EFFECTS OF INLET CONDITIONS ON CULVERT DISCHARGE

A PAPER
submitted to Oregon State University
in partial fulfillment of
the requirements for the degree of

MASTER OF FORESTRY

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INTRODUCTION

Oregon has thousands of culverts along mountainous roads that interact with perennial streams, intermittent streams, and intercepted subsurface flow from hill slopes. Culverts installed at stream crossings are designed to move water under the road and avoid failure of the fill. Similarly, ditch relief culverts transfer water through a road prism.

There are two main issues that are often considered when designing a stream crossing culvert: fish passage and peak flow. For example, Oregon Department of Fish and Wildlife (ODFW) has developed fish passage guidelines that apply to any stream utilized by fish (ODFW, 1997). In addition, Oregon's Forest Practice rules require culvert drainage structures in forest roads to pass a peak flow that at least corresponds to the 50-yr return interval (ODF, 1995).

The inlet area of installed culverts is sometimes damaged or reduced in size after installation in forest roads. Reductions in the cross sectional area of inlets is usually related to factors such as sediment deposition, debris blockage, and structural damage. The major concern with partially plugged culvert inlets (reduced flow area) is that the reduction of flow area of the culvert inlet increases the possibility of failure during a peak flow. Piehl (1987) made a random sample selection of stream crossing culverts and ditch relief culverts on the Oregon Coast Range. He found that the average inlet cross-sectional area of stream crossing culverts was 88% of the original end area. Denting and sediment blockage were the most frequent factors causing reduction.

Understanding the hydraulic conditions of partially plugged culverts is fundamental evaluating their effect on peak flow events. Depth of flow, flow velocity, and available area for flow are critical factors considered by the guidelines and regulations of the ODFW and Oregon Department of Forestry (ODF). With a better understanding of culvert inlet conditions water resource managers will be able to establish priorities of maintenance, estimate risk of failure, predict implications relative to high flows, and identify culverts that need to be replaced.

The overall purpose of this project is to evaluate potential effects of inlet constrictions on culvert discharge. Analysis and recommendations for peak discharges will be presented after evaluating the effects of inlet conditions on flow capacity.

OBJECTIVES

- To determine the reduction of hydraulic capacity in culverts for peak flow events due to reduction of area of flow.
- To determine changes in velocity of flow in culverts due to sediment deposition and woody debris lodged across the inlet.

LITERATURE REVIEW

Most of the literature associated with constrictions of stream crossing culverts is based on the identification of the type of constriction and the quantification of the cross-sectional area of the inlet that is available for flow. While abundant literature regarding culvert hydraulics is available, this information only provides guidelines based on theoretical and experimental relationships for clear-water and seldom acknowledges the potential for deposition of sediment or debris at the inlet. In general, there has been little research that has evaluated the effects of inlet conditions upon culvert discharge.

In a study of culvert inlets in the Oregon Coast Range, Ledwith et al. (1997) found that from a total of 18 culverts with reduction of inlet area, 39% were associated with sediment deposition, 22% with woody debris, and 33% with both large woody debris and sediment. In a similar study, Piehl (1987) found that from all culverts with reduction of inlet cross sections 9% was related with organic debris and 16% a combination of both sediment and organic debris.

Ledwith et al. (1997) identified woody debris plugging and sediment deposition as the governing factors for inlet reduction. Plugging of culverts by woody debris is likely initiated by a piece of wood lodged across the inlet, which in turn increases the possibility for more debris to accumulate and the culvert inlet to be partially or completely plugged, (Figure 1). Similarly, sediment deposition comprising colluvium or bedload particles can also reduce the inlet area. Ponding of water at a culvert inlet due to plugging results in

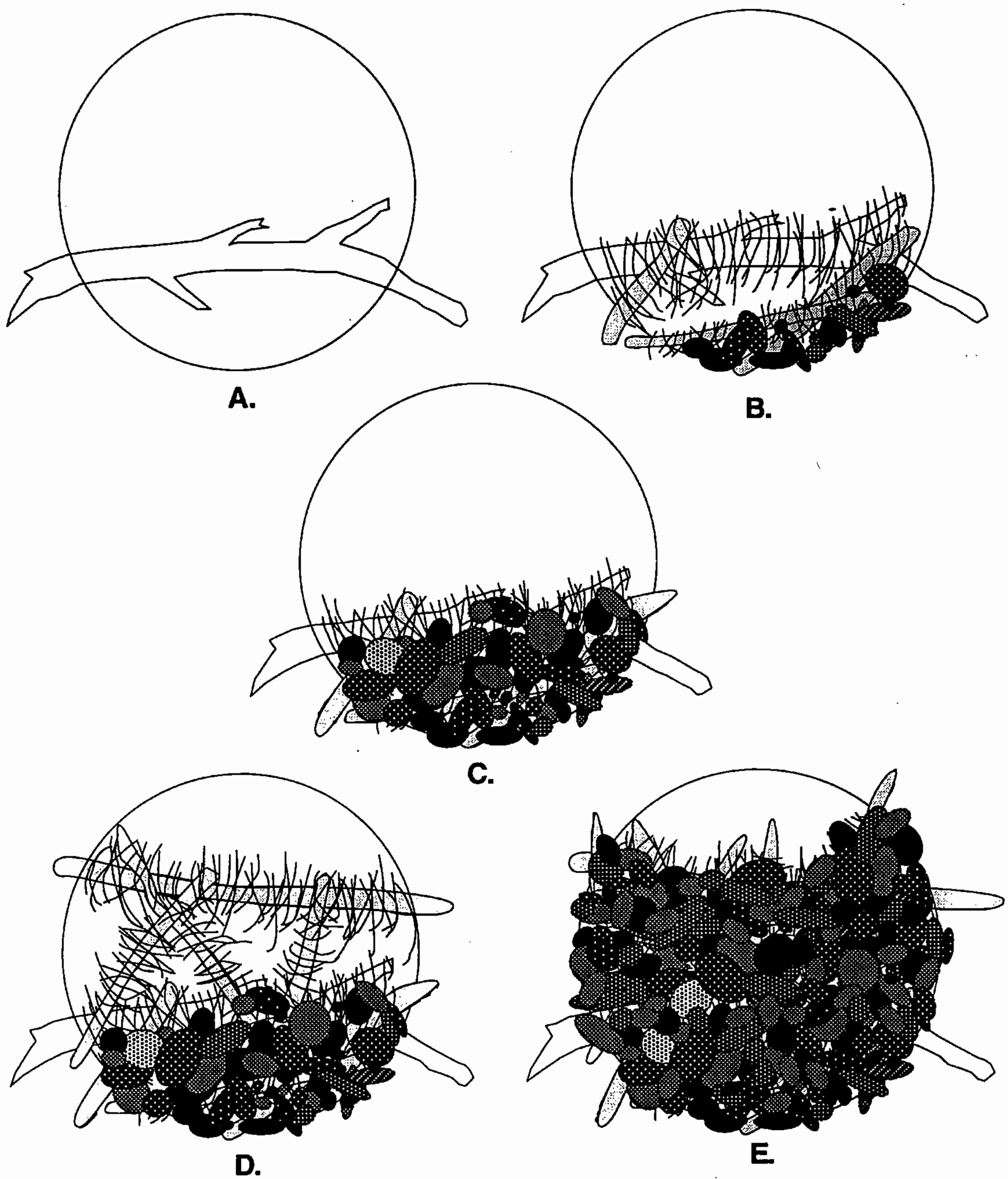


Figure 1. Progress in reduction of flow area in a culvert inlet from a single piece lodging across the inlet (A) to a nearly plugged wood/sediment matrix (E) (Adapted from Ledwidth et al. 1997).

deposition of sediment, which eventually may lead the flow to exit the stream channel and damage the road prism or cause saturation of earth fills over the culvert.

One approach to measuring the discharge of a plugged culvert is explained by Kohler and Hager (1997). They evaluated the accuracy of a "pipe flume" to measure discharge in partially filled pipes. A pipe flume is a device mounted temporarily in a channel for discharge measurement and uses a cylindrical element positioned axially into a channel of well defined geometry. Their device was able to account for the effects of pipe filling, element constriction, and element position.

Vassilios and Tsihtintzis (1995) presented a study case in which the actual capacity of a stream crossing culvert was 20% of the calculated design capacity as a result of sediment deposition. Thus, 2000 cubic feet per second (cfs) discharge caused local flooding despite the fact that the original hydraulic capacity of the culvert was calculated to be 6000 cfs. The following relatioship illustrates the effects of several variables on channel capacity:

$$QS \approx Q_s d_{50}$$

where Q = discharge, S = slope, Q_s = sediment transport capacity, and d_{50}= the median grain size of the bed material. Based on this relationship, a reduction in sediment transport capacity can be expected if the slope of the channel is reduced, assuming Q and d_{50} remain unchanged. Using survey methods, Vassilios and Tsihtintzis (1995) found that the slope of the culvert barrel was 60% of the channel slope, i.e., a 60% reduction in sediment transport capacity.

Literature regarding experimental studies in laboratory conditions for pipes flowing partially full or with reductions in cross sectional area is scarce. However, studies have been conducted with a variably-sloped culvert connected to a rectangular flume, which in turn is connected to a reservoir (Rajaratnam et al. 1989, Rajaratnam and Katopodis 1990, Mainali and Rajaratnam 1994). Usually, a flow meter and a control valve are used to adjust of the amount of water that is supplied to the culvert.

As part of a larger study on culvert fishways, Rajaratnam and Katopodis (1990) studied the characteristics of flow in the entrance region of a circular pipe. Measurements of velocity and depth of flow over a range of discharges were evaluated in a plastic pipe with an inside diameter of 0.305 m and length of 6.3 m for slopes of 1, 3 and 5%. Figure 2 shows water surface profiles along the center plane of the upstream channel and for approximately 1 m inside the pipe. For the three slopes, when the discharge was increased there was also an increase in the "wavy profile" (i.e., changes in depth in the center profile) which attenuated further down the pipe until the depth of flow became constant. Velocities along the center plane were also measured (Figure 3) and indicate an abrupt acceleration in velocity at the culvert entrance. High velocities corresponded to large discharges; major changes in velocity did not occur as slope increased.

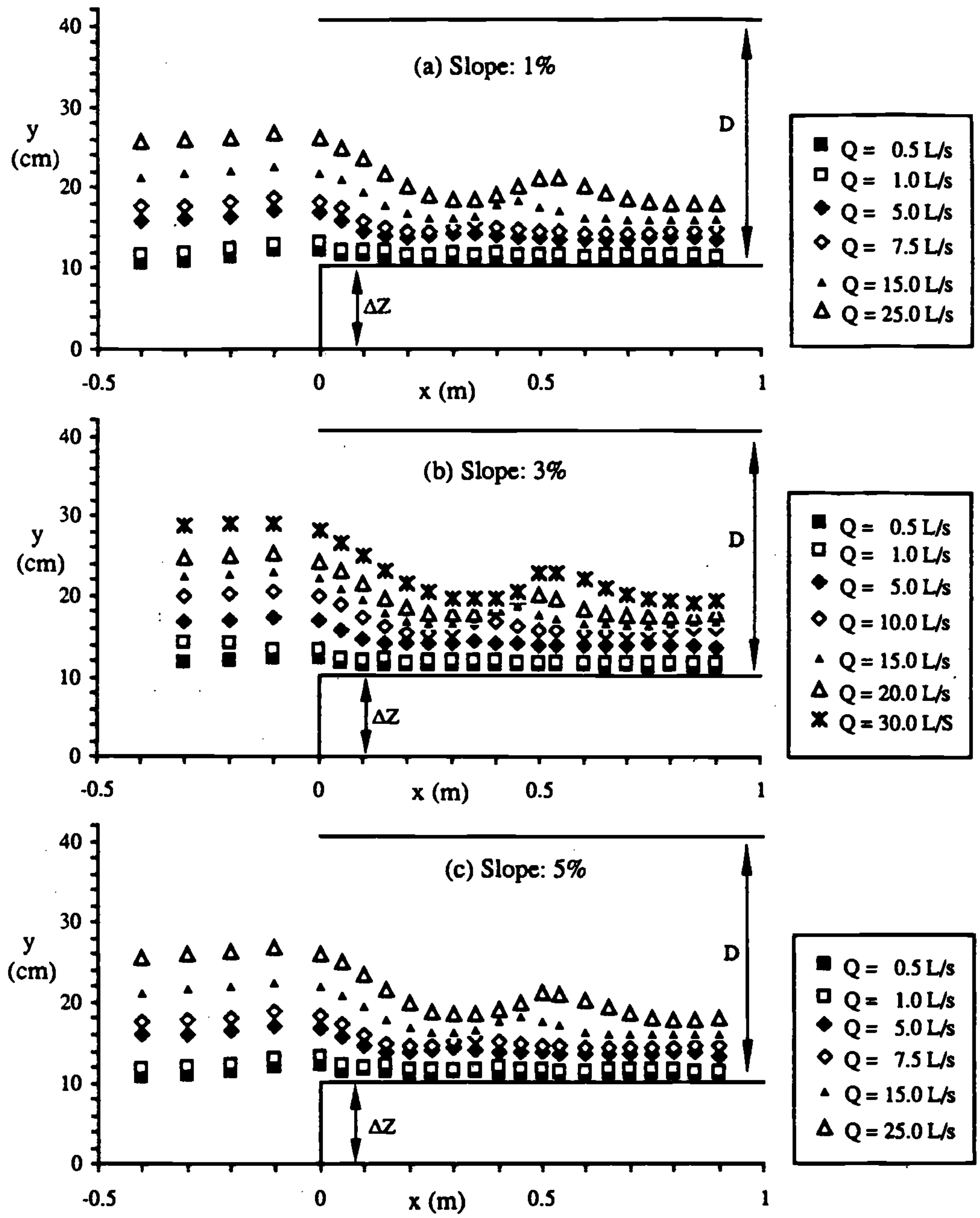


Figure 2. Water surface profiles over a range of discharges (Q); culvert inlet is at x=0 and D=0.305 m (Adapted from Rajaratman and Katopodis 1990).

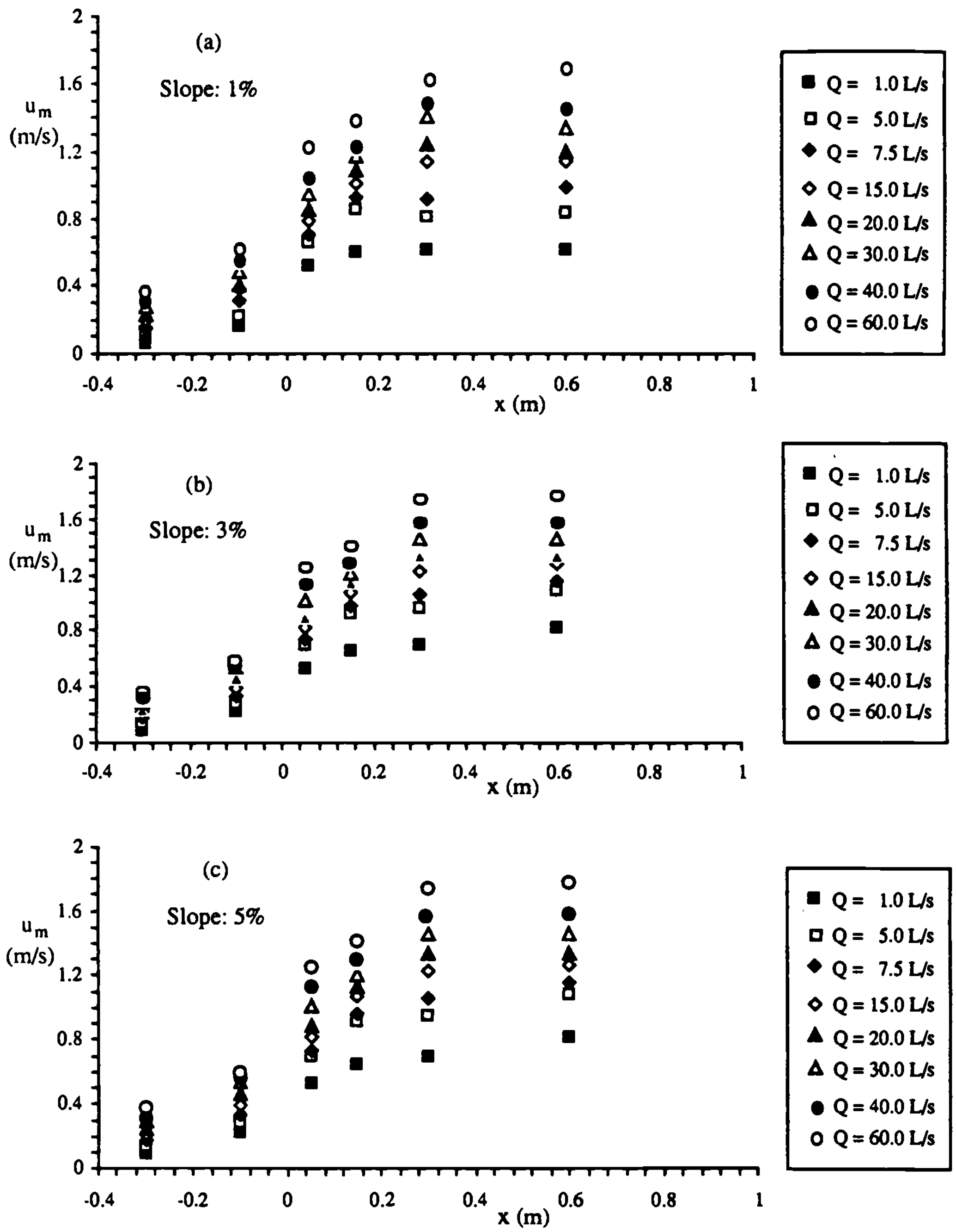


Figure 3. Longitudinal variation of point velocity over a range of discharges (Q); culvert inlet is at x=0 (Adapted from Rajaratman and Katopodis 1990).

Rajaratman and Katopodis (1990) presented a hydraulics study for a culvert modified to improve fish passage conditions. The proposed culvert was divided into a number of cells which provided resting areas and a velocity barrier. This design was based on the idea that fish use their burst speed to get past a barrier and rest in the next pool. Flow equations and equations for the barrier velocity were developed to simulate the hydraulic conditions in this new culvert design.

White (1996) studied countersunk culverts as an alternative for fish migration. Countersunk structures allow water resource managers to place natural substrate inside the culvert, simulating natural channel conditions. A streambed of natural substrates is currently believed to be effective in fish passage design since it reduces average stream velocity and creates low velocity pockets. The design of culverts with regard of fish migration must account for a wide range of hydraulic conditions under which the fish can proceed upstream. Water velocity is a critical factor. For juvenile salmonids information suggest that velocity in the 1 ft/s to 2 ft/s range or lower depending on the size of fish is passable.

Mott (1994) inidicates that open channel flow can be classified into three main types depending on the discharge and depth: (1) uniform steady flow where both discharge and depth are constant, (2) varied steady flow where the discharge remains constant but the depth of the fluid varies along the section of interest, and (3) unsteady varied flow, in which both discharge and depth varies vary. The variety of flow conditions encountered with various stream systems makes estimation of design flows difficult. However, culvert design is simplified when flow type can be classified as supercritical or subcritical. In general, shallow and high velocities of flow, known as “supercritical” characterize inlet control and is the most common situation encountered for culverts. For this case, the flow passes through critical depth at the inlet of the pipe. On the other hand, outlet control has deep and low velocities of flow known as "subcritical" and flow will pass through critical depth at the outlet of the pipe (ODOT, 1990).

Subcritical flow in the culvert barrel is the most appropriate design for fish passage since low velocities and large water depths characterize this type of flow. In other words, outlet control flow conditions are preferable to inlet control conditions when fish passage is desired. However, this is an uncommon situation for culverts installed in the Oregon Coast Range, not only because of relatively steep channel slopes (often larger than 6%, in the Oregon Coast Range (Piehl 1987)), but also due to the difficulties in the design of culverts with outlet control. Where culvert gradients are relatively low, obstructions downstream of a culvert or frictional resistance to flow within a pipe may cause subcritical flow to develop within the culvert; installations operating with these conditions require relatively detailed hydraulic assesments (Pyles 1998).

METHODOLOGY

While flow velocity or discharge is commonly estimated with the Manning's equation (1) empirically obtained resistant coefficients and characteristics of the channel are needed to solve this equation:

$$V=(1.49/n)R_h^{2/3}S_e^{1/2} \qquad (1)$$

where:

- $V=$ Average flow velocity, ft/sec
- $n=$ Manning's channel roughness value
- $R_h=$ Hydraulic radius = Area/wetted perimeter, ft^2/ft
- $S_e=$ Slope, ft/ft

A table with empirically obtained resistance coefficients (n) is provided in appendix A. In the following computations it is assumed that corrugated metal pipes have a resistance coefficient of 0.024 and constrictions have a resistance coefficient of 0.030. A weighted roughness coefficient must be computed (see equation 2) when the channel is composed of more than one subsection with different roughness values. This weighted resistance or composite roughness coefficient is used to represent the entire channel cross section and is know as composite roughness (Meadows and Walski 1997).

The formula used to calculate the weighted coefficient is as follows:

$$n_t=[\Sigma wp_i(n_i)^{3/2}/wp_t]^{2/3} \qquad (2)$$

Where:

- $n_t=$ Weighted coefficient
- $wp_i=$ Wetted perimeter of the subsection (i).
- $n_i=$ Manning's channel roughness value of subsection (i).
- $wp_t=$ Total wetted perimeter

The procedure used to determine the composite roughness coefficient for various inlet and flow conditions is explained in Appendix B.

A software program named Flow Master developed by Haestad Methods was used to calculate flow in open channels based on Manning's equation, and allowed for simulation of differing culvert inlet conditions. The shape of an 18-inch corrugated metal pipe culvert was simulated using the coordinates of the circle equation with radius equal to nine inches. Constrictions at the inlet were then simulated with increases of two inches in horizontal and vertical directions as shown in Figure 4. The effects of constrictions on maximum discharge and velocity were evaluated for depths of flow ranging from 0 to 18 inches in corrugated metal pipes.

Two different types of constriction at the culvert inlet were considered: 1) sedimentation on the bed of the culvert, and 2) vertical wood piece of varying width. For this study, sediment was considered as horizontal constriction and debris as vertical constriction. To allow for comparison between horizontal and vertical constriction effects, the following parameters were held constant:

Size of constrictions: 2, 4, 6 and 8 inches
Slope: 6%
Culvert type: 18-in corrugated metal pipe
Culvert Roughness coefficient: 0.024
Constriction Roughness coefficient: 0.030

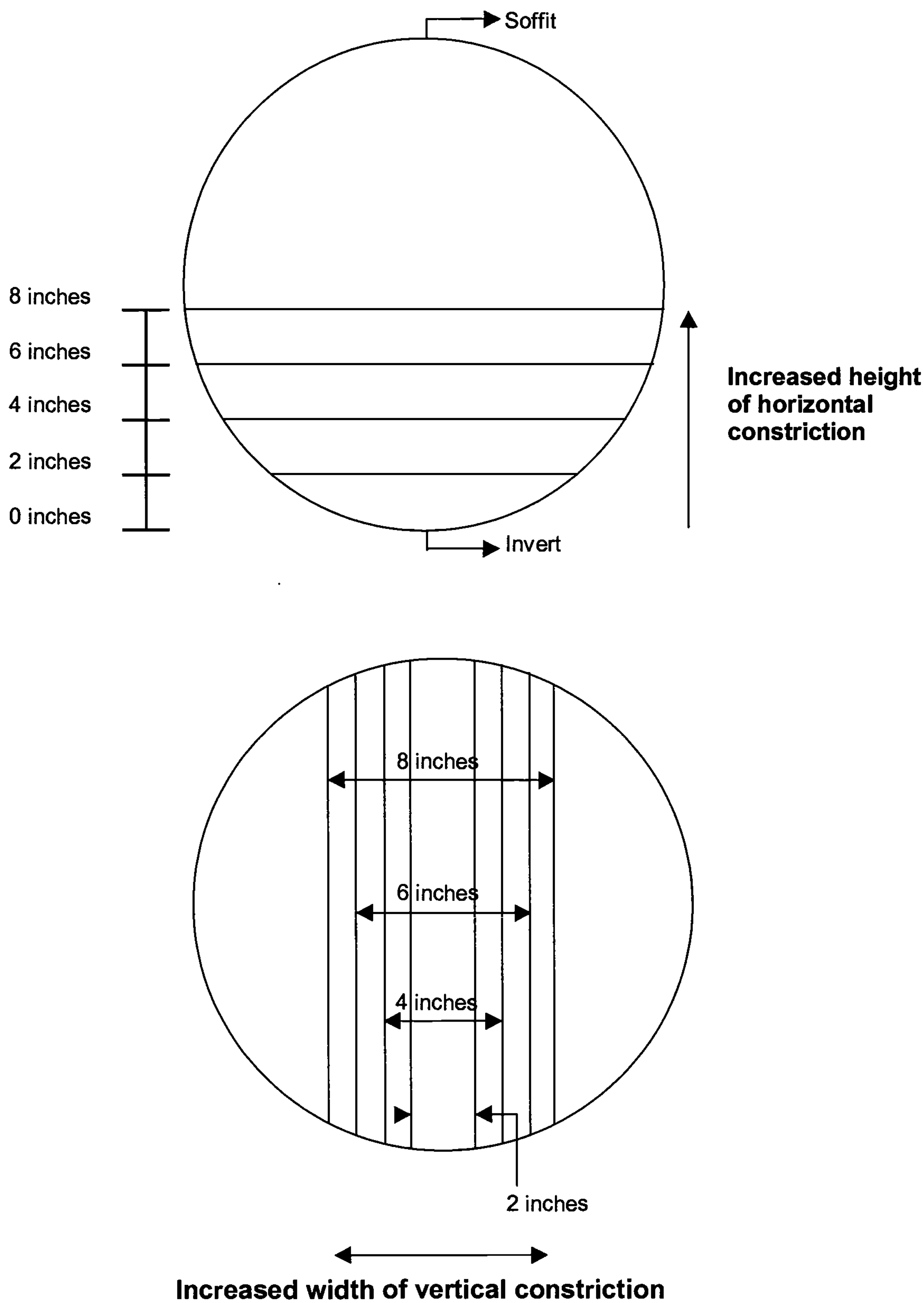


Figure 4. Simulation of horizontal and vertical constriction at the culvert inlet.

RESULTS AND DISCUSSION

Culvert slope, hydraulic roughness and inlet shape of the inlet are important factors influencing the capability of a culvert to transport water. These factors are often important whether a culvert is under inlet or outlet control.

Effect of roughness coefficient in flow class.

The flow class associated with a given discharge can change from supercritical to subcritical (inlet control to outlet control) as the roughness coefficient increases (e.g., due to constrictions at the culvert inlet). A culvert designed to function in supercritical conditions with a designed flow of 7.0 cfs changes to a subcritical condition when the roughness coefficient (n) is increased from 0.04 to 0.06 (Figure 5). The critical depth for a discharge of 7.0 cfs is 1.2 ft and the normal depth for a 0.04 and 0.06 roughness coefficients is 1.13 and 1.36 respectively.

Effect of slope in maximum discharges and velocities.

There is a direct relationship between velocity and slope in culvert flow (Figure 6-b). In the case of unplugged culverts, the only resistance to flow along most of the culvert is due to the roughness coefficient (n) (for a corrugated metal pipe n=0.024). It was found that the flow class is supercritical in all the slopes larger than 2% except for depths of flow between 0.2 and 0.8 ft at the 2 % slope. For a corrugated metal pipe of 18 inches in diameter, maximum flow velocity increases from 5 ft/s to 11.5 ft/s when slope is increased from 2% to 10%. Rothwell (1978) recommends placing culverts at a minimum

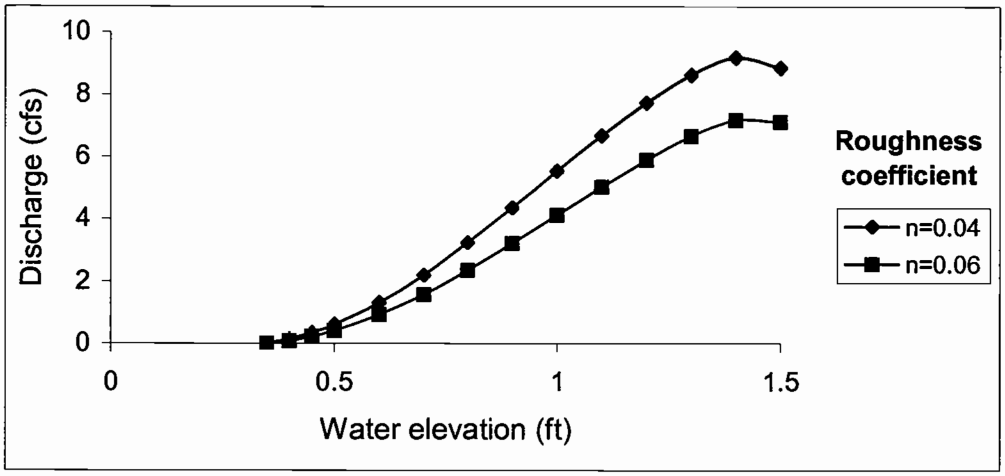


Figure 5. Effect of roughness coefficient (n) of a horizontal constriction (4 inches above invert) on flow class for an 18 inch diameter pipe with a 6% slope.

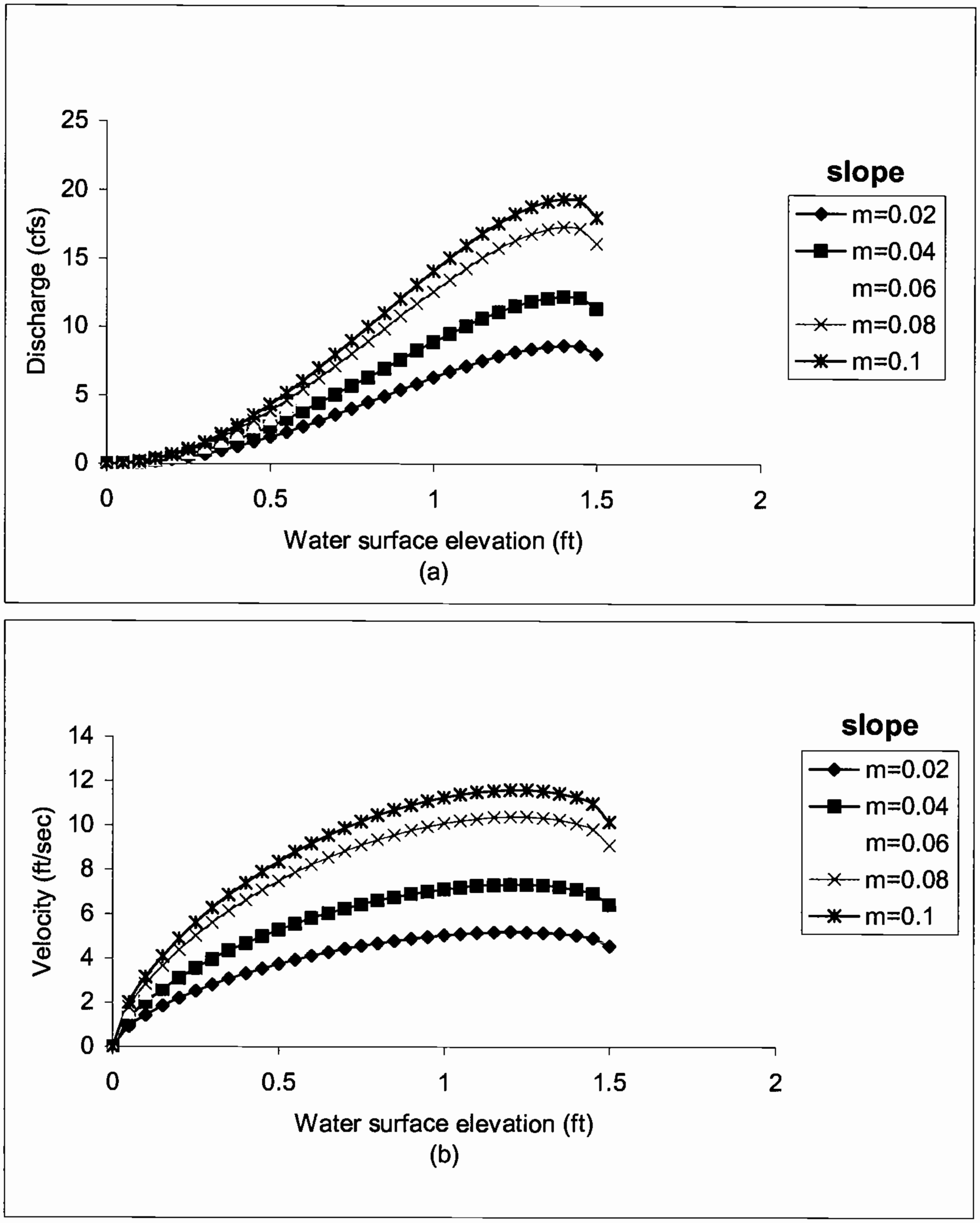


Figure 6. Effects of slope (m) on: (a) discharge and (b) velocity, assuming barrel friction as the factor limiting flow (Manning's n=0.024)

3 % slope to maintain high water velocities and prevent deposition of sediment. In a case study, of Amargosa Creek, California, Vassilios and Tsihrintzis (1995) suggested that the failure of a stream-crossing culvert was due to slope reduction of the natural channel by 60%. The authors suggested a wider culvert with more barrels and a steeper slope as a possible solution to this capacity problem. However, increases in slope may be detrimental for fish passage, whereas pipes installed at low to moderate slopes facilitate fish passage (Pyles 1998).

Effects of constrictions in discharge.

Hydraulic capacity in unplugged culverts is higher than in plugged culverts. There are three reasons for this: (1) plugged culverts have a reduction of area available for flow, (2) plugged culverts increase the depth of flow due to an increase in the roughness coefficient, and (3) wetted perimeter may increase depending on the type of constriction.

Effect of horizontal constriction in discharge.

Reduction in hydraulic capacity for horizontal constrictions is mainly due to the reduction of area of flow at the culvert invert. Four different levels of horizontal constrictions were simulated at the culvert inlet: 2, 4, 6, and 8 inches in height above the culvert invert (figure 4). Discharges were calculated for all possible water depths up to a maximum of 18 inches under inlet control. The maximum depth of water changed depending on the depth of the horizontal constriction, from the invert to the soffit in the unplugged case, and from the horizontal constriction surface to the soffit in the plugged cases. The maximum discharge for each level of horizontal constriction is when the depth of flow is approximately 1.4 feet above the culvert invert. Maximum discharge then decreases slightly when the pipe is flowing full (Figure 7).

Wetted perimeter and roughness coefficient effects were found to be insignificant. Figure 7 shows that the increase in maximum discharges due to horizontal constrictions was approximately 2 cfs for each case. The reduction in maximum discharge with increasing obstruction height is primarily due to the reduction of area available for flow.

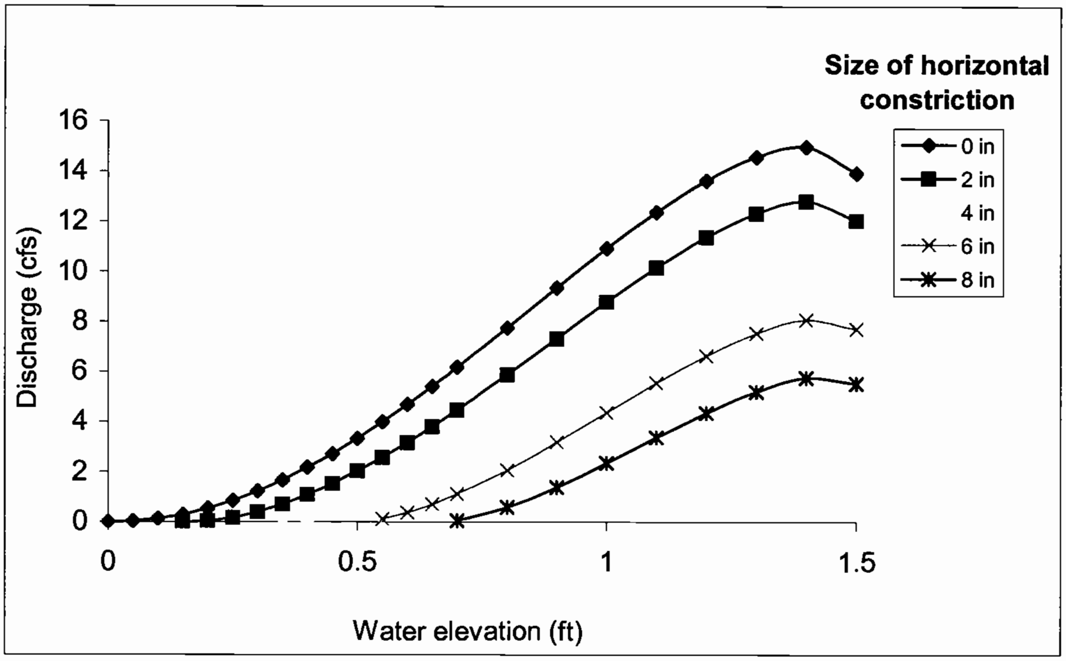


Figure 7. Effects of horizontal constriction on discharge for an 18 inch pipe and slope of 6% with inlet control.

Effect of vertical constriction in discharge.

Vertical constriction has a larger effect on hydraulic capacity than horizontal constriction. This is mainly due to increases in the wetted perimeter. Manning's equation (1) shows that discharge is inversely proportional to wetted perimeter. Thus, an increase in length of wetted perimeter due to vertical constriction will result in a reduction of discharge. Differences in depth of flow can be as large as 6 inches between a culvert with a 2 inch vertical constriction and a culvert flowing free of constriction (Figure 8).

Calculated maximum discharges for each simulated constriction are presented in Table 1. The greatest change in maximum discharge was a 50 % reduction between an unplugged culvert and one with a 2 inch vertical constriction. The change from unplugged to plugged condition also affects flow class (subcritical or supercritical). A culvert with a 6% slope and flowing with a discharge of 1 cfs will change from supercritical to subcritical flow when a 2-inch vertical constriction is simulated. As a result, constrictions at culvert inlets may be beneficial for fish passage since they create the necessary conditions for subcritical flow.

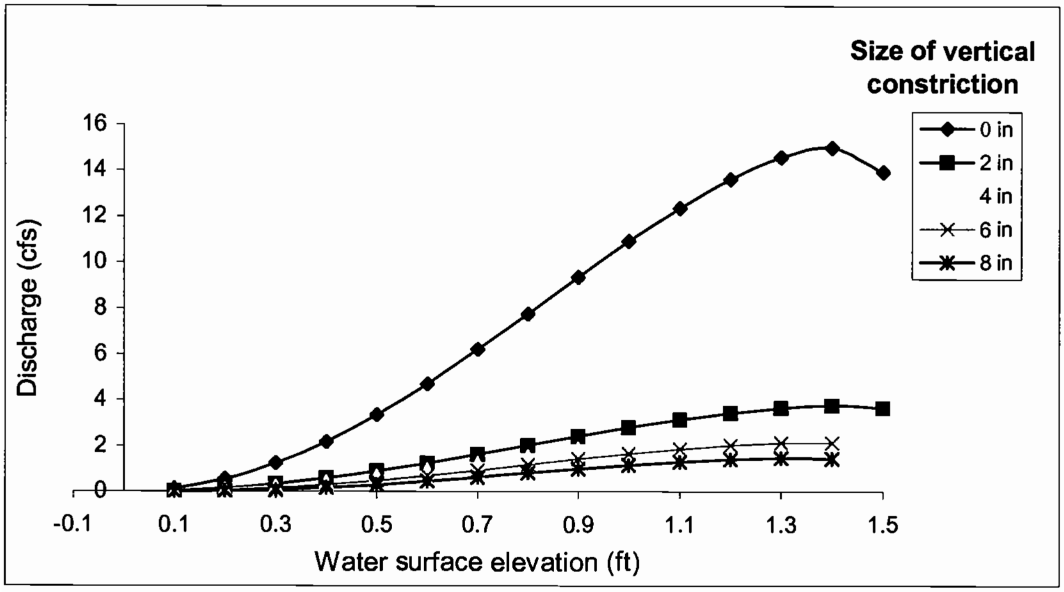


Figure 8. Effect of vertical constriction on discharge for an 18 inch diameter pipe with inlet control and a slope of 6% with inlet control

Table 1. Effect of vertical and horizontal constrictions in maximum discharge (cfs).

Type of constriction	Size of constriction (inches)	Maximum Discharge (cfs)	Cumulative % decreases in Max. Discharge	Flow area (ft^2)	Wetted perimeter (ft)
HORIZONTAL	0	15	--	1.71	3.93
	2	12.8	14	1.61	3.85
	4	10.5	30	1.42	3.7
	6	8.1	46	1.23	3.73
	8	5.8	61	0.96	3.46
VERTICAL	0	15	--	1.71	3.93
	2	7.5	50	1.48	6.56
	4	5.8	62	1.24	6.36
	6	4.2	72	1.02	6.14
	8	2.9	81	0.78	5.34

Effect of horizontal and vertical constriction on velocity

Constrictions at the culvert inlet reduce velocity of flow. Reduction in the velocity of flow in plugged culverts is subject to higher resistance to flow as a result of the increase in wetted perimeter. The reduction due to a vertical constriction is much larger than with a horizontal constriction. Figure 9 (a) shows the reduction in flow velocity at 1 cfs discharge for the different constrictions. A 13% and 22% reduction in velocity was calculated for the first 2 inches of constriction in the horizontal and vertical scenarios, respectively. The first 2 inches increment in the vertical constriction has a larger reduction in end area than horizontal constriction, thus increasing the resistance to flow and reducing velocity of flow. Figure 9 (b) allows for comparison between reduction in end area with flow velocity.

The largest effect on velocity of flow came from vertical constriction due to the increase in wetted perimeter. The ability of the culvert to pass water under inlet control is greatly reduced as the vertical constriction size increases, which suggests that a culvert with this type of constriction will have subcritical flow during peak events. A reduction of maximum velocity of 30% was calculated between a culvert flowing unplugged and a culvert flowing with a 2 inch vertical constriction and a discharge of 5.2 cfs. The effects of horizontal constrictions in velocity were not significant and maximum velocities were limited by the hydraulic capacity of the culvert after constriction (Figure 10 a-b).

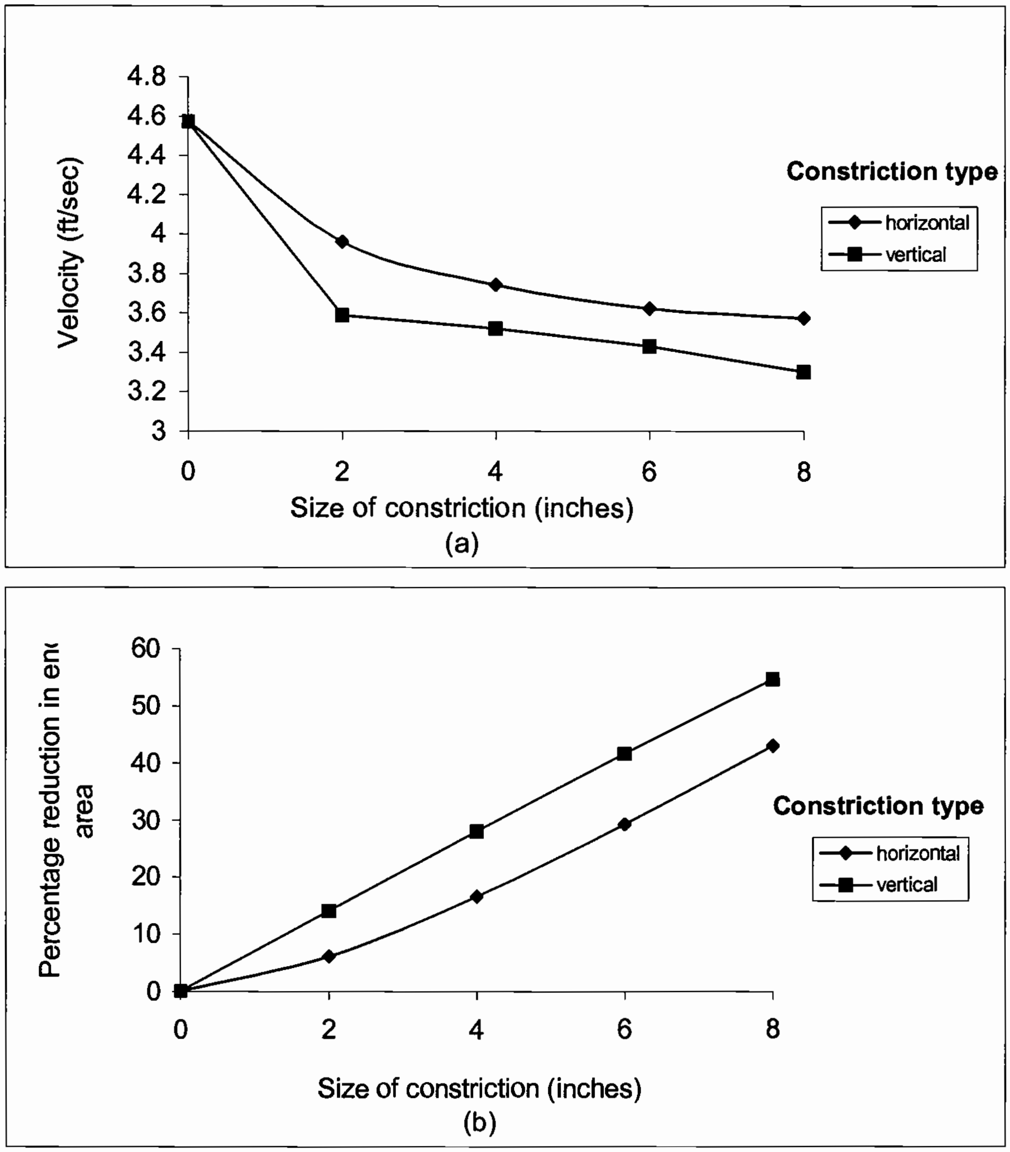
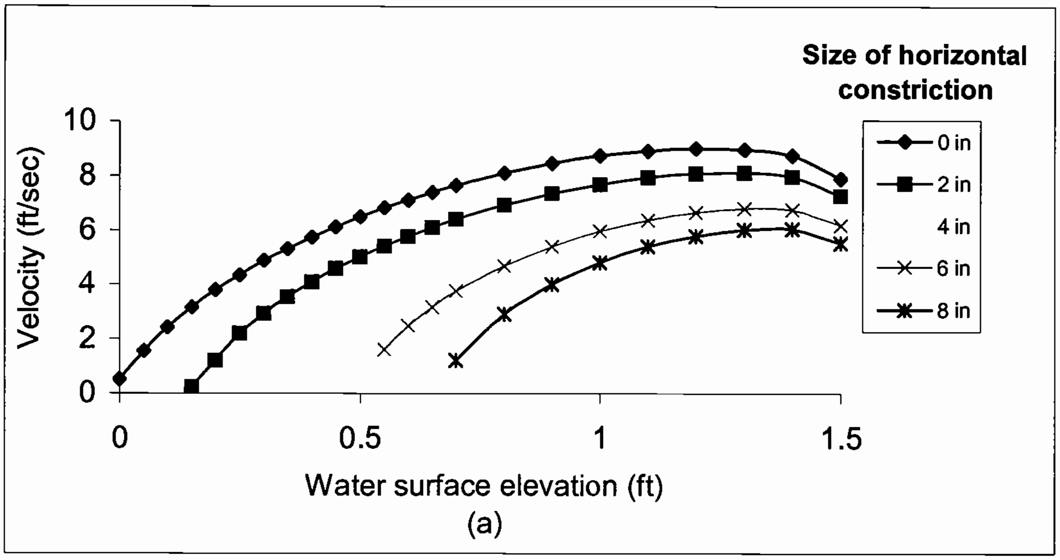


Figure 9 Effect of constriction type on: (a) flow velocity with a discharge equal to 1cfs and (b) percentage reduction in end area. These relations are for an 18 inch diameter pipe.



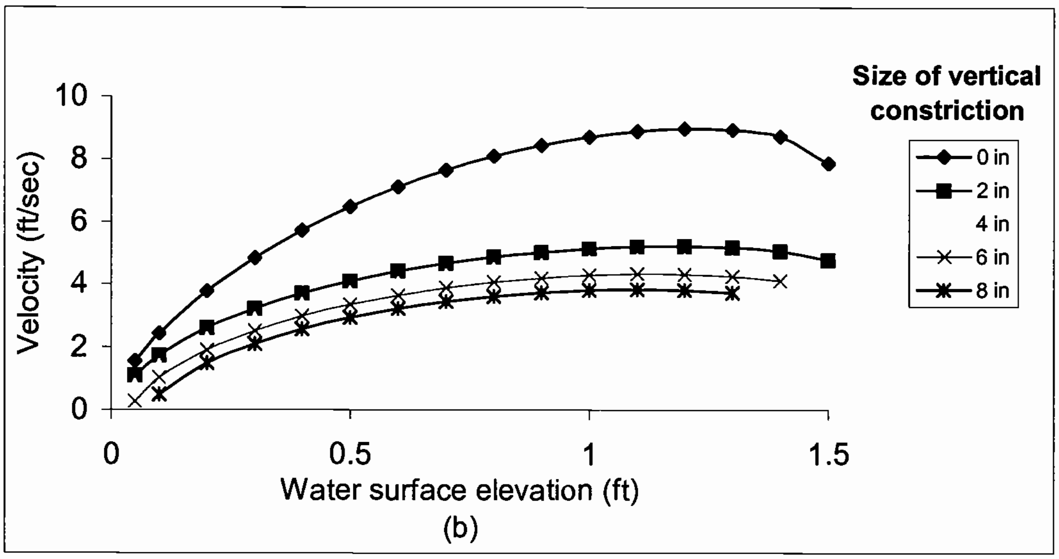


Figure 10. Effect of constriction in velocity: (a) horizontal (b) vertical for a 18 inch diameter culvert with inlet control

CONCLUSIONS

- Studies regarding constrictions in pipes or culverts indicate complex hydraulic conditions occur, most of the research in this field is based on data collected from controlled laboratory conditions. Simulation of flow at culvert inlets is too simplified to assess conditions of flow inside the culvert.

- Design of culvert installation should account for potential changes in the culvert inlet due to deposition of debris or sediment. Results of these analyses indicate that hydraulic capacity is greatly reduced when a constriction occurs at the inlet. Special concern is associated with vertical constrictions since they have large effect on wetted perimeter and hydraulic capacity.

- The design of culverts for fish passage and for high flow capacity represent conflicting goals. A steep-slope design for culverts insures high sediment transport capacity and reduces the probability of clogging due to sediment deposition. However, these culverts also have relatively high flow velocities, which are detrimental to fish passage.

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APPENDIX A

Roughness Values, Manning's Formula
(Adapted from Meadows 1997)

Commonly used roughness values for different materials are:	Minimum	Normal	Maximum
Channel Type and Description			
A. Closed Conduits Flowing Partly Full			
A-1. Metal			
a. Brass, smooth	0.009	0.01	0.013
b. Steel			
1.Lockbar and welded	0.01	0.012	0.014
2.Riveted and spiral	0.013	0.016	0.017
c. Cast iron			
1.Coated	0.01	0.013	0.014
2.Uncoated	0.011	0.014	0.016
d. Wrought iron			
1.Black	0.012	0.014	0.015
2.Galvanized	0.013	0.016	0.017
e. Corrugated metal			
1.Subdrain	0.017	0.019	0.021
2.Storm drain	0.021	0.024	0.03
A-2. Nonmetal			
a. Lucite	0.008	0.009	0.01
b. Glass	0.009	0.01	0.013
c. Cement			
1.Neat, surface	0.01	0.011	0.013
2.Mortar	0.011	0.013	0.015
d. Concrete			
1.Culvert, straight and free of debris	0.01	0.011	0.013
2.Culvert with bends, connections, and some some debris	0.011	0.013	0.014
3.Finished	0.011	0.012	0.014
4.Sewer with manholes, inlet, etc., straight	0.013	0.015	0.017
5.Unfinished, steel form	0.012	0.013	0.014
6.Unfinished, smooth wood form	0.012	0.014	0.016
7.Unfinished, rough wood form	0.015	0.017	0.02
e. Wood			
1.Stave	0.01	0.012	0.014
2.Laminated, treated	0.015	0.017	0.02
f. Clay			
1.Common drainage tile	0.011	0.013	0.017
2.Vitrified sewer	0.011	0.014	0.017
3.Vitrified sewer with manholes, inlet, etc.	0.013	0.015	0.017
4.Vitrified subdrain with open joint	0.014	0.016	0.018
g. Brickwork			
1.Glazed	0.011	0.013	0.015
2.Lined with cement mortar	0.012	0.015	0.017
h. Sanitary sewers coated with sewage slimes, with bends and connections	0.012	0.013	0.016
i. Paved invert, sewer, smooth bottom	0.016	0.019	0.02
j. Rubble masonry, cemented	0.018	0.025	0.03

	k. PVC	0.007	0.009	0.011
B.	Lined or Built-up Channels			
	B-1. Metal			
	a. Smooth steel surface			
	1.Unpainted	0.011	0.012	0.014
	2.Painted	0.012	0.013	0.017
	b. Corrugated	0.021	0.025	0.03
	B-2. Nonmetal			
	a. Cement			
	1.Neat, surface	0.01	0.011	0.013
	2.Mortar	0.011	0.013	0.015
	b. Wood			
	1.Planed, untreated	0.01	0.012	0.014
	2.Planed, creosoted	0.011	0.012	0.015
	3.Unplaned	0.011	0.013	0.015
	4.Plank with battens	0.012	0.015	0.018
	5.Lined with roofing paper	0.01	0.014	0.017
	c. Concrete			
	1.Trowel finish	0.011	0.013	0.015
	2.Float finish	0.013	0.015	0.016
	3.Finished, with gravel on bottom	0.015	0.017	0.02
	4.Unfinished	0.014	0.017	0.02
	5.Gunite, good section	0.016	0.019	0.023
	6.Gunite, wavy section	0.018	0.022	0.025
	7.On good excavated rock	0.017	0.02	
	8.On irregular excavated rock	0.022	0.027	
	d. Concrete bottom float finished with sides of			
	1.Dressed stone in mortar	0.015	0.017	0.02
	2.Random stone in mortar	0.017	0.02	0.024
	3.Cement rubble masonry, plastered	0.016	0.02	0.024
	4.Cement rubble masonry	0.02	0.025	0.03
	5.Dry rubble or riprap	0.02	0.03	0.035
	e. Gravel bottom with sides of			
	1.Formed concrete	0.017	0.02	0.025
	2.Random stone in mortar	0.02	0.023	0.026
	3.Dry rubble or riprap	0.023	0.033	0.036
	f. Brick			
	1.Glazed	0.011	0.013	0.015
	2.In cement mortar	0.012	0.015	0.018
	g. Masonry			
	1.Cemented rubble	0.017	0.025	0.03
	2.Dry rubble	0.023	0.032	0.035
	h. Dressed ashlar	0.013	0.015	0.017
	i. Asphalt			
	1.Smooth	0.013	0.013	
	2.Rough	0.016	0.016	
	j. Vegetal lining	0.03	.....	0.5
C.	Excavated Or Dredged			
	a. Earth, straight and uniform			
	1.Clean, recently completed	0.016	0.018	0.02
	2.Clean, after weathering	0.018	0.022	0.025

3.Gravel, uniform section, clean	0.022	0.025	0.03
4.With short grass, few weeds	0.022	0.027	0.033
b. Earth, winding and sluggish			
1.No vegetation	0.023	0.025	0.03
2.Grass, some weeds	0.025	0.03	0.033
3.Dense weeds or aquatic plants in deep channels	0.03	0.035	0.04
4.Earth bottom and rubble sides	0.028	0.03	0.035
5.Stony bottom and weedy banks	0.025	0.035	0.04
6.Cobble bottom and clean sides	0.03	0.04	0.05
c. Dragline-excavated or dredged			
1.No vegetation	0.025	0.028	0.033
2.Light brush on banks	0.035	0.05	0.06
d. Rock cuts			
1.Smooth and uniform	0.025	0.035	0.04
2.Jagged and irregular	0.035	0.04	0.05
e. Channels not maintained, weeds and brush uncut			
1.Dense weeds, high as flow depth	0.05	0.08	0.12
2.Clean bottom, brush on sides	0.04	0.05	0.08
3.Same, highest stage of flow	0.045	0.07	0.11
4.Dense brush, high stage	0.08	0.1	0.14
D. Natural Streams			
D-1. Minor streams (top width at flood stage < 100 ft)			
a. Streams on plain			
1.Clean, straight, full stage, no rifts or deep pools	0.025	0.03	0.033
2.Same as above, but more stones and weeds	0.03	0.035	0.04
3.Clean, winding, some pools and shoals	0.033	0.04	0.045
4.Same as above, but some weeds and stones stones	0.035	0.045	0.05
5.Same as above, lower stages, more ineffective slope and sections	0.04	0.048	0.055
6.Same as 4, but more stones	0.045	0.05	0.06
7.Sluggish reaches, weedy, deep pools	0.05	0.07	0.08
8.Very weedy reaches, deep pools, or floodways with heavy stand of timber and underbrush	0.075	0.1	0.15
b. Mountain streams, no vegetation in channel, banks usually seep, trees and brush along banks submerged at high stages			
1.Bottom: gravels, cobbles and few boulders	0.03	0.04	0.05
2.Bottom: cobbles with large boulders	0.04	0.05	0.07
D-2. Flood plains			
a. Pasture, no brush			
1.Short grass	0.025	0.03	0.035
2.High grass	0.03	0.035	0.05
b. Cultivated areas			

		1.No crop	0.02	0.03	0.04
		2.Mature row crops	0.025	0.035	0.045
		3.Mature field crops	0.03	0.04	0.05
	c.	Brush			
		1.Scattered brush, heavy weeds	0.035	0.05	0.07
		2.Light brush and trees, in winter	0.035	0.05	0.06
		3.Light brush and trees, in summer	0.04	0.06	0.08
		4.Medium to dense brush, in winter	0.045	0.07	0.11
		5.Medium to dense brush, in summer	0.07	0.1	0.16
	d.	Trees			
		1.Dense willows, summer, straight	0.11	0.15	0.2
		2.Cleared land with tree stumps, no sprouts	0.03	0.04	0.05
		3.Same as above, but with heavy growth of sprouts	0.05	0.06	0.08
		4.Heavy stand of timber, a few down trees, little undergrowth, flood stage below branches	0.08	0.1	0.12
		5.Same as above, but with flood stage reaching branches	0.1	0.12	0.16
D-3.	Major streams (top width as flood stage > 100 ft)				
		The n value is less than that for minor streams of silmilar description, because banks offer less effective resistance.			
	a.	Regular section with no boulders or brush	0.025	.....	0.06
	b.	Irregular and rough section	0.035	.....	0.1

APPENDIX B.

Horton composite roughness equation .

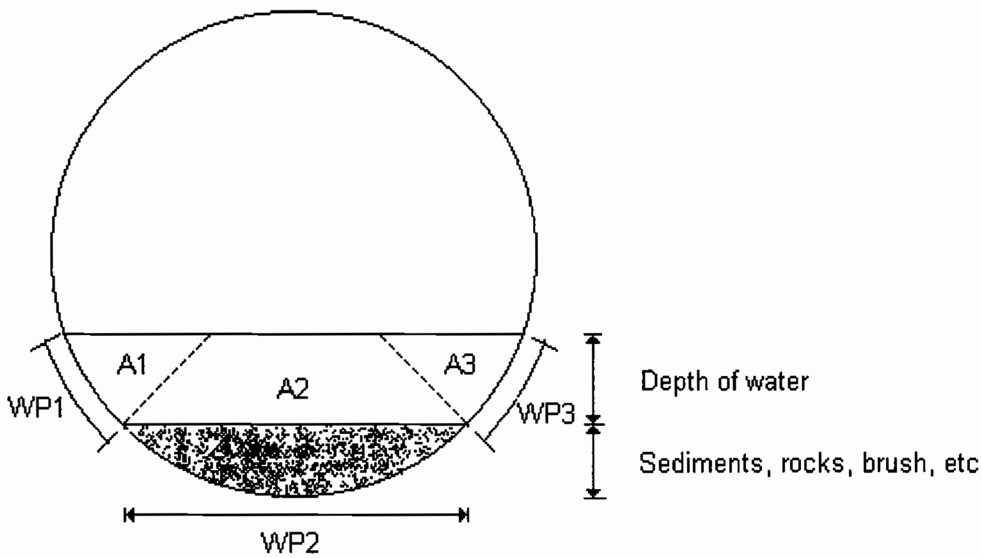
Horton equation is developed from Manning's equation.

$$V=(1.49/n)*A*R^{2/3}S^{1/2}$$

Where:

V= Average flow velocity, ft/sec.
n= Manning's channel roughness value.
R= Hydraulic radius,ft
R= Area/wetted perimeter
S= Slope
Q= Discharge (ft^3/sec)
A= Cross sectional area of water, ft^2

Cross-section of a channel with different roughness coefficients.



The hydraulic radios for the channel is:

$R_{total}=A_{total}/WP_{total}$ Solving for Area, $A_{total}= R_{total}\ WP_{total}$ (1)

The hydraulic radios for a segment is:

$R_i=A_i/WP_i$, Solving for Area, $A_i= R_i\ WP_I$

$\Sigma Ai=A_{total}=\Sigma\ R_i\ WP_i$ (2)

Since equation (1)=equation (2)

$R_{total}\ WP_{total} =\Sigma\ R_i\ WP_i$ (3)

From Manning's equation we can solve for hydraulic radios (R) and assume that the average velocity is the same for all segments:

$$R^{2/3}=Vn/1.49\ S^{1/2}$$

$$R_{total}=(Vn_{total}/1.49\ S^{1/2})^{3/2}$$ and,

$$R_i\ =(Vn_i/1.49\ S^{1/2})^{3/2}$$

Substituting into equation (3)

$$WP_{total}(V\ n_{total}/1.49\ S^{1/2})^{3/2}=\Sigma WP_i(V\ n_i/1.49\ S^{1/2})^{3/2}$$

Since $(V/1.49\ S^{1/2})$ is in both sides of the equations can be canceled.

$$WP_{total}*n_{total}^{3/2}=\Sigma WP_i \cdot n_i^{3/2}$$ Then solving for n_{total}, the weighted roughness coefficient is:

$$n_{total}=(\Sigma WP_i \cdot n_i^{3/2}/WP_{total})^{2/3}$$