REDUCING LOCALIZED IMPACTS TO RIVER SYSTEMS THROUGH PROPER GEOMORPHIC SIZING OF ON-CHANNEL AND FLOODPLAIN OPENINGS AT ROAD/RIVER INTERSECTIONS

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Executive Summary

This study used present day technologies to quantify the impact of roadway embankments on a naturally stable river/floodplain system. Through assessing different combinations of roadway openings, the study demonstrated that incorporating basic geomorphic Principles into road/river intersection design can significantly improve impact mitigation. The results show that many benefits, both short and long term, can be gained by incorporating basic geomorphology Principles, outlined within, into the design of road/river intersections (i.e., culverts and bridge openings).

Stemming from a concurrent geomorphology study it was observed that essentially all the on-channel culverts were too wide for the given watershed causing effects of Flood Flow Confinement (FFC) (see FFC segment of this document). Generally, over-wide on-channel inverts create localized anomalies in the river channel system by drastically changing flow continuity and sediment transport dynamics. Given the spatial distribution of our road/river intersections across the landscape, disregarding geomorphology in our road/river intersection design will have profound and long term cumulative effects on our river systems. Although this study assessed a single site, the Principles outlined within will have similar, beneficial results when properly applied at any scale. This study quantified the effects of various placements of openings in conveying water and sediment. Then it identified the optimal configuration critical to long term, naturally functioning river systems on the landscape. As a result, this paper recommends a fundamental change in design approach of our road/river intersections using a minimum 2 stage (channel and floodplain) approach to mitigate impacts and improve long term channel and floodplain function.

This Study examined and compared several design configurations, which are simplified in the following four steps and figures:

Step One: Study assessed stable conditions prior to a road design and construction:

Typical Plan View of road design configurations assessed

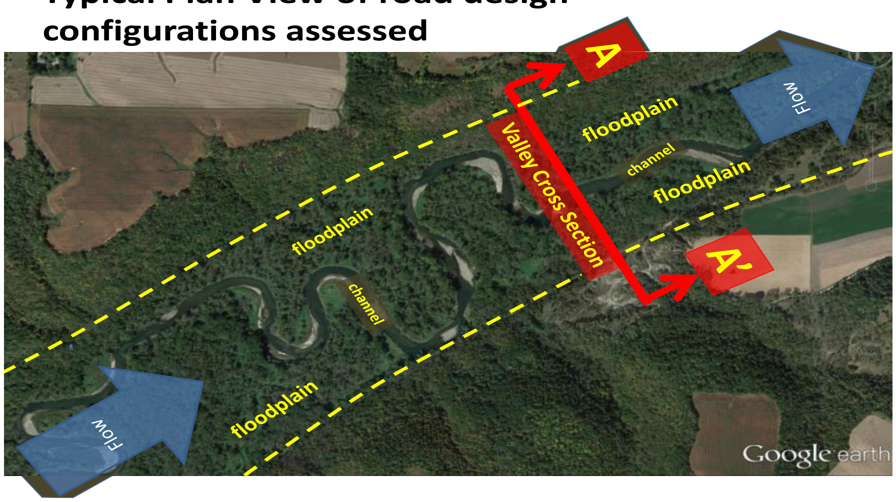

Figure 1(a): Typical plan view of alluvial fill valley (i.e., natural conditions)

NOTE: Please refer to the above plan view for all referenced A-A' cross sections

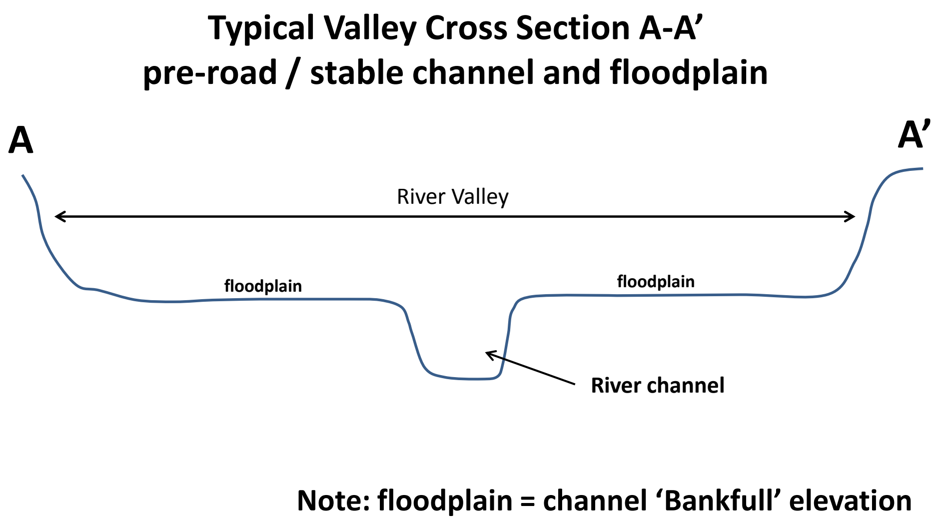

Figure 1(b): Typical cross section of stable channel and floodplain, no road.

Step Two: Based on collected field data, various configurations of openings for a proposed road were assessed. See HEC_RAS modeling segment for all configurations assessed. The diagram below displays a commonly found valley cross section on our landscape:

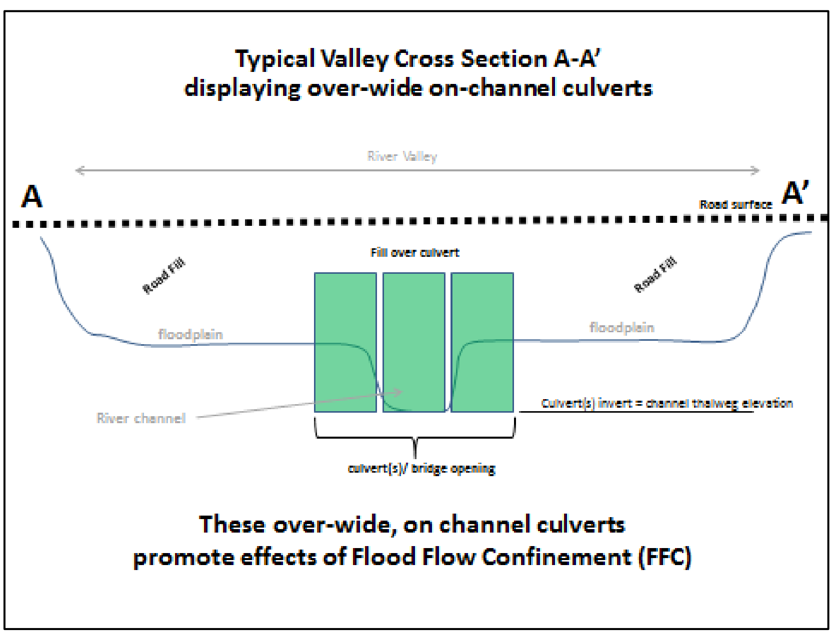

Figure 2: Commonly found cross section A-A’ showing over-widened on-channel culverts.

Step Three: The study assessed various valley cross section A-A' configurations using the same effective cross sectional area for conveyance. The opening configuration below displays an example of one assessed valley cross section:

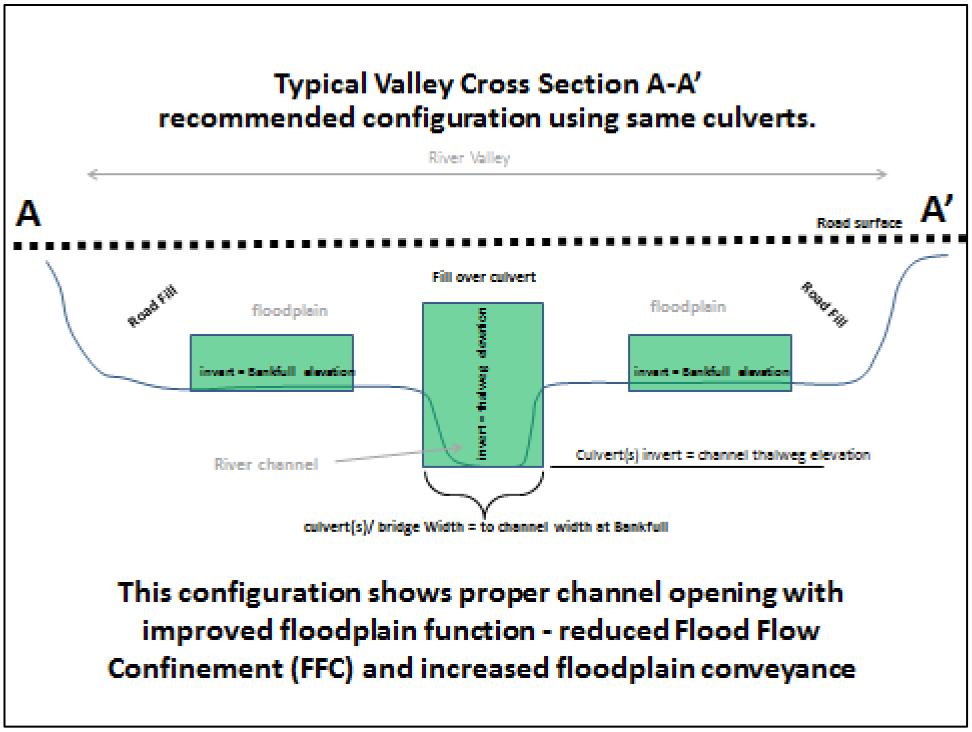

Figure 3: Typical cross section of floodplain showing distributed culverts across the valley.

Step Four: The study summarized and reported on findings. Where possible, the study provided recommendations to improving the design of road/river intersections to better mimic naturally occurring flood flows.

Study Results:

The authors of this *study do not recommend any reduction in existing cross sectional area for road/river intersections*.

The results of this study show that the impacts created from present day road/river intersection design can be better mitigated by applying the following Principles of geomorphology into the design of road/river intersections:

1. The design process must separate channel conveyance and floodplain conveyance (over-bank) into separate design entities.
2. Design channel conveyance opening width for channel equal to bankfull channel width.
3. Design floodplain (over-bank) conveyance area as large as possible. Set invert(s) of opening(s) equal to bankfull elevation and space equally across entire floodplain.

Principles of Geomorphology for Road/River intersection design

From a calibrated model, this study quantified river system impacts. By employing the design concepts diagramed below, improved mitigation of road impacts on river system are gained. Although not complete, these key concepts are illustrated in the following two figures:

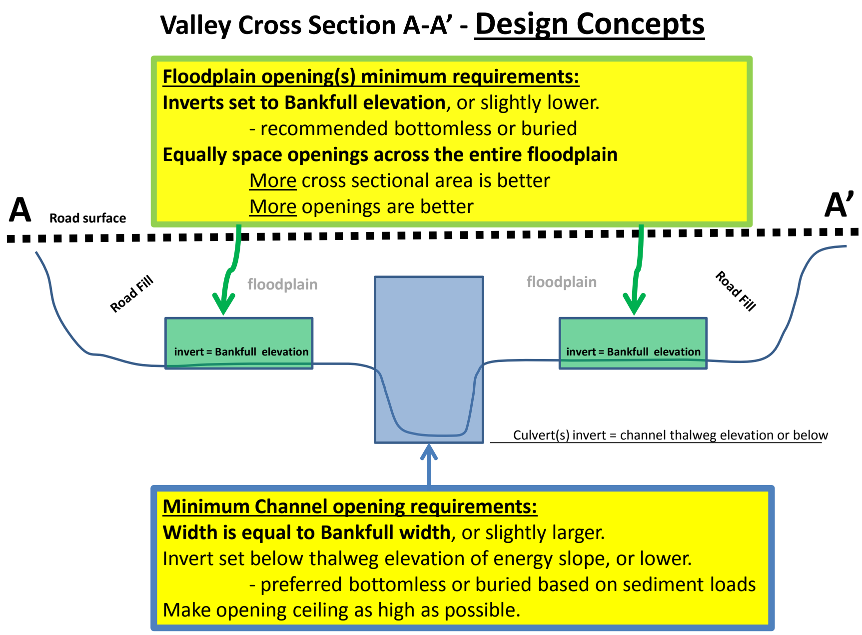

Figure 4: Recommended consideration to proper sizing of openings in a road/river intersection.

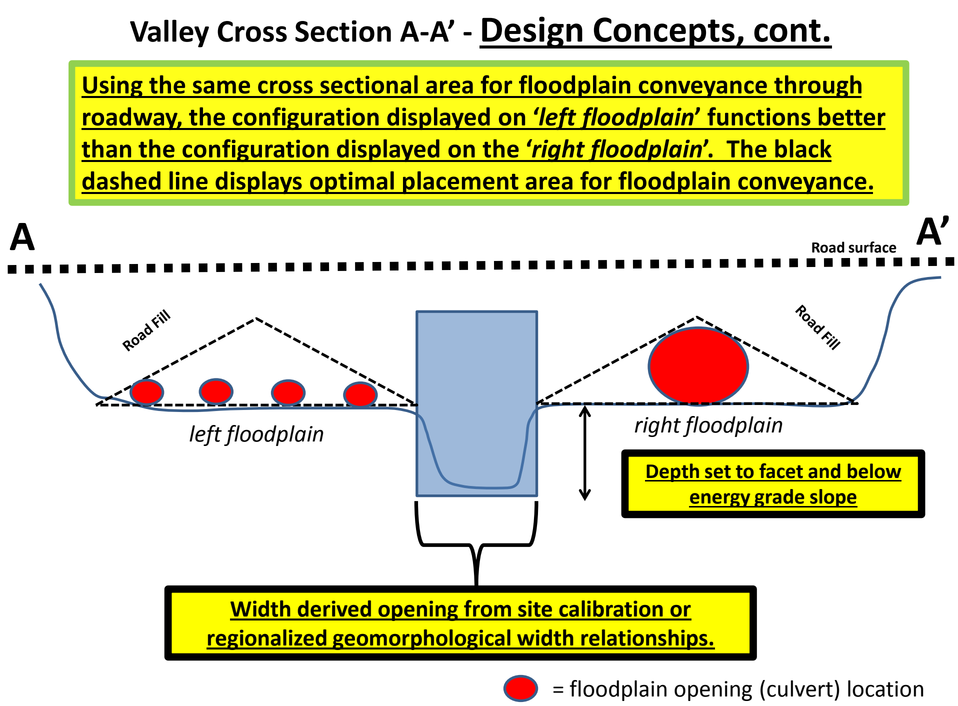

Figure 5: Recommended consideration to proper placement of openings in a road/river intersection

As illustrated above in figures 4 and 5, by using site based channel/floodplain morphology, the following design metrics should be site derived and validated for each of the following:

Channel Opening Width: The width of channel openings should be set equal to, or slightly larger than the channel bankfull width. The designed channel bankfull width should be validated with regionalized bankfull channel width curves and measured from aerial photography above and below the site.

Channel Opening Invert: Bottomless culverts are recommended. In cases where a bottomless culvert cannot be used, the invert of culvert should be placed sufficiently low enough to allow un-inhibited movement of bedload (i.e., set lower than maximum entrainment depth).

Floodplain Openings (over-banks): Floodplain opening should be spaced evenly across the entire floodplain. Openings should be centered on both right and left floodplain and evenly spaced across each floodplain. Floodplain openings inverts should be set on the floodplain (bankfull elevation) and should be aligned to be parallel to the fall line of the valley.

See **Information Resources** at the end of this document for additional information and design resources.

Introduction

BRIEF REVIEW OF RIVER PRINICPLES:

A stable river is intricately tied to both its water and sediment it conveys and maintains its channel dimension, meander pattern, and longitudinal profile along its valley over-time. To maintain this naturally stable form, the river channel must maintain flow continuity for all three of these metrics to effectively manage its water and sediment across the landscape. When stable, very little channel based erosion occurs.

When a change occurs in one of these three intricately related channel and floodplain metrics, the river system will initiate a re-adjustment process, typically in all three, until it re-establishes a stable form. From this change, a common result will be the re-establishment of a stable form at a lower elevation; thus causing an excess in sediment contribution from channel and floodplain throughout this re-adjustment process. Today, a commonly found imposed change to a channel can be found at many road/river intersections, where the changed metric is channel width. Many over-widened channel widths are imposed onto the river system due to inappropriate road design causing this river re-adjustment until it recreates a stable form, if possible. A common recurring indicator for these over wide on-channel road intersections is a required 'clean out' maintenance; which imposes known long term adverse consequences to the river system.

Depending upon the location of these over-widened channels within its watershed, the design of these can cause significant impact to the river system and require extended temporal and spatial scales to re-adjust to a stable form. Although this study did not assess any systematic impact(s), it does summarize many localized impacts of over-widened channel widths (i.e., a change in form) at road/river intersections.

RESOURCE IMPLICTIONS:

Sediment as a Pollutant:

Sediment is the number one water pollutant in the world. According to the Environmental Protection Agency, sediment pollution causes $16 billion in environmental damage annually due to its adverse effects on water quality and recreation; wildlife; and land surrounding streams. The USDA/NRCS estimates that sediment pollution causes $17 billion in loss of productivity annually to cropland and pastureland.

Excess sediment impacts navigable waters. According to the US Army Corps of Engineer St. Paul Minnesota District, a total of 871,500 cubic yards has been dredged since 1985 from 28 locations of the Upper Mississippi River stretching from Minneapolis, MN to Guttenberg, IA, to maintain the required 9-feet channel depth.

There are several sources of excess sediment and pollution in our waters, one source is stream bank erosion. Inadequately designed road/river intersections (bridges and culverts) can cause excessive stream bank erosion. Given the spatial distribution of our road/river intersections, this channel source of sediment can be huge when no consideration to land form is incorporated into the design of these road/river intersections. According to a study conducted by the National Cooperative Highway

Research Program in 1998, the primary cause of damage to bridges was scour around the abutments and approach embankments. The study stated in its recommendations that "consideration should be given to the problem of detecting and evaluating gradual channel shift alignment changes of streams over time." Unfortunately, in review of several hydrologic and hydraulic modeling, sediment processes are not fully understood, adequately measured, quantified or reported.

This study is an initial effort to addresses sediment transport and stream instability by assessing impacts of a road/river intersection and understanding their departure from natural conditions. By examining the effects of various intersection designs (i.e., various opening placement) in a stable stream, specific hydraulic stressors were quantified and compared. These stressors were measured throughout the reach to determine impact on flooding risk, stream stability, sediment transport, and profile continuity. They included the following:

1- Water surface elevations.
2- Velocity changes.
3- Shear stress.
4- Energy gradient.
5- Stream system stability.

As previously stated, sediment is not well understood or documented. Future work will use the above metrics along with many others to better understand and document systemic impacts of road/river intersection designs on the landscape. See Future of Study segment of this report for more detailed understanding of purpose of this study. Although this study emphasized its analysis on water, it does broadly address sediment transport by quantifying the above with future plans on producing addendums to this report specifically addressing quantified sediment dynamics and natural systems impact.

Roads/ Infrastructure on the landscape:

Roads transect our landscape approximately every square mile and intersect our river systems more than any other anthropogenic structure.

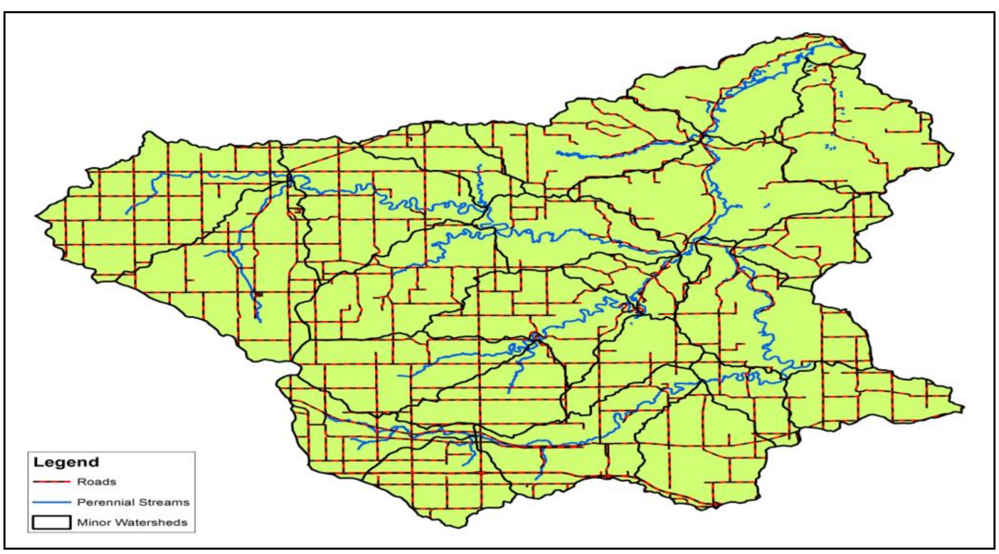

Figure 6, this graphic shows a highly dissected river system by roads*; a typical distribution pattern for our road networks found throughout Minnesota's landscape*

Road networks are essential to society, but the applied design of these at river intersections (floodplains and river channels) require properly sized openings for both floodplain and channel land form. When road/river designs fail to account for each separately design entity, the channel and floodplain will be forced to adapt to the road design. One typical consequence of inappropriate design will be a change in flood pulse across the landscape. The cumulative systematic changes to flood timing are not well understood but play a critical role for long term river system stability and function. Although this study does not attempt to understand systematic changes, it does quantify local impacts and propose methods and basic design Principles to improve mitigation of these impacts.

This study quantifies design configurations of road/river intersections to improve the following:

1. Water conveyance
2. Sediment transport and management
3. Long term stream channel stability
4. Floodplain connectivity
5. Reduction of localized sediment erosion
6. Reduction in road maintenance and long term maintenance costs
7. Improvement of natural system function, understanding and management
8. Initiation of adaptive management into road design

This study utilized a common 'industry standard' hydraulic model, HEC-RAS to quantify specific stressors. It modeled five different conveyance configurations at the road/river intersection. The five scenarios are:

1. Natural conditions, without confinement
2. Geo-morphologically based design (using bankfull width metric)
3. Standard DOT bridge response
4. Commonly observed, over sized on channel culvert
5. Culverts distributed throughout the floodplain

The goal of this study is to understand, quantify, and document proposed practices to reduce Flood Flow Confinement impacts on our landscape.

FLOOD FLOW CONFINEMENT (FFC):

Flood Flow Confinement (FFC)-defined

FFC is defined as constriction of a river's floodplain that impedes the natural conveyance of water and sediment down the valley.

Flood Flow Confinement caused by present day river/road intersection design - defined.

A Flood Flow Confinement (FFC) imposed on a river system by the act of designing a road/river intersection using a single discharge, then assigning this discharge to a single on-channel opening.

Locations and Indicators of FFC on the landscape:

Typically FFC caused from road design can be found in drainage areas that use culverts on perennial channels. However, the effects of FFC can also be observed by larger bridged systems. Each road/river intersection is unique and will require individual assessment for FFC.

A typical field indicator when assessing a site for FFC is channel or bank armoring (e.g. 'riprap')

The photos and illustrations below demonstrate other simplified visuals on how to identify FFC on the landscape:

Figure 7(a) and 7(b): Identification of FFC. 1(a) standing on a roadway looking upstream at the river channel. 1(b) aerial view of the same intersection. Notice the over-widening of the perennial channel at the road intersection.

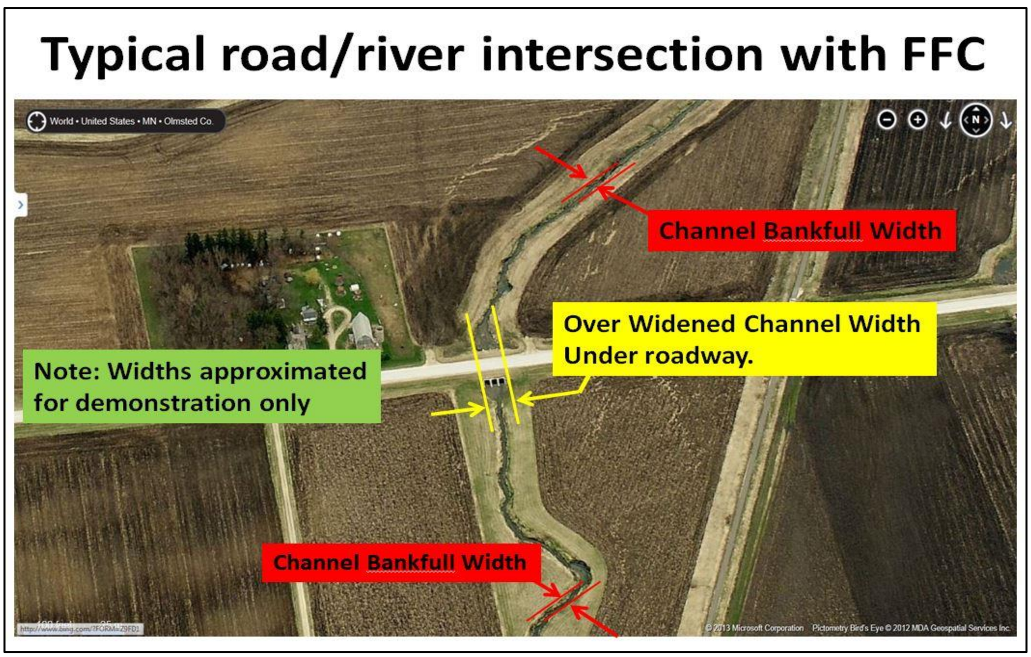

Figure 7(c): Typical Flood Flow Confinement found on the landscape. Notice the lack of channel width continuity going through the roadway.

Figure 7(d): Typical Flood Flow Confinement found on the landscape. Notice the riprap lined channels which lack a defined floodplain. Over widened flat channel bottom promoting deposition and a high variability of channel widths.

Valley impacts from FFC on the landscape:

Impacts of FFC on river floodplains can vary and future studies will address specific impacts based upon valley type. But one FFC effect on a floodplain is the buildup of fine sediments (>2mm) upstream of the road, causing an energy grade disconnect. The following floodplain profile demonstrates this commonly found FFC effect, energy slope disconnect, at a bridged road/river intersection:

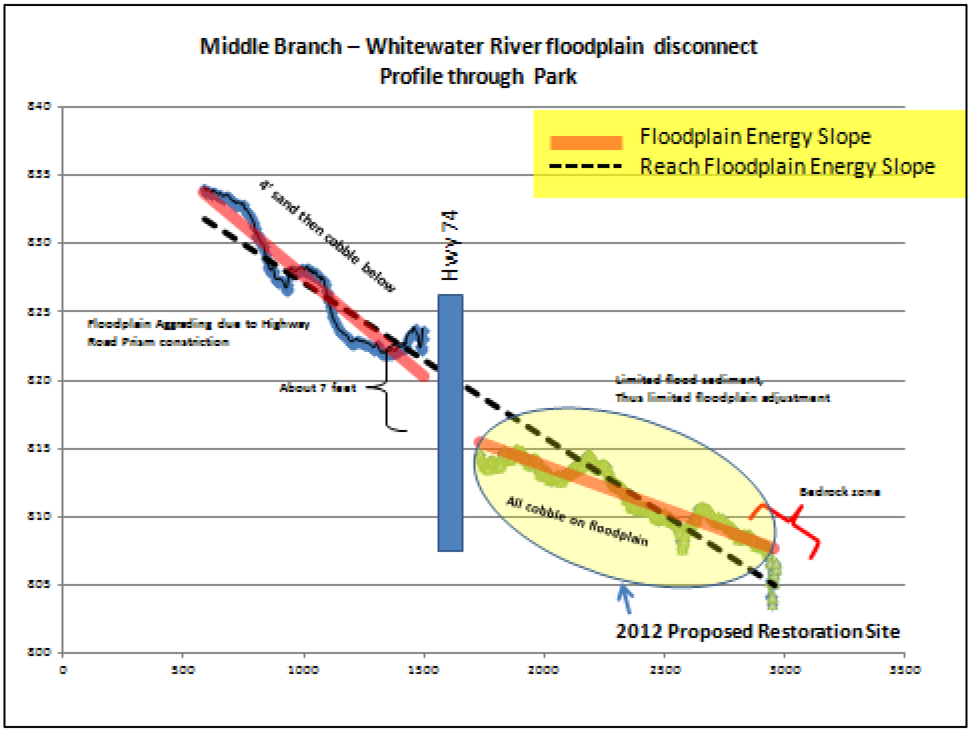

Figure 8: FFC effect on river profile. Aggraded floodplain upstream side of road fill prism causing a reach level disconnect in energy. This impact was identified on a Rosgen Type 8a Valley type.

Common indicators of FFC:

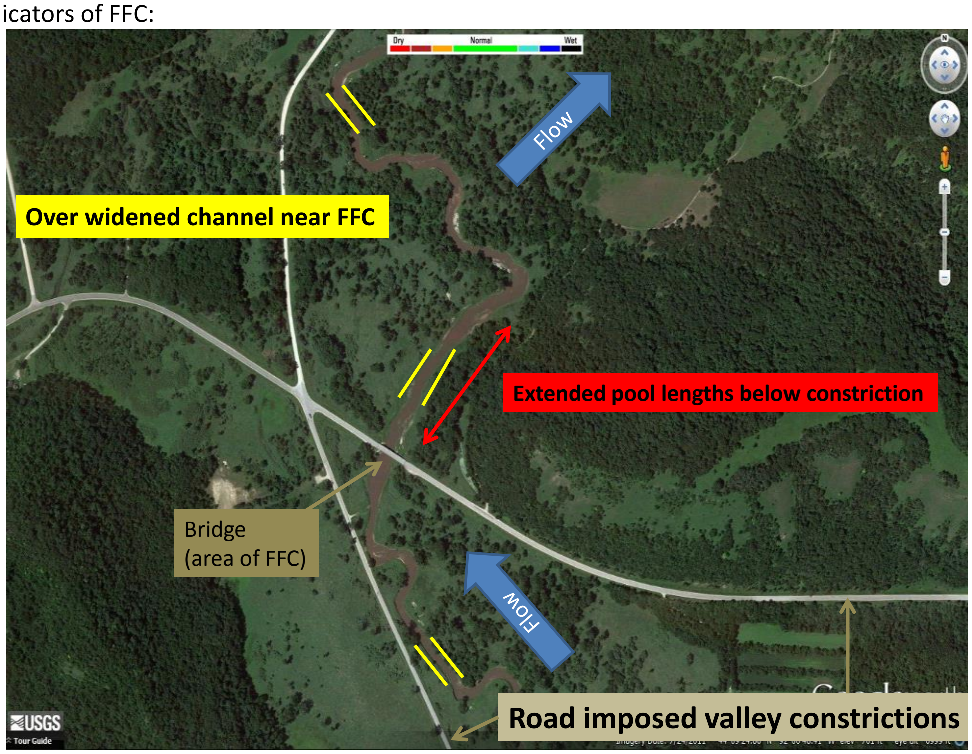

Figure 9: This graphic demonstrates 2 common indicators of FFC caused from roads.

The above examples are commonly found on our landscape and are good sites to implement geomorphic Principles outlined in this document. Other sites to consider would be the 'high maintenance' sites where periodic 'cleanout' is required to maintain adequate design flow requirements.

Local Effects of Flood Flow Confinement (FFC):

The excess channel width at this road intersection causes an extreme drop in channel shear stress. This drop in shear stress causes deposition of fine sediments within this over-wide road intersection. This design has many impacts, including the following:

1. Reduction in water conveyance
2. Increased maintenance costs due to "clean outs"
3. Unbalanced sediment transport metrics
4. Longitudinal loss of biological connectivity during low flow conditions.
5. Localized of shear stress resulting in deposition
6. Loss of major floodplain function (e.g. effective flow area) and connectivity
7. Other, site specific, impacts.
8. Increased streambank erosion
9. Headwater aggradation.
10. Road fill scour
11. Increase channel blockages due to debris jams.

STUDY BACKGROUND:

There is no naturally stable stream channel in the world that varies its channel width by an order of one magnitude within its given Valley (with the exception of some bedrock and active alluvial fan river valleys). Yet, over the past several years a co-author of this paper had observed many replacements of over-sized on-channel culverts, under road intersections across a large spatial area of southeastern Minnesota.

Given the amount of roadways dissecting our landscape, the cumulative impact of improper morphology at road/river intersections can adversely impact our river systems in many ways. When the metric of channel width is not accounted for into the road/river intersection design, the intersection will disrupt the continuity of channel flow dynamics, thus causing an anomaly within the stream system. This study quantified some of these impacts and found anomalies / disruptions and provided measures to incorporate into the design of road/river intersections to better mitigate impacts of roads.

<u>Present Day road/river intersection design issue:</u>

The problem involves setting multiple over-sized on-channel culvert(s) to an invert elevation equal to the thalweg (i.e., flow line) making the channel too wide for the given site channel width requirement. This problem is caused by designing these culverts without applying known geomorphic channel widths to ensure channel continuity in conveyance. The authors believe that this is due to a present day roadway design requirement of grouping both floodplain flow and channel flow into one discharge unit, then confining that discharge to the river channel only. Essentially this design approach allocates all the flows, both floodplain and channel, to the channel and does not consider floodplain as a separate design entity. This design approach impacts the river system in many known and unknown ways. See some known ways outlined in the Effects of Flood Flow Confinement (FFC). The following graphics were generated to provide clarity in understanding of this design issue. Over-wide channel openings can be found throughout our landscape. Sizing of opening based on channel width and addressing floodplain separately provides improved conveyance and management of water and sediment across our landscape.

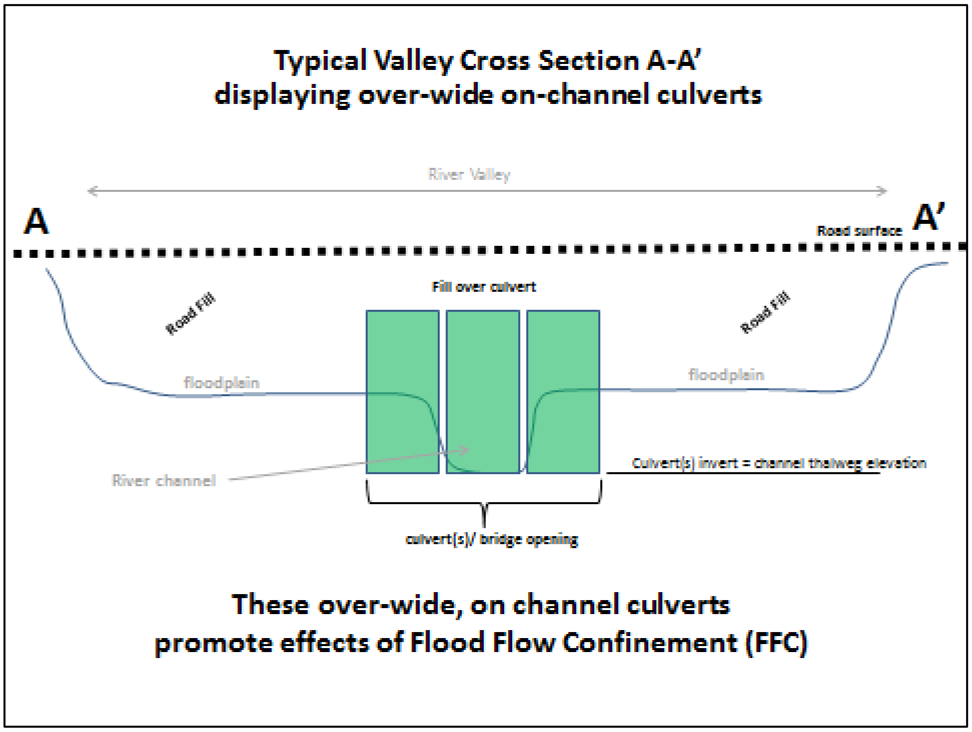

Figure10: This diagram shows a commonly found design or a road/river intersection promoting FFC

Figure 10 shows a common valley cross section of an incoming river channel into an over wide (3 culvert) road intersection.

Based on metrics of a river channel, channel width is highly correlated with drainage area. The plot below shows the variability between channel width and road/river intersection widths for the Whitewater River watershed located in southeastern Minnesota. The blue line shows the natural channel width while the red line shows channel widths under roads.

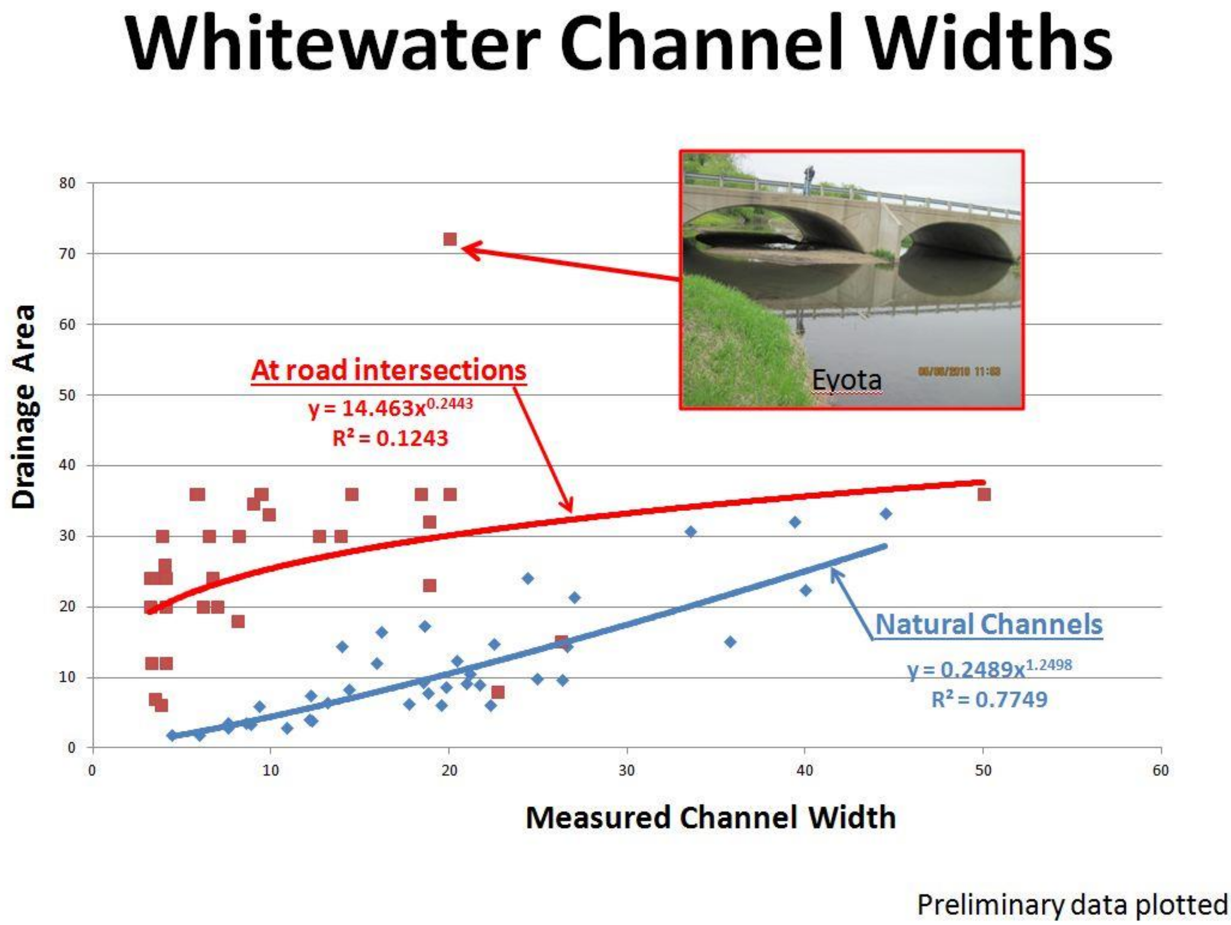

Figure 11: Channel widths for stream channel vs. road intersections

The above graph shows both natural channel widths (blue) and channel widths at road/river intersections (red) at road/river intersections. Notice the road/river intersection show little correlation to drainage area while the natural channel widths are highly correlated to drainage area. When natural channel widths are stratified using the entrenchment ratio and the width to depth ratio (i.e., Rosgen stream type), the correlation values improve to the upper 90 percentile ranges.

When plotted, the newly re-constructed road/river intersections show an increasing trend of on-channel cross sectional area. There are likely many justifiable reasons to an increase of cross sectional area at these newly designed road-river intersections (e.g. changing land use, increased storm intensities, modified river systems, etc.), which all are proper and good for the river system. This study discovered that the placement of openings under the roadway played a critical role to long term river stability and floodplain function.

By adopting the site-based morphological metric of channel width to the channel and treating floodplain flows separately, the design will improve the long term stability and functions for our river systems by reducing total impact of the road on the river system. Once adopted, this approach will bring about the opportunity for adaptive management of our road/river intersections and will allow long term understanding of system response to road impact.

STUDY OBJECTIVES:

This Study assesses impact created from a commonly found road/river intersection design. From this assessment came the initial finding on the Effects of Flood Flow Confinement (FFC) and outlines methods for the reduction of FFC. The study accomplishes this by quantifying several alternative configurations of opening placement to optimize flood conveyance and mitigate impacts of the road on the river/floodplain system. It then summarizes the design concepts to improving design of the road/river intersections by creating the *Principles of Geomorphology for Road/River intersection design.*

Roads can impact rivers in many ways. This study is part of an on-going study to provide guidance on better natural systems management by employing adaptive management into the management of them. The results of this initial study will not change, but the recommendations from it may be modified for clarity. This document will adapt as needed and be available for downloading.

Again, this study does NOT recommend any reduction in cross sectional area for conveyance in the downstream direction. Wherever possible it is beneficial to both river and floodplain function to **increase cross-sectional area allocated to the floodplain** to alleviate effects of Flood Flow Confinement (FFC).

The Study

THE WHITEWATER RIVER:

The Whitewater River watershed was used for this study. The Whitewater River witnessed significant flooding events and severe sedimentation and erosion problems in the past. Most of the field data obtained for this study was obtained from a larger geo-morphology based study by DNR's Stream Habitat Program. Furthermore, the watershed is currently undergoing FEMA hydraulic modeling and remapping by DNR's Floodplain Program. These two together with a large temporal and spatial dataset made the Whitewater watershed an ideal site to utilize for this study.

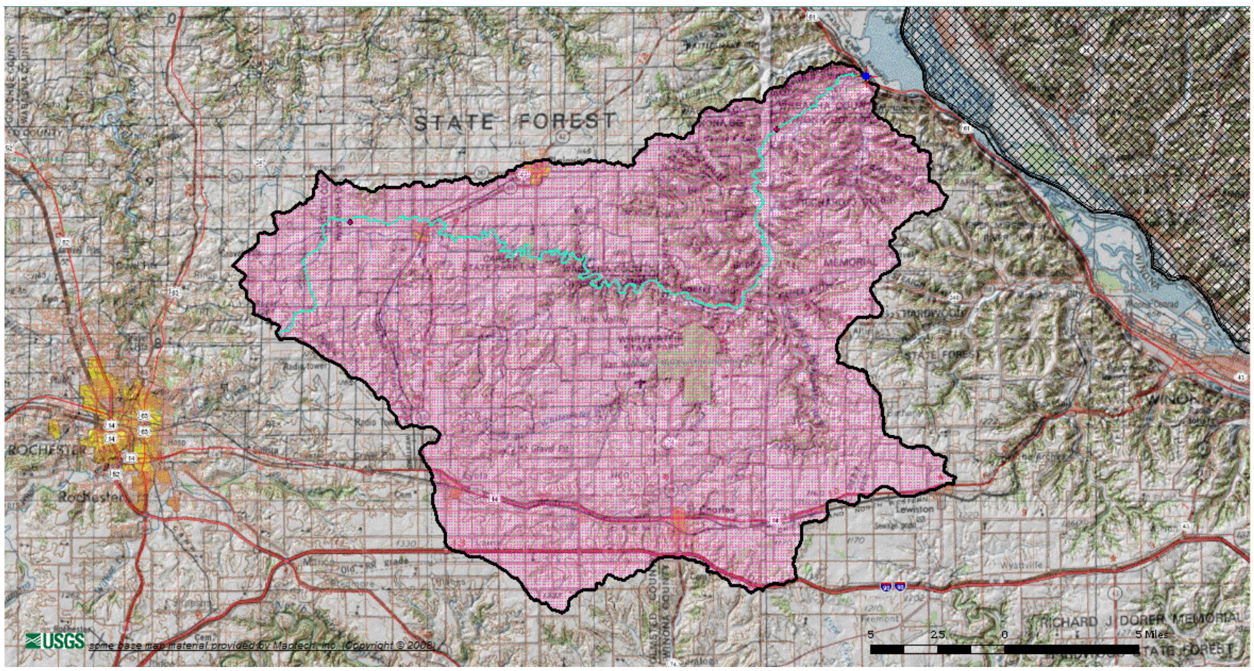

Figure 12: Whitewater River Watershed Size, USGS Base Map

The Whitewater River watershed is located in South Eastern Minnesota. It has a drainage area of approximately 321 square miles and a 1-percent chance of annual flow of approximately 22,100 CFS at its confluence with the Mississippi River. This site was selected for the following reasons:

1. History of severe sedimentation and erosion, flooding and bridge washouts: Site has witnessed events of historic flooding in the past (20 times per year in 1920's, 28 times in 1931, one big event in 2007), where farms and small towns were flooded and bridges washed out. The severe sedimentation and erosion problems and degradation of water quality lead to conservation efforts by various organizations such as the Izaak Walton League of MN, Soil and Water Conservation Districts and various local organizations.
2. On-going data measurement and surveying by DNR Stream Habitat Program: The site has been under study by the Stream Habitat Program for the last 15 years, during which significant spatial and temporal data set were measured and evaluated.

3. Current FEMA Study: Special Flood Hazard Areas (SFHA) of Winona County are currently undergoing H&H modeling and re-mapping to show the latest flood risk areas based on the updated topographic changes and hydrologic conditions. Therefore it was possible to utilize these hydraulic models to further build them and incorporate the geomorphic details. Once the form of the channel was built, it was tested by flowing water through it at various flow conditions. Later, the sediment transport capabilities were run in the model.
4. The selected reach included restored sections where the channel was connected to the floodplain at bankfull conditions as well as incised areas upstream and downstream.

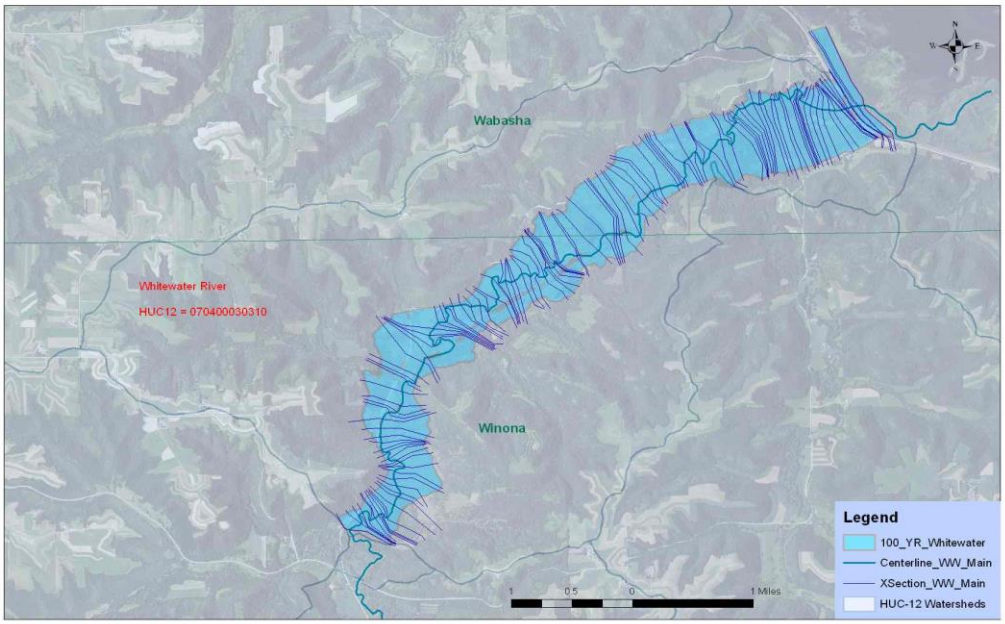

Figure 13: One-percent annual chance flow delineation for Whitewater River lower reach

Methodology

Computer modeling along with field collected and office analyzed geomorphic assessments were both used in this study to address various culvert(s) and bridge opening(s) design configurations at a hypothetical road-river intersection. It assessed 'typically found' valley cross sections of bridge/culvert openings configuration throughout Minnesota's landscape. It then re-configured the same cross sectional area to determine if improvements to the river system can be achieved. Improvement was defined as lessening the impact by creating a more natural flow regime down the valley. It compares a natural flow hydrograph to the various hydrographs created by placing various configurations of a road across the valley and stream channel.

Review of Site Assessment:

In the study, five different floodplain crossing scenarios were modeled. Each scenario had a specific culvert configuration. HEC-RAS, an industry standard modeling software package, was used to determine and assess the following parameters, across entire site, for each scenario using both steady and unsteady flow calculation methods:

water surface elevation

velocity

shear stress

sediment mass change and transport capabilities

energy slope gradient

mass balance

The results of the modeling simulations proved that impacts from road embankments can be better mitigated through proper flood distribution and proper sizing of openings across the floodplain. By increasing the effective flow areas on the floodplain and properly sizing of on-channel openings based on channel width, both conveyance and channel stability was improved.

HEC-RAS Modeling:

HEC-RAS 4.1.0 was used in this project. The hydraulic model, which was developed by the USACE, is a useful tool for analyzing channel hydraulics at various flood stages and flow conditions. It can run sediment transport limited to transport in channel beds. It can also handle bridges and culverts, supercritical and subcritical flows and rapidly varied flows using momentum equations. Different flow conditions include steady, unsteady and quasi-steady flows. HEC-GeoRAS 10 was utilized to interface between HEC-RAS with ArcGIS. The floodplain geometry was extracted using ArcGIS 10 and exported into HEC-RAS for processing. Then the output was imported back into ArcGIS for mapping the results.

A. Geometry:

The latest LiDAR (Light Detection and Ranging) with 3-meter resolution data was used to extract the geometry for the lower Whitewater River. Then, the surveyed sections of the pools and riffles were incorporated into the geometry.

B. Hydrological Input:

For steady state conditions, the flow frequencies for the following storms were included: 1.5YR, 2YR, 5YR, 10YR, 25YR, 50YR, 100YR and 500YR.

For unsteady states conditions (as well as quasi-unsteady for sediment transport), the discharges measured during the storm of September 2010 were used. The storm reached a maximum discharge rate of 10804.27 CFS on September 24, 2010. This was equivalent to the 10-YR storm (10800 CFS) according to the USGS regression equations, as determined by USGS StreamStats.

C. Flow Conditions:
   1- Steady state conditions
   2- Unsteady state condition
   3- Sediment transport using quasi-state conditions

D. Criteria used to determine results:
   1- Water surface elevation
   2- Velocity
   3- Shear stress
   4- Channel bed sediment transport
   5- Gradient – energy slope

E. Modeling Steps:

   1- Geometry: Floodplain geometry was extracted from the 3-meter DEM (digital elevation model) obtained using conventional LiDAR technology. The DEM shapefile was available through the DNR Quick Layers tool. Using the DEM shapefile, it was possible to cut layers representing the channel, banks, flow paths, bridges and cross-section layers. These layers were imported into HEC-RAS through HEC-GeoRAS. Since conventional LiDAR technology does not penetrate through the water surface, additional pool and riffle cross-section measurements, already collected by the Stream Habitat Program through the on-going monitoring, were added into the model in order to capture the missing channel bathymetry.

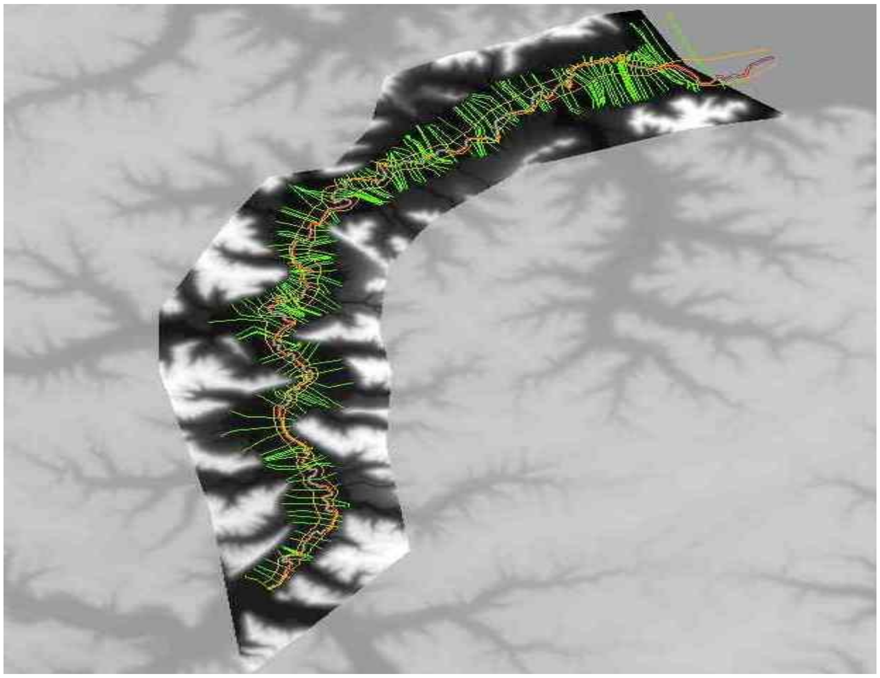

Figure 14: DEM model used as basis for lower reach of Whitewater River

2- Profile:

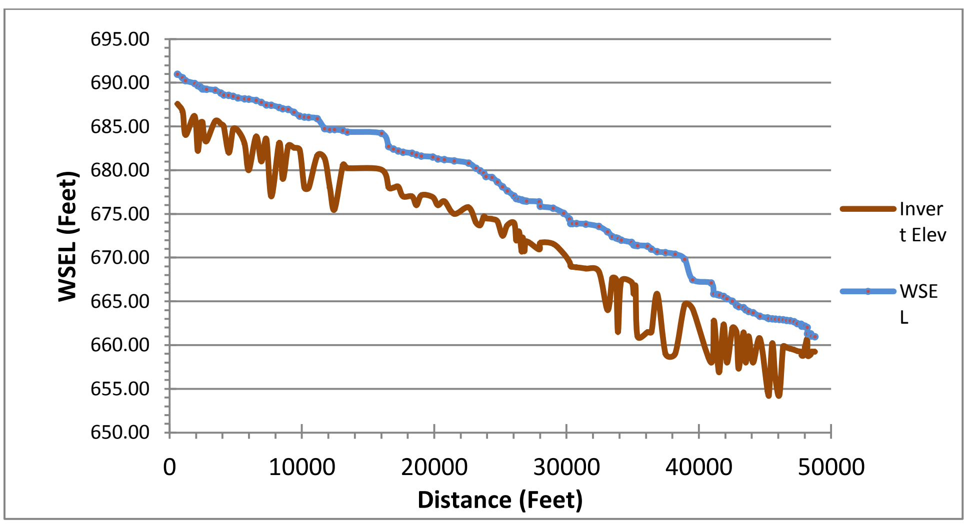

Figure 15: Profile for lower Whitewater River showing riffles and pools

The channel profile above shows the geometry after incorporating the riffle and pool sections into the model. Due to the restoration project in the middle section of the model (between RAS River Stations 9563.675 and 5454.041), the channel invert depths appears shallower indicating better vertical connectivity between the channel and its floodplain. However, upstream and downstream of that section, the stream is incised and disconnected from its floodplain, causing excess erosion and deposition downstream all the way into the Mississippi River.

3- Hydrograph:

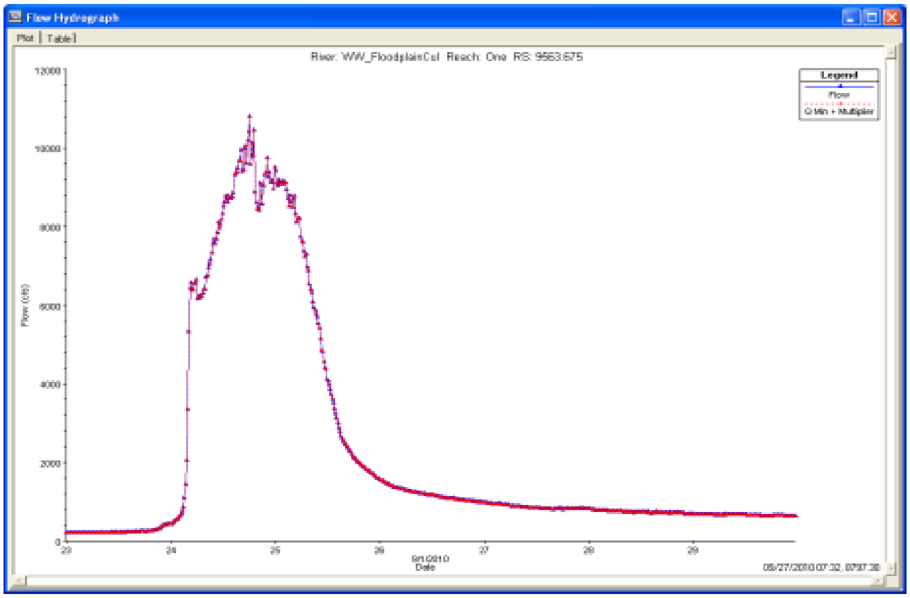

Figure 16: Hydrograph representing September 2010 storm

The model hydrograph was obtained from the September 2010 storm discharge rates recorded at intervals of 15 minutes. These measurements are based on the Beaver Creek USGS gage, which is currently being maintained and monitored by DNR's Division of Ecological and Water Resources.

4- Bridges and Crossings:

There were five bridges included in the model:

i. South bound I-61 bridge (MNDOT 79002, US of confluence)
ii. North bound I-61 bridge (MNDOT 79002, US of confluence)
iii. 61 Railroad bridge, upstream of I-61
iv. Snow mobile bridge
v. Beaver Creek bridge (MNDOT 85002, DS of Beaver Creek)

Bridge data was obtained using the MNDOT State Aid website for MNDOT 79002 and 85002 and DNR field survey.

5- Run steady state and calibrate.

After running the steady state model for the whole reach, the water surface elevations were compared with two observed elevation points located at the restored area and at the Beaver Creek Bridge. The model was therefore calibrated based on the two field measured elevation points.

6- Modeling Confinement Scenarios:

In order to evaluate the effects of channel confinement on the Whitewater River, a section of approximately 6270-ft in river linear length was extracted from the model extending from a distance of approximately 25,000-ft upstream of the confluence with the Mississippi River. The extracted model was within the restored area of the channel, where the active channel is connected with its floodplain into which it would naturally overtop above the bankfull discharge.

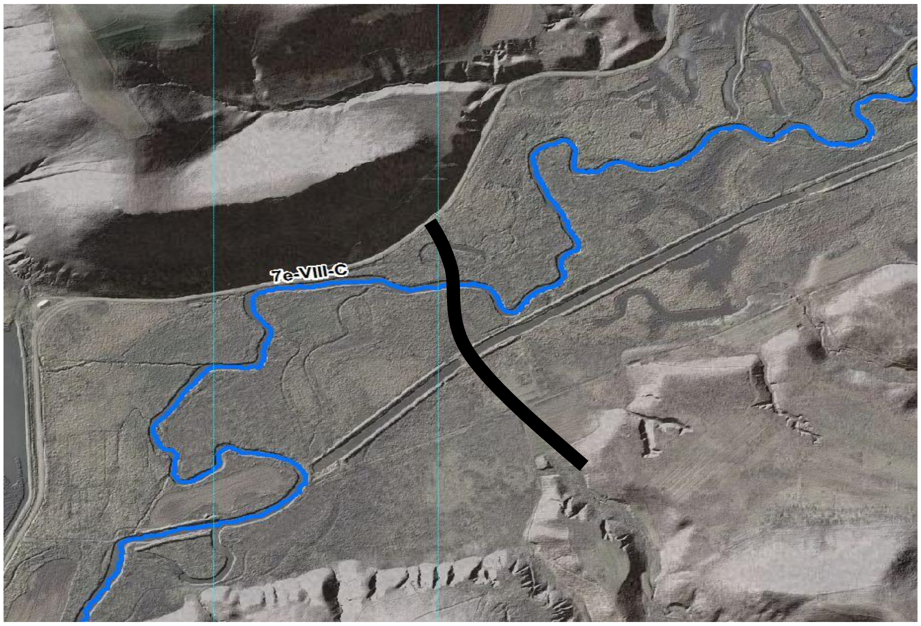

Figure 17: Location of hypothetical bridge

Within the extracted model, a bridge was hypothetically located as shown in the figure above. The location was selected in a constricted area. After locating the bridge, the following scenarios were considered:

1. Scenario One. Natural conditions (without a bridge):

The model was run without any confinement and results were used as baseline to compare with the bridge scenarios below.

2. Scenario Two. Bridge width opening limited to bankfull width:

For this scenario, the bridge was sized in a way that prevents the water from overtopping the road embankment at its 10-YR storm peak. According to the model, the road does over-top for higher flow frequencies.

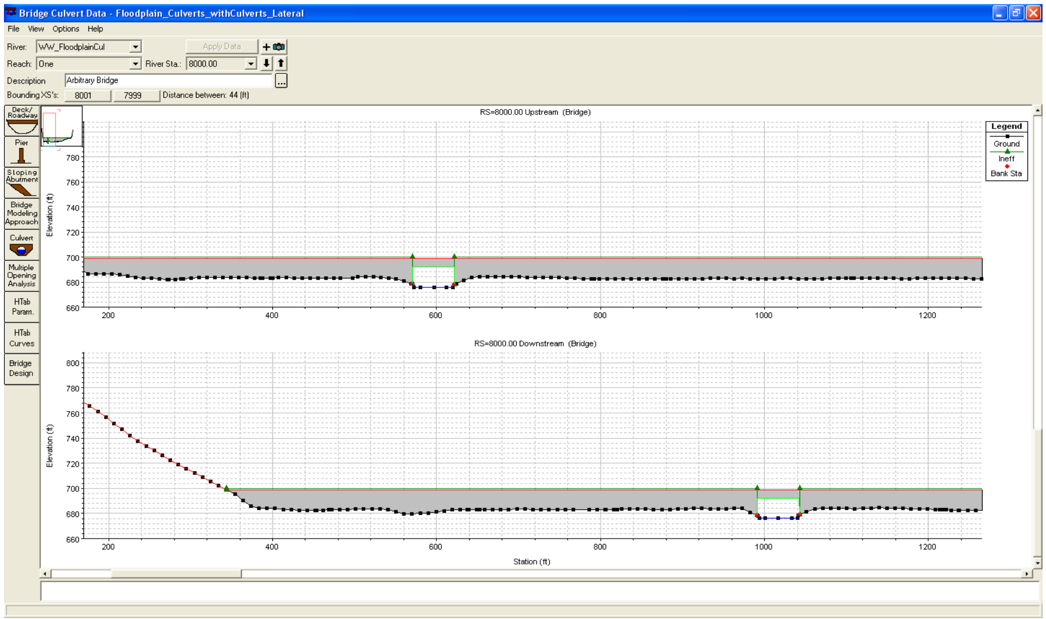

Figure 18: Hypothetical bridge with bankfull width opening

3. Scenario Three. Beaver Creek MNDOT bridge:

This is an actual MNDOT Bridge (no. 85002) located upstream near the Beaver Creek tributary. This scenario was run to compare with results of the bankfull width bridge above.

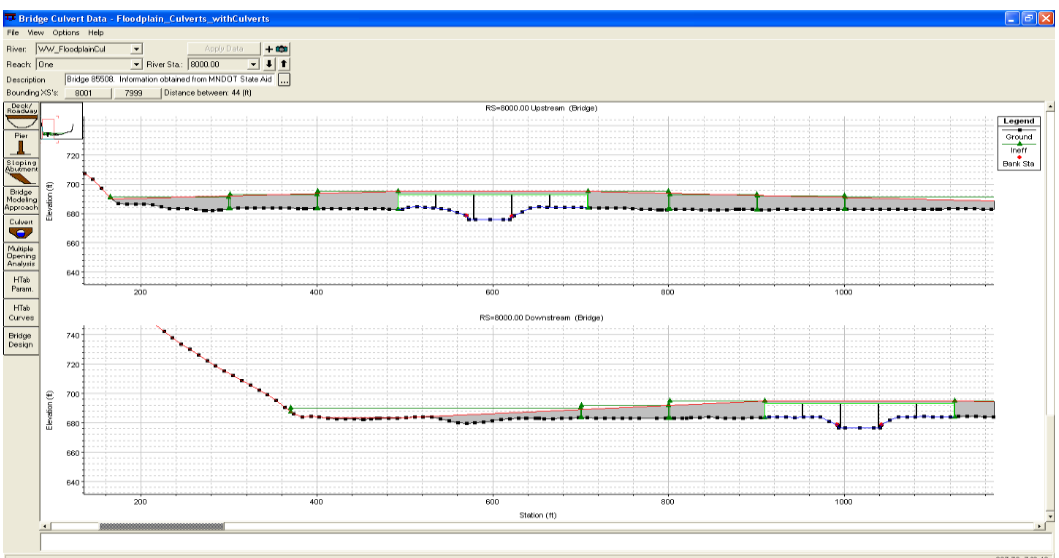

Figure 19: Beaver Creek MNDOT Bridge

Figure 20: Photo of Beaver Creek bridge (a 'commonly found' structure on the landscape)

4. Scenario Four. Culverts placed in channel only with no overbank relief:

In this scenario, the floodplain culverts were all placed in the channel with an opening area that extends beyond the natural bankfull width. Thus, this scenario representing oversized channel culverts was intended to replicate several bridges observed in the southeastern area of the state where the conveyance is confined to the channel only. The remaining floodplain does not contribute to conveyance (ineffective flow) unless the bridge overtops, which is not the case for this storm where the maximum discharge reaches 10% annual chance, a relatively more frequent event than the 1% annual chance which causes the bridge to overtop.

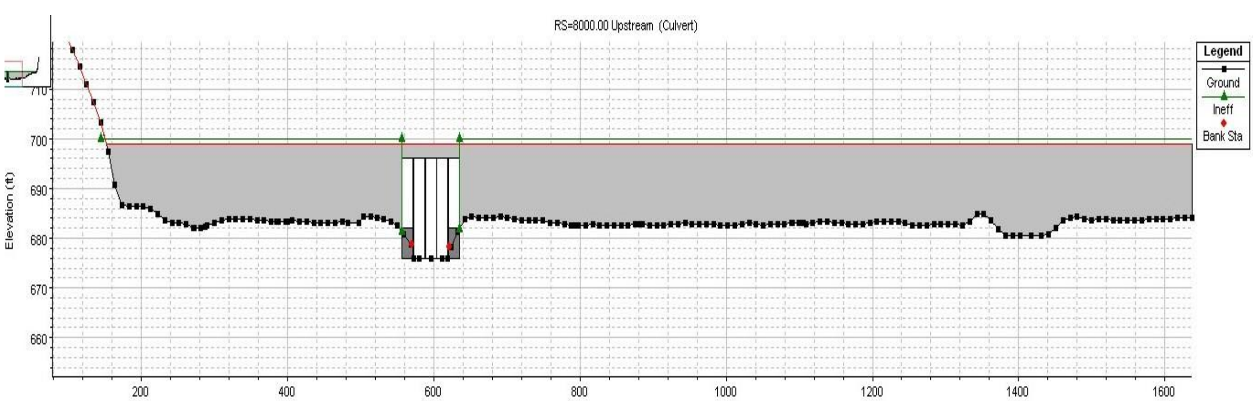

Figure 21: Schematic of the confined bridge opening showing culverts

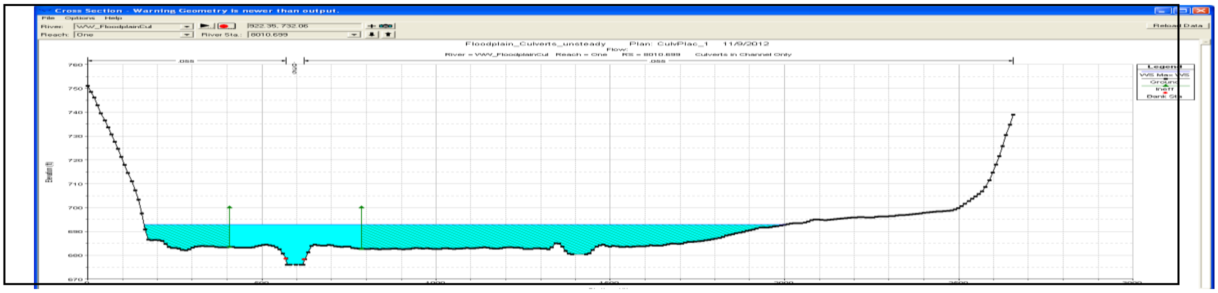

Figure 22: Ineffective flows just upstream of the confined bridge opening

5. Scenario Five. Culverts distributed throughout the floodplain (active channel and overbanks):

In this scenario the same total opening area used above was distributed over the whole floodplain width (channel and overbanks). In the channel, three culverts are placed along the bankfull width. In the overbanks, the remaining culverts were placed throughout the floodplain with invert elevations starting at the bankfull elevation. Thus, as soon as the channel was overtopped for flows exceeding bankfull discharge, the overbank culverts would start contributing to conveyance, acting like floodplain relief culverts. The overbank culverts were distributed in a way that maximizes the area contributing to conveyance, unlike the previous scenario where the culverts were only placed in the active channel.

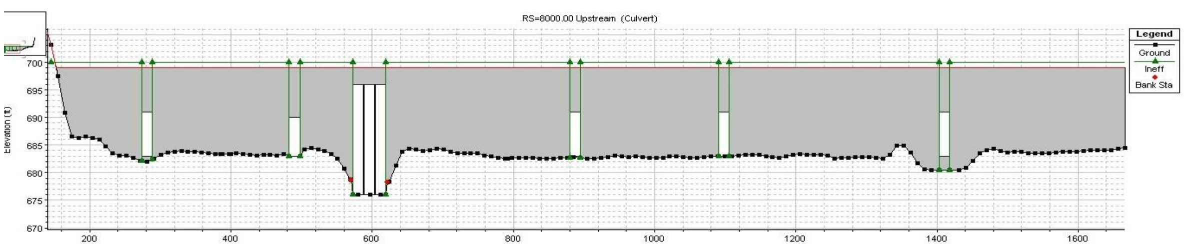

Figure 23: Schematic of the bridge openings showing distributed culverts

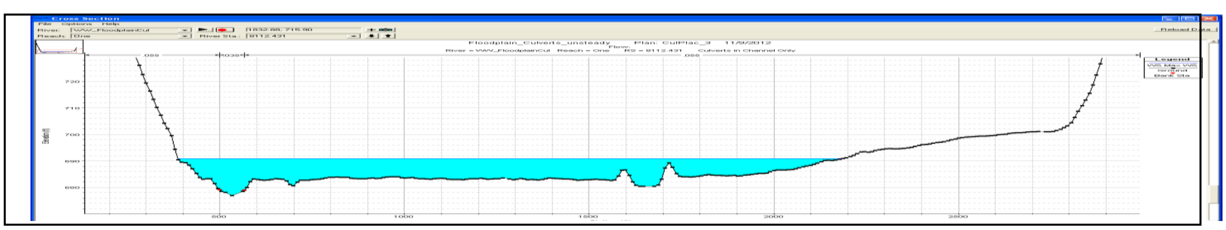

Figure 24: Effective flows just upstream of the bridge openings with distributed culverts

Study graphs and results

Impact of bridge on natural flow:

A. Scenario Two: Bankfull width opening:
Figure (25) compares the effects of the bridge on the maximum water surface elevation just upstream of the bridge. According to the graph, the bridge causes an elevation increase of up to 4.75-ft under the maximum discharge. Note that the maximum discharge in this hypothetical case corresponds to the ten percent annual chance flow (10-YR storm), which does not overtop the bridge. When running the 1-percent annual chance flow in a steady state simulation, the bridge overtopped, as would typically be the case for higher less frequent storms (See Figure 26). So the bridge effect on water surface elevations in this case involves the more frequent storms that would naturally cause the channel to overtop in order to access the floodplain.

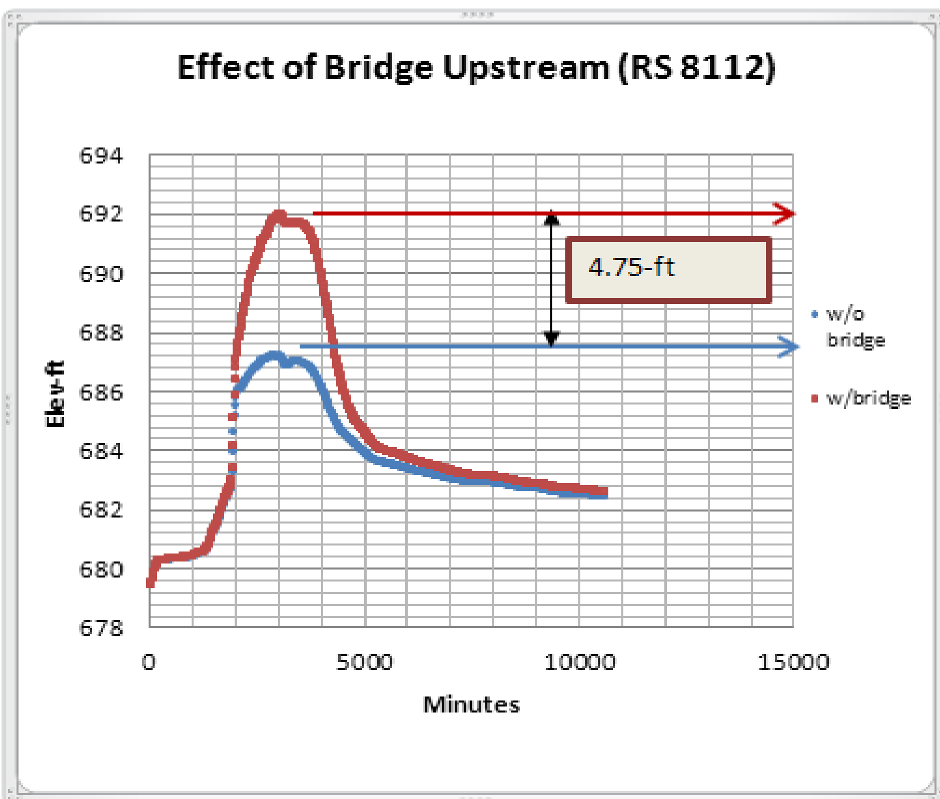

Figure 25: Difference in water surface elevations (WSEL) between confined bridge opening and natural conditions upstream of bridge

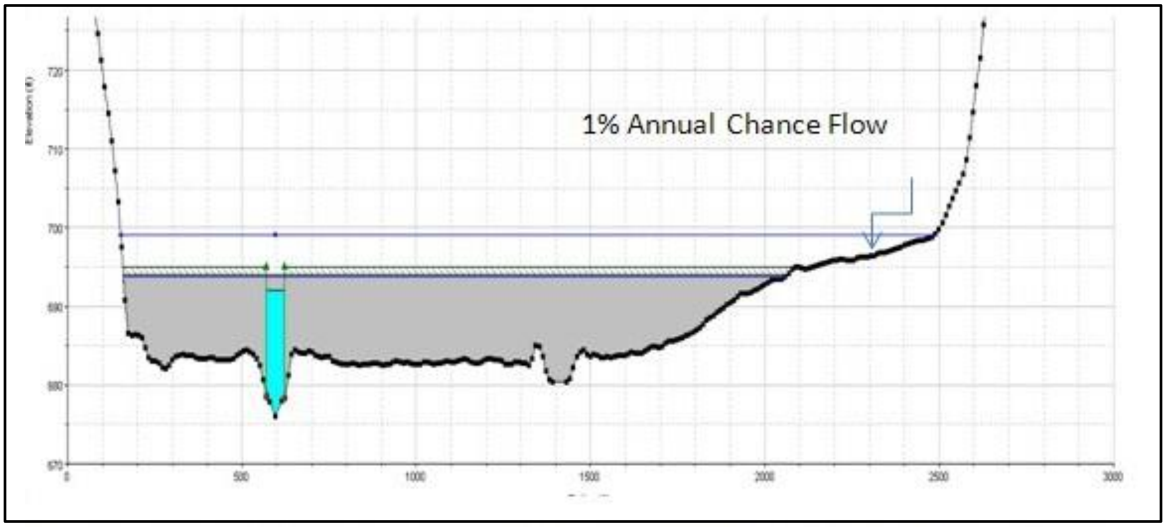

Figure 26: Confined bridge opening showing the 1-percent annual chance flow elevation above the high chord

Figure (27) shows the impact of the bridge on the surface water elevation downstream of the bridge, which is less than 0.5-ft for the maximum discharge limit. However, downstream impacts on other parameters such as velocity, shear stress and sediment transport are more significant, as will be shown later.

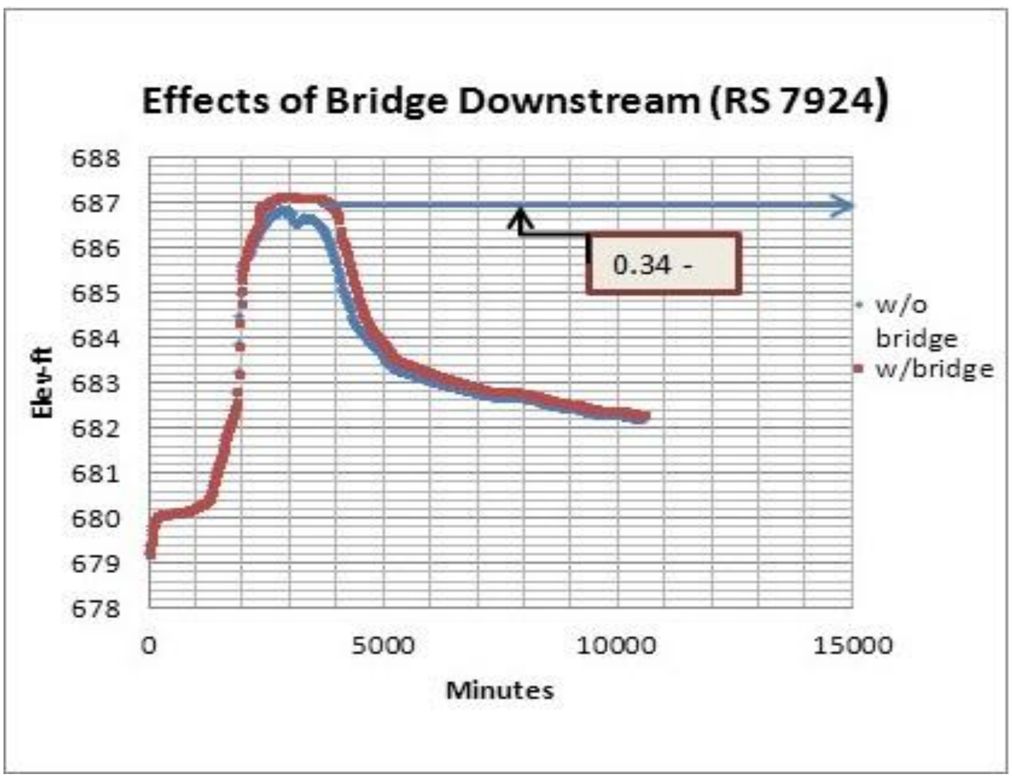

Figure 27: Difference in water surface elevations (WSEL) between confined bridge opening and natural conditions downstream of bridge

In order to further quantify the impact of the bridge on natural flow conditions, water was hypothetically (in the model only) withdrawn upstream of the bridge until the water surface elevations representing the natural (Scenario One) and bridge (Scenario Two) conditions became equal. Thus, water flow in the active channel was allowed to flow through the culvert for flows up to bankfull conditions. Flows exceeding bankfull conditions, which would normally cause the stable channel banks to overtop, was hypothetically removed. This water amounted to a total maximum flow reduction of 42.5%. For that to happen, more than 16,000 Ac-ft will have to be stored, removed or re-routed in order to counteract the overall effects of the bridge, as shown in Figure (28). This is equivalent to placing a long span bridge, which would be cost prohibitive and unreasonable, thus necessitating the application of other methods to minimize the effects of the bridge as much as feasible.

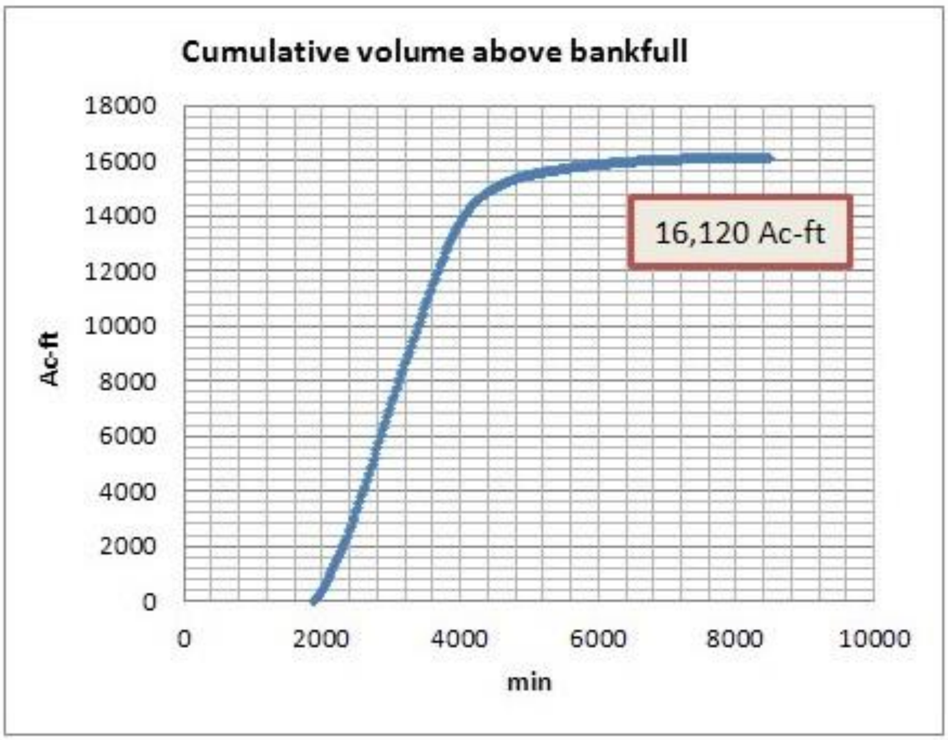

Figure 28: Cumulative volume required to offset impacts of embankments

B. Scenario Three: Beaver Bridge Opening.

Figures (29) and (30) show the impact of the Beaver MNDOT Bridge on water surface elevation. According to Figure (29), the bridge causes an increase of 2.6-ft over natural conditions just upstream of the bridge. This rise is less when compared with Scenario Two due to the wider bridge opening extending beyond the bankfull width.

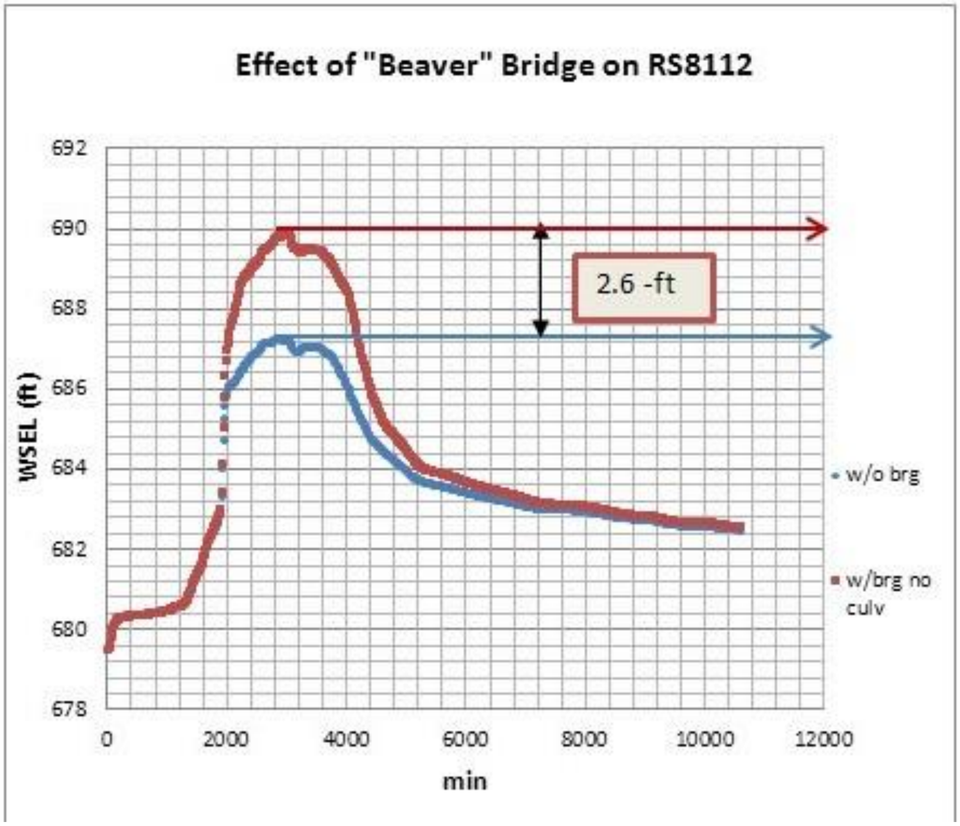

Figure 29: Difference in water surface elevations (WSEL) between MNDOT Beaver Bridge opening and natural conditions upstream of bridge

According to Figure (30), the bridge does not overtop for the 1-percent annual chance flow under steady conditions. But note that the water does flow around the bridge.

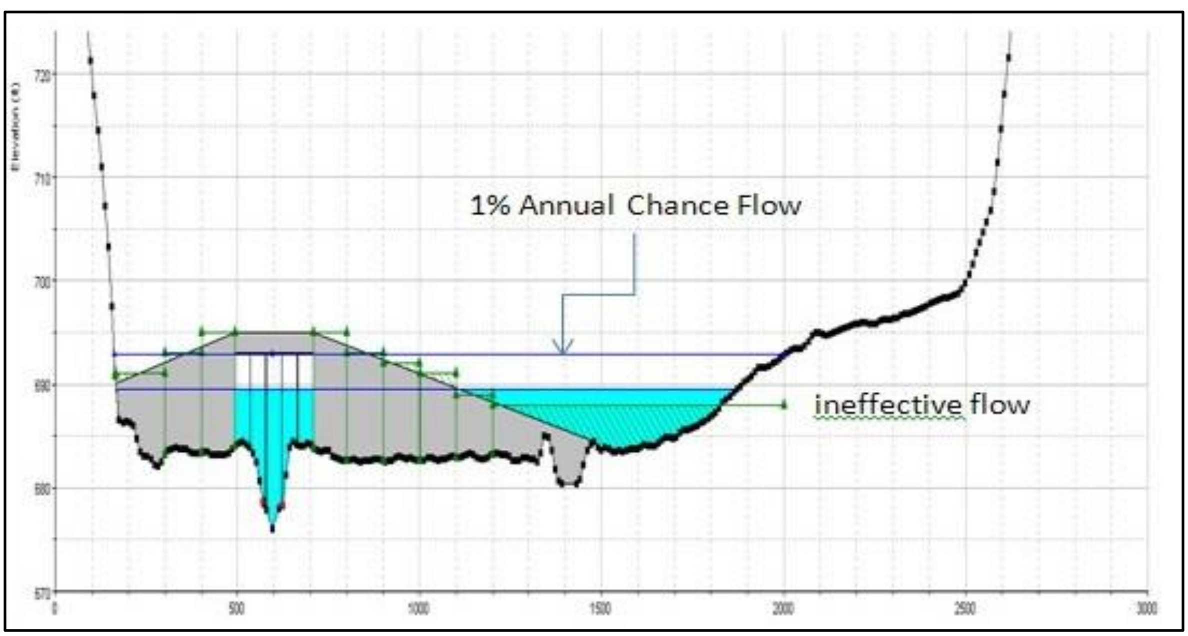

Figure 30: MNDOT Bridge showing the 1-percent annual chance flow elevation above the high chord

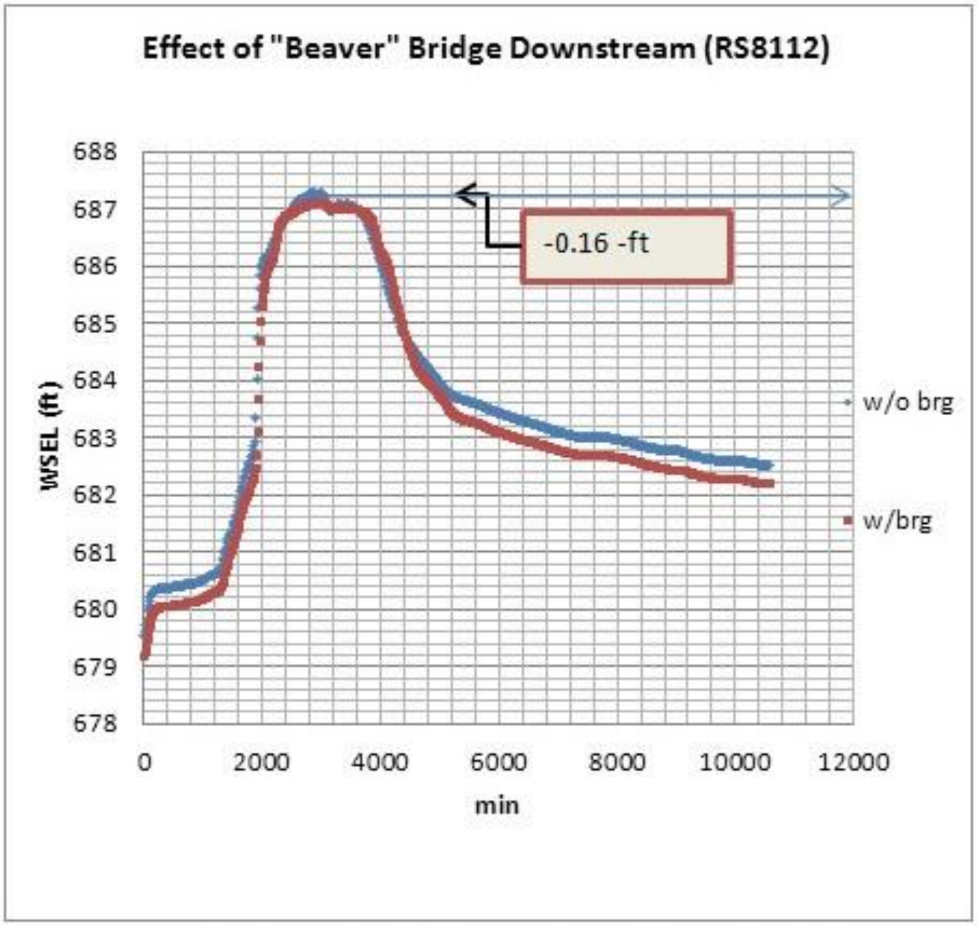

Figure 31: Difference in water surface elevations (WSEL) between MNDOT Beaver Bridge opening and natural conditions downstream of bridge

Regarding the downstream conditions of the bridge, the Beaver Bridge does not cause a change in the water surface elevations. However, there are impacts involving other hydraulic parameters such as velocity, shear stress and sediment transport.

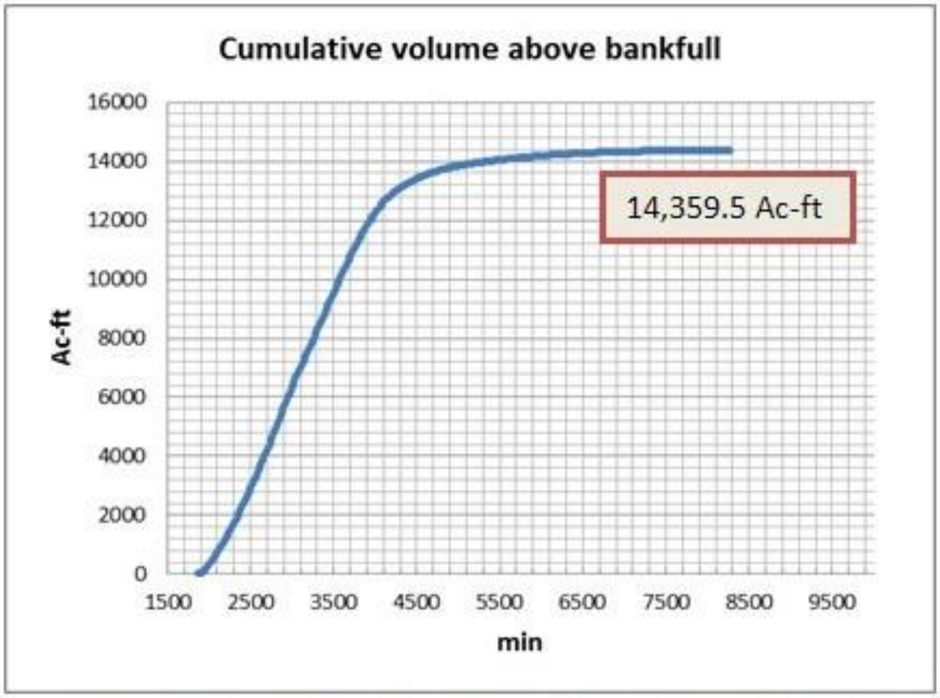

Figure 32: Cumulative volume required to offset impacts of embankments for MNDOT Bridge

In order to quantify the complete impact of the Beaver Bridge on the water surface elevation, approximately 14,000 Ac-ft of water will have to be removed above the bankfull discharge limit. As can be seen, the wider bridge opening allows more conveyance when compared to the hypothetical bridge (Scenario Two).

Culvert Placements:

A. WSEL and Effective/Ineffective Flows:

Figure (33) compares the maximum water surface elevations for four different culvert configurations representing various culvert placements ranging from natural conditions without any crossing (Scenario One) to confining all culverts in the channel (Scenario Four). In addition, Scenario Six was added to represent a hybrid between Scenarios Four and Five, where all overbank culverts -with the same area as in Scenario Five- are placed next to the channel culverts after reversing the length and width- at bankfull elevation. Table One summarizes the results by comparing the impact of each scenario to natural conditions. The third column compares the percentage of possible WSEL reductions when providing floodplain relief culverts in the overbank areas (Scenarios Five and Six) instead of confining the culverts to the active channel only (Scenario Four).

Table One: Comparing impact and WSEL reductions:

Scenario	WSEL – Natural Conditions	WSEL Reduction from Scenario Four
Four	5.8	
Five	2.8	51
Six	4.4	25

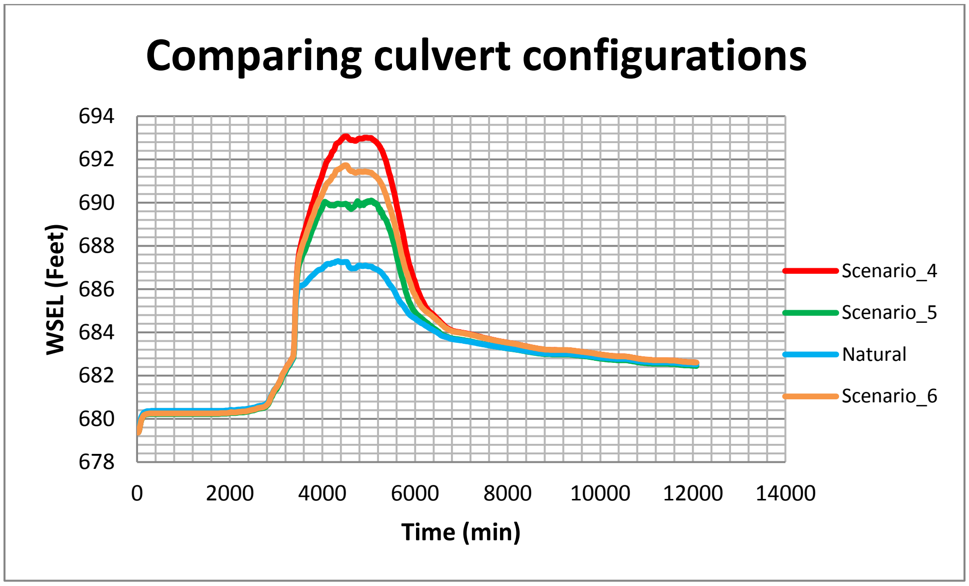

Figure 33: Comparing WSEL for various bridge openings and culvert configurations upstream of bridge

By keeping all the hydrologic and hydraulic parameters constant, the changes to the WSEL values are directly related to the extent of area contributing to conveyance. In Figure (34) representing Scenario Four, the conveyance is limited to the contraction limits extending from the channel, where areas outside these limits are rendered ineffective, and would contribute to water storage only, but not conveyance.

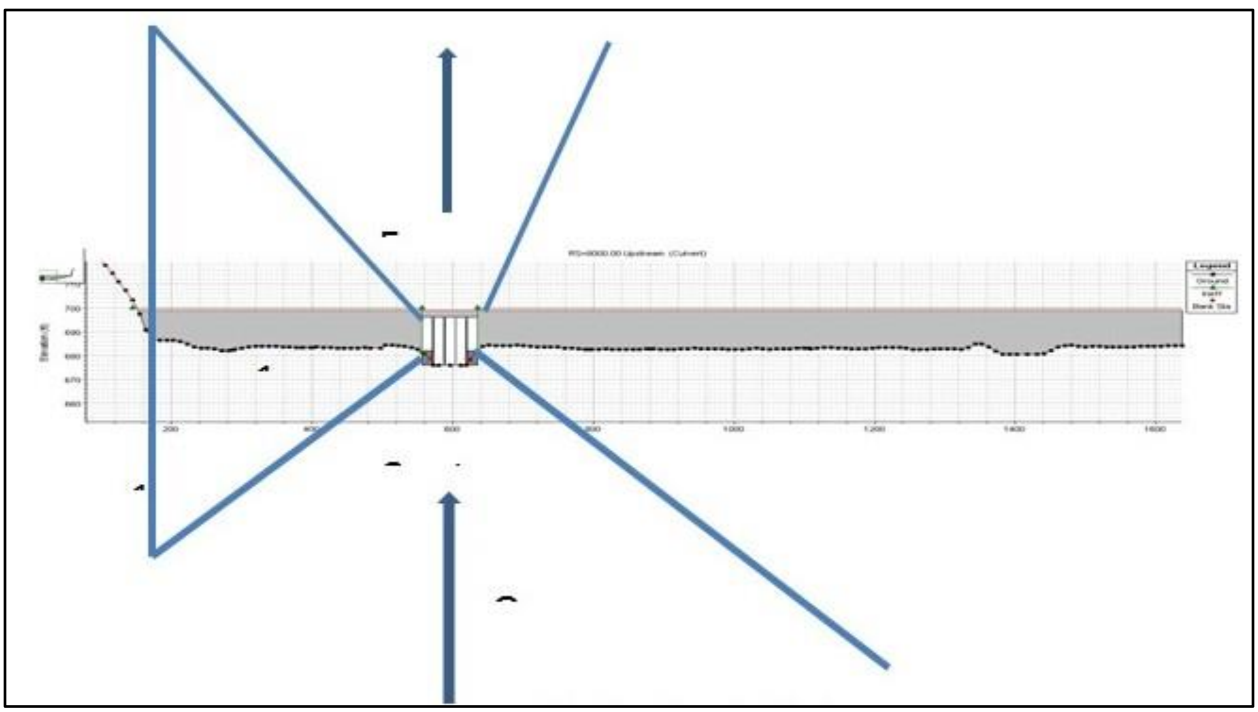

Figure 34: Schematic of flow through confined bridge

Conversely, in Figure (35) representing Scenario Five, the effective flow area extends throughout the floodplain due to the wider distribution of the overbank culverts upstream of the bridge. In both scenarios, volume balance calculations between upstream and downstream volumes of the embankment accounted for 99.9% of the flowing volume (135,000 cubic feet). The volume balance calculation was performed using the trapezoidal rule method of the output hydrograph. Thus, distributing the culverts throughout the valley will minimize flow constrictions due to the road embankment. However, offsetting the total impact of the bridge can only happen if the bridge was replaced with a long span bridge or if flow above bankfull conditions are completely re-routed or/and stored. Given the economical feasibility factor, placing floodplain relief culverts and distributing them along the floodplain may be the best alternative.

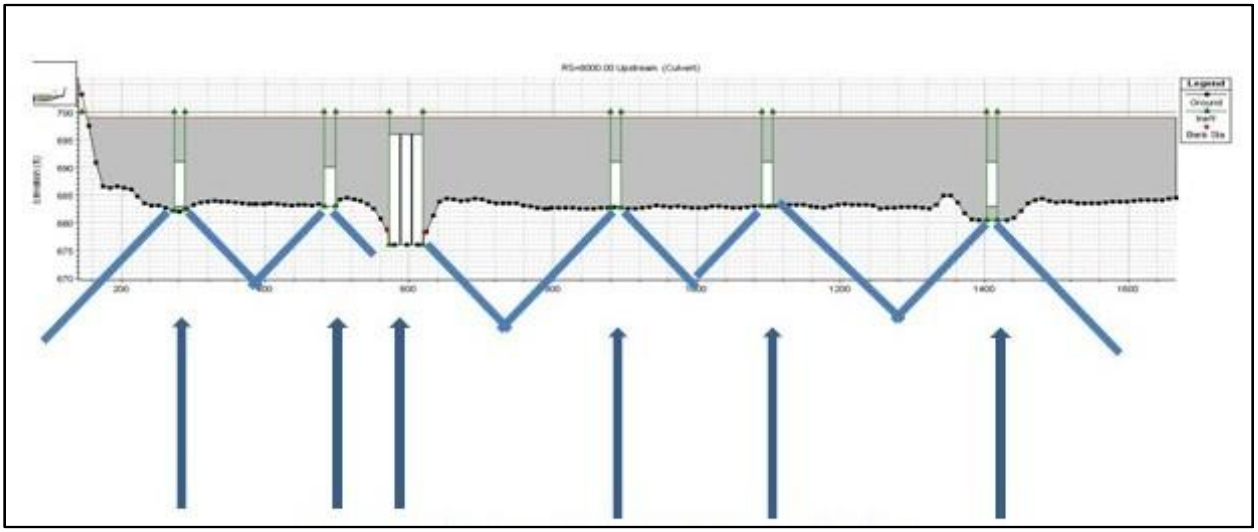

Figure 35: Schematic of flow through distributed culverts

B. Velocity:

Figure (36) shows the velocity profile in the active channel (excluding the overbanks) for Scenarios One (natural), Four (over-widened channel only) and Five (bankfull channel and overbanks). The red line representing Scenario Four (culverts in channel only) has a lesser peak velocity than the green line, representing Scenario Five (culverts in channel and overbanks), at the culverts. However, from the figure, the velocity in Scenario Five adjusts more rapidly to its near natural conditions, immediately upstream and downstream of the culvert, than it does in Scenario Four. This is due to the wider effective flow area that distributes the conveyance to the whole floodplain.

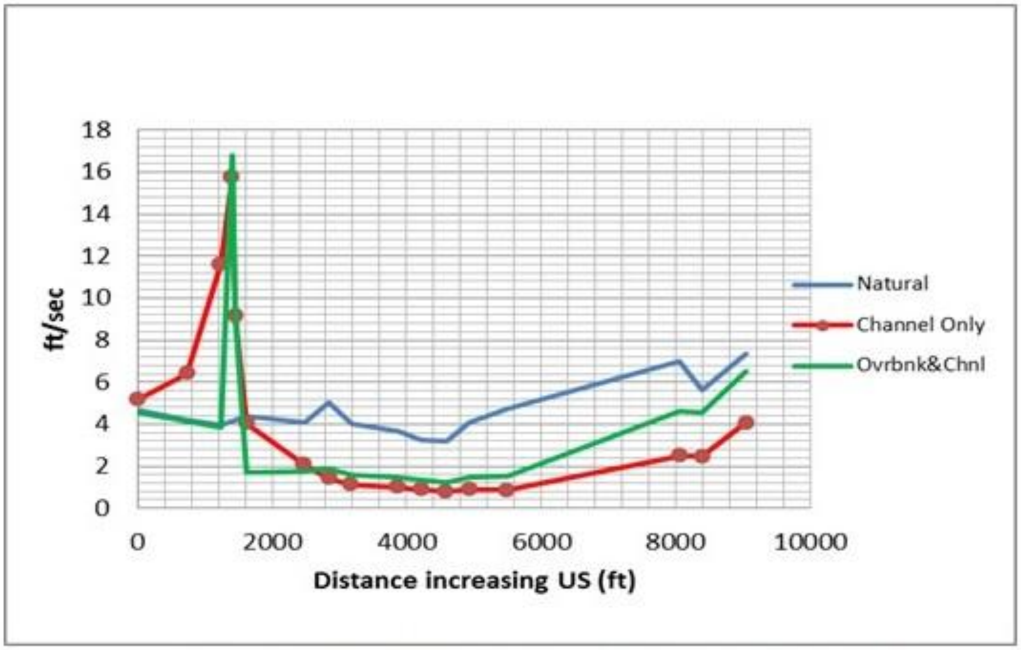

Figure 36: Effects of Culvert Placement on Peak channel velocity profile

Figure (37) shows the total velocity profile (including overbanks) for Scenarios One, Four and Five. From the figure, the peak total velocity is highest for in Scenario Four (culverts in over-widened channel only). Furthermore, the velocity recovery after reaching the peak is more favorable in Scenario Five (culverts in bankfull channel and overbanks).

Due to the larger constriction of Scenario Four, the velocity profile tends to decrease upstream from the crossing when compared to the natural condition. A decrease in velocity upstream of the crossing also occurs in Scenario Five but to a lesser extent than Scenario four. As a result, distributing floodplain relief culverts throughout the floodplain provides better longitudinal connectivity as well as lateral connectivity.

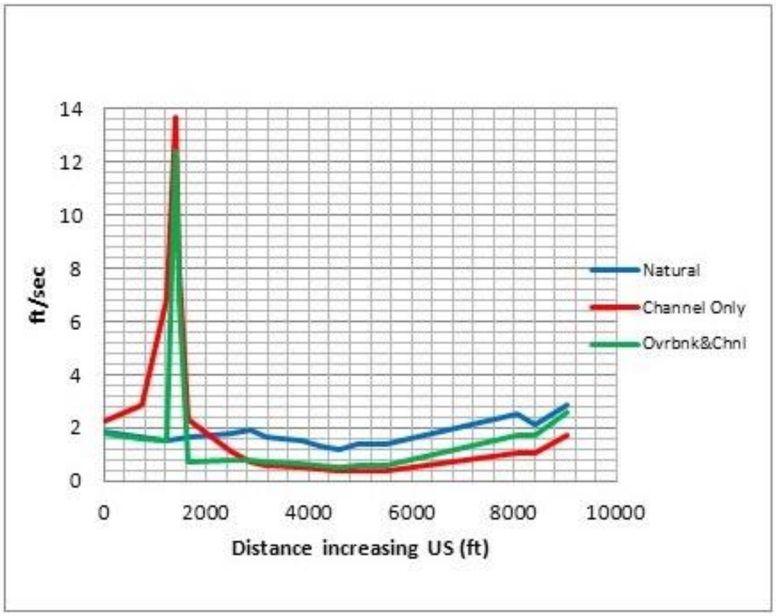

Figure 37: Total maximum velocity in floodplain

C. Maximum Shear Stress:

Figure (38) shows the channel bed shear stress. If the shear stress exceeds the critical shear stress of the channel bed, then bed erosion begins to take place. So the parameter is important when evaluating sediment transport. According to the graph, Scenario Four exhibits a higher shear stress at the channel and a slower recovery than Scenario Five downstream of the culvert. As a result, the modeling results prove that by distributing floodplain relief throughout the channel, the shear stress is reduced by approximately 24%.

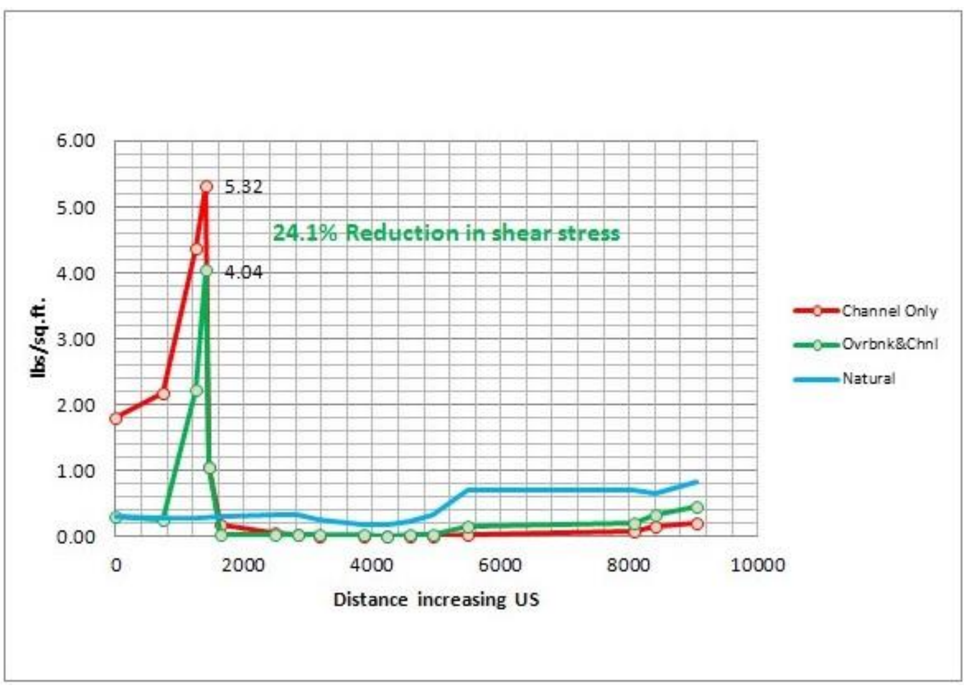

Figure 38: Shear stress profile

D. Sediment Transport:

Figures (39) and (40) show the profiles for the cumulative mass change and maximum sediment discharge, respectively for Scenarios One (natural), Four (culverts in over-widened channel only) and Five (culverts in bankfull channel and overbanks). Due to the natural confinement of the channel at the location of the hypothetical bridge, maximum sediment transport and erosion take place. The figure also shows that the effects of further constricting the flow due to the bridge would cause sediment deposition upstream and erosion downstream. However, the erosion is more significant when confining the conveyance to the channel only (Scenario Four). Distributing the culverts throughout the floodplain, would cause a faster recovery where the channel adjusts itself nearer to natural conditions downstream of the culvert.

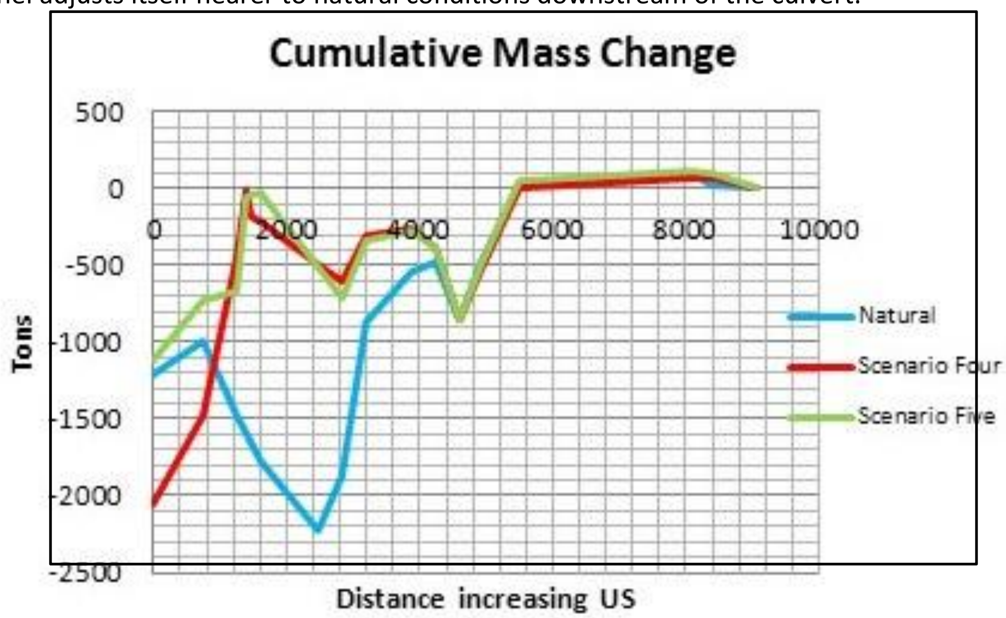

Figure 39: Profile showing cumulative mass change

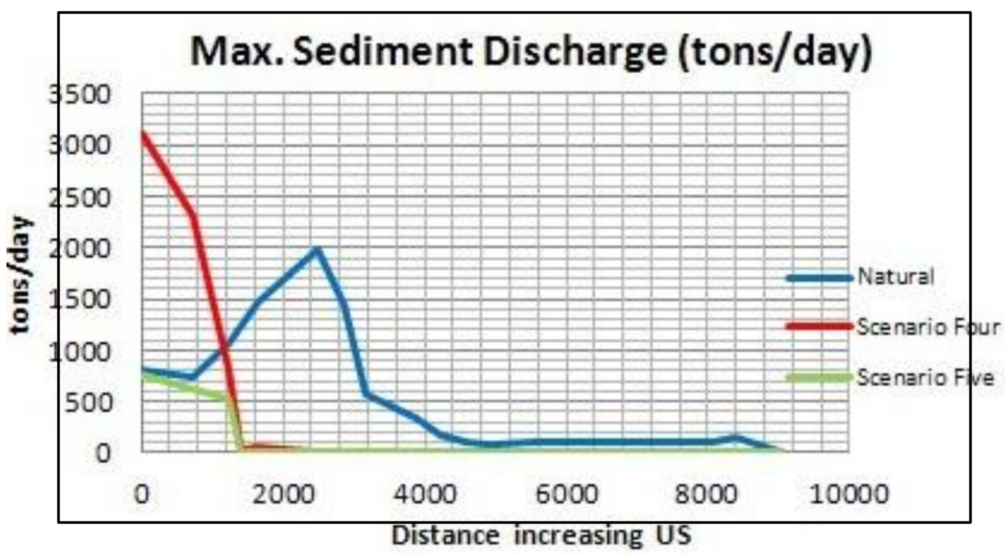

Figure 40: Profile showing maximum sediment discharge

E. Energy Gradient Slope:

Figures (41) show the profiles for the energy gradient slope at maximum discharge for Scenarios One (natural), Four (culverts in over-widened channel only) and Five (culverts in bankfull channel and overbanks). The peak point representing the FFC scenario occurs just upstream of the opening. It indicates a discontinuity in the profile due to the confinement of the channel. By providing relief culverts at overbanks, continuity is achieved as depicted by the green markers which represent the distributed culvert scenario.

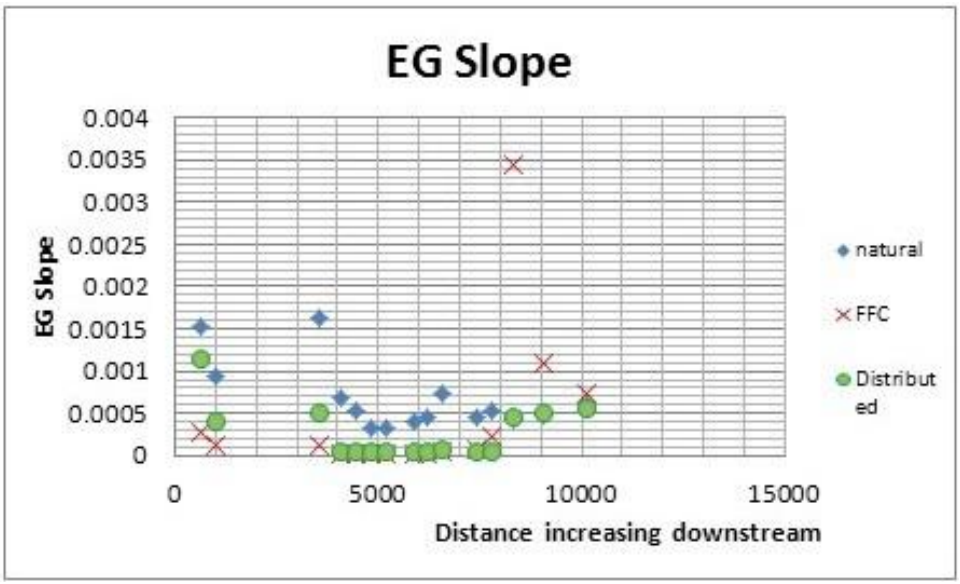

Figure 41: Profile showing Energy Gradient Slope at maximum Discharge

Summary of Results

Table Two: Comparing bridge impact on natural flow for two bridges

	Confined bankfull bridge	MNDOT
Head-loss (10-YR)	4.75	2.6
Max. peak flow reduction required to offset embankment impacts	42.5%	48.8%
Volume required to be re-routed to offset embankment impact	16,120 Ac-ft	14,360 Ac-ft

Table Three: Comparing results of two bridge opening scenarios on the natural channel flow

	Confined Culverts	Distributed Culverts
Max. WSEL increase over natural conditions	5.8-ft	2.8-ft
Max. Peak velocity in channel	15.8 –ft/s	16.2 –ft/s
Max. Total velocity in floodplain	13.7 –ft/s	12.4 – ft/s
Max. Shear Stress	5.32 lbz/sq.ft	4.04 lbs/sq.ft.
Cumulative sediment mass change	-2062.7 Tons (uncalibrated)	-1111.4 Tons

HYDRAULIC MODEL LIMITATIONS:

1. HEC-RAS model is a one-dimensional model. So assumptions have to be made in the model regarding lateral flow.
2. Hydraulic models do not simulate the complex spherical flows around pools and meanders where up-welling and down-welling take place.
3. For the sediment transport component, HEC-RAS 4.1.0 simulates sediment transport in the channel bed only and does not include bank erosion and deposition. However, after the release of the Bank-Stability and Toe-Erosion Model (BSTEM) as a module within HEC-RAS 4.2, simulating bank erosion will become possible.
4. Simulating unsteady flow could prove challenging for the model's stability since the model does not like sudden varied geometry like bridges, steep slopes and other abrupt changes.
5. More testing of bridges and in various watersheds are needed, specifically for bridges that exhibit erosion problems and lack of connectivity despite already meeting the FEMA requirements based on the 1-percent annual chance flow.

Discoveries, Review of Conclusions and Recommendations:

This study concluded that improvement can be made to road/river intersection design. Although the recommendations within study demonstrate many improvements for long term water resource successes, it does not imply to be a sole solution to the problems we have with sediment. The authors invite open dialog on other potential solutions and/or improvements to our road/river intersection design to better mitigate impact.

The following illustrations are included to outline and review some key concepts that governed this study. The intent is to improve our road/river intersections by assessing on the ground practices then providing alternative approaches, or changes to road design process. It is known that each site has its own limitations and design requirements, but it is hoped the Key Design Concepts be given proper consideration when assessing and designing a road/river intersection. The implementation of the Key Design Concepts, outlined below, is recommended to be initially applied at “high maintenance” road/river intersections. Designers should properly design, construct and then monitor these sites to instill confidence into the application of Key Design Concepts to their work.

This Study examined and compared several design configurations, which are outlined in the following steps and figures:

Step One: Study assessed stable conditions prior to a road design and construction:

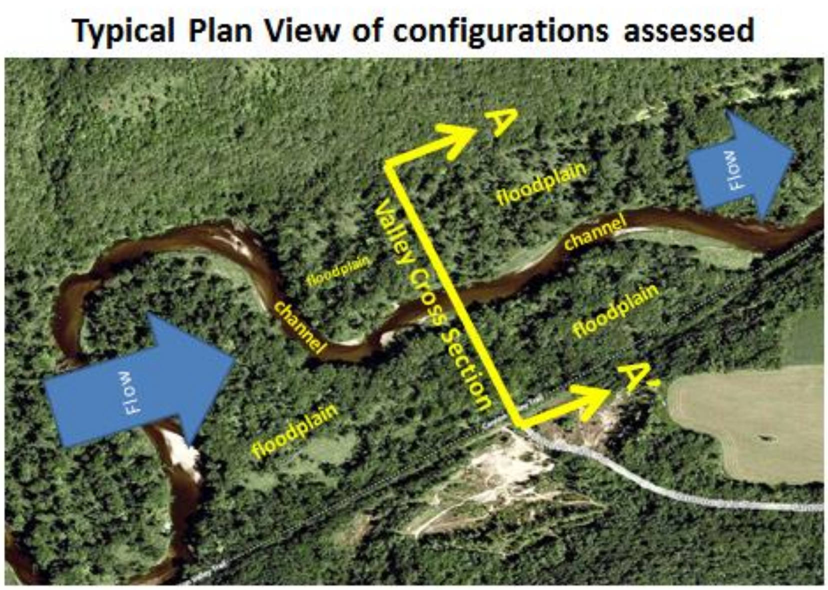

Figure 42(a): Typical plan view based on natural conditions

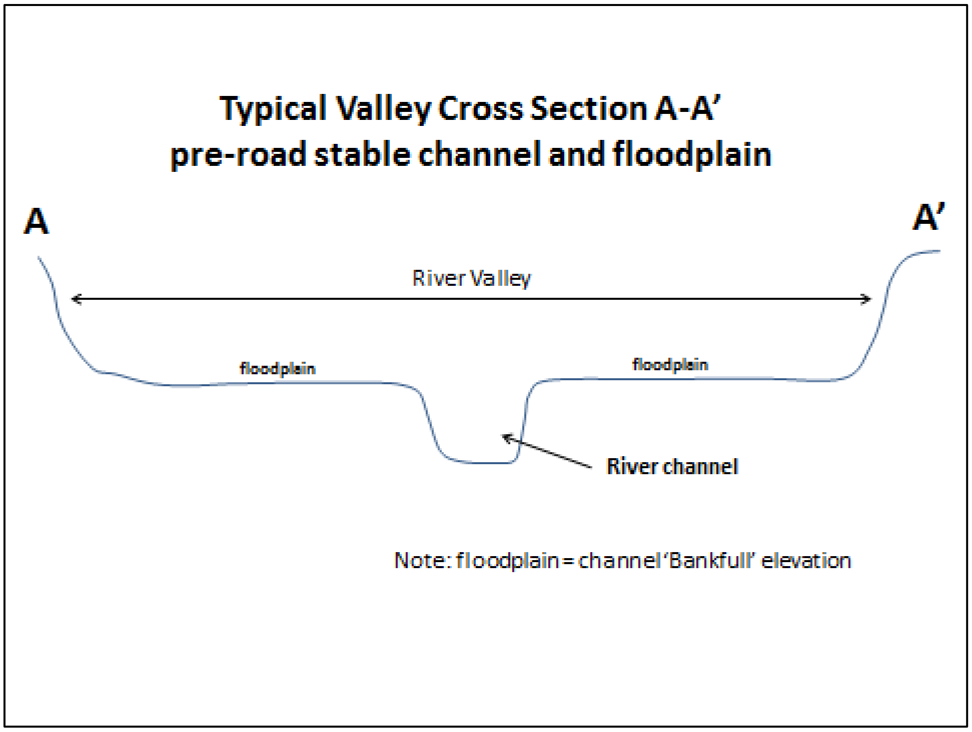

Figure 42(b): Typical cross section of stable channel and floodplain, no road.

Step Two: Based on an understanding of the sites geomorphology, various configurations were assessed through the roadway. See HEC_RAS modeling segment for all configurations assessed. The diagram below displays a commonly found valley cross section on our landscape:

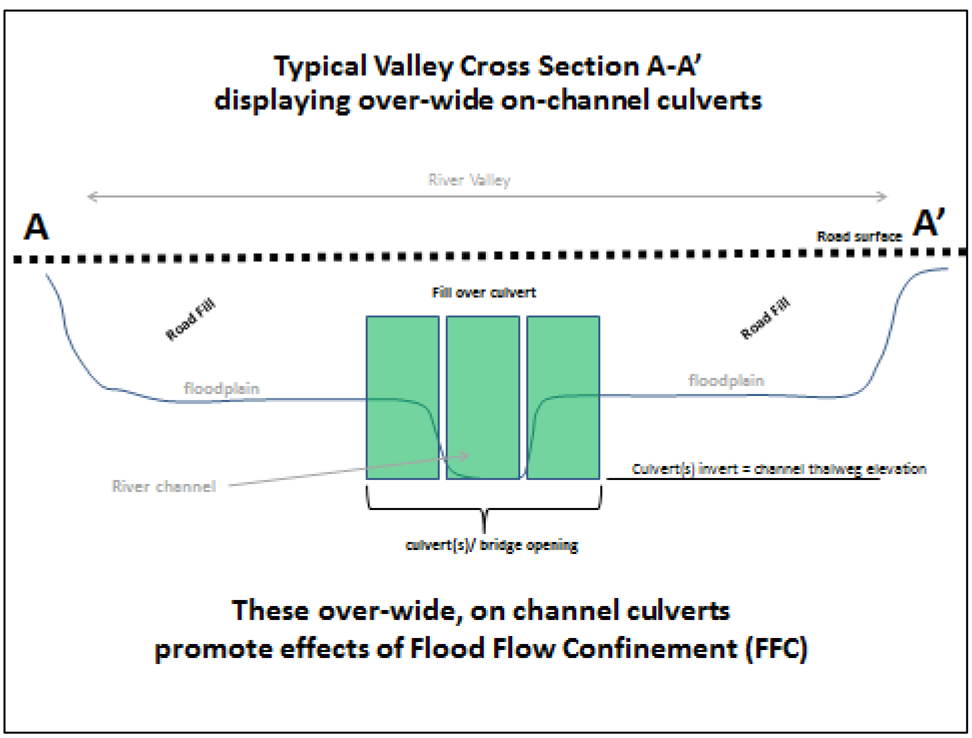

Figure 43: Typical cross section of floodplain showing over-widened culverts in the active channel.

Step Three: The study assessed various valley cross section configurations, using the same effective cross sectional area for conveyance, but applying the Principles of Geomorphology to Road/River Intersection Design into it. The opening configuration below displays an example of one assessed valley cross section:

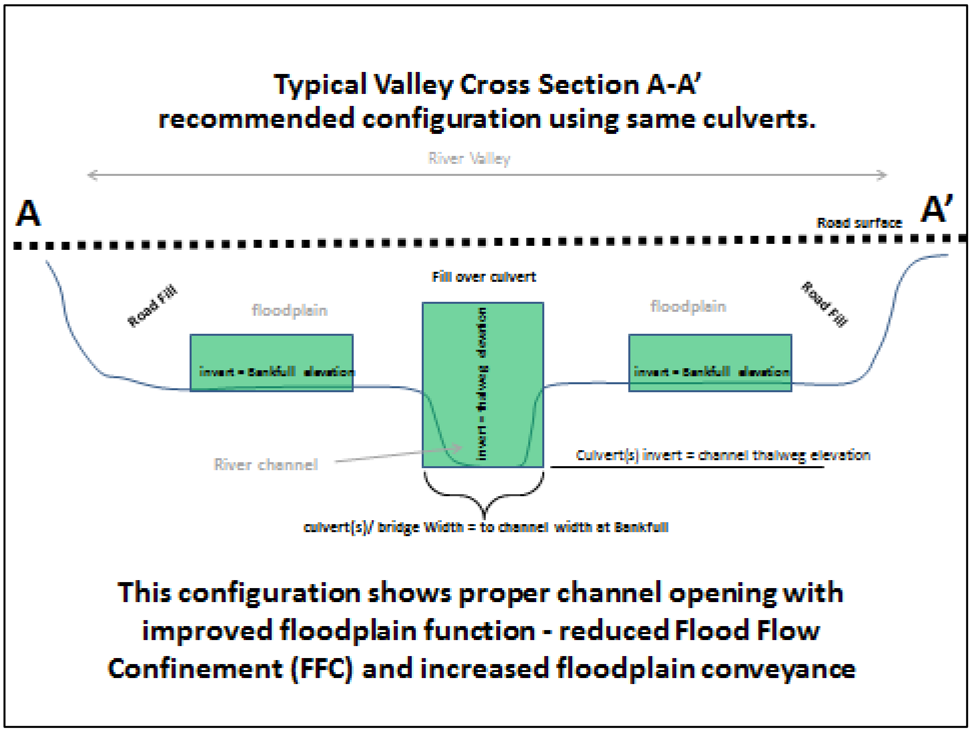

Figure 44: Typical cross section of floodplain showing distributed culverts in the active channel and over banks.

Step Four: The study summarized and reported on findings. Where possible, the study provided recommendations to improving the design of road/river intersections to better mimic natural flood flows.

Study Results:

Again, the authors of this *study do not recommend any reduction in existing cross sectional area for road/river intersections.*

The results of this study show that the impacts created from present day road/river intersection design can be better mitigated by applying the following Principles of geomorphology into the design of road/river intersections:

1. The design process must separate channel conveyance and floodplain conveyance (over-bank) into separate design entities.
2. Design channel conveyance opening width for channel equal to bankfull channel width.
3. Design floodplain conveyance area should be as large as possible. Set invert(s) of opening(s) equal to bankfull elevation and space equally across entire floodplain.

Principles of Geomorphology for Road/River intersection design

From a calibrated model, this study quantified river system impacts. By employing the design concepts diagramed below, improved mitigation of road impacts on river system are gained. Although not complete, these key concepts are illustrated in the following two figures:

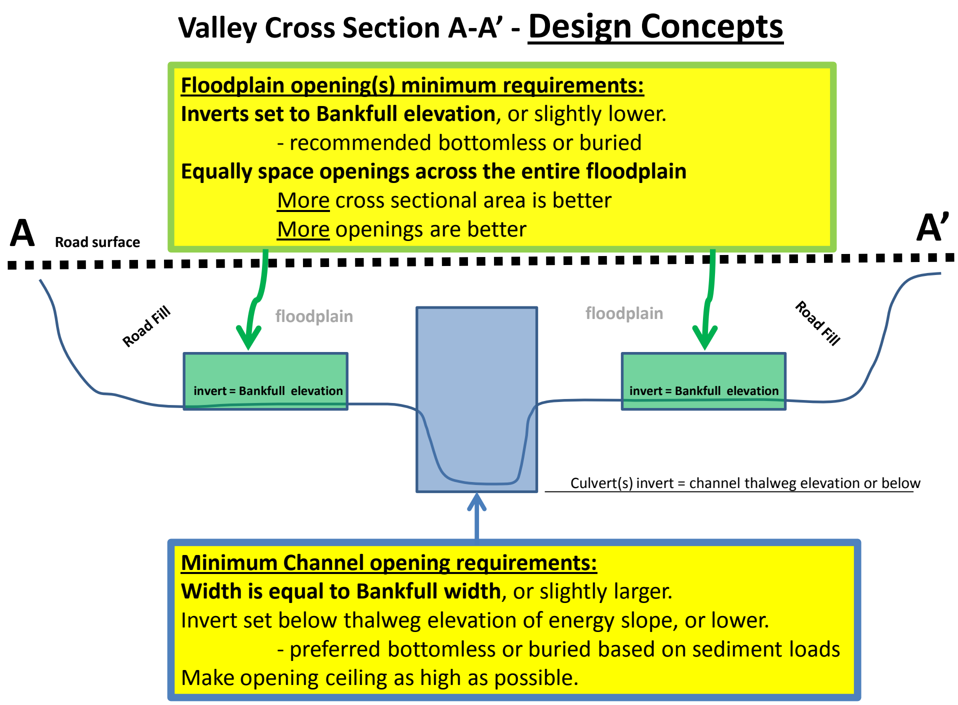

Figure 45: Recommended consideration to proper sizing of openings in a road/river intersection.

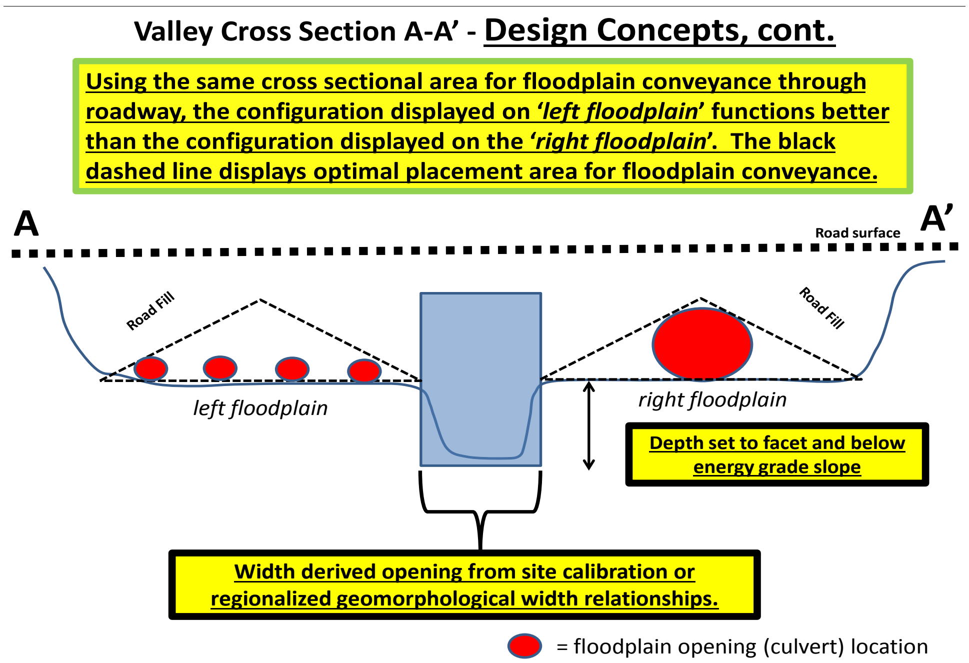

Figure 46: Recommended consideration to proper placement of openings in a road/river intersection

Using site based channel/floodplain morphology, the following design metrics should be site derived and validated for each of the following:

Channel Opening Width: The width of channel openings should be set equal to, or slightly larger than the channel bankfull width. The designed channel bankfull width should be validated with regionalized bankfull channel width curves and measured from aerial photography above and below the site.

Channel Opening Depth: The depth of opening should be set sufficiently lower than bedload sediment entrainment depth. These depths should be based upon appropriate facet (riffle, pool) assigned at road/river intersection. A rule of thumb is to bury the invert deep enough to allow the largest sediment particle to transport through opening. The alignment of channel opening(s) should be aligned to the river channel pattern and not set perpendicular to the roadway as a cost savings measure.

Floodplain Openings: Floodplain opening should be spaced evenly across the entire floodplain. Openings should be centered on both right and left floodplain and evenly spaced across each floodplain. Floodplain openings inverts should be set on the floodplain (bankfull elevation) and should be aligned to be parallel to the fall line of the valley.

See **Information Resources** at the end of this document for additional information and design resources.

The following conceptual graphics are provided to assist in geomorphic principal understanding and application:

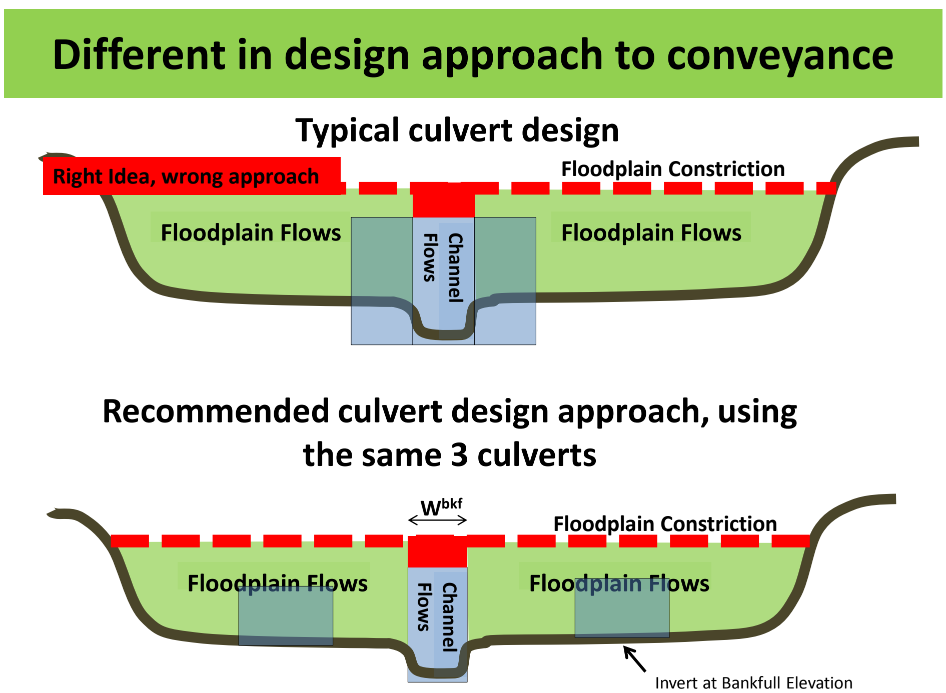

Figure 47: General conceptual change to road/river design process

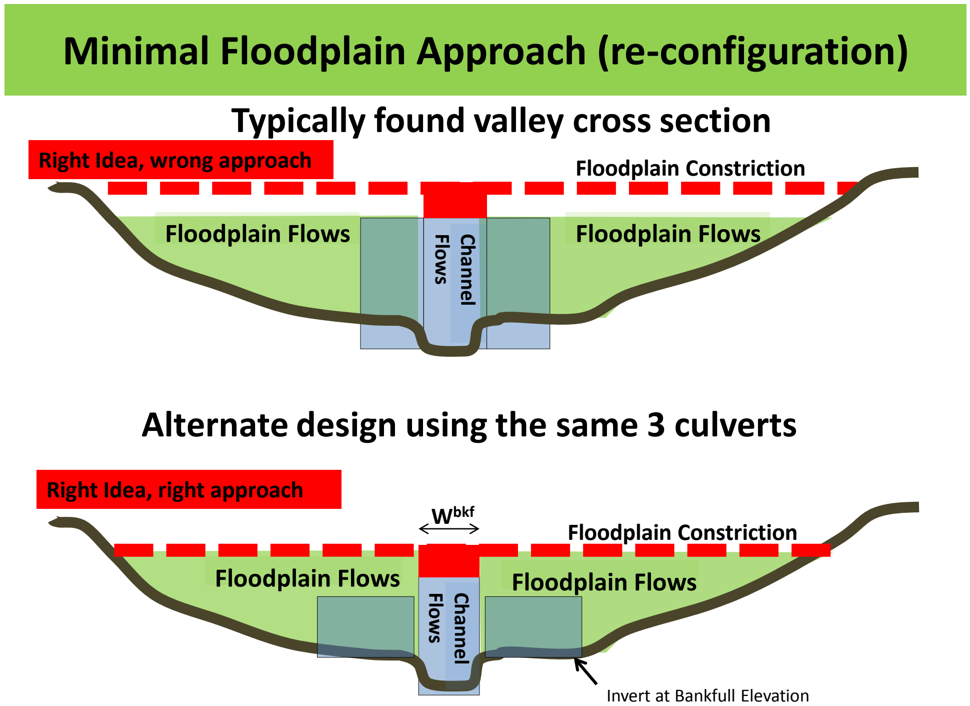

Figure 48: General conceptual change to road/river design process in confined valley

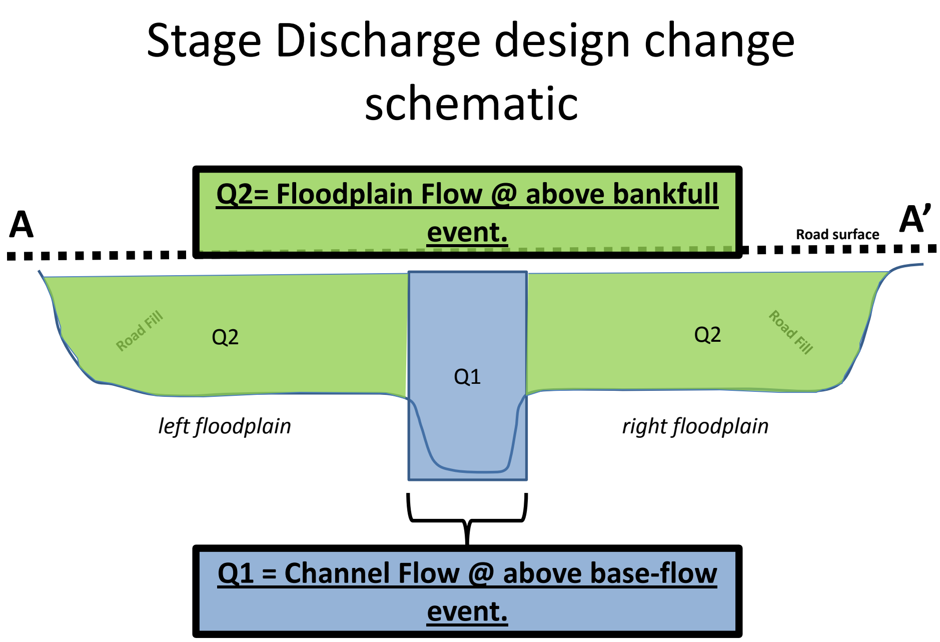

Figure 49: Fundamental change to road/river design process

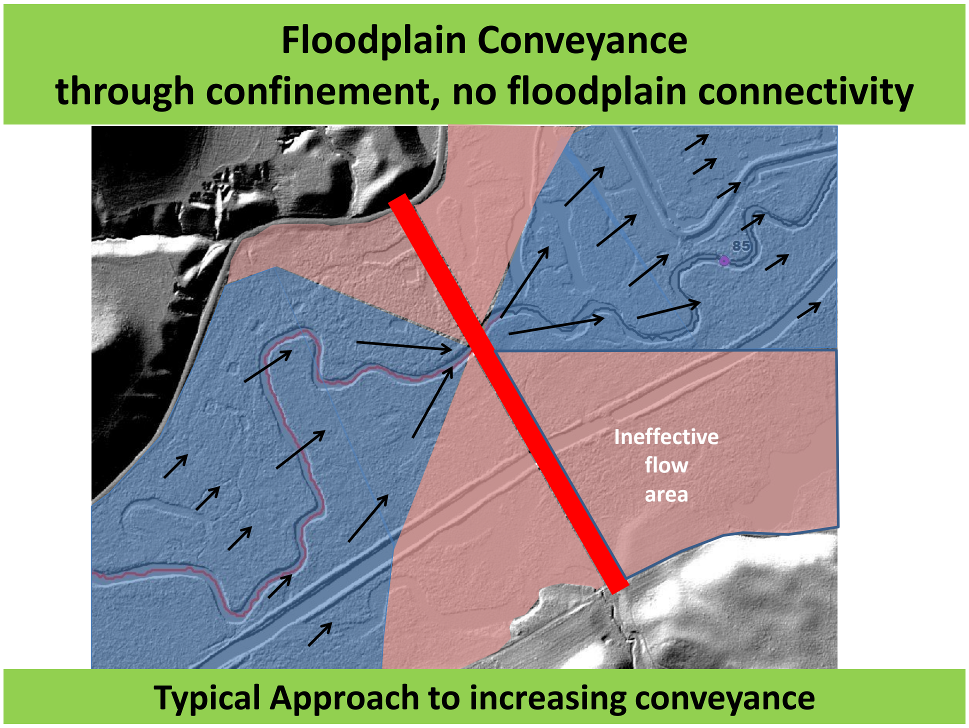

Figure 50: Present day Design promoting FFC. Blue depicts effective flow area.

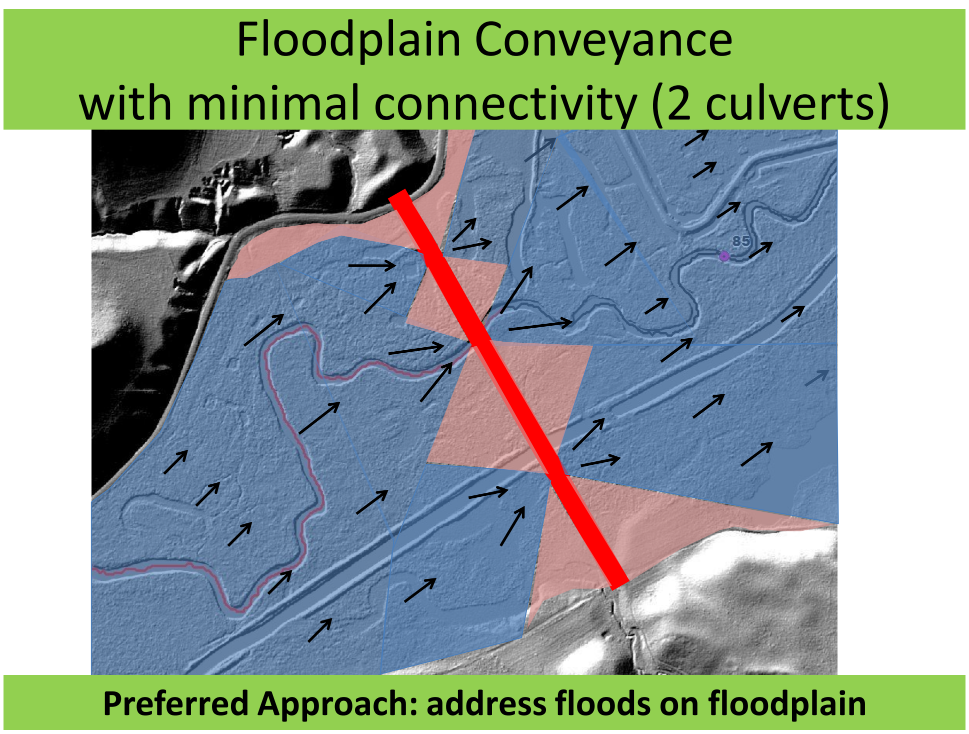

Figure 51: Preferred design to quantify and improve effective flow area (blue area)

Channel Width

The primary basis for bankfull channel width as the initial design dimension for all road/river intersections is to maintain continuity of channel hydraulics and sediment transport dynamics through the roadway. If properly applied, these intersections will be designed and built according to the natural sediment transport and flow consistent with the given the specific stream type and watershed size. As a result, this will alleviate unbalanced metric of channel width, commonly found across today's landscape at road/river intersections; thus drastically reducing in-channel sediment contributions caused by over-widened channels at road/river intersections. These imposed anomalies in channel width have many un-intended consequences which only some are outlined under the Effects of Flood Flow Confinement section of this document.

Fluvial Processes in Geomorphology, 1964, 1992 states: "There are eight interrelated variables involved in the downstream changes in river slope and channel form: **Width,** Depth, Velocity, Slope, Sediment load, Sediment Size, Hydraulic roughness, and discharge. Considering the variable Width is presently not part of design and affects the other 7 tied variables, thus causing imbalance of unknown duration and spatial distribution across our landscape/river systems.

The proposed design bankfull width dimension should be documented for each road/river intersection plan, a good starting point, when beginning a project, is to simply measure the channel width, away from the road and many locations near the project site from an aerial photo. Once researched, the designed channel width should be consistent with a known bankfull channel width and cross referenced to available regionalized width curves, based on drainage area (see Information and Additional Resources section at the end of this document).

Different floodplain metrics (i.e., slope) and material types can vary the desired (stable) channel width. Therefore consideration must be given to these floodplain metrics and materials for design. As a design beginning point, the Type of Valley must be understood. Efforts to designate Valley Types across Minnesota are underway. Once established and cataloged, a much more robust regionalized channel and floodplain width curves will be established and made available. Through time and understanding, by using adaptive management, many of the required channel and floodplain metrics will be documented and be made available as created. One such example of this can be found today in Whitewater Watershed Geomorphic Assessment (WWGA) located in southeastern Minnesota completed by the Minnesota DNR, Stream Habitat Program. For this Whitewater Project, a continuous channel forming flow model of the entire perennial channel network within the drainage area was established based on all 110 defined geomorphic reaches utilizing 127 representative sites across the entire Whitewater watershed. After establishing an empirically based model of channel forming (i.e., bankfull/dominant/effective) flow throughout, an assessment of all channel metrics were analyzed.

From this model, two common stream metrics (cross sectional area and channel width) based on the channel bankfull were compared. Given the variable nature of stream channels and their related sediment loads, the streams we stratified by entrenchment and width to depth ratios and material type using Rosgen Stream Classification System. Of all the channel metrics, Bankfull Channel Width provided the best correlation when normalized on Drainage Area.

This assessment of channel metrics for this project demonstrated that Width is the best metric to base beginning channel design than all others for the road/river intersection design. This fact agrees with the findings reported by Dunne and Leopold as thus stated: "The most consistent parameter is bankfull width, for it more than any other easily measured characteristic of the channels correlated with flow parameters such as average annual discharges and discharges having specific recurrence intervals" *(Water in Environmental Planning, T. Dunne and L.B. Leopold 1978).*

Finally, this report summarized initial findings of an on-going collaboration within the Minnesota Department of Natural Resources, Division of Ecological and Water Resources. Continuing dialog within the professional community, modeling refinements, changes and new discoveries may require updates to be released.

Information and Additional Resources

The following websites provide more basis and background for this study. They also provide a up-to-date resource for this study and additional future related studies.

Minnesota DNR – Stream Habitat Program:

http://www.dnr.state.mn.us/eco/streamhab/about.html

Minnesota DNR – Floodplain Mapping Program:

http://www.dnr.state.mn.us/waters/watermgmt_section/floodplain/index.html

This document (up-to-date) along with related studies and regional curves can be downloaded at this site when available:

http://www.dnr.state.mn.us/eco/streamhab/index.html

click on: Geomorphology

Other related information:

Best Practices Manual (see MESBOAC section):

http://files.dnr.state.mn.us/waters/watermgmt_section/pwpermits/gp_2004_0001_chapter2.pdf

Response to questions during various presentation events:

Will overbank culverts cause changes to the floodway delineation affecting adjacent landowners?

Our model results are based on the 10% annual chance flow and primarily addresses flows that exceed the bankfull flows where the river overtops the banks. The magnitude of these relatively more frequent flows affect channel stability since the channel is meant to overtop its banks and access its floodplain. The floodway, on the other hand is determined at much higher flows, where the river either overtops the bridge or already passes through a larger bridge opening. In any case, the proposed distributed openings should incorporate floodway runs and delineations especially if the bridge is located in a detailed study area.

Recommend performing mass balance calculations upstream and downstream of the bridge.

Mass or volume balance calculations were conducted for upstream and downstream cross-sections from the bridge using the hydrographs in both the confined and distributed conditions. As a result, 99.9% of conveyed volume was accounted for indicating that the reduction in water surface elevations using overbank culverts was not due to changes in the water budget balance.

How will you account for overbank scouring potentially caused by overbank culverts?

The table below compares the velocities for the three scenarios: natural (no bridge), confined and distributed.

Table Four: Summary of velocity values from model results

Scenario	Cross-section	Channel (ft/s)	Left Overbank (ft/s)	Right Overbank (ft/s)
Natural	US	4.06	1.47	1.52
	DS	4.37	1.38	1.46
Confined	Immediate US	9.12	No conveyance	No Conveyance
	Immediate DS	15.63	No conveyance	No conveyance
	172-ft US	4.05	1.83	1.81
	172-ft DS	11.54	3.78	3.51
Distributed	Immediate US	9.85	4.06	4.25
	Immediate DS	18.54	6.17	7.51
	172-ft US	1.75	0.68	0.69
	172-ft DS	4.17	1.43	1.44

From the table above and model results, the effect of velocities just downstream of the overbank culverts are localized and can be addressed as a specific design issue. Since the velocities recover faster through distributing the conveyance as depicted in the Table above and contribute to overall improvements of the floodplain system, the benefits of addressing the sediment problems and channel stability outweighs the problem of potential scouring just downstream of the overbank culverts.

Will overbank culverts cause impact to downstream structures due to increasing conveyance?

The embankment is not a flood control structure and therefore should not function, let alone be permitted as one. The study hydraulic model targets the 10 year storm and above bankfull conditions which occur more frequently than the 50 YR or 100YR storms. The higher storms already require the bridge to be designed to different risk standards affecting downstream structures. In our example, the 100 year storm causes the bridge to overtop. So the impact to downstream structures is not controlled by our approach. Please note that it is stream stability that is being addressed in our study and not flood risk. However, stream stability has long term benefits to safety and structural integrity of the bridge. Furthermore, any proposed bridge designs are already required to show hydraulic analysis to meet FEMA's risks and other necessary safety precautions, depending on location of bridge and zoning.

For other questions and feedback regarding this study contact:

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Future of study

1. Using modeling to quantify sediment dynamics at roads
2. Stability of river channels at roads (aggradation/degradation)
3. Assessing and reducing cumulative impacts on river systems from roads.
4. Proper sizing of floodplain culverts
5. Quantifying benefits of sinuous channels
6. Channel armoring reduction Principles… Is there a need to armor our rivers?
7. Recommend best management practices for general permits and local government ordinances.
8. Recommend best management practices for ASFPM committees.
9. Conduct sediment transport modeling using various models (i.e., BSTEM, Flowsed/Powersed, etc).
10. Create and distribute regionalized design metrics based on watershed size.
11. Include other H&H modeling in the study, especially 2-D modeling.

References:

(1) Minnesota DNR – stream Habitat Program:
http://www.dnr.state.mn.us/eco/streamhab/about.html

(2) Minnesota DNR water resources webpage:
http://www.dnr.state.mn.us/water/index.html

(3) Hydrologic Engineering Center, HEC-RAS River Analysis System, Version 4.0.0, March 2008, U.S. Army Corps of engineers, Davis California

(4) HEC-RAS River Analysis System, Chapter 16, Advanced Features for Unsteady Flow Routing, US Army Corps of Engineers, March 2008.

(5) ArcGIS Desktop 10.0 and MN DNR Quick Layers.

(6) Highway Infrastructure Damage Caused by the 1994 Upper Mississippi River Basin Flooding, NCHRP Report 417, National Cooperative Highway Research Program, 1998

(7) Help Keep Excess Sediment Out of Our Creeks, Streams and Rivers, Mid-America Regional Council.

(8) Upper Mississippi River 9-Foot project Channel Maintenance, Minnsota/Wisconsin/Iowa, Information Paper, US Army Corps of Engineers

(9) Sedimentation in the Upper Mississippi Basin, US Army Corps of Engineers, March 2006

List of Figures and Tables