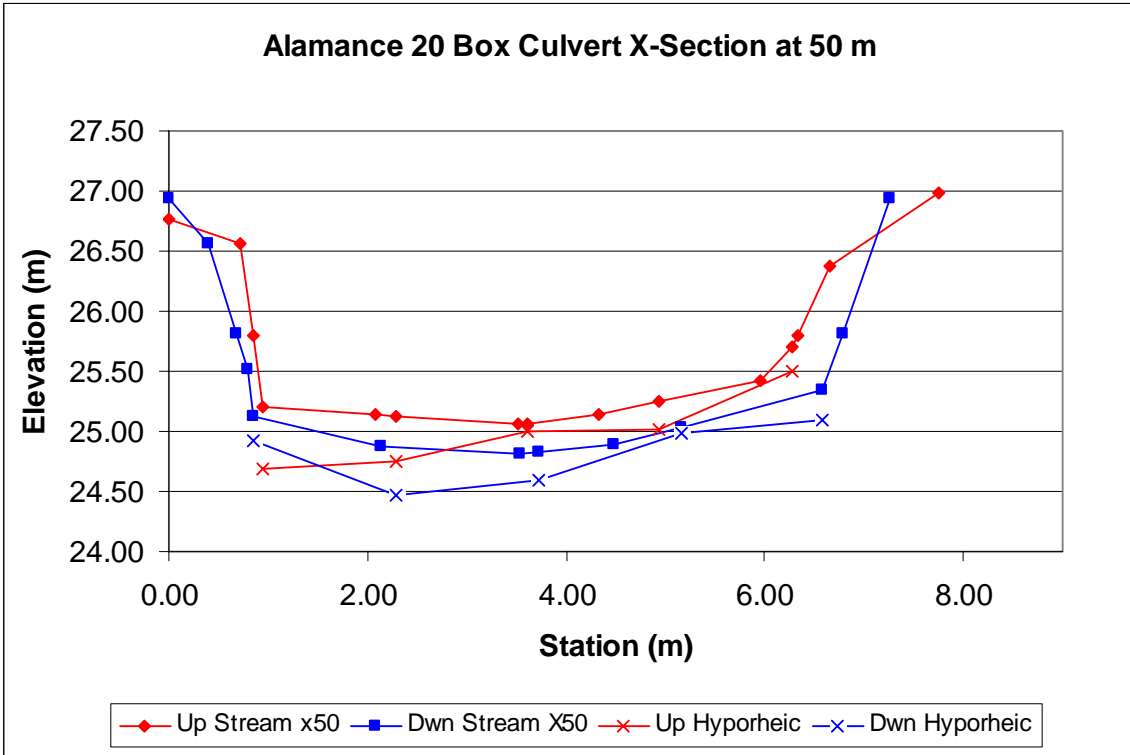


**Appendix C: Cross Sectional Area, Longitudinal Profile, Planar, and Mussel
Number Graphs. (In Alphabetical Order)**

Alamance 20 Cross Section, Longitudinal Profile, and Planar Graphs

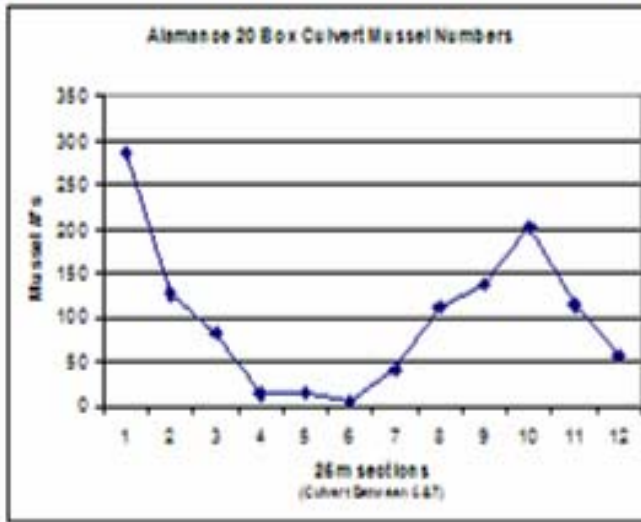






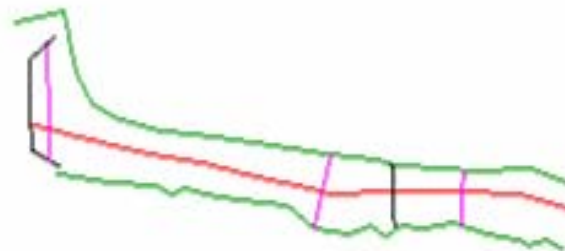
*Graph not to scale, please email author for originals.

Alamance 20 Box Culvert Planar View and Substrate Sections (1:480)

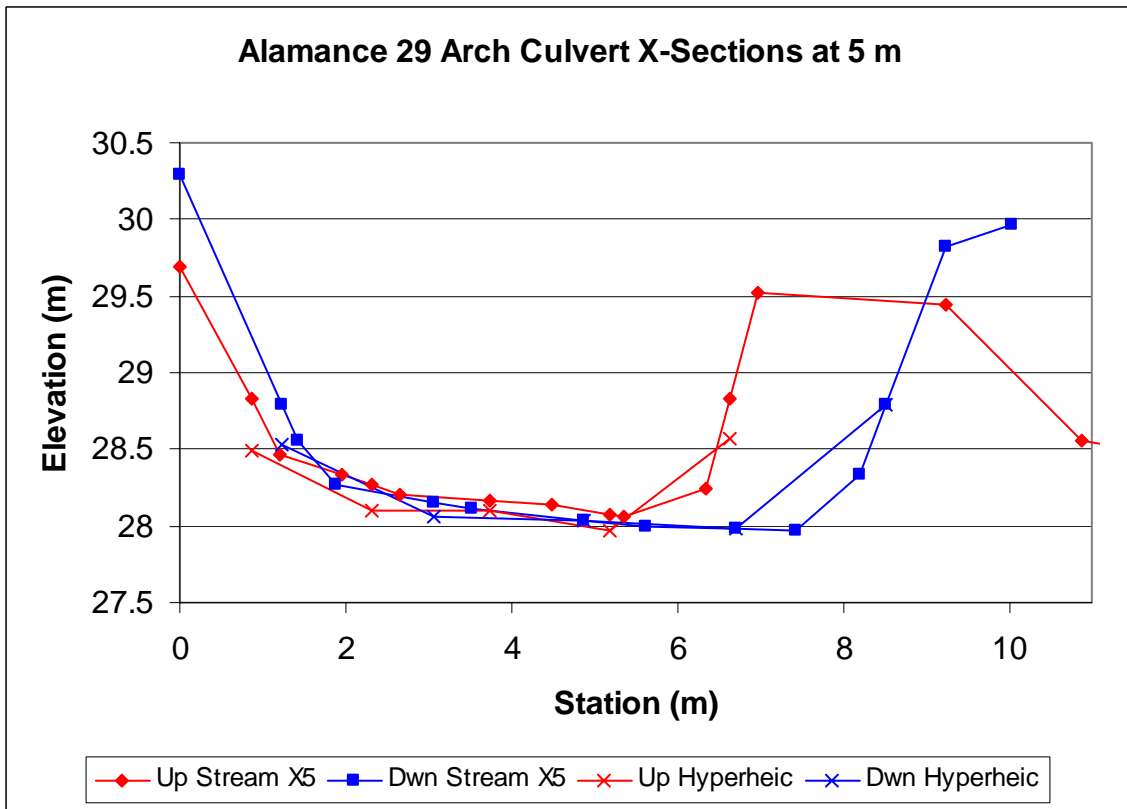
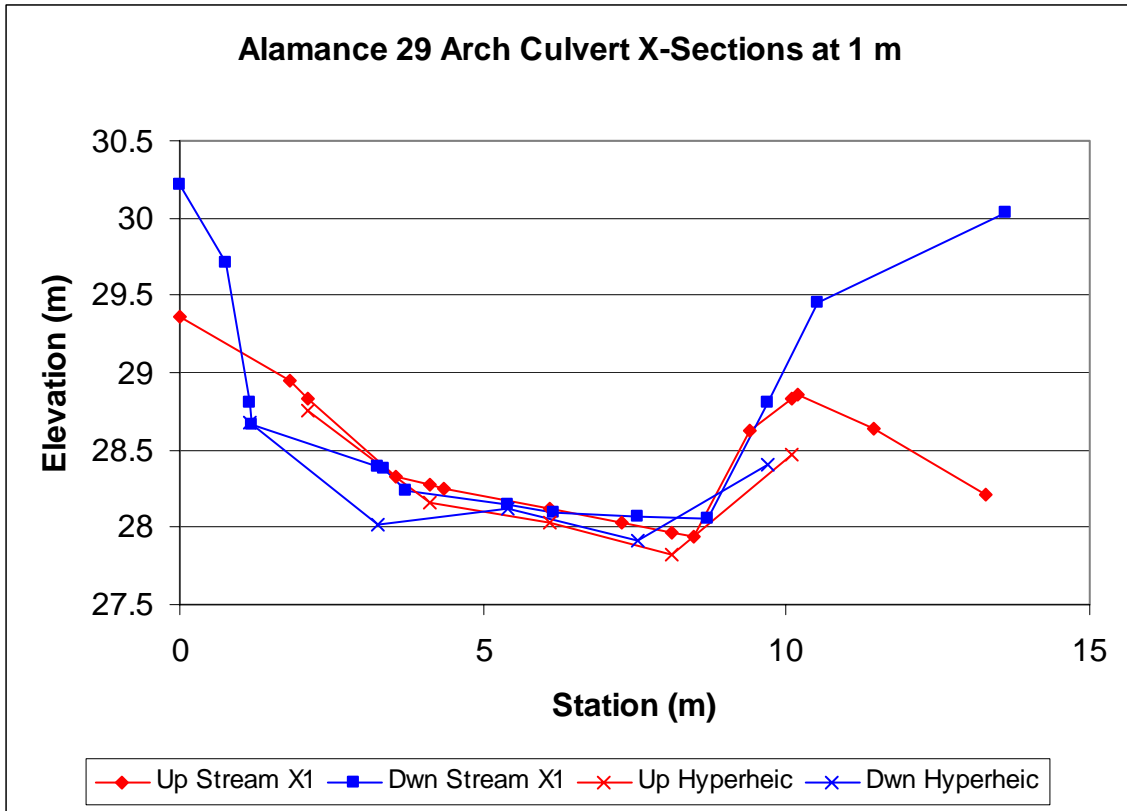


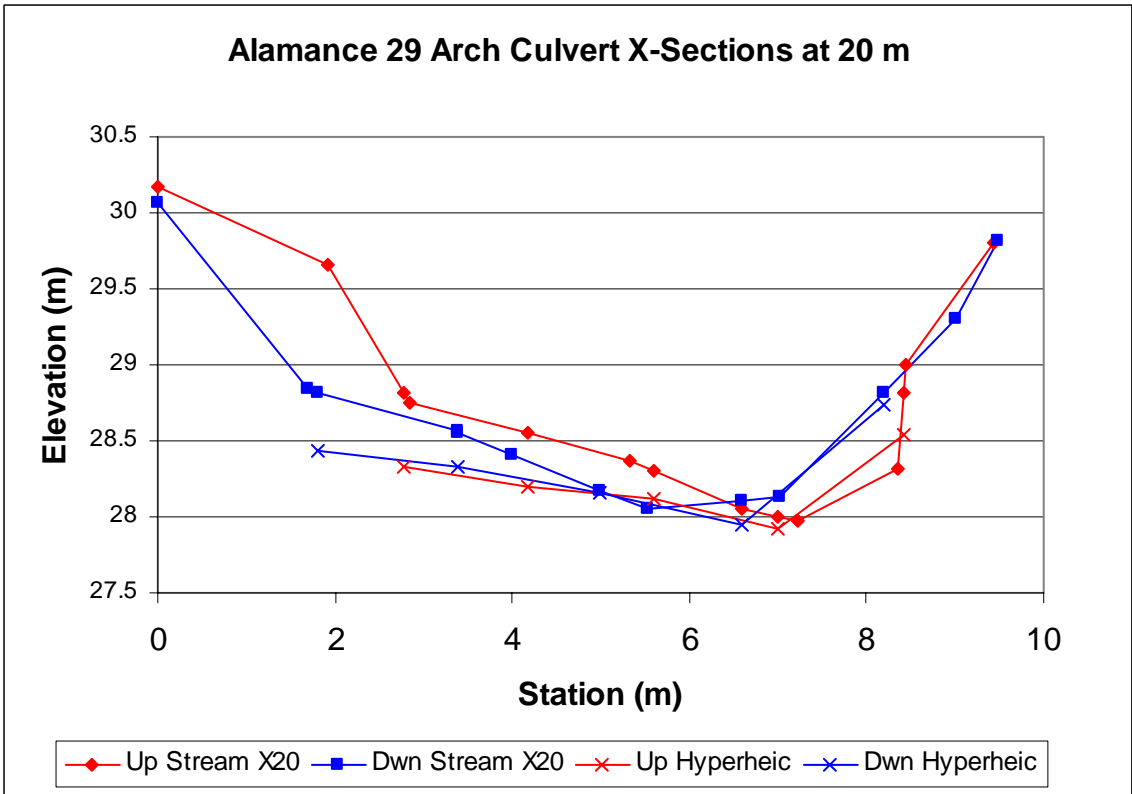
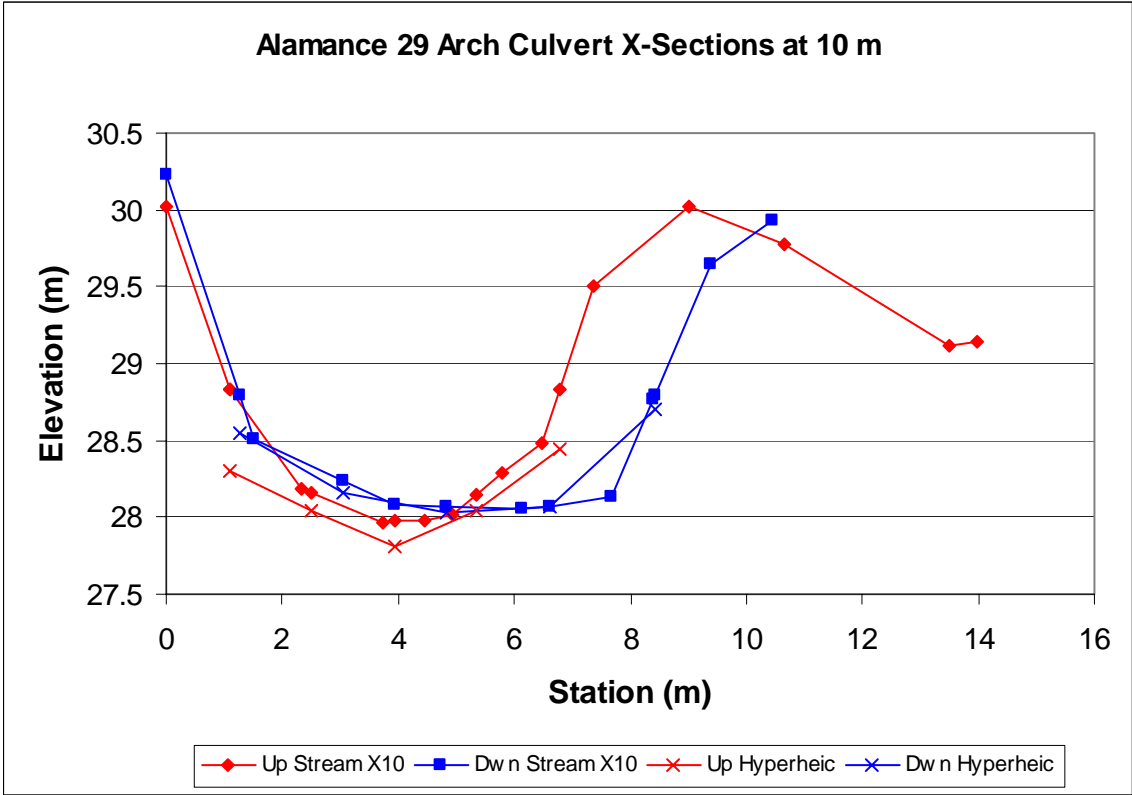
Field Notes: Banks are mud and sand, sand accumulation near culvert

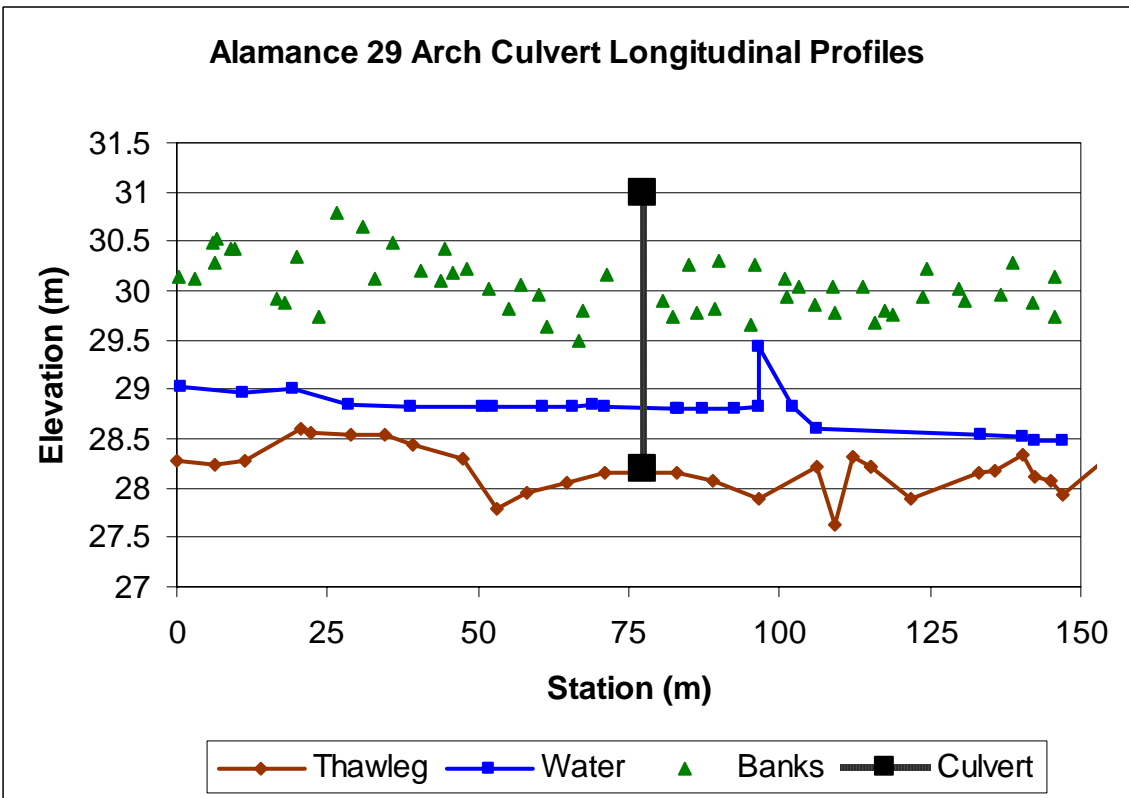
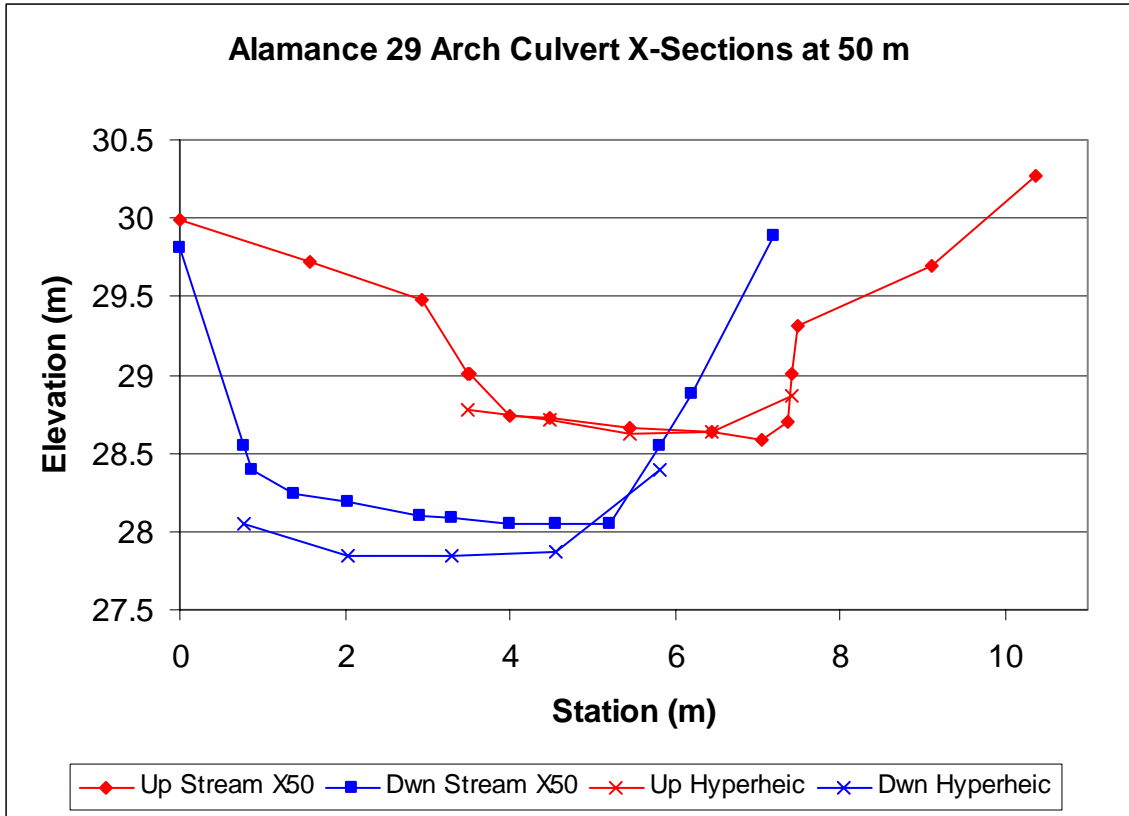
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c/g	s/c	g/c	s/c	g/c	c/g	g/c	s/c	s	c	c/g	s



Alamance 29 Cross Section, Longitudinal Profile, and Planar Graphs

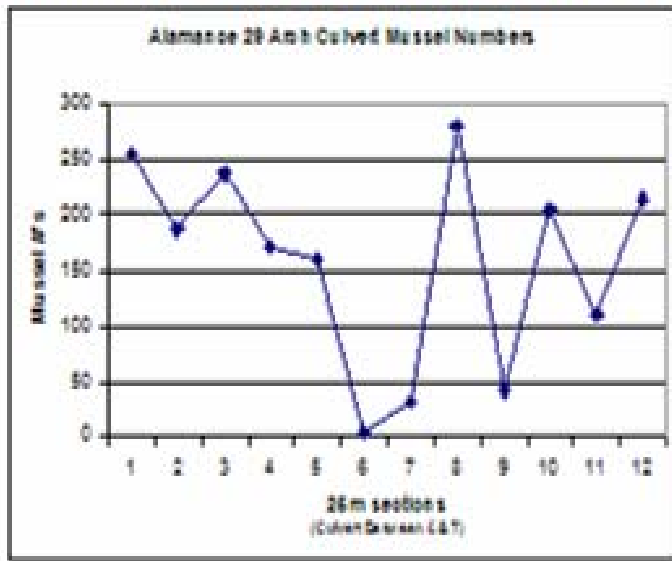






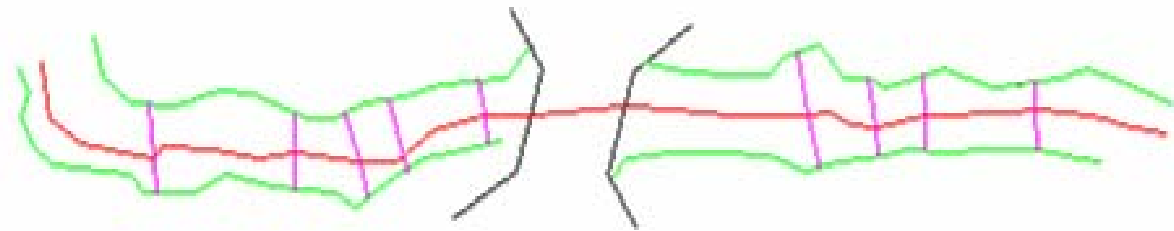
*Graph not to scale, please email for originals.

Alamance 29 Arch Culvert Planar View and Substrate Sections (1:480)

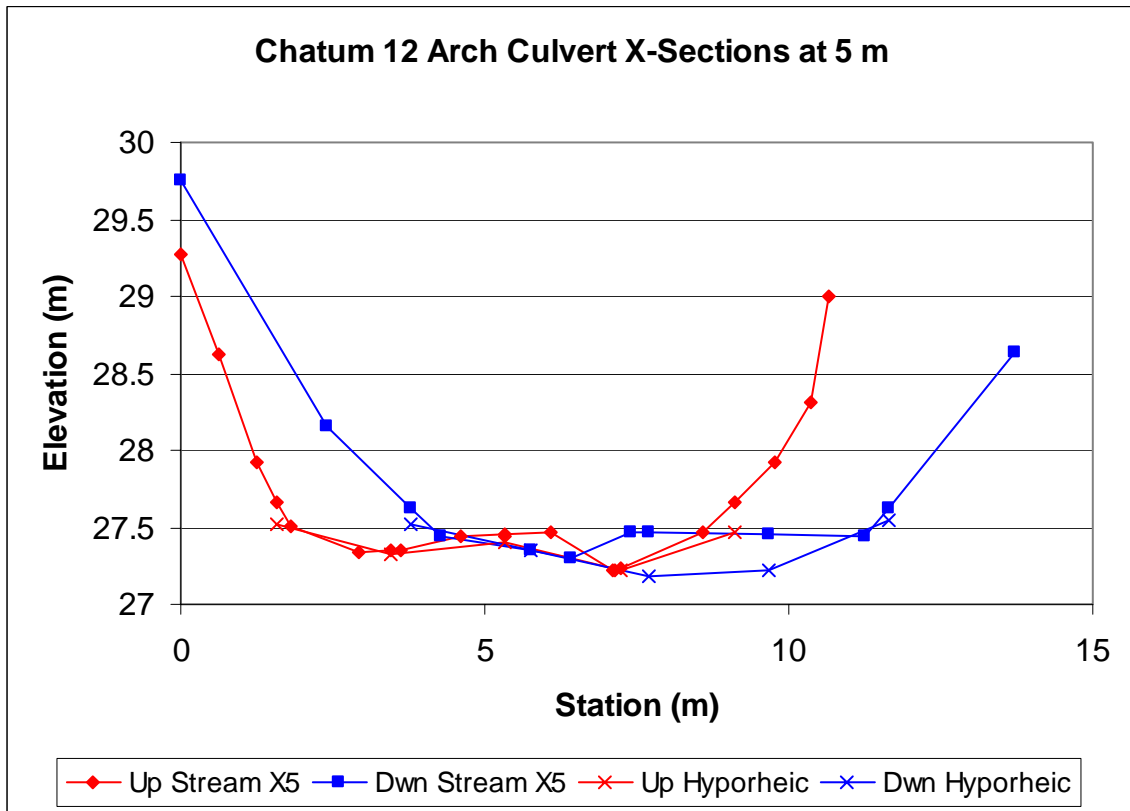
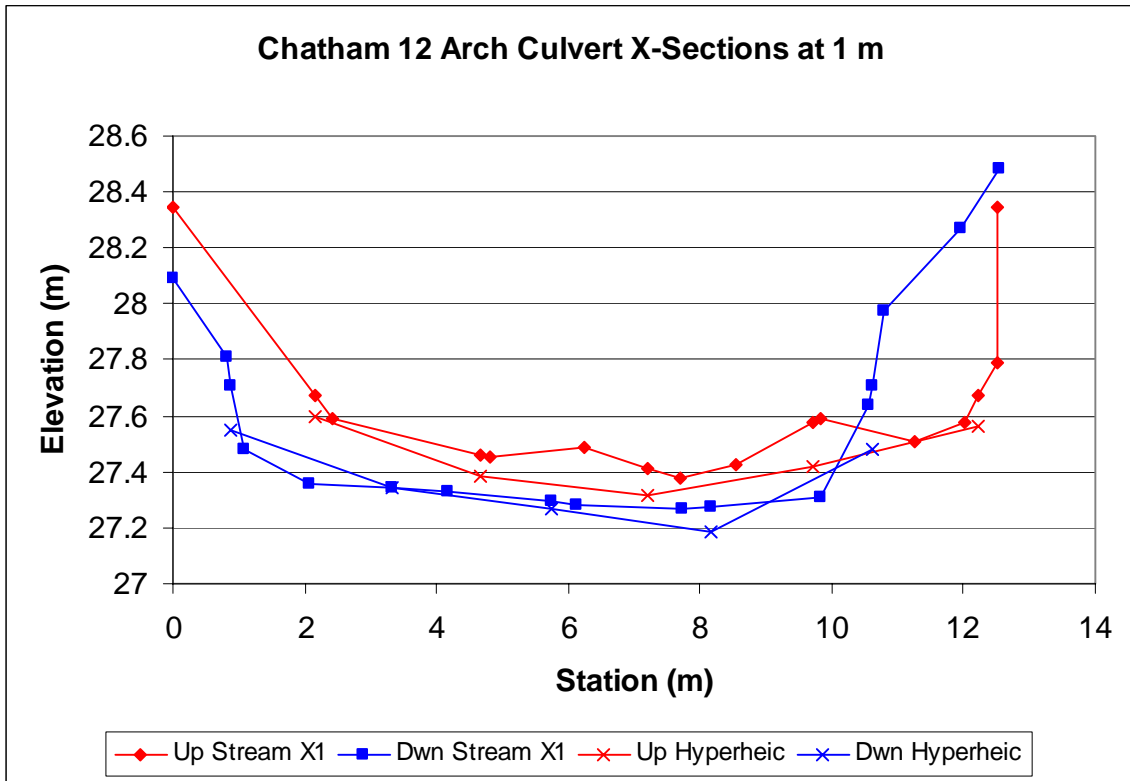


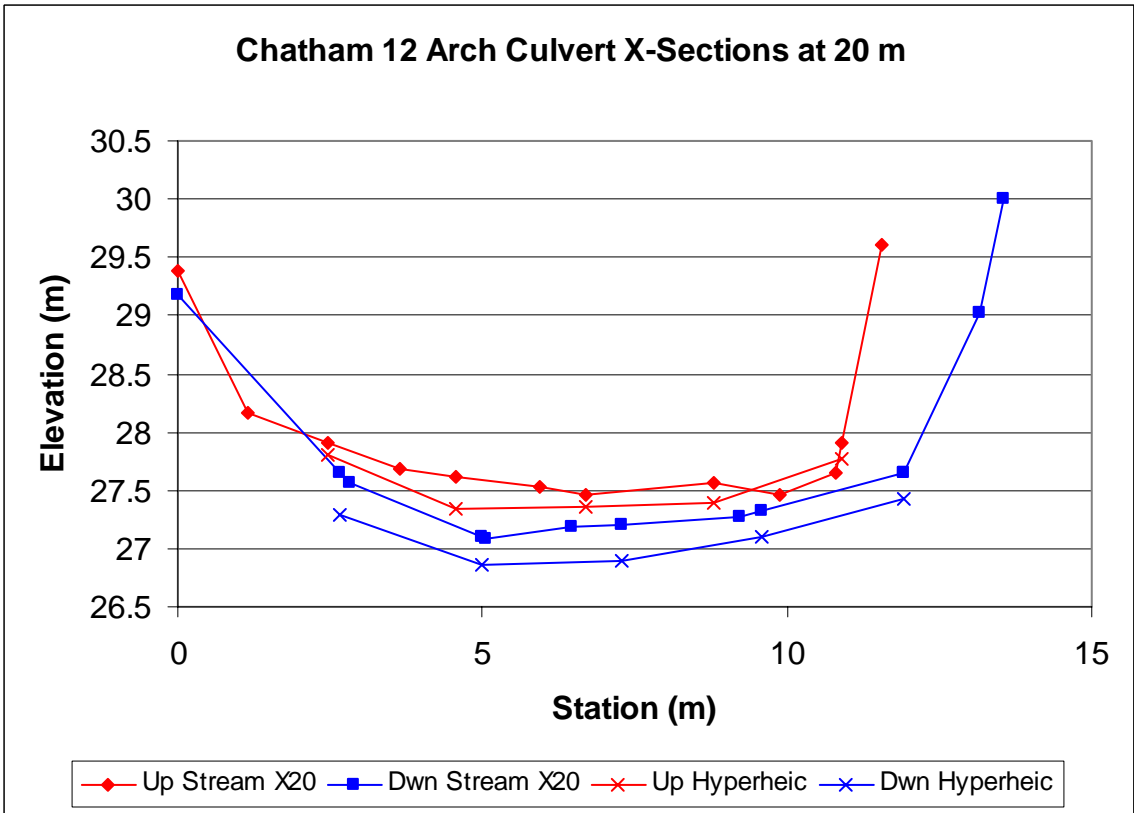
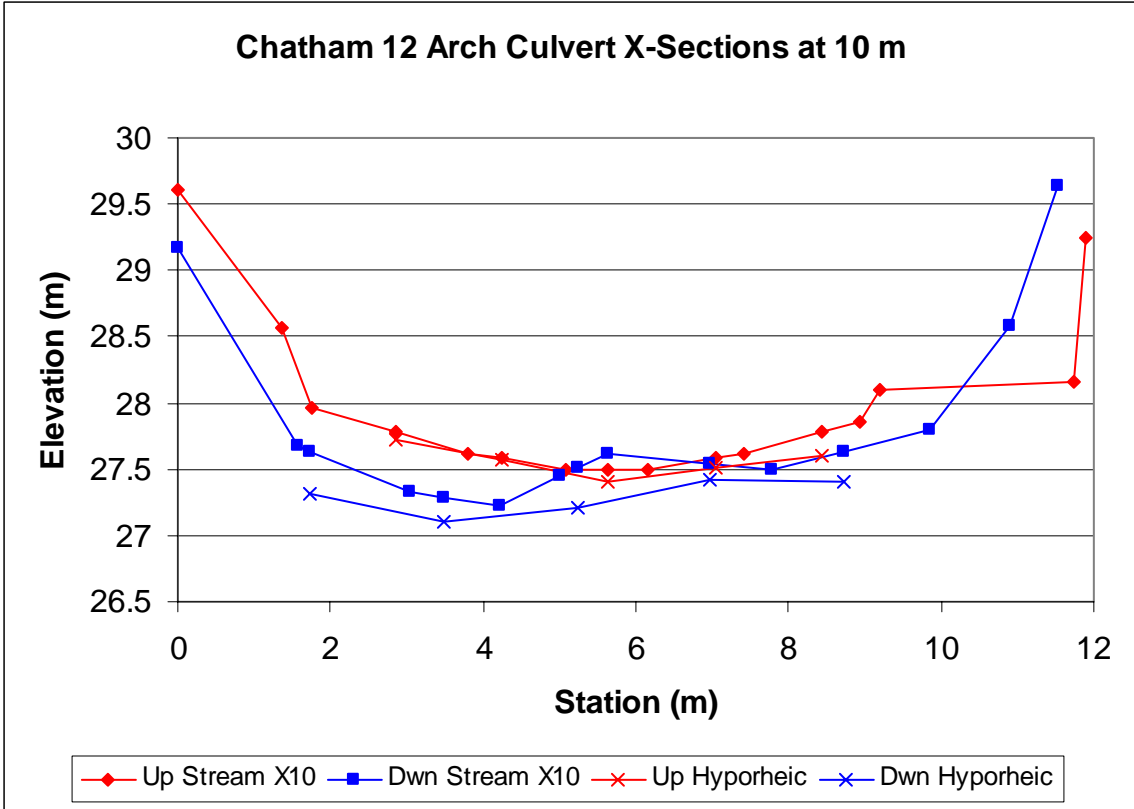
Field Notes: Saprolite near the substrate surface and exposed

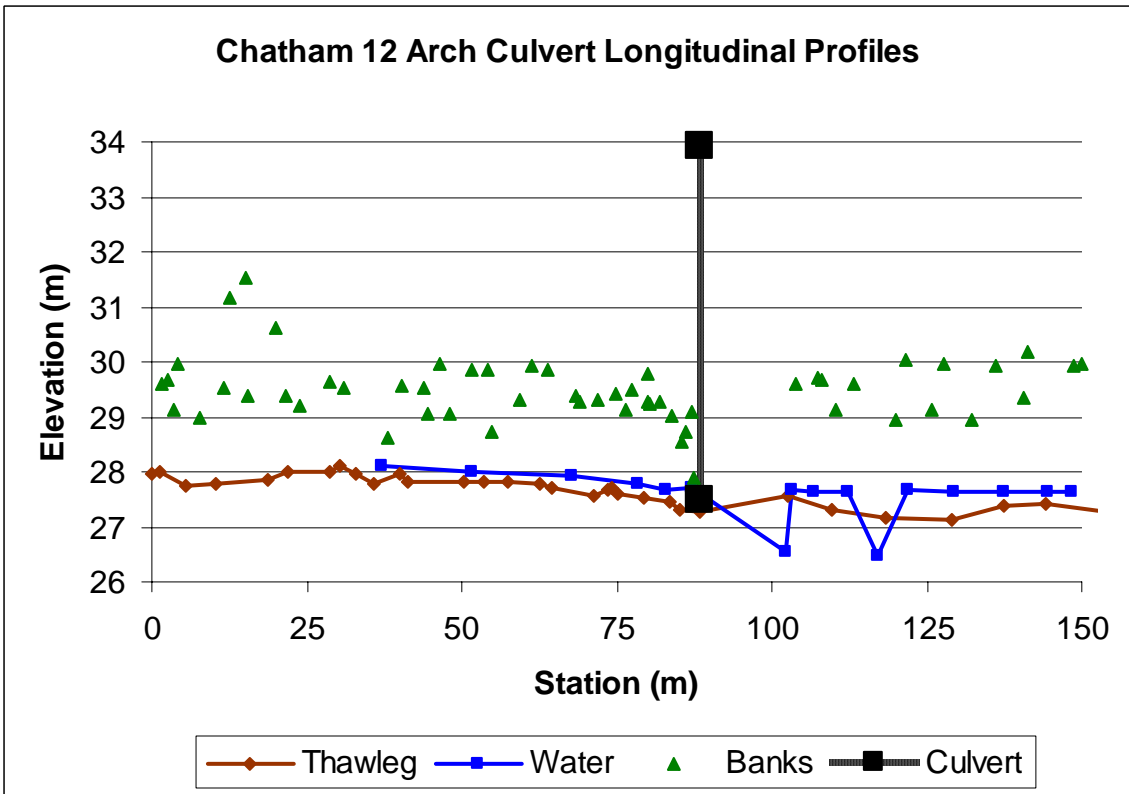
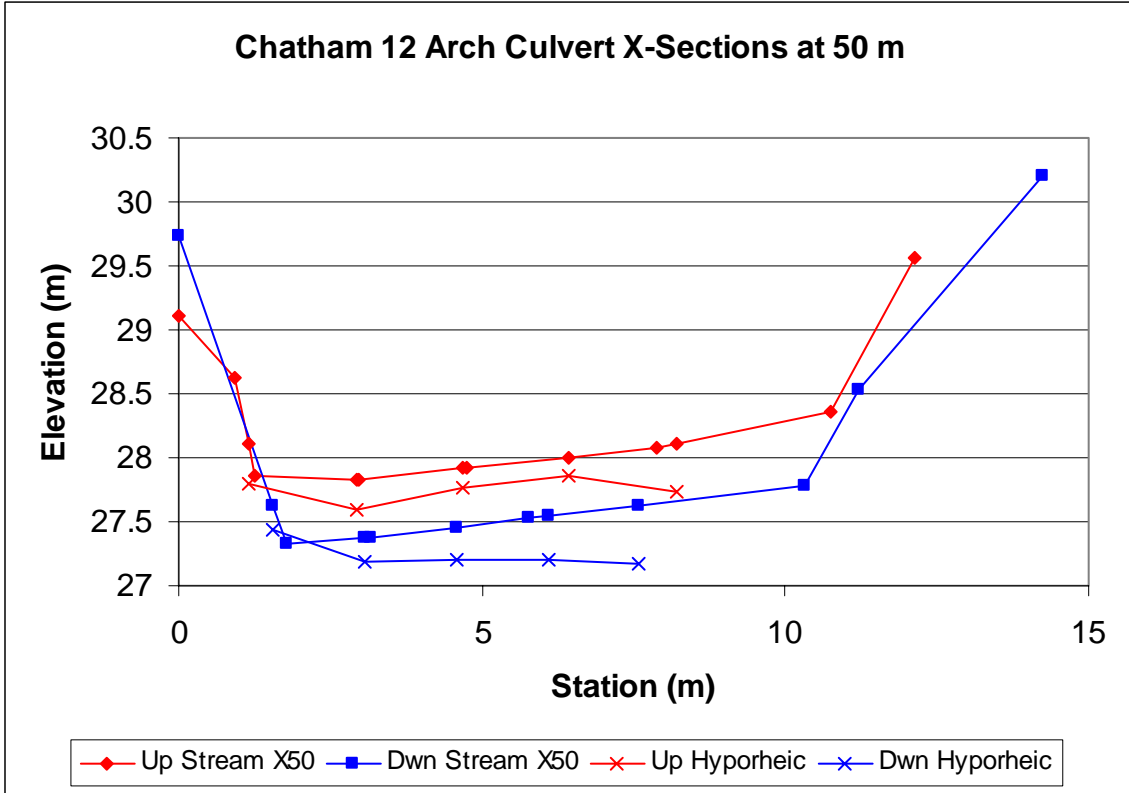
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c/b	c/g	g/s	b/s	b/c	b	a	c/g	g/s	g	g/c



Chatham 12 Cross Section, Longitudinal Profile, and Planar Graphs

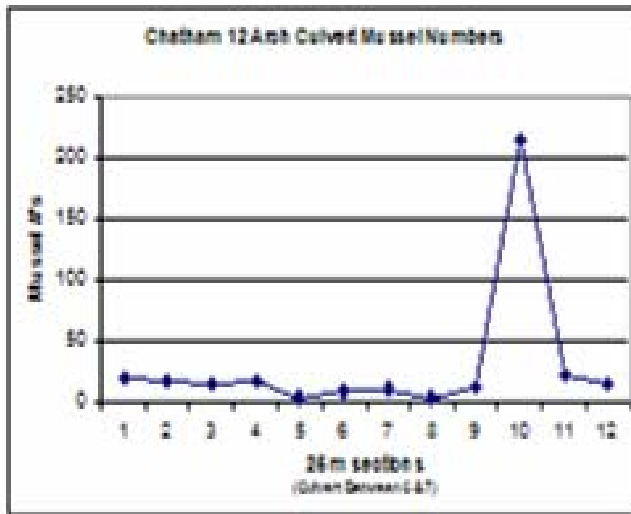






*Graph not to scale, please email for originals.

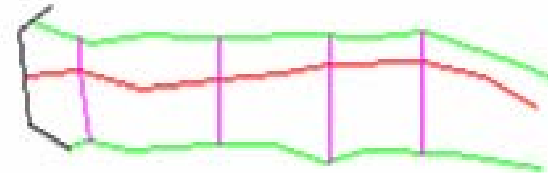
Chatham 12 Arch Culvert Planar View with Substrate Sections (1:480)



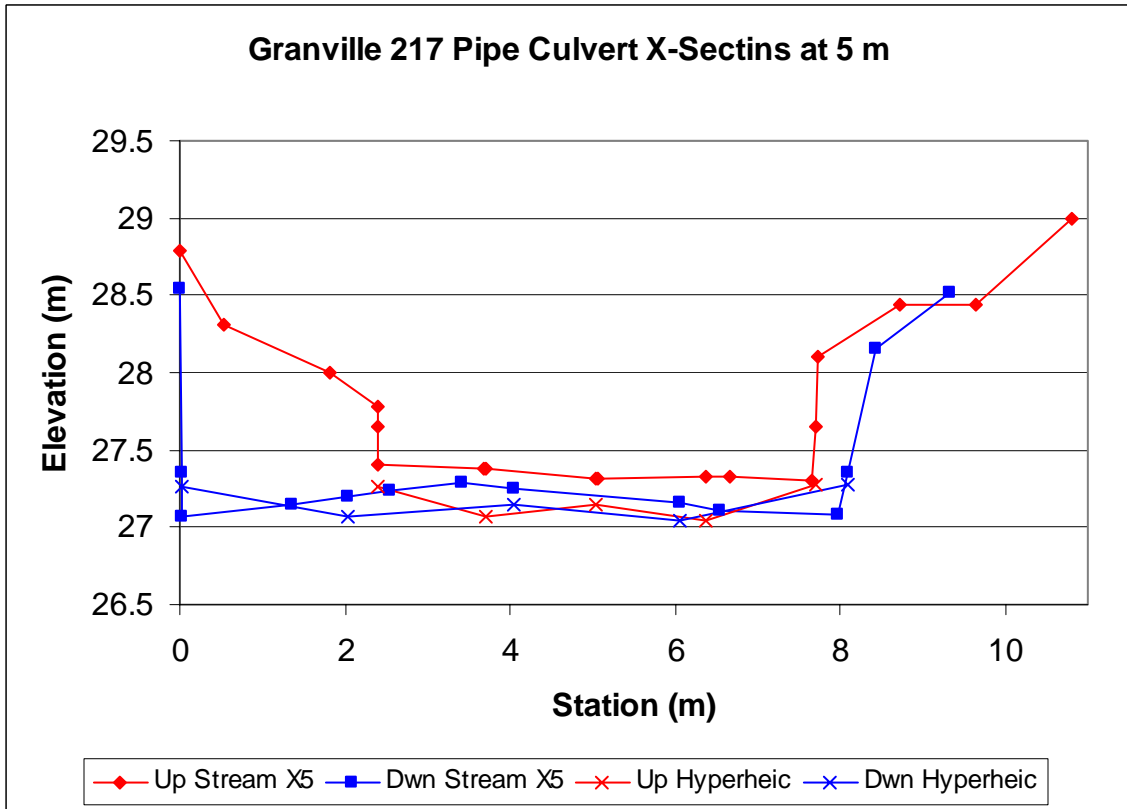
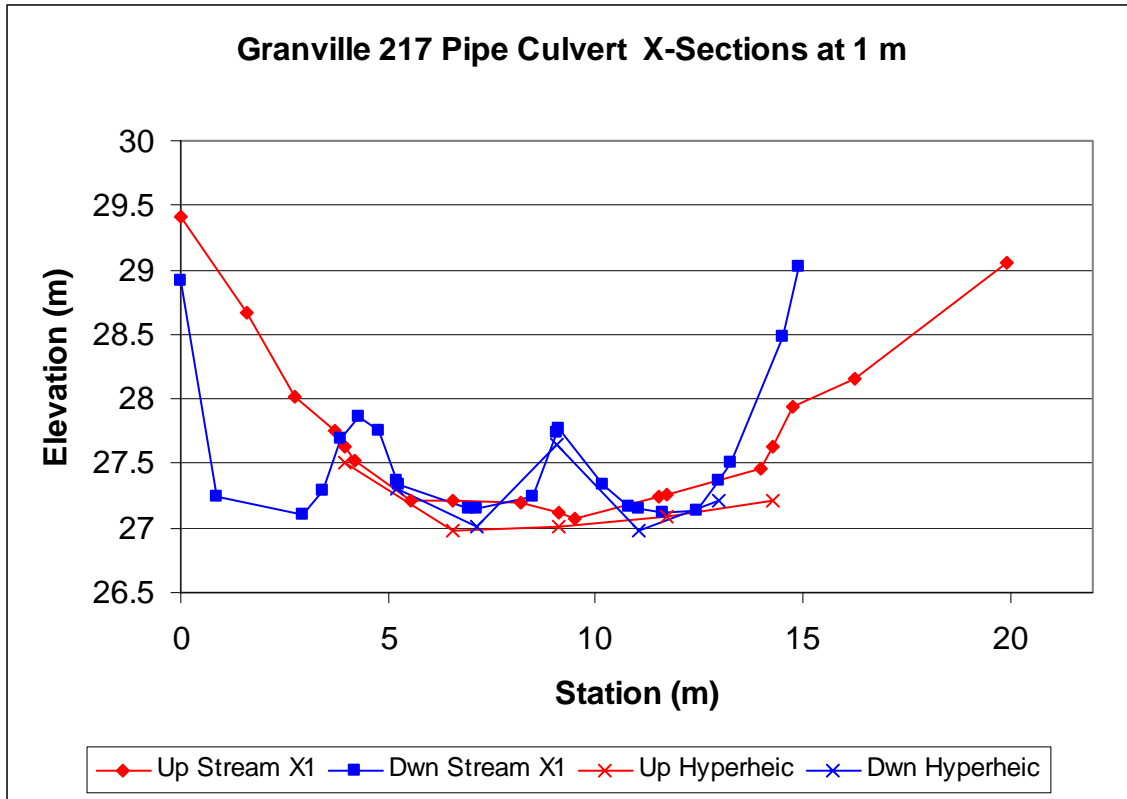
Field Notes: Gravel pockets behind boulders, Finer gravel near banks

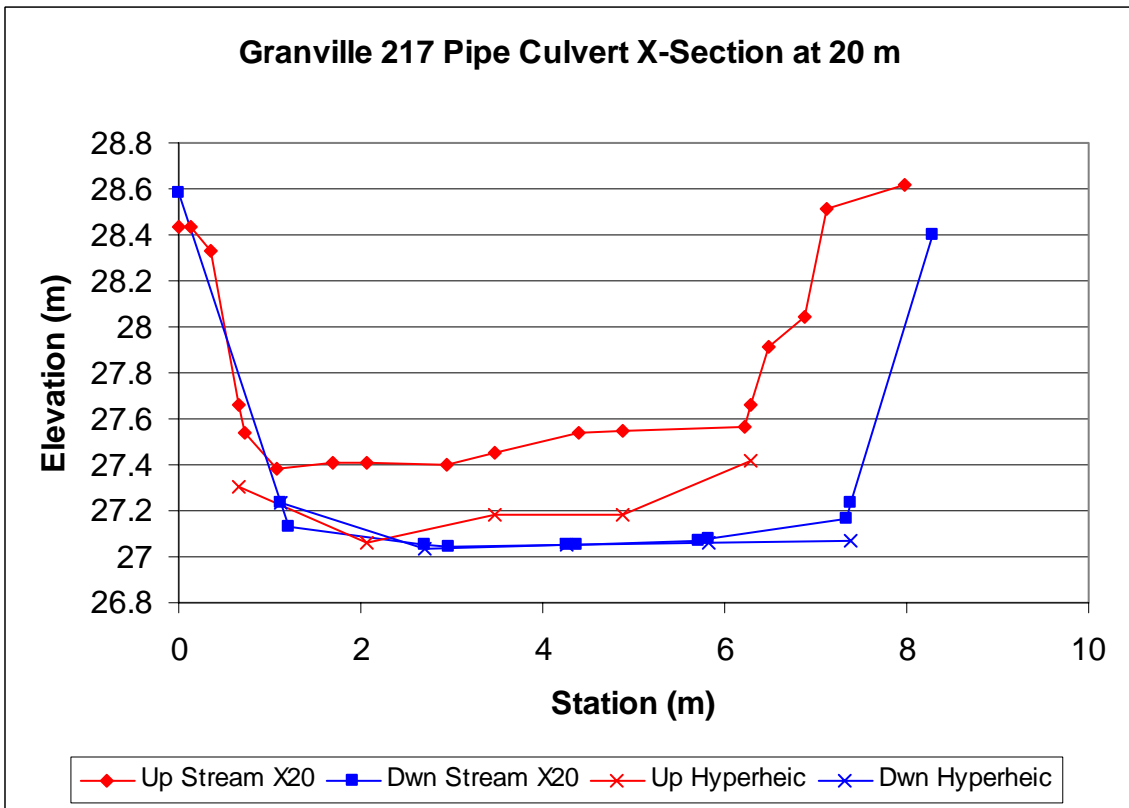
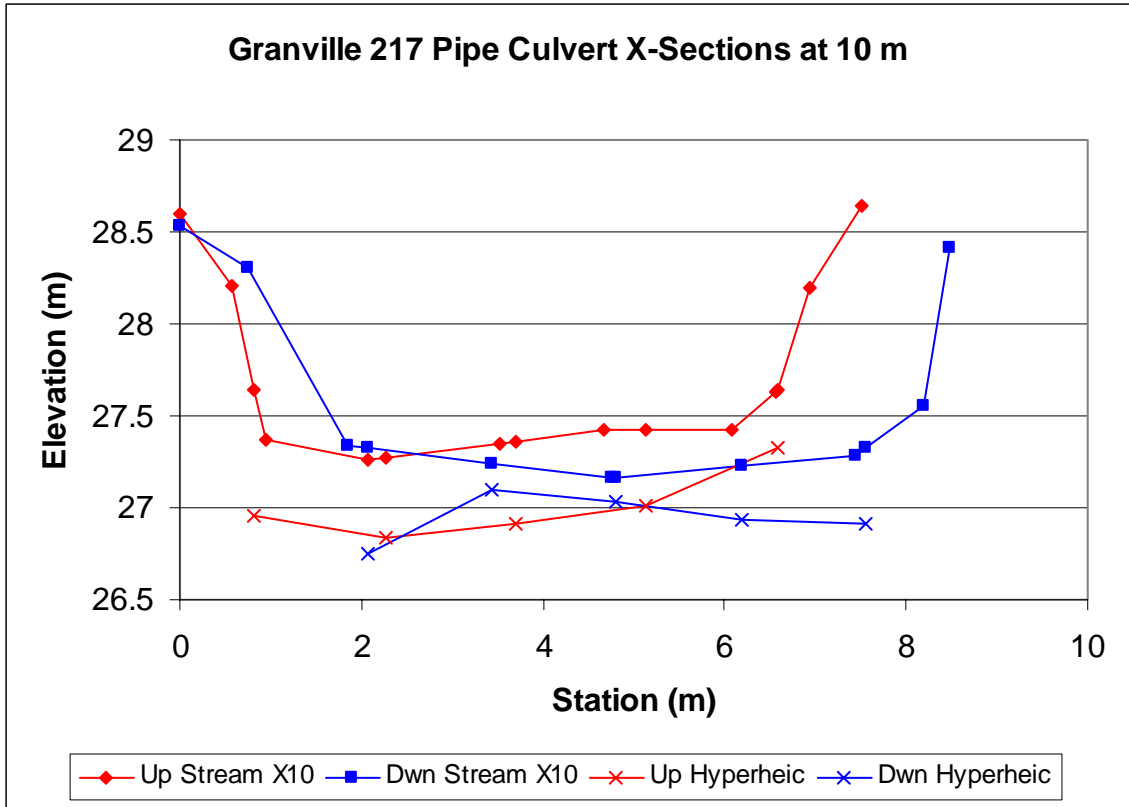
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c/b c/g g/c c/g b/s b/g

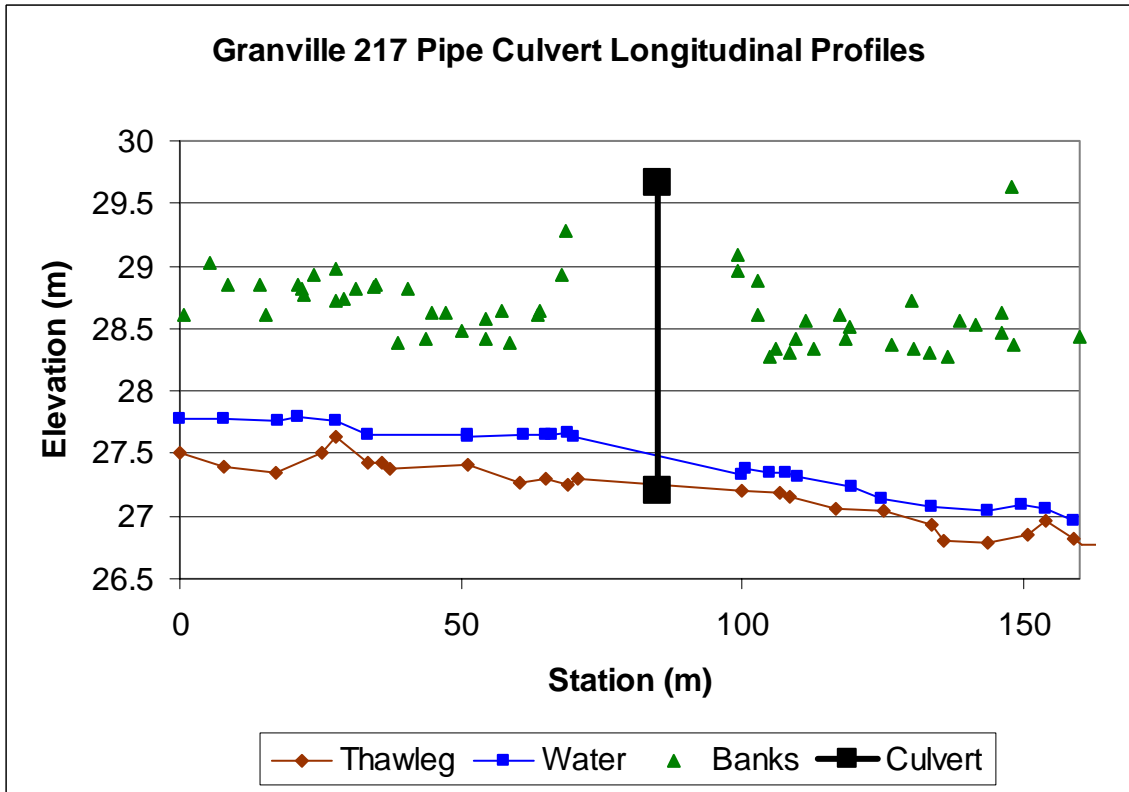
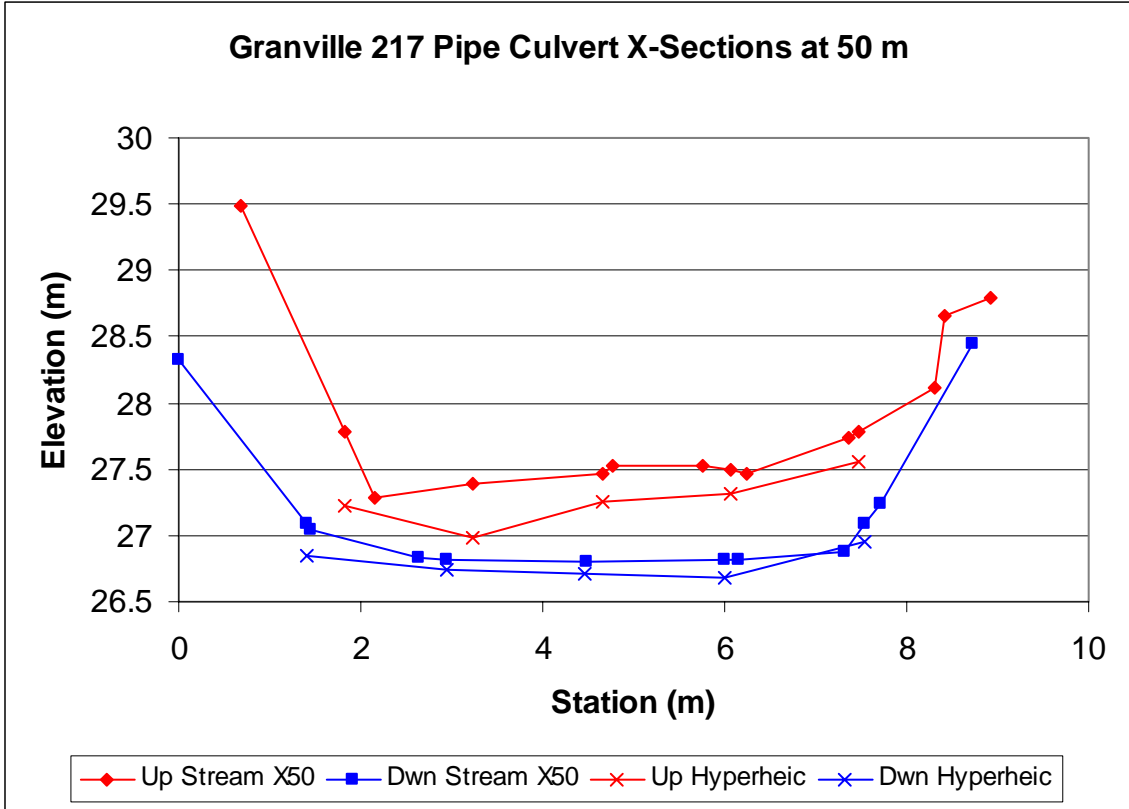
t0 t1 t2 t3 t4
g/c c/g g/c c/g g/c



Granville 217 Cross Section, Longitudinal Profile, and Planar Graphs

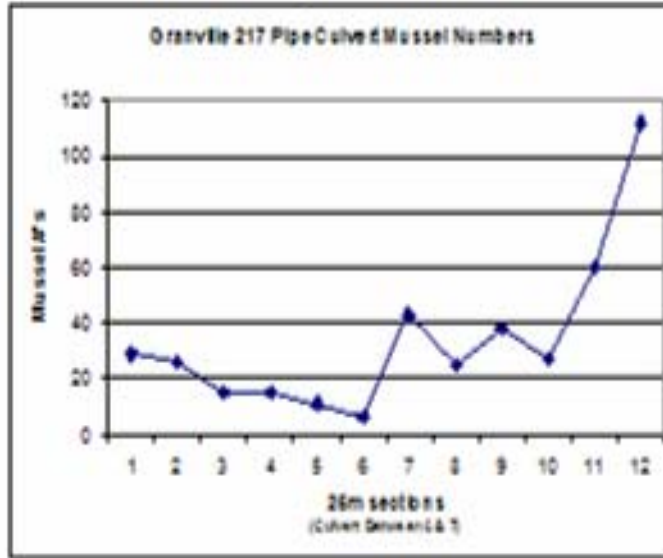




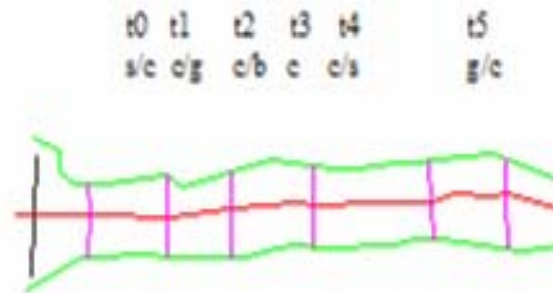
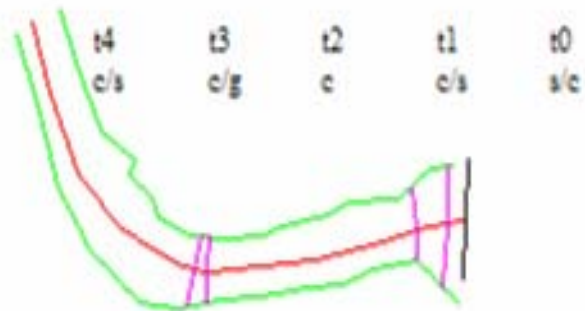


*Graph not to scale, please email for originals.

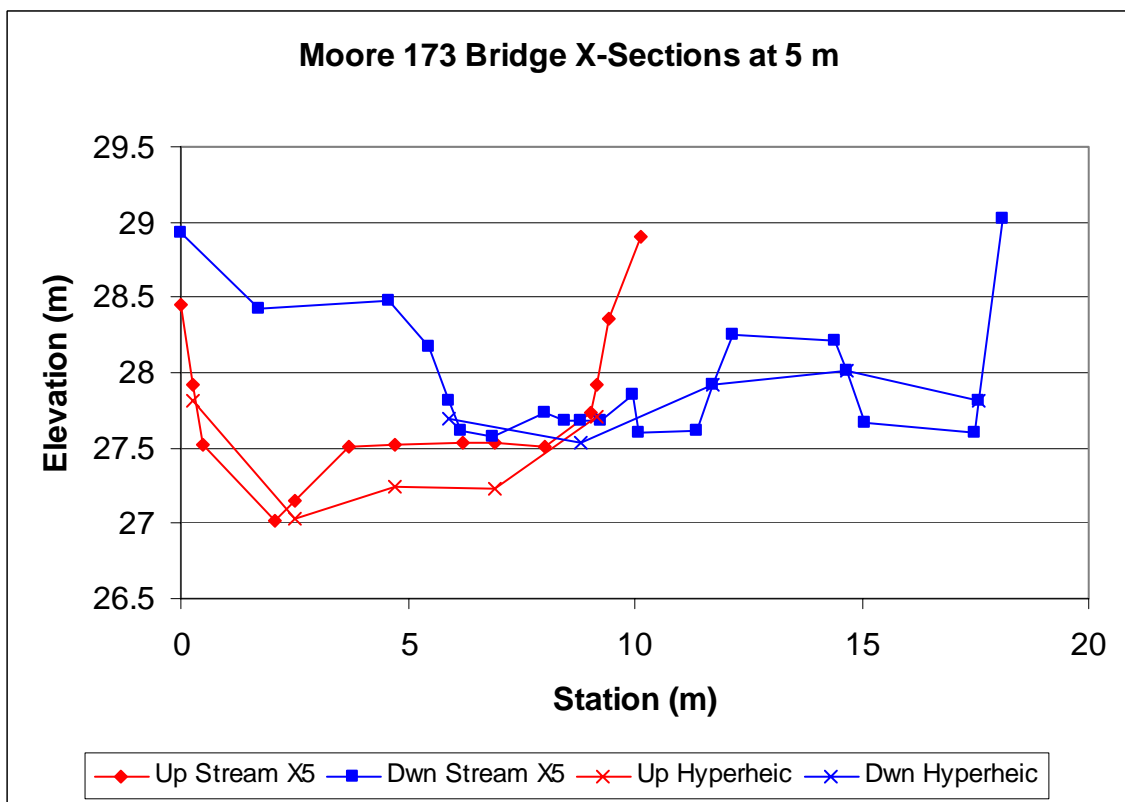
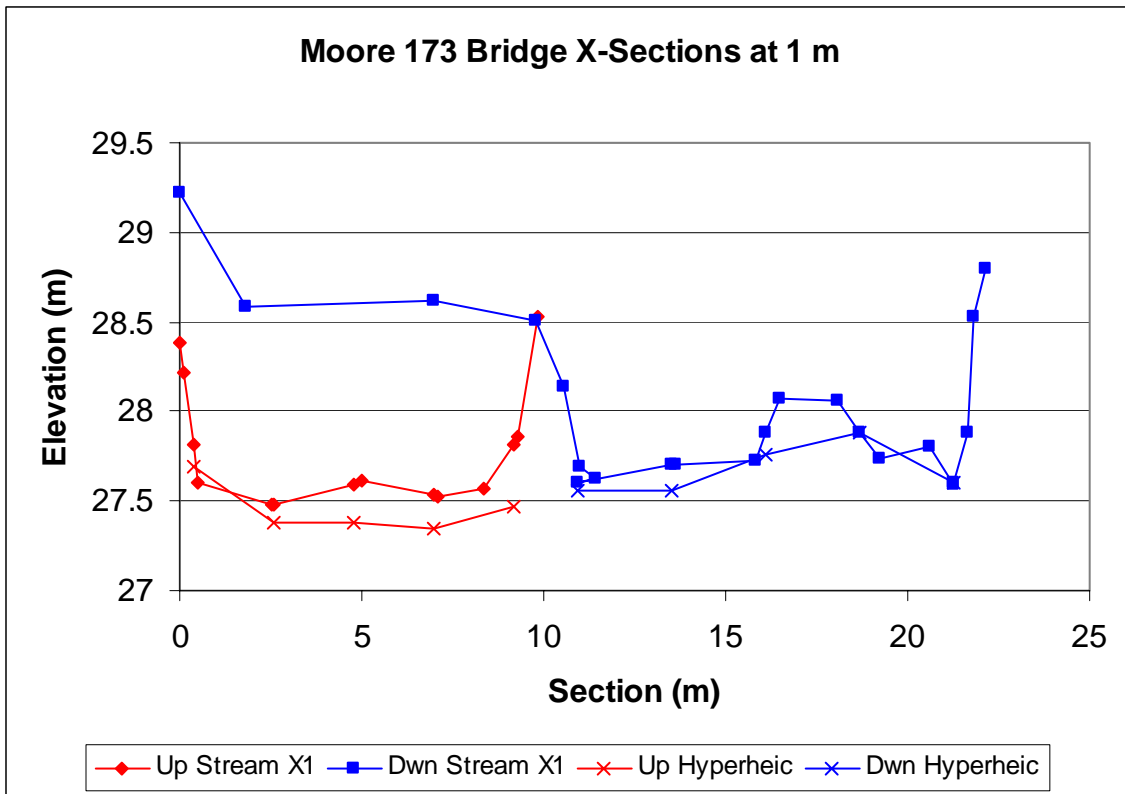
Granville 217 Pipe Culvert Planar View and Substrate Sections (1:480)

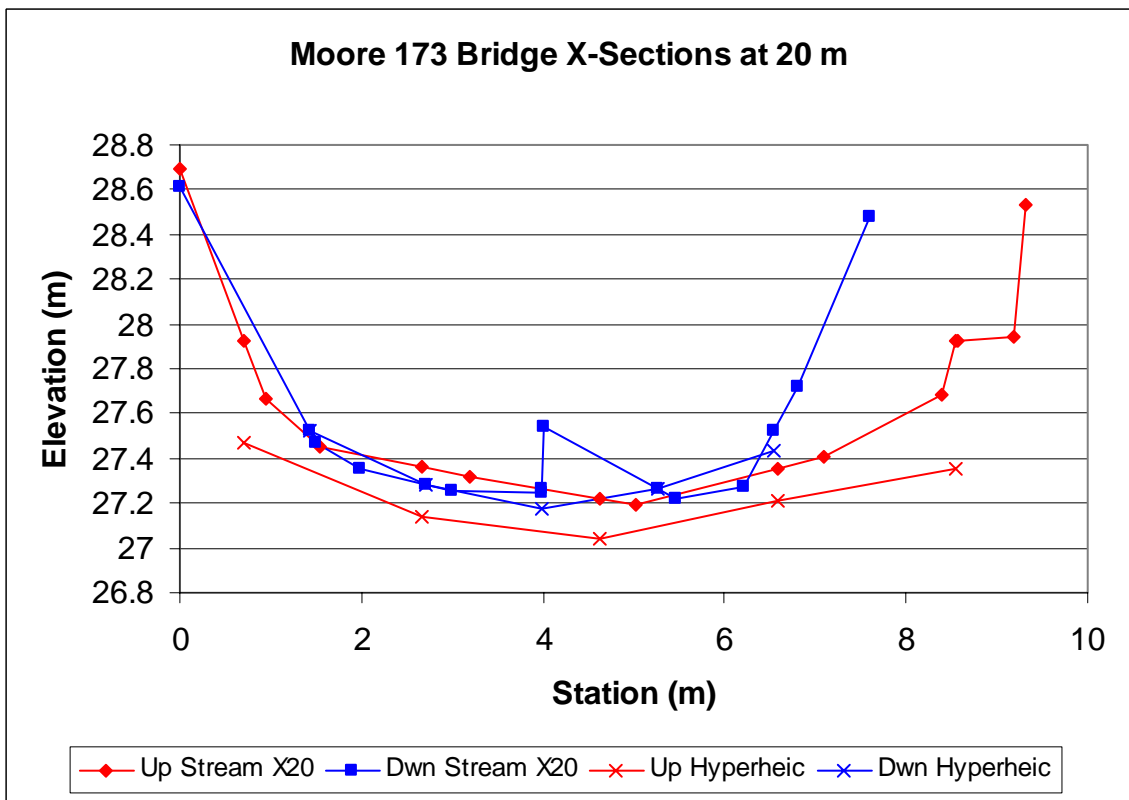
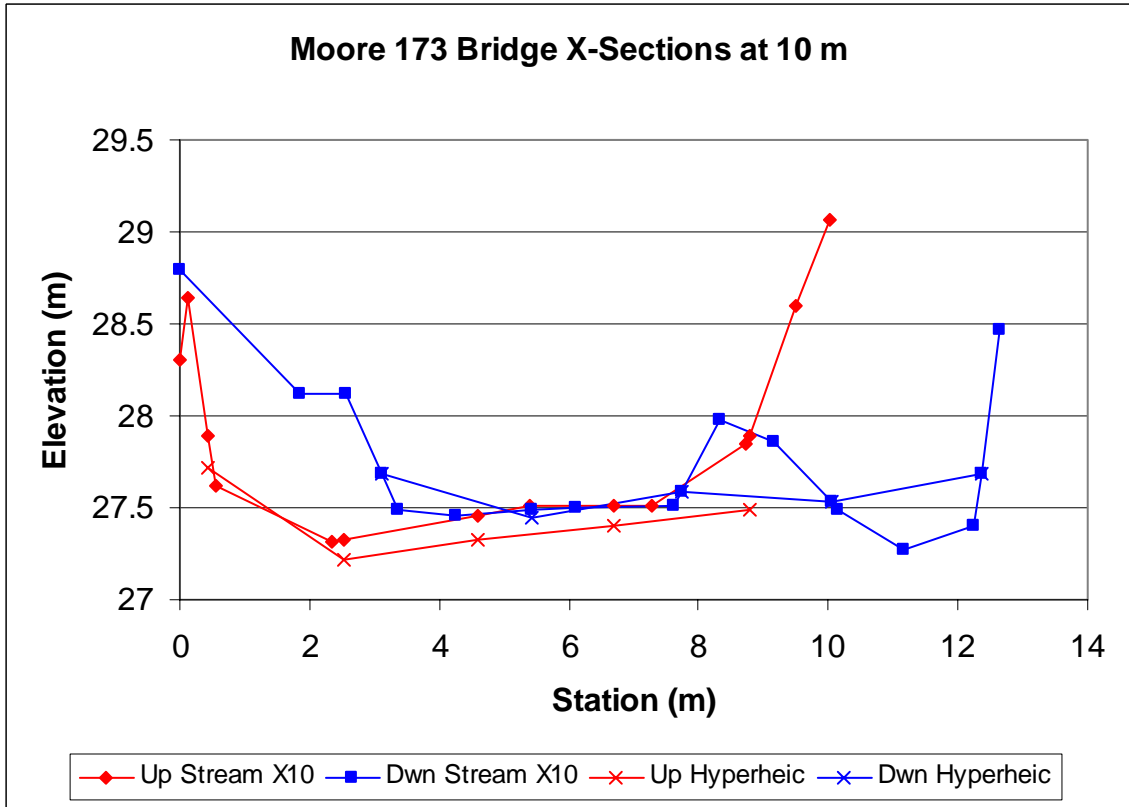


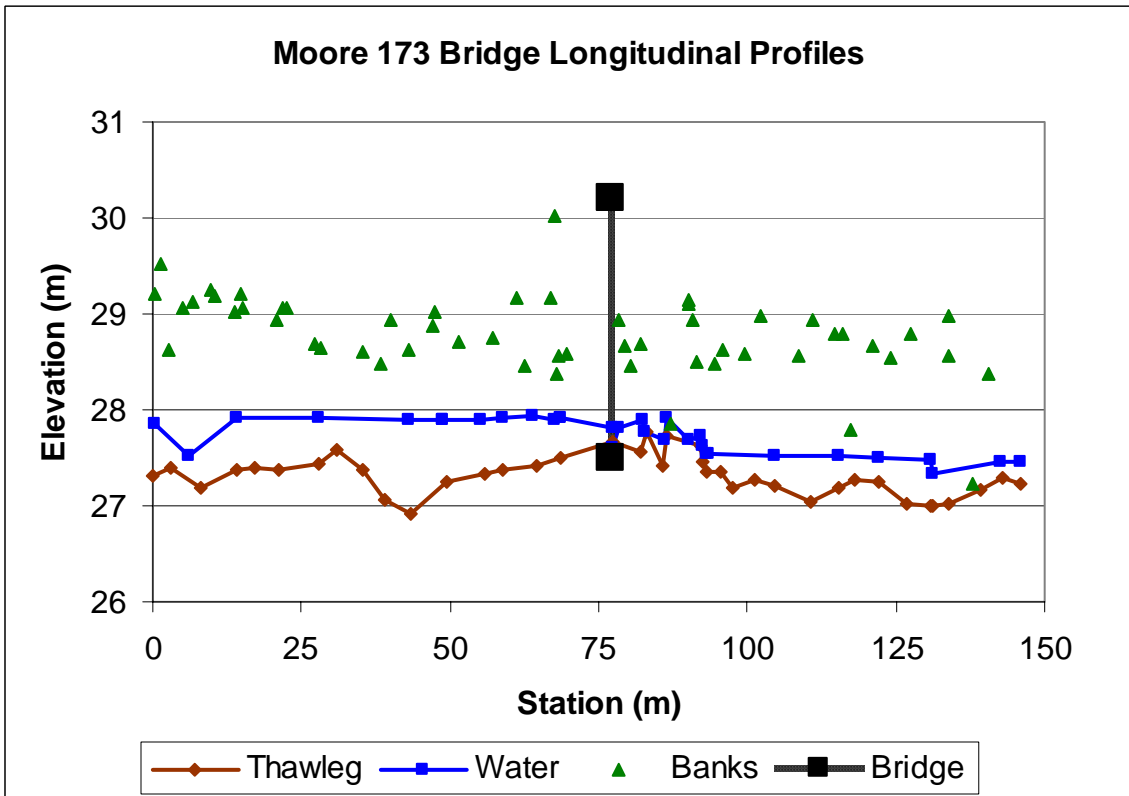
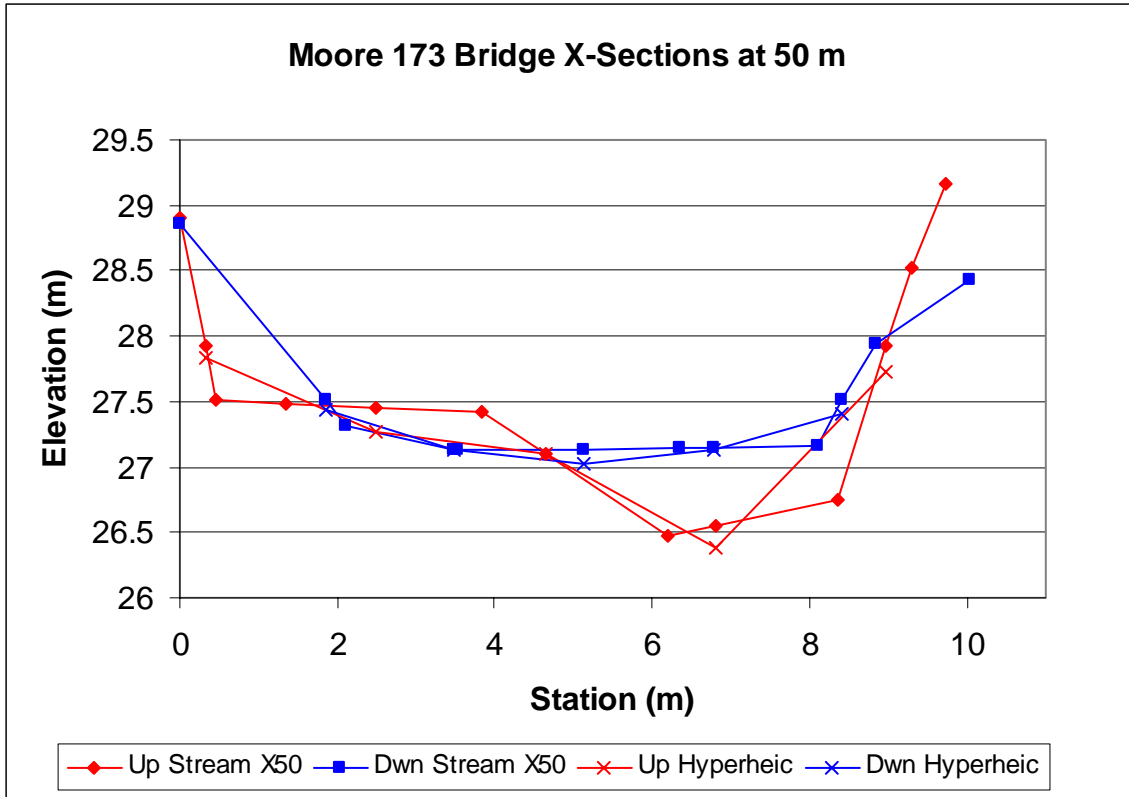
Field Notes: Banks eroded, sands on banks



Moore 173 Cross Section, Longitudinal Profile, and Planar Graphs

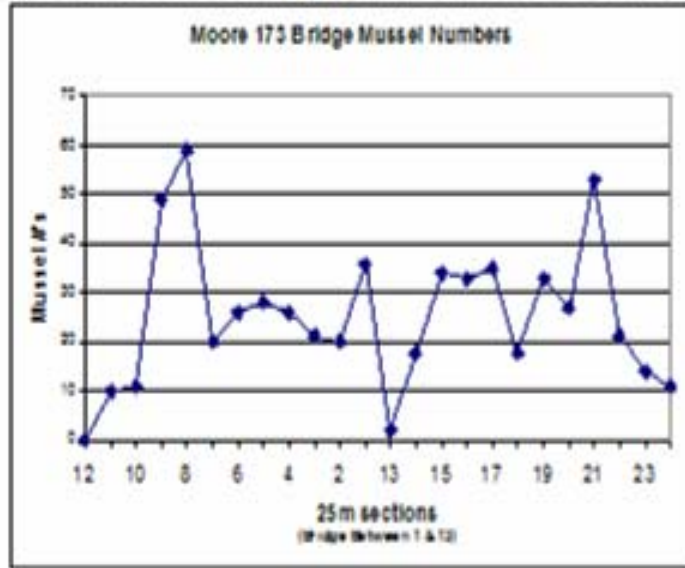




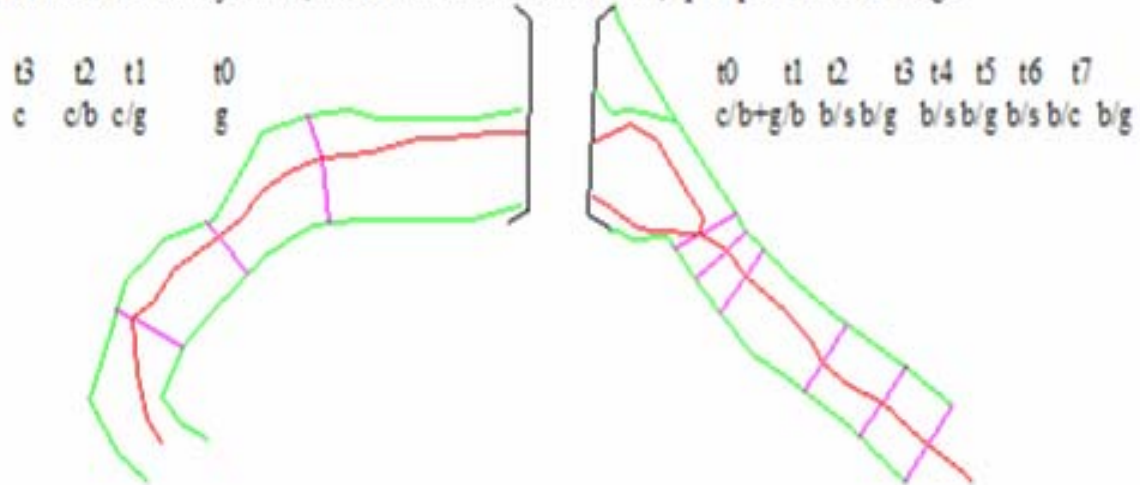


*Graph not to scale, please email author for originals.

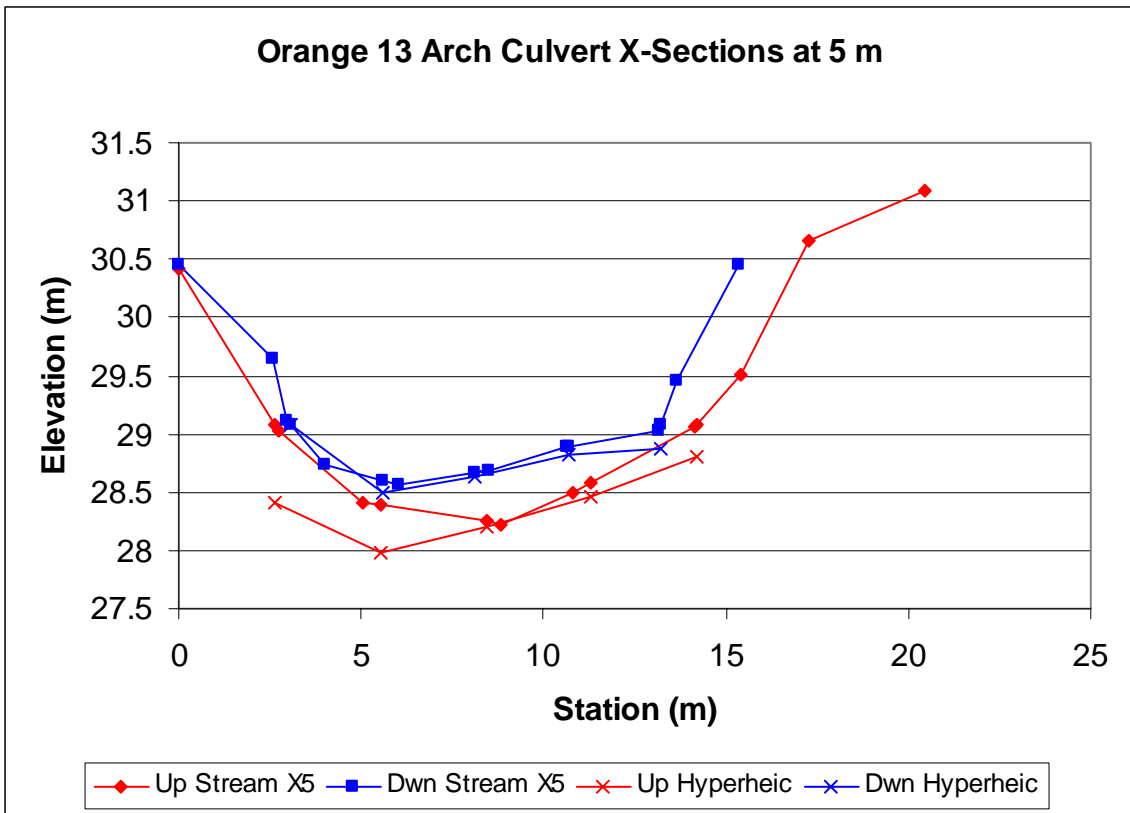
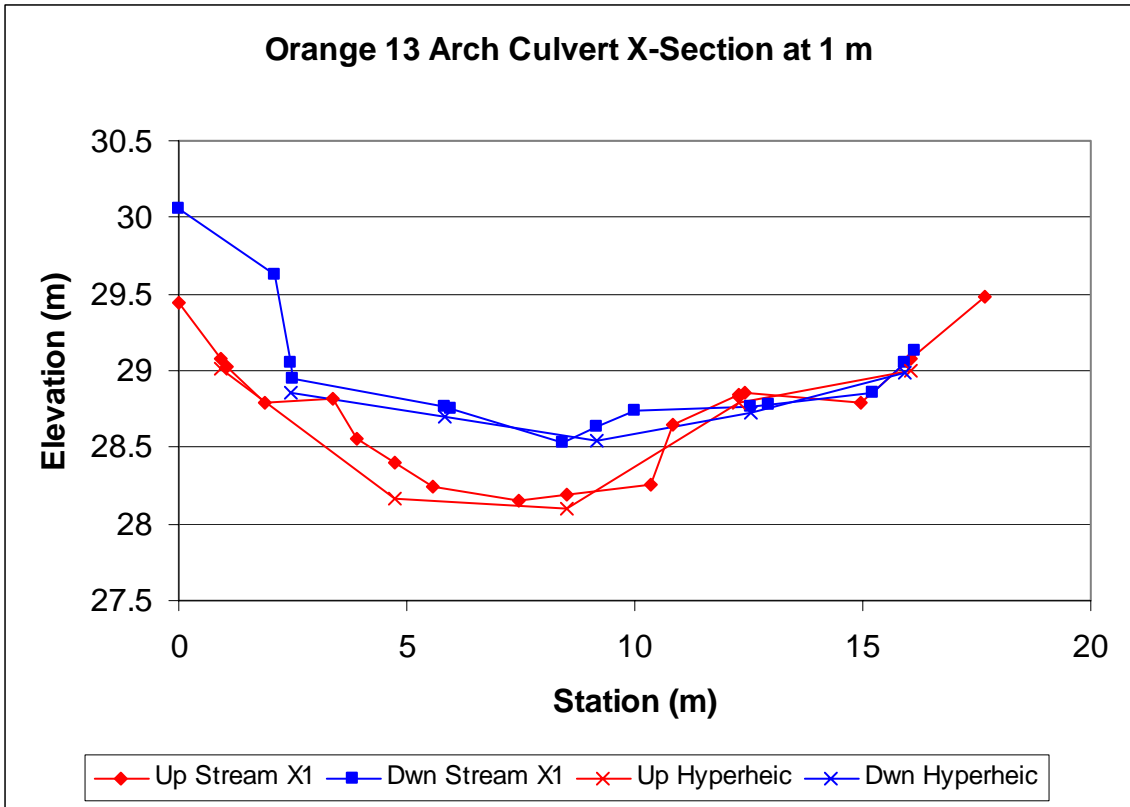
Moore 173 Bridge Planar Views and Substrate Sections (1:480)

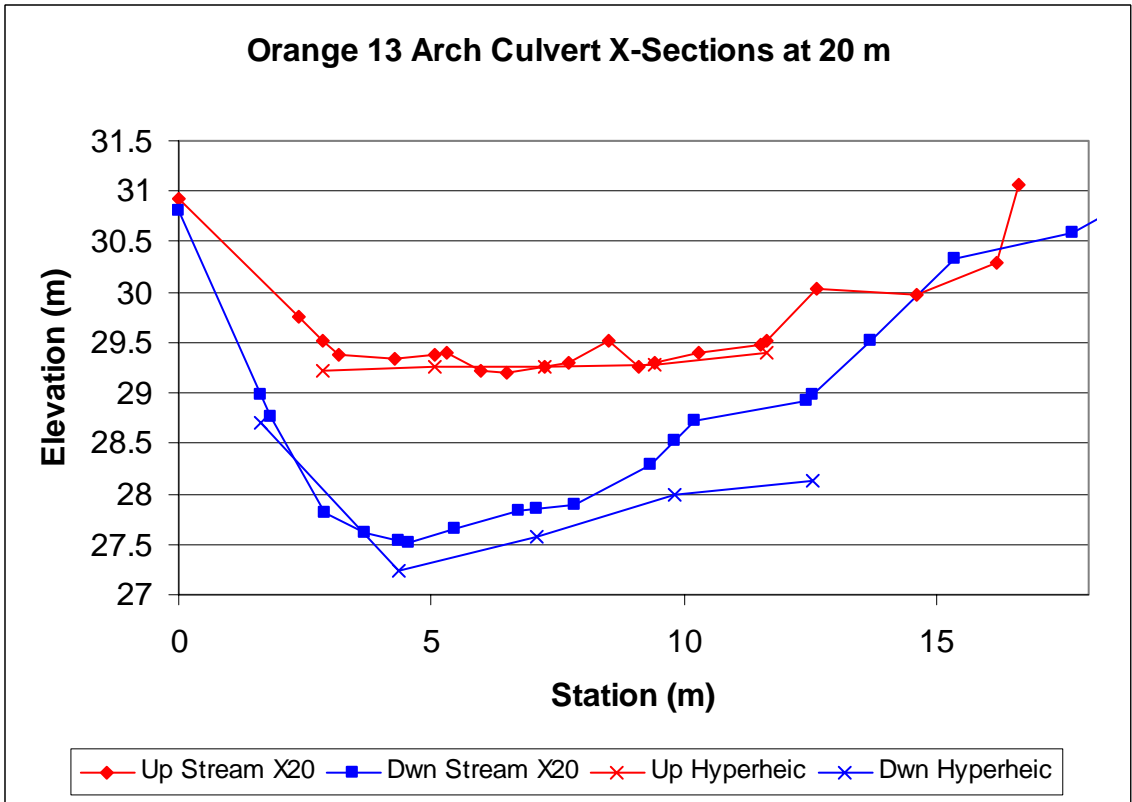
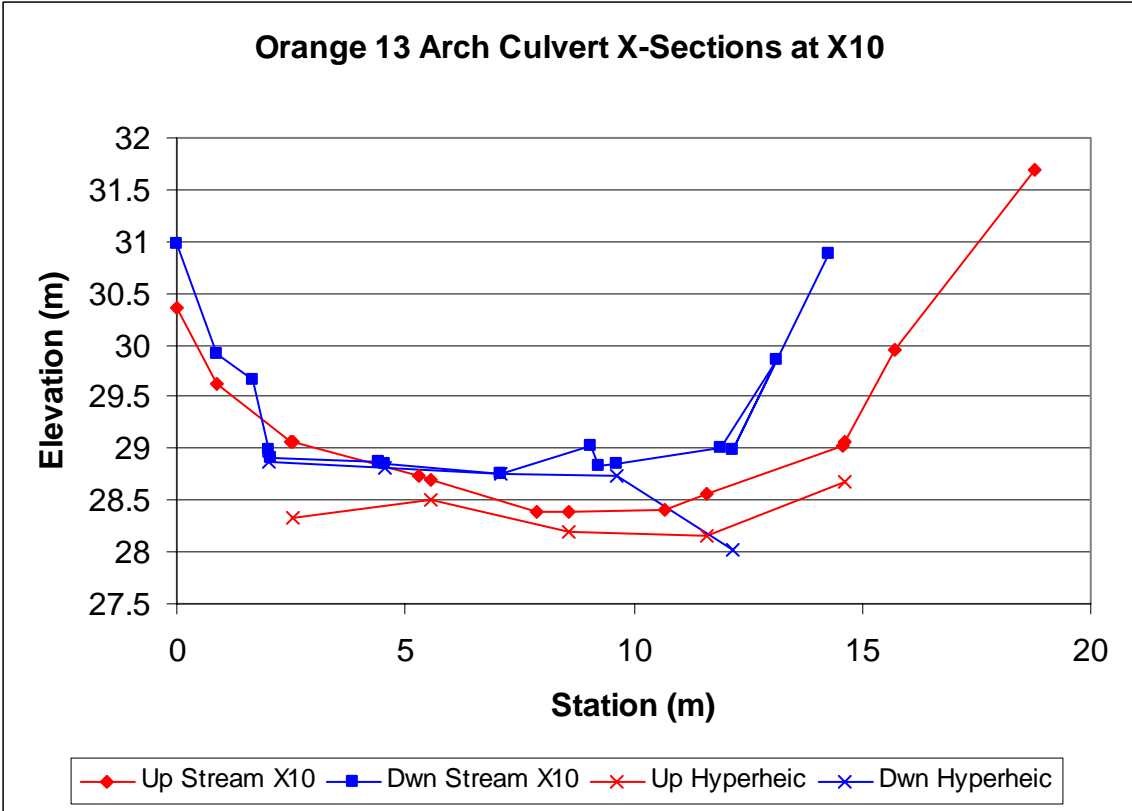


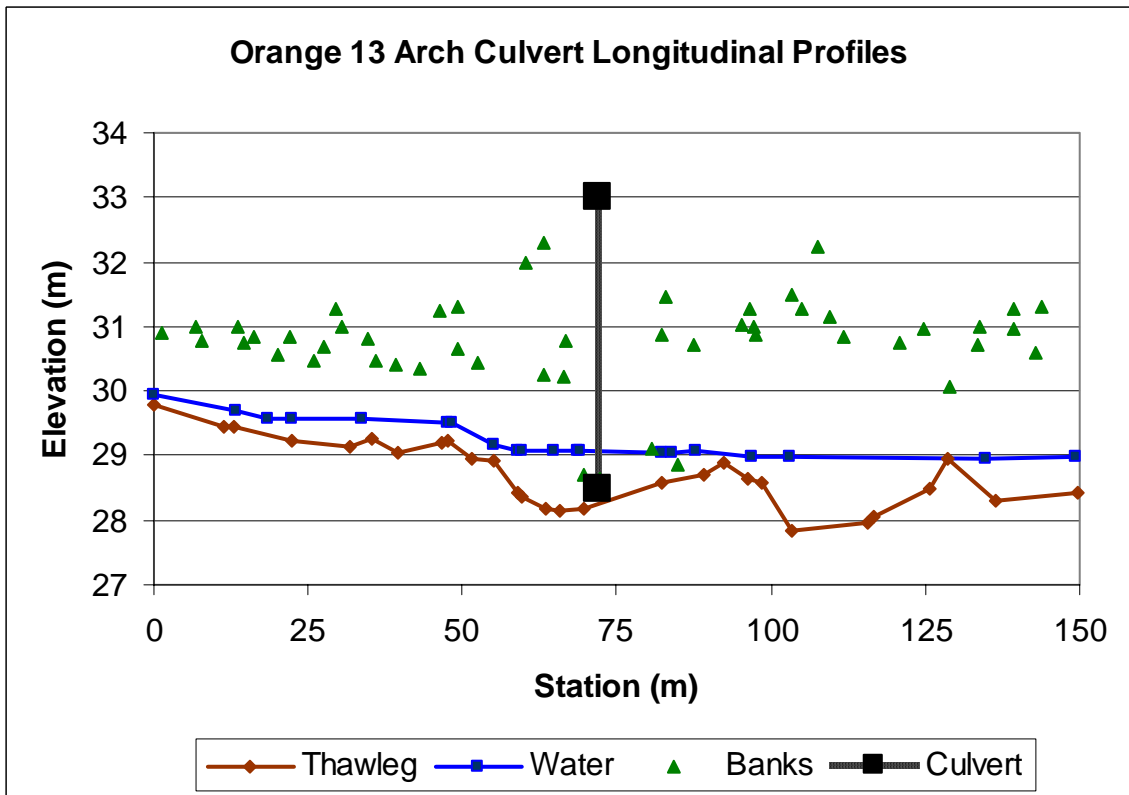
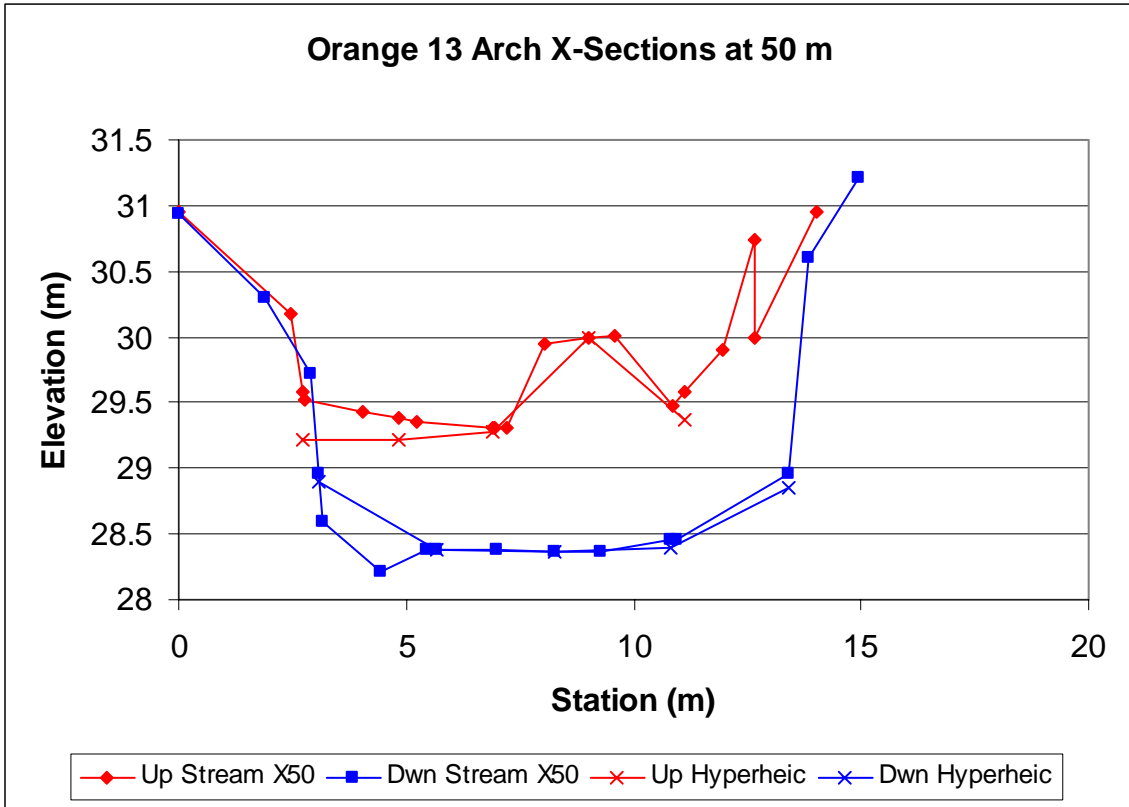
Field Notes: Sandy banks, mid-channel bar downstream, spoil piles next to bridge



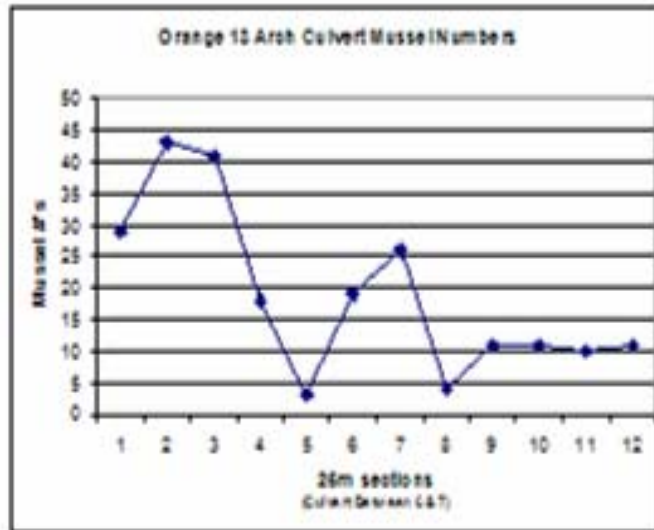
Orange 13 Cross Section, Longitudinal Profile, and Planar Graphs





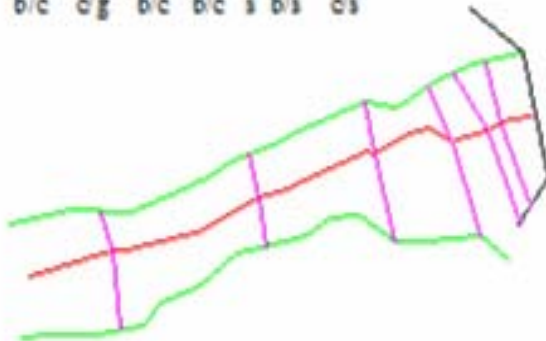


Orange 13 Arch Culvert Planar View and Substrate Sections (1:480)

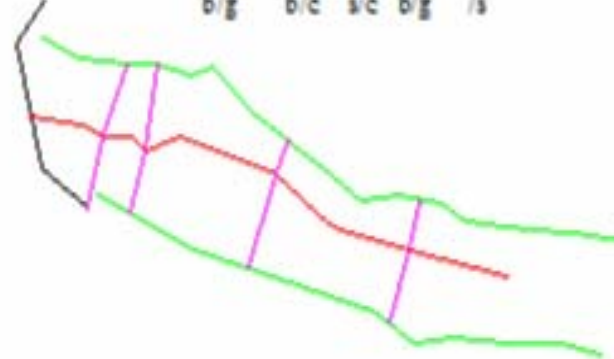


Field Notes: Sand on banks

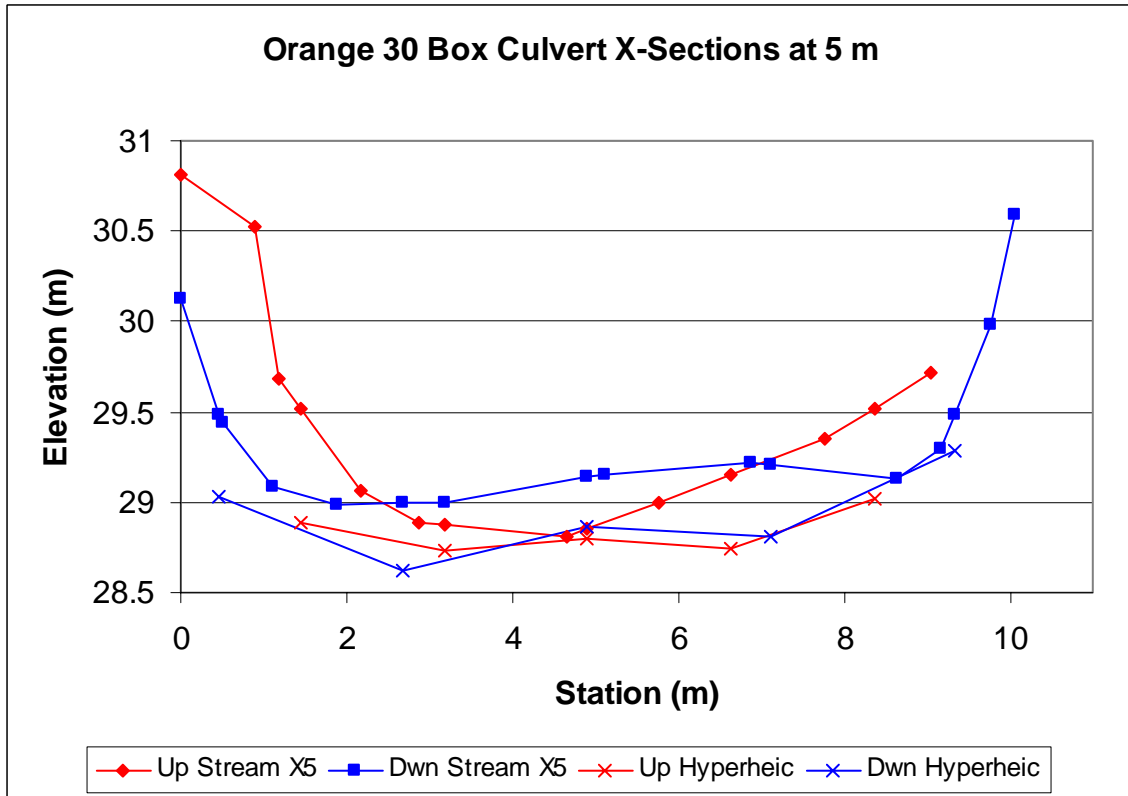
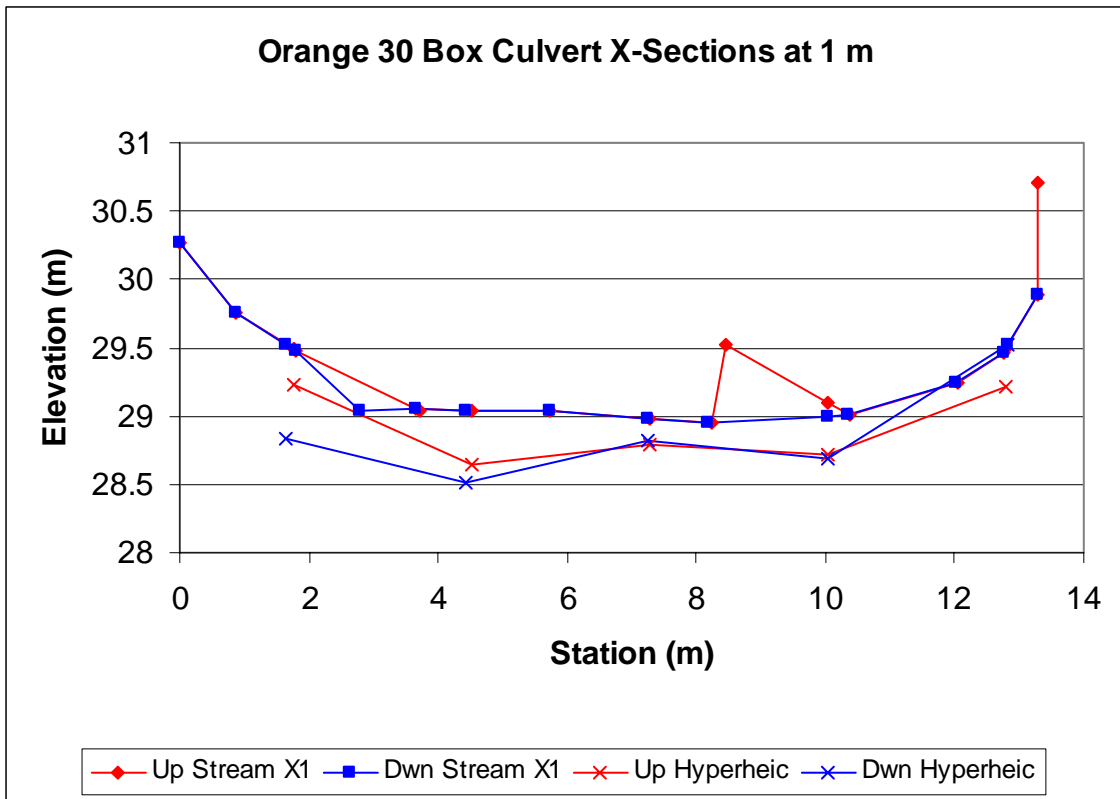
t6 t5 t4 t3 t2 t1 t0
b/c c/g b/c b/c s b/s c/s

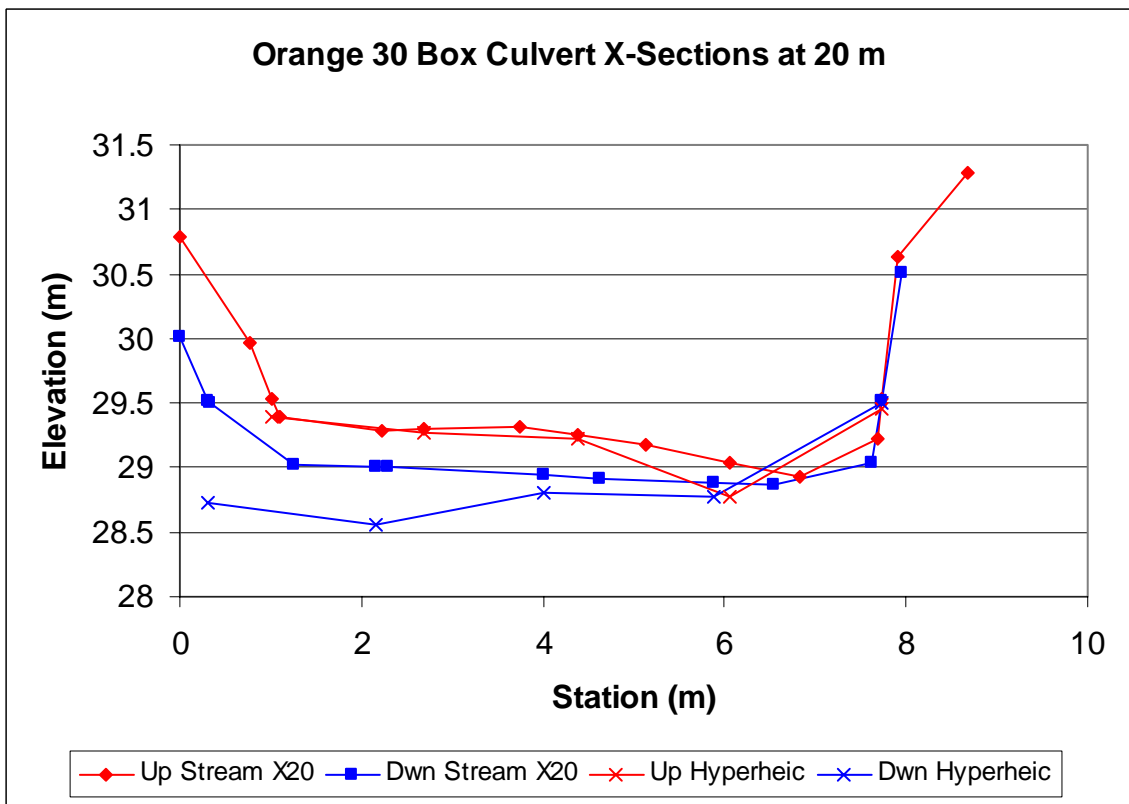
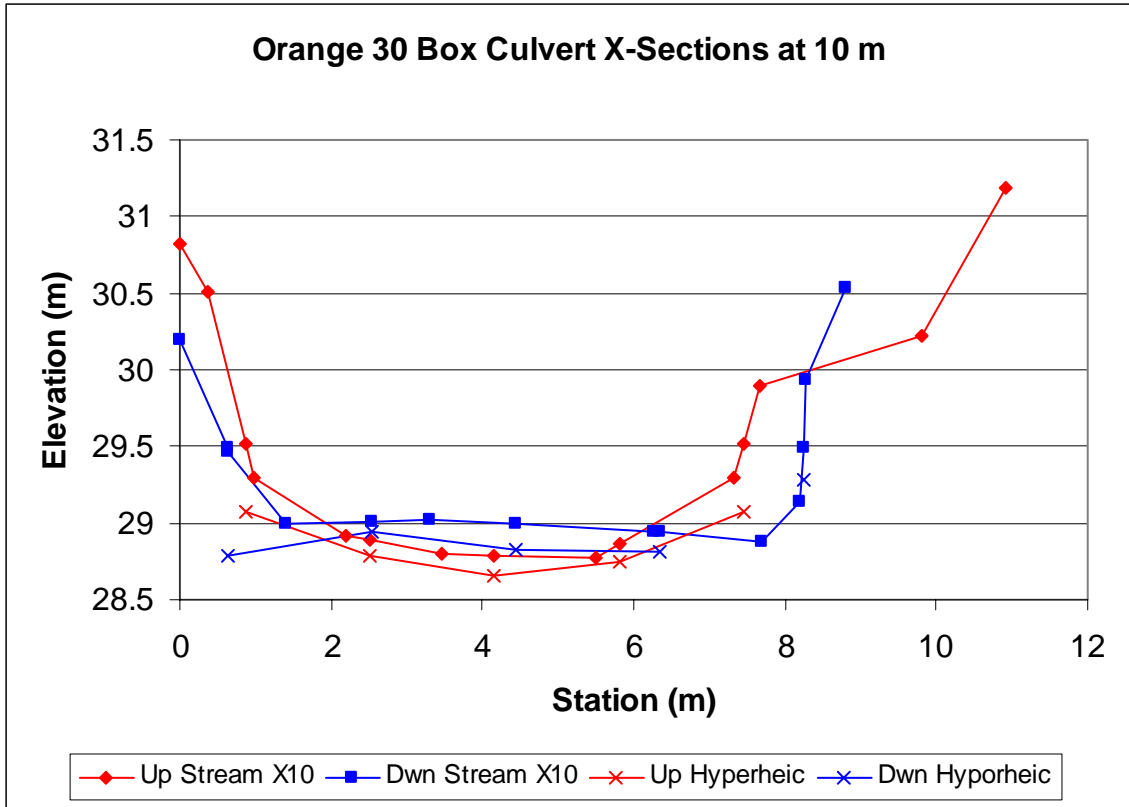


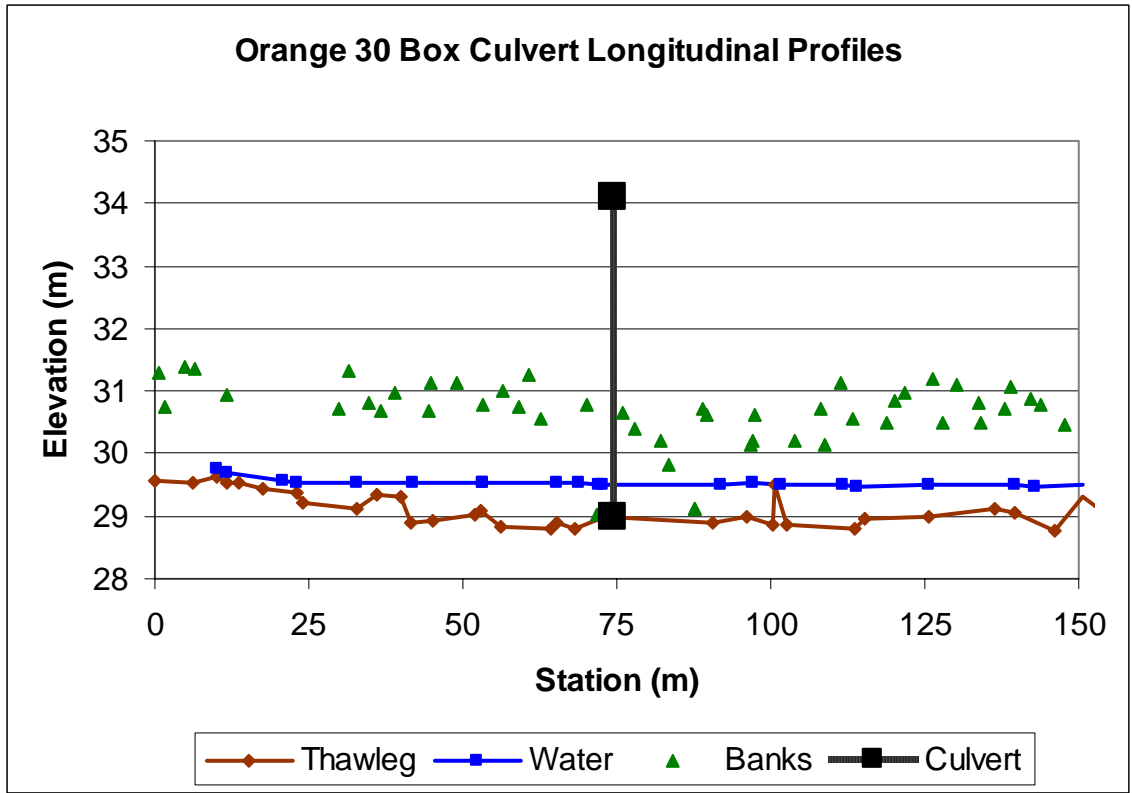
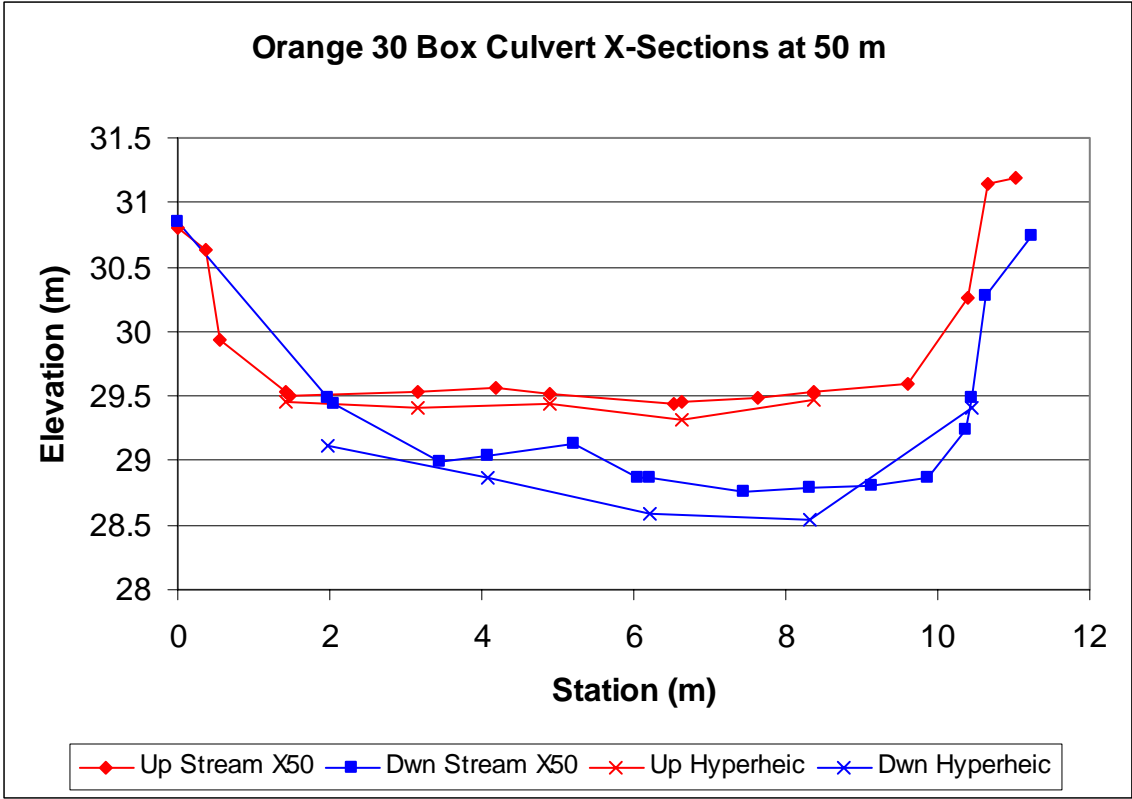
t0 t1 t2 t3 t4
b/g b/c s/c b/g /s



Orange 30 Cross Section, Longitudinal Profile, and Planar Graphs

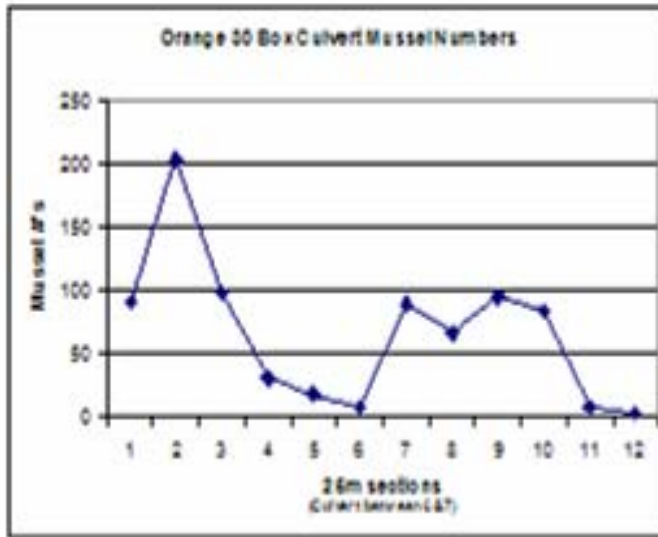






*Graph not to scale, please email author for originals.

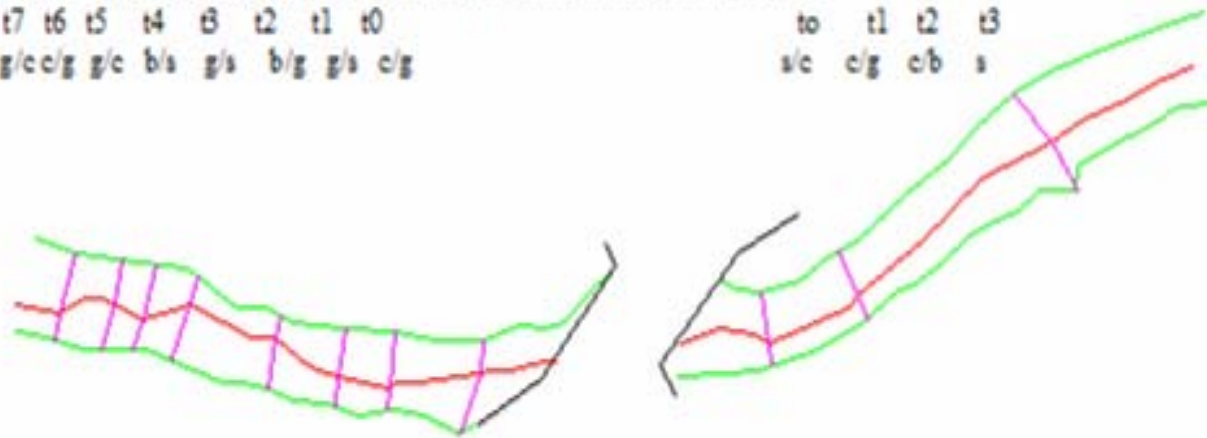
Orange 30 Box Culvert Planar View and Substrate Sections (1:480)



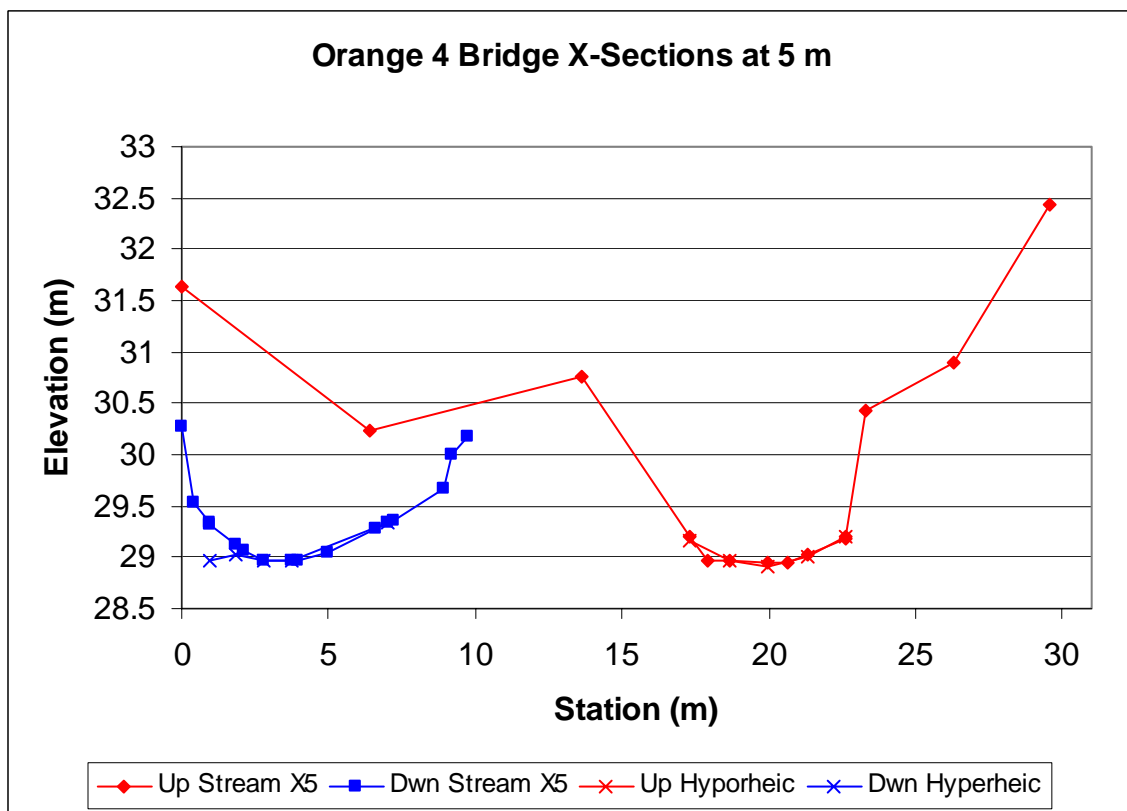
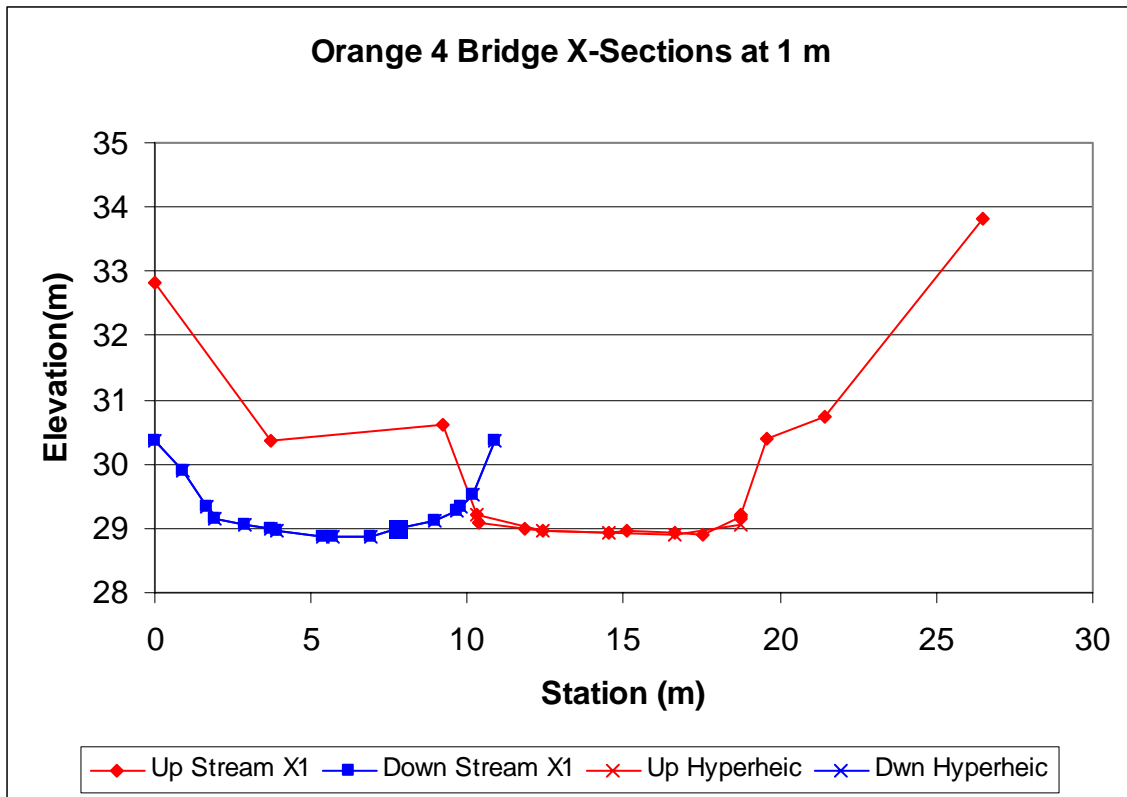
Field Notes: Bankfull being established on left bank below and in culvert, Sandy banks, undulations in longitudinal profile due to bedrock under sand, methane, anaerobic conditions

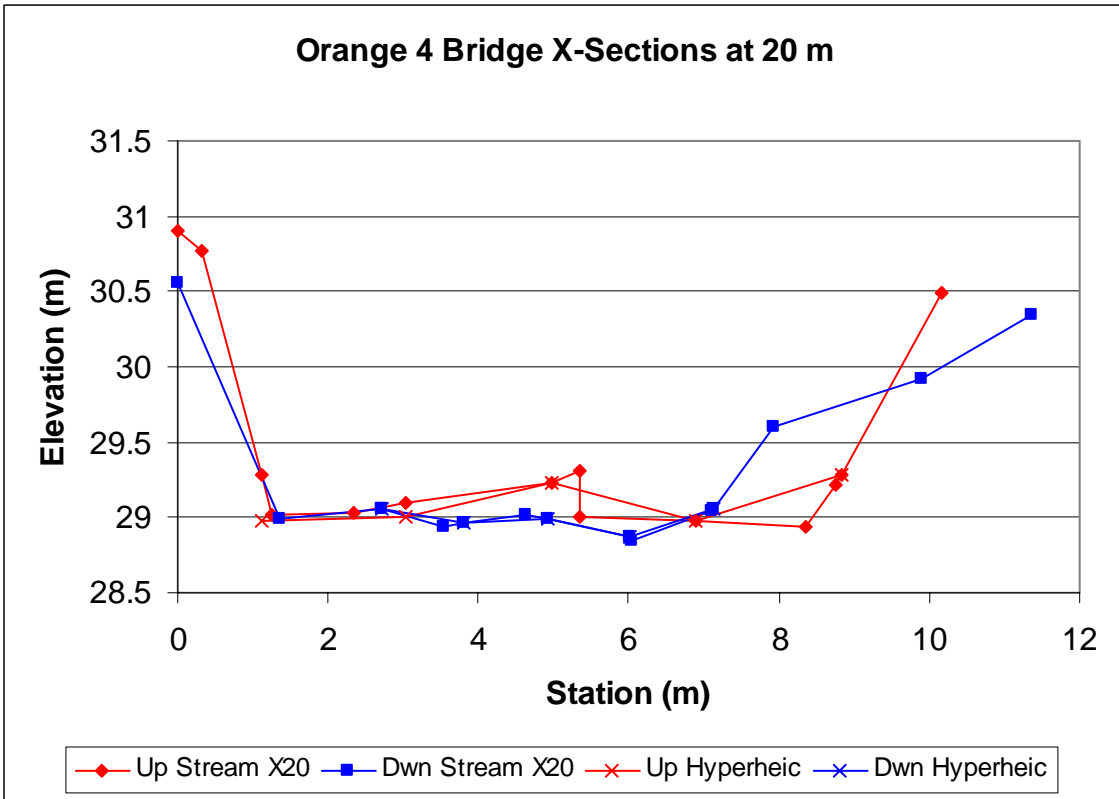
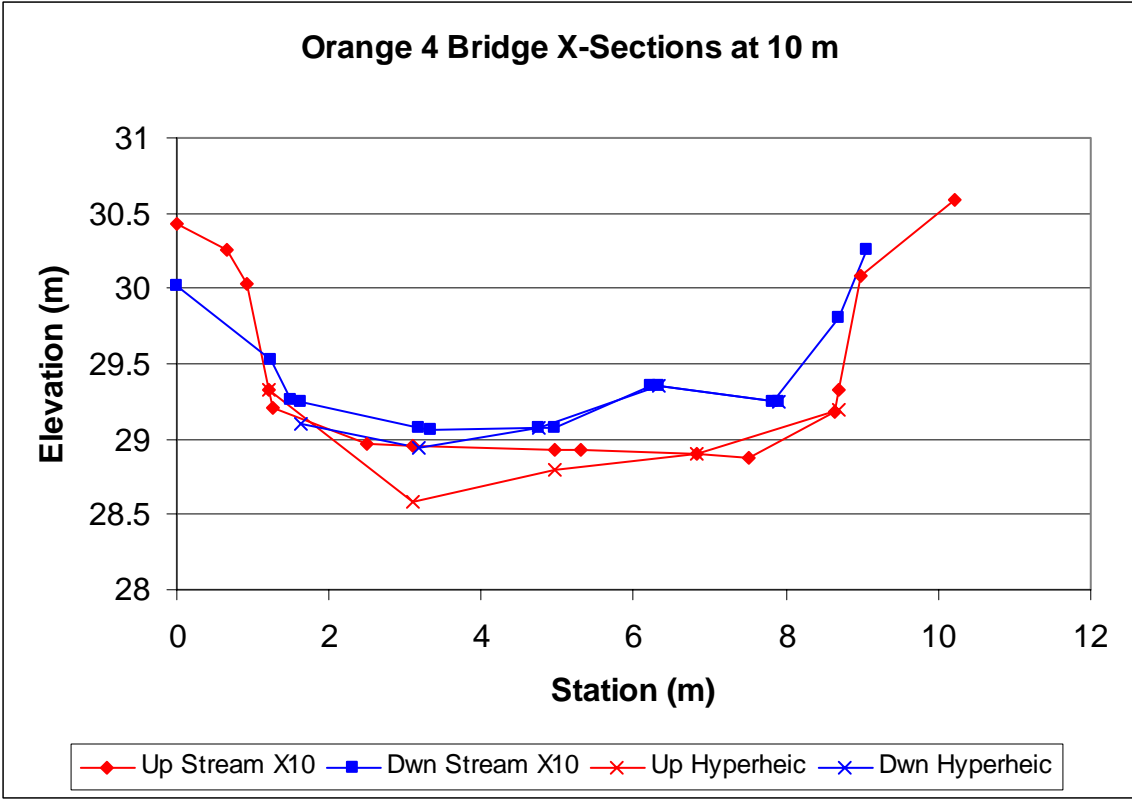
t8 t7 t6 t5 t4 t3 t2 t1 t0
g/b g/c c/g g/c b/s g/s b/g g/s c/g

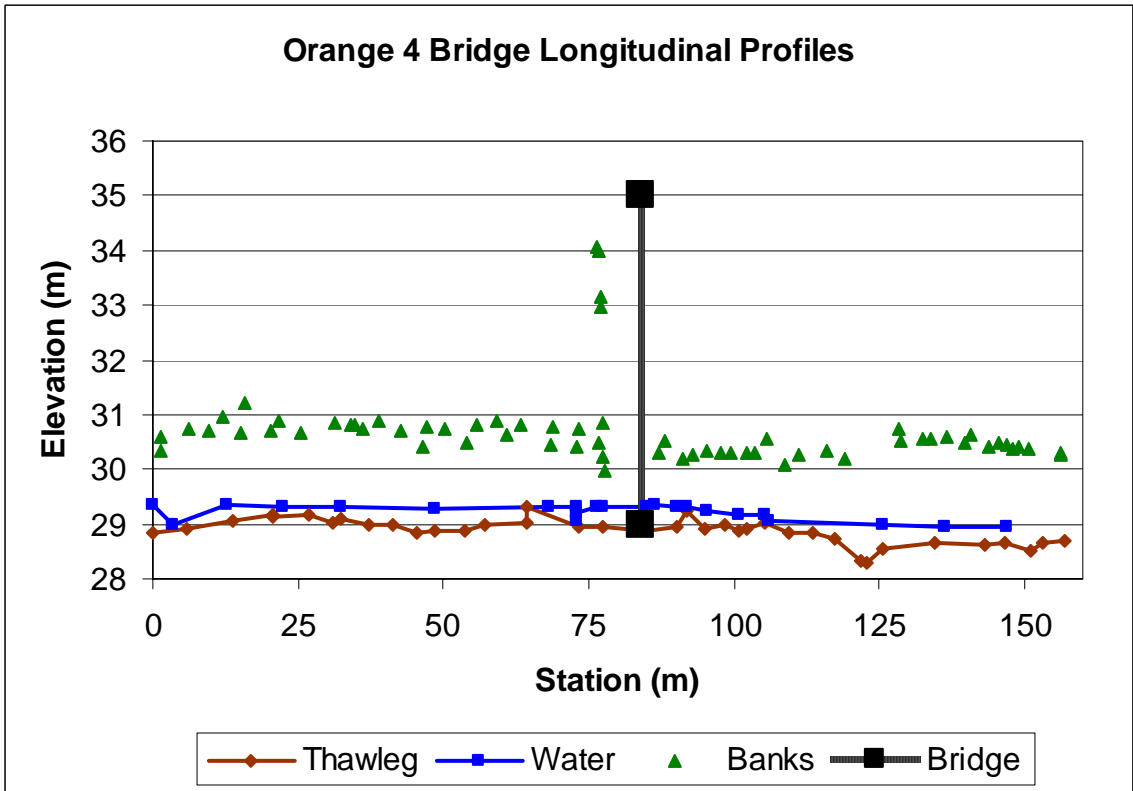
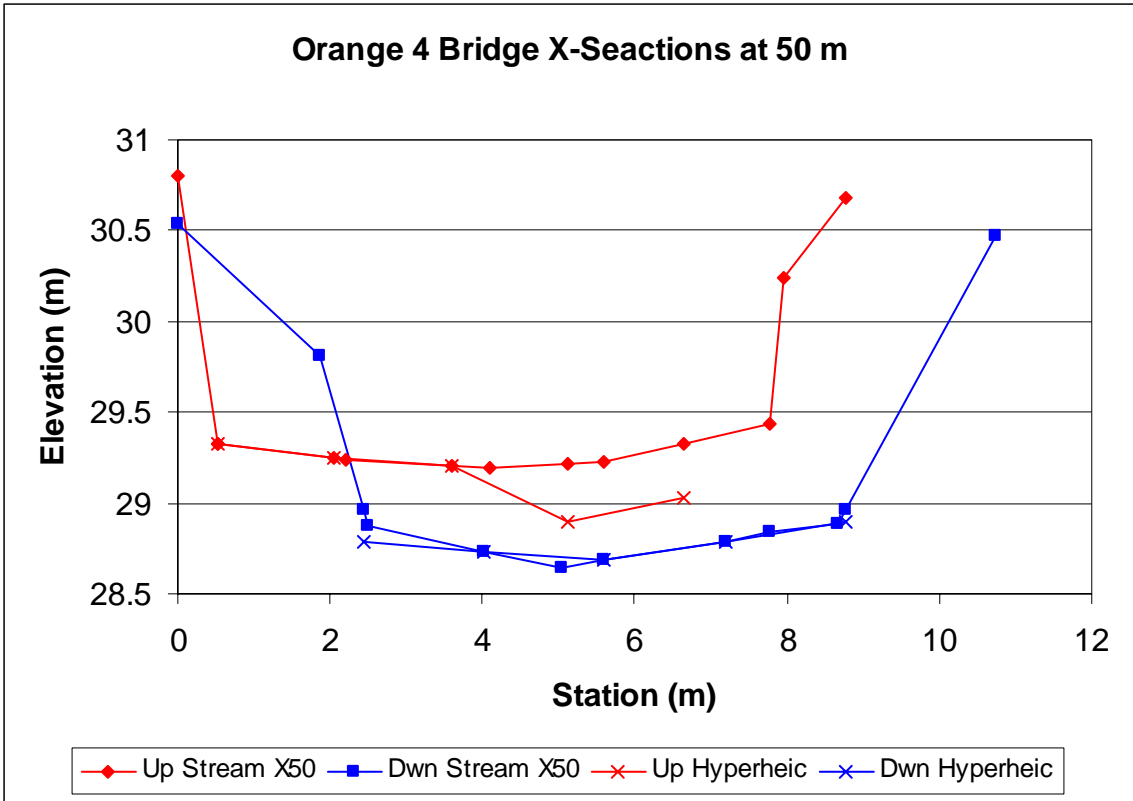
t0 t1 t2 t3
s/c c/g c/b s



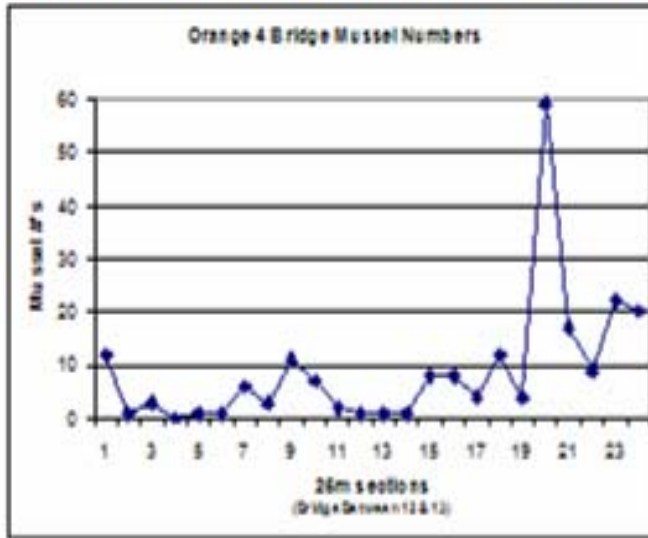
Orange 4 Cross Section, Longitudinal Profile, and Planar Graphs







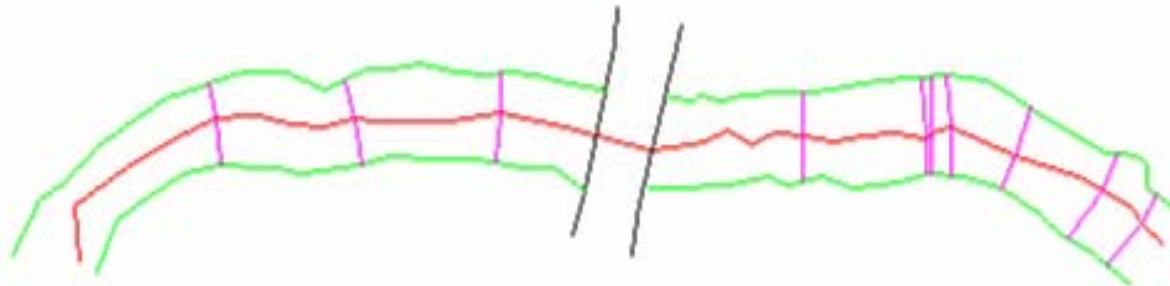
Orange 4 Bridge Planar View and Substrate Sections (1:480)



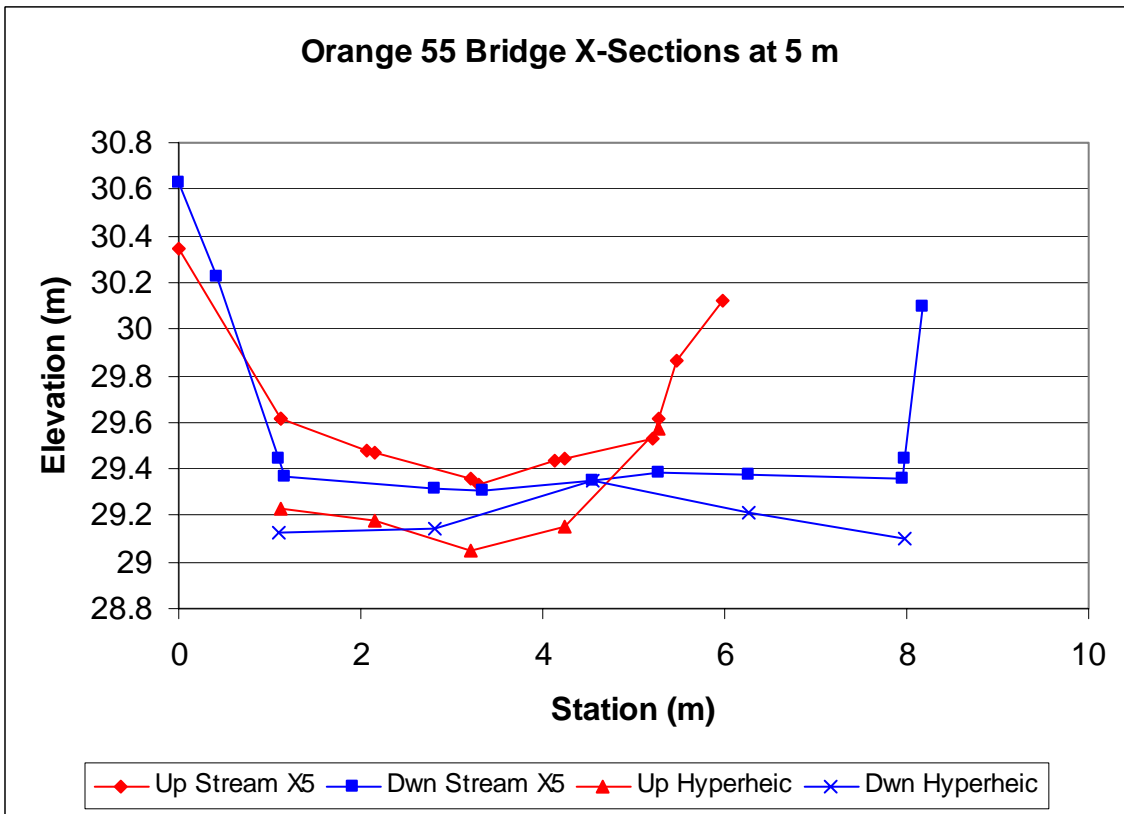
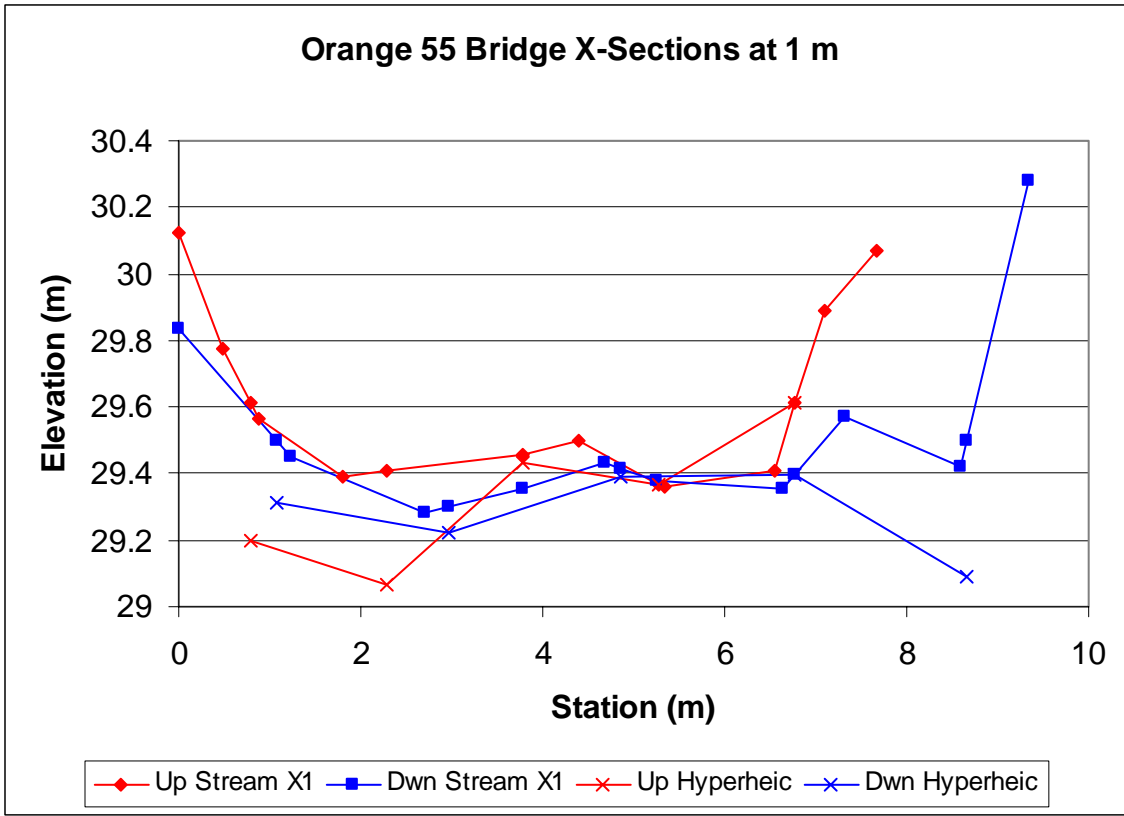
Field Notes: Riffles due to bedrock outcrops, sand and gravel edges on turns, mud banks on straight sections, bankfull indicators forming.

t3 t2 t1 t0
b/g b/s b/c b

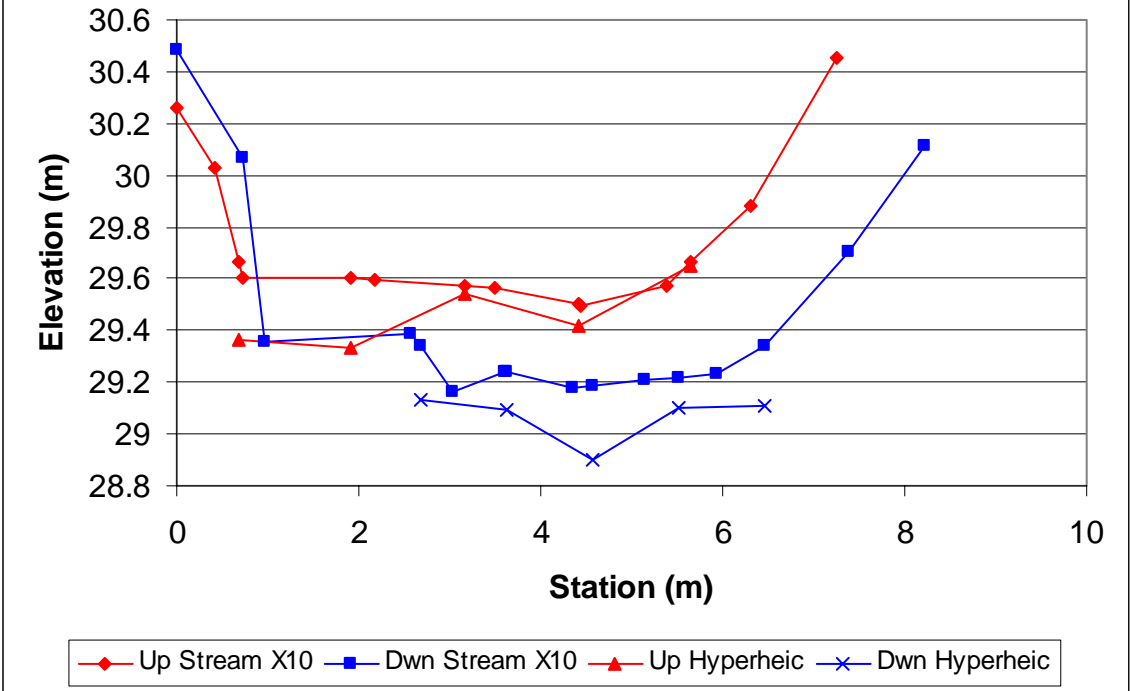
t0 t1 t2 t3 t4 t5 t6
b/g b/c b/g b b/g b/s b



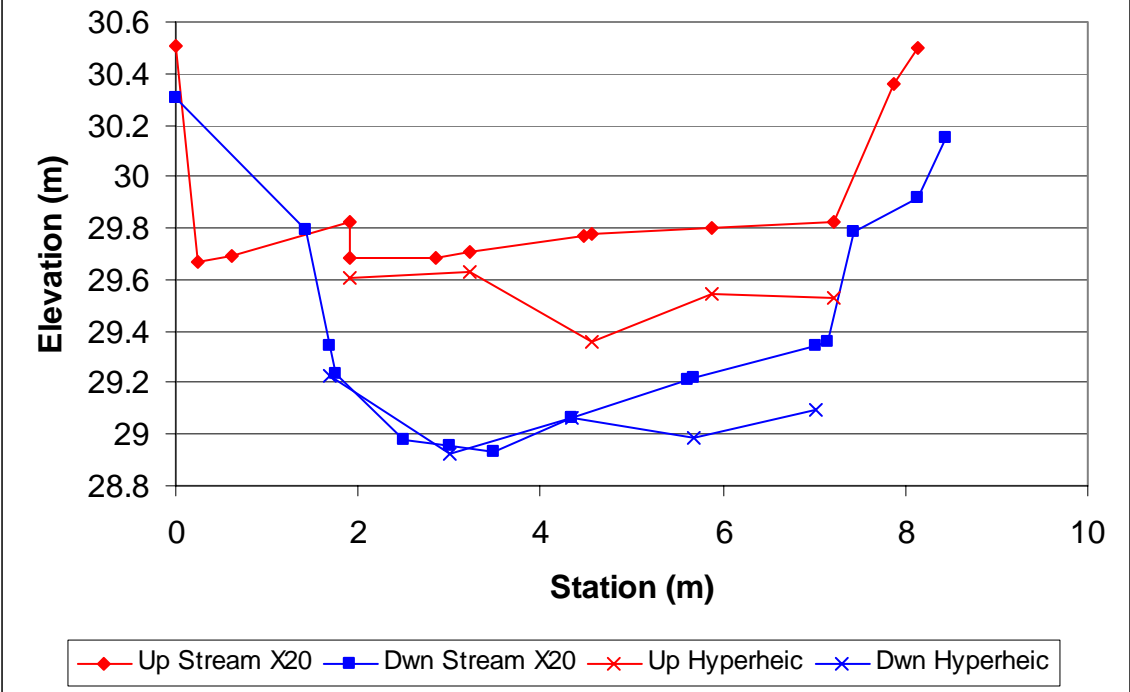
Orange 55 Cross Section, Longitudinal Profile, and Planar Graphs

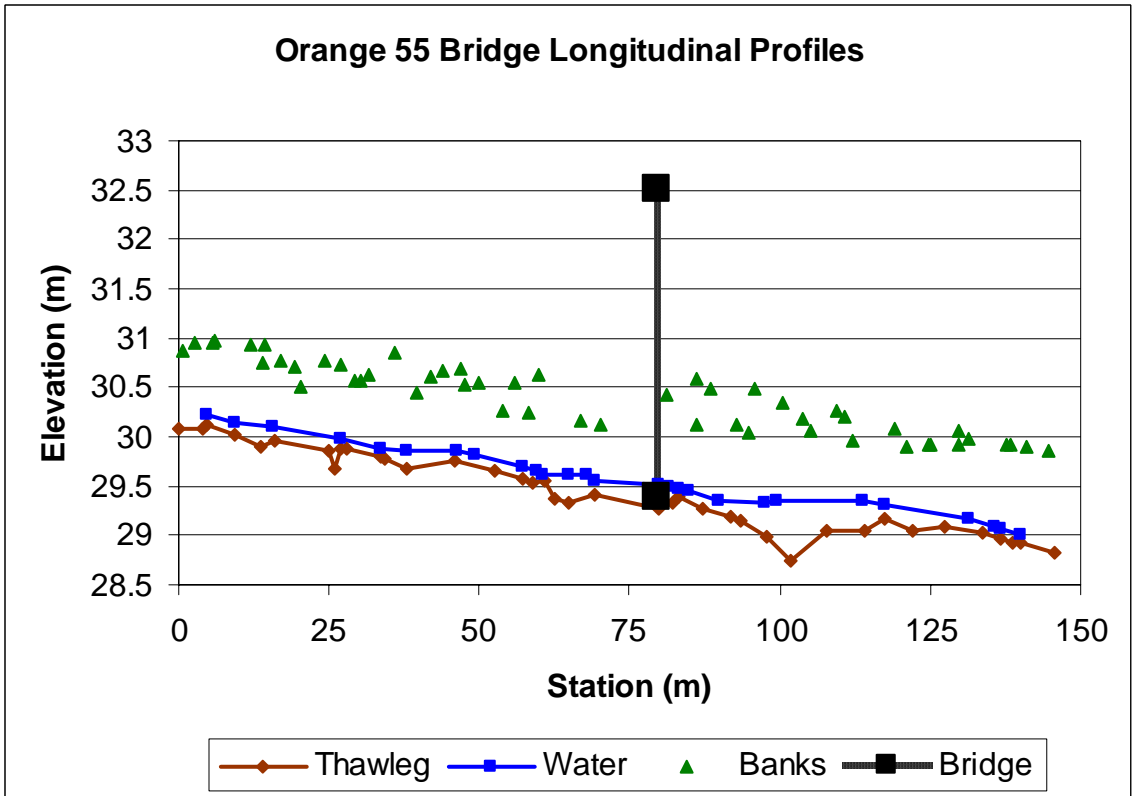
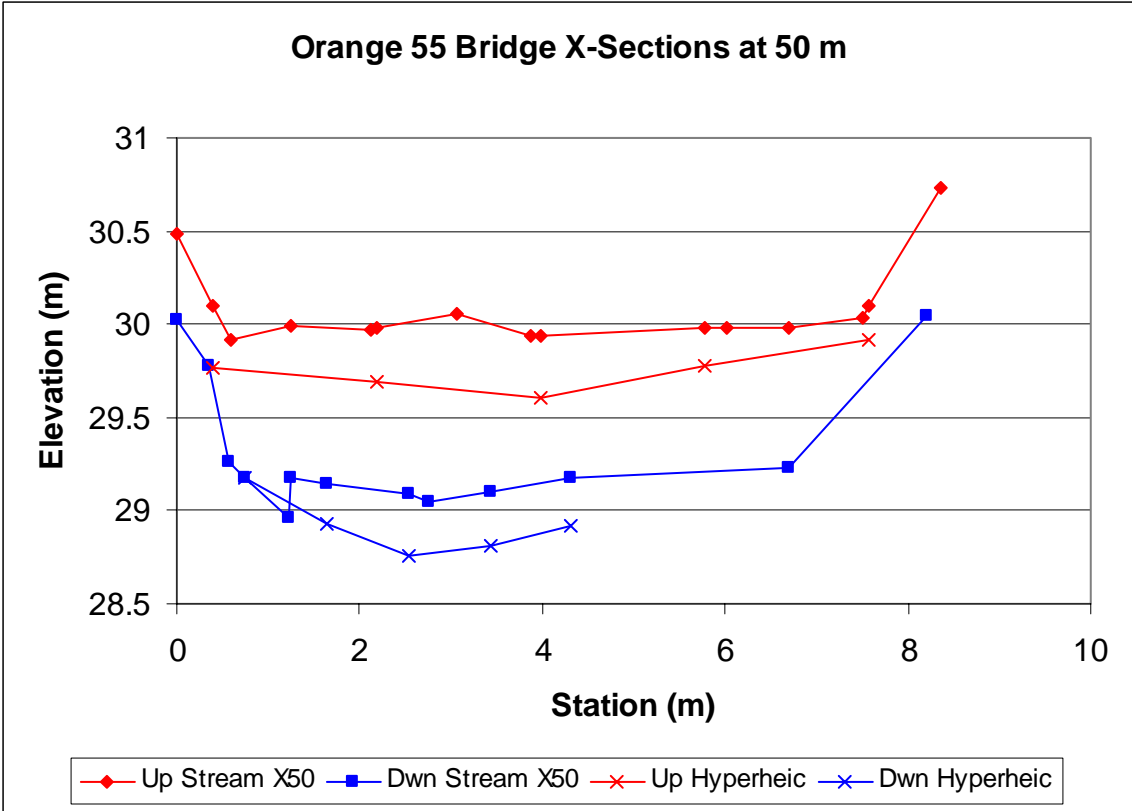


Orange 55 Bridge X-Sections at 10 m

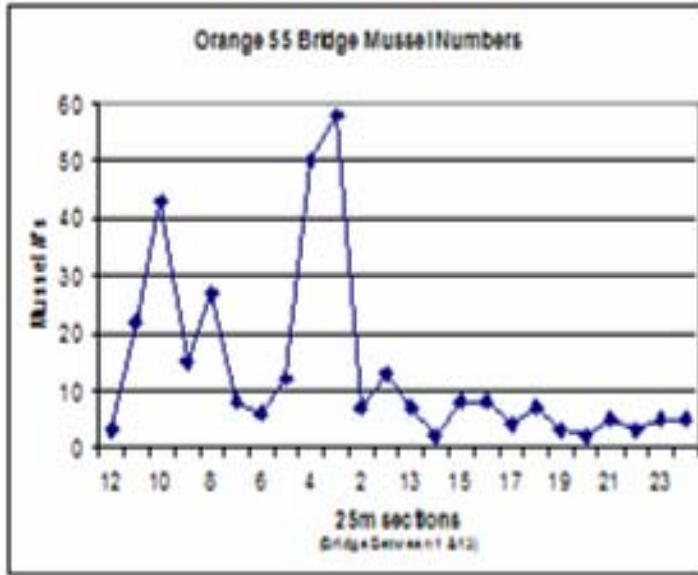


Orange 55 Bridge X-Sections at 20 m





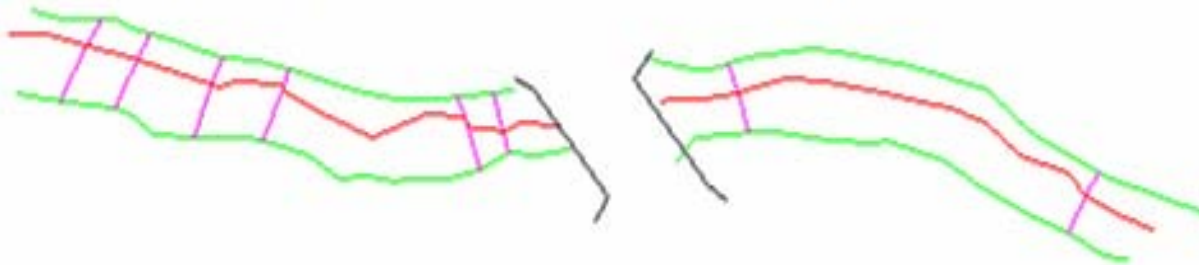
Orange 55 Bridge Planar View and Substrate Sections (1:480)



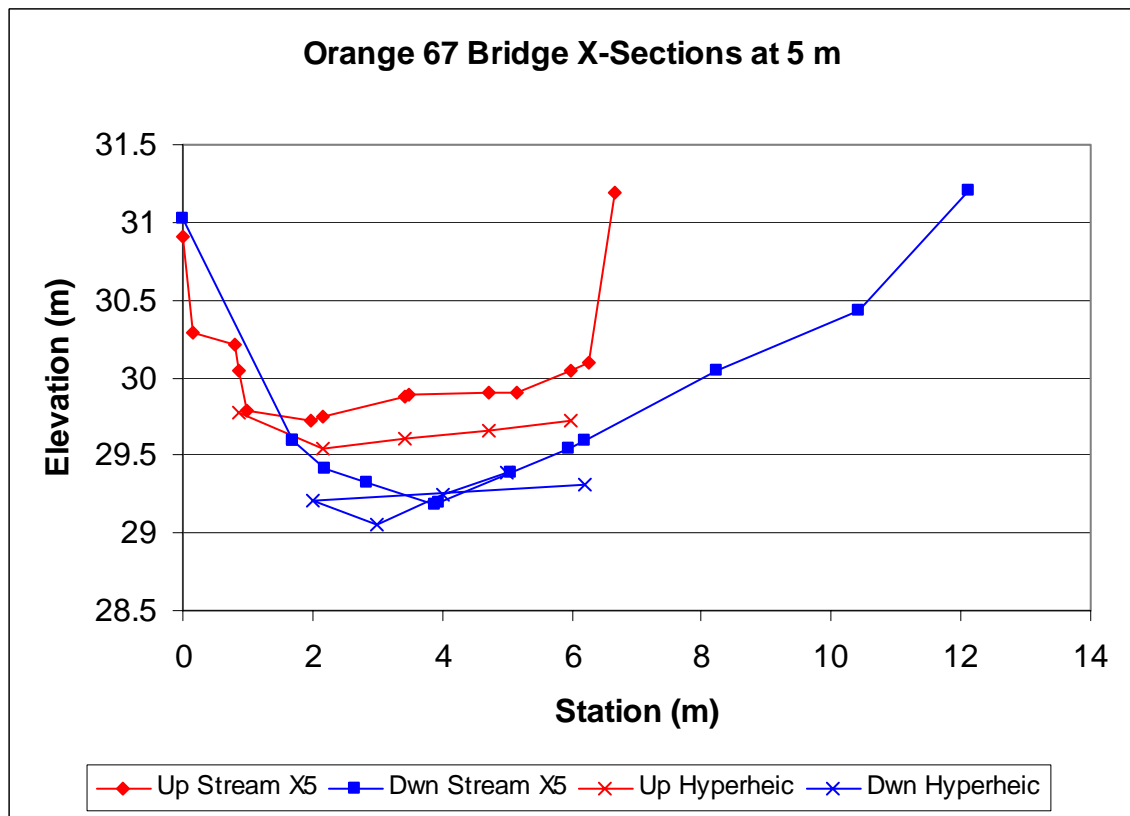
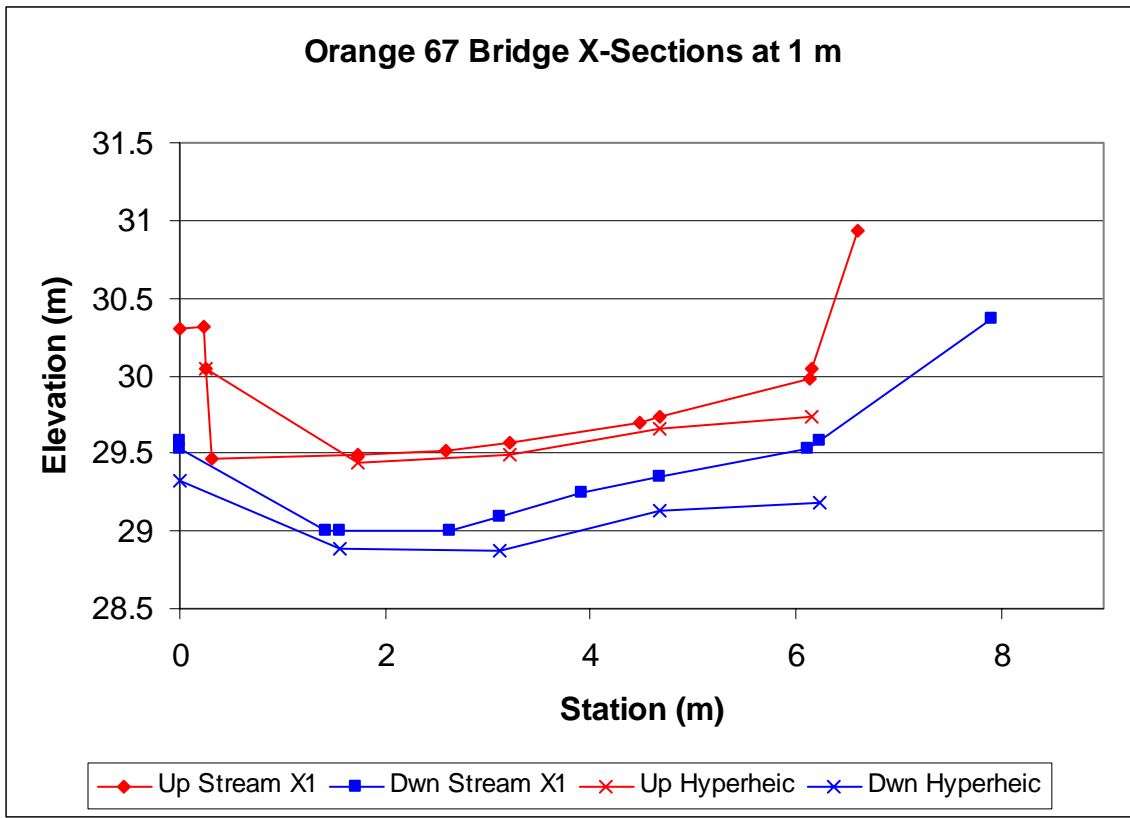
Field Note: Small gravel pockets behind boulders

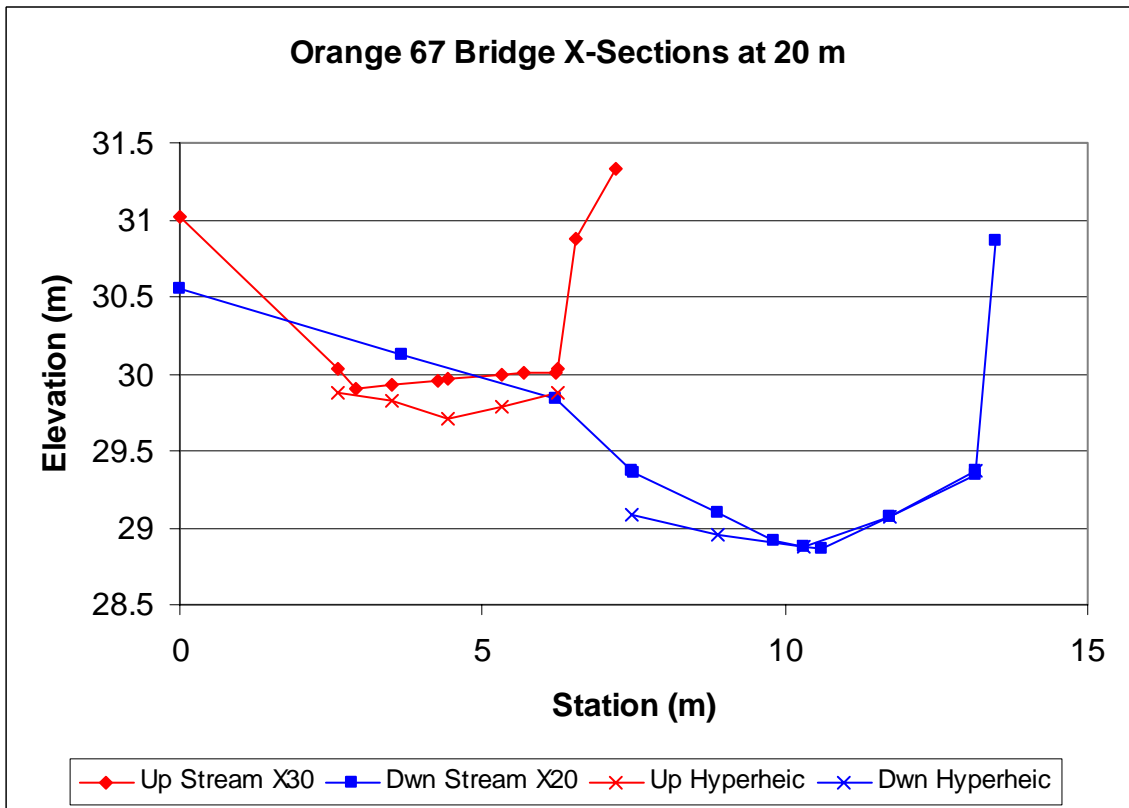
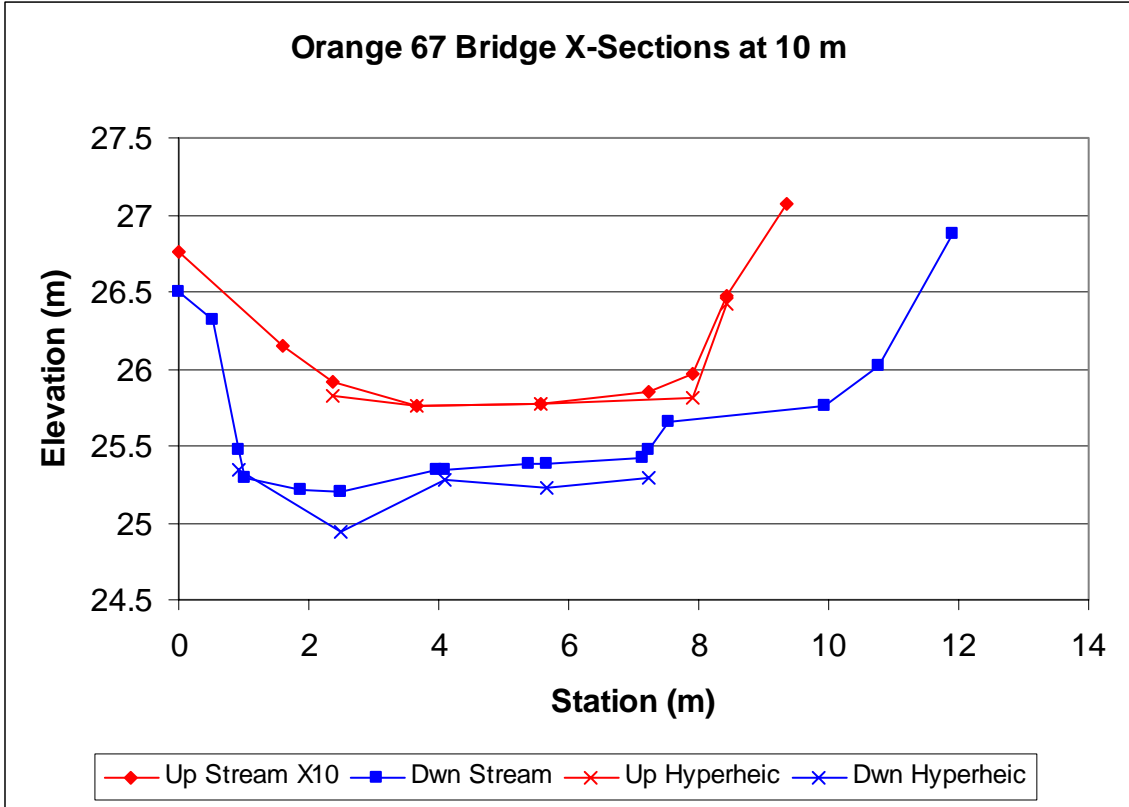
t7 t6 t5 t4 t3 t2 t1 t0
 c c/g c g/c c c/g c c/b

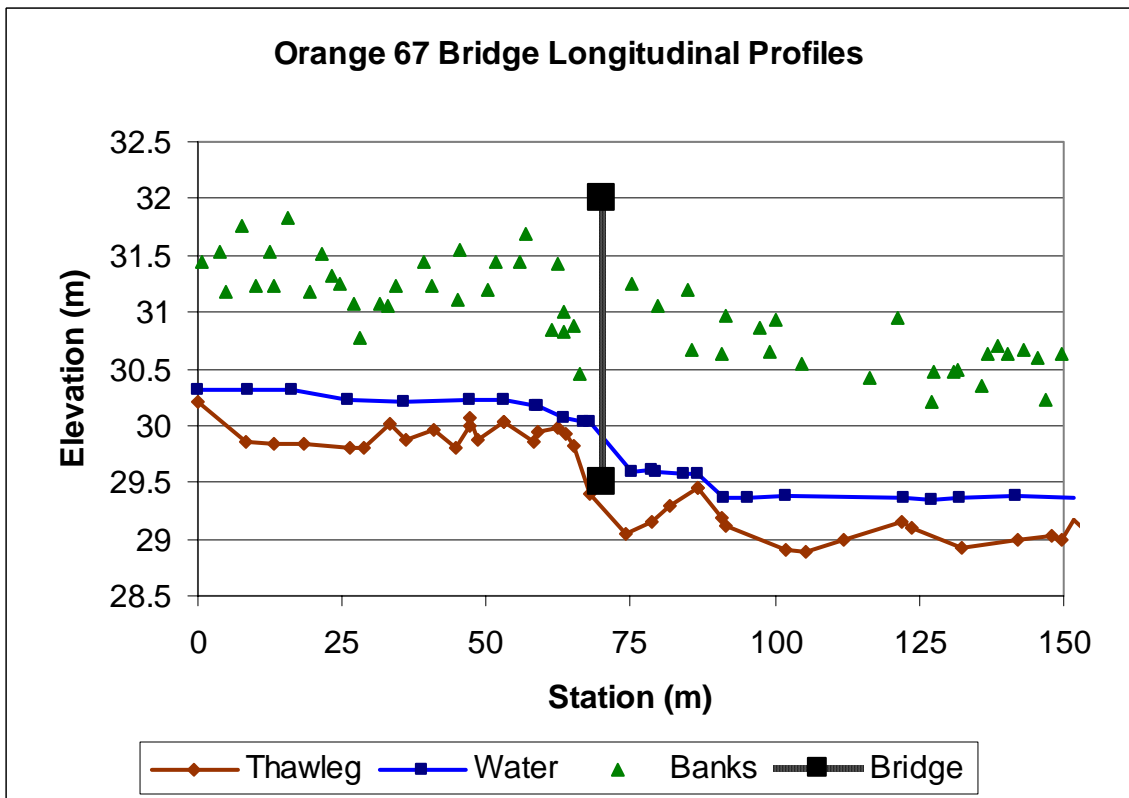
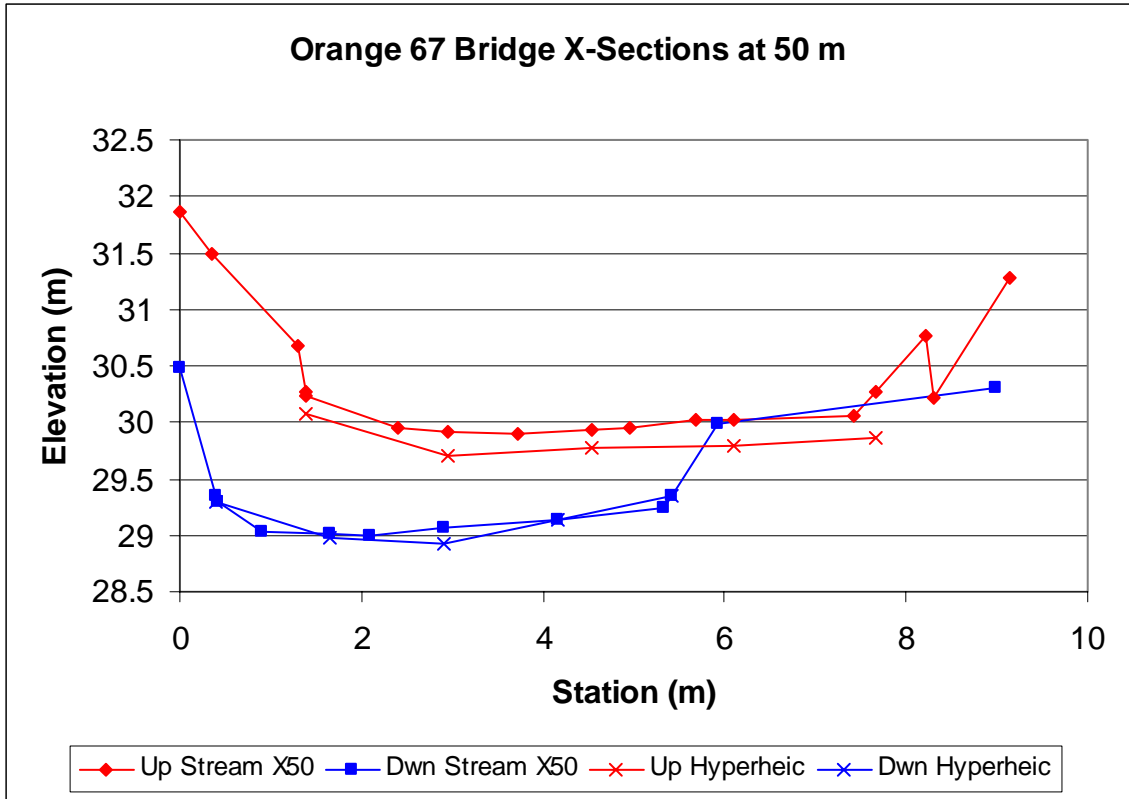
t0 t1 t2
 c/b c c/g



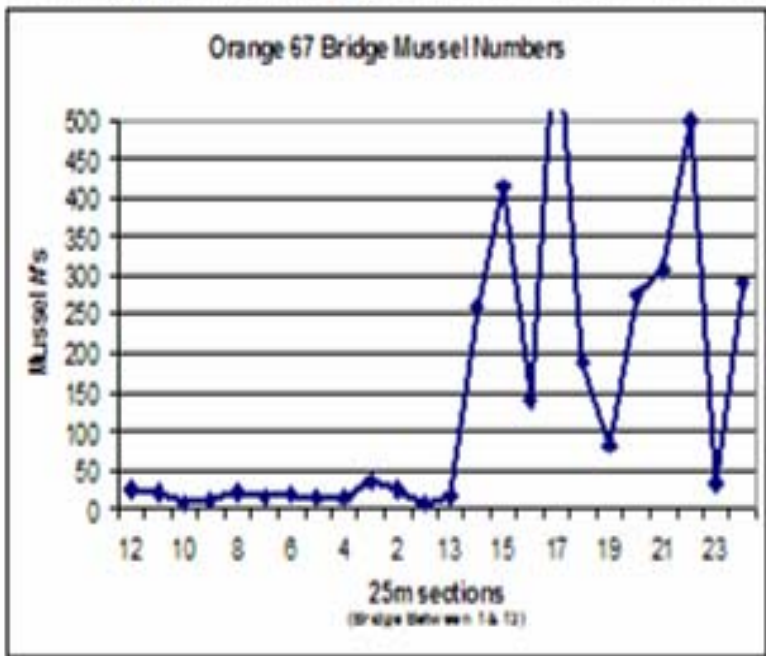
Orange 67 Cross Section, Longitudinal Profile, and Planar Graphs



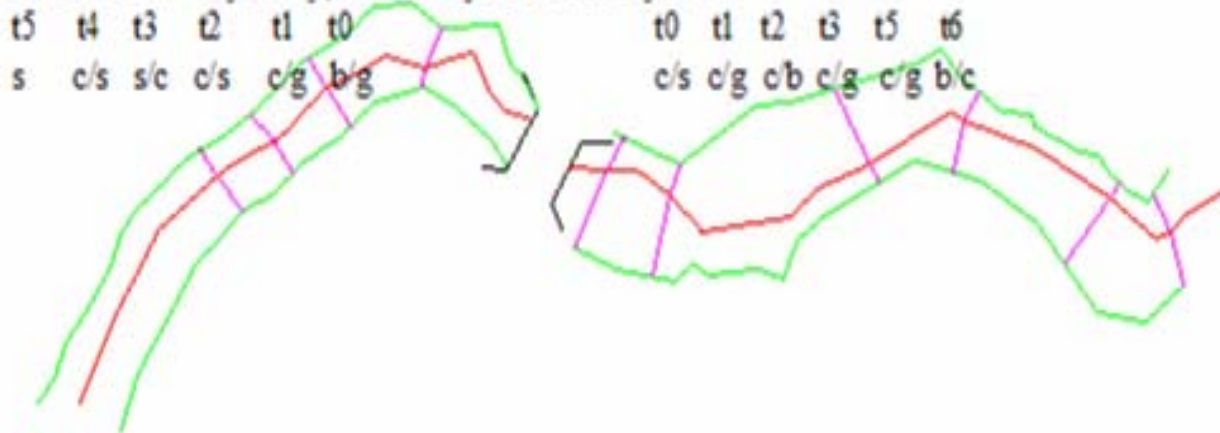




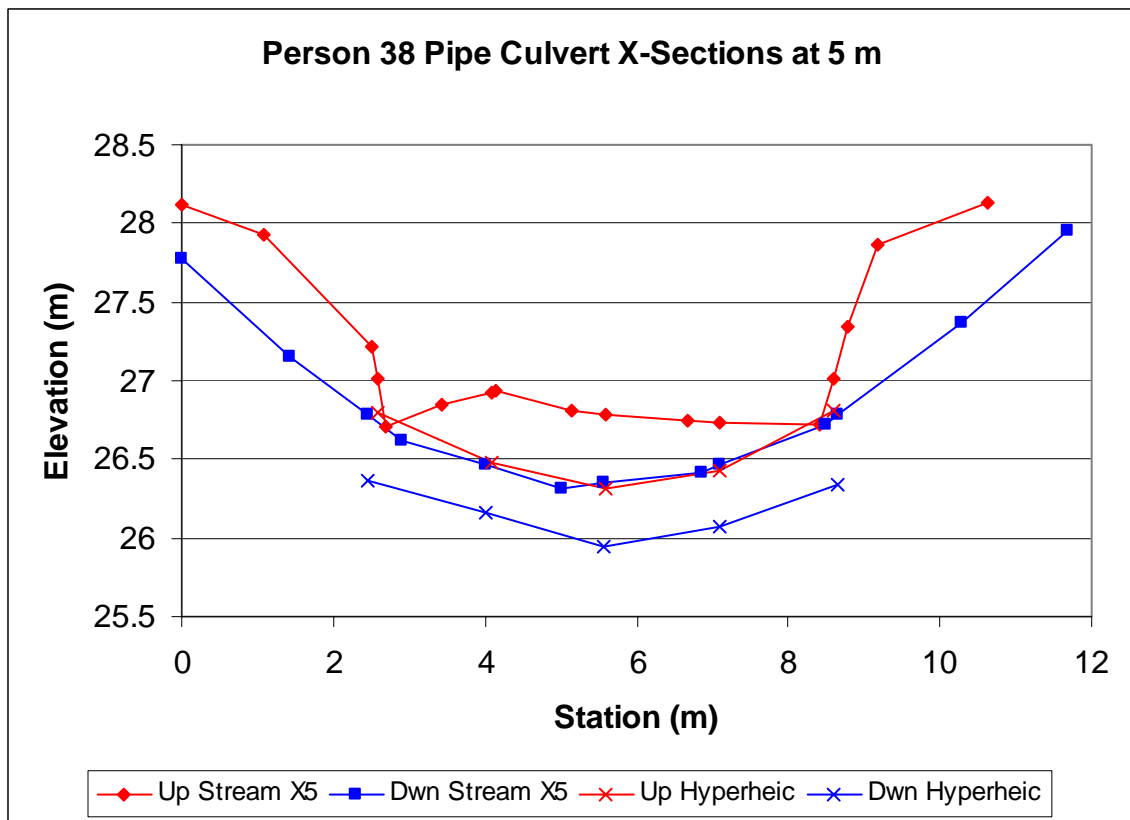
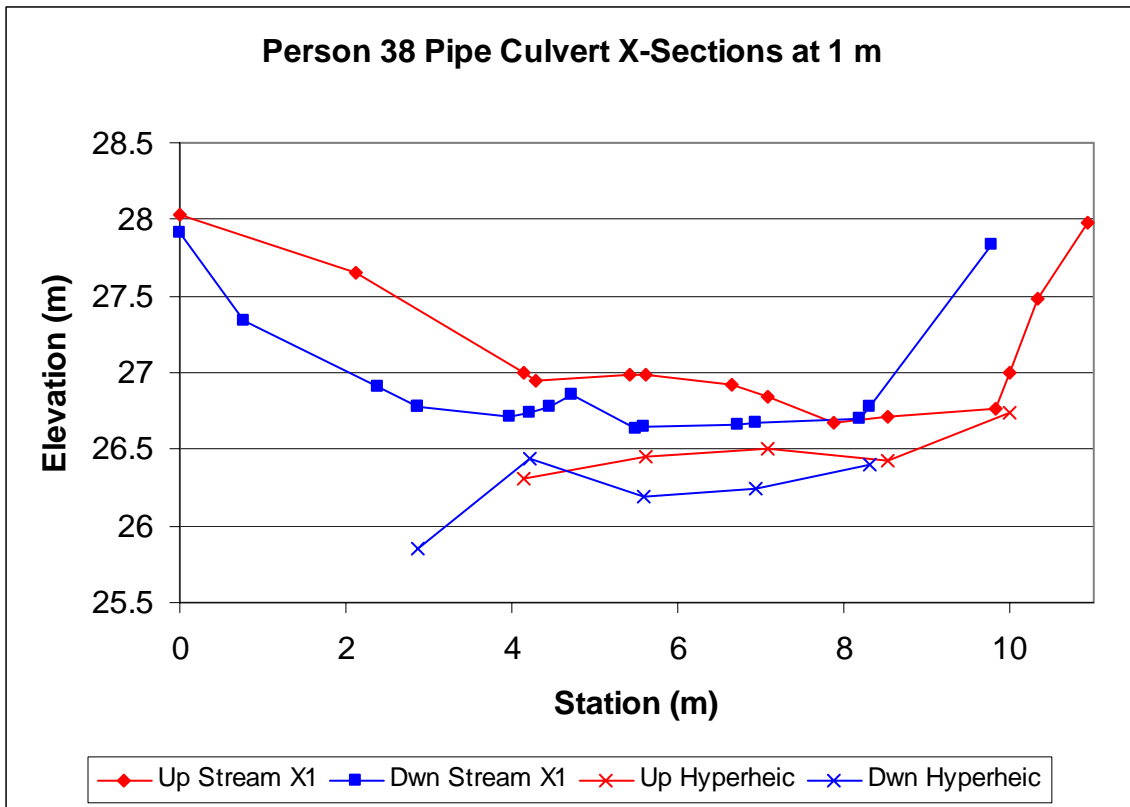
Orange 67 Bridge Planar View and Substrate Sections (1:480)

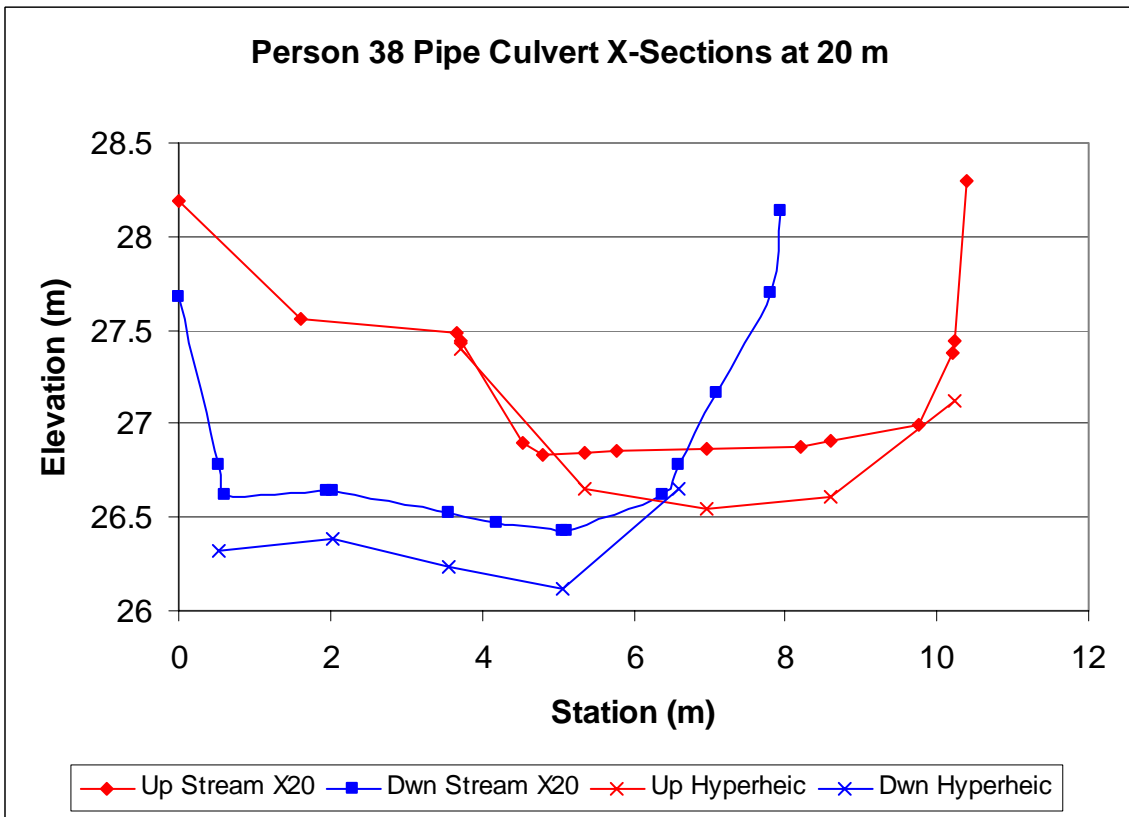
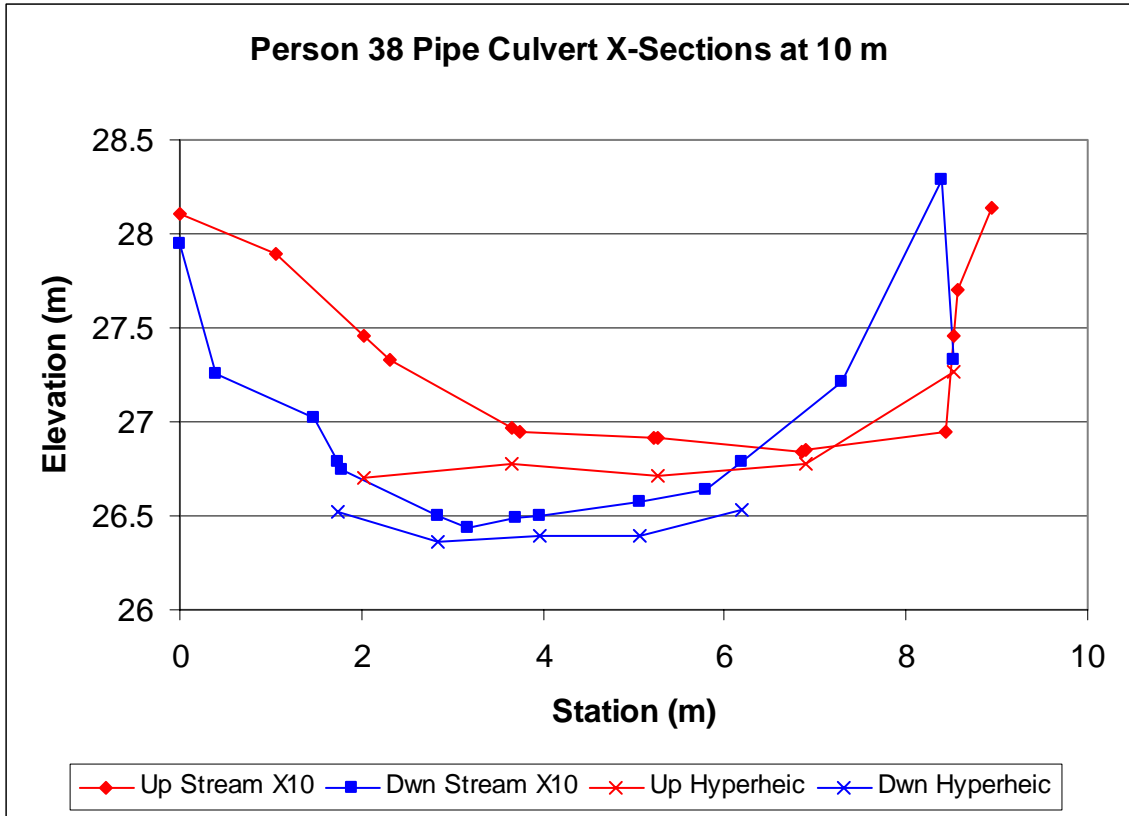


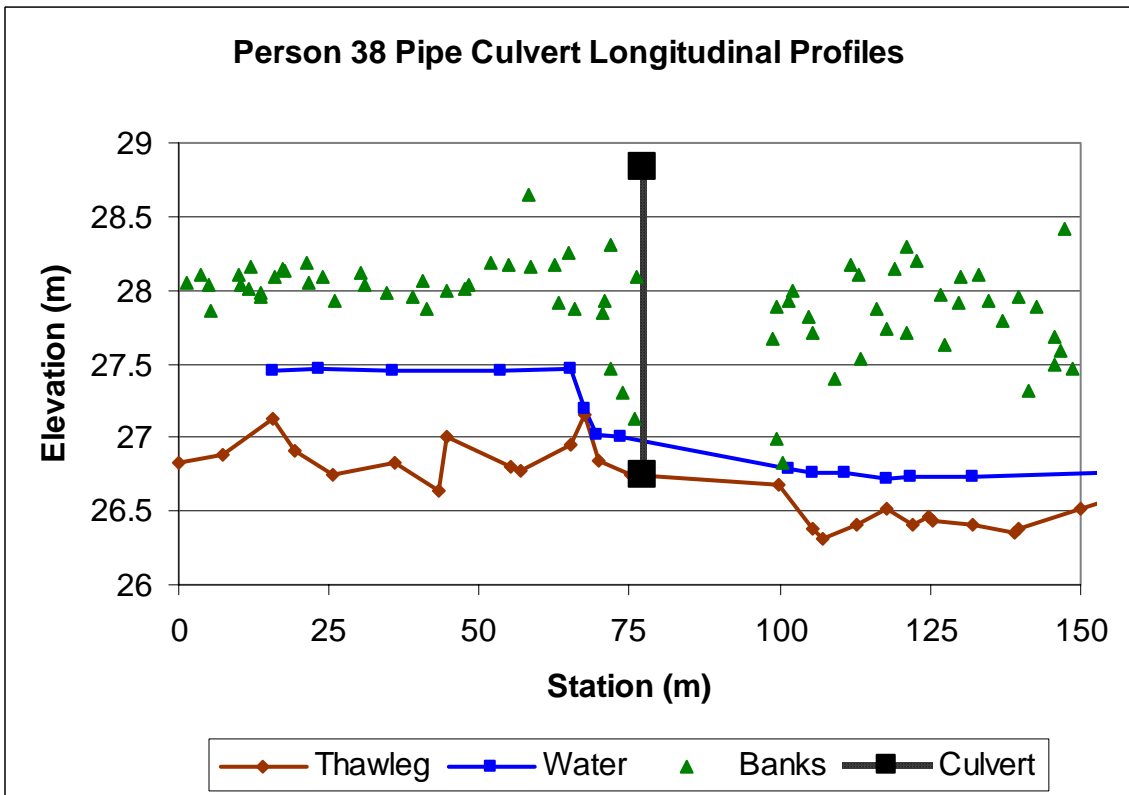
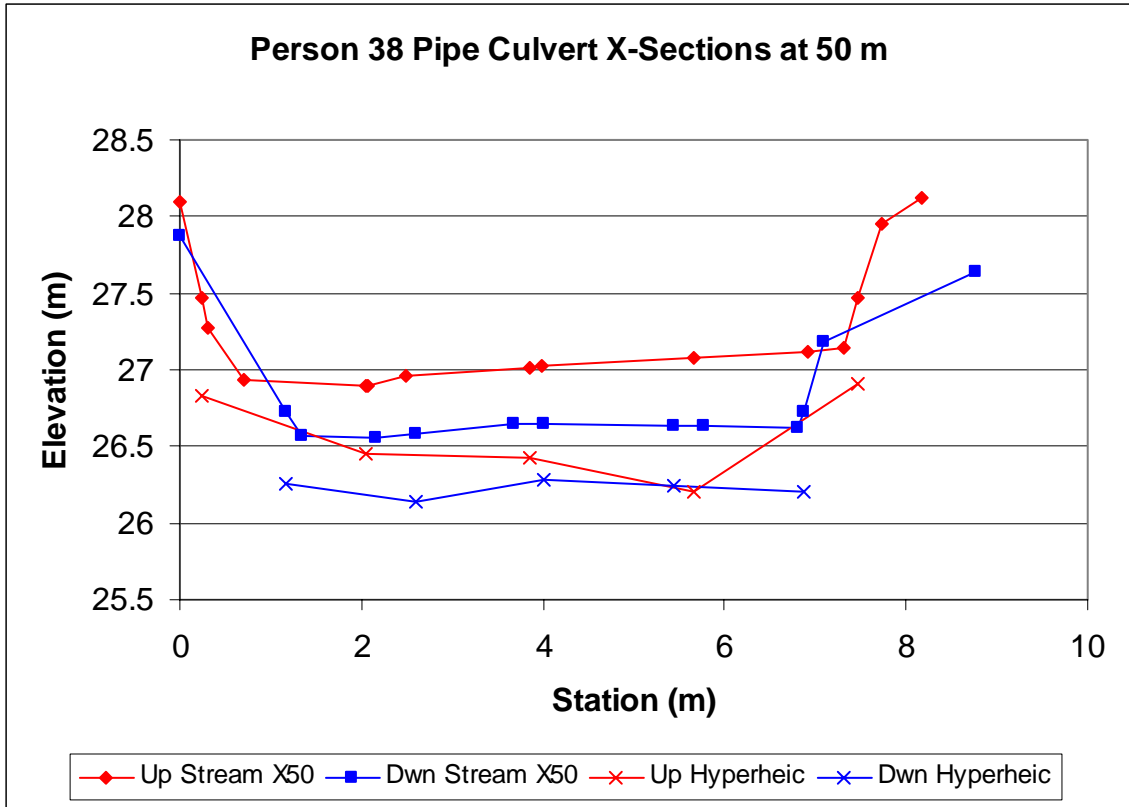
Field Notes: Very sandy, riffles may be buried by sand



Person 38 Cross Sections, Longitudinal Profile, and Planar Graphs

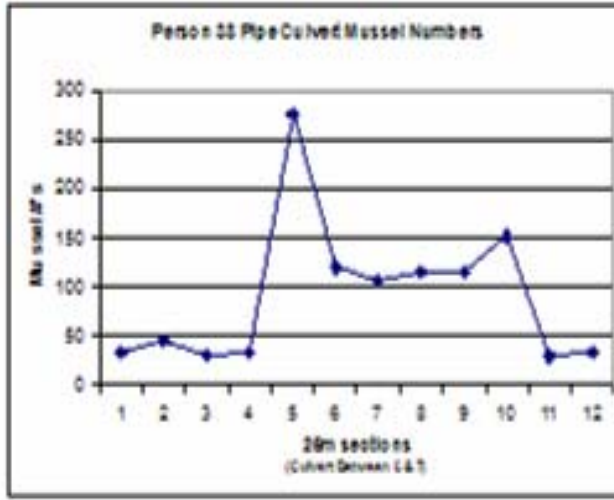






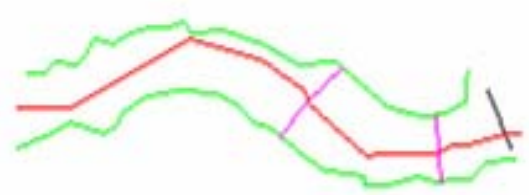
*Graph not to scale, please email author for originals.

Person 38 Pipe Culvert Planar View and Substrate Sections (1:480)

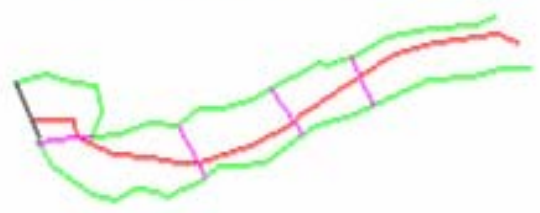


Field Notes: Sand forming bankfull indicators

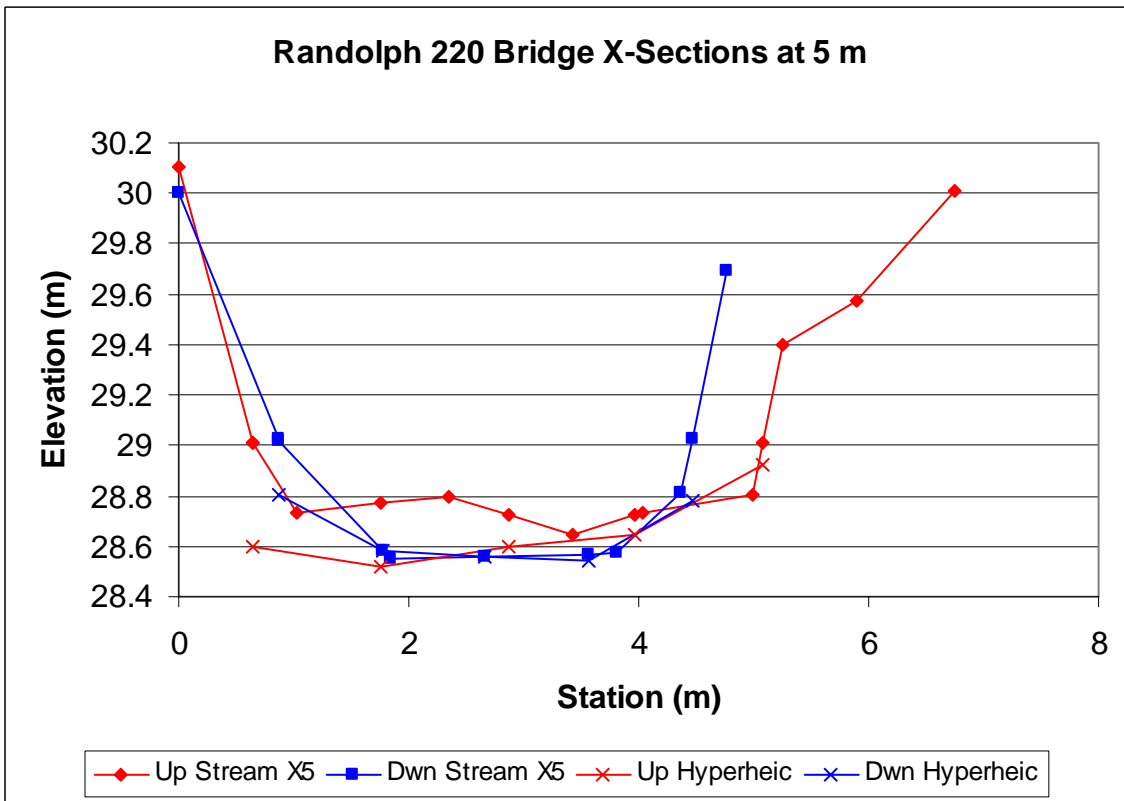
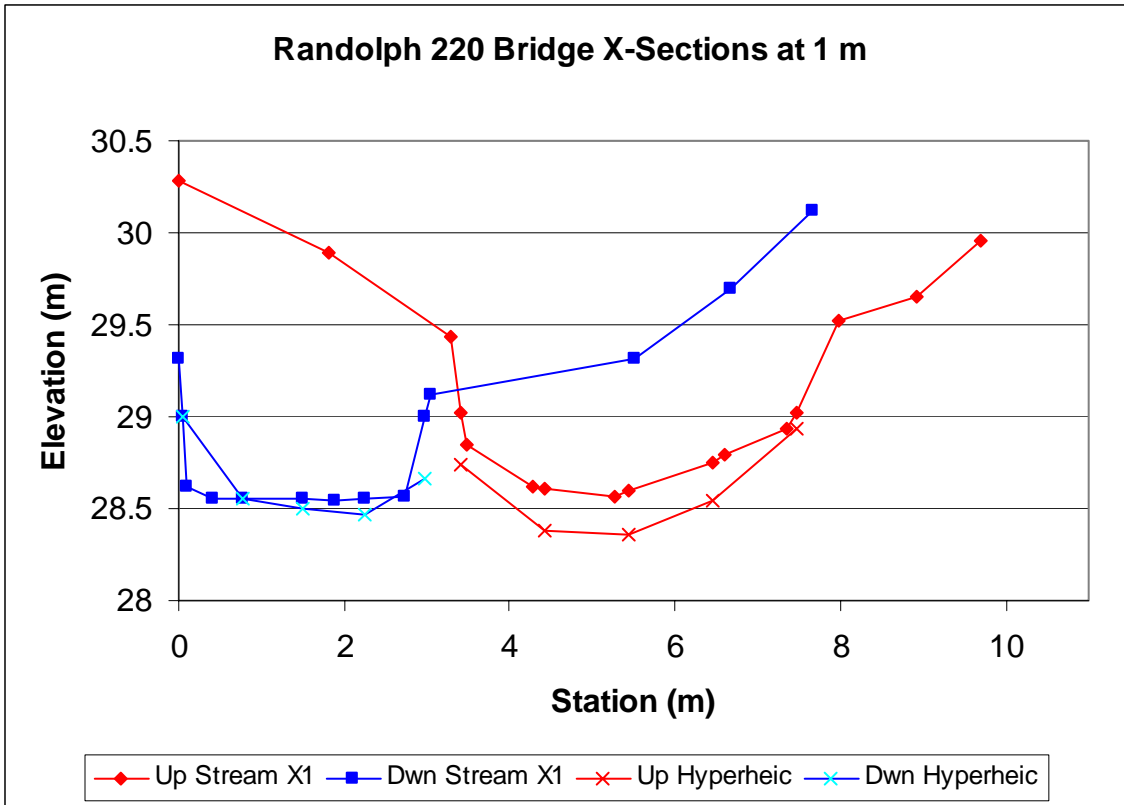
t2 t1 t0
g/s g/c c/g

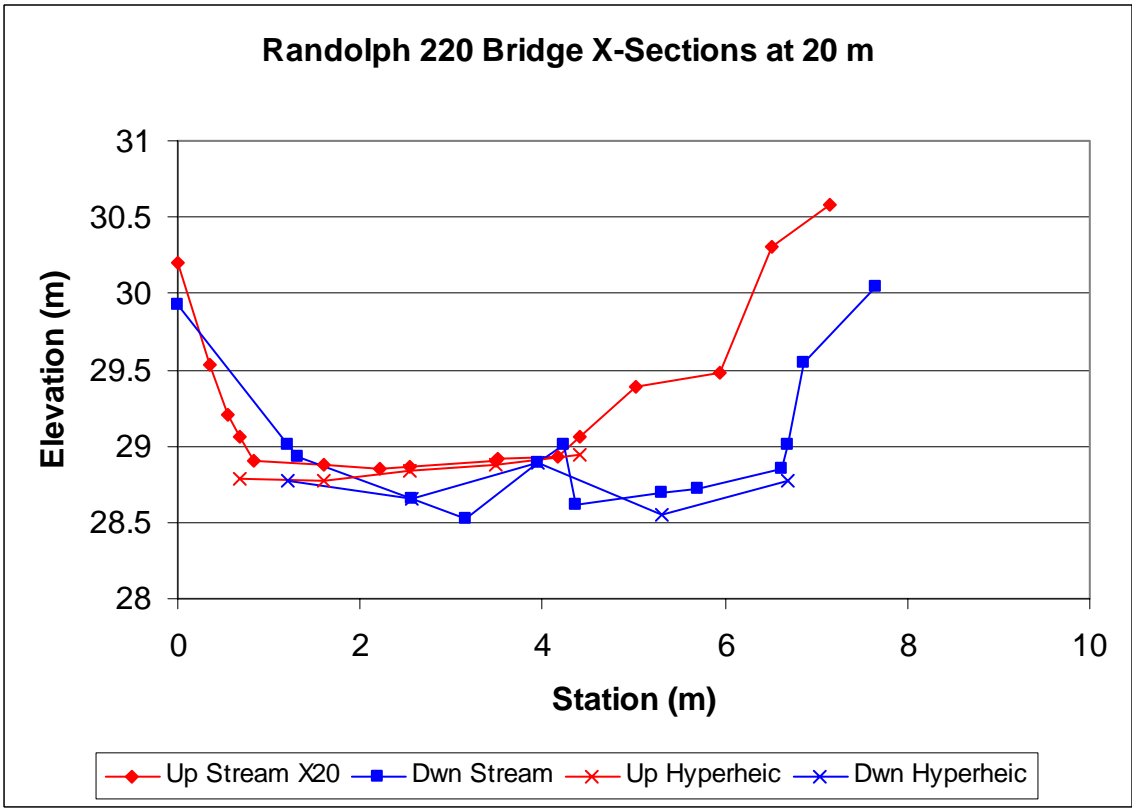
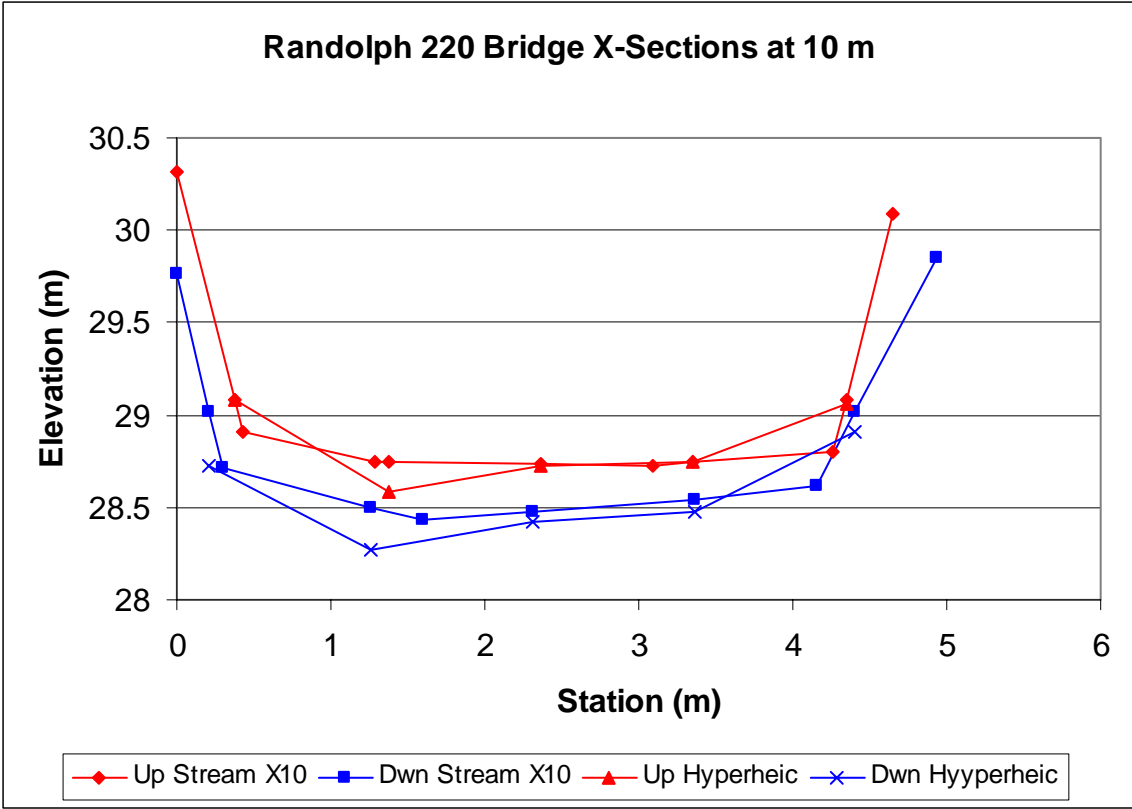


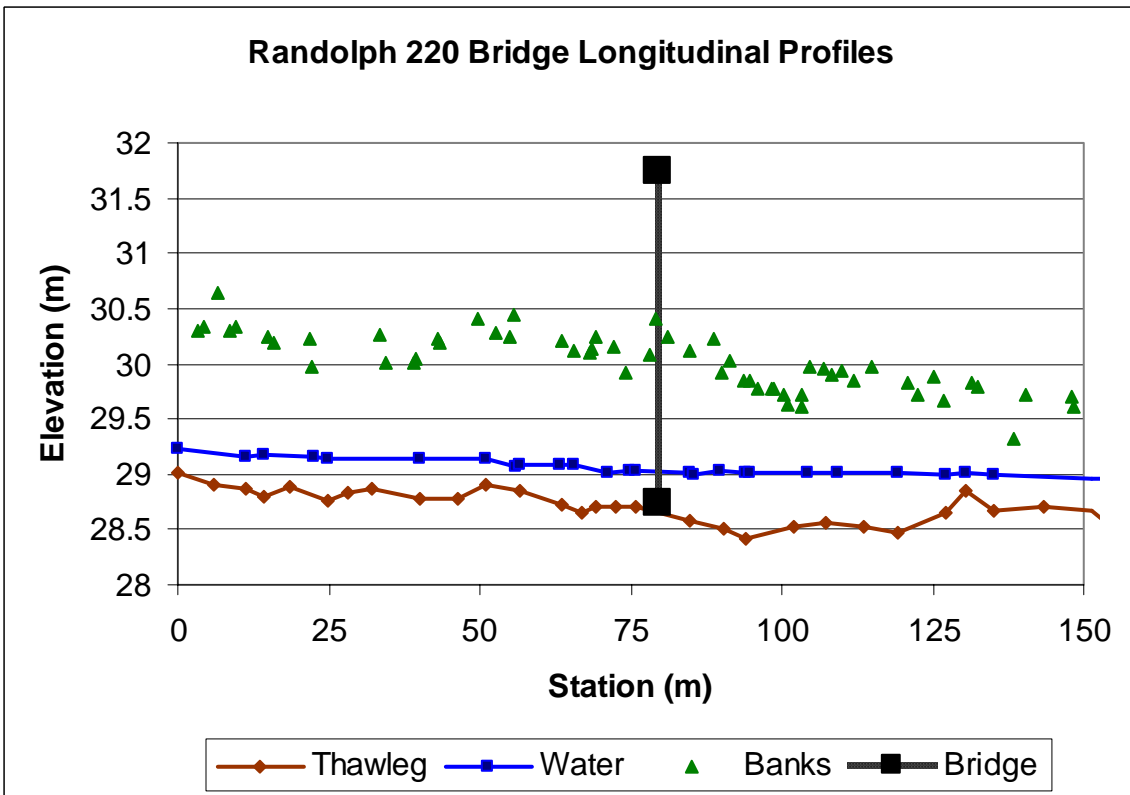
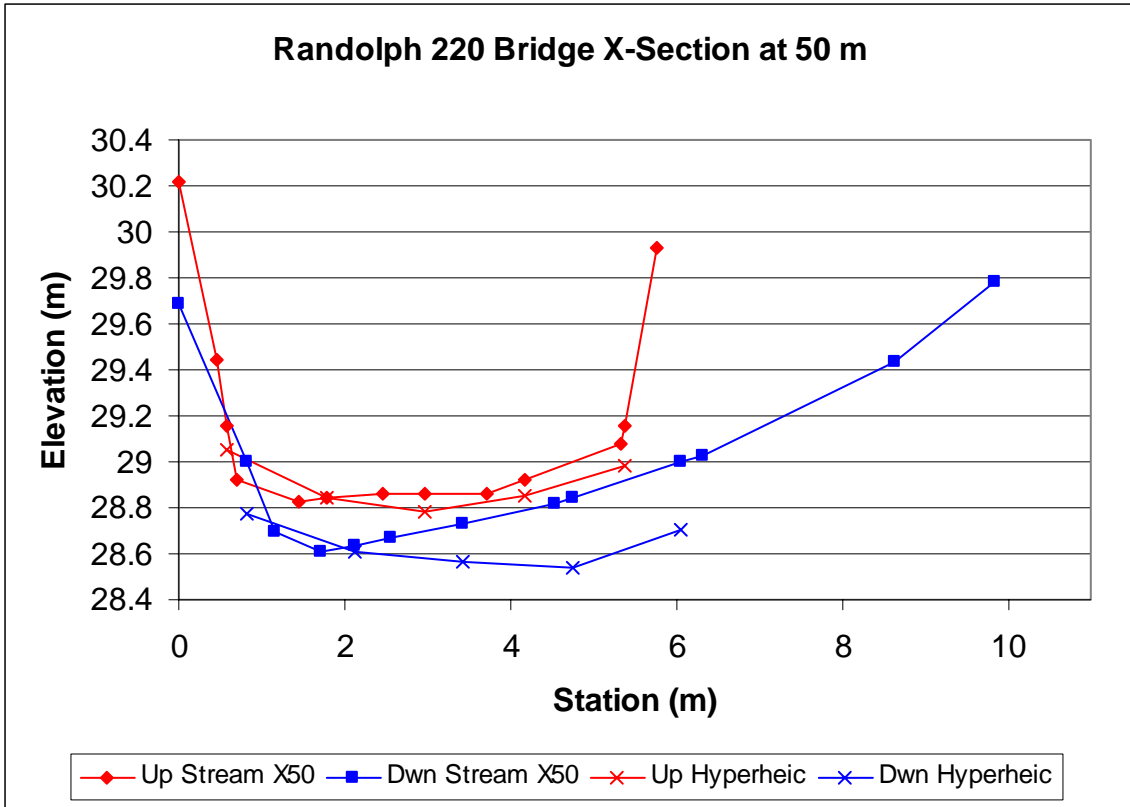
t0 t1 t2 t3 t4
s/g g/c g/s s/g s/g



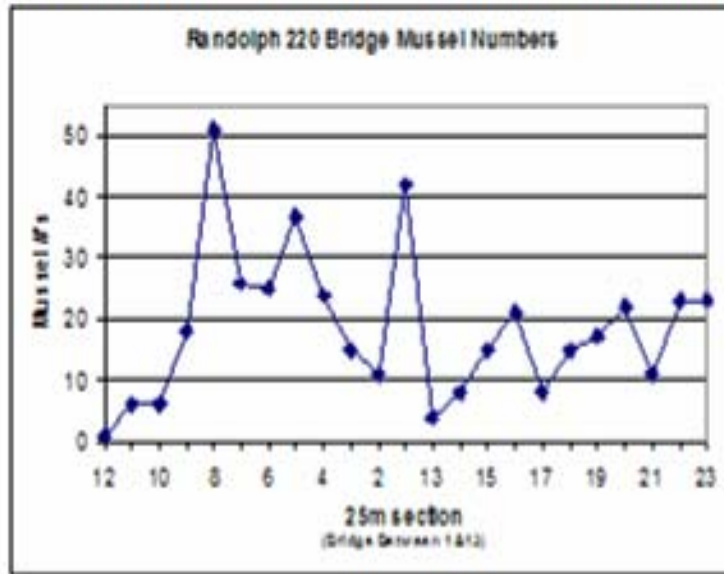
Randolph 220 Cross Section, Longitudinal Profile, and Planar Graphs





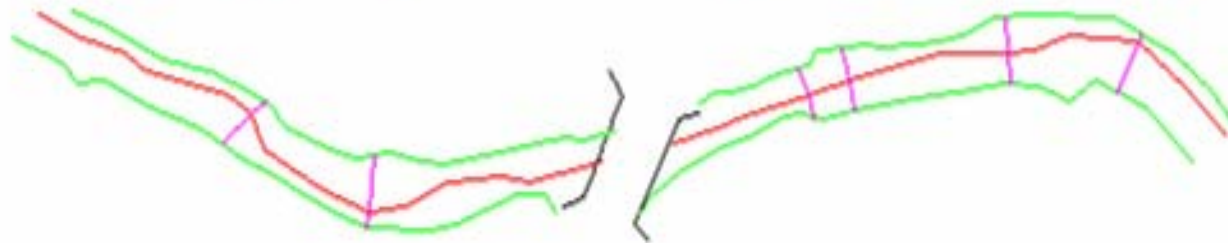


Randolph 220 Bridge Planar View and Substrate Sections (1:480)

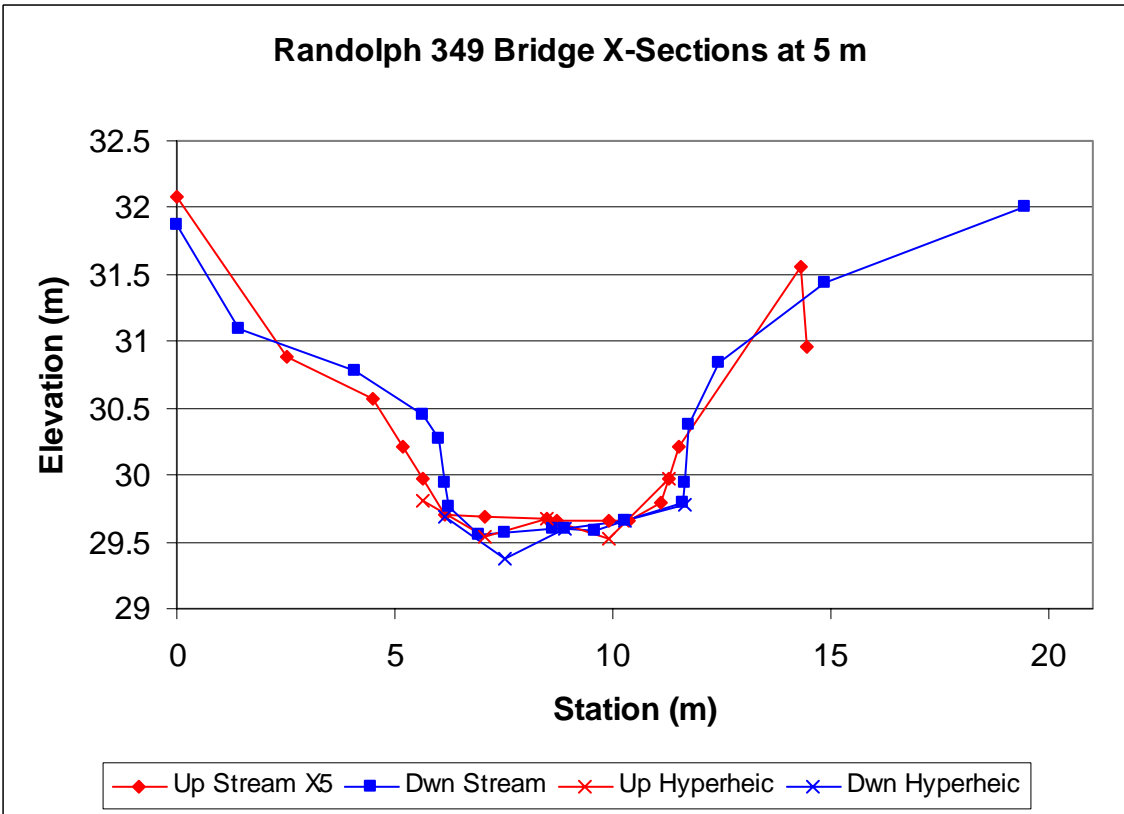
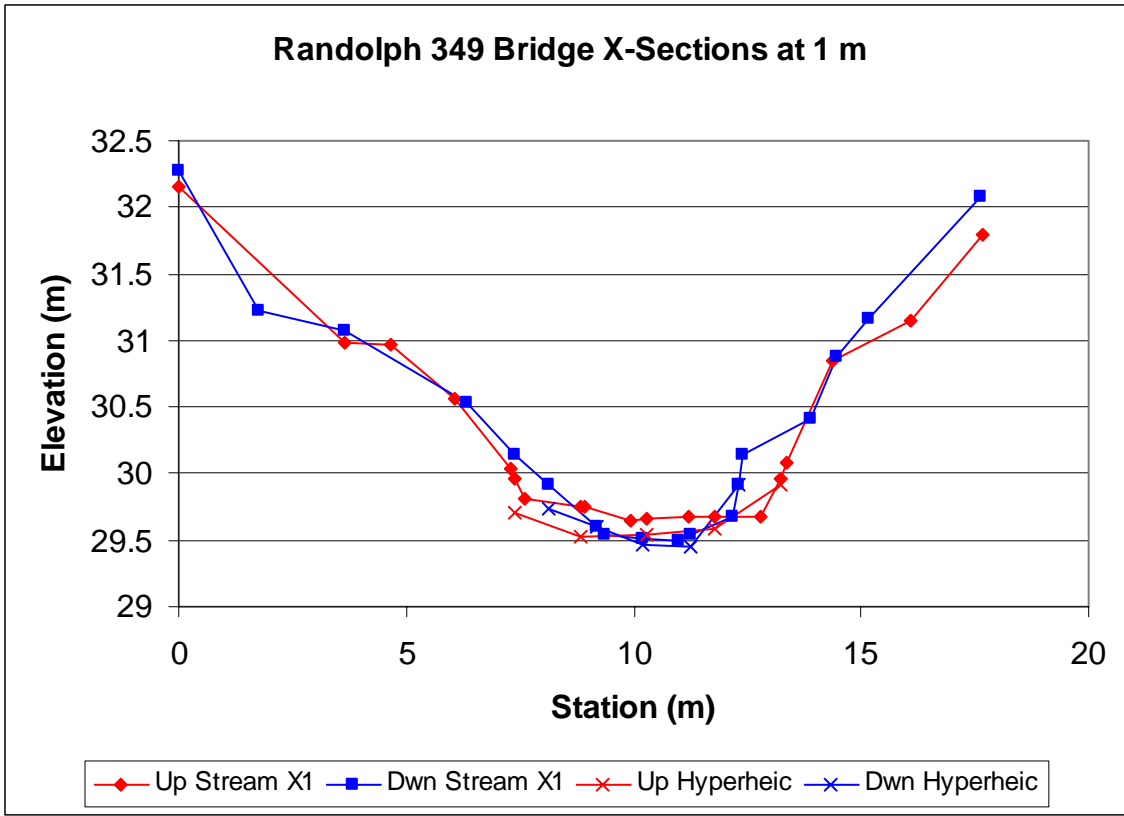


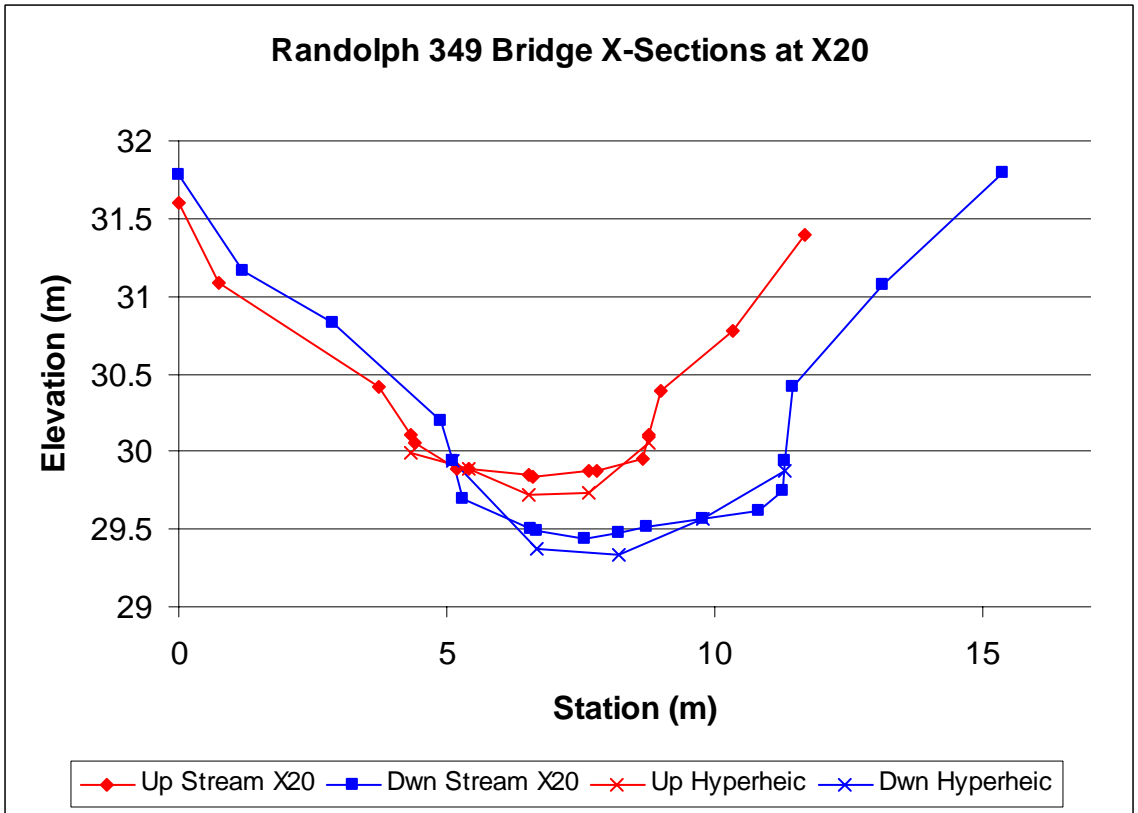
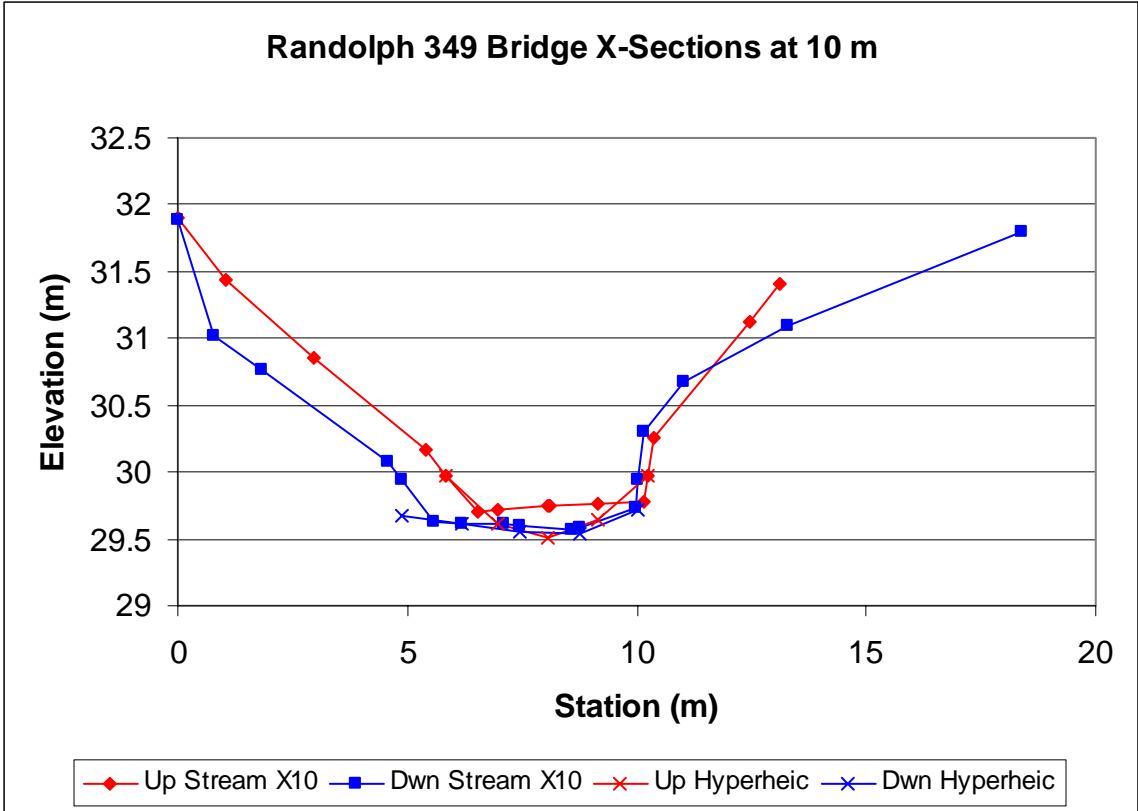
Field Notes: Developing midchannel bars of gravel and sand while bedrock exposed on sides of channel

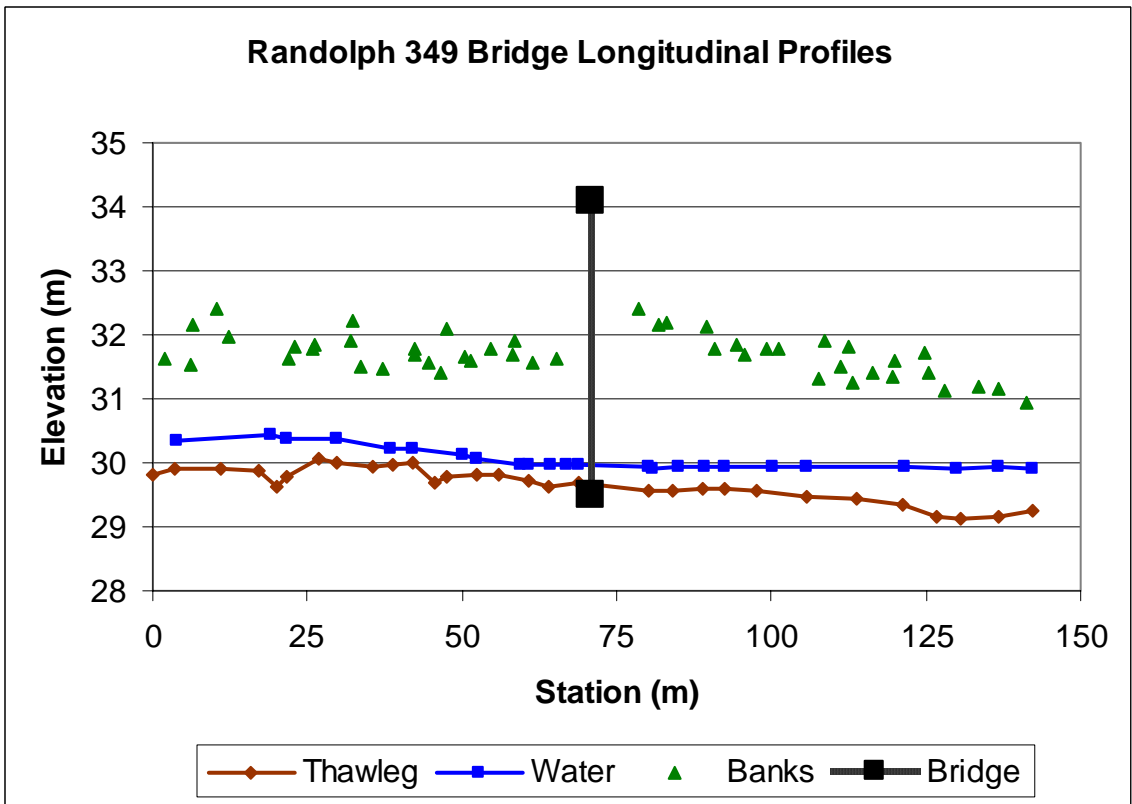
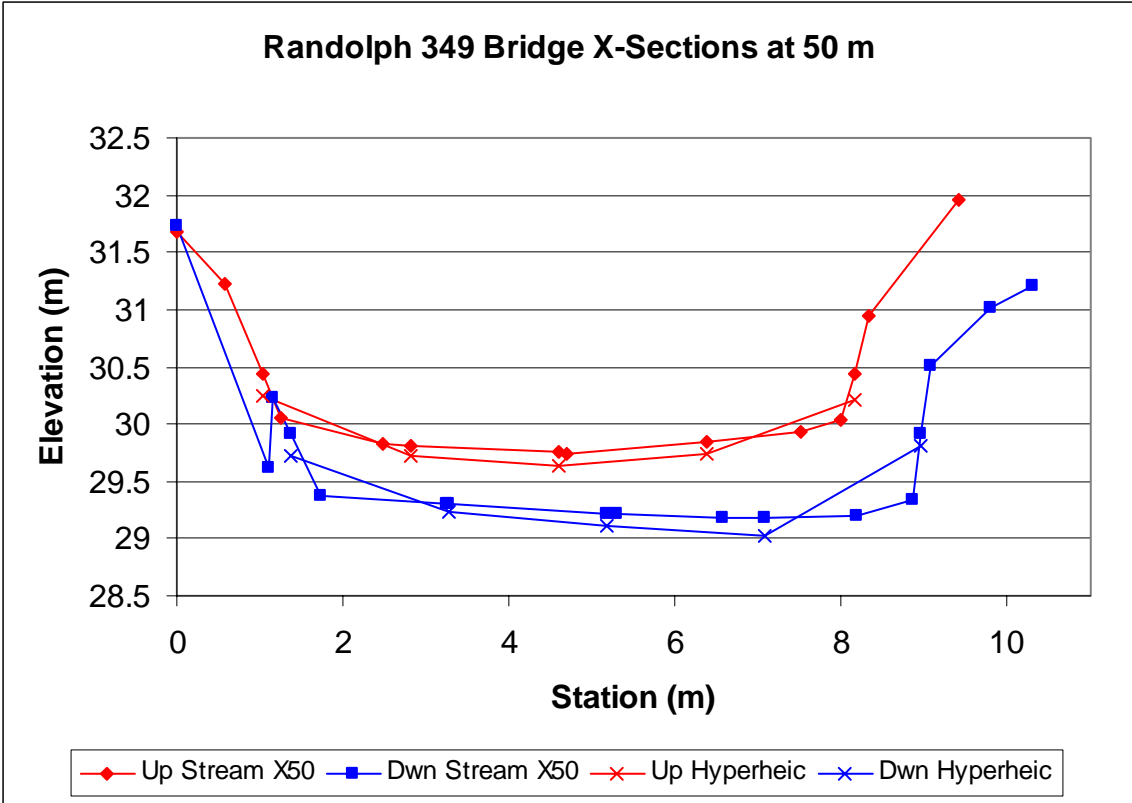
t2	t1	t0	t0	t1	t2	t3	t4
c/g	b/c	b/g	b/g	b	b/g	s/g	b/g



Randolph 349 Cross Section, Longitudinal Profile, and Planar Graphs

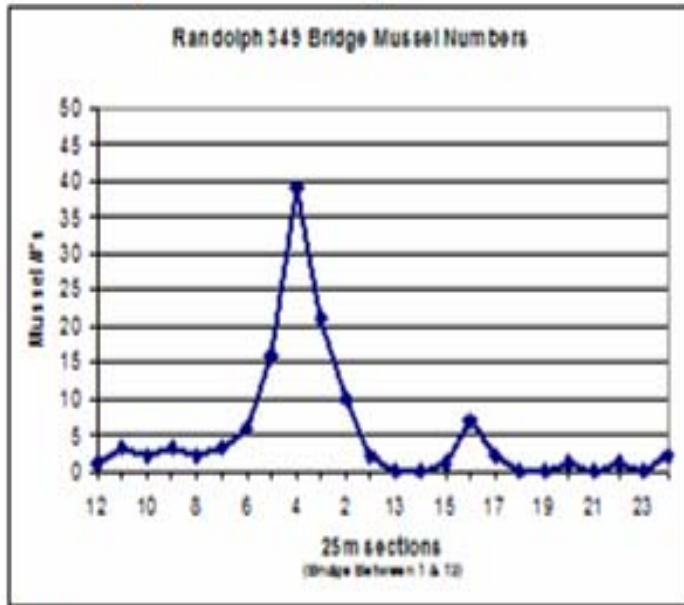




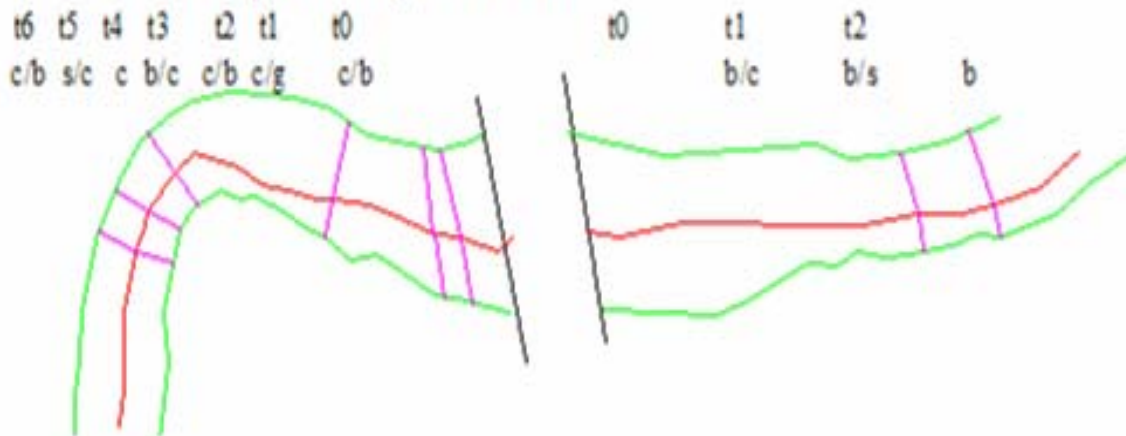


*Graph not to scale, please email author for originals.

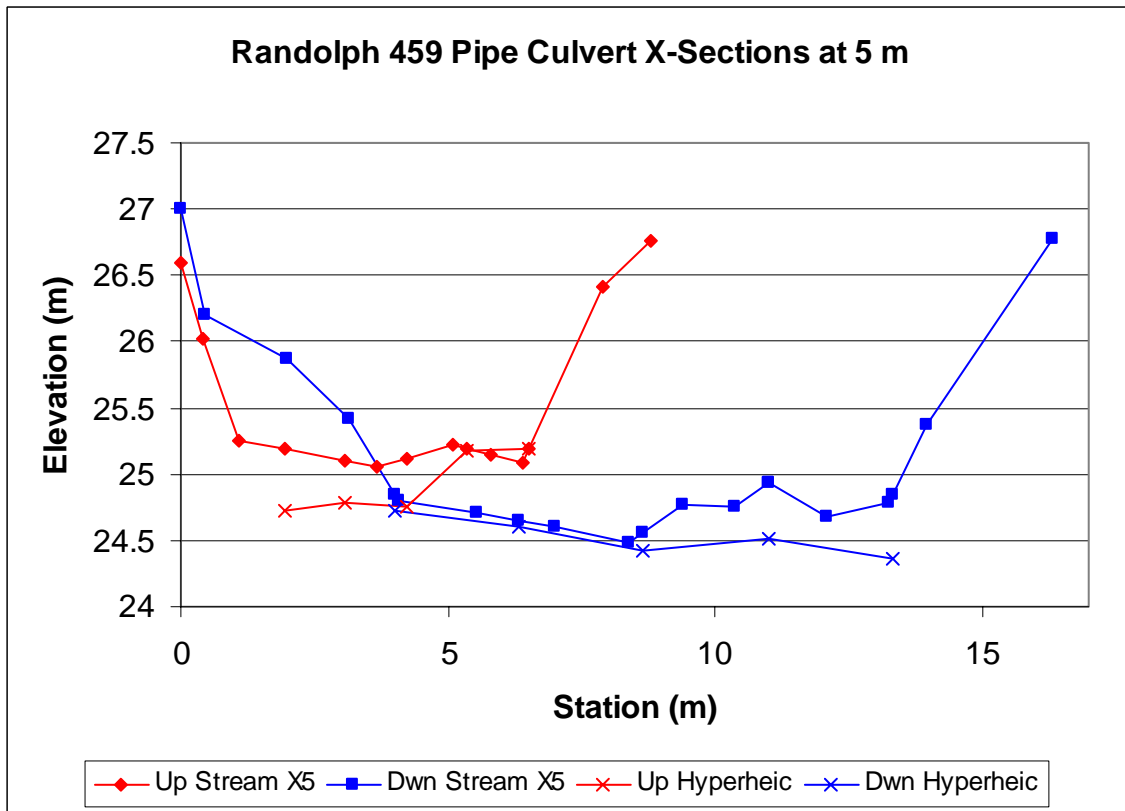
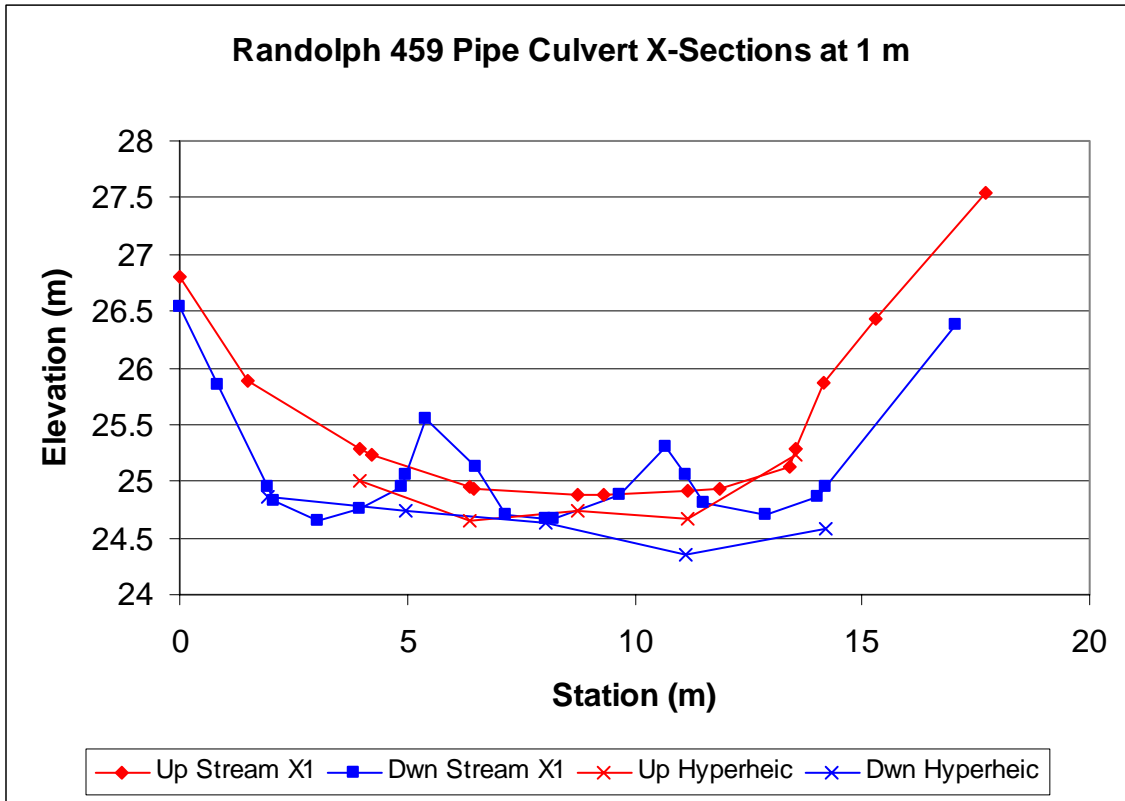
Randolph 349 Bridge Planar View and Substrate Sections (1:480)

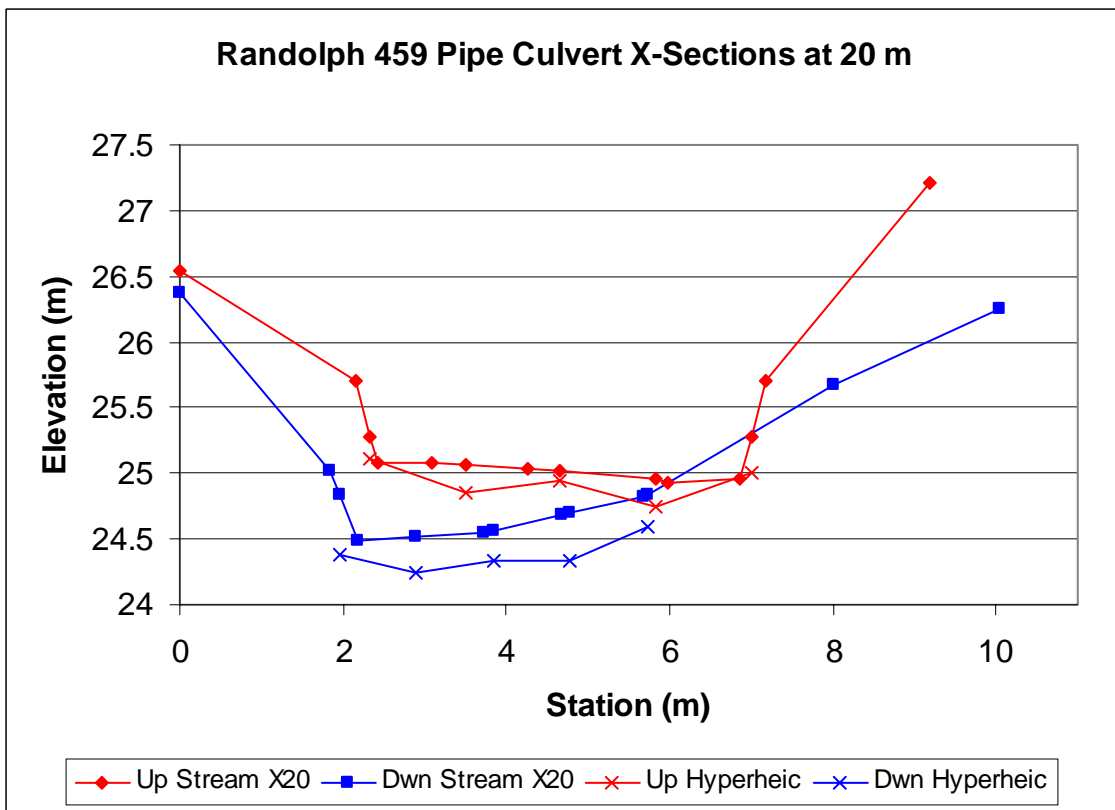
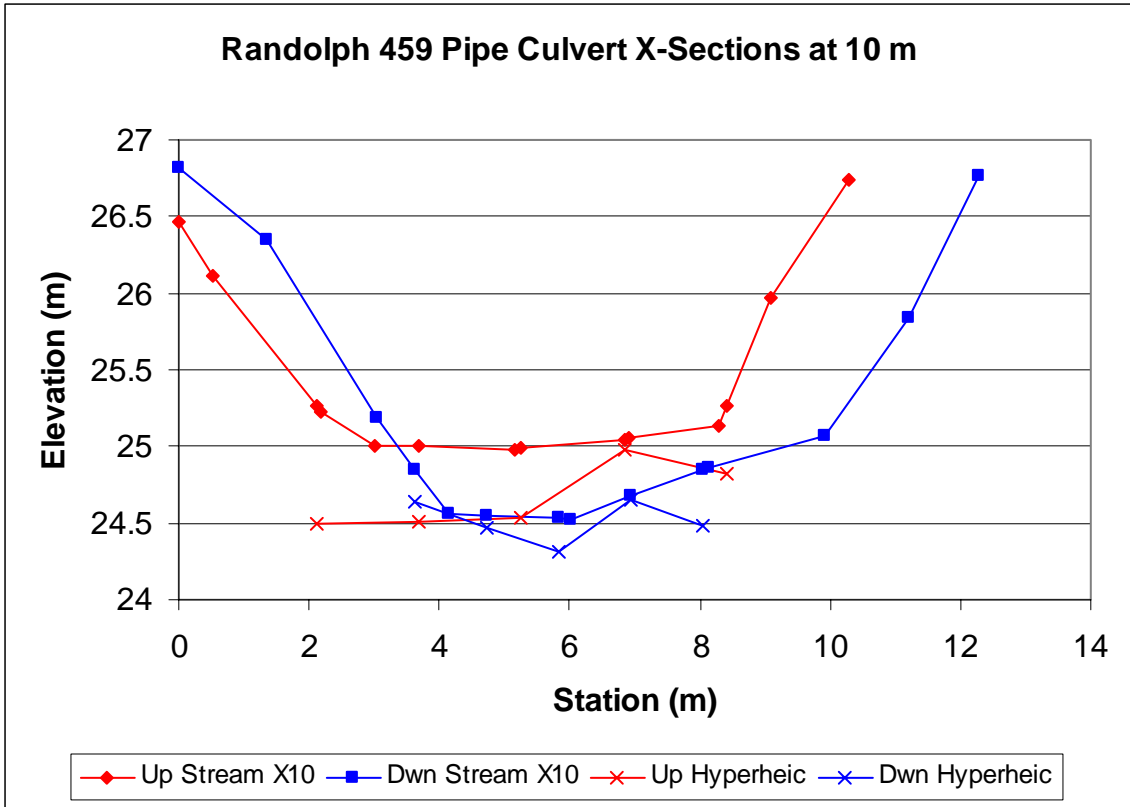


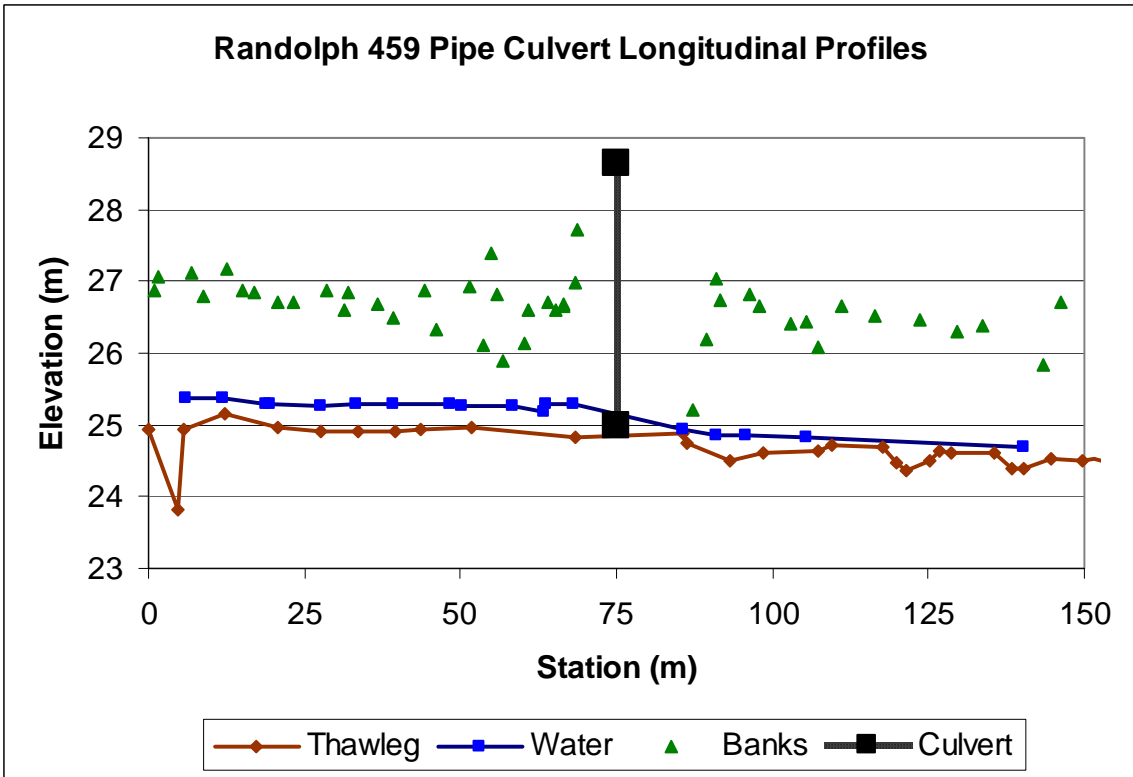
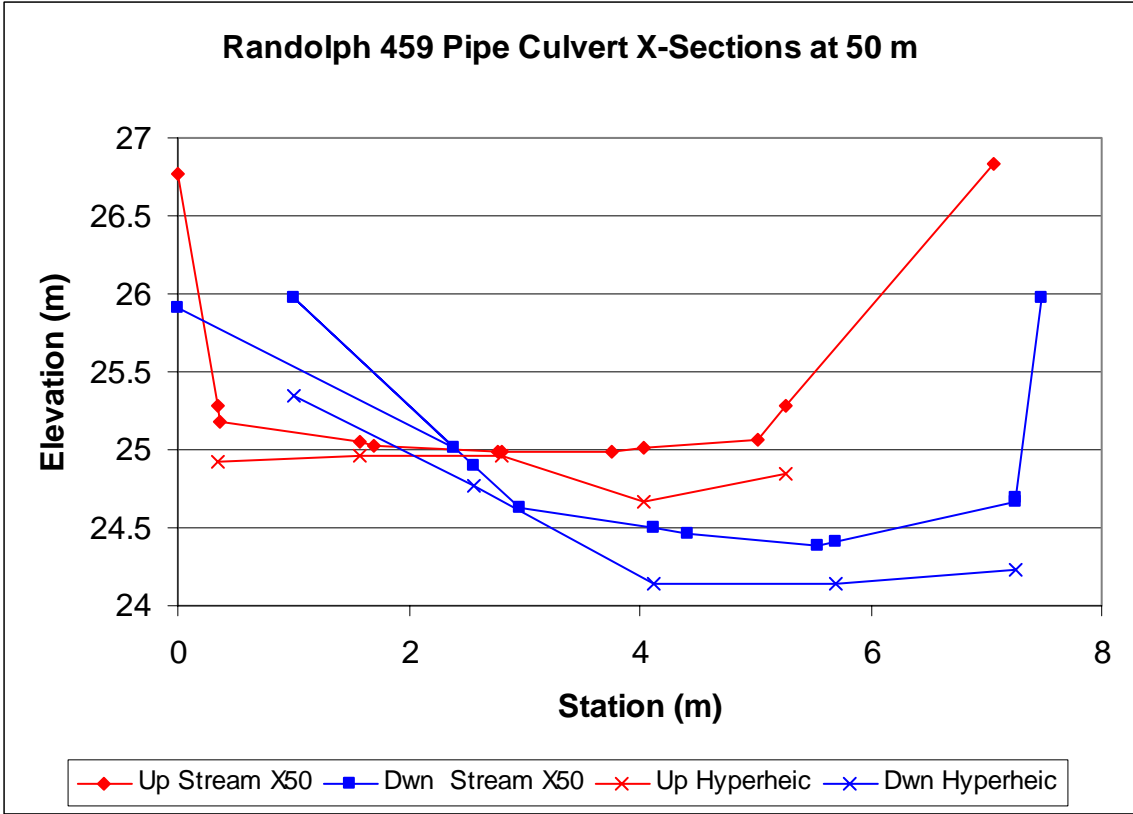
Field Notes: Gravel patches along banks but thin



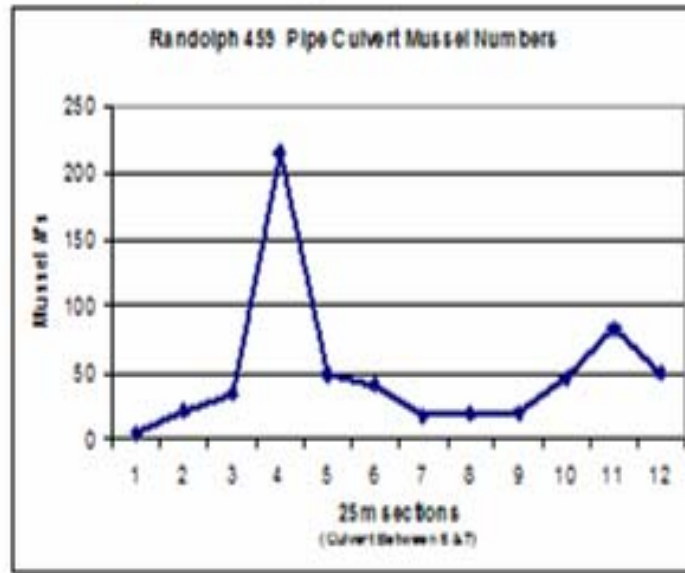
Randolph 459 Cross Section, Longitudinal Profile, and Planar Graphs







Randolph 459 Pipe Culvert Planar View and Substrate Sections (1:480)

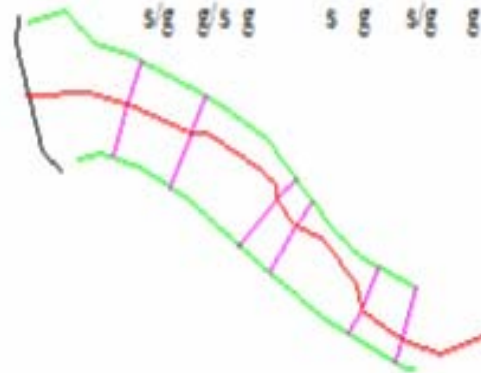


Field Notes: Two midchannel bars below culvert

t3	t2	t1	t0
s/g	g/c	s/g	g/c



t0	t1	t2	t3	t4	t5	t6
s/g	g/s	g	s	g	s/g	g

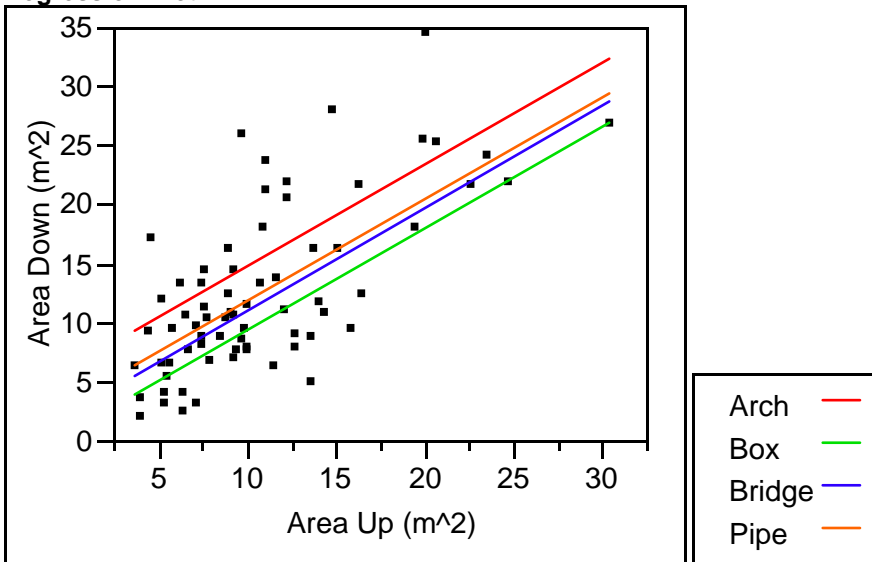


Appendix D: Statistical Tables and Graphs
Cross Section Area Statistics
Hyporheic Depth Statistics
Habitat Area Statistics

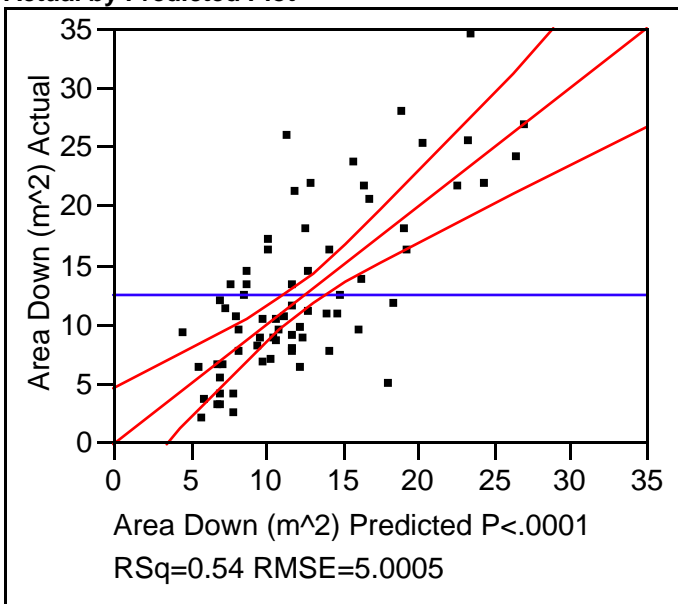
Cross Section Area Statistics

Comparison of All Crossing Types:

Response Area Down (m²)
Whole Model
Regression Plot



Actual by Predicted Plot



Summary of Fit

RSquare	0.538971
RSquare Adj	0.5106
Root Mean Square Error	5.000476
Mean of Response	12.53429
Observations (or Sum Wgts)	70

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	4	1900.0888	475.022	18.9973
Error	65	1625.3095	25.005	Prob > F
C. Total	69	3525.3983		<.0001

Lack Of Fit

Source	DF	Sum of Squares	Mean Square	F Ratio
Lack Of Fit	64	1618.1274	25.2832	3.5203
Pure Error	1	7.1821	7.1821	Prob > F
Total Error	65	1625.3095		0.4041
				Max RSq
				0.9980

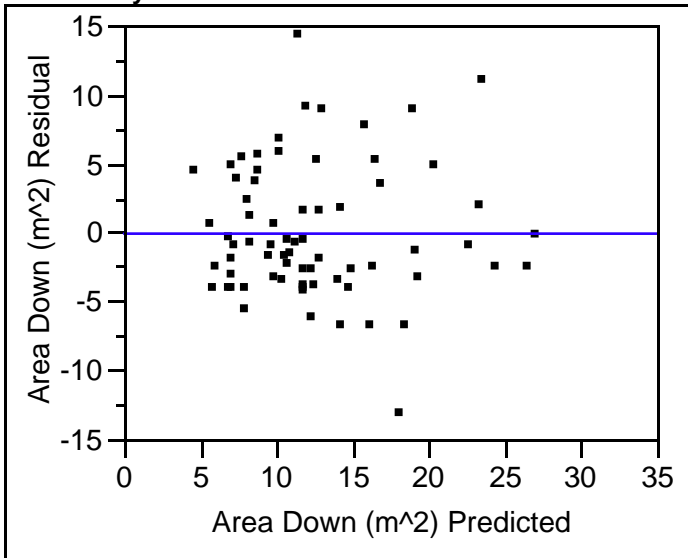
Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob> t
Intercept	3.1376031	1.459145	2.15	0.0353
Area Up (m ²)	0.8616149	0.114871	7.50	<.0001
Type [Arch]	3.0762538	1.133326	2.71	0.0085
Type [Box]	-2.369936	1.296354	-1.83	0.0721
Type [Bridge]	-0.718023	0.941777	-0.76	0.4486

Effect Tests

Source	Nparm	DF	Sum of Squares	F Ratio	Prob > F
Area Up (m ²)	1	1	1406.7895	56.2609	<.0001
Type	3	3	209.2605	2.7896	0.0474

Residual by Predicted Plot



Least Squares Means Table

Level	Least Sq Mean	Std Error	Mean
Arch	15.595120	1.3137415	17.4160
Box	10.148930	1.5908621	11.4560
Bridge	11.800844	0.9292679	10.5007
Pipe	12.530572	1.2911755	12.4387

LSMeans Differences Tukey HSD

Alpha=
0.050 Q=
2.63676LSMean[i] By LSMean[j]

Mean[i]-Mean[j]	Arch	Box	Bridge	Pipe
Std Err Dif				
Lower CL Dif				
Upper CL Dif				
Arch	0	5.44619	3.79428	3.06455
	0	2.04258	1.63512	1.84364
	0	0.06038	-0.5171	-1.7967
	0	10.832	8.10569	7.92578
Box	-5.4462	0	-1.6519	-2.3816
	2.04258	0	1.85871	2.04994
	-10.832	0	-6.5529	-7.7868
	-0.0604	0	3.24905	3.02355
Bridge	-3.7943	1.65191	0	-0.7297
	1.63512	1.85871	0	1.58947
	-8.1057	-3.2491	0	-4.9208
	0.51714	6.55288	0	3.46133
Pipe	-3.0645	2.38164	0.72973	0
	1.84364	2.04994	1.58947	0
	-7.9258	-3.0236	-3.4613	0
	1.79668	7.78684	4.92079	0

Level		Least Sq Mean
Arch	A	15.595120
Pipe	A B	12.530572
Bridge	A B	11.800844
Box	B	10.148930

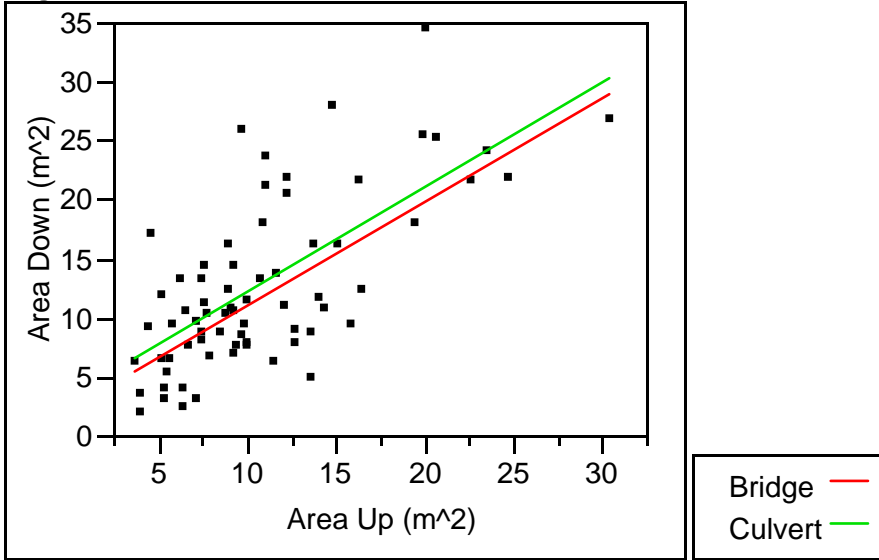
Levels not connected by same letter are significantly different (alpha =.05)

Comparison of Bridges vs Culverts:

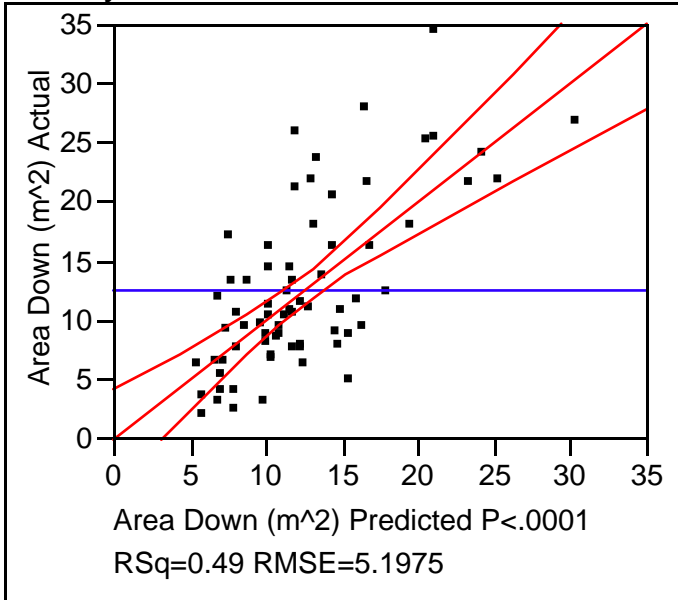
Response Area Down (m²)

Whole Model

Regression Plot



Actual by Predicted Plot



Summary of Fit

RSquare	0.486592
RSquare Adj	0.471266
Root Mean Square Error	5.197542
Mean of Response	12.53429
Observations (or Sum Wgts)	70

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	2	1715.4305	857.715	31.7502
Error	67	1809.9678	27.014	Prob > F
C. Total	69	3525.3983		<.0001

Lack Of Fit

Source	DF	Sum of Squares	Mean Square	F Ratio
Lack Of Fit	66	1802.7857	27.3149	3.8032
Pure Error	1	7.1821	7.1821	Prob > F
Total Error	67	1809.9678		0.3902
				Max RSq
				0.9980

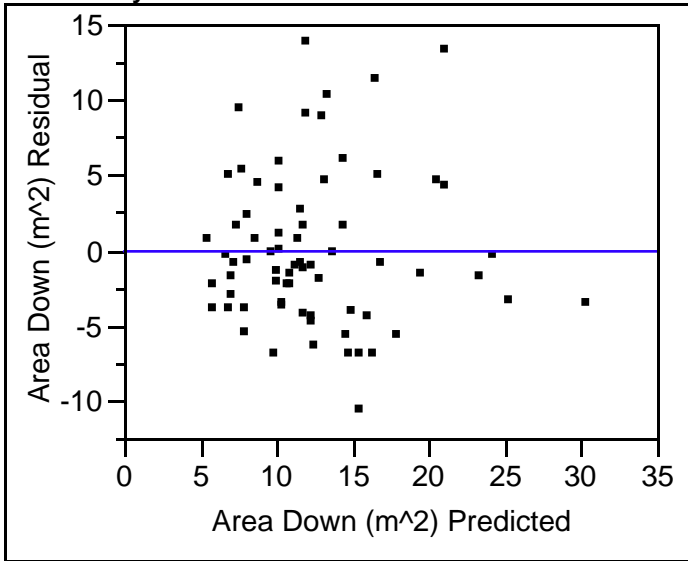
Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob> t
Intercept	2.8624687	1.411758	2.03	0.0466
Area Up (m^2)	0.8802023	0.11819	7.45	<.0001
Bridge vs Culvert[Bridge]	-0.61722	0.646772	-0.95	0.3434

Effect Tests

Source	Nparm	DF	Sum of Squares	F Ratio	Prob > F
Area Up (m^2)	1	1	1498.3112	55.4633	<.0001
Bridge vs Culvert	1	1	24.6022	0.9107	0.3434

Residual by Predicted Plot



Least Squares Means Table

Level	Least Sq Mean	Std Error	Mean
Bridge	11.828892	0.96555143	10.5007
Culvert	13.063331	0.83261826	14.0595

LSMeans Differences Student's t

Alpha=
0.050 t=
1.99601LSMean[ij] By LSMean[j]

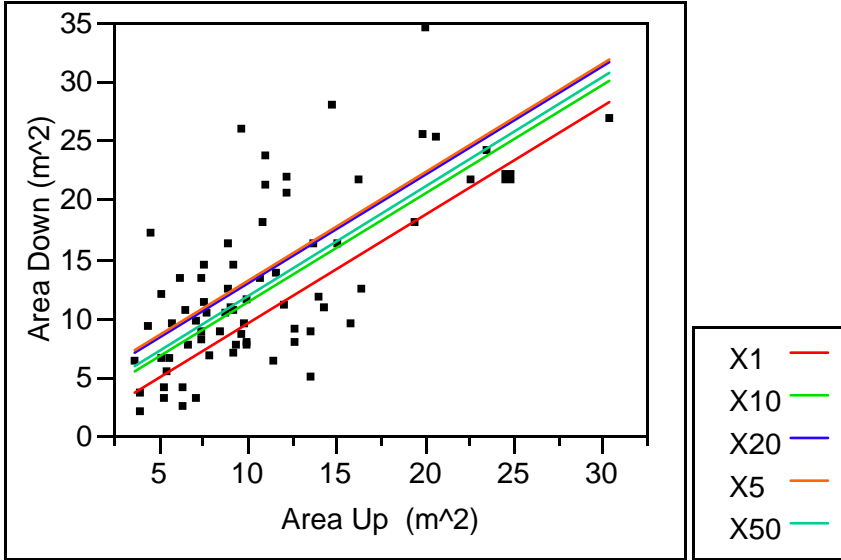
Mean[i]-Mean[j]	Bridge	Culvert
Std Err Dif		
Lower CL Dif		
Upper CL Dif		
Bridge	0	-1.2344
	0	1.29354
	0	-3.8164
	0	1.34748
Culvert	1.23444	0
	1.29354	0
	-1.3475	0
	3.81636	0

Level	Least Sq Mean
Culvert A	13.063331
Bridge A	11.828892

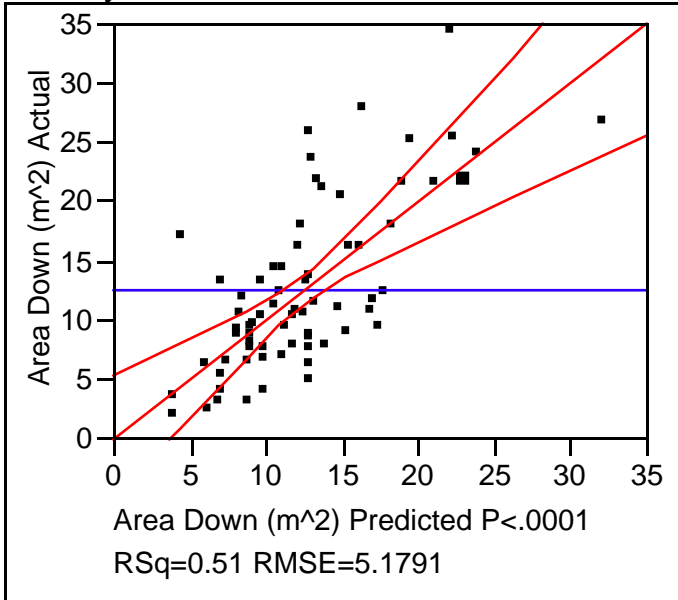
Levels not connected by same letter are significantly different

Comparison of Cross Section Locations:

Response Area Down (m²)
Whole Model
Regression Plot



Actual by Predicted Plot



Summary of Fit

RSquare	0.513054
RSquare Adj	0.475011
Root Mean Square Error	5.179102
Mean of Response	12.53429
Observations (or Sum Wgts)	70

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	5	1808.7199	361.744	13.4863
Error	64	1716.6784	26.823	Prob > F
C. Total	69	3525.3983		<.0001

Lack Of Fit

Source	DF	Sum of Squares	Mean Square	F Ratio
Lack Of Fit	63	1565.1244	24.843	0.1639
Pure Error	1	151.5541	151.554	Prob > F
Total Error	64	1716.6784		0.9838
				Max RSq
				0.9570

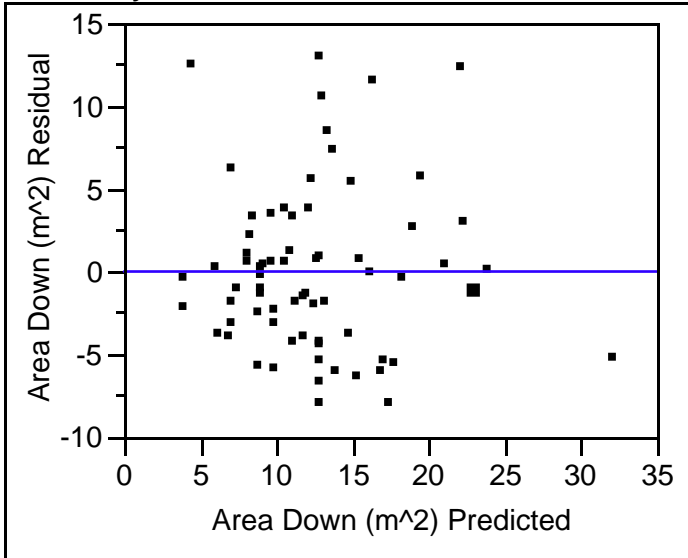
Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob> t
Intercept	2.4709257	1.398767	1.77	0.0821
Area Up (m ²)	0.9242616	0.115204	8.02	<.0001
Station[X1]	-2.250884	1.243856	-1.81	0.0751
Station[X10]	-0.409562	1.23819	-0.33	0.7419
Station[X20]	1.103739	1.240863	0.89	0.3771
Station[X5]	1.4101441	1.239381	1.14	0.2595

Effect Tests

Source	Nparm	DF	Sum of Squares	F Ratio	Prob > F
Area Up (m ²)	1	1	1726.4999	64.3662	<.0001
Station	4	4	117.8915	1.0988	0.3649

Residual by Predicted Plot



Least Squares Means Table

Level	Least Sq Mean	Std Error	Mean
X1	10.283402	1.3893760	11.2471
X10	12.124724	1.3843052	11.9714
X20	13.638025	1.3866969	12.9671
X5	13.944430	1.3853706	14.4064
X50	12.680848	1.3862027	12.0793

LSMeans Differences Tukey HSD

Alpha=

0.050 Q=

2.80707LSMean[j] By LSMean[j]

Mean[i]-Mean[j] Std Err Dif Lower CL Dif Upper CL Dif	X1	X10	X20	X5	X50
X1	0 0 0 0	-1.8413 1.96246 -7.3501 3.66744	-3.3546 1.96809 -8.8792 2.16994	-3.661 1.95852 -9.1587 1.83666	-2.3974 1.96722 -7.9196 3.12466
X10	1.84132 1.96246 -3.6674 7.35009	0 0 0 0	-1.5133 1.95858 -7.0112 3.98456	-1.8197 1.95902 -7.3188 3.67939	-0.5561 1.95831 -6.0532 4.941
X20	3.35462 1.96809 -2.1699 8.87919	1.5133 1.95858 -3.9846 7.01117	0 0 0 0	-0.3064 1.9626 -5.8156 5.20275	0.95718 1.95754 -4.5378 6.45211
X5	3.66103 1.95852 -1.8367 9.15871	1.81971 1.95902 -3.6794 7.3188	0.30641 1.9626 -5.2028 5.81556	0 0 0 0	1.26358 1.962 -4.2439 6.77105
X50	2.39745 1.96722 -3.1247 7.91955	0.55612 1.95831 -4.941 6.05324	-0.9572 1.95754 -6.4521 4.53776	-1.2636 1.962 -6.771 4.24389	0 0 0 0

Level		Least Sq Mean
X5	A	13.944430
X20	A	13.638025
X50	A	12.680848
X10	A	12.124724
X1	A	10.283402

Levels not connected by same letter are significantly different (alpha =.05)

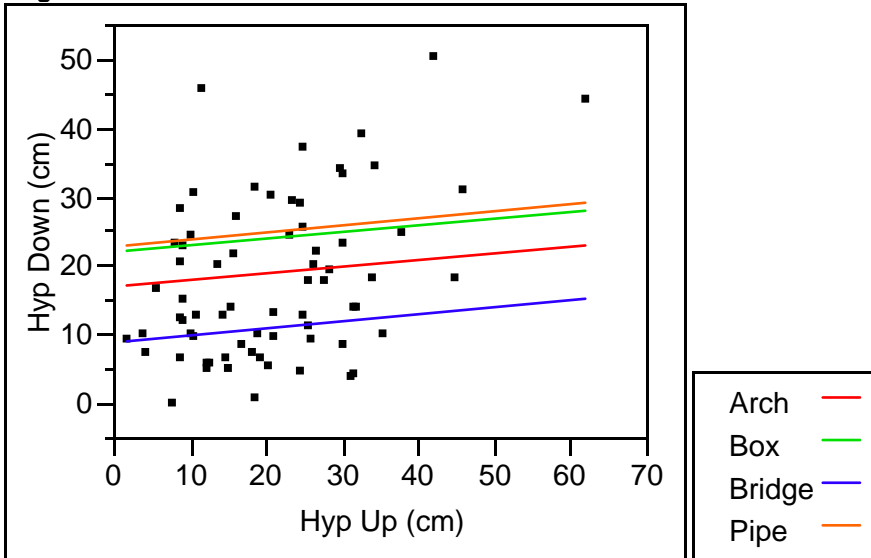
Hyporheic Zone Depth Statistics

Comparison of All Crossing Types:

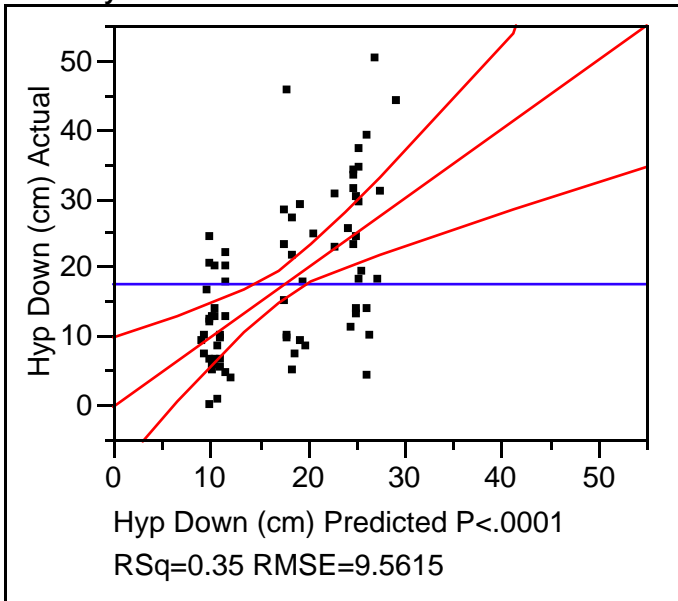
Response Hyp Down (cm)

Whole Model

Regression Plot



Actual by Predicted Plot



Summary of Fit

RSquare	0.34532
RSquare Adj	0.305032
Root Mean Square Error	9.56145
Mean of Response	17.69543
Observations (or Sum Wgts)	70

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	4	3134.3896	783.597	8.5713
Error	65	5942.3868	91.421	Prob > F
C. Total	69	9076.7763		<.0001

Lack Of Fit

Source	DF	Sum of Squares	Mean Square	F Ratio
Lack Of Fit	64	5890.4687	92.0386	1.7728
Pure Error	1	51.9180	51.9180	Prob > F
Total Error	65	5942.3868		0.5446
				Max RSq
				0.9943

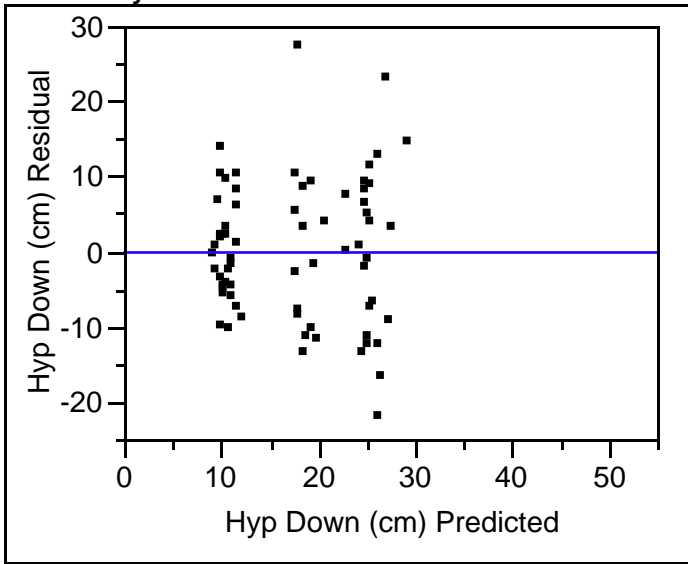
Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob> t
Intercept	17.718798	3.174117	5.58	<.0001
Hyp Up (cm)	0.1007816	0.127313	0.79	0.4315
Type[Arch]	-0.818557	2.225495	-0.37	0.7142
Type[Box]	4.1991827	2.501256	1.68	0.0980
Type[Bridge]	-8.615822	2.010913	-4.28	<.0001

Effect Tests

Source	Nparm	DF	Sum of Squares	F Ratio	Prob > F
Hyp Up (cm)	1	1	57.2884	0.6266	0.4315
Type	3	3	1707.3880	6.2253	0.0009

Residual by Predicted Plot



Least Squares Means Table

Level	Least Sq Mean	Std Error	Mean
Arch	19.023061	2.4971139	18.7260
Box	24.040801	3.0915252	24.5510
Bridge	11.225796	1.9021808	10.6277
Pipe	25.076814	2.8665174	26.2300

LSMeans Differences Tukey HSD

Alpha=
0.050 Q=
2.63676LSMean[i] By LSMean[j]

Mean[i]-Mean[j]	Arch	Box	Bridge	Pipe
Std Err Dif				
Lower CL Dif				
Upper CL Dif				
Arch	0	-5.0177	7.79727	-6.0538
	0	4.03446	3.04742	3.94282
	0	-15.656	-0.2381	-16.45
	0	5.62015	15.8326	4.34252
Box	5.01774	0	12.815	-1.036
	4.03446	0	3.76162	3.98706
	-5.6202	0	2.89651	-11.549
	15.6556	0	22.7335	9.47691
Bridge	-7.7973	-12.815	0	-13.851
	3.04742	3.76162	0	3.74655

	-15.833	-22.733	0	-23.73
	0.23806	-2.8965	0	-3.9723
Pipe	6.05375	1.03601	13.851	0
	3.94282	3.98706	3.74655	0
	-4.3425	-9.4769	3.97226	0
	16.45	11.5489	23.7298	0

Level		Least Sq Mean
Pipe	A	25.076814
Box	A	24.040801
Arch	A B	19.023061
Bridge	B	11.225796

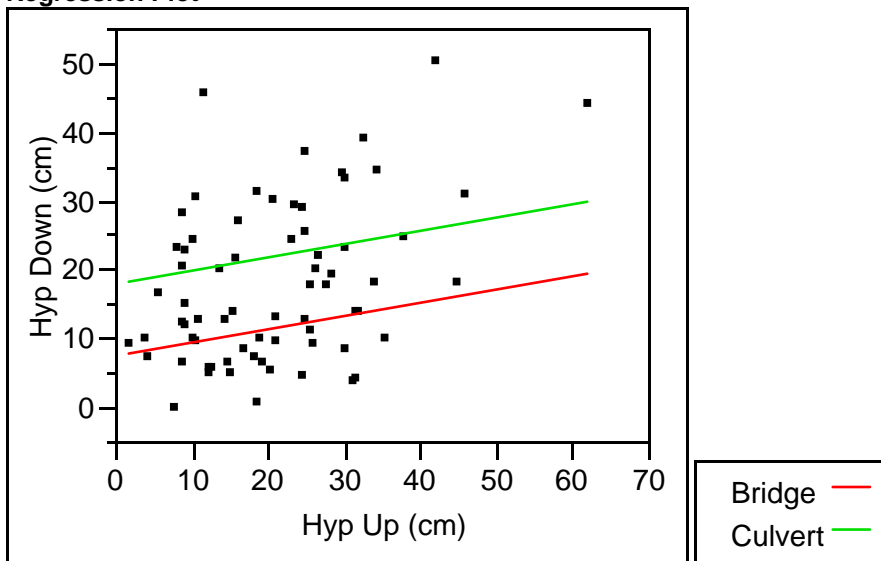
Levels not connected by same letter are significantly different (alpha =.05)

Comparison of Bridges vs Culverts:

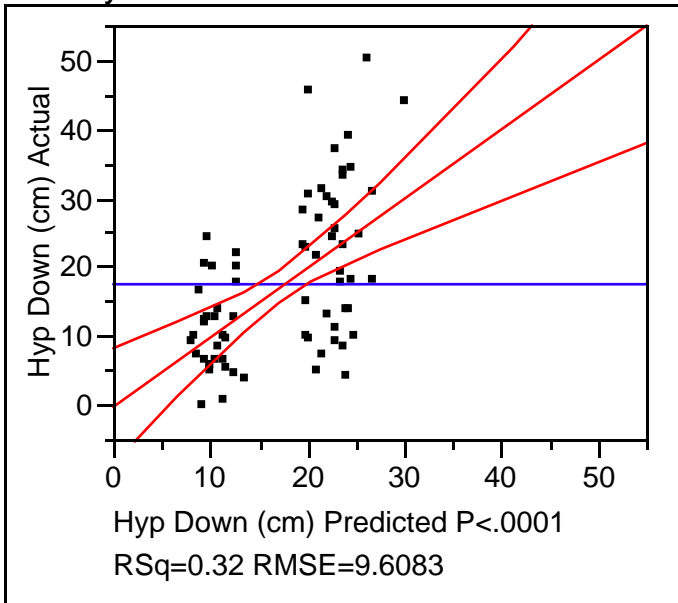
Response Hyp Down (cm)

Whole Model

Regression Plot



Actual by Predicted Plot



Summary of Fit

RSquare	0.318542
RSquare Adj	0.2982
Root Mean Square Error	9.608332
Mean of Response	17.69543
Observations (or Sum Wgts)	70

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	2	2891.3340	1445.67	15.6593
Error	67	6185.4424	92.32	Prob > F
C. Total	69	9076.7763		<.0001

Lack Of Fit

Source	DF	Sum of Squares	Mean Square	F Ratio
Lack Of Fit	65	6104.4921	93.9153	2.3203
Pure Error	2	80.9502	40.4751	Prob > F
Total Error	67	6185.4424		0.3483
				Max RSq
				0.9911

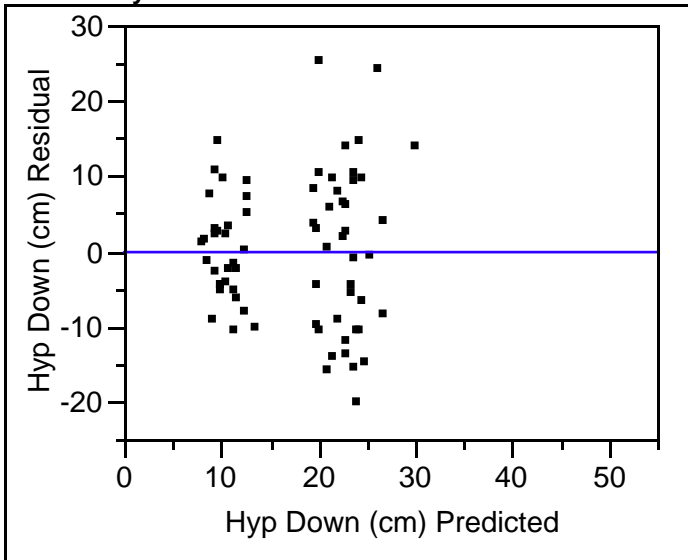
Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob> t
Intercept	12.88507	2.577356	5.00	<.0001
Hyp Up (cm)	0.1932361	0.113248	1.71	0.0926
Bridge vs Culvert[Bridge]	-5.180808	1.300845	-3.98	0.0002

Effect Tests

Source	Nparm	DF	Sum of Squares	F Ratio	Prob > F
Hyp Up (cm)	1	1	268.7879	2.9115	0.0926
Bridge vs Culvert	1	1	1464.3324	15.8615	0.0002

Residual by Predicted Plot



Least Squares Means Table

Level	Least Sq Mean	Std Error	Mean
Bridge	11.774505	1.8785836	10.6277
Culvert	22.136122	1.6006579	22.9963

LSMeans Differences Student's t

Alpha=
0.050 t=

1.99601LSMean[i] By LSMean[j]

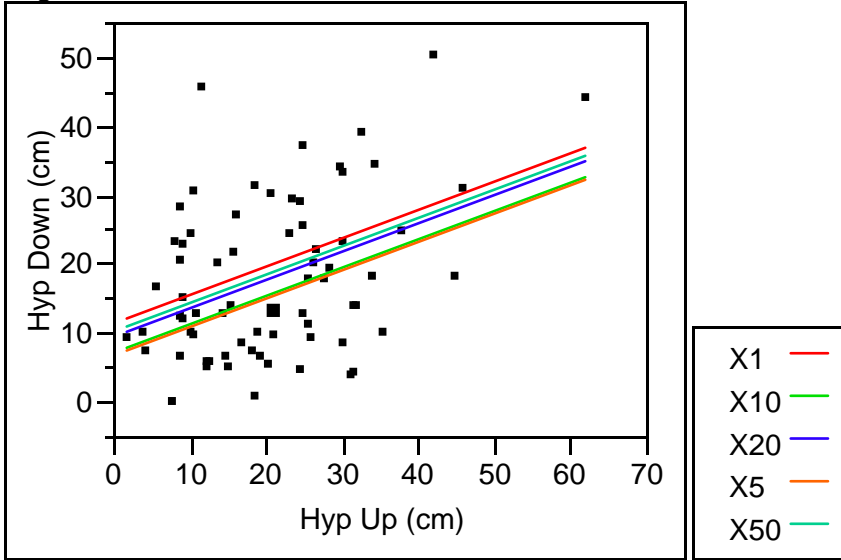
Mean[i]-Mean[j]	Bridge	Culvert
Std Err Dif		
Lower CL Dif		
Upper CL Dif		
Bridge	0	-10.362
	0	2.60169
	0	-15.555
	0	-5.1686
Culvert	10.3616	0
	2.60169	0
	5.16862	0
	15.5546	0

Level		Least Sq Mean
Culvert	A	22.136122
Bridge	B	11.774505

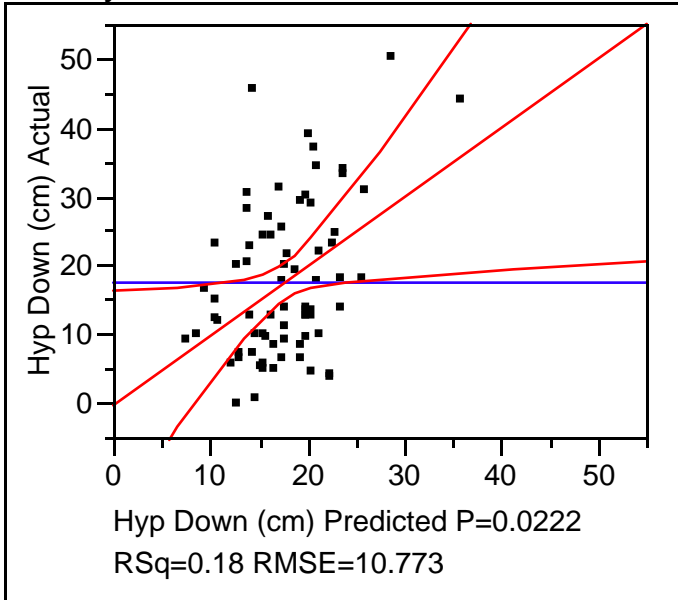
Levels not connected by same letter are significantly different (alpha= .05)

Comparison of Cross Section Locations:

Response Hyp Down (cm)
 Whole Model
 Regression Plot



Actual by Predicted Plot



Summary of Fit

RSquare	0.181724
RSquare Adj	0.117796
Root Mean Square Error	10.77273
Mean of Response	17.69543
Observations (or Sum Wgts)	70

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	5	1649.4666	329.893	2.8426
Error	64	7427.3097	116.052	Prob > F
C. Total	69	9076.7763		0.0222

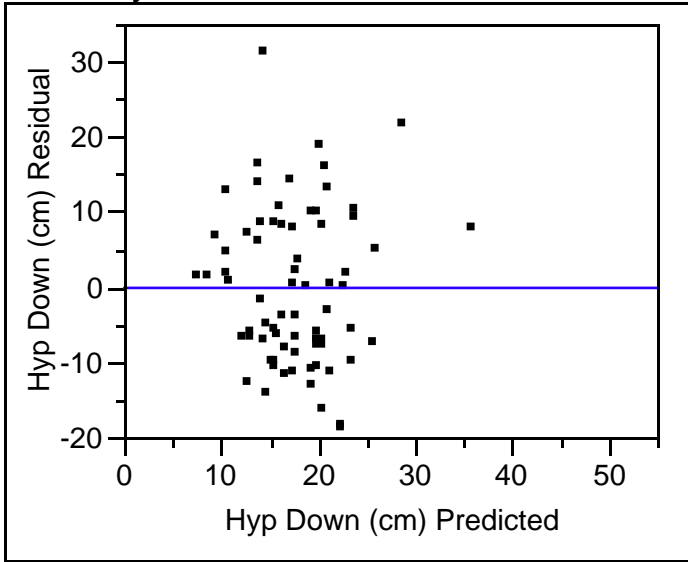
Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob> t
Intercept	9.0250679	2.727244	3.31	0.0015
Hyp Up (cm)	0.4116282	0.114138	3.61	0.0006
Station[X1]	2.3196352	2.58523	0.90	0.3729
Station[X10]	-1.886788	2.576863	-0.73	0.4667
Station[X20]	0.4899755	2.579776	0.19	0.8500
Station[X5]	-2.252977	2.582005	-0.87	0.3862

Effect Tests

Source	Nparm	DF	Sum of Squares	F Ratio	Prob > F
Hyp Up (cm)	1	1	1509.3837	13.0061	0.0006
Station	4	4	222.4650	0.4792	0.7508

Residual by Predicted Plot



Least Squares Means Table

Level	Least Sq Mean	Std Error	Mean
X1	20.015064	2.8881301	19.1936
X10	15.808641	2.8806435	16.1450
X20	18.185404	2.8832492	17.6300
X5	15.442451	2.8852436	16.1193
X50	19.025583	2.8808990	19.3893

LSMeans Differences Tukey HSD

Alpha=
0.050 Q=
2.80707LSMean[i] By LSMean[j]

Mean[i]-Mean[j]	X1	X10	X20	X5	X50
Std Err Dif					
Lower CL Dif					
Upper CL Dif					
X1	0	4.20642	1.82966	4.57261	0.98948
	0	4.08435	4.07238	4.09285	4.08495
	0	-7.2586	-9.6018	-6.9163	-10.477
	0	15.6715	13.2611	16.0615	12.4562
X10	-4.2064	0	-2.3768	0.36619	-3.2169
	4.08435	0	4.07921	4.0728	4.07172
	-15.671	0	-13.827	-11.066	-14.647
	7.25862	0	9.07386	11.7988	8.21264
X20	-1.8297	2.37676	0	2.74295	-0.8402
	4.07238	4.07921	0	4.08602	4.07968
	-13.261	-9.0739	0	-8.7268	-12.292
	9.60178	13.8274	0	14.2127	10.6118
X5	-4.5726	-0.3662	-2.743	0	-3.5831
	4.09285	4.0728	4.08602	0	4.07263
	-16.062	-11.799	-14.213	0	-15.015
	6.9163	11.0664	8.72678	0	7.84903

X50	-0.9895	3.21694	0.84018	3.58313	0
	4.08495	4.07172	4.07968	4.07263	0
	-12.456	-8.2126	-10.612	-7.849	0
	10.4773	14.6465	12.2921	15.0153	0

Level		Least Sq Mean
X1	A	20.015064
X50	A	19.025583
X20	A	18.185404
X10	A	15.808641
X5	A	15.442451

Levels not connected by same letter are significantly different (alpha = .05)

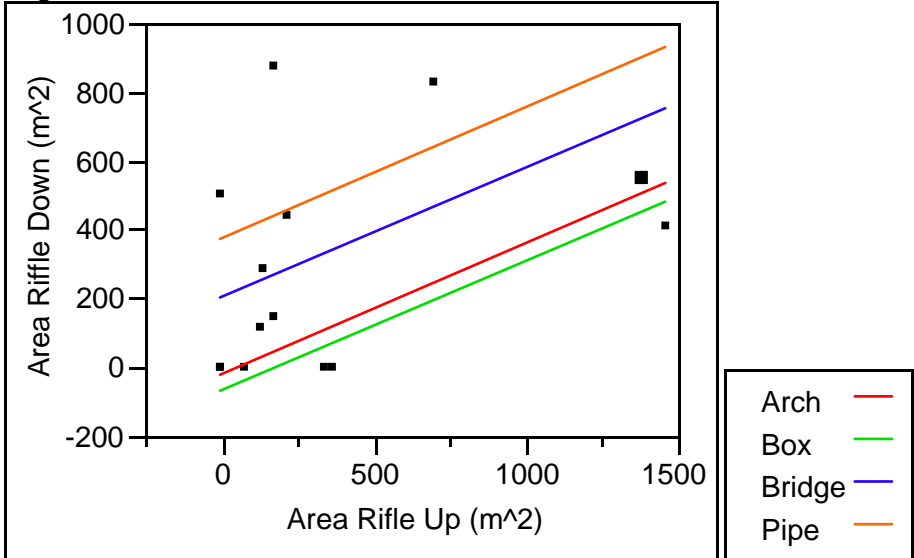
Habitat Area Statistics

Comparison of All Crossing Types:

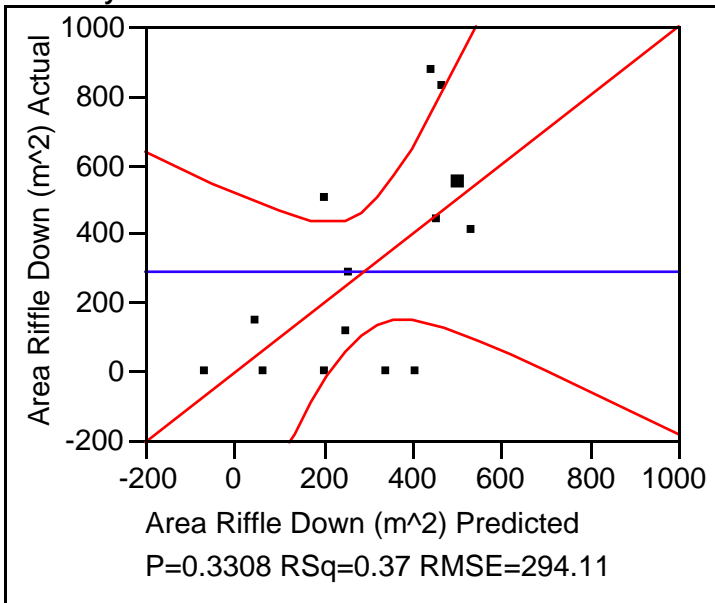
Response Area Riffle Down (m²)

Whole Model

Regression Plot



Actual by Predicted Plot



Summary of Fit

RSquare	0.371339
RSquare Adj	0.091934
Root Mean Square Error	294.1114
Mean of Response	294.4371
Observations (or Sum Wgts)	14

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	4	459854.4	114964	1.3290

Source	DF	Sum of Squares	Mean Square	F Ratio
Error	9	778513.8	86502	Prob > F
C. Total	13	1238368.2		0.3308

Lack Of Fit

Source	DF	Sum of Squares	Mean Square	F Ratio
Lack Of Fit	8	654511.83	81814	0.6598
Pure Error	1	124002.00	124002	Prob > F
Total Error	9	778513.83		0.7468
				Max RSq
				0.8999

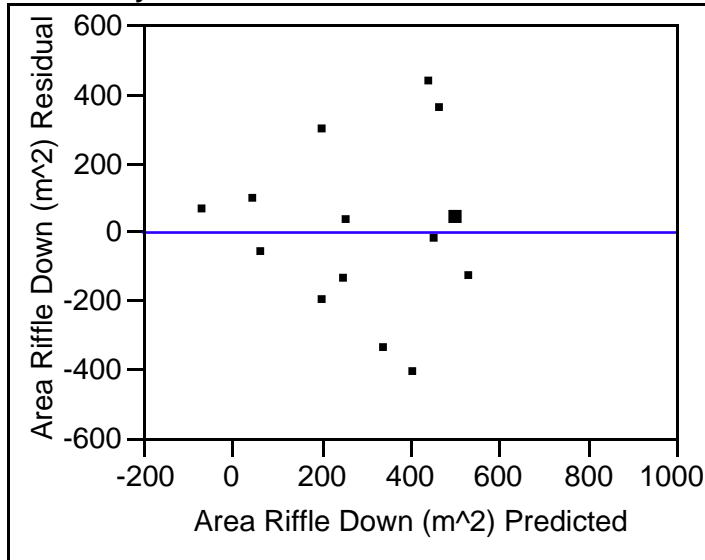
Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob> t
Intercept	124.42875	126.7824	0.98	0.3520
Area Rifle Up (m^2)	0.3788447	0.242259	1.56	0.1523
Type[Arch]	-142.0251	209.3639	-0.68	0.5146
Type[Box]	-189.6412	177.7226	-1.07	0.3137
Type[Bridge]	78.241551	126.5575	0.62	0.5517

Effect Tests

Source	Nparm	DF	Sum of Squares	F Ratio	Prob > F
Area Rifle Up (m^2)	1	1	211537.16	2.4455	0.1523
Type	3	3	288818.39	1.1130	0.3937

Residual by Predicted Plot



Least Squares Means Table

Level	Least Sq Mean	Std Error	Mean
Arch	122.10017	229.13496	362.687
Box	74.48411	213.35277	0.000
Bridge	342.36685	125.11649	287.362
Pipe	517.55005	177.51470	436.630

LSMeans Differences Tukey HSD

Alpha=
0.050 Q=
3.12182LSMean[i] By LSMean[j]

Mean[i]-Mean[j]	Arch	Box	Bridge	Pipe
Std Err Dif				
Lower CL Dif				
Upper CL Dif				
Arch	0	47.6161	-220.27	-395.45
	0	335.675	281.033	316.127
	0	-1000.3	-1097.6	-1382.3
	0	1095.53	657.069	591.44
Box	-47.616	0	-267.88	-443.07
	335.675	0	240.464	268.517
	-1095.5	0	-1018.6	-1281.3
	1000.3	0	482.801	395.196

Bridge	220.267	267.883	0	-175.18
	281.033	240.464	0	208.627
	-657.07	-482.8	0	-826.48
	1097.6	1018.57	0	476.113
Pipe	395.45	443.066	175.183	0
	316.127	268.517	208.627	0
	-591.44	-395.2	-476.11	0
	1382.34	1281.33	826.48	0

Level		Least Sq Mean
Pipe	A	517.55005
Bridge	A	342.36685
Arch	A	122.10017
Box	A	74.48411

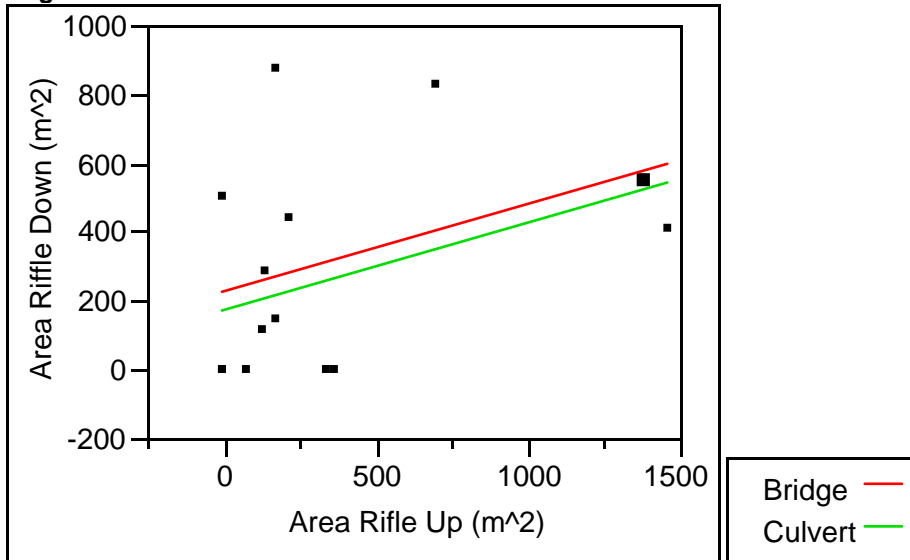
Levels not connected by same letter are significantly different (alpha =.05)

Comparison of Bridges vs Culverts:

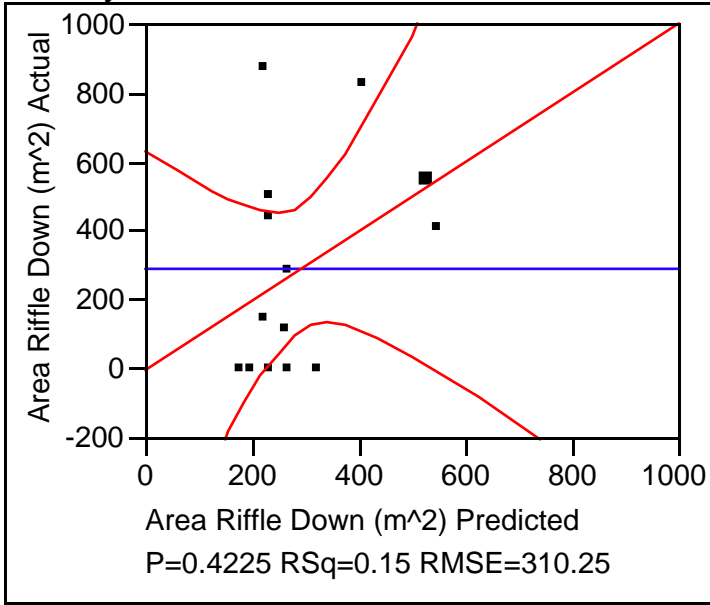
Response Area Riffle Down (m²)

Whole Model

Regression Plot



Actual by Predicted Plot



Summary of Fit

RSquare	0.145008
RSquare Adj	-0.01044
Root Mean Square Error	310.2484
Mean of Response	294.4371
Observations (or Sum Wgts)	14

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	2	179573.8	89786.9	0.9328
Error	11	1058794.5	96254.0	Prob > F
C. Total	13	1238368.2		0.4225

Lack Of Fit

Source	DF	Sum of Squares	Mean Square	F Ratio
Lack Of Fit	10	934792.5	93479	0.7539
Pure Error	1	124002.0	124002	Prob > F
Total Error	11	1058794.5		0.7238
				Max RSq
				0.8999

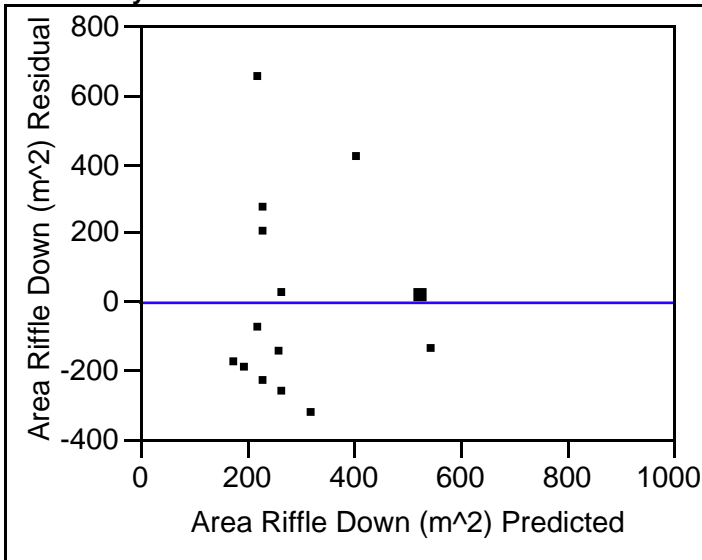
Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob> t
Intercept	204.94486	106.0156	1.93	0.0794
Area Rifle Up (m ²)	0.2527359	0.185307	1.36	0.1999
Bridge vs Culvert[Bridge]	25.917268	87.02153	0.30	0.7714

Effect Tests

Source	Nparm	DF	Sum of Squares	F Ratio	Prob > F
Area Rifle Up (m ²)	1	1	179048.13	1.8602	0.1999
Bridge vs Culvert	1	1	8537.76	0.0887	0.7714

Residual by Predicted Plot



Least Squares Means Table

Level	Least Sq Mean	Std Error	Mean
Bridge	324.05688	129.48445	287.362
Culvert	272.22234	111.52999	299.744

LSMeans Differences Student's t

Alpha=
0.050 t=
2.20099LSMean[i] By LSMean[j]

Mean[i]-Mean[j]	Bridge	Culvert
Std Err Dif		
Lower CL Dif		
Upper CL Dif		
Bridge	0	51.8345
	0	174.043
	0	-331.23
	0	434.901
Culvert	-51.835	0
	174.043	0
	-434.9	0
	331.232	0

Level		Least Sq Mean
Bridge	A	324.05688
Culvert	A	272.22234

Levels not connected by same letter are significantly different (alpha = .05)

Appendix E: Data Tables

Cross Section Areas

<u>Site Name</u>		X-Area (m ²)	X-Area (m ²)	
		<i>UpStrm</i>	<i>Dwn Strm</i>	<i>Difference</i>
Chatham 12 Arch	X1	9.42	7.53	-1.89
	X5	14.20	11.62	-2.58
	X10	15.22	16.05	0.82
	X20	12.37	20.40	8.02
	X50	11.20	23.59	12.39
Granville 217 Pipe	X1	24.71	21.84	-2.87
	X5	10.11	11.36	1.25
	X10	7.46	7.93	0.47
	X20	5.90	9.34	3.44
	X50	7.76	10.38	2.62
Orange 4 Bridge	X1	19.53	17.88	-1.65
	X5	9.72	8.51	-1.21
	X10	11.61	6.16	-5.45
	X20	12.14	10.95	-1.19
	X50	10.82	13.31	2.48
Orange 30 Box	X1	13.73	8.63	-5.10
	X5	4.58	9.17	4.58
	X10	9.28	14.37	5.10
	X20	7.68	11.27	3.59
	X50	16.47	12.33	-4.14
Orange 67 Bridge	X1	4.06	1.85	-2.21
	X5	6.27	13.18	6.91
	X10	6.68	10.48	3.80
	X20	5.33	11.87	6.54
	X50	9.28	6.94	-2.34
Person 38 Pipe	X1	8.56	8.70	0.14
	X5	9.37	10.51	1.14
	X10	7.53	8.70	1.17
	X20	10.11	7.57	-2.55
	X50	7.92	6.73	-1.19
Rand 349 Bridge	X1	20.78	25.19	4.41
	X5	16.35	21.67	5.32
	X10	12.33	21.90	9.56
	X20	11.09	21.10	10.00
	X50	13.84	16.09	2.25
Alamance 20 Box	X1	7.23	3.02	-4.21
	X5	30.49	26.81	-3.68
	X10	12.78	7.79	-4.99
	X20	12.73	8.96	-3.77
	X50	9.08	12.21	3.14
Moore 173 Bridge	X1	7.45	13.28	5.83
	X5	9.04	16.10	7.06
	X10	9.96	9.41	-0.55

		X-Area (m ²)	X-Area (m ²)	
		UpStrm	Dwn Strm	Difference
	X20	14.35	10.81	-3.54
	X50	15.96	9.38	-6.58
Alamance 29 Arch	X1	4.66	17.02	12.36
	X5	7.74	14.42	6.68
	X10	11.70	13.69	1.99
	X20	9.17	10.67	1.49
	X50	7.18	9.67	2.49
Orange 55 Bridge	X1	4.11	3.54	-0.58
	X5	5.39	3.09	-2.31
	X10	5.45	4.02	-1.43
	X20	5.69	6.35	0.66
	X50	3.74	6.28	2.54
Orange 13 Arch	X1	13.71	4.93	-8.77
	X5	19.94	25.30	5.36
	X10	23.56	23.94	0.38
	X20	20.09	34.49	14.40
	X50	14.86	27.92	13.06
Rand 220 Bridge	X1	6.41	2.41	-4.00
	X5	6.51	4.03	-2.48
	X10	5.51	5.30	-0.21
	X20	6.77	7.51	0.74
	X50	5.20	6.43	1.23
Rand 459 Pipe	X1	22.67	21.64	-1.03
	X5	9.72	25.92	16.21
	X10	11.04	17.86	6.82
	X20	8.85	10.25	1.40
	X50	10.01	7.85	-2.16

Hyporheic Depth Measurements

Site Name		Ave Depth	Ave Depth	Difference
		UpStrm	Dwn Strm	
Chatham 12 Arch	X1	10.28	10.03	-0.25
	X5	9.14	15.11	5.97
	X10	8.38	23.24	14.86
	X20	16.26	26.92	10.66
	X50	24.64	28.70	4.06
Granville 217 Pipe	X1	21.21	12.83	-8.38
	X5	35.43	9.91	-25.52
	X10	45.85	30.86	-14.99
	X20	31.50	4.06	-27.44
	X50	32.00	13.72	-18.28
Orange 4 Bridge	X1	4.32	7.24	2.92
	X5	1.78	8.96	7.18
	X10	12.57	5.59	-6.98
	X20	8.00	0.00	-8.00
	X50	12.36	4.70	-7.66
Orange 30 Box	X1	29.95	34.04	4.09
	X5	34.42	34.16	-0.26
	X10	25.02	25.27	0.25
	X20	10.79	30.35	19.56
	X50	9.14	22.73	13.59
Orange 67 Bridge	X1	10.41	24.13	13.71
	X5	25.78	17.78	-8.00
	X10	5.72	16.38	10.66
	X20	16.99	8.52	-8.47
	X50	24.77	4.32	-20.45
Person 38 Pipe	X1	42.06	50.32	8.26
	X5	32.65	38.97	6.32
	X10	28.45	19.03	-9.42
	X20	23.74	29.10	5.35
	X50	62.13	43.94	-18.19
Rand 349 Bridge	X1	14.97	6.32	-8.65
	X5	9.03	12.32	3.29
	X10	9.29	11.68	2.39
	X20	8.90	6.45	-2.45
	X50	14.45	12.58	-1.87
Alamance 20 Box	X1	30.13	33.16	3.03
	X5	31.74	13.74	-18.00
	X10	25.68	11.03	-14.65
	X20	34.26	18.06	-16.19
	X50	30.13	22.97	-7.16
Moore 173 Bridge	X1	19.55	6.32	-13.23
		Ave Depth	Ave Depth	
		UpStrm	Dwn Strm	Difference
	X5	20.32	5.10	-15.23

	X10	18.65	0.77	-17.87
	X20	31.23	3.55	-27.68
	X50	12.71	5.74	-6.97
Alamance 29 Arch	X1	15.87	21.61	5.74
	X5	18.52	7.35	-11.16
	X10	25.94	9.16	-16.77
	X20	27.81	17.81	-10.00
	X50	8.90	28.06	19.16
Orange 55 Bridge	X1	15.74	13.87	-1.87
	X5	26.39	19.81	-6.58
	X10	13.87	20.06	6.19
	X20	25.16	12.71	-12.45
	X50	26.90	22.00	-4.90
Orange 13 Arch	X1	10.52	9.42	-1.10
	X5	30.32	8.26	-22.06
	X10	38.13	24.77	-13.35
	X20	11.68	45.48	33.81
	X50	15.35	4.97	-10.39
Rand 220 Bridge	X1	21.10	9.42	-11.68
	X5	19.16	9.81	-9.35
	X10	3.94	10.06	6.13
	X20	11.03	12.45	1.42
	X50	8.77	20.19	11.42
Rand 459 Pipe	X1	20.84	30.00	9.16
	X5	23.23	24.39	1.16
	X10	44.84	18.13	-26.71
	X20	18.65	31.36	12.71
	X50	25.01	36.83	11.82

Riffle Areas

Site	Up/Dwn	Total (ft ^2)	Total (m^2)
Chatham 12	Up	4520.59	1377.89259
Chatham 12	Dwn	1782.27	543.242502
Granville 217	Up	568.33	173.22909
Granville 217	Dwn	2866.66	873.768593
Orange 4	Up	1213.31	369.821385
Orange 4	Dwn	0	0
Orange 30	Up	1129.49	344.272738
Orange 30	Dwn	0	0
Orange 67	Up	464.13	141.468544
Orange 67	Dwn	942.39	287.243965
Person 38	Up	248.93	75.8747866
Person 38	Dwn	0	0
Rand 349	Up	0	0
Rand 349	Dwn	0	0
Alamance 20	Up	0	0
Alamance 20	Dwn	0	0
Moore 173	Up	0	0
Moore 173	Dwn	1633.83	497.99744
Alamance 29	Up	562.86	171.561814
Alamance 29	Dwn	461.78	140.752256
Orange 55	Up	2290.71	698.216898
Orange 55	Dwn	2697.61	822.241526
Orange 13	Up	4796.32	1461.93611
Orange 13	Dwn	1325.66	404.066081
Rand 220	Up	432.41	131.800171
Rand 220	Dwn	382.84	116.691051
Rand 459	Up	709.78	216.343575
Rand 459	Dwn	1430.82	436.119239

Substrate Areas

			T0		T1	
			Area	Type	Area	Type
Chatham 12	Up Strm	FT^2	2013.9	Bedrock w/Gravel	2566.02	Bedrock w/Sand
		M^2	613.8442		782.132	
	Dwn Strm	FT^2	1118.46	Gravel w/Cobble	2447.96	Cobble w/Gravel
		M^2	340.9108		746.147	
Granville 217Pipe	Up Strm	FT^2	371.6	Sand w/Cobble	495.59	Cobble w/Sand
		M^2	113.2651		151.058	
	Dwn Strm	FT^2	866.47	Sand w/Cobble	887.47	Cobble w/Gravel
		M^2	264.1033		270.504	
Orange 4 Bridge	Up Strm	FT^2	1393.15	Bedrock	2062.81	Bedrock w/Cobble
		M^2	424.6373		628.752	
	Dwn Strm	FT^2	1929.91	Bedrock w/Gravel	1839.57	Bedrock w/ Cobble
		M^2	588.2437		560.708	
Orange 30 Box	Up Strm	FT^2	994.09	Cobble w/Gravel	1098.02	Gravel w/Sand
		M^2	303.0023		334.681	
	Dwn Strm	FT^2	1039.88	Sand w/Cobble	1074.22	Cobble w/Gravel
		M^2	316.9593		327.426	
Orange 67 Bridge	Up Strm	FT^2	985.42	Bedrock w/Cobble	1029.07	Cobble w/Gravel
		M^2	300.3597		313.664	
	Dwn Strm	FT^2	326.19	Cobble w/Sand	980.16	Cobble w/Gravel
		M^2	99.42392		298.756	
Person 38	Up Strm	FT^2	887.05	Cobble w/Gravel	2070.61	Gravel w/Cobble
		M^2	270.3761		631.13	
	Dwn Strm	FT^2	750.68	Sand w/Gravel	1552.02	Gravel w/Cobble
		M^2	228.81		473.061	
Rand 349 Bridge	Up Strm	FT^2	900.11	Cobble w/Bedrock	458.92	Cobble w/Gravel
		M^2	274.3569		139.881	
	Dwn Strm	FT^2	5899.28	Bedrock w/Cobble	993.1	Bedrock w/Sand
		M^2	1798.122		302.701	
4 Box 87	Up Strm	FT^2	1027.64	Sand w/Cobble	585.78	Gravel w/Cobble
		M^2	313.2285		178.548	
	Dwn Strm	FT^2	285.9	Sand	3211.1	Cobble w/Gravel
		M^2	87.14338		978.755	
Moore 173	Up Strm	FT^2	2916.84	Gravel w/Sand	1561.19	Cobble w/Gravel
		M^2	889.0636		475.856	
	Dwn Strm	FT^2	19991.65	Cobble w/Bedrock	256.66	
		M^2	6093.529		78.2309	
Orange 29 Arch	Up Strm	FT^2	558.34	Bedrock	887.64	Bedrock w/Cobble
		M^2	170.1841		270.556	
	Dwn Strm	FT^2	2376.69	Sand	928.08	Cobble w/ Gravel
		M^2	724.4239		282.882	
Orange 55 Br	Up Strm	FT^2	449.99	Cobble w/Bedrock	308.2	Cobble
		M^2	137.1586		93.9405	
	Dwn Strm	FT^2	875.67	Cobbel w/Bedrock	3970.73	Cobble
		M^2	266.9075		1210.29	
Orange Cnt 57	Up Strm	FT^2	759.58	Cobble w/Sand	469.51	Bedrock w/Sand
		M^2	231.5228		143.108	
	Dwn Strm	FT^2	1702.32	Bedrock w/Gravel	862.11	Bedrock w/Cobble

		M^2	518.8734		262.774	
Rand 10 Brd	Up Strm	FT^2	1899.81	Bedrock w/Gravel	1068.05	Bedrock w/ Cobble
		M^2	579.0691		325.546	
	Dwn Strm	FT^2	974.78	Bedrock w/Gavel	360.43	Bedrock
		M^2	297.1166		109.86	
Rand 459	Up Strm	FT^2	3269.61		523.42	
		M^2	996.5892		159.54	
	Dwn Strm	FT^2	1833.75	Sand w/Gravel	1002.13	Gravel w/Sand
		M^2	558.9338		305.453	

Site Name			T2		T3	
			Area	Type	Area	Type
Chatham 12	Up Strm	FT^2	1112.98	Cobble w/Sand	1249.54	Gravel w/Cobble
		M^2	339.2404		380.864	
	Dwn Strm	FT^2	2077.73	Gravel w/Cobble	1930.85	Cobble w/Gravel
		M^2	633.2998		588.53	
Granville 217Pipe	Up Strm	FT^2	2076.22	Cobble	151.41	Cobble w/Gravel
		M^2	632.8396		46.1503	
	Dwn Strm	FT^2	733.17	Cobble w/Bedrock	1069.12	Cobble
		M^2	223.4729		325.872	
Orange 4 Bridge	Up Strm	FT^2	1994.74	Bedrock w/Sand	2626.35	Bedrock w/ Gravel
		M^2	608.0041		800.521	
	Dwn Strm	FT^2	116.29	Bedrock w/Gravel	298.69	Bedrock
		M^2	35.44562		91.0418	
Orange 30 Box	Up Strm	FT^2	659.49	Bedrock w/Gravel	795.54	Gravel w/Sand
		M^2	201.015		242.484	
	Dwn Strm	FT^2	3037.05	Cobble w/Bedrock	2662.69	Sand
		M^2	925.7041		811.598	
Orange 67 Bridge	Up Strm	FT^2	645.17	Cobble w/Sand	546.98	Sand w/Cobble
		M^2	196.6502		166.722	
	Dwn Strm	FT^2	2984.47	Cobble w/Bedrock	1278.6	Cobble w/Gravel
		M^2	909.6775		389.722	
Person 38	Up Strm	FT^2	3776.11	Gravel w/Sand		
		M^2	1150.972			
	Dwn Strm	FT^2	1164.7	Gravel w/Sand	819.96	Sand w/Gravel
		M^2	355.0049		249.927	
Rand 349 Bridge	Up Strm	FT^2	1637.67	Cobble w/Bedrock	2405.68	Bedrock w/Cobble
		M^2	499.1679		733.26	
	Dwn Strm	FT^2	2101.79	Bedrock		
		M^2	640.6334			
4 Box 87	Up Strm	FT^2	346.47	Cobble w/Gravel	571.05	Gravel w/Cobble
		M^2	105.6053		174.058	
	Dwn Strm	FT^2	866.18	Cobble w/Gravel	681.43	Sand
		M^2	264.0149		207.702	
Moore 173	Up Strm	FT^2	1288.88	Cobble w/Bedrock	1528.48	Cobble
		M^2	392.8554		465.886	
	Dwn Strm	FT^2	325.69		1296.1	
		M^2	99.27152		395.056	
Orange 29 Arch	Up Strm	FT^2	549.24	Bedrock w/Sand	711.96	Gravel w/Sand

		M^2	167.4104		217.008	
	Dwn Strm	FT^2	527.53	Cobble w/Sand	1192.65	Gravel w/Sand
		M^2	160.7931		363.524	
Orange 55 Br	Up Strm	FT^2	2123.88	Cobble w/Gravel	751.69	Cobble
		M^2	647.3665		229.118	
	Dwn Strm	FT^2	1100.99	Cobble w/Gravel		
		M^2	335.5858			
Orange Cnt 57	Up Strm	FT^2	1043.19	Sand	1764.49	Bedrock w/Cobble
		M^2	317.9682		537.823	
	Dwn Strm	FT^2	3316.38	Sand w/Cobble	2724.16	Bedrock w/Gravel
		M^2	1010.845		830.334	
Rand 10 Brd	Up Strm	FT^2	1637.89	Cobble w/Gravel		
		M^2	499.2349			
	Dwn Strm	FT^2	1252.39	Bedrock w/Sand	1210.08	Sand w/Gravel
		M^2	381.7331		368.837	
Rand 459	Up Strm	FT^2	1875.97		370.55	
		M^2	571.8026		112.945	
	Dwn Strm	FT^2	1475.83	Gravel	420.69	Sand
		M^2	449.8385		128.228	

Site Name			T4		T5	
			Area	Type	Area	Type
Chatham 12	Up Strm	FT^2	3281.64	Cobble w/Gravel		Cobble w/Bedrock
		M^2	1000.256			
	Dwn Strm	FT^2	2336.28	Gravel w/Cobble		
		M^2	712.1068			
Granville 217Pipe	Up Strm	FT^2	2992.29	Cobble w/Sand		
		M^2	912.0611			
	Dwn Strm	FT^2	1302.45	Cobble w/Sand	998.07	Gravel w/Cobble
		M^2	396.9916		304.215	
Orange 4 Bridge	Up Strm	FT^2				
		M^2				
	Dwn Strm	FT^2	1046.52	Bedrock w/Gravel	1282.68	Bedrock w/Sand
		M^2	318.9832		390.966	
Orange 30 Box	Up Strm	FT^2	1166.45	Bedrock w/Sand	583.38	Gravel w/Cobble
		M^2	355.5383		177.816	
	Dwn Strm	FT^2				
		M^2				
Orange 67 Bridge	Up Strm	FT^2	2358.7	Cobble w/Sand		Sand
		M^2	718.9405			
	Dwn Strm	FT^2	1463.32	Cobble w/Bedrock	1137.41	Cobble w/Bedrock
		M^2	446.0254		346.687	
Person 38	Up Strm	FT^2				
		M^2				
	Dwn Strm	FT^2	1500.92	Sand w/Gravel		
		M^2	457.486			
Rand 349 Bridge	Up Strm	FT^2	498.84	Cobble	404.35	Sand w/Cobble
		M^2	152.0483		123.247	
	Dwn Strm	FT^2				

		M^2				
4 Box 87	Up Strm	FT^2	548.5	Sand w/Cobble	757.78	Gravel w/Cobble
		M^2	167.1848		230.974	
	Dwn Strm	FT^2	1120.71			
		M^2	341.5966			
Moore 173	Up Strm	FT^2				
		M^2				
	Dwn Strm	FT^2	834.24		757.95	
		M^2	254.2794		231.026	
Orange 29 Arch	Up Strm	FT^2	1222.71	Cobble w/Gravel	1877.6	Cobble w/Bedrock
		M^2	372.6865		572.299	
	Dwn Strm	FT^2	1594.75	Gravel		Gravel w/Cobble
		M^2	486.0857			
Orange 55 Br	Up Strm	FT^2	938.13	Gravel w/Cobble	612.14	Cobble
		M^2	285.9455		186.583	
	Dwn Strm	FT^2				
		M^2				
Orange Cnt 57	Up Strm	FT^2	2026.62	Bedrock w/Cobble	2451.12	Cobble w/Bedrock
		M^2	617.7213		747.11	
	Dwn Strm	FT^2	3978.68	Bedrock w/Sand		
		M^2	1212.716			
Rand 10 Brd	Up Strm	FT^2				
		M^2				
	Dwn Strm	FT^2	914.81	Bedrock w/Gravel		
		M^2	278.8375			
Rand 459	Up Strm	FT^2				
		M^2				
	Dwn Strm	FT^2	1022.59	Gravel	521.15	Sand w/Gravel
		M^2	311.6892		158.848	

Site Name			T6		T7	
			Area	Type	Area	Type
Chatham 12	Up Strm	FT^2				
		M^2				
	Dwn Strm	FT^2				
		M^2				
Granville 217Pipe	Up Strm	FT^2				
		M^2				
	Dwn Strm	FT^2	597.12			
		M^2	182.0044			
Orange 4 Bridge	Up Strm	FT^2				
		M^2				
	Dwn Strm	FT^2	738.9	Bedrock	386.78	
		M^2	225.2195		117.892	
Orange 30 Box	Up Strm	FT^2	445.26	Cobble w/Gravel	680.27	Gravel w/Cobble
		M^2	135.7169		207.349	
	Dwn Strm	FT^2				
		M^2				
Orange 67 Bridge	Up Strm	FT^2				

		M^2				
	Dwn Strm	FT^2	684.88	Cobble w/Gravel		Bedrock w/ Cobble
		M^2	208.754			
Person 38	Up Strm	FT^2				
		M^2				
	Dwn Strm	FT^2				
		M^2				
Rand 349 Bridge	Up Strm	FT^2	2121.52	Cobble w/Bedrock		
		M^2	646.6472			
	Dwn Strm	FT^2				
		M^2				
4 Box 87	Up Strm	FT^2	1347.78	Sand w/Cobble	554.54	Cobble w/Sand
		M^2	410.8083		169.026	
	Dwn Strm	FT^2				
		M^2				
Moore 173	Up Strm	FT^2				
		M^2				
	Dwn Strm	FT^2	1382.42			
		M^2	421.3667			
Orange 29 Arch	Up Strm	FT^2				
		M^2				
	Dwn Strm	FT^2				
		M^2				
Orange 55 Br	Up Strm	FT^2	836.25	Cobble w/Gravel		Cobble
		M^2	254.8921			
	Dwn Strm	FT^2				
		M^2				
Orange Cnt 57	Up Strm	FT^2	1856.86	Bedrock w/Cobble		
		M^2	565.9778			
	Dwn Strm	FT^2				
		M^2				
Rand 10 Brd	Up Strm	FT^2				
		M^2				
	Dwn Strm	FT^2				
		M^2				
Rand 459	Up Strm	FT^2				
		M^2				
	Dwn Strm	FT^2	829.61	Gravel		
		M^2	252.8682			

Site Name			T8		Total	
			Area	Type		
Chatham 12	Up Strm	FT^2			8210.18	FT^2
		M^2			2502.493	M^2
	Dwn Strm	FT^2			8792.82	FT^2
		M^2			2680.084	M^2
Granville 217Pipe	Up Strm	FT^2			5715.51	FT^2
		M^2			1742.109	M^2
	Dwn Strm	FT^2			5587.4	FT^2
		M^2			1703.06	M^2

Orange 4 Bridge	Up Strm	FT^2			6683.9	FT^2
		M^2			2037.277	M^2
	Dwn Strm	FT^2			5709.43	FT^2
		M^2			1740.255	M^2
Orange 30 Box	Up Strm	FT^2	571.19	Gravel/Cobble/Bedrock	5999.6	FT^2
		M^2	174.1		1828.7	M^2
	Dwn Strm	FT^2			6773.96	FT^2
		M^2			2064.728	M^2
Orange 67 Bridge	Up Strm	FT^2			4579.92	FT^2
		M^2			1395.977	M^2
	Dwn Strm	FT^2			8528.84	FT^2
		M^2			2599.622	M^2
Person 38	Up Strm	FT^2			5846.72	FT^2
		M^2			1782.102	M^2
	Dwn Strm	FT^2			5037.6	FT^2
		M^2			1535.479	M^2
Rand 349 Bridge	Up Strm	FT^2			7526.98	FT^2
		M^2			2294.251	M^2
	Dwn Strm	FT^2			3094.89	FT^2
		M^2			943.3339	M^2
4 Box 87	Up Strm	FT^2			4711.9	FT^2
		M^2			1436.205	M^2
	Dwn Strm	FT^2			5879.42	FT^2
		M^2			1792.069	M^2
Moore 173	Up Strm	FT^2			4378.55	FT^2
		M^2			1334.598	M^2
	Dwn Strm	FT^2			4853.06	FT^2
		M^2			1479.231	M^2
Orange 29 Arch	Up Strm	FT^2			5249.15	FT^2
		M^2			1599.96	M^2
	Dwn Strm	FT^2			4243.01	FT^2
		M^2			1293.285	M^2
Orange 55 Br	Up Strm	FT^2			5570.29	FT^2
		M^2			1697.845	M^2
	Dwn Strm	FT^2			5071.72	FT^2
		M^2			1545.879	M^2
Orange Cnt 57	Up Strm	FT^2			9611.79	FT^2
		M^2			2929.709	M^2
	Dwn Strm	FT^2			10881.33	FT^2
		M^2			3316.67	M^2
Rand 10 Brd	Up Strm	FT^2			2705.94	FT^2
		M^2			824.7805	M^2
	Dwn Strm	FT^2			3737.71	FT^2
		M^2			1139.268	M^2
Rand 459	Up Strm	FT^2			2769.94	FT^2
		M^2			844.288	M^2
	Dwn Strm	FT^2			5272	FT^2
		M^2			1606.925	M^2