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Modeling a Change in Flowrate through Detention or Additional Pavement on the Receiving Stream: Final Report

Theodore G. Cleveland, Marian R. Schwarz, and Cristal C. Tay

Performed in Cooperation with the Texas Department of Transportation

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16. Abstract

The addition or removal of flow from a stream affects the water surface downstream and possibly upstream. The extent of such effects is generally determined by modeling the receiving stream. Guidance that concisely describes how far up/downstream a hydraulic model needs to extend to fully describe those effects was developed for rapid model construction to assess changes in anticipated discharge.

The "rule of thumb" enables designers/modeler to predetermine the level of effort such a model would require.

A spreadsheet-based tool named `BoundaryDistanceRuleOfThumb-2015.xlsm` was built to make the distance estimates based on four different methods based on literature review and a generic modeling study conducted as part of this research.

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Modeling a Change in Flowrate through Detention or Additional Pavement on the Receiving Stream

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Modeling a Change in Flowrate through Detention or Additional Pavement on the Receiving Stream

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February 15, 2016

Abstract

The addition or removal of flow from a stream affects the water surface elevations in the vicinity of hydraulic structures (bridges, culvert systems). Currently, the extent of such effects is only known by hydraulic modeling the receiving stream relative to a structure of interest. Guidance that describes how far up/downstream a hydraulic model needs to extend will be useful for rapid model construction to assess effect of changes in anticipated discharge on a structure without modeling the entire stream system.

This document uses the results of a generic modeling study to estimate where boundaries should be located in hydraulic models to assess the effect of change in discharge near and around obstructions (culverts, bridge piers, gabions, and similar hydraulic structures).

The goal of the study is to identify distances relative based on some common metric where model boundaries should be established – beyond these distances, hydraulic calculations based on the simpler slope-area method would apply; within these distances, hydraulic modeling using HEC-RAS, WSPRO, or similar tools would be required for precise description of water surface elevations and force calculations.

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1. Introduction

Culverts, bridges, and other obstructions change the water surface profile in a channel at a given time; it is widely accepted that the addition or removal of flow from a stream may affect the water surface downstream and possibly upstream. Currently, the extent of any effects is only known by modeling the receiving stream.

The research goal is to identify distances relative to some common metric where model boundaries should be established – beyond these distances, hydraulic calculations based on the simpler slope-area method would apply; within these distances, hydraulic modeling using HEC-RAS, WSPRO, or similar tools would be necessary for precise description of water surface elevations and force calculations.

2. Background

The question of how far to model upstream and downstream of a structure is not insignificant, and practical guidance is often by peer-to-peer, non-authoritative communication. On a recent modeler's forum (**?**) the following question was posed by a forum member

> "What would be the minimum required upstream and downstream model extents required for hydraulic modeling of bridge crossings on rivers and wide creeks?"

The responses could be grouped into three categories:

1. The first group suggests to model up and downstream until the effect is not detectable (presumably using pre-change and post-change model). this response was the common response from experts self-identified as computational fluid dynamics experts, and one practice leader at a consulting firm.
2. The second group suggests that 155 – 200 meters is a distance beyond which hydraulic structure effects become irrelevant. This response was common among many self-identified hydraulics engineers working at various firms; clearly a rule of thumb is implied as many of these responders also stated that if results seem odd, then they would extend distances.
3. The third group referenced guidelines based on Samuels (1989) paper where the question was examined in the context of riverine flow and distance that backwater effects would propagate in a hydraulic model.

The project conducted a modeling study to address the question posed above by scenario modeling several conditions. The results of the modeling study were then used to produce a guidance tool for the boundary distances upstream and downstream of a structure.

3. Literature Review

The literature review focused on current practice in hydraulic modeling as to how far a model should extend to capture the phenomenon of interest. Many sources recommend use of engineering judgment (Parmley, 1992; Norman and Houghtalen, 2001) through water surface observation (Ricci et. al., 2001) or purpose based cross sections (Sellin, 1970; Federal Emergency Management Agency, 2004; Wake, 2010) without any specifics on distance.

Barnard et. al. (2013) defines longitudinal profile as the stream reach that includes the culvert. The longitudinal profile is developed by measuring the elevation of the bed, water surface level and bank slope; an example of a longitudinal profile in an existing stream is shown in Figure 1. It is assumed, in this research, that the extents of the longitudinal profile represent the boundary conditions upstream and downstream of an obstruction.

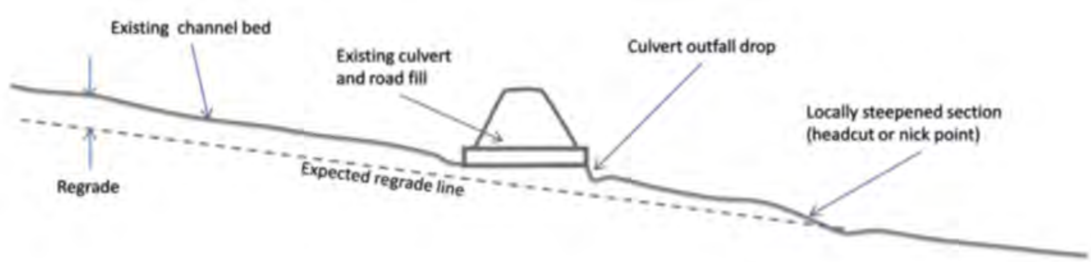


Figure 1. Longitudinal Profile of an Existing Stream (Barnard et. al., 2013)

Bodhaine (1968) describes indirect methods for measurement of peak discharge at culverts. Bodhaine recommends locating the approach section one culvert width upstream from the culvert entrance. When wingwalls exist, the recommended distance upstream from the end of the wingwalls is equal to the width between wingwalls at their upstream end. If there is not considerable contraction caused by the wingwalls, the approach section may be closer than this, but not closer than one culvert width.

Samuels (1989) provides a simple estimation of reach length to assess how the length of channel is affected by works downstream. Samuels states that the appropriate distance between the project area and the model boundary is the backwater length for the river and that the boundaries should be located so that any error in estimating water levels at that point, should not materially affect the study area. The backwater length (L) is defined as $L = 0.7\frac{D}{S_0}$ where D bankfull depth is and S_0 is the mean channel slope.

Samuels (1990) discusses one dimensional models of flow in open channels as a fundamental analytic tool. Samuels describes cross-section sites and the distances between them. At sites of key interest; sites adjacent to major structures; sites that are representative of river geometry; cross sections should be 20 bankful widths apart as a first estimate ; cross sections should be no more than of $0.2\frac{D}{S_0}$ apart, where D is the bankfull depth of flow and S_0 is the channel slope; cross section a maximum of $\frac{L}{30}$ apart where L is the length scale of the physically important wave; cross sections a minimum of $\frac{10^{d-q}}{S_0 \epsilon_s}$ apart, and finally, cross sections should be located so that the area ratio lies between $\frac{2}{3}$ and $\frac{3}{2}$ for successive sections.

Fulford (1995) defines the assumed boundary conditions used in the Culvert Analysis Program (CAP) culvert analyses. Usually the approach section is located one opening width from the culvert entrance or, if wingwalls exist, a distance upstream from the end of the wingwalls equal to the width between the wingwalls at their upstream end. This assumption is inherent in culvert analyses in CAP.

The Dam Safety Section, Arizona Department of Water Resources (2002) created a state standard for floodplain hydraulic modeling to provide guidance in fulfilling the requirements of Flood Insurance Studies, as well as local community and county flood damage prevention ordinances. Figure 2 is a definitional sketch from the Arizona guidance document. The Arizona standard recommends that four cross sections be used. One on either side of the obstruction, one at the upstream end of the contraction reach and one at the downstream end of the expansion reach.

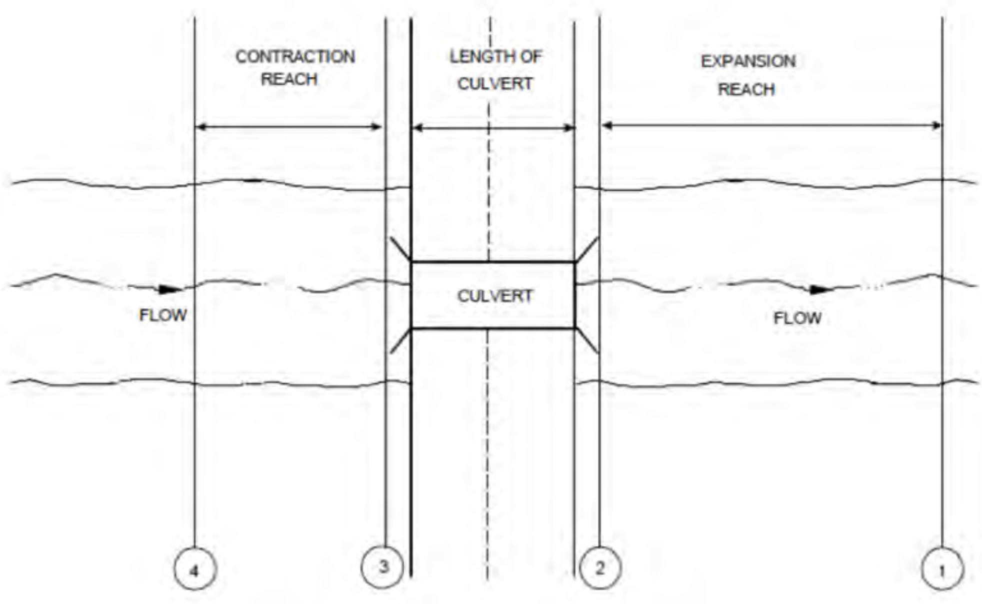


Figure 2. Contraction and Expansion Reaches at a Typical Road Crossing (Dam Safety Section, Arizona Department of Water Resources, 2002)

Referring to Figure 2, the guidance document recommends the following regarding the outer two cross sections:

1. Section 1 should be located sufficiently downstream from the structure so that the flow is not affected by the structure. An iterative process may be used to

determine what is "sufficiently downstream" and a suggested starting expansion ratio is 3:1 (longitudinal to lateral distance). Field studies found expansion ratios varying from 0.5 to 4 longitudinal units for each lateral unit. The expansion distance varies depending upon the degree of constriction, the shape of the constriction and the magnitude and velocity of the flow. If the expansion reach requires a long distance, then intermediate cross sections should be placed within the expansion reach in order to adequately model friction losses.

2. Section 4 of Figure 2 should be located where the flowlines are approximately parallel and the cross section is fully effective. Because flow contractions can occur over a shorter distance than flow expansions, a suggested starting contraction ratio is 1 longitudinal to 1 lateral distance.

   In addition, the Arizona guidance recommends another method that also requires an iteration process and again, a suggested starting contraction ratio is 1 longitudinal to 1 lateral distance (one times the average length of the side constriction caused by the structure abutments). Field studies found contraction ratios varying from 0.3 to 2.5 longitudinal units for each lateral unit.

The Oregon Department of Transportation (2005) discusses the field data they require to conduct bridge backwater analyses using a digital terrain model (DTM) for rivers in Oregon. Figure 3 is a definitional sketch from the document that displays the recommended boundary conditions. In the figure, b is the bridge waterway opening width, the approach section must be located a distance of b upstream and the two downstream cross sections must be taken at b and $3b$[1] Distance between sections are measured along the channel centerline (thalweg). These values are based on channel curves and skewness of the bridge waterway sections, variations based on skewness and channel curves are included in the document.

[1] $3b$ from the bridge. The figure shows the distance as b and then an additional $2b$.

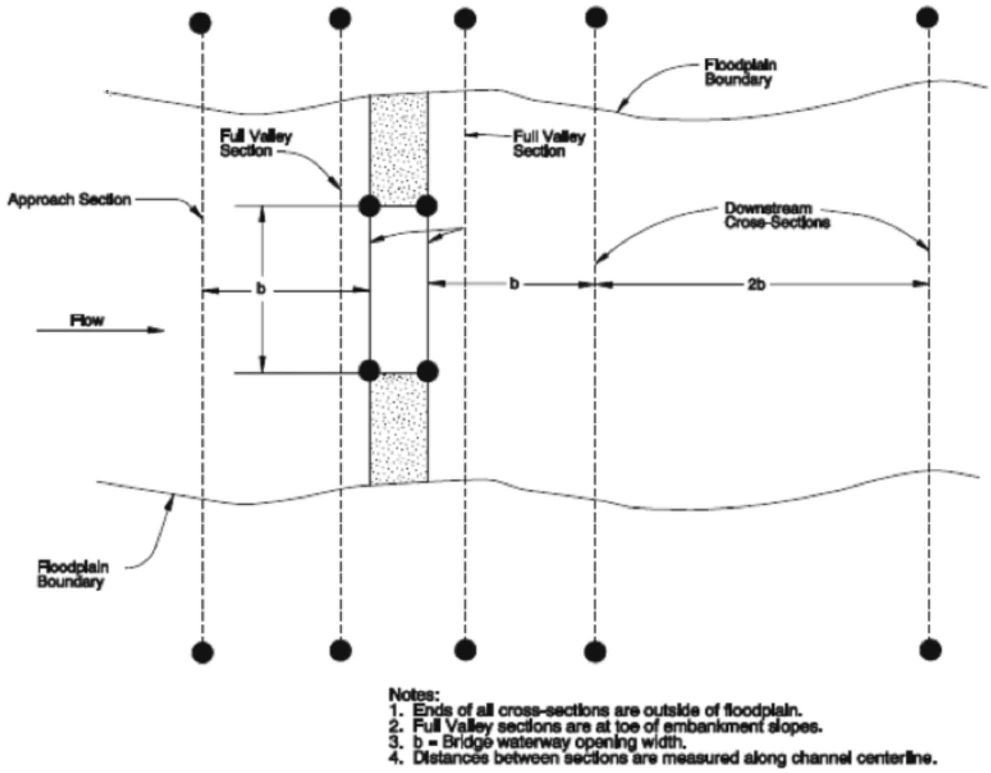


Figure 3. Boundary Conditions at a Single Opening Stream Crossing with No Skew (Oregon Department of Transportation, 2005)

Castellarin et.al. (2009) discusses guidance on choosing a suitable set of cross sections for the representation of the natural geometry of a river, specifically for use in Preissmann Scheme 1D hydraulic models. Models of a 55 km reach of the River Po, Italy, and a 16 km reach of the River Severn, United Kingdom were used for investigation. From these case studies "obvious guidelines" for cross section placement are: a cross section at the model upstream and downstream ends, cross sections at either side of structures where an internal boundary is set, a cross section at each point of interest and cross sections at all available stream gages and stages.

More specific guidelines are given as a distance between cross sections, Δx, was recommended as $\Delta x \approx kB$ where B=bankfull topwidth of the main channel; and k=constant (with a recommended range from 10 to 20).

Elsewhere in Castellarin et.al. (2009), a method, based on an estimate of backwater effects for subcritical flows, suggests that $\Delta x < \frac{0.2(1-F^2)D}{s} \approx 0.2D/S_0$ when $F^2 \to 0$ where D=bankfull depth of flow and S_0= main channel slope. Beyond this length, the backwater upstream of a control (as well as other disturbance) decays to less than 0.1 of the original value.

The authors also recommended minimum distance between cross sections is $\Delta x > \frac{10^{d-q}}{S_0 \epsilon_s}$ in which q=number of decimal digits of precision; d represents the digits lost due to cancellation of the leading digits of the stage values; S_0=average surface slope; and ϵ_s=relative error on surface slope that can be tolerated in the computation.

Wildland Hydrology Inc. (2013) discusses stream habitat measurement techniques. Relevant to this research, a minimum longitudinal profile length guideline recommended is 20 to 30 bankfull channel widths, and such a length could serve as a reasonable guideline for evaluating the effect of a flow change.

The Nebraska Department of Roads (2015) developed guidance for hydrologic and hydraulic analyses at Nebraska bridge sites to develop the preliminary bridge data sheets that define bridge design parameters. Cross sections that define the 100 year floodplain are evaluated using HEC-RAS (Hydraulic Engineering Center River Analyses System). The suggested upstream floodplain cross-section is approximately one bridge length upstream from the bridge. The minimum upstream distance recommended to the upstream cross section is of 100 feet and a maximum distance of 500 feet.

The guidance further recommends that the analyst locate the downstream floodplain cross-section approximately one-half of the floodplain width downstream from the bridge, with a minimum distance of 300 feet and a maximum distance of 1,500 feet for the downstream cross section.

Wide floodplains transitioning to narrow hydraulic structure openings and developed property located within 1,500 feet upstream may warrant an additional upstream cross section to accurately reflect changes occurring in the floodplain and to ensure the upstream-most cross section is far enough upstream that the water surface profiles no longer experience influences due to the hydraulic structure.

The Nebraska Department of Roads (2015) and the Dam Safety Section, Arizona Department of Water Resources (2002) treat culverts as similar to bridges except that culvert hydraulics equations are used to compute inlet control losses rather than contraction coefficients. A typical box culvert road crossing is similar to a bridge in many ways with the walls and roof of the culvert corresponding to the abutments and low chord of the bridge, respectively. The layout of cross sections, the use of the ineffective flow areas, the selection of loss coefficients, and most other aspects of bridge analysis are applicable to culverts as well, with the added requirement that culvert entrance and exit loss coefficients are computed.

3.1. Synthesis and Conclusions

Recommended distance to boundaries, not specifically stated for upstream or downstream, from the various sources examined include:

1. the backwater length based upon bankfull depth and mean slope (Samuels, 1989),

2. expansion ratios using longitude and latitude (Dam Safety Section, Arizona Department of Water Resources, 2002),
3. equations based upon bankfull surface width, bankfull depth of flow, and main channel slope (Castellarin et.al., 2009).

Recommended distances to the boundary, specifically for the approach sections, include:

1. one culvert width (Bodhaine, 1968),
2. one opening width (Fulford, 1995; Oregon Department of Transportation, 2005),
3. 20 to 30 times the bankfull channel width (Wildland Hydrology Inc., 2013),
4. 100 feet minimum distance with a maximum distance of 500 feet (Nebraska Department of Roads, 2015).

Recommended distance to the boundary specifically for downstream sections, include:

1. Three opening widths (Oregon Department of Transportation, 2005)
2. a minimum distance of 300 feet and a maximum distance of 1,500 feet (Nebraska Department of Roads, 2015).

Related guidance in terms of cross section stationing is reported in Samuels (1989) as:

1. cross sections should be 20 bankful widths apart as a first estimate,
2. cross-sections should be no more than $0.2\frac{D}{S_0}$ apart, where D is the bankful depth, and S_0 is the channel slope,
3. cross sections should be no more than $\frac{L}{30}$ apart where Ls is the length scale of the physically important wave.

Based upon the literature reviewed, the opening width is a characteristic dimension that should be used to establish modeling distances. Bankful width is the other characteristic dimension that should be used to establish modeling distances.

4. HEC-RAS Studies

A HEC-RAS modeling study was conducted to investigate the effect of boundary location in cases where discharge is changed. These case studies were used to evaluate approaches identified in the literature review. In each scenario a reference channel without a hydraulic structure was simulated, then a structure was added and comparisons made to this reference simulation. The discharges were varied through two orders of magnitude.

Water depth differences exceeding 0.08 foot absolute (1 inch) was the criterion used to determine the distances from the obstruction still had an effect on the computed water surface. That is, the influence distance was the distance to the first cross section from the obstruction where the difference in computed hydraulic depth was less than 0.08 feet. The influence distance may be upstream of the obstruction or downstream (supercritical).

4.1. Modeling Design

Different models were created to analyze the longitudinal extent (river distance) of hydraulic structure influence under different discharge conditions. Four categories of channels were considered: (1) A straight channel with non-skew hydraulic elements, (2) a straight channel with skewed elements, (3) a curved channel with non-skew hydraulic elements , and (4) a curved channel with skewed elements.

Three different categories of hydraulic elements were considered: (1) None – a base case to compare effects of structure on water surface elevation and flowpath, (2) a bridge with two piers and an abutment, and (4) an embankment with two culverts.

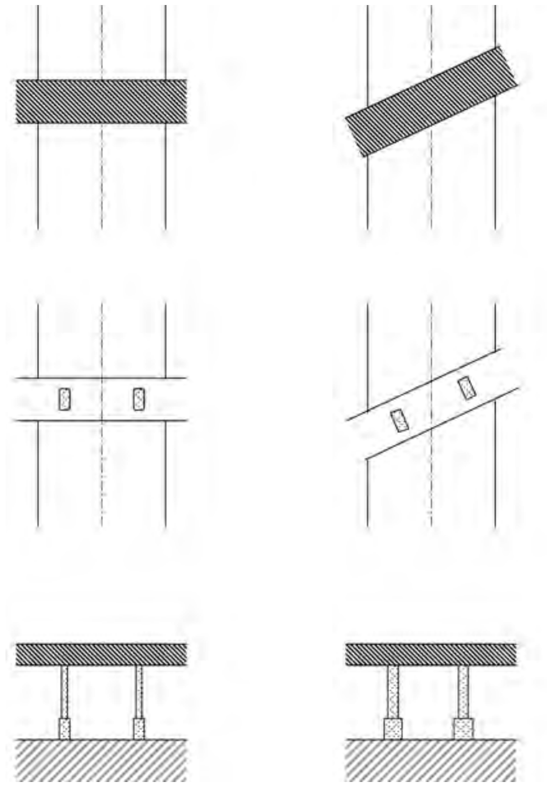
The hydraulic elements with non-skew are aligned with the local channel centerline and the skewed elements are aligned at a 15^o skew angle, relative to the channel centerline.

Figure 4 is a plan view sketch of the non-skew and skew configurations used. The left panel illustrates how bridge piers are conceptualized in HEC-RAS with and without skew. The right panel illustrates how culvert systems are conceptualized in HEC-RAS with and without skew.

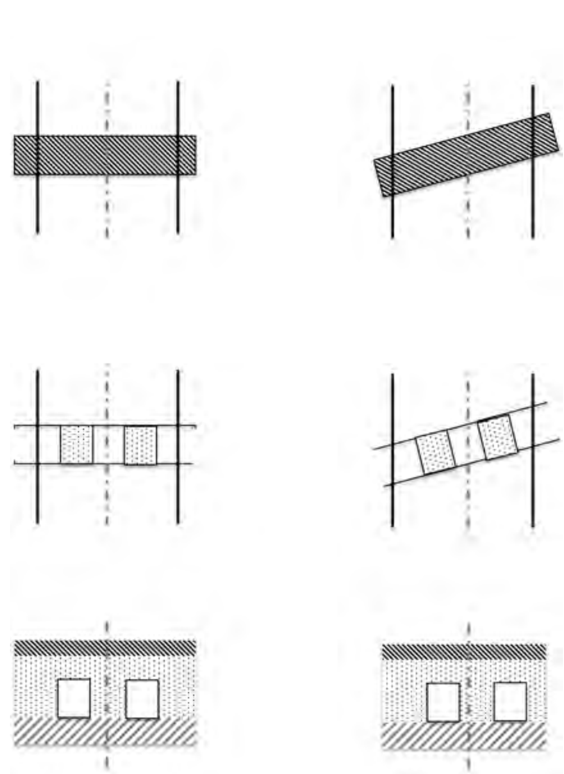
Three different longitudinal (channel bottom) slopes were considered: dimensionless slopes of 0.005 (0.5%), 0.01 (1%), and 0.02 (2%).

Each configuration is modeled with six different discharge rates: 15cfs, 100cfs, 150cfs, 500cfs, 1000cfs, and 1500cfs.

The approach and exit channel configurations were built in a narrow and wide condition. A total of 432 simulations are represented.



(a) Plan and Elevation sketches of bridge hydraulic element. Left set of panels is the aligned configuration. Right set of panels is the skew configuration. The effect of the skew angle is to make the bridge piers appear "wider" to the flow



(b) Plan and Elevation sketches of culvert hydraulic element. Left set of panels is the aligned configuration. Right set of panels is the skew configuration. The effect of the skew angle is to make the culvert pair appear to shift to one side of the stream

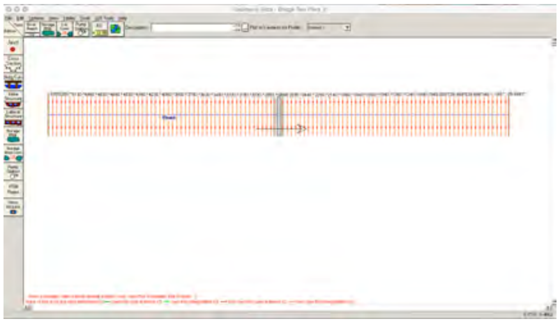
Figure 4. Plan and Elevation sketches of aligned and skew elements depicting the angle relative to channel centerline, and "hydraulic" appearance of the section as water approaches.

4.2. Narrow/Wide Straight Channel

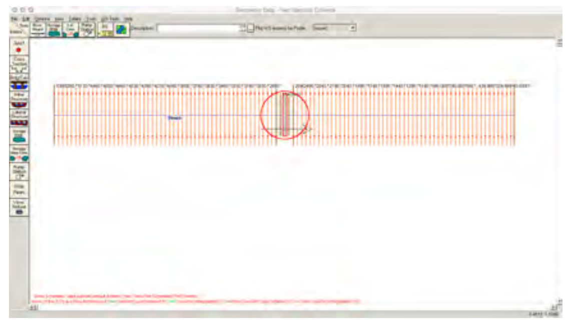
The straight channel was modeled as 5380 ft. long, which allows $\approx \frac{1}{2}$ mile of channel in each direction away from the hydraulic structure. Figure 5 is a screen capture of the geometry interfaces for the straight channel models.

The cross-sections are longitudinally 50 ft apart except at the structure where the program defaults determine the relative positioning of the element within the channel. The shaded rectangle in the middle of the channel plan-view plot is the location of the hydraulic structure (No structure; a bridge; or a culvert system). Flow is from left to right and is indicated by the arrow on the figure; in HEC-RAS, flow is from larger to smaller river station.

The wide channel models replicate the longitudinal geometric ratios of the narrow



(a) HEC-RAS Straight Channel (Narrow) plan view geometry. The structure is located in the middle of the figure (indicated by the grey rectangle). Flow in the system is from left-to-right (from large river station value to small river station value.)



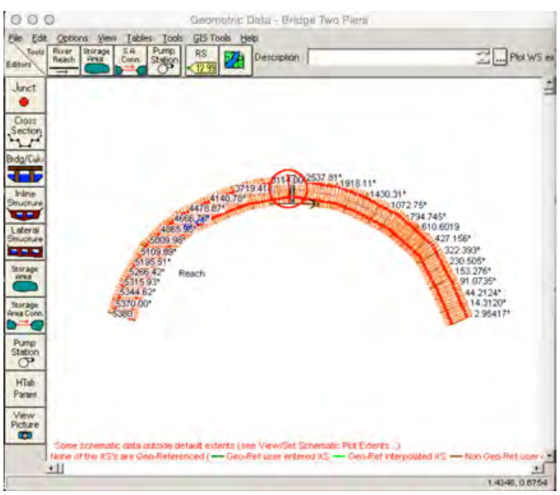
(b) HEC-RAS Straight Channel (Wide) plan view geometry. The structure is located in the middle of the figure (indicated by the grey rectangle). The channel "width" decreases in the vicinity of the structure whose physical characteristics are unchanged from the narrow channel models

Figure 5. Narrow and Wide, Straight Channel plan view geometry.

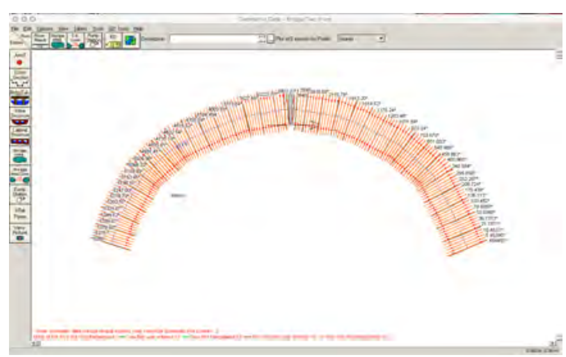
system, but are 3-times wider than the hydraulic structure.[2] The channel width is reduced in the hydraulic structure area to the narrow channel configuration(s) at the hydraulic structure.

4.3. Narrow/Wide Curved Channel

Figure 6 shows the HEC-RAS geometry interface for the narrow and wide curved channel models.



(a) HEC-RAS (Narrow) Curved Channel.



(b) HEC-RAS (Wide) Curved Channel.

Figure 6. HEC-RAS Plan view of narrow and wide curved channel configurations.

[2]This construct is to study the effect of a wide channel being forced through a relatively narrow section.

The curved channel has the centerline axis matching the length of the straight channel, however the inside of the curve and the outside of the curve are shorter and longer, respectively than the related straight channel. The radius of curvature at the centerline is nearly 1700 feet (about 1/3 of a mile), selected to be about the curvature on the Brazos River near Rosenberg, Texas.

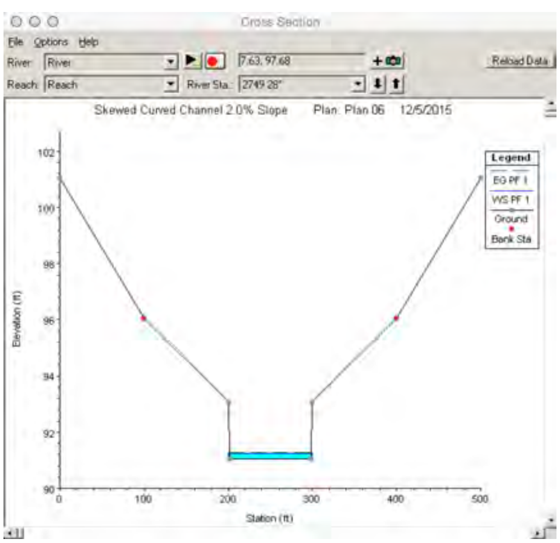
In either panel (left or right) the cross-sections have variable spacing to accommodate the curvature of the channel. The spacing at either end of the model region is quite small, but approaches 50 feet at the structure. Because the spacing is variable (and starts small), there are almost 50-percent more cross sections in the curved models.

4.4. Typical Cross Sections

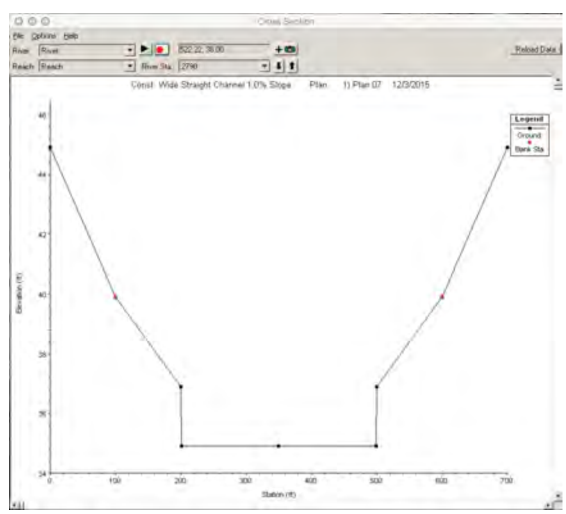
Two categories of cross sections were used; channel and far-field, and hydraulic structure sections. The channel and far-field sections are channel cross sections that are used both reference simulations as well as hydraulic structure simulations.

4.4.1. Channel and Far-Field Cross Sections

Figure 7 displays the two channel cross sections for the narrow (left panel) and wide (right panel) channel models.



(a) HEC-RAS (Narrow) Channel cross-section geometry.



(b) HEC-RAS (Wide) Channel cross-section geometry.

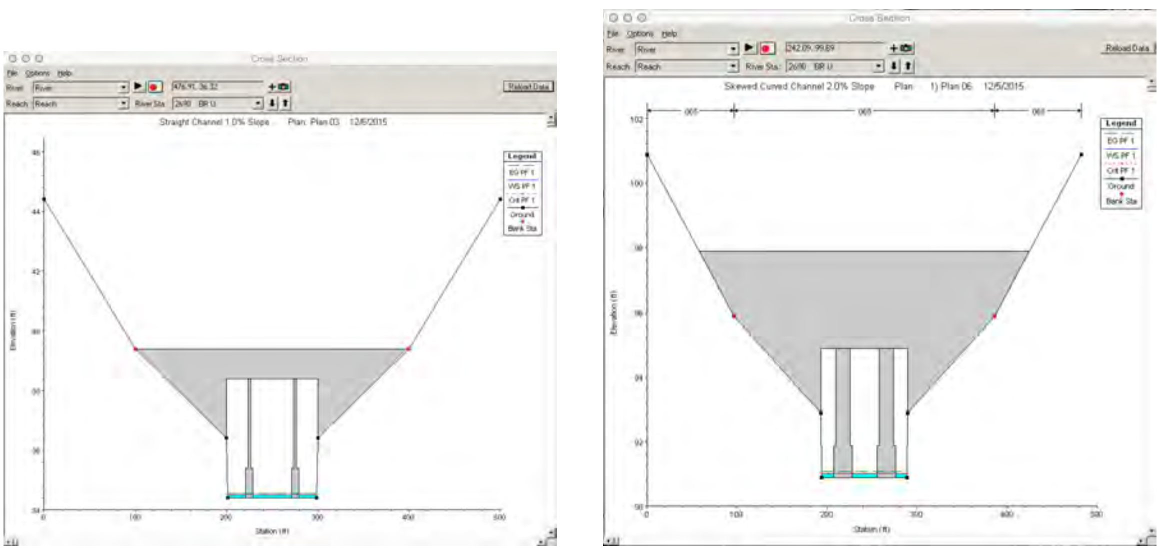
Figure 7. HEC-RAS Channel cross-section geometry. The approaching and exiting cross-sections all have the same geometry (except elevation of channel bottom, which is adjusted to reflect different longitudinal slope).

The far-field section is the name used herein to indicate a cross section located away from the hydraulic structure where the effect of the structure on the flow depth has become negligible (hence the adjective “far”). The section geometric are all the same so a far-field section is identical to nay channel cross section, except at the structure.

The two panels Figure 7 are at different locations in their respective models (hence the difference in bottom elevations), but otherwise convey the principal difference between a narrow and wide section as used in the research.

4.4.2. Bridge Aligned and Skew Cross Sections

Figure 8 depicts the cross section for the aligned and skewed bridge piers. The figure illustrates the increased apparent width of the bridge piers as a consequence of the skew angle.



(a) HEC-RAS (Narrow) Bridge (in-line with flow direction) cross-section geometry.

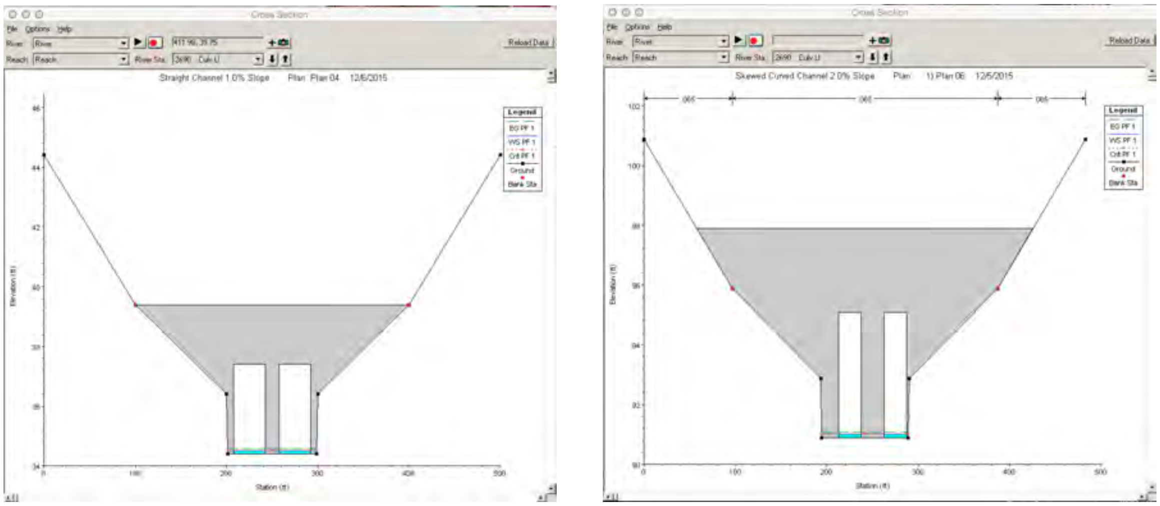
(b) HEC-RAS (Narrow) Bridge (15^o skew angle with flow direction) cross-section geometry.

Figure 8. HEC-RAS (Narrow) Channel cross-section geometry. The approaching and exiting cross-sections all have the same geometry (except elevation of channel bottom, which is adjusted to reflect different longitudinal slope).

In the study, the internal (to HEC-RAS) default skew settings were used after the angle was specified.

4.4.3. Culvert Aligned and Skew Cross Sections

Figure 9 depicts the cross section for the aligned and skewed culvert section. The figure illustrates the apparent shifting of the culverts to one side of the channel as a consequence of skew angle.



(a) HEC-RAS (Narrow) Culvert (aligned with flow direction) cross-section geometry.

(b) HEC-RAS (Narrow) Culvert (15^o skew angle with flow direction) cross-section geometry.

Figure 9. HEC-RAS (Narrow) Channel cross-section geometry. The approaching and exiting cross-sections all have the same geometry (except elevation of channel bottom, which is adjusted to reflect different longitudinal slope).

In the study, the internal (to HEC-RAS) default skew settings were used after the angle was specified.

The wide channel cases used identical cross sections for the structures – that is the wide channel reduces to the narrow channel configuration in the vicinity of the structure, then expands back to the wide channel after the structure.

The culvert system provides roughly 70% open area whereas the bridge system provides nearly 95% open area as compared the the open channel at 3 feet fill depth.

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4.5. Modeling Results

The modeling results from the HEC-RAS simulations are presented and interpreted in the following subsections. The results are presented for different configurations with the bridge pier case and the culvert case for each longitudinal flow condition. The reference case is plotted as the narrow thickness line for each condition.

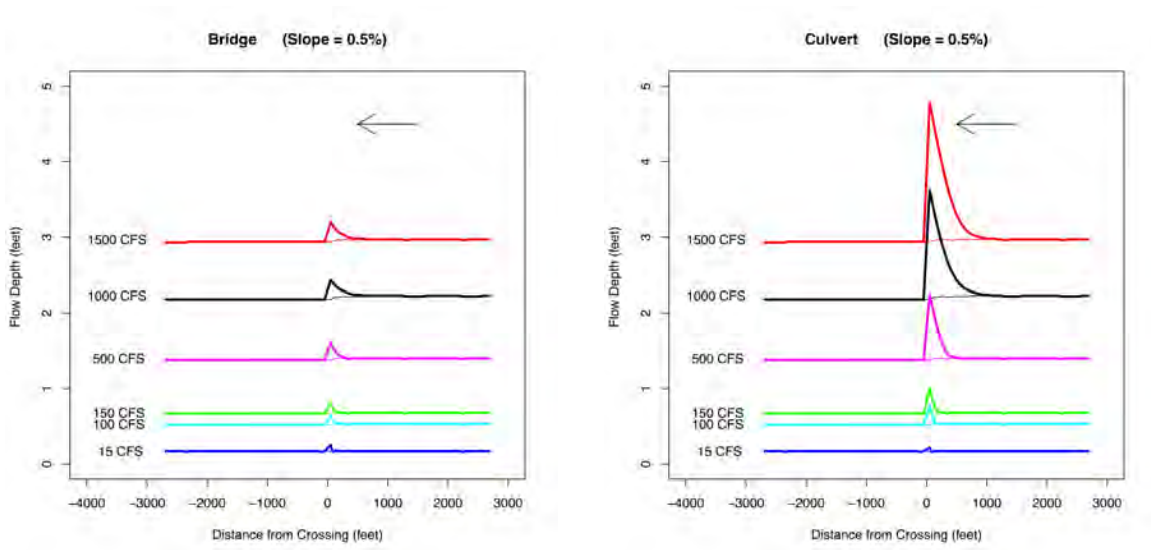
The results are plots of the water depth relative to the channel bottom (depth component of specific energy); and are plotted in this fashion to enhance comparisons between different longitudinal slopes.

4.5.1. Narrow Straight Channel – No Skew

This subsection presents the results for the three slopes for a narrow, straight channel with the hydraulic structures aligned with the channel centerline.

Longitudinal Slope 0.5 percent

Figure 10 is a plot pair of the flow depth in the channel (relative to the channel bottom) for the bridge piers and the culvert pair, respectively. The left panel illustrates the effect of the bridge piers; the right panel illustrates the effect of the culverts.



(a) Flow Depth with Bridge Piers **(b)** Flow Depth with Twin Culverts

Figure 10. Flow Depths for Bridge Piers and Culvert

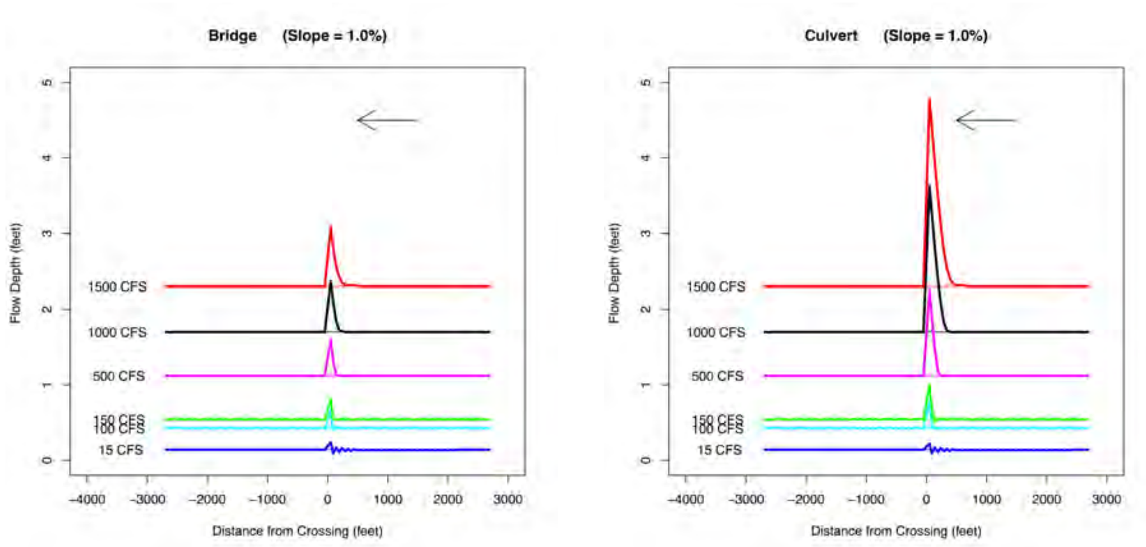
The plots show the different plow depth profiles increasing from 15 CFS to 1500 CFS. The structure is located in the middle of the plots (at $x = 0$). Both plots show the structure-induced behavior with comparatively thick lines. The thin lines (of the same color as each thick line) represent the configuration without a structure.

Both plots illustrate the increasing magnitude of flow depth disturbance with increasing discharge – an anticipated result. The distance upstream of the structure (region of effect) also increases with discharge, also an anticipated impact.

The culvert system has a greater impact in both magnitude and upstream backwater propagation. At the highest flow rate simulated, the backwater effect extends about 1000 feet upstream of the structure.

Longitudinal Slope 1.0 percent

Figure 11 is a plot pair of the flow depth in the channel (relative to the channel bottom) for the bridge piers and the culvert pair, respectively. The left panel illustrates the effect of the bridge piers; the right panel illustrates the effect of the culverts.



(a) Flow Depth with Bridge Piers **(b)** Flow Depth with Twin Culverts

Figure 11. Flow Depths for Bridge Piers and Culvert

The plots show the different plow depth profiles increasing from 15 CFS to 1500 CFS. The structure is located in the middle of the plots (at $x = 0$). Both plots show the structure-induced behavior with comparatively thick lines. The thin lines (of the same color as each thick line) represent the configuration without a structure.

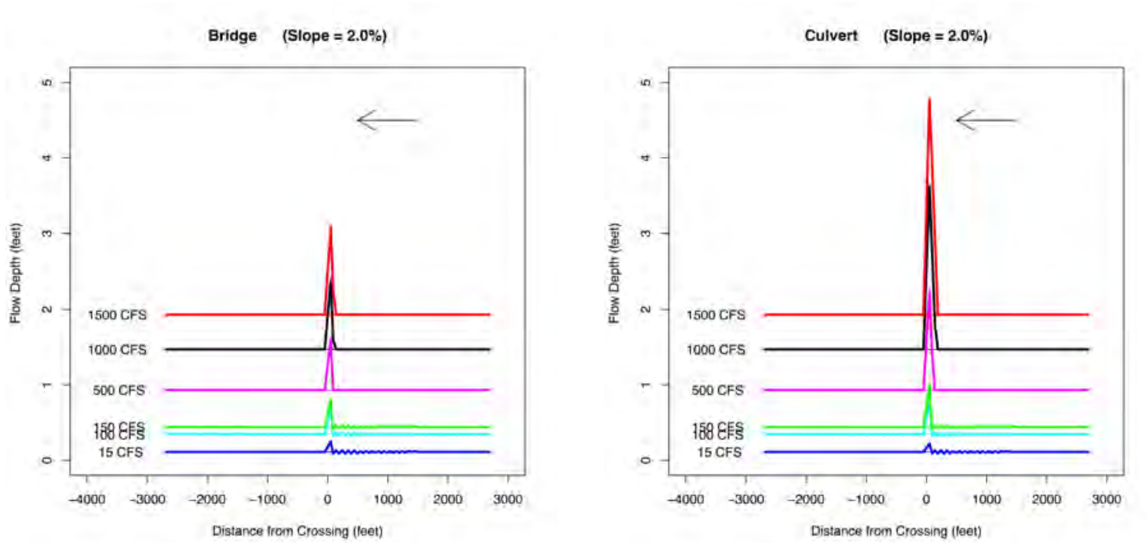
Both plots illustrate the increasing magnitude of flow depth disturbance with increasing discharge – an anticipated result. The distance upstream of the structure (region of effect) also increases with discharge, also an anticipated impact.

The culvert system has a greater impact in both magnitude and upstream backwater propagation. At the highest flow rate simulated, the backwater effect extends about 600 feet upstream of the structure.

The flow depths are smaller in comparison to the 0.5 percent slope case for otherwise the same conditions. The smaller depths are anticipated as the greater topographic slope increases the gravitational force component on the flow and reduces the pressure force (depth in open channel flow) requirement to sustain a particular discharge value. Furthermore, the reduced depth corresponds to greater water speeds, that in turn reduces the backwater distance effect of the hydraulic structures.

Longitudinal Slope 2.0 percent

Figure 12 is a plot pair of the flow depth in the channel (relative to the channel bottom) for the bridge piers and the culvert pair, respectively. The left panel illustrates the effect of the bridge piers; the right panel illustrates the effect of the culverts.



(a) Flow Depth with Bridge Piers **(b)** Flow Depth with Twin Culverts

Figure 12. Flow Depths for Bridge Piers and Culvert

The plots show the different plow depth profiles increasing from 15 CFS to 1500 CFS. The structure is located in the middle of the plots (at $x = 0$). Both plots show the structure-induced behavior with comparatively thick lines. The thin lines (of the same color as each thick line) represent the configuration without a structure.

Both plots illustrate the increasing magnitude of flow depth disturbance with increasing discharge – an anticipated result. The distance upstream of the structure (region of effect) also increases with discharge, also an anticipated impact.

The culvert system has a greater impact in both magnitude and upstream backwater propagation. At the highest flow rate simulated, the backwater effect extends about

200 feet upstream of the structure.

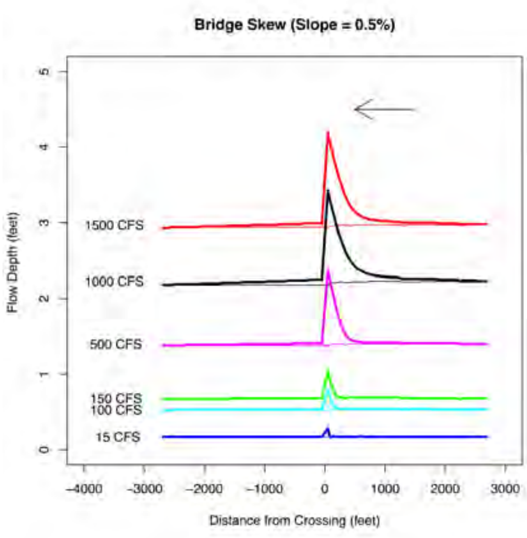
The flow depths are smaller in comparison to the 0.5- and 1.0- percent slope cases for otherwise the same conditions. The smaller depths are anticipated as the greater topographic slope increases the gravitational force component on the flow and reduces the pressure force (depth in open channel flow) requirement to sustain a particular discharge value. Furthermore, the reduced depth corresponds to greater water speeds, that in turn reduces the backwater distance effect of the hydraulic structures.

4.5.2. Narrow Straight Channel – 15^o Skew

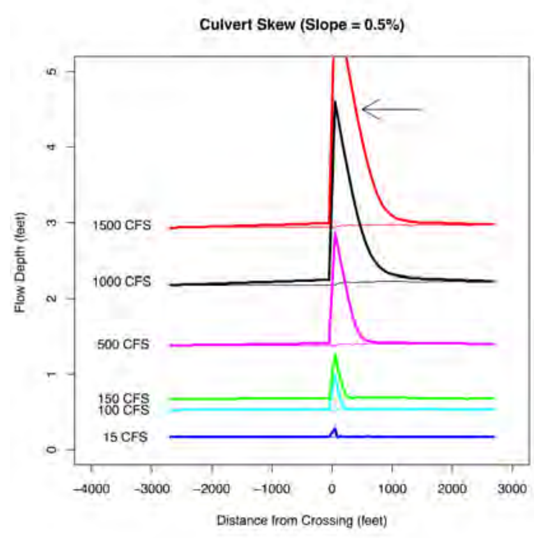
This subsection presents the results for the three slopes for a narrow, straight channel with the hydraulic structures rotated 15^o relative to the channel centerline.

Longitudinal Slope 0.5 percent

Figure 13 is a plot pair of the flow depth in the channel (relative to the channel bottom) for the bridge piers and the culvert pair, respectively. The left panel illustrates the effect of the bridge piers; the right panel illustrates the effect of the culverts.



(a) Flow Depth with Bridge Piers



(b) Flow Depth with Twin Culverts

Figure 13. Flow Depths for Bridge Piers and Culvert

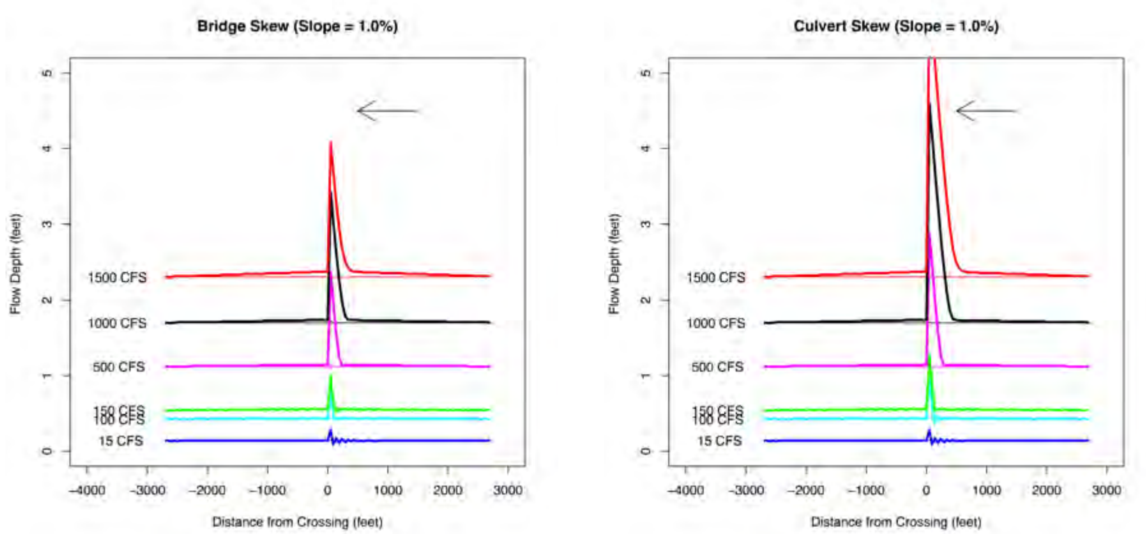
The plots show the different plow depth profiles increasing from 15 CFS to 1500 CFS. The structure is located in the middle of the plots (at $x = 0$). Both plots show the structure-induced behavior with comparatively thick lines. The thin lines (of the same color as each thick line) represent the configuration without a structure.

Both plots illustrate the increasing magnitude of flow depth disturbance with increasing discharge – an anticipated result. The distance upstream of the structure (region of effect) also increases with discharge, also an anticipated impact.

The culvert system has a greater impact in both magnitude and upstream backwater propagation. At the highest flow rate simulated, the backwater effect extends nearly 1500 feet upstream of the structure, a 1.5 increase as compared the the aligned structure case for the same channel.

Longitudinal Slope 1.0 percent

Figure 14 is a plot pair of the flow depth in the channel (relative to the channel bottom) for the bridge piers and the culvert pair, respectively. The left panel illustrates the effect of the bridge piers; the right panel illustrates the effect of the culverts.



(a) Flow Depth with Bridge Piers **(b)** Flow Depth with Twin Culverts

Figure 14. Flow Depths for Bridge Piers and Culvert

The plots show the different plow depth profiles increasing from 15 CFS to 1500 CFS. The structure is located in the middle of the plots (at $x = 0$). Both plots show the structure-induced behavior with comparatively thick lines. The thin lines (of the same color as each thick line) represent the configuration without a structure.

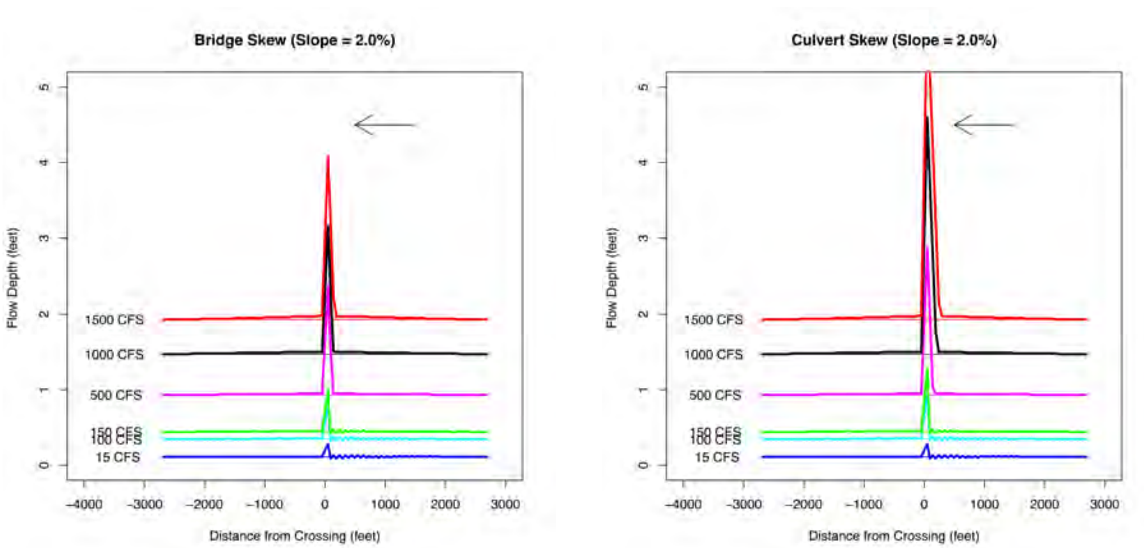
Both plots illustrate the increasing magnitude of flow depth disturbance with increasing discharge – an anticipated result. The distance upstream of the structure (region of effect) also increases with discharge, also an anticipated impact.

The culvert system has a greater impact in both magnitude and upstream backwater propagation. At the highest flow rate simulated, the backwater effect extends about 1000 feet upstream of the structure; about double of the aligned structure case for the same channel.

The flow depths are smaller in comparison to the 0.5 percent slope case for otherwise the same conditions. The smaller depths are anticipated as the greater topographic slope increases the gravitational force component on the flow and reduces the pressure force (depth in open channel flow) requirement to sustain a particular discharge value. Furthermore, the reduced depth corresponds to greater water speeds, that in turn reduces the backwater distance effect of the hydraulic structures.

Longitudinal Slope 2.0 percent

Figure 15 is a plot pair of the flow depth in the channel (relative to the channel bottom) for the bridge piers and the culvert pair, respectively. The left panel illustrates the effect of the bridge piers; the right panel illustrates the effect of the culverts.



(a) Flow Depth with Bridge Piers **(b)** Flow Depth with Twin Culverts

Figure 15. Flow Depths for Bridge Piers and Culvert

The plots show the different plow depth profiles increasing from 15 CFS to 1500 CFS. The structure is located in the middle of the plots (at $x = 0$). Both plots show the structure-induced behavior with comparatively thick lines. The thin lines (of the same color as each thick line) represent the configuration without a structure.

Both plots illustrate the increasing magnitude of flow depth disturbance with increasing discharge – an anticipated result. The distance upstream of the structure (region of effect) also increases with discharge, also an anticipated impact.

The culvert system has a greater impact in both magnitude and upstream backwater propagation. At the highest flow rate simulated, the backwater effect extends about 400 feet upstream of the structure.

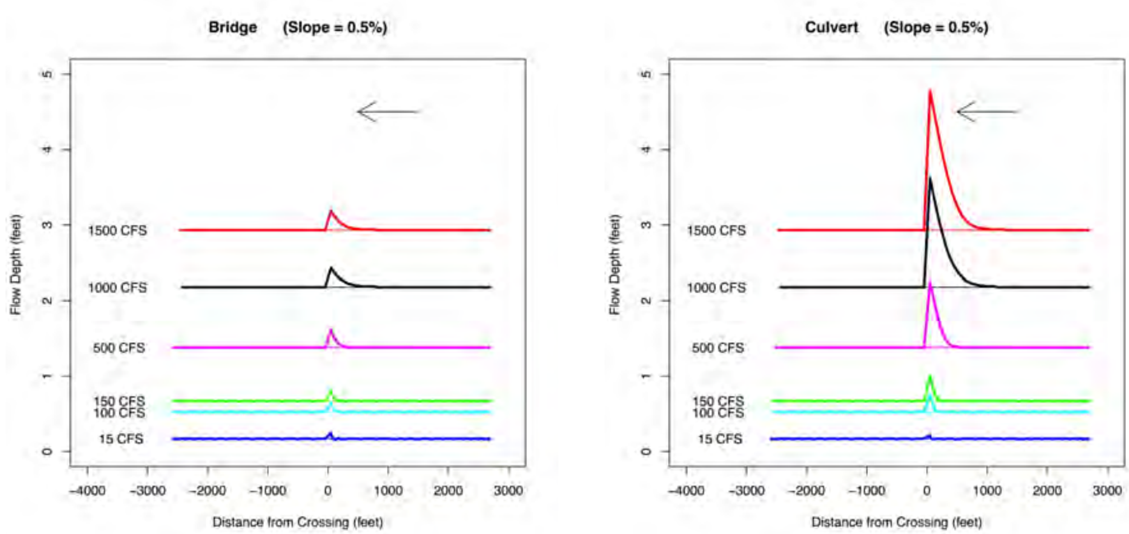
The flow depths are smaller in comparison to the 0.5- and 1.0- percent slope cases for otherwise the same conditions. The smaller depths are anticipated as the greater topographic slope increases the gravitational force component on the flow and reduces the pressure force (depth in open channel flow) requirement to sustain a particular discharge value. Furthermore, the reduced depth corresponds to greater water speeds, that in turn reduces the backwater distance effect of the hydraulic structures.

4.5.3. Narrow Curved Channel – No Skew

This subsection presents the results for the three slopes for a narrow, straight channel with the hydraulic structures rotated 15^o relative to the channel centerline.

Longitudinal Slope 0.5 percent

Figure 16 is a plot pair of the flow depth in the channel (relative to the channel bottom) for the bridge piers and the culvert pair, respectively. The left panel illustrates the effect of the bridge piers; the right panel illustrates the effect of the culverts.



(a) Flow Depth with Bridge Piers **(b)** Flow Depth with Twin Culverts

Figure 16. Flow Depths for Bridge Piers and Culvert

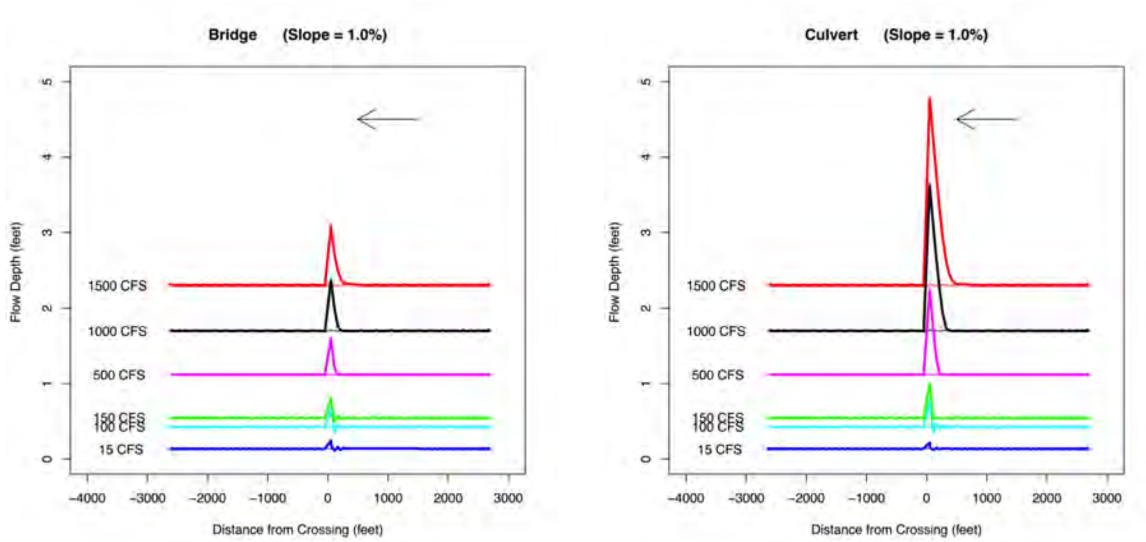
The plots show the different plow depth profiles increasing from 15 CFS to 1500 CFS. The structure is located in the middle of the plots (at $x = 0$). Both plots show the structure-induced behavior with comparatively thick lines. The thin lines (of the same color as each thick line) represent the configuration without a structure.

Both plots illustrate the increasing magnitude of flow depth disturbance with increasing discharge – an anticipated result. The distance upstream of the structure (region of effect) also increases with discharge, also an anticipated impact.

The culvert system has a greater impact in both magnitude and upstream backwater propagation. At the highest flow rate simulated, the backwater effect extends nearly 1000 feet upstream of the structure, a doubling as compared the the aligned structure case for the same channel.

Longitudinal Slope 1.0 percent

Figure 17 is a plot pair of the flow depth in the channel (relative to the channel bottom) for the bridge piers and the culvert pair, respectively. The left panel illustrates the effect of the bridge piers; the right panel illustrates the effect of the culverts.



(a) Flow Depth with Bridge Piers **(b)** Flow Depth with Twin Culverts

Figure 17. Flow Depths for Bridge Piers and Culvert

The plots show the different plow depth profiles increasing from 15 CFS to 1500 CFS. The structure is located in the middle of the plots (at $x = 0$). Both plots show the structure-induced behavior with comparatively thick lines. The thin lines (of the same color as each thick line) represent the configuration without a structure.

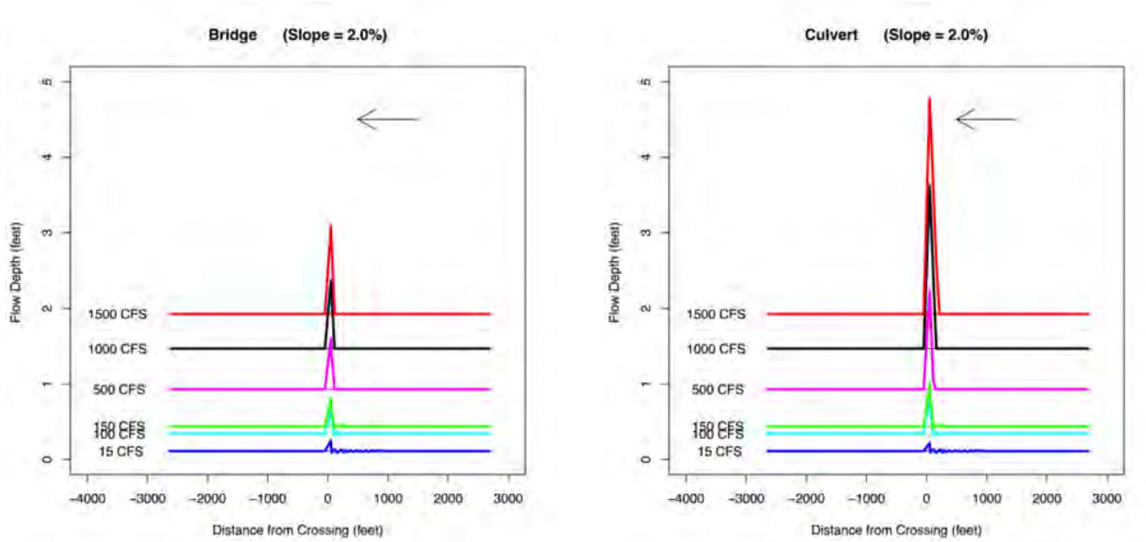
Both plots illustrate the increasing magnitude of flow depth disturbance with increasing discharge – an anticipated result. The distance upstream of the structure (region of effect) also increases with discharge, also an anticipated impact.

The culvert system has a greater impact in both magnitude and upstream backwater propagation. At the highest flow rate simulated, the backwater effect extends about 500 feet upstream of the structure; about double of the aligned structure case for the same channel.

The flow depths are smaller in comparison to the 0.5 percent slope case for otherwise the same conditions. The smaller depths are anticipated as the greater topographic slope increases the gravitational force component on the flow and reduces the pressure force (depth in open channel flow) requirement to sustain a particular discharge value. Furthermore, the reduced depth corresponds to greater water speeds, that in turn reduces the backwater distance effect of the hydraulic structures.

Longitudinal Slope 2.0 percent

Figure 18 is a plot pair of the flow depth in the channel (relative to the channel bottom) for the bridge piers and the culvert pair, respectively. The left panel illustrates the effect of the bridge piers; the right panel illustrates the effect of the culverts.



(a) Flow Depth with Bridge Piers **(b)** Flow Depth with Twin Culverts

Figure 18. Flow Depths for Bridge Piers and Culvert

The plots show the different plow depth profiles increasing from 15 CFS to 1500 CFS. The structure is located in the middle of the plots (at $x = 0$). Both plots show the structure-induced behavior with comparatively thick lines. The thin lines (of the same color as each thick line) represent the configuration without a structure.

Both plots illustrate the increasing magnitude of flow depth disturbance with increasing discharge – an anticipated result. The distance upstream of the structure (region of effect) also increases with discharge, also an anticipated impact.

The culvert system has a greater impact in both magnitude and upstream backwater propagation. At the highest flow rate simulated, the backwater effect extends about 200 feet upstream of the structure.

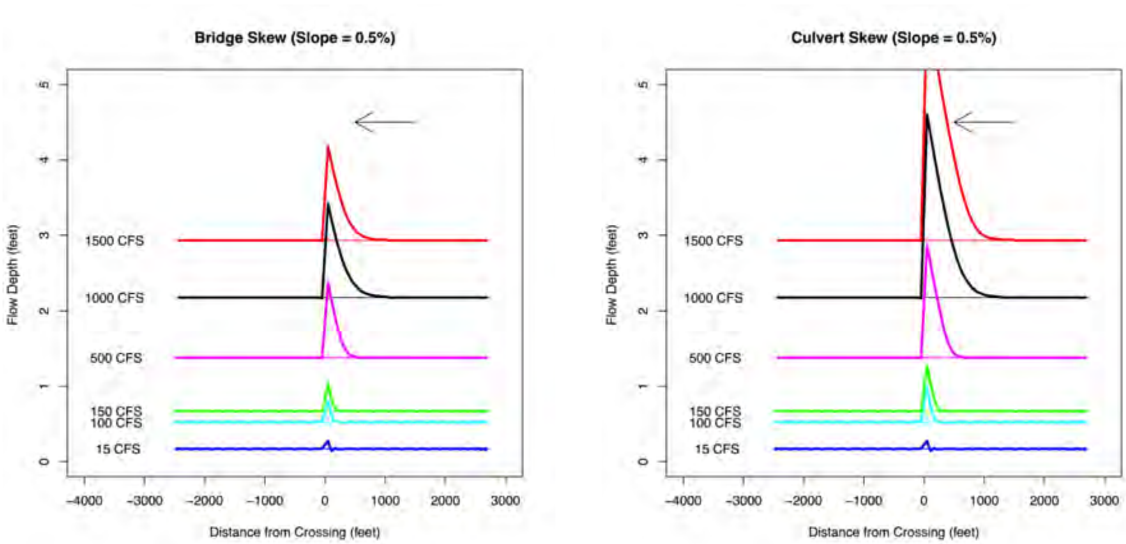
The flow depths are smaller in comparison to the 0.5- and 1.0- percent slope cases for otherwise the same conditions. The smaller depths are anticipated as the greater topographic slope increases the gravitational force component on the flow and reduces the pressure force (depth in open channel flow) requirement to sustain a particular discharge value. Furthermore, the reduced depth corresponds to greater water speeds, that in turn reduces the backwater distance effect of the hydraulic structures.

4.5.4. Narrow Curved Channel – 15^o Skew

This subsection presents the results for the three slopes for a narrow, straight channel with the hydraulic structures rotated 15^o relative to the channel centerline.

Longitudinal Slope 0.5 percent

Figure 19 is a plot pair of the flow depth in the channel (relative to the channel bottom) for the bridge piers and the culvert pair, respectively. The left panel illustrates the effect of the bridge piers; the right panel illustrates the effect of the culverts.



(a) Flow Depth with Bridge Piers **(b)** Flow Depth with Twin Culverts

Figure 19. Flow Depths for Bridge Piers and Culvert

The plots show the different plow depth profiles increasing from 15 CFS to 1500 CFS. The structure is located in the middle of the plots (at $x = 0$). Both plots show the structure-induced behavior with comparatively thick lines. The thin lines (of the same color as each thick line) represent the configuration without a structure.

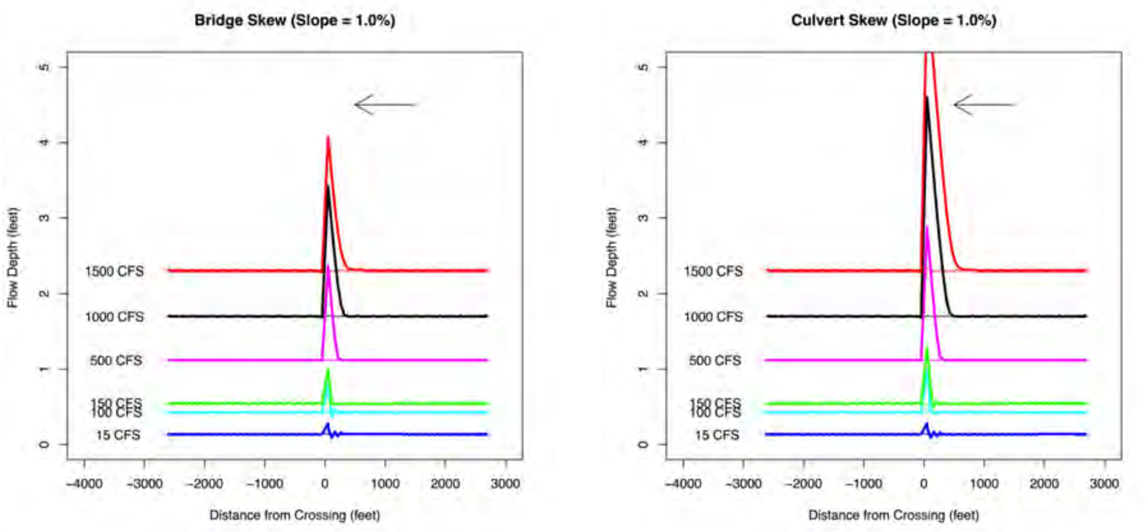
Both plots illustrate the increasing magnitude of flow depth disturbance with increasing discharge – an anticipated result. The distance upstream of the structure (region of effect) also increases with discharge, also an anticipated impact.

The culvert system has a greater impact in both magnitude and upstream backwater propagation. At the highest flow rate simulated, the backwater effect extends nearly

1000 feet upstream of the structure, a doubling as compared the the aligned structure case for the same channel.

Longitudinal Slope 1.0 percent

Figure 20 is a plot pair of the flow depth in the channel (relative to the channel bottom) for the bridge piers and the culvert pair, respectively. The left panel illustrates the effect of the bridge piers; the right panel illustrates the effect of the culverts.



(a) Flow Depth with Bridge Piers **(b)** Flow Depth with Twin Culverts

Figure 20. Flow Depths for Bridge Piers and Culvert

The plots show the different plow depth profiles increasing from 15 CFS to 1500 CFS. The structure is located in the middle of the plots (at $x = 0$). Both plots show the structure-induced behavior with comparatively thick lines. The thin lines (of the same color as each thick line) represent the configuration without a structure.

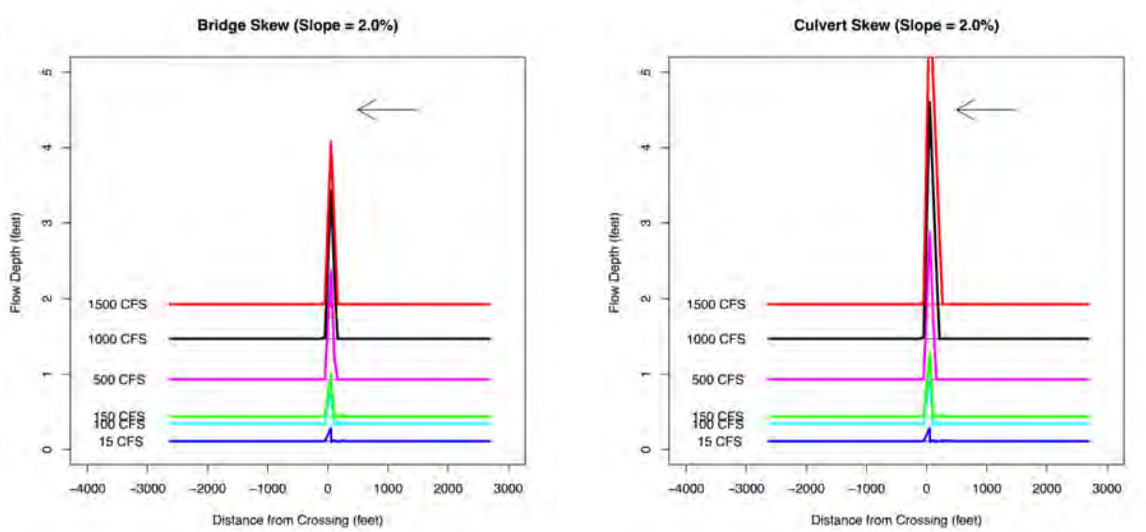
Both plots illustrate the increasing magnitude of flow depth disturbance with increasing discharge – an anticipated result. The distance upstream of the structure (region of effect) also increases with discharge, also an anticipated impact.

The culvert system has a greater impact in both magnitude and upstream backwater propagation. At the highest flow rate simulated, the backwater effect extends about 600 feet upstream of the structure; about double of the aligned structure case for the same channel.

The flow depths are smaller in comparison to the 0.5 percent slope case for otherwise the same conditions. The smaller depths are anticipated as the greater topographic slope increases the gravitational force component on the flow and reduces the pressure force (depth in open channel flow) requirement to sustain a particular discharge value. Furthermore, the reduced depth corresponds to greater water speeds, that in turn reduces the backwater distance effect of the hydraulic structures.

Longitudinal Slope 2.0 percent

Figure 21 is a plot pair of the flow depth in the channel (relative to the channel bottom) for the bridge piers and the culvert pair, respectively. The left panel illustrates the effect of the bridge piers; the right panel illustrates the effect of the culverts.



(a) Flow Depth with Bridge Piers **(b)** Flow Depth with Twin Culverts

Figure 21. Flow Depths for Bridge Piers and Culvert

The plots show the different plow depth profiles increasing from 15 CFS to 1500 CFS. The structure is located in the middle of the plots (at $x = 0$). Both plots show the structure-induced behavior with comparatively thick lines. The thin lines (of the same color as each thick line) represent the configuration without a structure.

Both plots illustrate the increasing magnitude of flow depth disturbance with increasing discharge – an anticipated result. The distance upstream of the structure (region of effect) also increases with discharge, also an anticipated impact.

The culvert system has a greater impact in both magnitude and upstream backwater propagation. At the highest flow rate simulated, the backwater effect extends about 300 feet upstream of the structure.

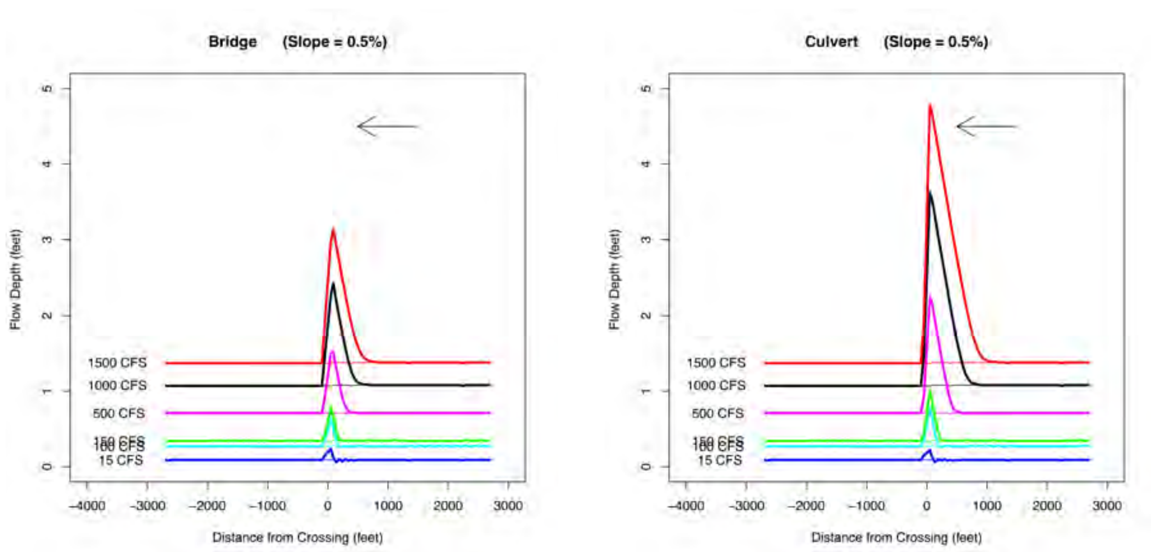
The flow depths are smaller in comparison to the 0.5- and 1.0- percent slope cases for otherwise the same conditions. The smaller depths are anticipated as the greater topographic slope increases the gravitational force component on the flow and reduces the pressure force (depth in open channel flow) requirement to sustain a particular discharge value. Furthermore, the reduced depth corresponds to greater water speeds, that in turn reduces the backwater distance effect of the hydraulic structures.

4.5.5. Wide Straight Channel – No Skew

This subsection presents the results for the three slopes for a narrow, straight channel with the hydraulic structures aligned with the channel centerline.

Longitudinal Slope 0.5 percent

Figure 22 is a plot pair of the flow depth in the channel (relative to the channel bottom) for the bridge piers and the culvert pair, respectively. The left panel illustrates the effect of the bridge piers; the right panel illustrates the effect of the culverts.



(a) Flow Depth with Bridge Piers **(b)** Flow Depth with Twin Culverts

Figure 22. Flow Depths for Bridge Piers and Culvert

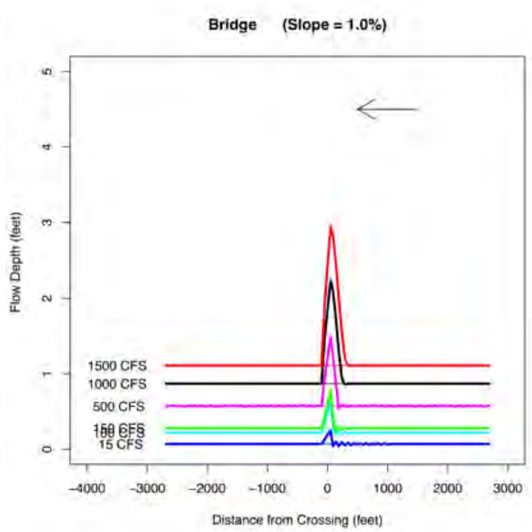
The plots show the different plow depth profiles increasing from 15 CFS to 1500 CFS. The structure is located in the middle of the plots (at $x = 0$). Both plots show the structure-induced behavior with comparatively thick lines. The thin lines (of the same color as each thick line) represent the configuration without a structure.

Both plots illustrate the increasing magnitude of flow depth disturbance with increasing discharge – an anticipated result. The distance upstream of the structure (region of effect) also increases with discharge, also an anticipated impact.

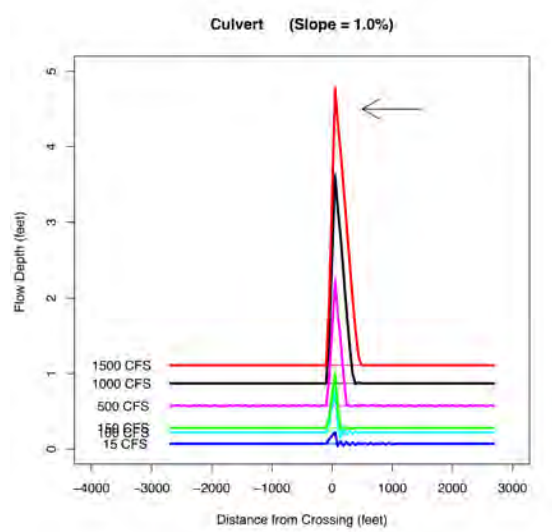
The culvert system has a greater impact in both magnitude and upstream backwater propagation. At the highest flow rate simulated, the backwater effect extends about 1000 feet upstream of the structure.

Longitudinal Slope 1.0 percent

Figure 23 is a plot pair of the flow depth in the channel (relative to the channel bottom) for the bridge piers and the culvert pair, respectively. The left panel illustrates the effect of the bridge piers; the right panel illustrates the effect of the culverts.



(a) Flow Depth with Bridge Piers



(b) Flow Depth with Twin Culverts

Figure 23. Flow Depths for Bridge Piers and Culvert

The plots show the different plow depth profiles increasing from 15 CFS to 1500 CFS. The structure is located in the middle of the plots (at $x = 0$). Both plots show the structure-induced behavior with comparatively thick lines. The thin lines (of the same color as each thick line) represent the configuration without a structure.

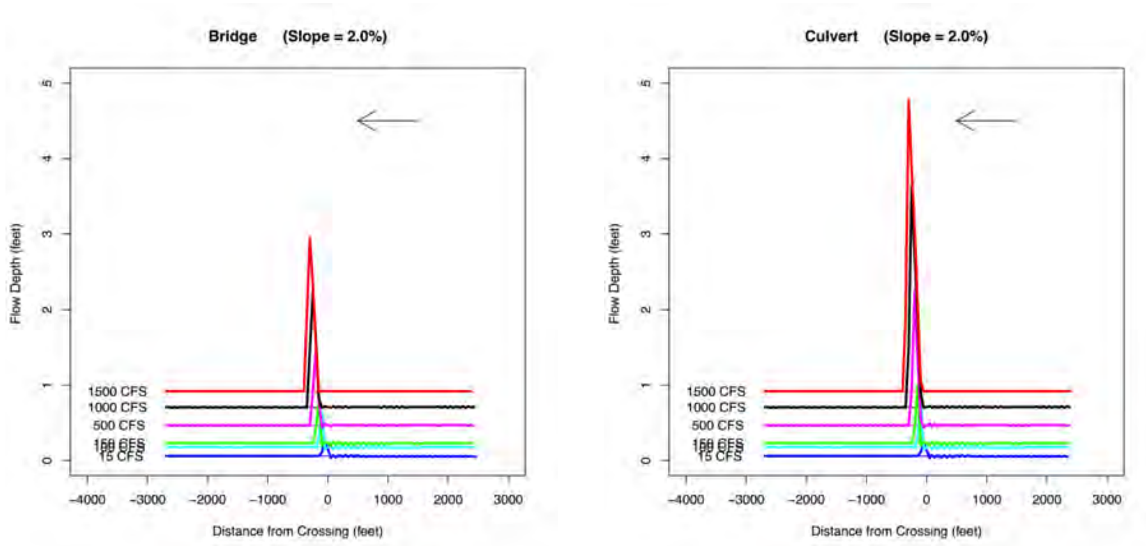
Both plots illustrate the increasing magnitude of flow depth disturbance with increasing discharge – an anticipated result. The distance upstream of the structure (region of effect) also increases with discharge, also an anticipated impact.

The culvert system has a greater impact in both magnitude and upstream backwater propagation. At the highest flow rate simulated, the backwater effect extends about 500 feet upstream of the structure.

The flow depths are smaller in comparison to the 0.5 percent slope case for otherwise the same conditions. The smaller depths are anticipated as the greater topographic slope increases the gravitational force component on the flow and reduces the pressure force (depth in open channel flow) requirement to sustain a particular discharge value. Furthermore, the reduced depth corresponds to greater water speeds, that in turn reduces the backwater distance effect of the hydraulic structures.

Longitudinal Slope 2.0 percent

Figure 24 is a plot pair of the flow depth in the channel (relative to the channel bottom) for the bridge piers and the culvert pair, respectively. The left panel illustrates the effect of the bridge piers; the right panel illustrates the effect of the culverts.



(a) Flow Depth with Bridge Piers **(b)** Flow Depth with Twin Culverts

Figure 24. Flow Depths for Bridge Piers and Culvert

The plots show the different plow depth profiles increasing from 15 CFS to 1500 CFS. The structure is located in the middle of the plots (at $x = 0$). Both plots show the structure-induced behavior with comparatively thick lines. The thin lines (of the same color as each thick line) represent the configuration without a structure.

Both plots illustrate the increasing magnitude of flow depth disturbance with increasing discharge – an anticipated result. The distance upstream of the structure (region of effect) also increases with discharge, also an anticipated impact.

The culvert system has a greater impact in both magnitude and upstream backwater propagation. At the highest flow rate simulated, the frontwater effect extends about 400 feet downstream of the structure. For these conditions the flow is supercritical – an unanticipated result when the simulations were created, but nevertheless useful.

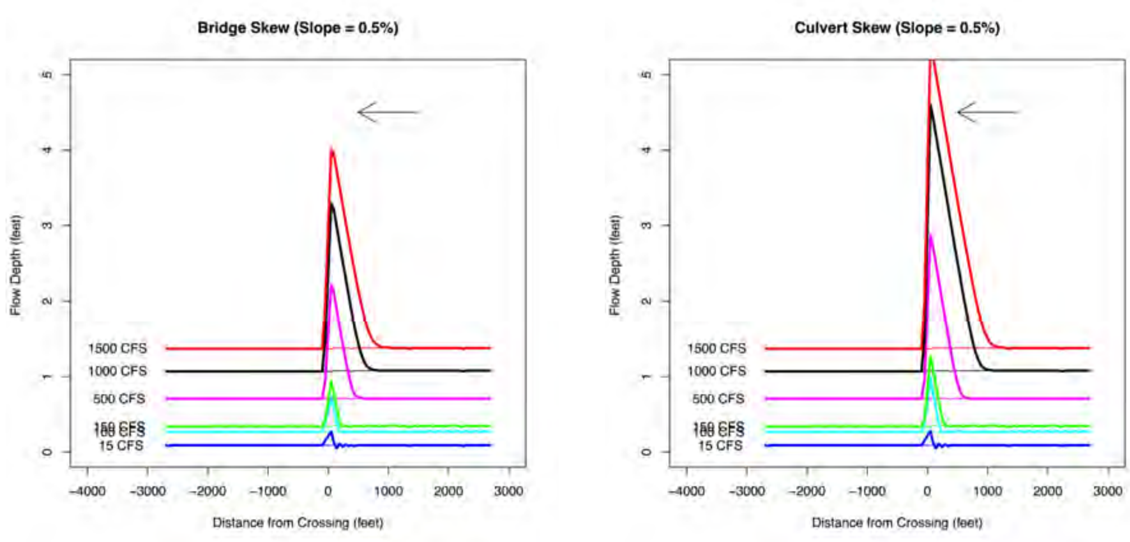
The flow depths are smaller in comparison to the 0.5- and 1.0- percent slope cases for otherwise the same conditions. The smaller depths are anticipated as the greater topographic slope increases the gravitational force component on the flow and reduces the pressure force (depth in open channel flow) requirement to sustain a particular discharge value. Furthermore, the reduced depth corresponds to greater water speeds, that in turn reduces the backwater distance effect of the hydraulic structures.

4.5.6. Wide Straight Channel – 15^o Skew

This subsection presents the results for the three slopes for a narrow, straight channel with the hydraulic structures rotated 15^o relative to the channel centerline.

Longitudinal Slope 0.5 percent

Figure 25 is a plot pair of the flow depth in the channel (relative to the channel bottom) for the bridge piers and the culvert pair, respectively. The left panel illustrates the effect of the bridge piers; the right panel illustrates the effect of the culverts.



(a) Flow Depth with Bridge Piers **(b)** Flow Depth with Twin Culverts

Figure 25. Flow Depths for Bridge Piers and Culvert

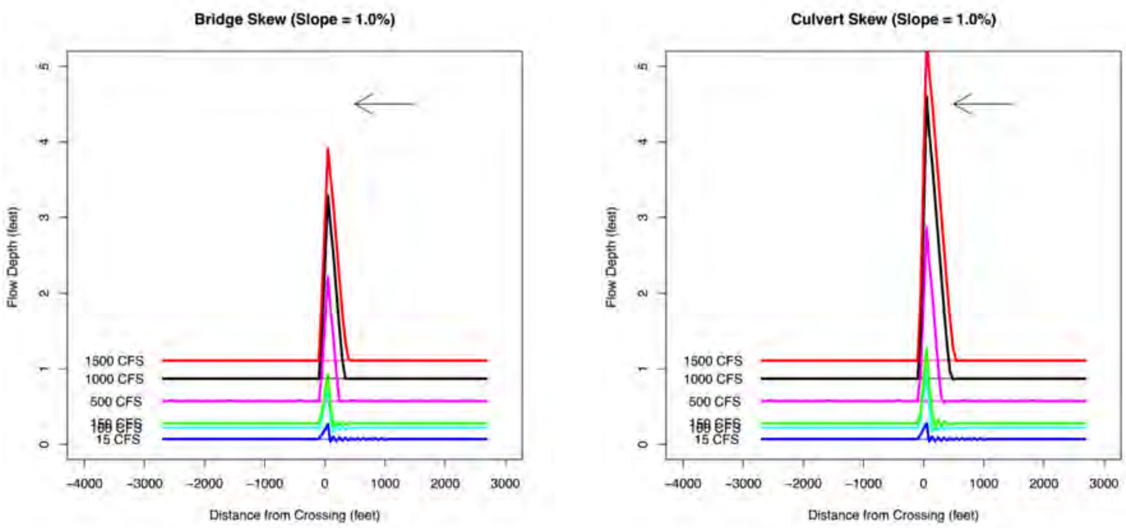
The plots show the different plow depth profiles increasing from 15 CFS to 1500 CFS. The structure is located in the middle of the plots (at $x = 0$). Both plots show the structure-induced behavior with comparatively thick lines. The thin lines (of the same color as each thick line) represent the configuration without a structure.

Both plots illustrate the increasing magnitude of flow depth disturbance with increasing discharge – an anticipated result. The distance upstream of the structure (region of effect) also increases with discharge, also an anticipated impact.

The culvert system has a greater impact in both magnitude and upstream backwater propagation. At the highest flow rate simulated, the backwater effect extends nearly 1000 feet upstream of the structure, a doubling as compared the the aligned case.

Longitudinal Slope 1.0 percent

Figure 26 is a plot pair of the flow depth in the channel (relative to the channel bottom) for the bridge piers and the culvert pair, respectively. The left panel illustrates the effect of the bridge piers; the right panel illustrates the effect of the culverts.



(a) Flow Depth with Bridge Piers (b) Flow Depth with Twin Culverts

Figure 26. Flow Depths for Bridge Piers and Culvert

The plots show the different plow depth profiles increasing from 15 CFS to 1500 CFS. The structure is located in the middle of the plots (at $x = 0$). Both plots show the structure-induced behavior with comparatively thick lines. The thin lines (of the same color as each thick line) represent the configuration without a structure.

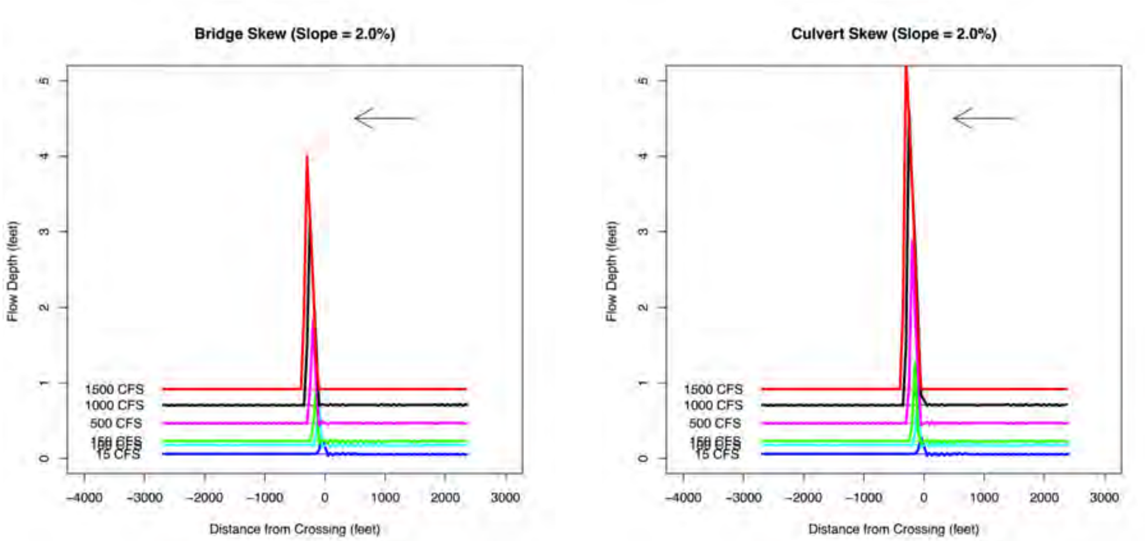
Both plots illustrate the increasing magnitude of flow depth disturbance with increasing discharge – an anticipated result. The distance upstream of the structure (region of effect) also increases with discharge, also an anticipated impact.

The culvert system has a greater impact in both magnitude and upstream backwater propagation. At the highest flow rate simulated, the backwater effect extends about 500 feet upstream of the structure; about double of the aligned structure case for the same channel.

The flow depths are smaller in comparison to the 0.5 percent slope case for otherwise the same conditions. The smaller depths are anticipated as the greater topographic slope increases the gravitational force component on the flow and reduces the pressure force (depth in open channel flow) requirement to sustain a particular discharge value. Furthermore, the reduced depth corresponds to greater water speeds, that in turn reduces the backwater distance effect of the hydraulic structures.

Longitudinal Slope 2.0 percent

Figure 27 is a plot pair of the flow depth in the channel (relative to the channel bottom) for the bridge piers and the culvert pair, respectively. The left panel illustrates the effect of the bridge piers; the right panel illustrates the effect of the culverts.



(a) Flow Depth with Bridge Piers

(b) Flow Depth with Twin Culverts

Figure 27. Flow Depths for Bridge Piers and Culvert

The plots show the different plow depth profiles increasing from 15 CFS to 1500 CFS. The structure is located in the middle of the plots (at $x = 0$). Both plots show the structure-induced behavior with comparatively thick lines. The thin lines represent the configuration without a structure.

The plots illustrate an increasing magnitude of flow depth disturbance and the increasing influence distance of the structure with increasing discharge.

The culvert system has a greater impact in both magnitude and upstream backwater propagation. At the highest flow rate simulated, the frontwater effect extends about 200 feet downstream of the structure. For these conditions the flow is supercritical, an unanticipated result.

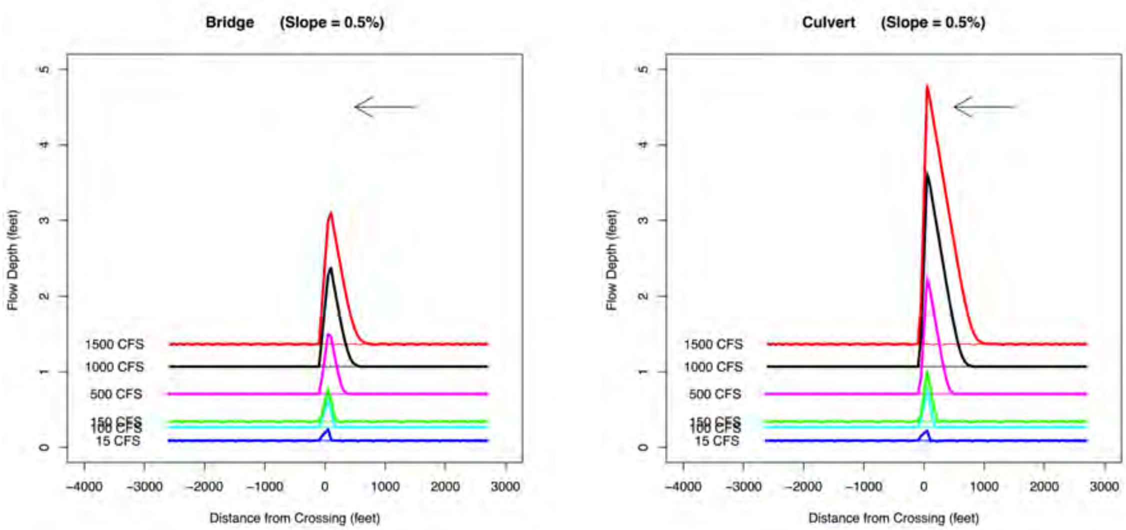
The flow depths are smaller in comparison to the 0.5- and 1.0- percent slope cases for otherwise the same conditions. The smaller depths are anticipated as the greater topographic slope increases the gravitational force component on the flow and reduces the pressure force requirement to sustain a particular discharge value. Furthermore, the reduced depth corresponds to greater water speeds, that in turn reduces the backwater distance effect of the hydraulic structures.

4.5.7. Wide Curved Channel – No Skew

This subsection presents the results for the three slopes for a narrow, straight channel with the hydraulic structures rotated 15^o relative to the channel centerline.

Longitudinal Slope 0.5 percent

Figure 28 is a plot pair of the flow depth in the channel (relative to the channel bottom) for the bridge piers and the culvert pair, respectively. The left panel illustrates the effect of the bridge piers; the right panel illustrates the effect of the culverts.



(a) Flow Depth with Bridge Piers **(b)** Flow Depth with Twin Culverts

Figure 28. Flow Depths for Bridge Piers and Culvert

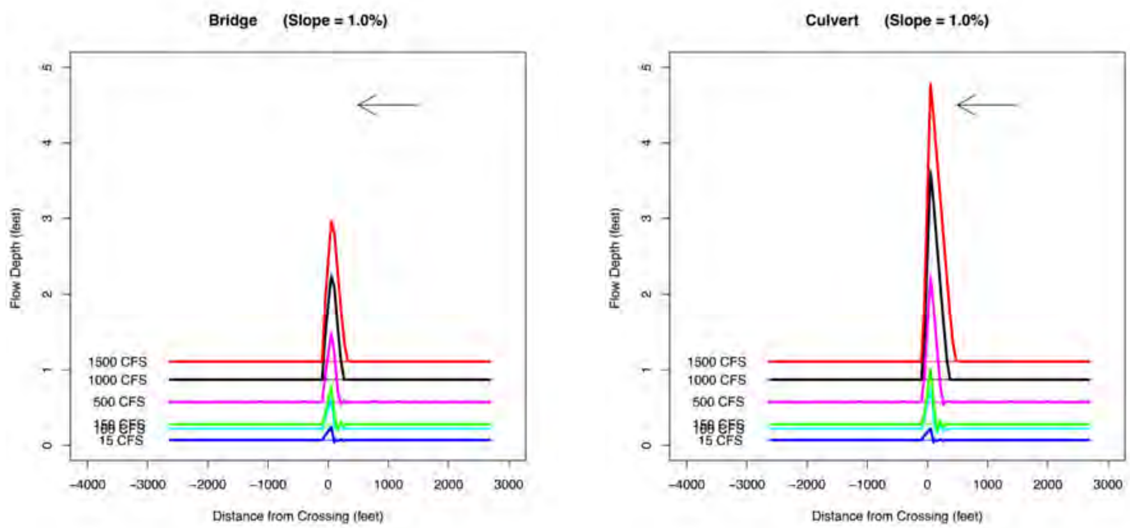
The plots show the different plow depth profiles increasing from 15 CFS to 1500 CFS. The structure is located in the middle of the plots (at $x = 0$). Both plots show the structure-induced behavior with comparatively thick lines. The thin lines (of the same color as each thick line) represent the configuration without a structure.

Both plots illustrate the increasing magnitude of flow depth disturbance with increasing discharge – an anticipated result. The distance upstream of the structure (region of effect) also increases with discharge, also an anticipated impact.

The culvert system has a greater impact in both magnitude and upstream backwater propagation. At the highest flow rate simulated, the backwater effect extends nearly 1000 feet upstream of the structure, a doubling as compared the the aligned structure case for the same channel.

Longitudinal Slope 1.0 percent

Figure 29 is a plot pair of the flow depth in the channel (relative to the channel bottom) for the bridge piers and the culvert pair, respectively. The left panel illustrates the effect of the bridge piers; the right panel illustrates the effect of the culverts.



(a) Flow Depth with Bridge Piers **(b)** Flow Depth with Twin Culverts

Figure 29. Flow Depths for Bridge Piers and Culvert

The plots show the different plow depth profiles increasing from 15 CFS to 1500 CFS. The structure is located in the middle of the plots (at $x = 0$). Both plots show the structure-induced behavior with comparatively thick lines. The thin lines (of the same color as each thick line) represent the configuration without a structure.

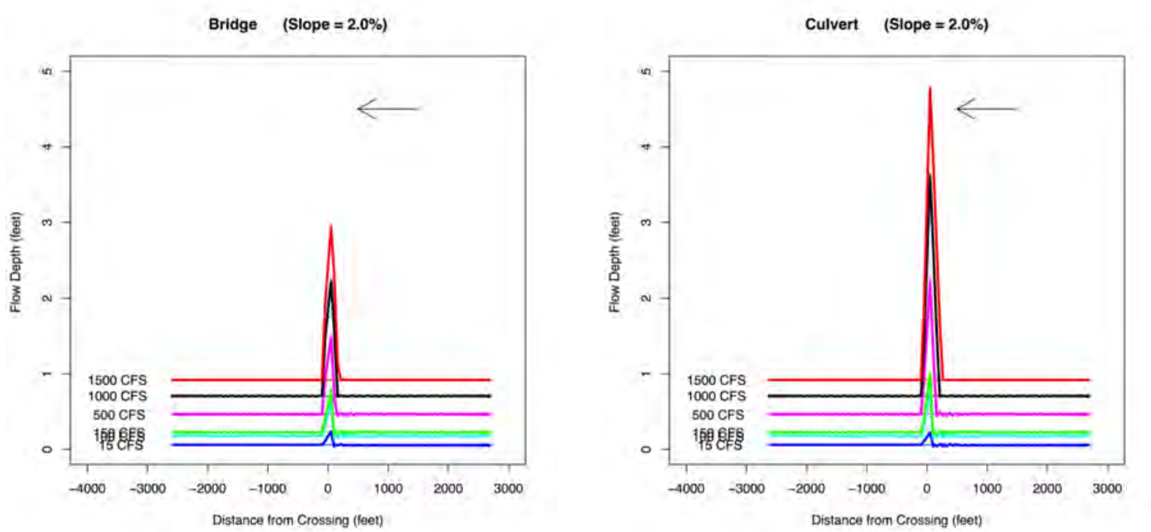
Both plots illustrate the increasing magnitude of flow depth disturbance with increasing discharge – an anticipated result. The distance upstream of the structure (region of effect) also increases with discharge, also an anticipated impact.

The culvert system has a greater impact in both magnitude and upstream backwater propagation. At the highest flow rate simulated, the backwater effect extends about 500 feet upstream of the structure; about double of the aligned structure case for the same channel.

The flow depths are smaller in comparison to the 0.5 percent slope case for otherwise the same conditions. The smaller depths are anticipated as the greater topographic slope increases the gravitational force component on the flow and reduces the pressure force (depth in open channel flow) requirement to sustain a particular discharge value. Furthermore, the reduced depth corresponds to greater water speeds, that in turn reduces the backwater distance effect of the hydraulic structures.

Longitudinal Slope 2.0 percent

Figure 30 is a plot pair of the flow depth in the channel (relative to the channel bottom) for the bridge piers and the culvert pair, respectively. The left panel illustrates the effect of the bridge piers; the right panel illustrates the effect of the culverts.



(a) Flow Depth with Bridge Piers **(b)** Flow Depth with Twin Culverts

Figure 30. Flow Depths for Bridge Piers and Culvert

The plots show the different plow depth profiles increasing from 15 CFS to 1500 CFS. The structure is located in the middle of the plots (at $x = 0$). Both plots show the structure-induced behavior with comparatively thick lines. The thin lines (of the same color as each thick line) represent the configuration without a structure.

Both plots illustrate the increasing magnitude of flow depth disturbance with increasing discharge – an anticipated result. The distance upstream of the structure (region of effect) also increases with discharge, also an anticipated impact.

The culvert system has a greater impact in both magnitude and upstream backwater propagation. At the highest flow rate simulated, the frontwater effect extends about 200 feet downstream of the structure.

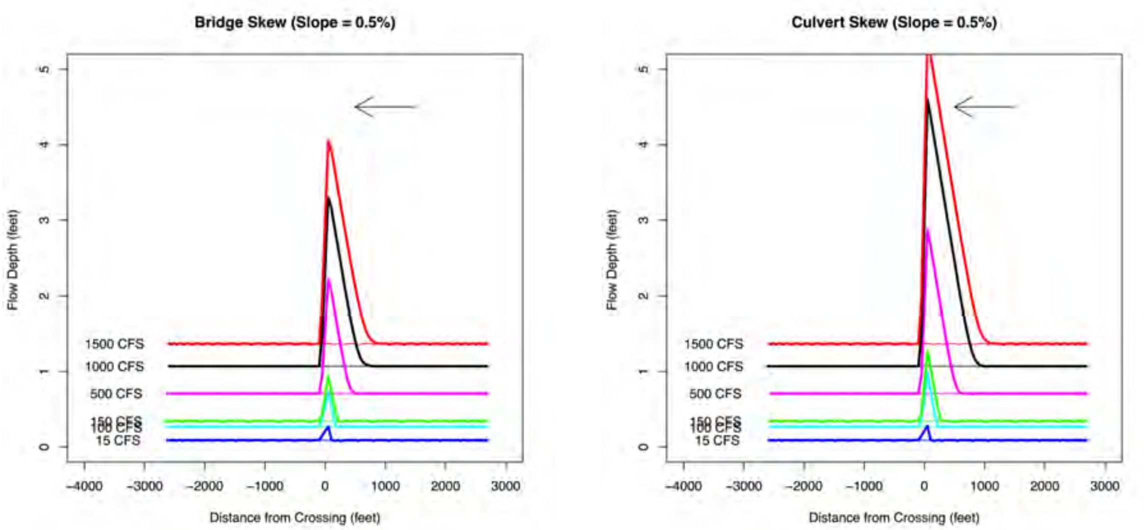
The flow depths are smaller in comparison to the 0.5- and 1.0- percent slope cases for otherwise the same conditions. The smaller depths are anticipated as the greater topographic slope increases the gravitational force component on the flow and reduces the pressure force (depth in open channel flow) requirement to sustain a particular discharge value. Furthermore, the reduced depth corresponds to greater water speeds, that in turn reduces the backwater distance effect of the hydraulic structures.

4.5.8. Wide Curved Channel – 15^o Skew

This subsection presents the results for the three slopes for a narrow, straight channel with the hydraulic structures rotated 15^o relative to the channel centerline.

Longitudinal Slope 0.5 percent

Figure 31 is a plot pair of the flow depth in the channel (relative to the channel bottom) for the bridge piers and the culvert pair, respectively. The left panel illustrates the effect of the bridge piers; the right panel illustrates the effect of the culverts.



(a) Flow Depth with Bridge Piers **(b)** Flow Depth with Twin Culverts

Figure 31. Flow Depths for Bridge Piers and Culvert

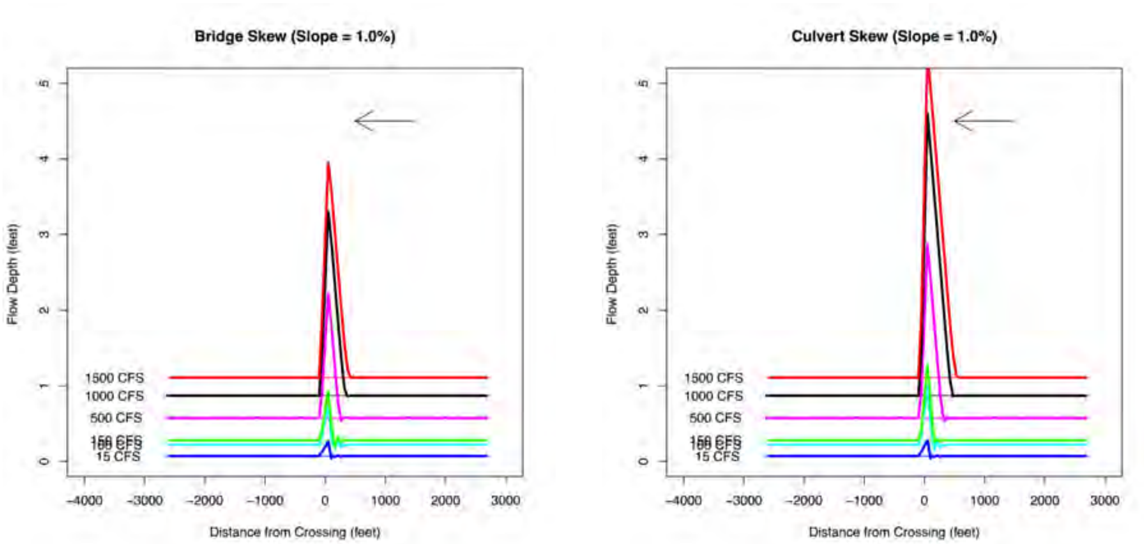
The plots show the different plow depth profiles increasing from 15 CFS to 1500 CFS. The structure is located in the middle of the plots (at $x = 0$). Both plots show the structure-induced behavior with comparatively thick lines. The thin lines (of the same color as each thick line) represent the configuration without a structure.

Both plots illustrate the increasing magnitude of flow depth disturbance with increasing discharge – an anticipated result. The distance upstream of the structure (region of effect) also increases with discharge, also an anticipated impact.

The culvert system has a greater impact in both magnitude and upstream backwater propagation. At the highest flow rate simulated, the backwater effect extends nearly 1000 feet upstream of the structure, a doubling as compared the the aligned structure case for the same channel.

Longitudinal Slope 1.0 percent

Figure 32 is a plot pair of the flow depth in the channel (relative to the channel bottom) for the bridge piers and the culvert pair, respectively. The left panel illustrates the effect of the bridge piers; the right panel illustrates the effect of the culverts.



(a) Flow Depth with Bridge Piers **(b)** Flow Depth with Twin Culverts
Figure 32. Flow Depths for Bridge Piers and Culvert

The plots show the different plow depth profiles increasing from 15 CFS to 1500 CFS. The structure is located in the middle of the plots (at $x = 0$). Both plots show the structure-induced behavior with comparatively thick lines. The thin lines (of the same color as each thick line) represent the configuration without a structure.

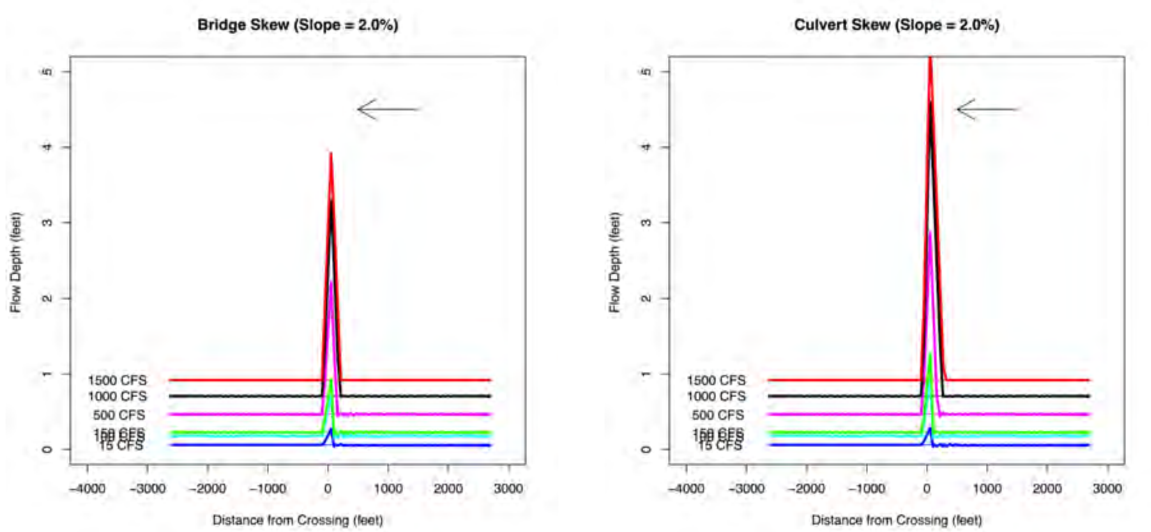
Both plots illustrate the increasing magnitude of flow depth disturbance with increasing discharge – an anticipated result. The distance upstream of the structure (region of effect) also increases with discharge, also an anticipated impact.

The culvert system has a greater impact in both magnitude and upstream backwater propagation. At the highest flow rate simulated, the backwater effect extends about 500 feet upstream of the structure; about double of the aligned structure case for the same channel.

The flow depths are smaller in comparison to the 0.5 percent slope case for otherwise the same conditions. The smaller depths are anticipated as the greater topographic slope increases the gravitational force component on the flow and reduces the pressure force (depth in open channel flow) requirement to sustain a particular discharge value. Furthermore, the reduced depth corresponds to greater water speeds, that in turn reduces the backwater distance effect of the hydraulic structures.

Longitudinal Slope 2.0 percent

Figure 33 is a plot pair of the flow depth in the channel (relative to the channel bottom) for the bridge piers and the culvert pair, respectively. The left panel illustrates the effect of the bridge piers; the right panel illustrates the effect of the culverts.



(a) Flow Depth with Bridge Piers **(b)** Flow Depth with Twin Culverts
Figure 33. Flow Depths for Bridge Piers and Culvert

The plots show the different plow depth profiles increasing from 15 CFS to 1500 CFS. The structure is located in the middle of the plots (at $x = 0$). Both plots show the structure-induced behavior with comparatively thick lines. The thin lines (of the same color as each thick line) represent the configuration without a structure.

Both plots illustrate the increasing magnitude of flow depth disturbance with increasing discharge – an anticipated result. The distance upstream of the structure (region of effect) also increases with discharge, also an anticipated impact.

The culvert system has a greater impact in both magnitude and upstream backwater propagation. At the highest flow rate simulated, the frontwater effect extends about 200 feet downstream of the structure. For the conditions of this configuration the flow is supercritical.

The flow depths are smaller in comparison to the 0.5- and 1.0- percent slope cases for otherwise the same conditions. The smaller depths are anticipated as the greater topographic slope increases the gravitational force component on the flow and reduces the pressure force (depth in open channel flow) requirement to sustain a particular discharge value. Furthermore, the reduced depth corresponds to greater water speeds, that in turn reduces the backwater distance effect of the hydraulic structures.

4.6. Interpretation and Summary

The simulations produced the following generalities:

- As longitudinal slope increases, flow depths decrease – an anticipated and intuitively reasonable result.
- The decreased depths will require increased velocities to convey a particular discharge.
- As longitudinal slope increases, the magnitude of disturbance (depth at the structure) increases.
- As longitudinal slope increases, the distance upstream/downstream[3] to the structure that the disturbance propagates decreases (based on visual inspection of the plots and a judgement of where the disturbance departs from the no structure case to a meaningful extent).
- Structures that are skew to the channel centerline always produced greater magnitude disturbance than the equivalent aligned cases.
- Curvature in the channel produced increased magnitudes of disturbance but had little effect on the distance the disturbance propagated. The researchers speculate that the curved channels have greater "storage" because the inside and outside of the curve have different lengths and the increased storage mitigated the distance effect observed in the straight channel cases.

Table 1 summarizes the disturbance distances for the culvert cases for the maximum discharge (1500 CFS) for the different channel types and aligned versus skew orientation. These culvert cases represent the most adverse conditions of the simulation series.

The list of generalities as well as Table 1 and similar observations for other discharges will be useful in developing a protocol for developing guidance that describes how far up/downstream a hydraulic model needs to extend to be useful for rapid model construction to assess changes in anticipated discharge.

The results fall closely with the guidelines recommended in Nebraska Department of Roads (2015), and further suggest that a reasonably prescriptive guidance can be created. Furthermore, the interpretation of Samuels (1989) guidance to use 20 channel widths as spacing, seems to be also an unintentional, but reasonable disturbance distance criterion.

[3] HEC-RAS applied to the wide channel configuration at largest slope predicts that the flow will be supercritical, and the disturbance propagates downstream.

Table 1. Disturbance (increased flow depths at structures) distance at largest flow for culvert (most adverse) cases. Bridge piers exhibit similar behavior, but magnitude of disturbance and propagation distance is smaller than for equivalent culvert cases.

		Type:	Narrow Straight Channel
Slope	Aligned	Skew	Remarks
0.5%	≈1000 ft.	≈1500 ft.	Skew increases distance about 60-200%
1.0%	≈ 600 ft.	≈1000 ft.	"
2.0%	≈ 200 ft.	≈ 400 ft.	"

		Type:	Narrow Curve Channel
Slope	Aligned	Skew	Remarks
0.5%	≈1000 ft.	≈1000 ft.	Curvature increases magnitude of disturbance
1.0%	≈ 500 ft.	≈ 500 ft.	Upstream propagation is reduced slightly
2.0%	≈ 200 ft.	≈ 200 ft.	Skew increases magnitude, but not distance

		Type:	Wide Straight Channel
Slope	Aligned	Skew	Remarks
0.5%	≈1000 ft.	≈1200 ft.	Skew increases propagation distance slightly
1.0%	≈ 500 ft.	≈ 600 ft.	Transitional sub- to supercritcal flow
2.0%	≈ 400 ft.	≈ 400 ft.	Supercritical flow – propagation downstream

		Type:	Wide Curved Channel
Slope	Aligned	Skew	Remarks
0.5%	≈1000 ft.	≈1000 ft.	No visible skew effect in plots
1.0%	≈ 500 ft.	≈ 500 ft.	Transitional sub- to supercritcal flow
2.0%	≈ 200 ft.	≈ 200 ft.	Supercritical flow – propagation downstream

5. Estimation Tool Development

An estimation tool in the form of a spreadsheet that helps hydraulic designers decide how far upstream or downstream a hydraulic model should extend in order to capture the effects of the water surface elevations was built. The tool uses dimensionless representation of common hydraulic parameters to estimate the distances upstream and downstream of the point of interest that a model should extend to capture changes in water surface elevations from either a geometric change or a discharge change. The modeling study generated water profiles for cases with structures (bridge piers and culverts) that could be compared to identical channels without structures. After considerable exploratory analysis of the results an approach was adopted to express the estimated distance as an equation based on ratios of hydraulic variables deemed to be obtainable in a typical situation.

The structure opening area is characterized as the total available flow area through the structure at some prescribed depth. In this study we selected the depth when the culvert would submerge and based the ratios on this depth. This area is compared to the far field flow area (a substantial distance away from the structure. The ratio of available flow area to far field area is herein called the area ratio, and is computed using Equation 1.

$$A_{ratio} = \frac{A_{opening}}{A_{farfield}} \tag{1}$$

A discharge ratio was defined in the same fashion – arbitrarily the value of 500 CFS was used as a reference discharge in this work. A discharge ratio is defined as the ratio of the discharge of interest to the reference discharge. The reference discharge should be a value that is anticipated to pass through the structure relatively easily.[4] The discharge ratio is computed using Equation 2.

$$Q_{ratio} = \frac{Q_{interest}}{Q_{reference}} \tag{2}$$

The longitudinal slope of the channel was expressed as the dimensionless slope (rather than percent slope).

The structure skew relative to the channel centerline was considered a binary variable (could take on a value of 0 or 1). Likewise whether the channel was curved or straight was also taken as a categorical variable.

These variables were used in a regression study to find a correlation that satisfies

$$DIST = f(Q_{ratio}, A_{ratio}, S_0, SKEW, CRV) \tag{3}$$

The HEC-RAS results were tabulated and are displayed in Table 2.[5]

The tabular columns are the dimensionless slope, S_0, the discharge ratio, Q_{RATIO}, the area ratio, A_{RATIO}, the $SKEW$ binary variable, the curvature binary variable, CRV, and the propagation distance in feet, $DIST$. The distance was selected as the first model cross section where the structure induced depth increase reduced to less that one inch of difference (0.08 feet). The disturbances actually propagate further, but the researchers deemed 1 inch as a meaningful stopping change in depth.

5.1. Correlation Model Determination

The correlation models were determined by loading the tabular information in Table 2 into the **R** (R Core Team, 2015) analysis package and various model structures were investigated.

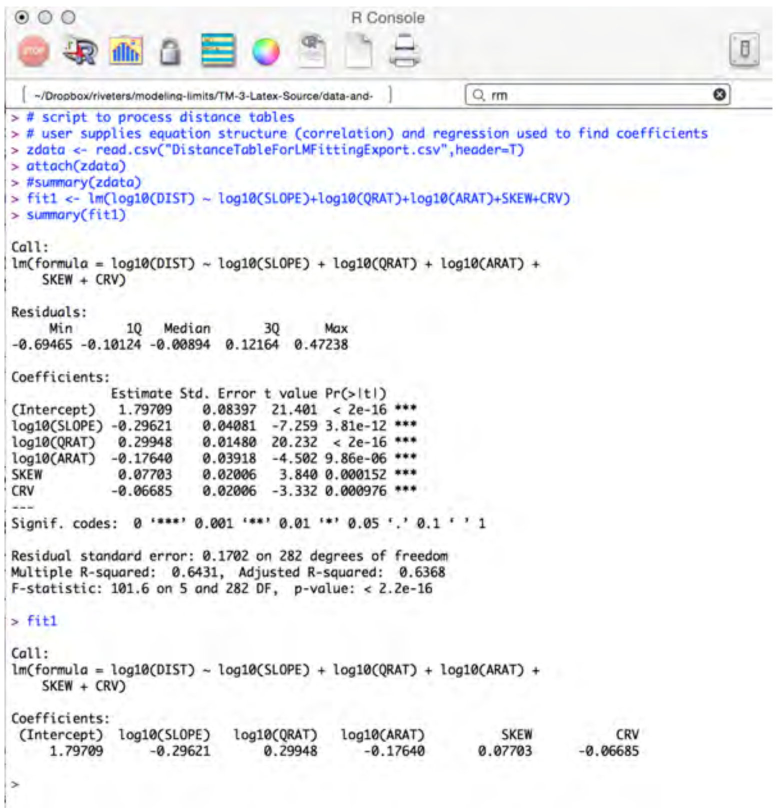
[4]Using a discharge that is known to overtop a structure is not useful.

[5]The table appears at the end of the document to make the narrative contiguous.

The provisional model is displayed in Equation 4.

$$
\begin{aligned}
LOG10(DIST) = \beta_0 + \beta_1 LOG10(S_0) + \beta_2 LOG10(Q_{RATIO}) \\
+\beta_3 LOG10(A_{RATIO}) + \beta_4 SKEW + \beta_5 CRV
\end{aligned}
\tag{4}
$$

Figure 34 is a screen capture of the **R** analysis package applied to the tabular data in Table 2.



```
R Console
~/Dropbox/riveters/modeling-limits/TM-3-Latex-Source/data-and-
rm
> # script to process distance tables
> # user supplies equation structure (correlation) and regression used to find coefficients
> zdata <- read.csv("DistanceTableForLMFittingExport.csv",header=T)
> attach(zdata)
> #summary(zdata)
> fit1 <- lm(log10(DIST) ~ log10(SLOPE)+log10(QRAT)+log10(ARAT)+SKEW+CRV)
> summary(fit1)

Call:
lm(formula = log10(DIST) ~ log10(SLOPE) + log10(QRAT) + log10(ARAT) +
    SKEW + CRV)

Residuals:
     Min       1Q   Median       3Q      Max
-0.69465 -0.10124 -0.00894  0.12164  0.47238

Coefficients:
             Estimate Std. Error t value Pr(>|t|)
(Intercept)   1.79709    0.08397  21.401  < 2e-16 ***
log10(SLOPE) -0.29621    0.04081  -7.259 3.81e-12 ***
log10(QRAT)   0.29948    0.01480  20.232  < 2e-16 ***
log10(ARAT)  -0.17640    0.03918  -4.502 9.86e-06 ***
SKEW          0.07703    0.02006   3.840 0.000152 ***
CRV          -0.06685    0.02006  -3.332 0.000976 ***
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Residual standard error: 0.1702 on 282 degrees of freedom
Multiple R-squared:  0.6431,	Adjusted R-squared:  0.6368
F-statistic: 101.6 on 5 and 282 DF,  p-value: < 2.2e-16

> fit1

Call:
lm(formula = log10(DIST) ~ log10(SLOPE) + log10(QRAT) + log10(ARAT) +
    SKEW + CRV)

Coefficients:
 (Intercept)  log10(SLOPE)   log10(QRAT)   log10(ARAT)          SKEW           CRV
     1.79709      -0.29621       0.29948      -0.17640       0.07703      -0.06685

>
```

Figure 34. Regression results for model structure of Equation 4.

Figure 35 is a screen capture of the requisite calculations to generate the plot in Figure 36. The model is first evaluated and produces an estimate of the logarithm of distance; the logarithm is then evaluated to produce the estimate of distance.

Figure 36 is a plot of the estimate (horizontal axis) and the HEC-RAS values that were used to generate the distance estimates. An equal value line is also displayed on the figure. The provisional estimation tool underestimates when the predicted distance is about 400 feet. The point cloud suggests curvature (the plot almost looks like a parabola).

```
> fit1

Call:
lm(formula = log10(DIST) ~ log10(SLOPE) + log10(QRAT) + log10(ARAT) +
    SKEW + CRV)

Coefficients:
 (Intercept)  log10(SLOPE)   log10(QRAT)  log10(ARAT)         SKEW          CRV
     1.79709      -0.29621       0.29948     -0.17640      0.07703     -0.06685

> MODEL0 <- 1.79709+(-0.29621*log10(SLOPE))+(0.29948*log10(QRAT))+(-0.17640*log10(ARAT))
+(0.07703*SKEW)+(-0.06685*CRV)
> MODEL1 <- 10^(MODEL0)
> #
> #
> plot(MODEL1,DIST,xlim=c(0,1200),ylim=c(0,1200),xlab="Rule-of-Thumb Influence Distance
(ft)",ylab="HEC-RAS Influence Distance (ft)",main="Provisional
Model",tck=1,pch=19,col=rgb(0,0,0,0.5))
> lines(c(0,1000),c(0,1000),col="Blue",lwd=3)
```

Figure 35. Regression results for model structure of Equation 4.

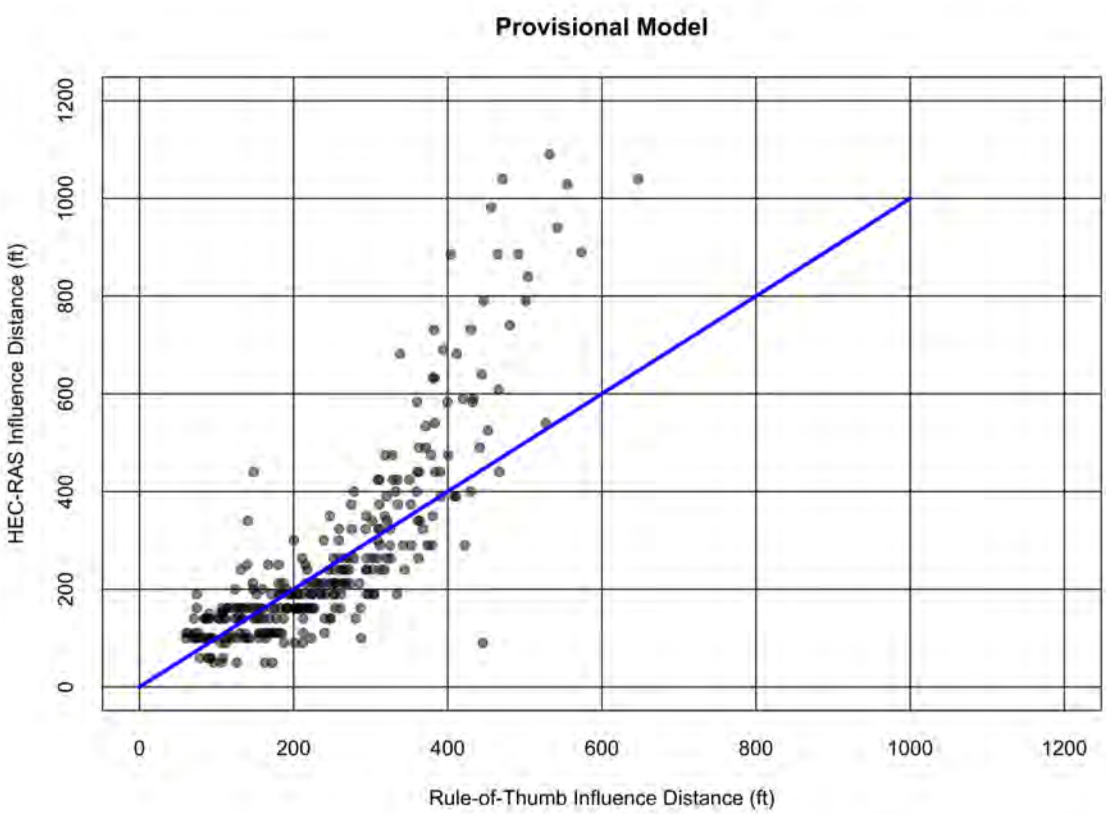


Figure 36. Provisional rule-of-thumb estimator model using Equation 4 structure. The horizontal axis is the model (after fitting) prediction. The vertical axis is the HEC-RAS simulation results that were tabulated and used to build the estimator tool. The provision model displays substantial curvature at a distance of about 400 feet.

A quadratic adjustment to the provisional model was suggested to reduce curvature. The structure of that correlation is given in Equation 5.

$$DIST = \alpha_0 + \alpha_1 DIST_{estimate} + \alpha_2 (DIST_{estimate})^2 \tag{5}$$

$DIST_{estimate}$ is the result of Equation 4. This second fit is arguably overfitting the model, but produces a rule-of-thumb that does not exhibit curvature.

Figure 37 is a screen capture of this second fitting process.

```
R Console
~/Dropbox/riveters/modeling-limits/TM-3-Latex-Source/data-        rm
> P1 <- MODEL1
> P2 <- MODEL1^2
> fit2 <- lm(DIST~P1+P2)
> summary(fit2)

Call:
lm(formula = DIST ~ P1 + P2)

Residuals:
    Min      1Q  Median      3Q     Max
-517.60  -40.80   -5.77   33.74  380.97

Coefficients:
              Estimate Std. Error t value Pr(>|t|)
(Intercept)  1.335e+02  2.463e+01   5.420 1.27e-07 ***
P1          -4.957e-01  1.920e-01  -2.582   0.0103 *
P2           3.501e-03  3.329e-04  10.517  < 2e-16 ***
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Residual standard error: 94.87 on 285 degrees of freedom
Multiple R-squared:  0.7864,	Adjusted R-squared:  0.7849
F-statistic: 524.7 on 2 and 285 DF,  p-value: < 2.2e-16

> fit2

Call:
lm(formula = DIST ~ P1 + P2)

Coefficients:
(Intercept)           P1           P2
 133.509872    -0.495671     0.003501

> #
> #
```

Figure 37. Regression results for model structure of Equation 5, using results from Equation 4 as predictor variables.

Figure 38 is a screen capture of the instructions to generate the plot in Figure 39. The model is first evaluated and produces an estimate of the logarithm of distance; the logarithm is then evaluated to produce the estimate of distance.

```
> fit2

Call:
lm(formula = DIST ~ P1 + P2)

Coefficients:
(Intercept)           P1           P2
 133.509872    -0.495671     0.003501

> #
> #
> PREDICT <- 133.509872 +     -0.495671*P1    + 0.003501*P2
> plot(PREDICT,DIST,xlim=c(0,1200),ylim=c(0,1200),xlab="Rule-of-Thumb Influence Distance
(ft)",ylab="HEC-RAS Influence Distance (ft)",main="Rule-of-Thumb Model with Polynomial
Adjustment",tck=1,pch=19,col=rgb(0,0,0,0.5))
> lines(c(0,1000),c(0,1000),col="Blue",lwd=3)
```

Figure 38. Regression results for model structure of Equation 5.

The resulting estimate of distance from Equation 5 is herein referred to as Method A.

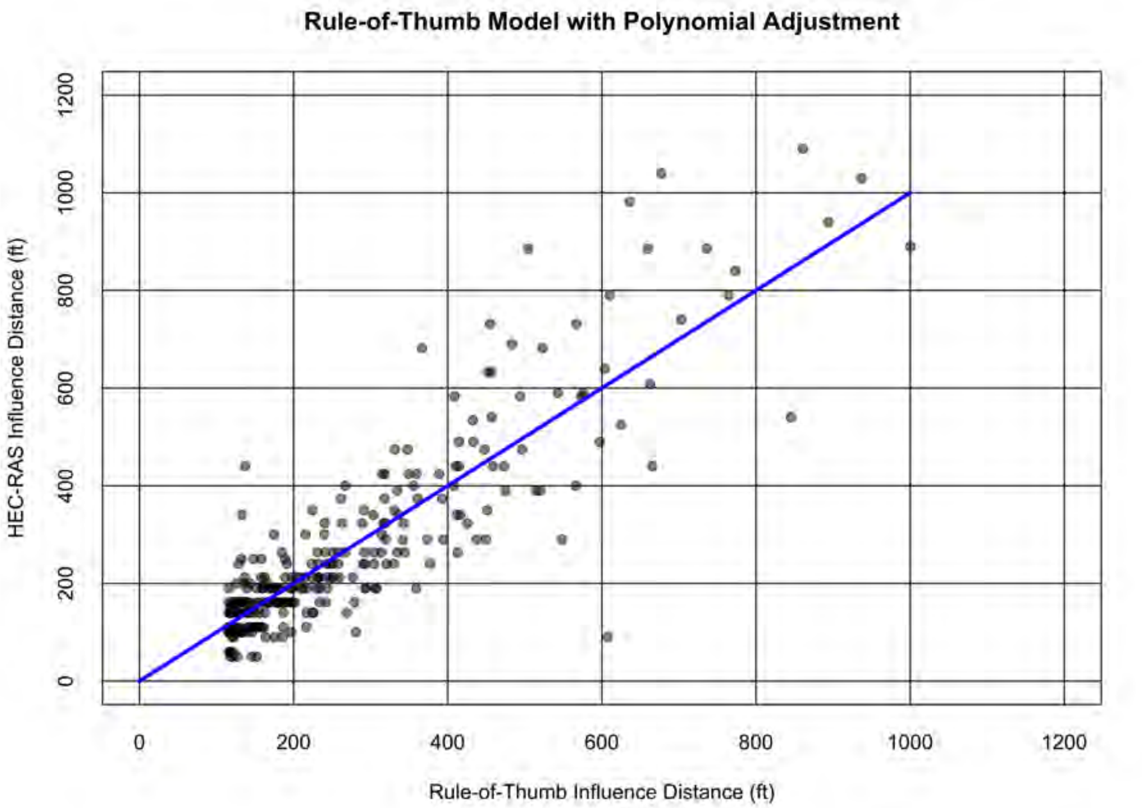


Figure 39. Rule-of-thumb estimator model using Equation 5 structure (polynomial adjustment to Equation 4). The horizontal axis is the model (after fitting) prediction. The vertical axis is the HEC-RAS simulation results that were tabulated and used to build the estimator tool.

Several other methods were included in the estimation tool (next section) based on the literature review.

Method B is based on Wildland Hydrology Inc. (2013). This method a guideline of 20 to 30 bankfull channel widths. The topwidth at the structure could serve as a reasonable surrogate for the baneful with when estimating a distance to set the model boundary.

Method C is based on Nebraska Department of Roads (2015), and is a prescription without regard to geometry – 100 to 500 feet approaching (upstream) and 300 to 1,500 feet departing (downstream). As a simplification, the tool uses a minimum distance of 300 feet (upstream or downstream) and a maximum distance of 1,500 feet (upstream or downstream) in its estimation.

Method D is based on Samuels (1989) and uses a characteristic length as $L = 0.2\frac{D}{S_0}$ apart, where D is the bankful depth, and S_0 is the channel slope. A rule-of-thumb for physical models that approximately 40 characteristic lengths are required to fully develop flow for an experimental model, thus the minimum distance is taken as $40 \times L$ and the maximum distance is $\frac{1}{3}$ of a log-cycle larger. As with Method B, the topwidth at the structure could serve as a reasonable surrogate for the baneful with when estimating a distance to set the model boundary.

5.2. Spreadsheet Implementation of Rule-of-Thumb Estimator

Figure 40 is the interface for `BoundaryDistanceRuleOfThumb-2015.xlsm`; a tool that implements the rule-of-thumb estimate from Equation 5, as well as estimates based on the other methods adapted from Wildland Hydrology Inc. (2013), Nebraska Department of Roads (2015), Samuels (1989), and Castellarin et.al. (2009).

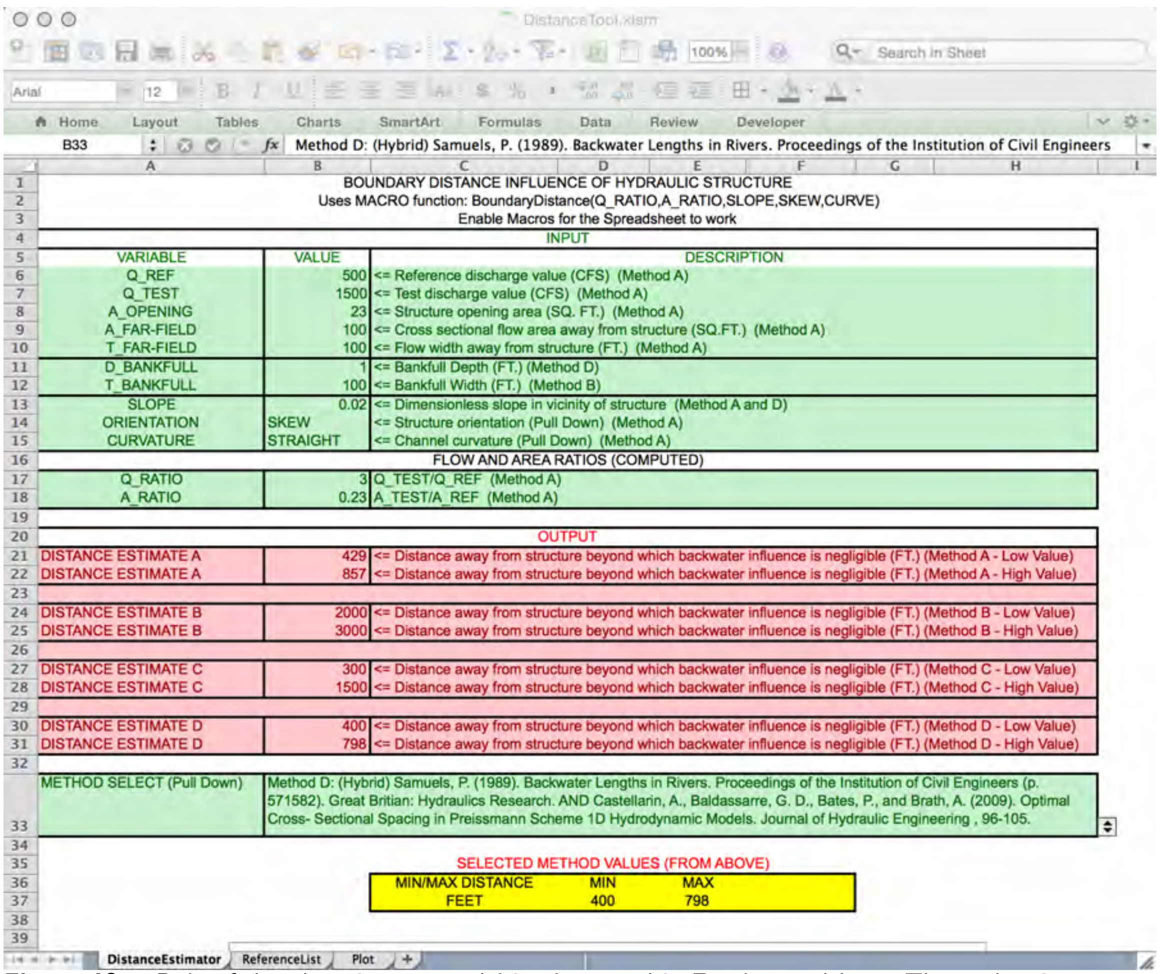


Figure 40. Rule-of-thumb estimator model implemented in Excel spreadsheet. The tool estimates the distance away from a structure that the structure will influence the water surface elevation. The distance may be either upstream (backwater), or downstream (frontwater) depending on whether flow is sub- or super-critical.

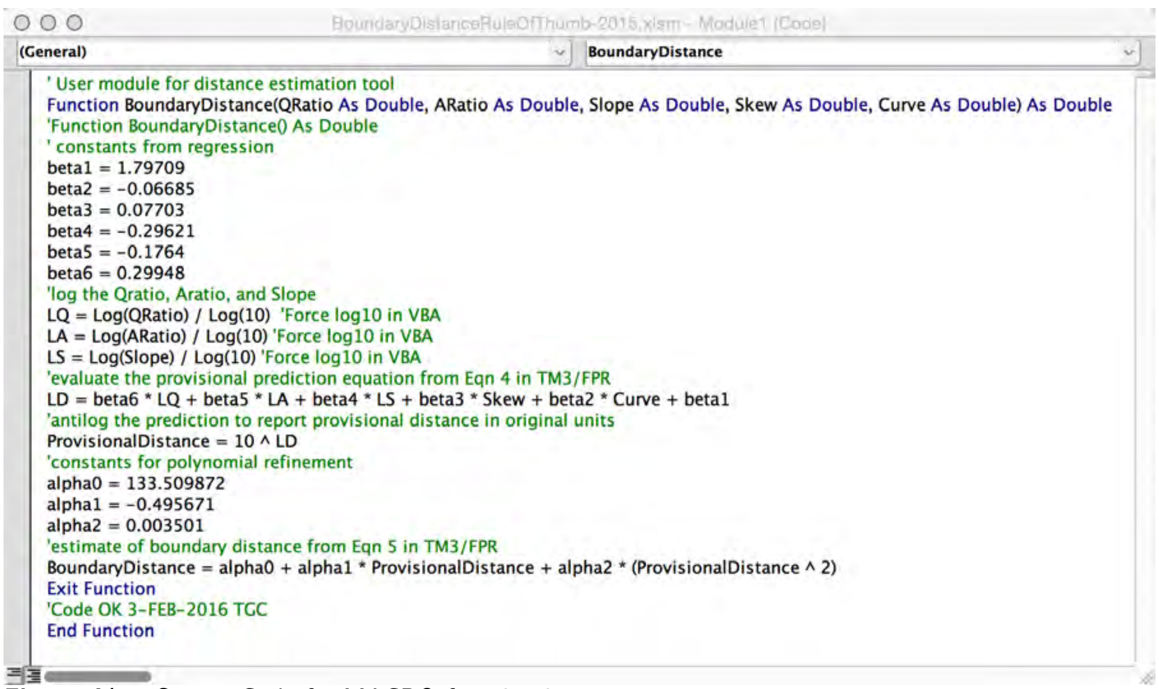
The designer specifies a reference discharge and a test discharge that represents the change in discharge that will approach the structure. These values are entered as

Q_{TEST} and Q_{REF}. The spreadsheet computes the flow ratio $\frac{Q_{TEST}}{Q_{REF}}$, and reports the value in the intermediate results portion of the interface.

The designer would next supply the open area of flow at the structure (e.g. the culvert open area when the water is at the soffit elevation) and the far-field flow area based on channel geometry for the same depth away from the structure. These values are entered as $A_{OPENING}$ and $A_{FAR-FIELD}$. The spreadsheet computes the area ratio $\frac{A_{OPENING}}{A_{FAR-FIELD}}$, and reports the value in the intermediate results portion of the interface.

The designer then supplies the dimensionless slope in the vicinity of the structure. This value is entered as $SLOPE$. The structure skew is a categorical variable and is selected in a pull-down-list in the spreadsheet. The channel curvature is also treated as categorical and is selected in a pull-down list.

Once these selections are completed, the spreadsheet implements Equations 4 and 5 using a VBA MACRO function depicted in Figure41. The MACRO function was used because the tool will be easier to understand and maintain.[6]




```
' User module for distance estimation tool
Function BoundaryDistance(QRatio As Double, ARatio As Double, Slope As Double, Skew As Double, Curve As Double) As Double
'Function BoundaryDistance() As Double
' constants from regression
beta1 = 1.79709
beta2 = -0.06685
beta3 = 0.07703
beta4 = -0.29621
beta5 = -0.1764
beta6 = 0.29948
'log the Qratio, Aratio, and Slope
LQ = Log(QRatio) / Log(10)  'Force log10 in VBA
LA = Log(ARatio) / Log(10) 'Force log10 in VBA
LS = Log(Slope) / Log(10) 'Force log10 in VBA
'evaluate the provisional prediction equation from Eqn 4 in TM3/FPR
LD = beta6 * LQ + beta5 * LA + beta4 * LS + beta3 * Skew + beta2 * Curve + beta1
'antilog the prediction to report provisional distance in original units
ProvisionalDistance = 10 ^ LD
'constants for polynomial refinement
alpha0 = 133.509872
alpha1 = -0.495671
alpha2 = 0.003501
'estimate of boundary distance from Eqn 5 in TM3/FPR
BoundaryDistance = alpha0 + alpha1 * ProvisionalDistance + alpha2 * (ProvisionalDistance ^ 2)
Exit Function
'Code OK 3-FEB-2016 TGC
End Function
```

Figure 41. Source Code for MACRO function in `BoundaryDistanceRuleOfThumb-2015.xlsm`.

6. Conclusions and Recommendations

The estimation tool provides a mechanism to estimate the distance from a structure that the impact from a change in flow attenuates. If there is a flow change contribution

[6] The code clearly implements the two equations in the memorandum, and is easier to understand than the equivalent computations imbedded into a worksheet.

within that distance, then hydraulic modeling would be suggested to approximate the change in water surface elevation near the structure. If the flow change contribution or multiple structures falls outside this distance, and the designer is confident the structure will pass the changed discharge, then the slope-area method would be a reasonable substitute (at or beyond the boundary distance) to estimate the water surface elevation changes induced by the change in flow. Similarly, if other structures exist within the estimated disturbance distance, then they too need to be included in a hydraulic model – the tool would then be re-applied at the adjacent structure to determine its influence distance(s). When a distance is found without any structures, then the modeler would have a location for applying boundary conditions thereby limiting the spatial extend of the model.

The rule-of-thumb would follow the following guidelines:

1. Estimate the approach flow far-field depth and far-field flow area of a reference discharge; enter these values into the tool.
2. Estimate the approach flow structure depth and flow area (that is the flow depth and area through the hydraulic structure); enter these values into the tool.
3. Estimate the approach flow far-field width (or bankfull width); enter this value into the tool.
4. Estimate the approach flow structure width; enter this value into the tool.
5. Estimate the channel slope; enter this value into the tool.
6. The tool will return four distance estimates:
   (a) An estimate based on the modeling study in this document (Method A);
   (b) An estimate based on Wildland Hydrology Inc. (2013) (Method B);
   (c) An estimate based on Nebraska Department of Roads (2015) (Method C); and
   (d) An estimate based on Samuels (1989), Castellarin et.al. (2009), and a rule-of-thumb for physical models that approximately 40 characteristic lengths are required to fully develop flow for an experimental model (Method D).
7. If the flow addition or change occurs within the smallest distances supplied by the estimation tool, then a hydraulic model of the structure and surrounding stream is indicated.
8. If the flow addition or change occurs beyond the largest distances supplied by the estimation tool, then simplified hydraulics, if otherwise applicable, is sufficient.

6.1. Suggested Additional Work

The research herein supports the literature guidelines – the range of influence is similar to that which the literature suggests. An estimation tool was built, but the estimation tool is based on only a few hundred simulations. A more extensive study would be beneficial in the future that should consider a broader range of flow ratios and area ratios. Furthermore, more skew angles should be examined as a way to extend that variable from a categorical variable to an actual metric; that same reasoning applies to channel curvature.

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Table 2. HEC-RAS inferred values from modeling study

S_0	Q_{RATIO}	A_{RATIO}	$SKEW$	CRV	$DIST$
0.005	0.03	0.95	0	0	50.00
0.005	0.2	0.95	0	0	90.00
0.005	0.3	0.95	0	0	90.00
0.005	1	0.95	0	0	190.00
0.005	2	0.95	0	0	290.00
0.005	3	0.95	0	0	290.00
0.01	0.03	0.95	0	0	140.00
0.01	0.2	0.95	0	0	140.00
0.01	0.3	0.95	0	0	50.00
0.01	1	0.95	0	0	140.00
0.01	2	0.95	0	0	190.00
0.01	3	0.95	0	0	240.00
0.02	0.03	0.95	0	0	140.00
0.02	0.2	0.95	0	0	140.00
0.02	0.3	0.95	0	0	340.00
0.02	1	0.95	0	0	90.00
0.02	2	0.95	0	0	140.00
0.02	3	0.95	0	0	140.00
0.005	0.03	0.7	0	0	90.00
0.005	0.2	0.7	0	0	190.00
0.005	0.3	0.7	0	0	190.00
0.005	1	0.7	0	0	390.00
0.005	2	0.7	0	0	690.00
0.005	3	0.7	0	0	90.00
0.01	0.03	0.7	0	0	140.00
0.01	0.2	0.7	0	0	140.00
0.01	0.3	0.7	0	0	190.00
0.01	1	0.7	0	0	240.00
0.01	2	0.7	0	0	340.00
0.01	3	0.7	0	0	490.00
0.02	0.03	0.7	0	0	190.00
0.02	0.2	0.7	0	0	240.00
0.02	0.3	0.7	0	0	440.00
0.02	1	0.7	0	0	140.00
0.02	2	0.7	0	0	190.00
0.02	3	0.7	0	0	190.00
0.005	0.03	0.95	1	0	140.00
0.005	0.2	0.95	1	0	190.00
0.005	0.3	0.95	1	0	240.00
0.005	1	0.95	1	0	440.00

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Table 2. HEC-RAS inferred values from modeling study — Continued

S_0	Q_{RATIO}	A_{RATIO}	$SKEW$	CRV	$DIST$
0.005	2	0.95	1	0	790.00
0.005	3	0.95	1	0	840.00
0.01	0.03	0.95	1	0	140.00
0.01	0.2	0.95	1	0	190.00
0.01	0.3	0.95	1	0	190.00
0.01	1	0.95	1	0	240.00
0.01	2	0.95	1	0	340.00
0.01	3	0.95	1	0	390.00
0.02	0.03	0.95	1	0	140.00
0.02	0.2	0.95	1	0	140.00
0.02	0.3	0.95	1	0	140.00
0.02	1	0.95	1	0	140.00
0.02	2	0.95	1	0	190.00
0.02	3	0.95	1	0	190.00
0.005	0.03	0.7	1	0	140.00
0.005	0.2	0.7	1	0	190.00
0.005	0.3	0.7	1	0	240.00
0.005	1	0.7	1	0	540.00
0.005	2	0.7	1	0	1040.00
0.005	3	0.7	1	0	1090.00
0.01	0.03	0.7	1	0	140.00
0.01	0.2	0.7	1	0	190.00
0.01	0.3	0.7	1	0	240.00
0.01	1	0.7	1	0	290.00
0.01	2	0.7	1	0	440.00
0.01	3	0.7	1	0	590.00
0.02	0.03	0.7	1	0	140.00
0.02	0.2	0.7	1	0	140.00
0.02	0.3	0.7	1	0	140.00
0.02	1	0.7	1	0	190.00
0.02	2	0.7	1	0	240.00
0.02	3	0.7	1	0	290.00
0.005	0.03	0.95	0	1	59.28
0.005	0.2	0.95	0	1	110.38
0.005	0.3	0.95	0	1	110.38
0.005	1	0.95	0	1	161.47
0.005	2	0.95	0	1	263.67
0.005	3	0.95	0	1	263.67
0.01	0.03	0.95	0	1	161.47
0.01	0.2	0.95	0	1	161.47
0.01	0.3	0.95	0	1	161.47

Continued on next page

Table 2. HEC-RAS inferred values from modeling study — Continued

S_0	Q_{RATIO}	A_{RATIO}	$SKEW$	CRV	$DIST$
0.01	1	0.95	0	1	161.47
0.01	2	0.95	0	1	212.57
0.01	3	0.95	0	1	263.67
0.02	0.03	0.95	0	1	110.38
0.02	0.2	0.95	0	1	161.47
0.02	0.3	0.95	0	1	161.47
0.02	1	0.95	0	1	110.38
0.02	2	0.95	0	1	110.38
0.02	3	0.95	0	1	110.38
0.005	0.03	0.7	0	1	50.00
0.005	0.2	0.7	0	1	110.38
0.005	0.3	0.7	0	1	161.47
0.005	1	0.7	0	1	373.61
0.005	2	0.7	0	1	682.03
0.005	3	0.7	0	1	731.44
0.01	0.03	0.7	0	1	59.28
0.01	0.2	0.7	0	1	161.47
0.01	0.3	0.7	0	1	110.38
0.01	1	0.7	0	1	212.57
0.01	2	0.7	0	1	323.22
0.01	3	0.7	0	1	424.00
0.02	0.03	0.7	0	1	110.38
0.02	0.2	0.7	0	1	161.47
0.02	0.3	0.7	0	1	161.47
0.02	1	0.7	0	1	161.47
0.02	2	0.7	0	1	161.47
0.02	3	0.7	0	1	212.57
0.005	0.03	0.95	1	1	59.28
0.005	0.2	0.95	1	1	161.47
0.005	0.3	0.95	1	1	161.47
0.005	1	0.95	1	1	373.61
0.005	2	0.95	1	1	632.61
0.005	3	0.95	1	1	583.19
0.01	0.03	0.95	1	1	59.28
0.01	0.2	0.95	1	1	161.47
0.01	0.3	0.95	1	1	110.38
0.01	1	0.95	1	1	212.57
0.01	2	0.95	1	1	323.22
0.01	3	0.95	1	1	373.61
0.02	0.03	0.95	1	1	110.38
0.02	0.2	0.95	1	1	161.47

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Table 2. HEC-RAS inferred values from modeling study — Continued

S_0	Q_{RATIO}	A_{RATIO}	$SKEW$	CRV	$DIST$
0.02	0.3	0.95	1	1	161.47
0.02	1	0.95	1	1	161.47
0.02	2	0.95	1	1	161.47
0.02	3	0.95	1	1	161.47
0.005	0.03	0.7	1	1	161.47
0.005	0.2	0.7	1	1	161.47
0.005	0.3	0.7	1	1	212.57
0.005	1	0.7	1	1	474.40
0.005	2	0.7	1	1	885.51
0.005	3	0.7	1	1	981.45
0.01	0.03	0.7	1	1	59.28
0.01	0.2	0.7	1	1	110.38
0.01	0.3	0.7	1	1	212.57
0.01	1	0.7	1	1	263.67
0.01	2	0.7	1	1	424.00
0.01	3	0.7	1	1	533.77
0.02	0.03	0.7	1	1	110.38
0.02	0.2	0.7	1	1	161.47
0.02	0.3	0.7	1	1	161.47
0.02	1	0.7	1	1	161.47
0.02	2	0.7	1	1	212.57
0.02	3	0.7	1	1	263.67
0.005	0.03	0.98	0	0	89.93
0.005	0.2	0.98	0	0	139.93
0.005	0.3	0.98	0	0	189.93
0.005	1	0.98	0	0	339.93
0.005	2	0.98	0	0	489.94
0.005	3	0.98	0	0	589.94
0.01	0.03	0.98	0	0	140.00
0.01	0.2	0.98	0	0	190.00
0.01	0.3	0.98	0	0	190.00
0.01	1	0.98	0	0	240.00
0.01	2	0.98	0	0	240.00
0.01	3	0.98	0	0	290.00
0.02	0.03	0.98	0	0	100.00
0.02	0.2	0.98	0	0	200.00
0.02	0.3	0.98	0	0	250.00
0.02	1	0.98	0	0	300.00
0.02	2	0.98	0	0	350.00
0.02	3	0.98	0	0	400.00
0.005	0.03	0.23	0	0	100.01

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Table 2. HEC-RAS inferred values from modeling study — Continued

S_0	Q_{RATIO}	A_{RATIO}	$SKEW$	CRV	$DIST$
0.005	0.2	0.23	0	0	189.93
0.005	0.3	0.23	0	0	239.93
0.005	1	0.23	0	0	439.94
0.005	2	0.23	0	0	739.94
0.005	3	0.23	0	0	939.95
0.01	0.03	0.23	0	0	140.00
0.01	0.2	0.23	0	0	190.00
0.01	0.3	0.23	0	0	190.00
0.01	1	0.23	0	0	240.00
0.01	2	0.23	0	0	390.00
0.01	3	0.23	0	0	490.00
0.02	0.03	0.23	0	0	150.00
0.02	0.2	0.23	0	0	200.00
0.02	0.3	0.23	0	0	250.00
0.02	1	0.23	0	0	300.00
0.02	2	0.23	0	0	350.00
0.02	3	0.23	0	0	400.00
0.005	0.03	0.98	1	0	50.00
0.005	0.2	0.98	1	0	100.01
0.005	0.3	0.98	1	0	189.00
0.005	1	0.98	1	0	439.94
0.005	2	0.98	1	0	639.94
0.005	3	0.98	1	0	789.94
0.01	0.03	0.98	1	0	140.00
0.01	0.2	0.98	1	0	190.00
0.01	0.3	0.98	1	0	190.00
0.01	1	0.98	1	0	240.00
0.01	2	0.98	1	0	340.00
0.01	3	0.98	1	0	390.00
0.02	0.03	0.98	1	0	100.00
0.02	0.2	0.98	1	0	200.00
0.02	0.3	0.98	1	0	250.00
0.02	1	0.98	1	0	300.00
0.02	2	0.98	1	0	350.00
0.02	3	0.98	1	0	400.00
0.005	0.03	0.23	1	0	50.00
0.005	0.2	0.23	1	0	100.01
0.005	0.3	0.23	1	0	289.00
0.005	1	0.23	1	0	607.94
0.005	2	0.23	1	0	889.95
0.005	3	0.23	1	0	1039.95

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Table 2. HEC-RAS inferred values from modeling study — Continued

S_0	Q_{RATIO}	A_{RATIO}	$SKEW$	CRV	$DIST$
0.01	0.03	0.23	1	0	140.00
0.01	0.2	0.23	1	0	190.00
0.01	0.3	0.23	1	0	240.00
0.01	1	0.23	1	0	290.00
0.01	2	0.23	1	0	440.00
0.01	3	0.23	1	0	540.00
0.02	0.03	0.23	1	0	150.00
0.02	0.2	0.23	1	0	200.00
0.02	0.3	0.23	1	0	250.00
0.02	1	0.23	1	0	300.00
0.02	2	0.23	1	0	350.00
0.02	3	0.23	1	0	400.00
0.005	0.03	0.98	0	1	100.00
0.005	0.2	0.98	0	1	160.00
0.005	0.3	0.98	0	1	212.22
0.005	1	0.98	0	1	323.22
0.005	2	0.98	0	1	474.40
0.005	3	0.98	0	1	583.19
0.01	0.03	0.98	0	1	100.00
0.01	0.2	0.98	0	1	109.35
0.01	0.3	0.98	0	1	212.22
0.01	1	0.98	0	1	263.67
0.01	2	0.98	0	1	263.67
0.01	3	0.98	0	1	323.22
0.02	0.03	0.98	0	1	100.00
0.02	0.2	0.98	0	1	152.00
0.02	0.3	0.98	0	1	100.00
0.02	1	0.98	0	1	160.79
0.02	2	0.98	0	1	160.79
0.02	3	0.98	0	1	212.22
0.005	0.03	0.23	0	1	109.35
0.005	0.2	0.23	0	1	160.79
0.005	0.3	0.23	0	1	212.22
0.005	1	0.23	0	1	424.00
0.005	2	0.23	0	1	682.03
0.005	3	0.23	0	1	885.51
0.01	0.03	0.23	0	1	100.00
0.01	0.2	0.23	0	1	109.35
0.01	0.3	0.23	0	1	160.79
0.01	1	0.23	0	1	263.67
0.01	2	0.23	0	1	373.61

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Table 2. HEC-RAS inferred values from modeling study — Continued

S_0	Q_{RATIO}	A_{RATIO}	$SKEW$	CRV	$DIST$
0.01	3	0.23	0	1	474.40
0.02	0.03	0.23	0	1	100.00
0.02	0.2	0.23	0	1	109.00
0.02	0.3	0.23	0	1	100.00
0.02	1	0.23	0	1	160.79
0.02	2	0.23	0	1	212.22
0.02	3	0.23	0	1	263.67
0.005	0.03	0.98	1	1	100.00
0.005	0.2	0.98	1	1	160.79
0.005	0.3	0.98	1	1	212.22
0.005	1	0.98	1	1	424.00
0.005	2	0.98	1	1	632.61
0.005	3	0.98	1	1	731.44
0.01	0.03	0.98	1	1	100.00
0.01	0.2	0.98	1	1	109.35
0.01	0.3	0.98	1	1	160.79
0.01	1	0.98	1	1	263.67
0.01	2	0.98	1	1	323.22
0.01	3	0.98	1	1	424.00
0.02	0.03	0.98	1	1	100.00
0.02	0.2	0.98	1	1	100.00
0.02	0.3	0.98	1	1	100.00
0.02	1	0.98	1	1	160.00
0.02	2	0.98	1	1	212.22
0.02	3	0.98	1	1	212.22
0.005	0.03	0.23	1	1	100.00
0.005	0.2	0.23	1	1	212.22
0.005	0.3	0.23	1	1	263.67
0.005	1	0.23	1	1	583.19
0.005	2	0.23	1	1	885.51
0.005	3	0.23	1	1	1029.42
0.01	0.03	0.23	1	1	100.00
0.01	0.2	0.23	1	1	160.79
0.01	0.3	0.23	1	1	160.79
0.01	1	0.23	1	1	323.22
0.01	2	0.23	1	1	474.40
0.01	3	0.23	1	1	524.79
0.02	0.03	0.23	1	1	100.00
0.02	0.2	0.23	1	1	100.00
0.02	0.3	0.23	1	1	109.35
0.02	1	0.23	1	1	212.22

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Table 2. HEC-RAS inferred values from modeling study — Continued

S_0	Q_{RATIO}	A_{RATIO}	$SKEW$	CRV	$DIST$
0.02	2	0.23	1	1	263.67
0.02	3	0.23	1	1	323.22