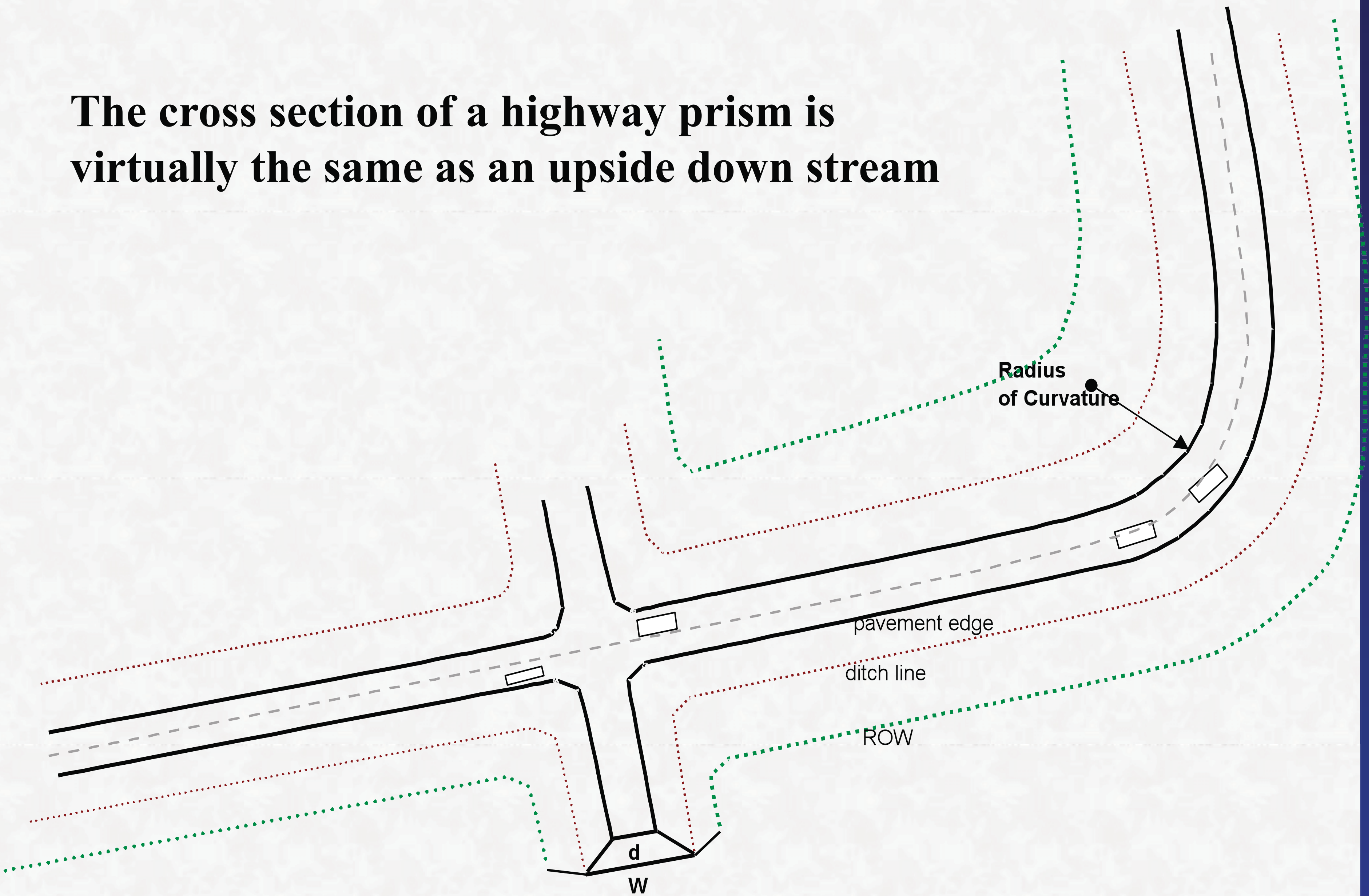
Added Introduction: Comparing highway design and stream design

Highway width is sized for the traffic, the width expanding as volume and speed increase . The ROW width is also designed to handle the speed and travel distance of vehicles careening off the pavement and allowing room for a safe stop.

Natural stream channels also have a characteristic bankfull width and a floodprone width that contains the floodplain. The floodplain allows the channel and its valley to handle the flow of water and sediment during floods where the velocity slows and sediment is then deposited on its floodplain. It's also the place fish go during floods to escape the high channel velocities.

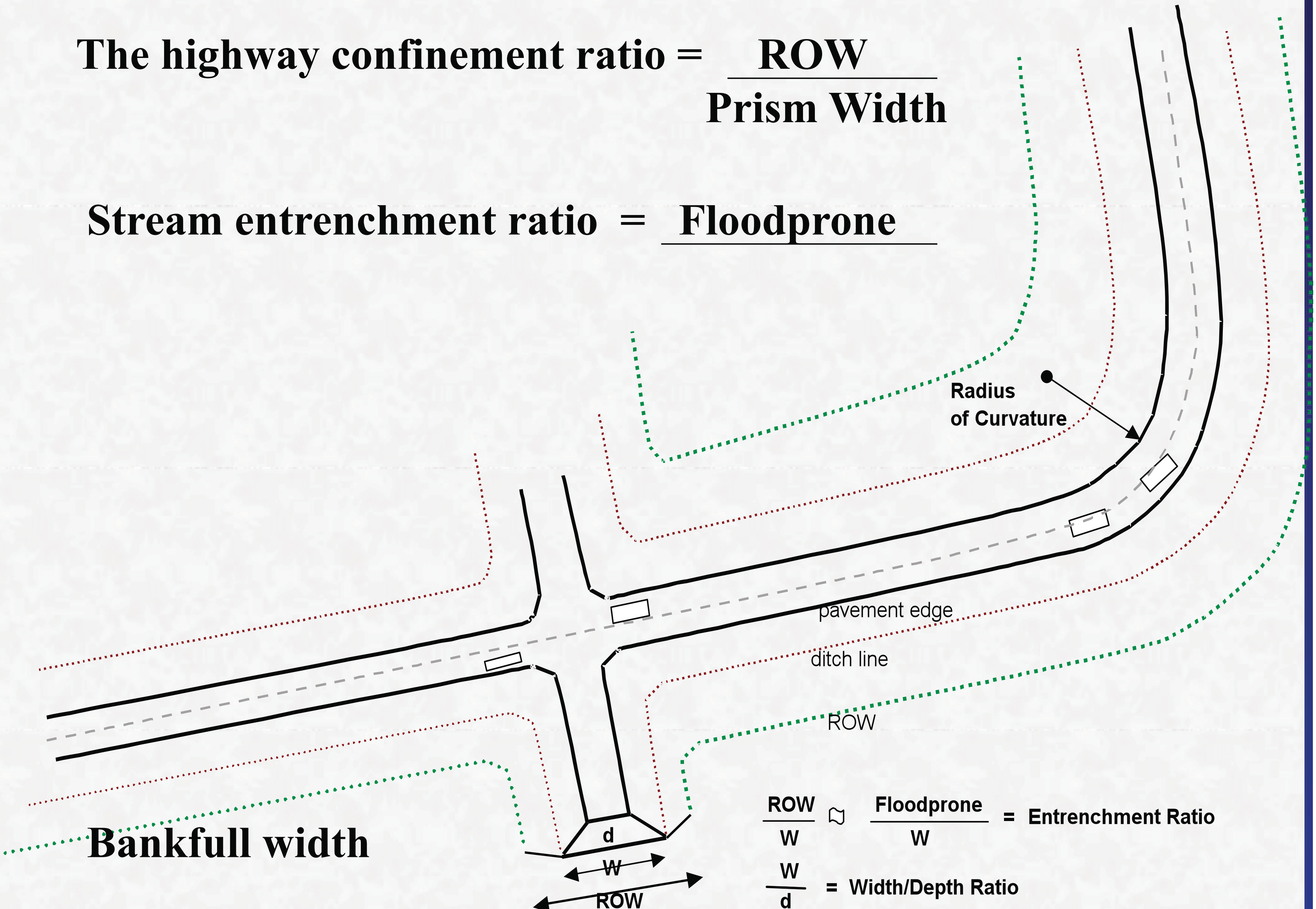
In a very real sense, both highways and streams have an entrenchment ratio (or confinement ratio) where the width containing fast flowing material is bordered by a region where flow is slowed and material is stopped.

The cross section of a highway prism is virtually the same as an upside down stream



The highway confinement ratio = $\dfrac{\text{ROW}}{\text{Prism Width}}$

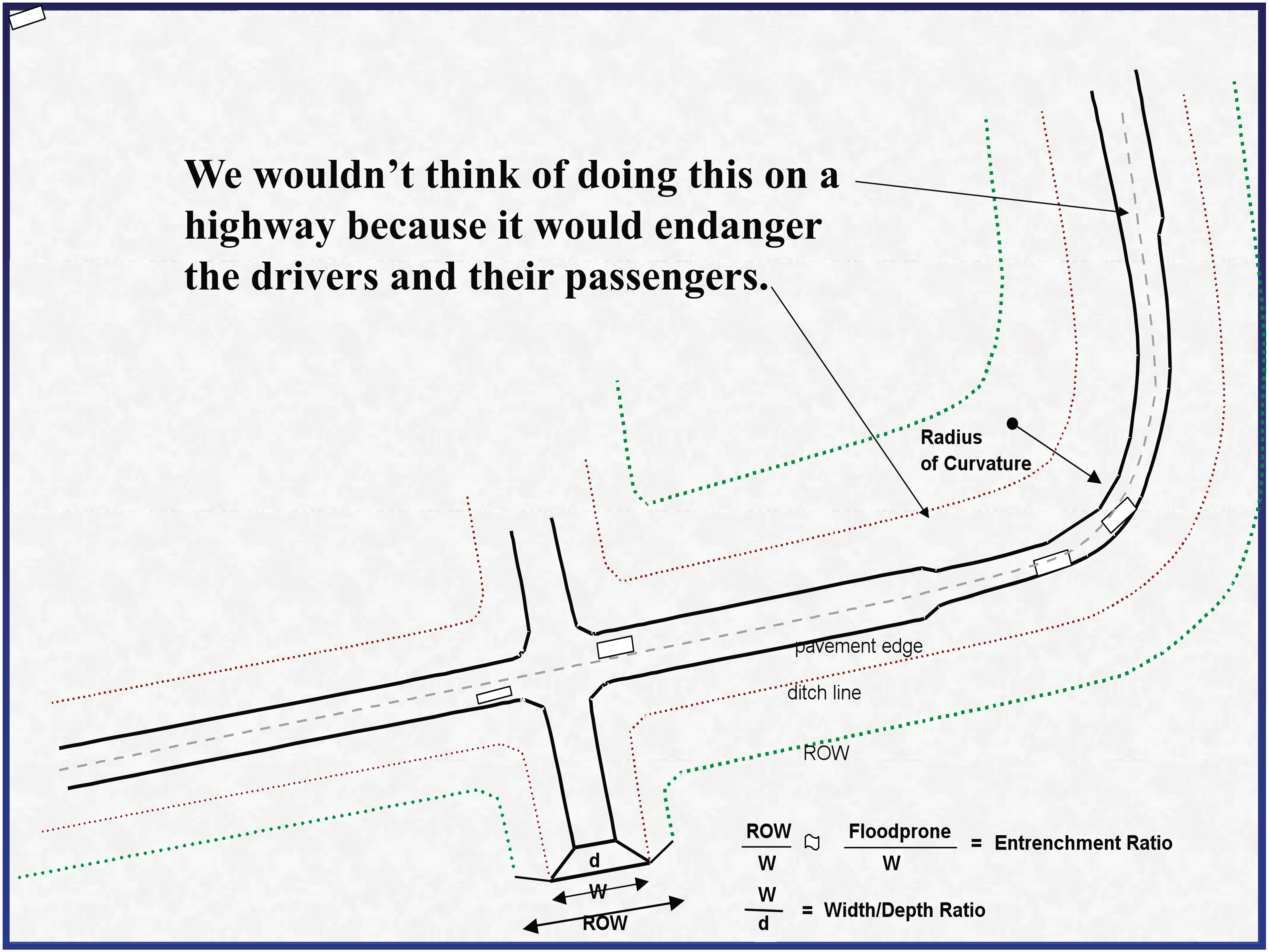
Stream entrenchment ratio = $\dfrac{\text{Floodprone}}{\quad}$

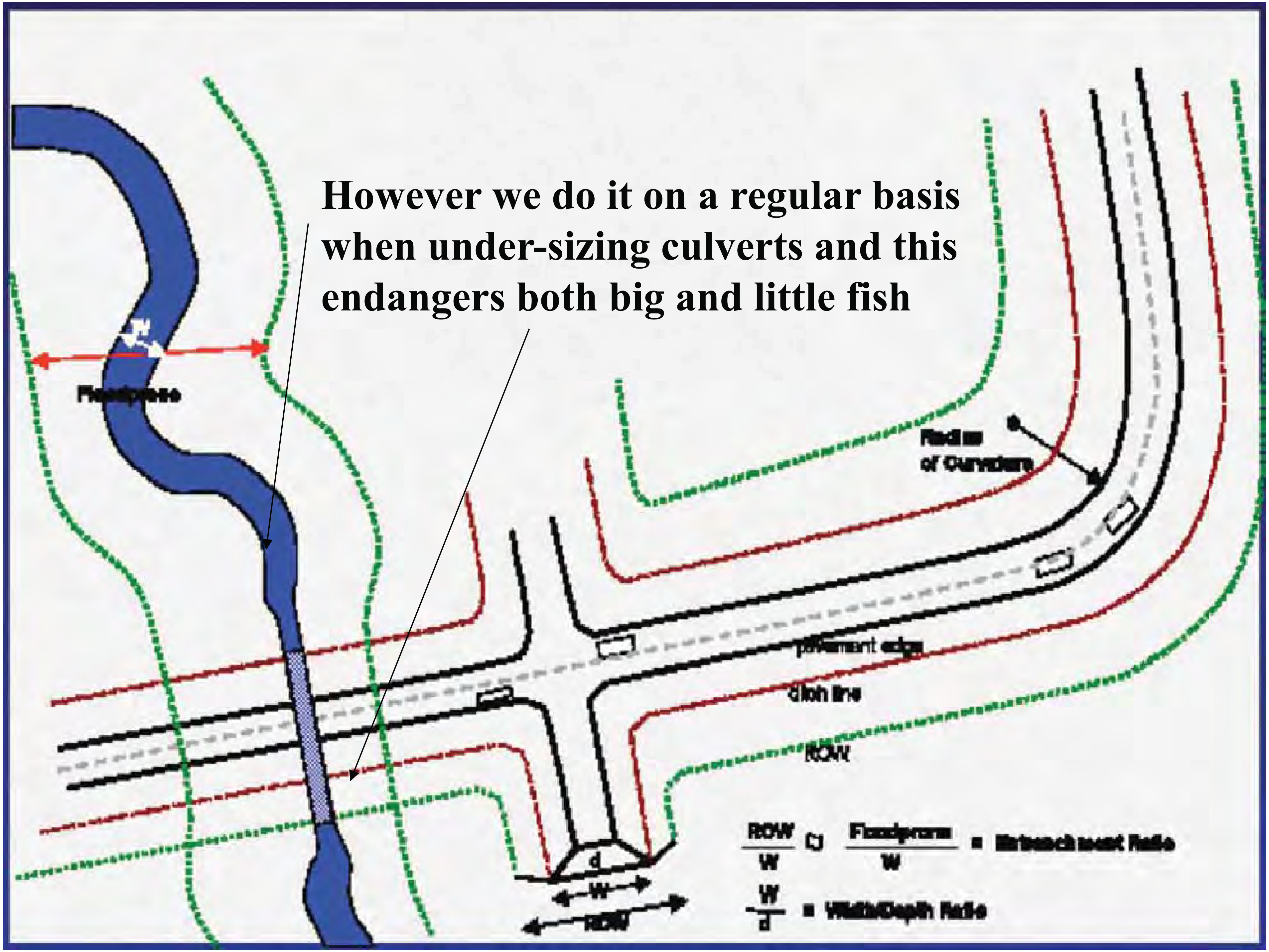


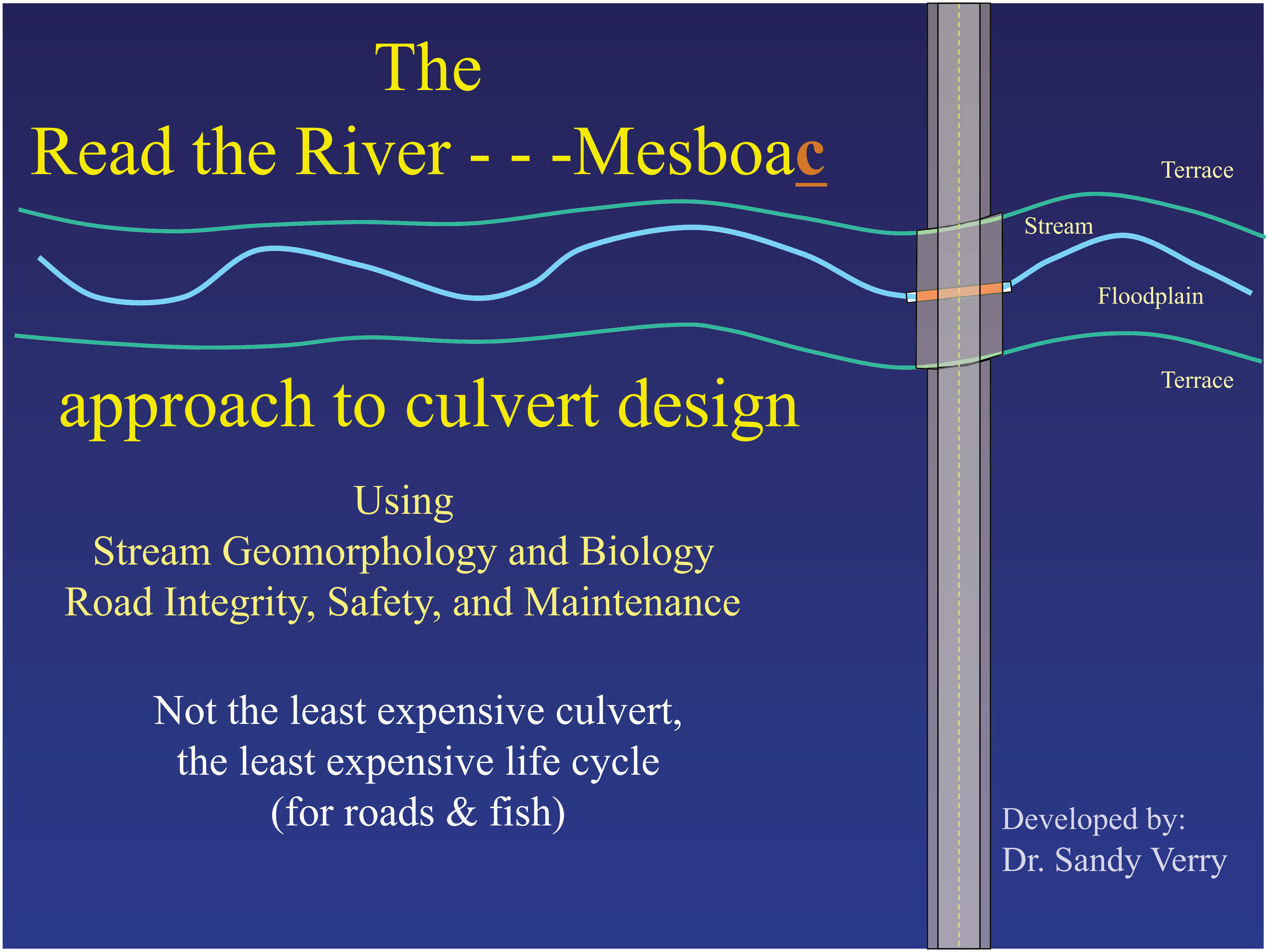
Bankfull width

$\dfrac{\text{ROW}}{\text{W}}$ ≅ $\dfrac{\text{Floodprone}}{\text{W}}$ = Entrenchment Ratio

$\dfrac{\text{W}}{\text{d}}$ = Width/Depth Ratio


We wouldn't think of doing this on a highway because it would endanger the drivers and their passengers.
Radius of Curvature
pavement edge
ditch line
ROW
d
W
ROW
ROW / W [illegible] Floodprone / W = Entrenchment Ratio
W / d = Width/Depth Ratio


However we do it on a regular basis when under-sizing culverts and this endangers both big and little fish
ROW
W
d


The
Read the River - - -Mesboac
approach to culvert design
Terrace
Stream
Floodplain
Terrace
Using
Stream Geomorphology and Biology
Road Integrity, Safety, and Maintenance
Not the least expensive culvert,
the least expensive life cycle
(for roads & fish)
Developed by:
Dr. Sandy Verry

Sizing & Placement of Stream Culverts

The Stream Will Tell You!

- **M**atch Culvert Width to Bankfull Stream Width
- **E**xtend Culvert Length through side slope toe
- **S**et Culvert Slope same as Stream Slope
- **B**ury Culvert 1/6th Bankfull Stream Width
- **O**ffset Multiple Culverts (floodplain ~ splits lower buried one)
- **A**lign Culvert with Stream (higher one ~ 1 ft. higher) (or dig with stream sinuosity)
- **C**onsider Headcuts and Cut-Offs

Dr. Sandy Verry
Chief Research Hydrologist
North Central Research Station
USDA Forest Service


An unstable stream will have poor habitat for fish and other organisms that inhabit it.
- Riffles become embedded.
- Pools fill in.
- Wider streams warm up.

Why is stream stability important?

Ecological - A stable stream will have the best habitat for the native species and therefore support the healthiest stream ecosystem.

Economical - A stable stream will have the slowest rate of change and best be able to handle its flood flows and sediment transport, thus reducing the likelihood of road or culvert failure.

So a stable Stream should be our goal!

The Read The River - - - Mesboac method can handle most culvert design needs

- But we all know each specific culvert site needs "adjustment" to achieve a long-term, functional installation

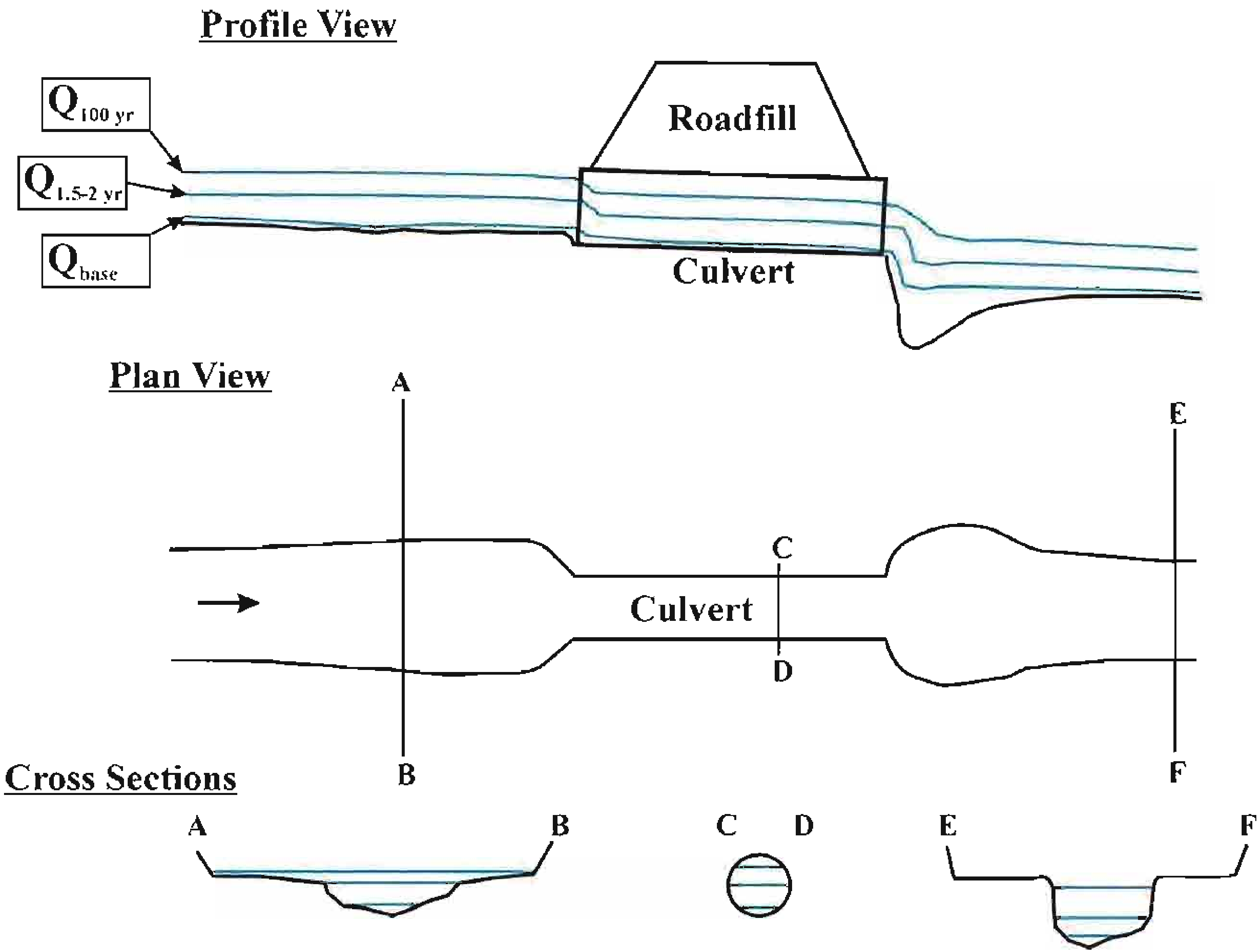
- Both the professional stream geomorphology approach using Mesboac and professional engineering hydraulic programs can ensure meeting both road and fish criteria

- Use culvert and channel flow programs as needed, e.g.
  - HEC-RAS, Culvert Master, Flow Master (www.haestad.com)
  - FishXing, WinXSPro from Stream Team (www.stream.fs.fed.us)
  - FishPass (Alaska DOTPF, C. E. Behlke, Fairbanks 907 457 5236)

Historical Perspective on Culvert Design

- Hydraulic design approach
  - Minimum size for a given design storm (initial culvert cost)
  - Overtopping (protecting the road prism)
  - Storage (using the road & flat valleys to store floodwater temporarily)
- Lack of cross-discipline communication
- Even so, centered on adult trout or salmon
- New stream geomorphology & stream biology knowledge

- Narrow culverts:
  - Enhance erosion of channel sides
  - Cause backwater conditions upstream increasing inlet head and thus exit velocities
  - Scour the outlet pool
  - Saturate the road fill leading to excessive flex during spring snowmelt or snow on rain events
  - Can lead to culvert piping along the outside of the culvert and then road failure
  - Can lead to unnecessary overtopping and road failure
  - Road failure at one site can trigger a domino effect on downstream crossings
- Wide culverts lessen debris or bedload blockage
- Wide culverts minimize channel aggradation upstream



Profile View
$Q_{100 yr}$
$Q_{1.5-2 yr}$
Q_{base}
Roadfill
Culvert
Plan View
A
B
C
D
E
F
Culvert
Cross Sections
A
B
C
D
E
F

Fundamental Stream and Culvert Interactions

- Fish and other aquatic organisms live and travel primarily along the channel margins. This is the environment under which they evolved and developed their swimming capabilities: 0 - 3 feet/sec

- When culverts less than the bankfull width restrict flow at a road prism, exit velocities from the culvert easily reach 5 feet/sec

- I have measured some up to $11^{1/2}$ feet/sec

Mesboac

Match the Width

- Stream shape (size) derives from natural watershed process that physically shape the channel to a characteristic width and depth
- The channel, so shaped, will carry the water, sediment, and debris of the watershed under similar conditions of climate and land use and remain stable in its sinuosity, w/d ratio, cross section area, and pool/riffle structure

Stream width is determined by:

- The Bankfull Discharge (flow)

- Texture of the material in the stream bottom and the stream banks

  - Clays and peats tend to have narrow width/depth ratios (< 12,)
  - Sands and gravels tend to have wider width/depth ratios (>12)

- Regardless of the w/d ratio match culvert width to bankfull stream width

Fundamental Stream Channel Interactions

- The highest stream velocities occur in the channel away from the sides and bottom
- The irregular sides and bottom with rocks, woody debris, vegetation, etc. have lower velocities of 0 - 3 feet/sec
- Average stream velocities at the bankfull stage are 3 – 6 feet/sec
  - Generally 3 ft/sec when channel slopes are less than 1%.
  - The average velocity goes up as channel slope increases above 1%

Max.Channel Depth Indices of Flow
for the Eastern United States

Recurr. Interval	$d/dmax_{bkf}$	Q/Q_{bkf}
50	2	4
25	1 3/4	3
10	1 1/2	2
Bankfull (1.5)	1	1
Ave. Flow	1/4	0.2

Est. from Leopold, Luna B. 1994. A view of the river. Harvard Univ. Press. Cambridge, Ma 298p.

Bankfull Flow

The calculation from data at a USGS gaging station

- Based on a frequency analysis of annual peaks
- The depositional flat (flooplain) upstream from the gage will correspond to the 1.2 to 1.8-year recurrence interval
- On average it is the 1.5-year event
- Both spring and fall spawning fish are responding to the near bankfull discharge rate - - - They have 4 to 7 days to spawn before absorbing their eggs
- Over the long span of years, the bankfull flow is the most prevalent flow that is fast enough to entrain the channel bottom and transport the bedload as well as the suspended sediment load
- Bankfull flow shapes the channel!

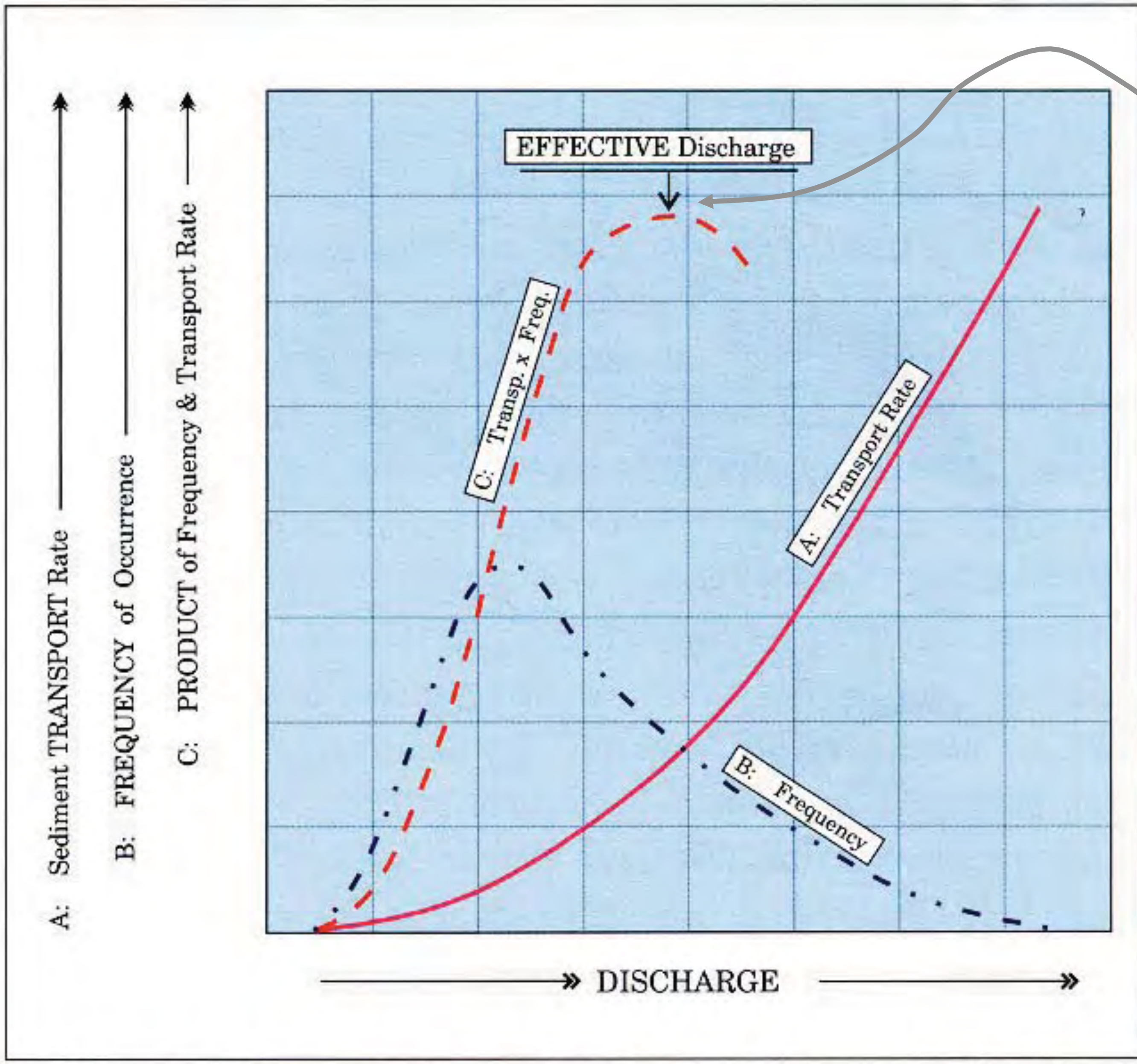


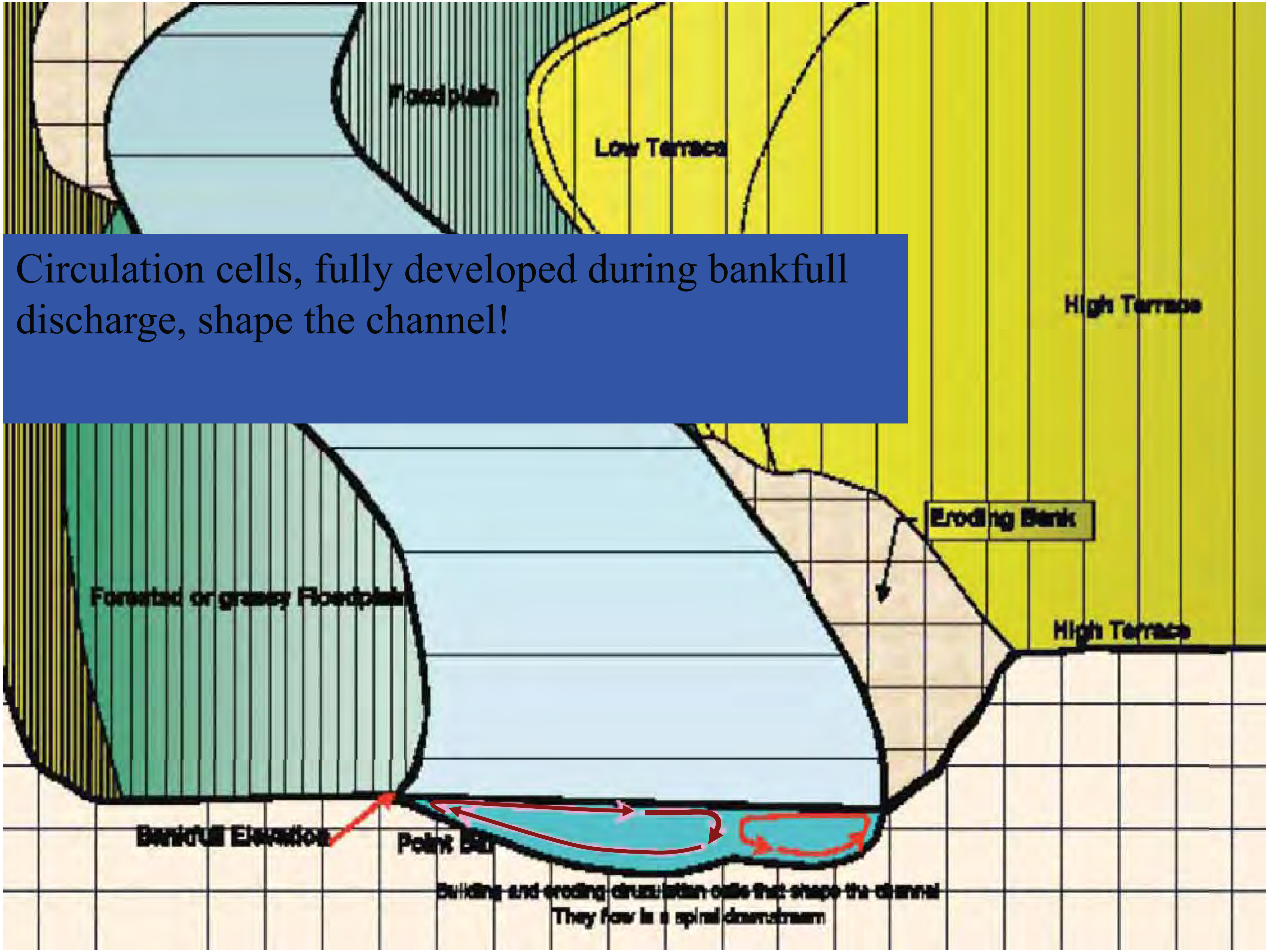
FIGURE 2-2. Relations between DISCHARGE, Sediment TRANSPORT Rate, FREQUENCY of Occurrence, and the PRODUCT of Frequency and Transport Rate. *(After Wolman and Miller, 1960)*

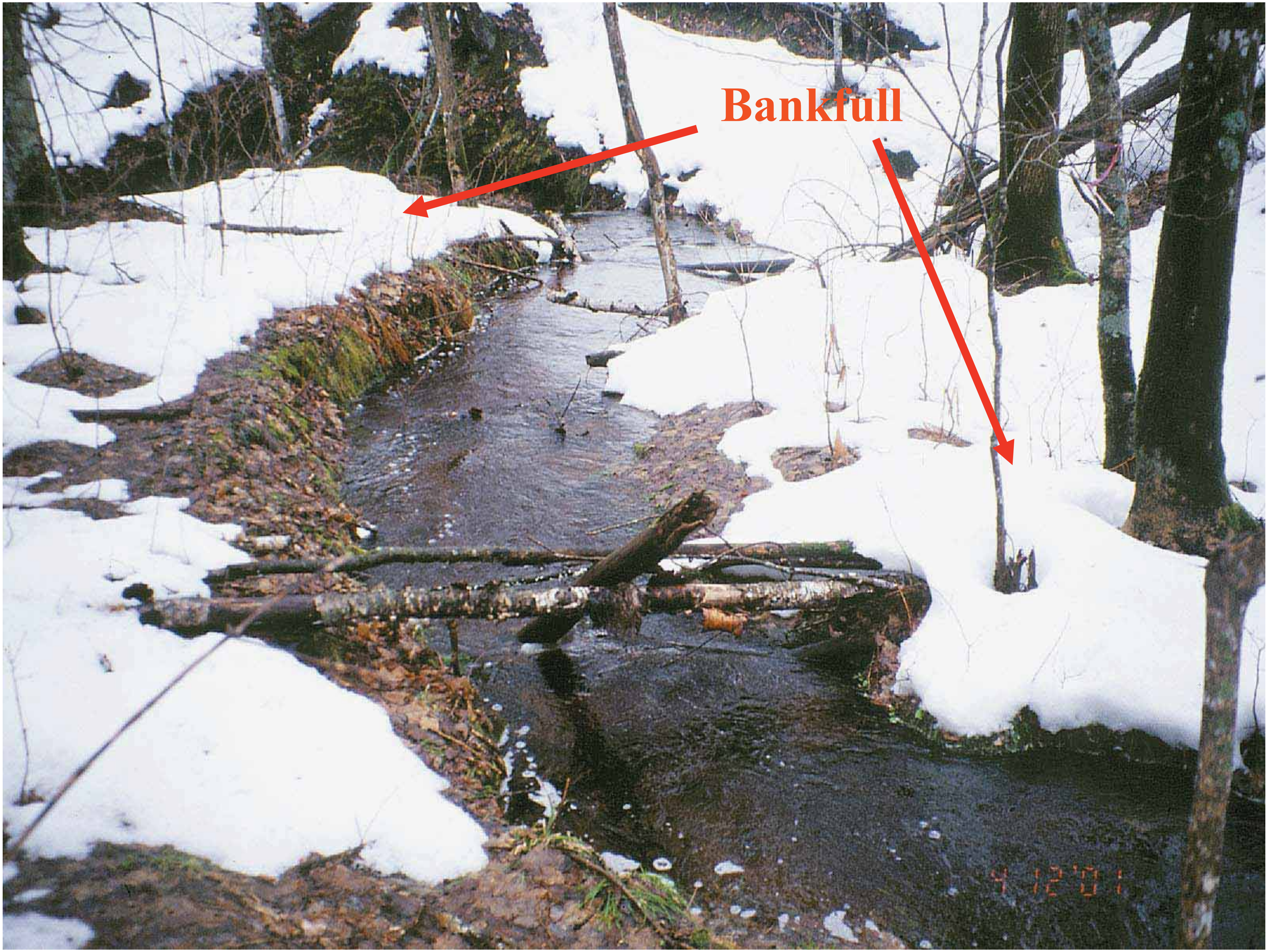
The most effective sediment discharge, over time, occurs, at the bankfull flow rate or approx. the 1.5-year recurrence interval

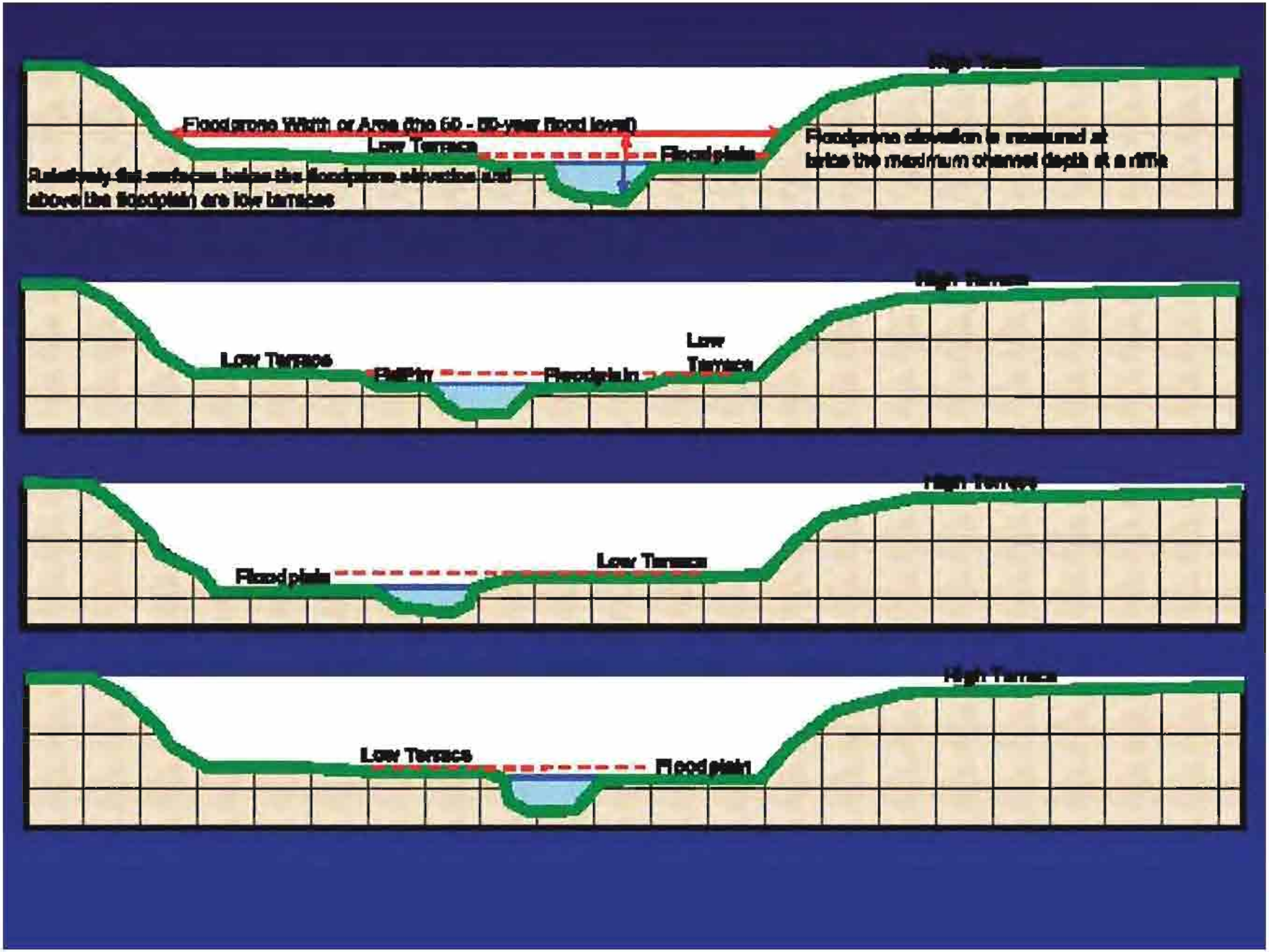
At the bankfull flow, the stream bottom picks up and moves, then redistributes its self in the same pool & riffle patterns existing prior to the bankfull discharge.

Very large cobble & boulders excepted

Circulation cells, fully developed during bankfull discharge, shape the channel!

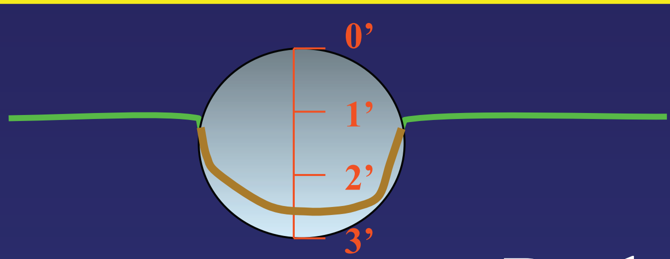



Bankfull
4 12'01

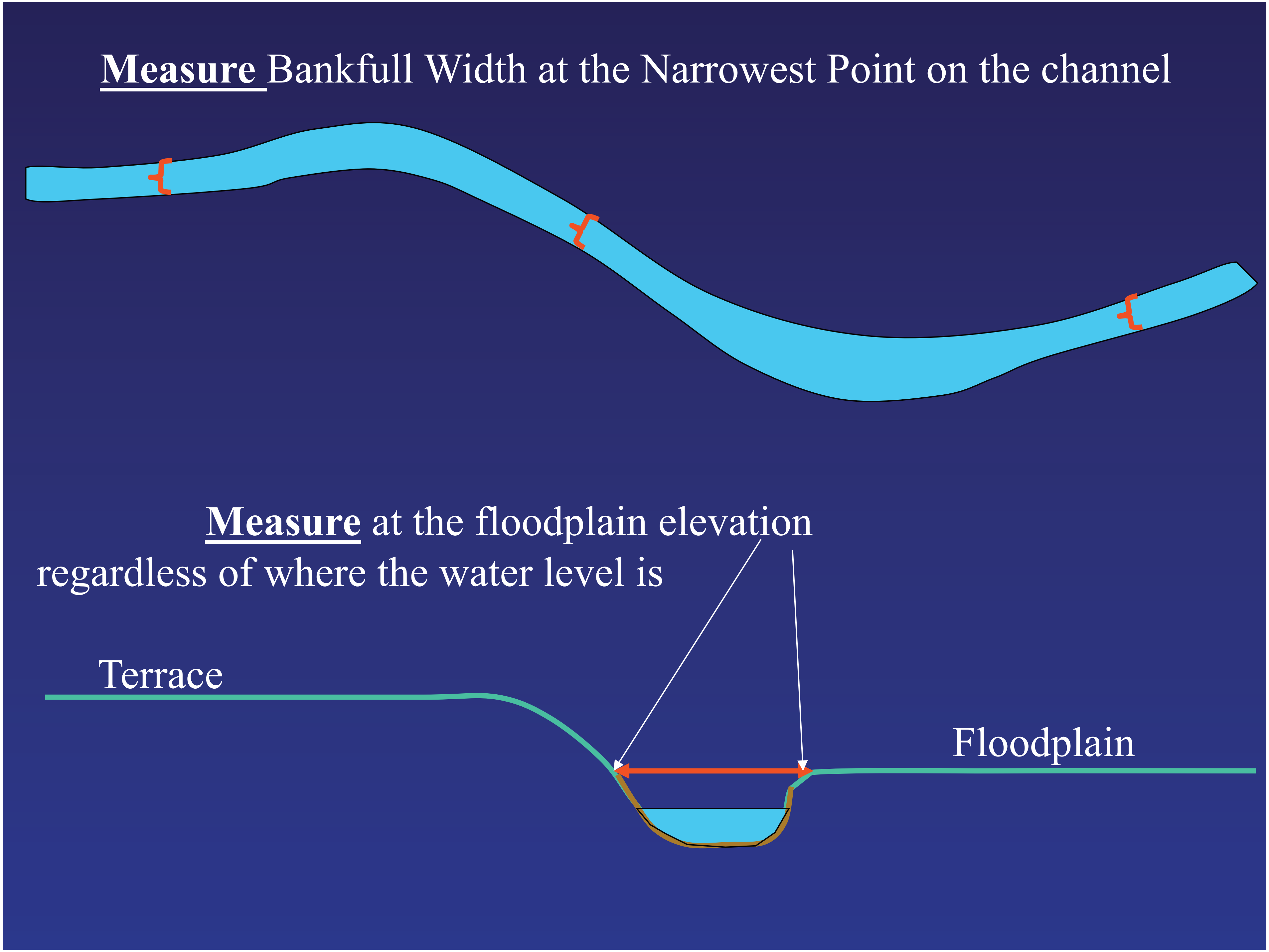

High Terrace
Floodprone Width or Area
Low Terrace
Floodplain
Floodprone elevation is measured at twice the maximum channel depth at a riffle
Relatively flat surfaces below the floodprone elevation and above the floodplain are low terraces
High Terrace
Low Terrace
Floodplain
Low Terrace
High Terrace
Low Terrace
Floodplain
High Terrace
Low Terrace
Floodplain

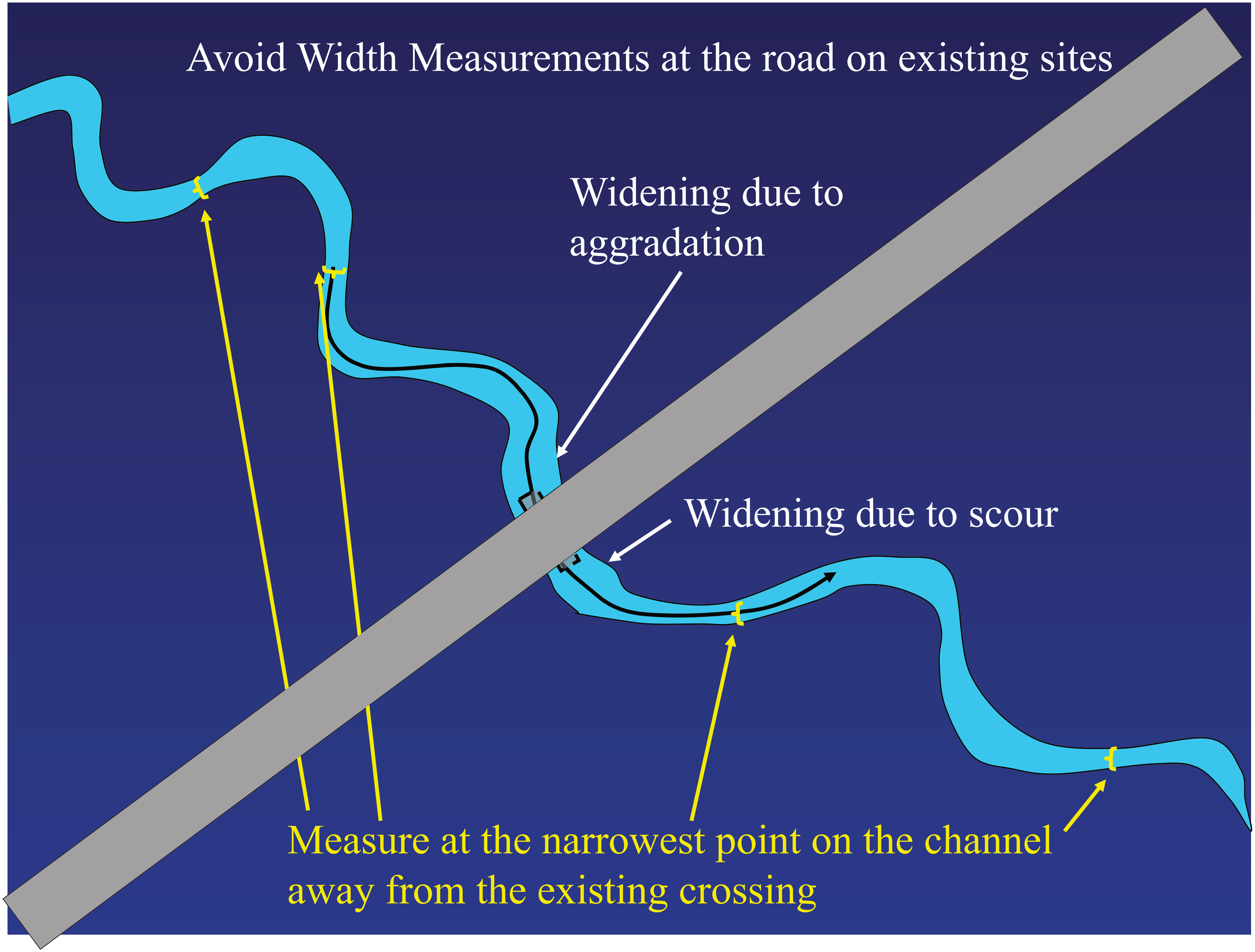
Mesboac Culvert Design –

- Match



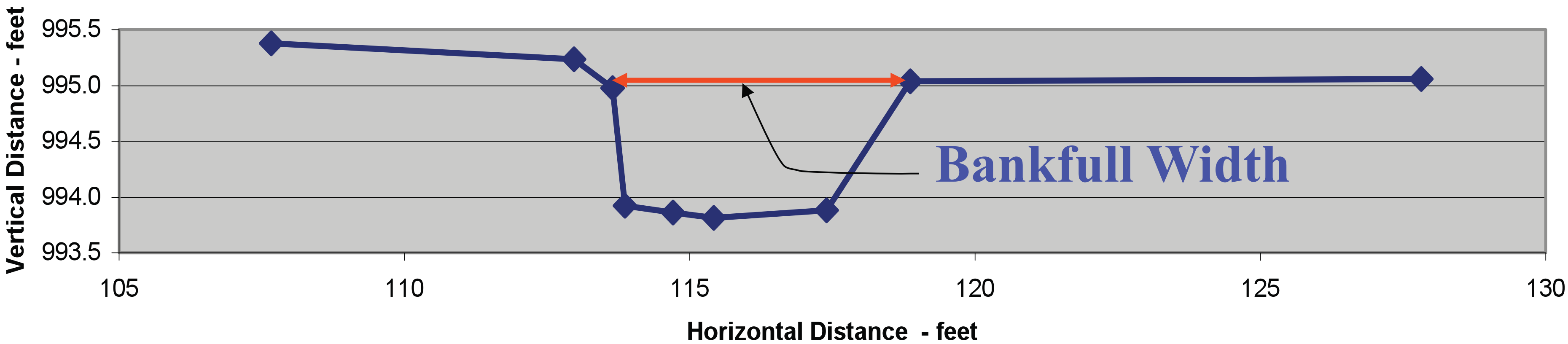
Bankfull width


Measure Bankfull Width at the Narrowest Point on the channel
Measure at the floodplain elevation
regardless of where the water level is
Terrace
Floodplain



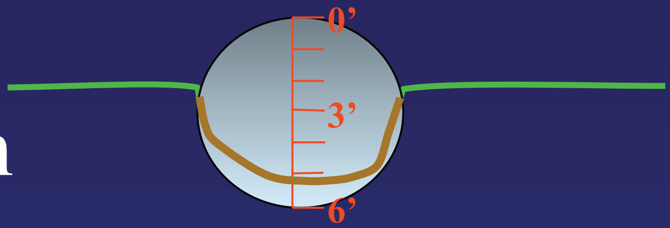
Avoid Width Measurements at the road on existing sites
Widening due to aggradation
Widening due to scour
Measure at the narrowest point on the channel away from the existing crossing

Pokegama Creek Plot 7 Transect 3

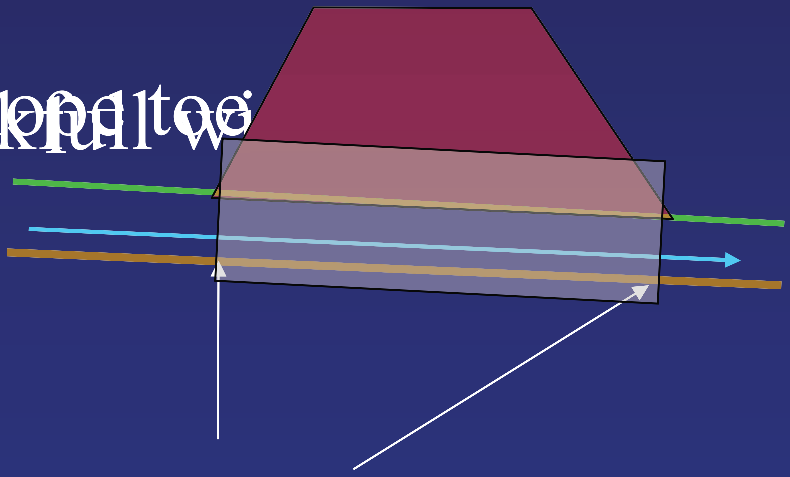


Mesboac Culvert Design –

- Match

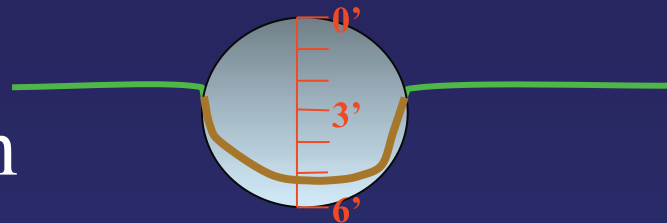


- Extend Culvert to side slope toe



Mesboac Culvert Design –

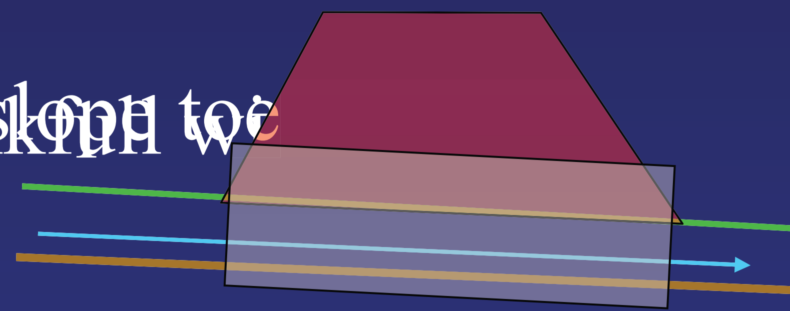
- Match



- Extend Culvert to side slope toe

Bankfull w

- Set on Channel Slope



Set & Bury

Failure to set culverts on the same slope as the stream (and bury them 1/6th width$_{BKF}$) **is the single reason that many culverts do not allow for fish passage!**

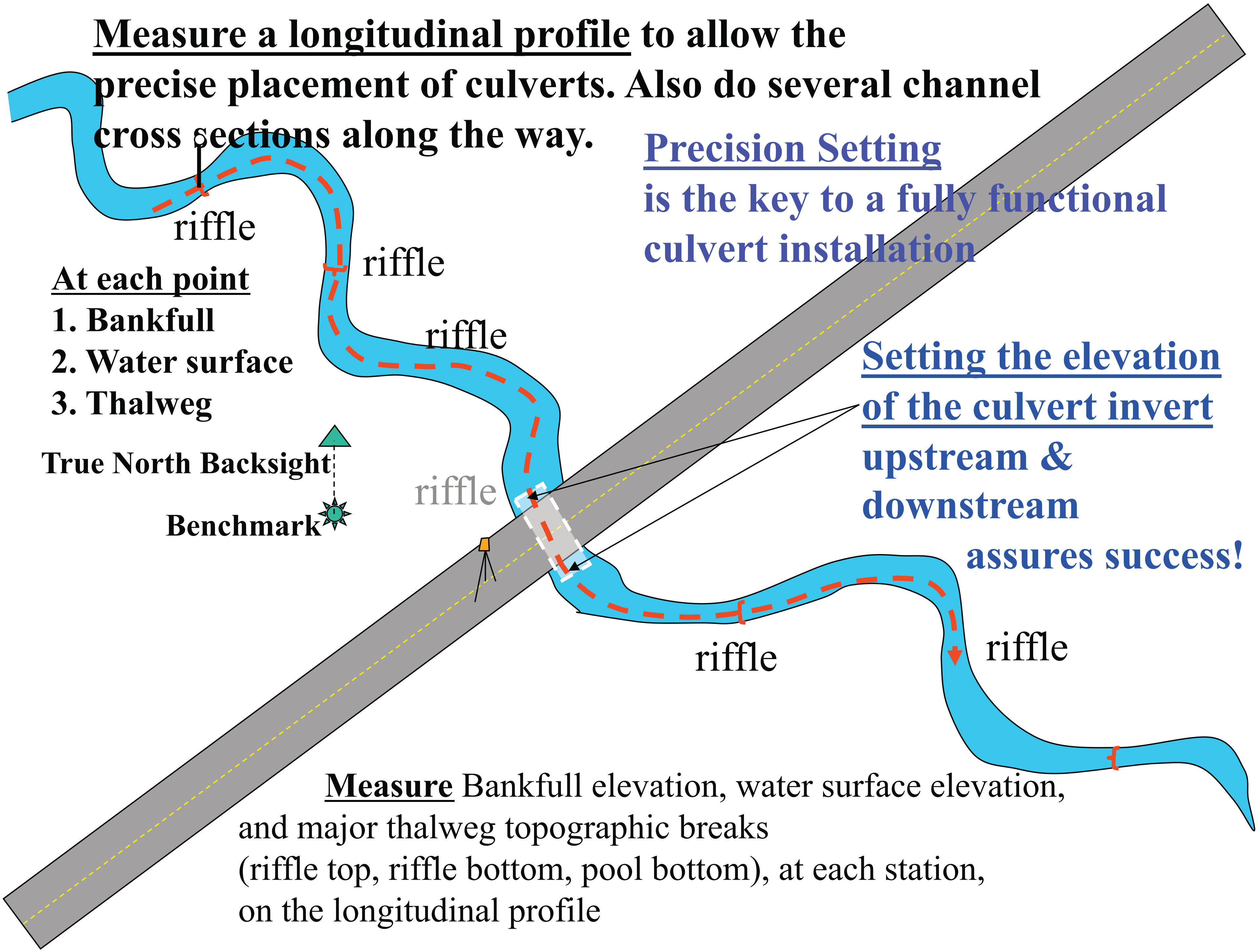
Slope can be measured as:

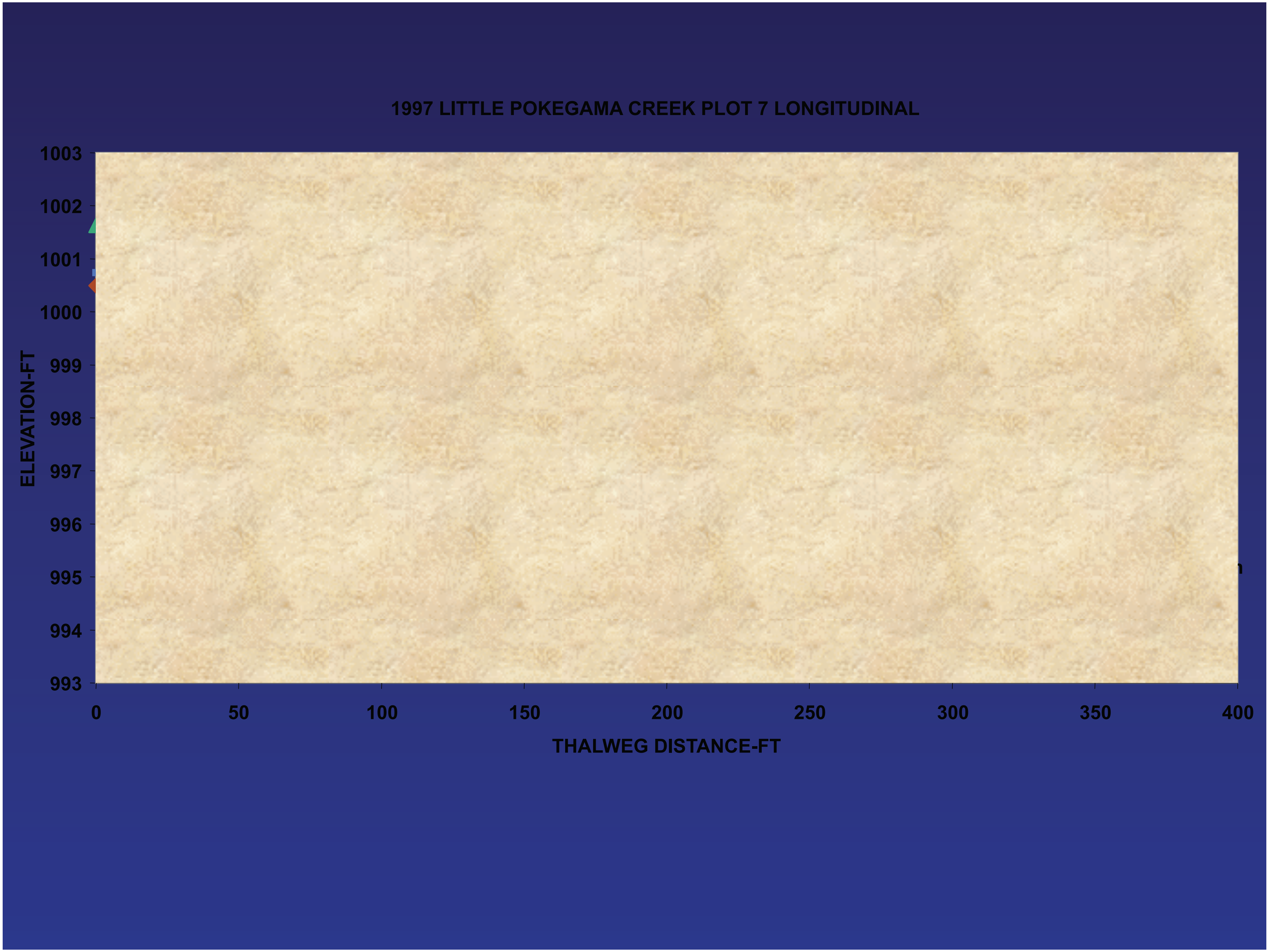
Slope along the bank (wider variation, than thalweg)

Slope of the water surface (big errors at low flow or in flooded channels, good at moderate to bankfull flows)

Slope of the thalweg (this, by far, is the best one)

Try as she might, this fish did not make it into the culvert to get where she wanted to go. Neither do most of her peers.

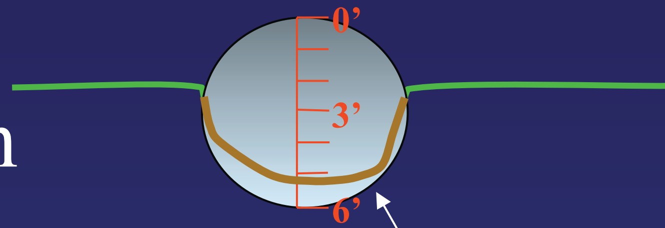

Measure a longitudinal profile to allow the precise placement of culverts. Also do several channel cross sections along the way.
Precision Setting
is the key to a fully functional culvert installation
riffle
riffle
riffle
riffle
riffle
riffle
At each point
1. Bankfull
2. Water surface
3. Thalweg
True North Backsight
Benchmark
Setting the elevation of the culvert invert
upstream & downstream
assures success!
Measure Bankfull elevation, water surface elevation, and major thalweg topographic breaks (riffle top, riffle bottom, pool bottom), at each station, on the longitudinal profile

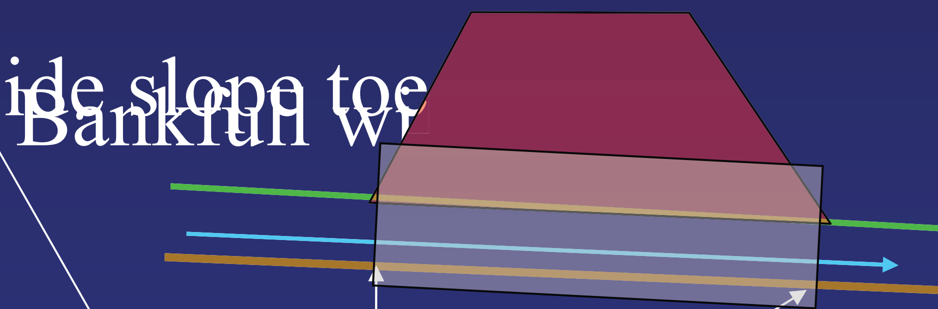


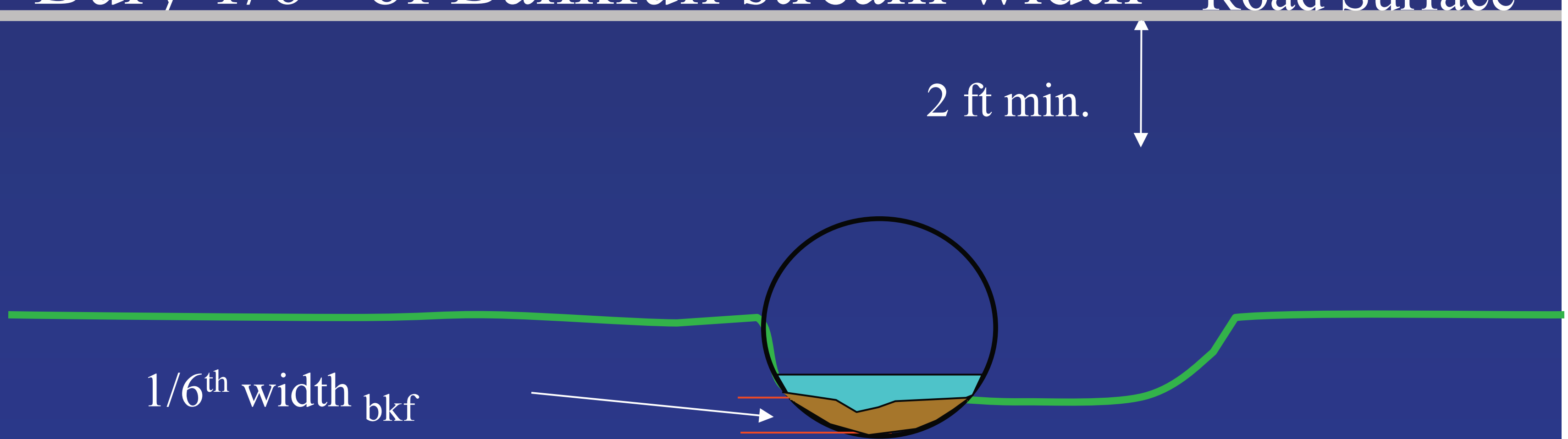
1997 LITTLE POKEGAMA CREEK PLOT 7 LONGITUDINAL
ELEVATION-FT
1003
1002
1001
1000
999
998
997
996
995
994
993
0
50
100
150
200
250
300
350
400
THALWEG DISTANCE-FT

Mesboac Culvert Design –

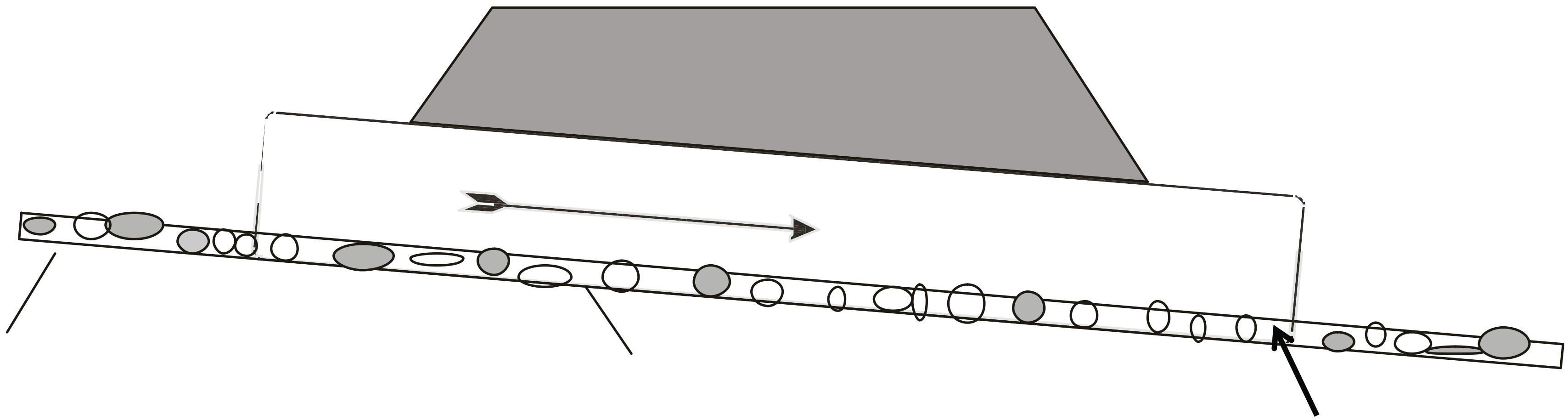
- Match
- Extend Culvert to side slope toe
- Set on Channel Slope
- Bury $1/6^{th}$ of Bankfull stream width







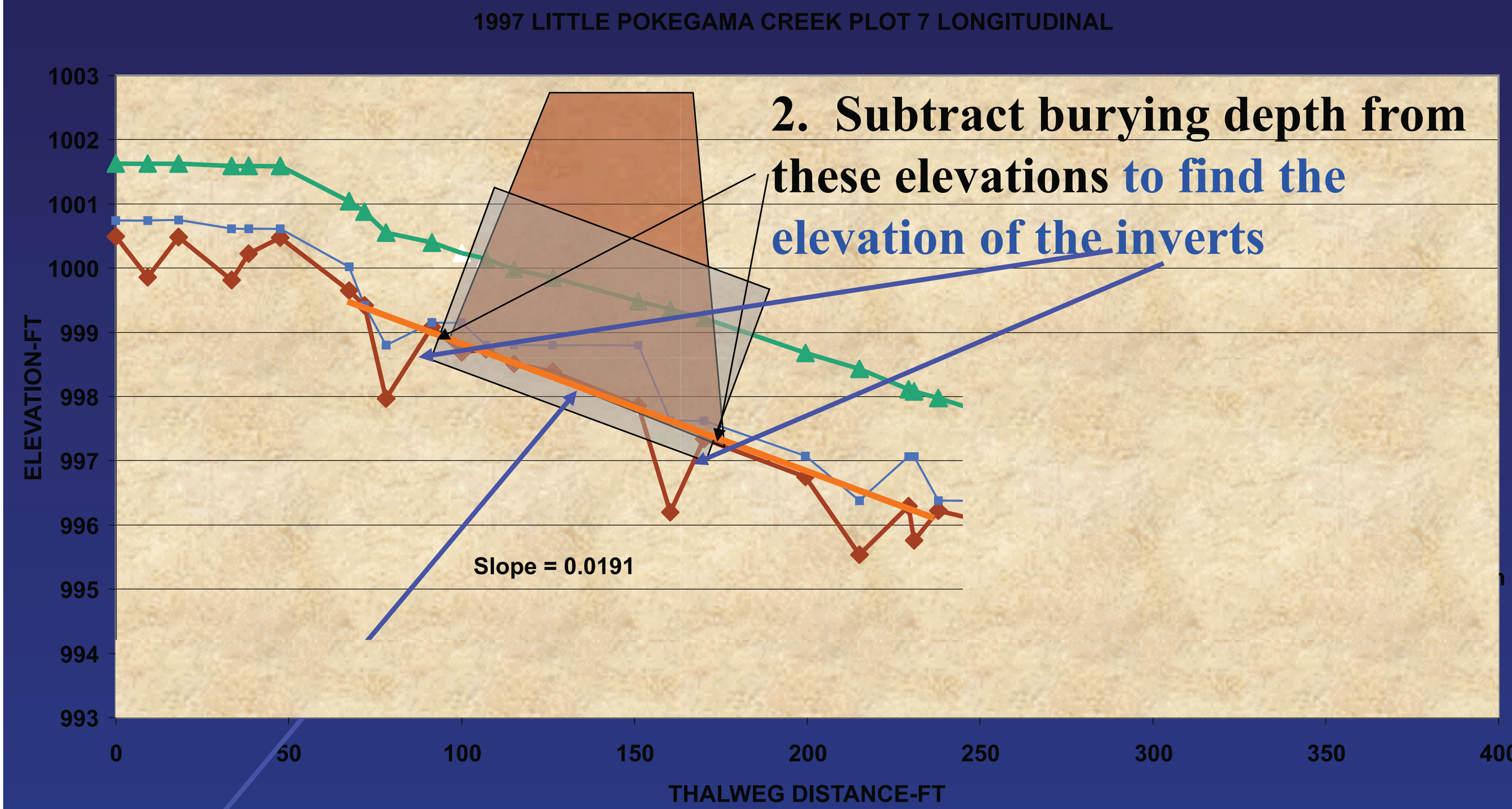
Mesboac Bury the Culvert



Bed inside culvert is about 1/6th the bankfull stream width

This is based on the scour depth of streams,
so it doesn't need to exceed 2 feet max

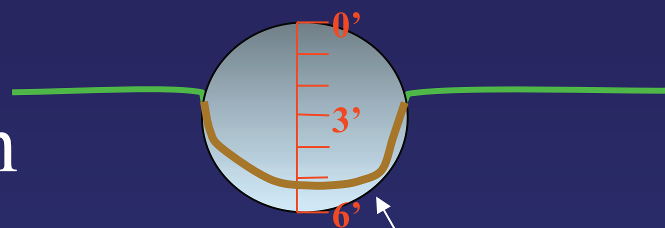
Let the bankfull discharge that lifts the stream bottom carry
both the water and the sediment through the culvert,
mimicking the hydraulics of the channel



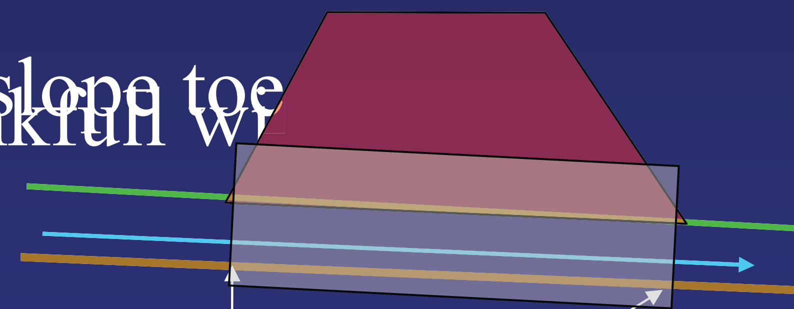
1. A line connecting the thalweg riffle points from above and below the crossing site is the most accurate estimate of stream bottom

Mesboac Culvert Design –

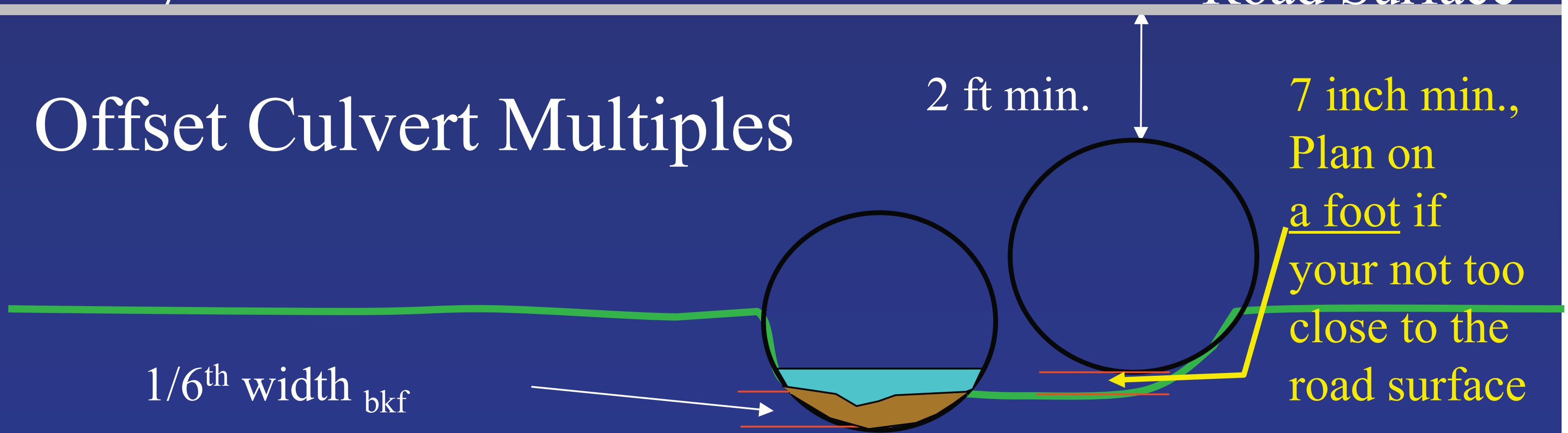
- Match



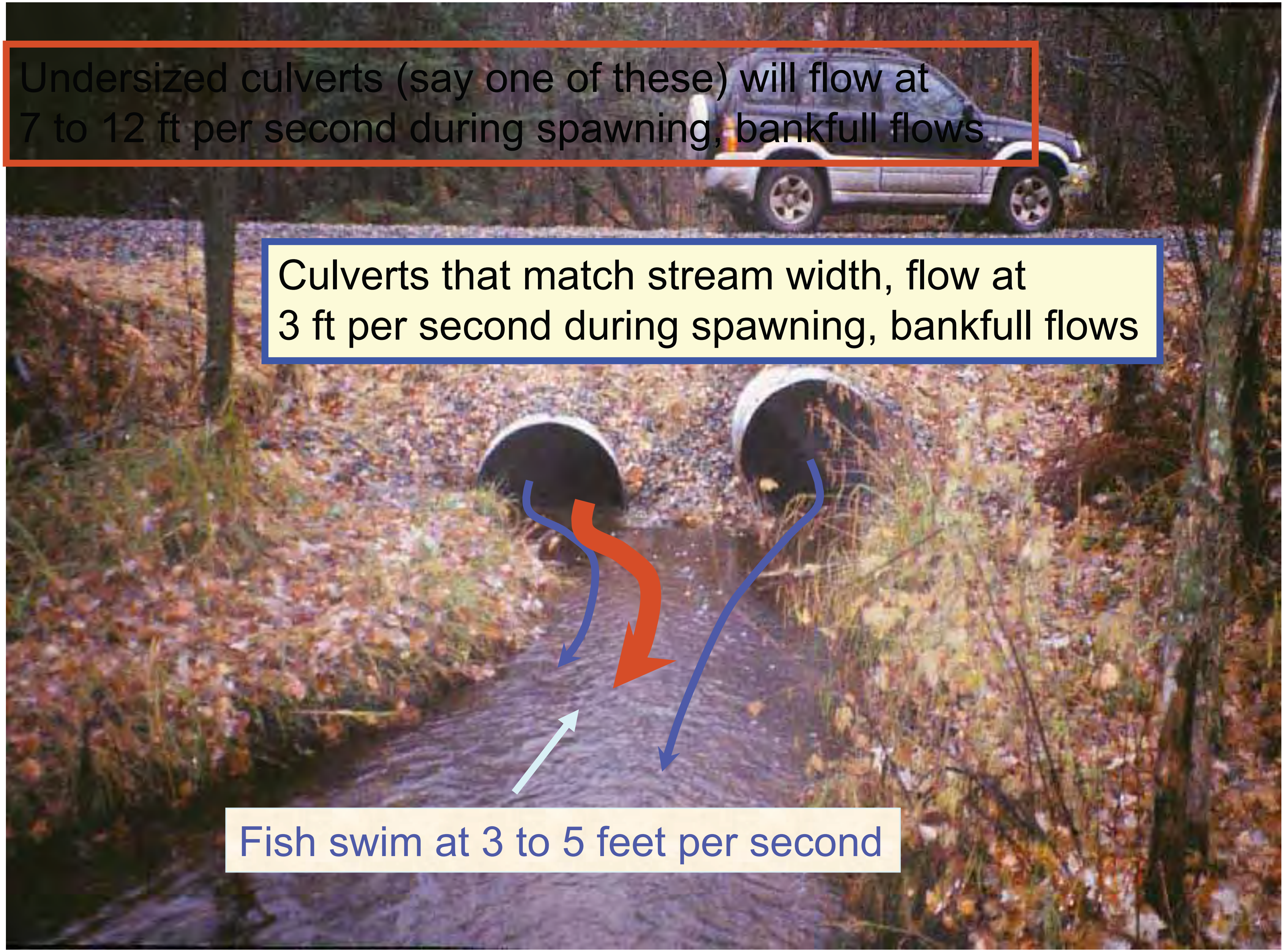
- Extend Culvert to side slope toe



- Set on Channel Slope
- Bury 1/6th of Bankfull stream width
- Offset Culvert Multiples



When using multiples, use the fewest and largest multiples possible

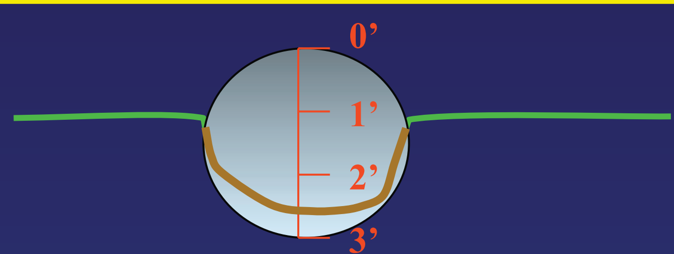

Undersized culverts (say one of these) will flow at
7 to 12 ft per second during spawning, bankfull flows.
Culverts that match stream width, flow at
3 ft per second during spawning, bankfull flows
Fish swim at 3 to 5 feet per second


Culvert width is only 1/3rd of Channel Width

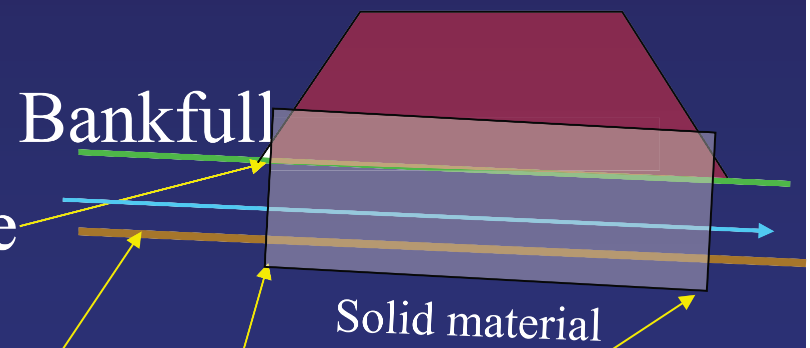

Combined Culvert Width Matches
Channel Width

Mesboac Culvert Design –

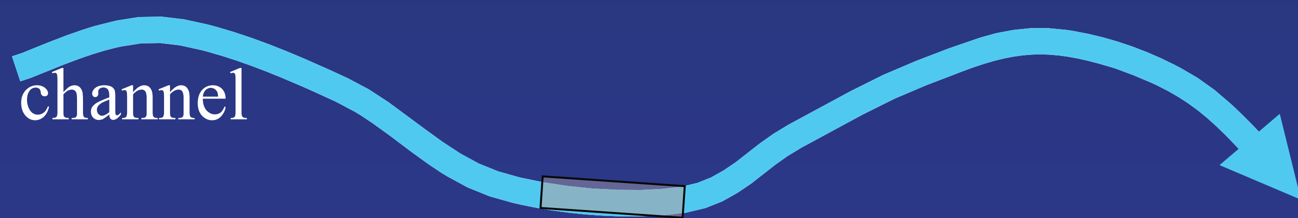
- Match



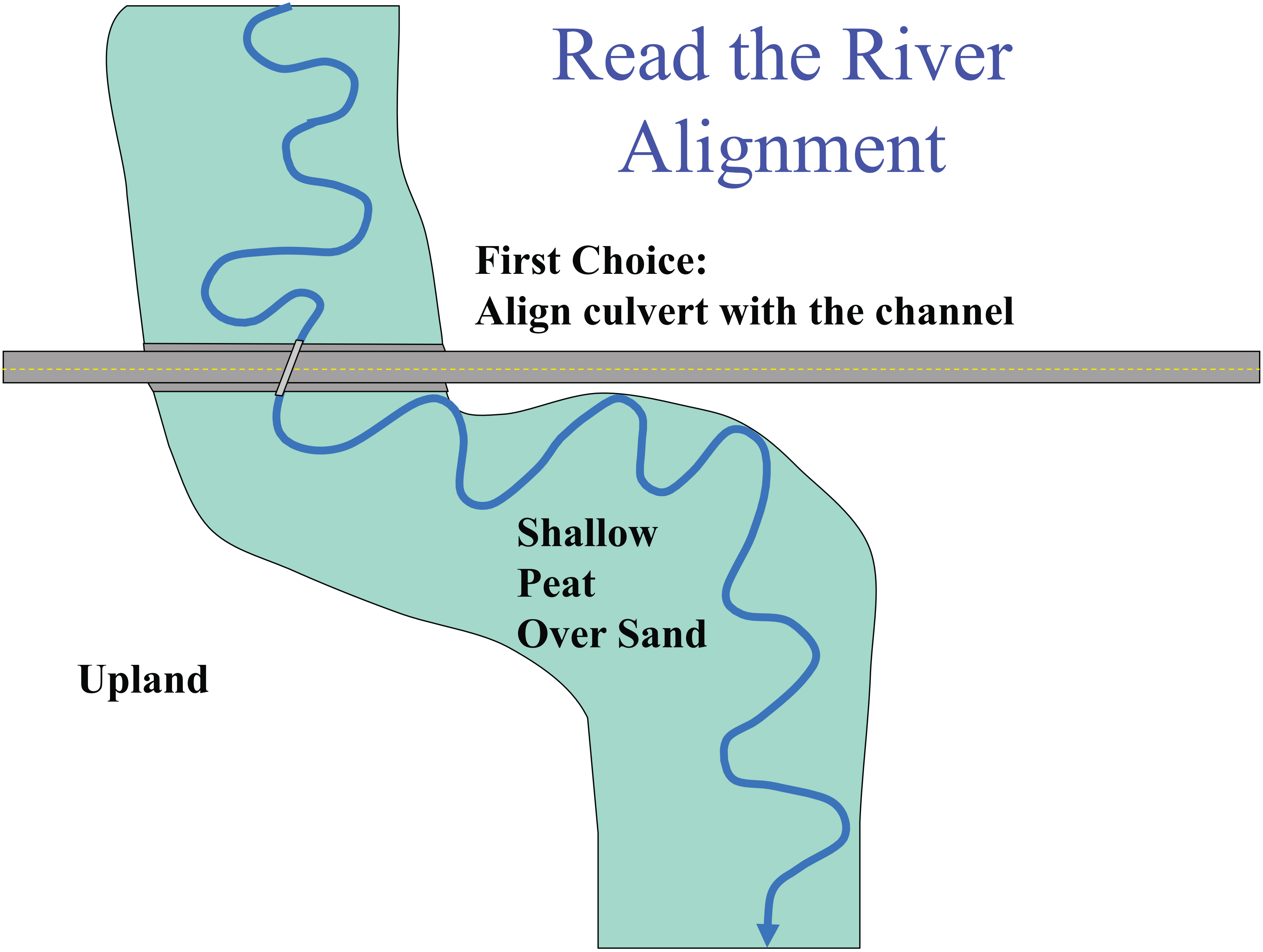
- Extend Culvert
  through the side slope toe



- Set Culvert same as Channel Slope
- Bury 1/6th of Bankfull stream width
- Align with channel

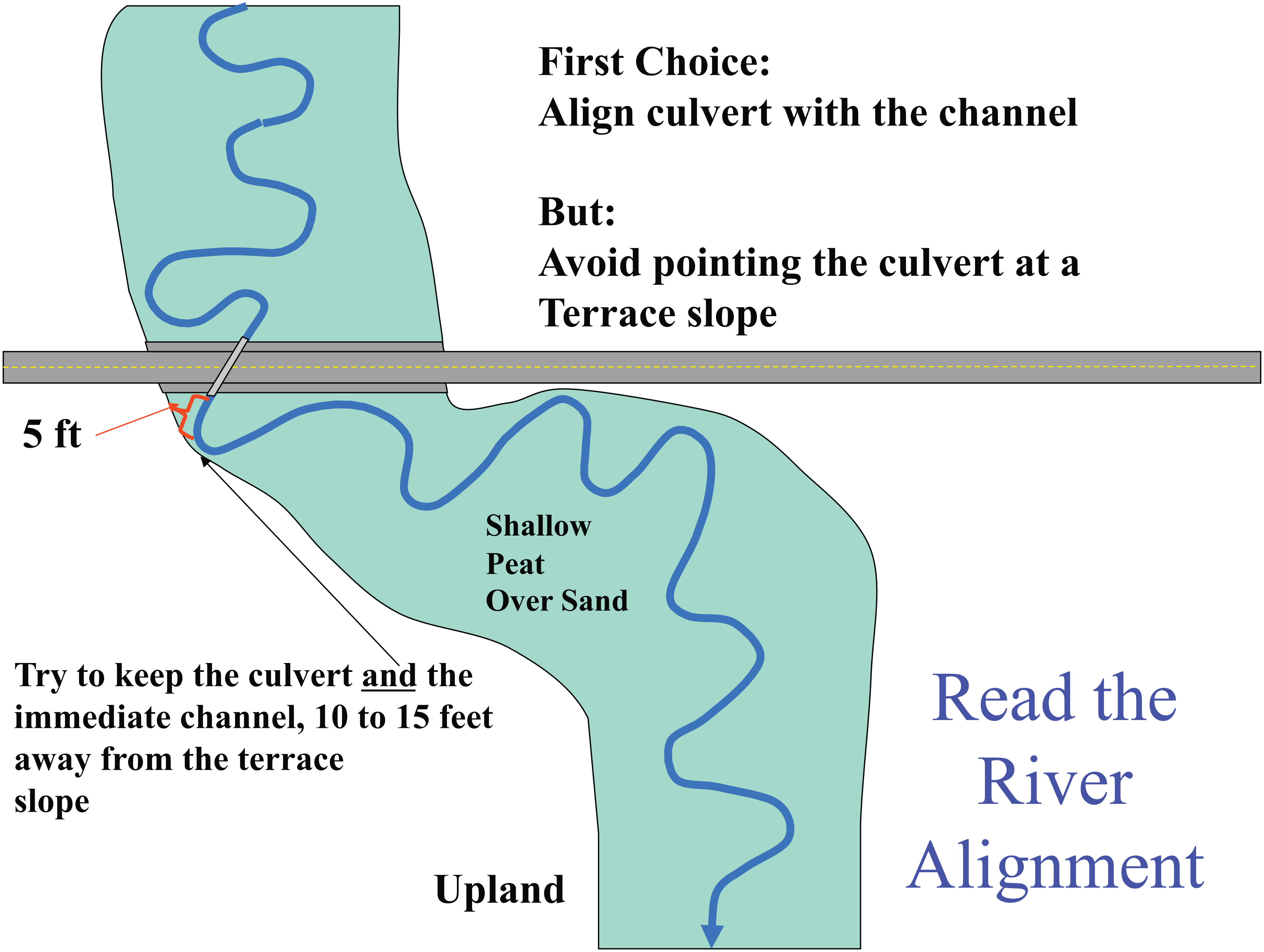


Read the River Alignment



First Choice:
Align culvert with the channel

But:
Avoid pointing the culvert at a Terrace slope

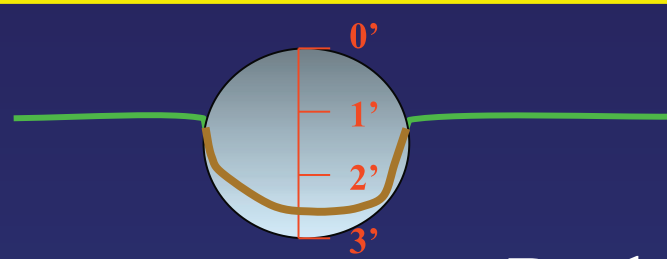


Try to keep the culvert <u>and</u> the immediate channel, 10 to 15 feet away from the terrace slope

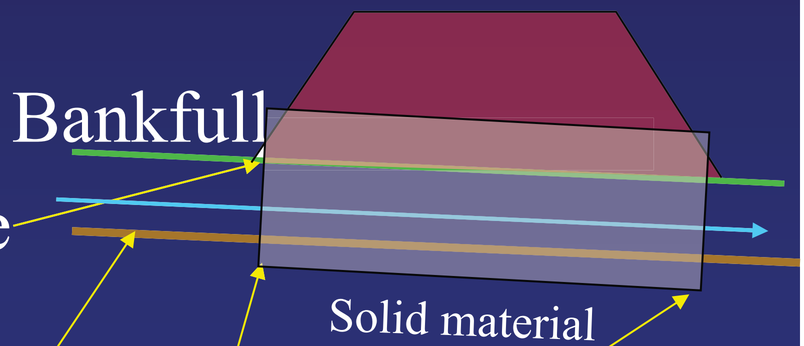
Read the River Alignment

Mesboac Culvert Design –

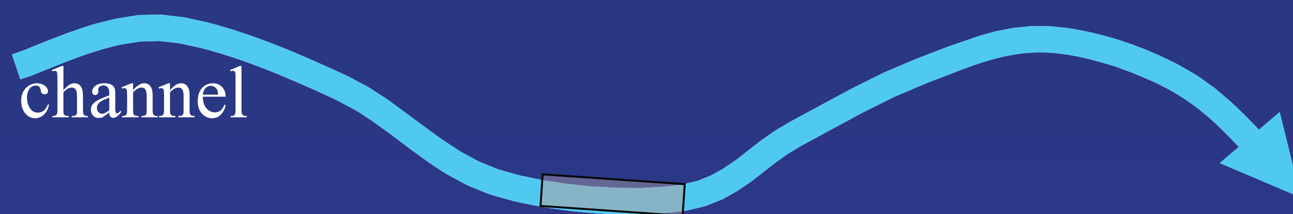
- Match



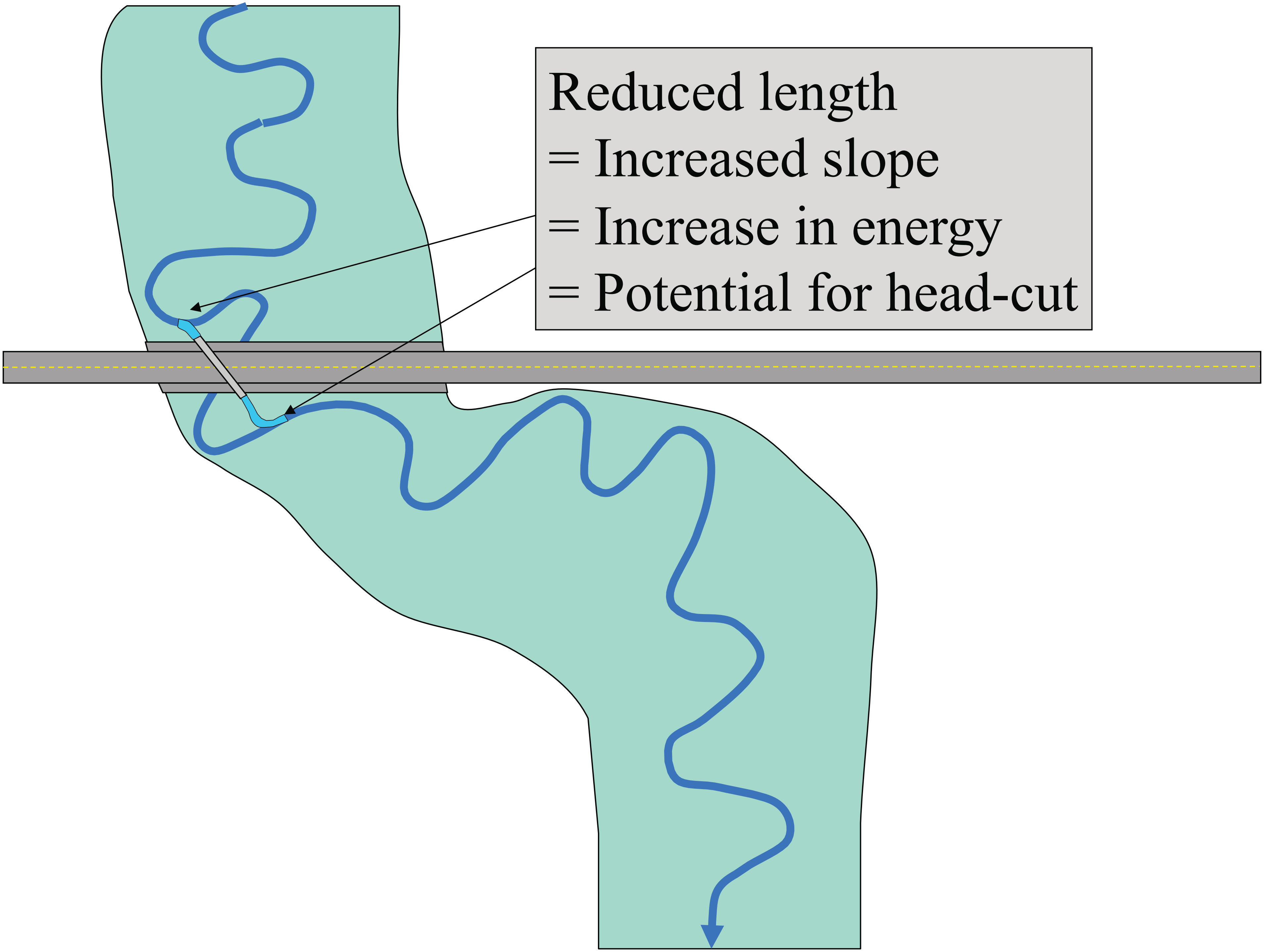
- Extend Culvert
  through the side slope toe

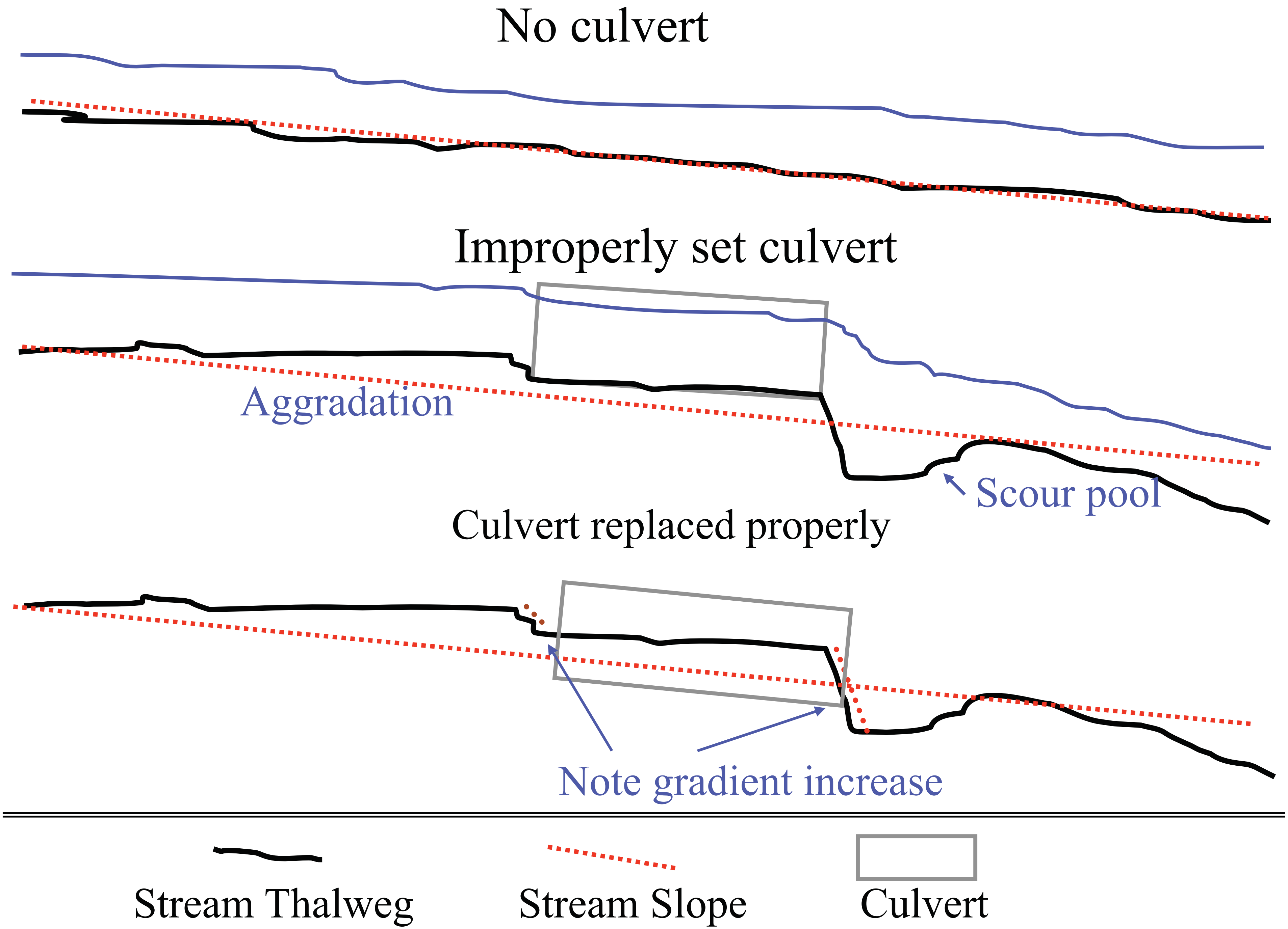


- Set Culvert same as Channel Slope
- Bury 1/6th of bankfull stream width
- Align with channel



- Consider headcut


Reduced length
= Increased slope
= Increase in energy
= Potential for head-cut


No culvert
Improperly set culvert
Aggradation
Scour pool
Culvert replaced properly
Note gradient increase
Stream Thalweg
Stream Slope
Culvert

Rate of Channel Adjustment

1979

1998

Channel Responses To An Undersized Culvert

Read The River

Bankfull-Method - - - Mesboac

Channel Velocity:

Manning Equation: $V = 1.5/n \; R^{2/3} S^{1/2}$

V = Velocity in feet per second
R = Hydraulic Radius = Xsec Area/Wetted Perimeter
S = Energy Slope ~ Thalweg Riffle Slope
n = Manning's n for a roughness factor (0.030, 0.035, up to 0.05)

Channel Discharge:

Discharge = V (XsecArea) (Calculate the Bankfull Q)

- Check your headwater levels with a culvert program at various flow events.
- Bankfull Discharge x 3 = Q25
- Bankfull Discharge x 4 = Q50

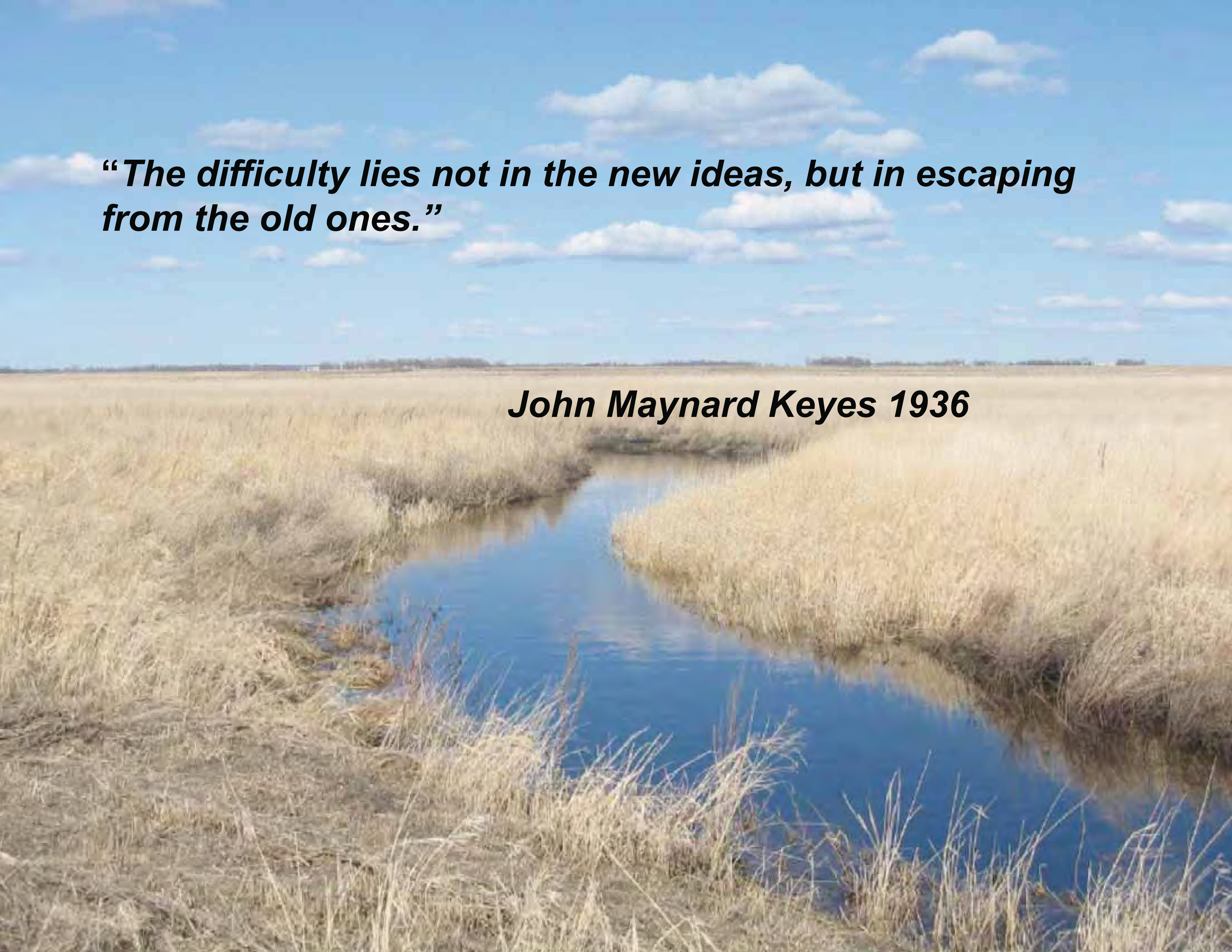
Read The River, Bankfull - - - Mesboac Method

Use HEC-RAS, Flowmaster or
WinXSPro to estimate channel discharge

Use Culvertmaster or FishXing
to estimate culvert exit velocity

* These will give you not only the variables on the previous slide, but water height at the inlet and outlet of the culvert

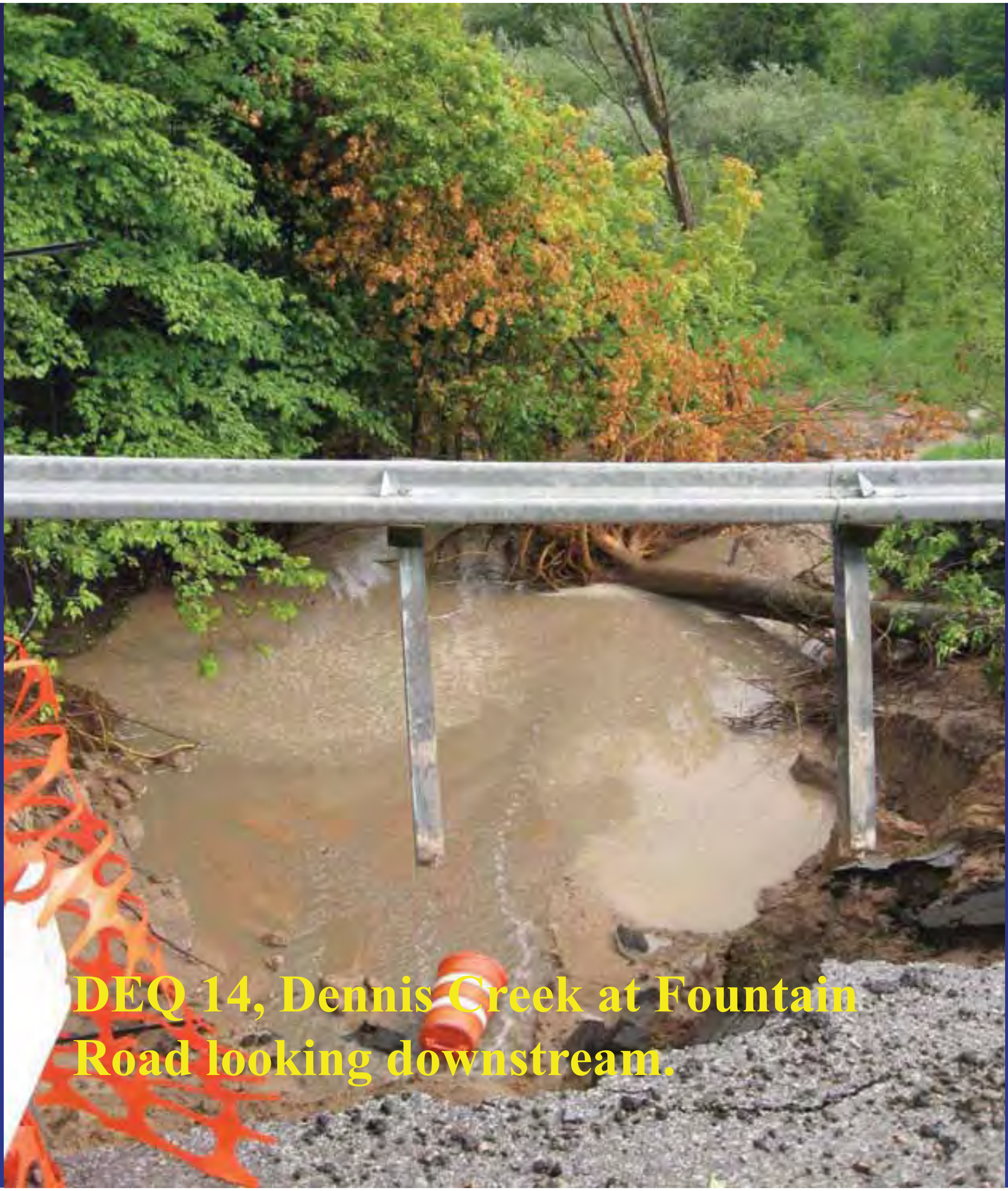
* Check for agreement with Mesboa criteria, and check data if they disagree by more than 20%


"The difficulty lies not in the new ideas, but in escaping from the old ones."
John Maynard Keyes 1936


DEQ 12, Tributary to Davis Creek at Townline Road.
Site 12-18 Townline RD


DEQ 12, Tributary to Davis Creek at Townline Road looking upstream.

DEQ 13, UnNamed Tributary to Dennis Creek looking downstream.


DEQ 14, Dennis Creek at Fountain
Road looking downstream.

DEQ 14, Dennis Creek at Fountain Road looking downstream.

DEQ 14, Dennis Creek at Fountain Road looking upstream.

DEQ 14, Dennis Creek at Fountain Road just upstream of culvert failure.

DEQ 23, Black Creek at Johnson Road looking west.

DEQ 23, Black Creek at Johnson Road looking upstream.

The broad, smooth bottom of this structure results in high velocities during high flow and shallow depths during low flow.


DEQ 1, Gurney Creek looking south.

DEQ 1, Gurney Creek looking at culverts washed out in Lake Michigan.

DEQ 4, Olson Creek looking west toward culvert.


DEQ 4, Olson Creek looking downstream.


DEQ 5, Olson Creek looking downstream.

DEQ 5, Olson Creek looking upstream.


DEQ 18, UnNamed Tributary to Middle Bayou looking upstream.

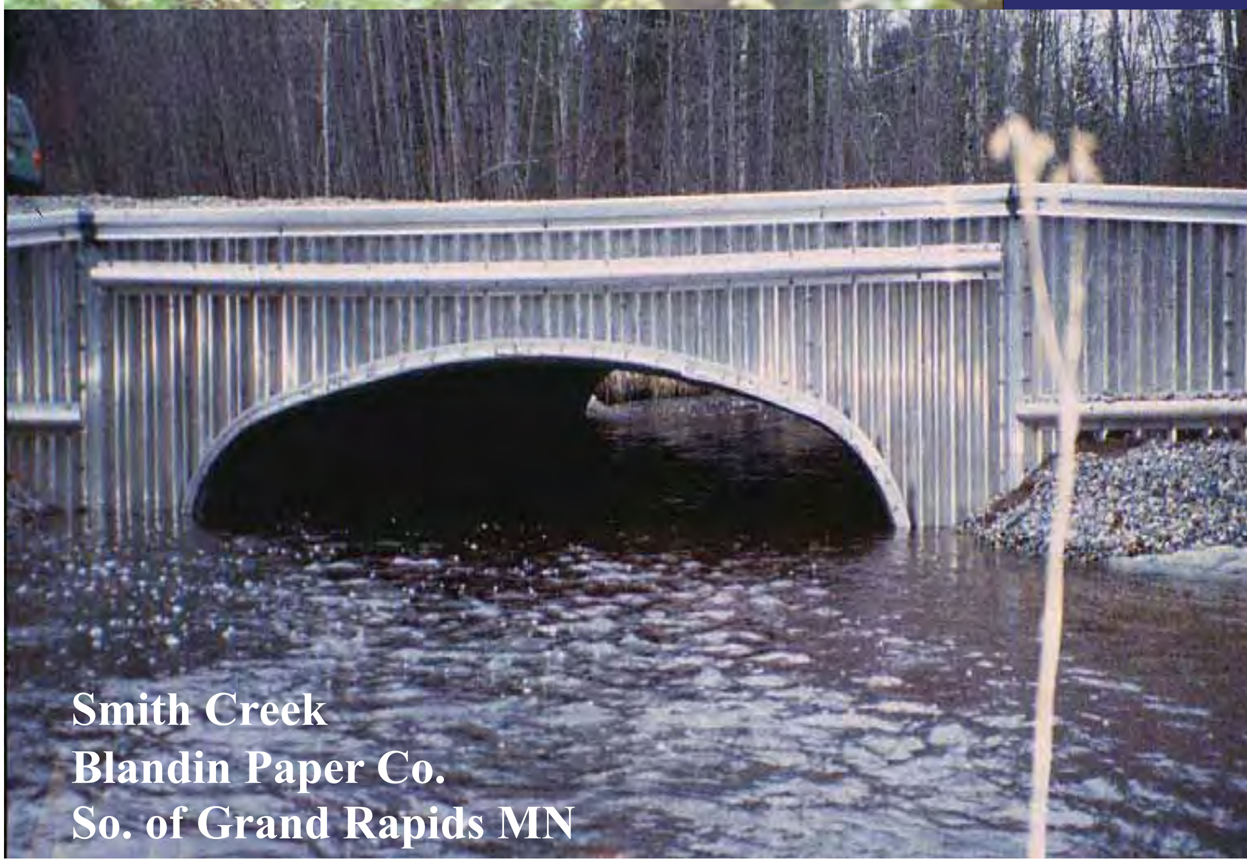

Culvert on Angling Road looking downstream to DEQ 18, UnNamed Tributary to Middle Bayou fish passage blockage with rock riffle.


DEQ 22, Looking south across
UnNamed Tributary to Middle
Bayou at Lincoln Road.

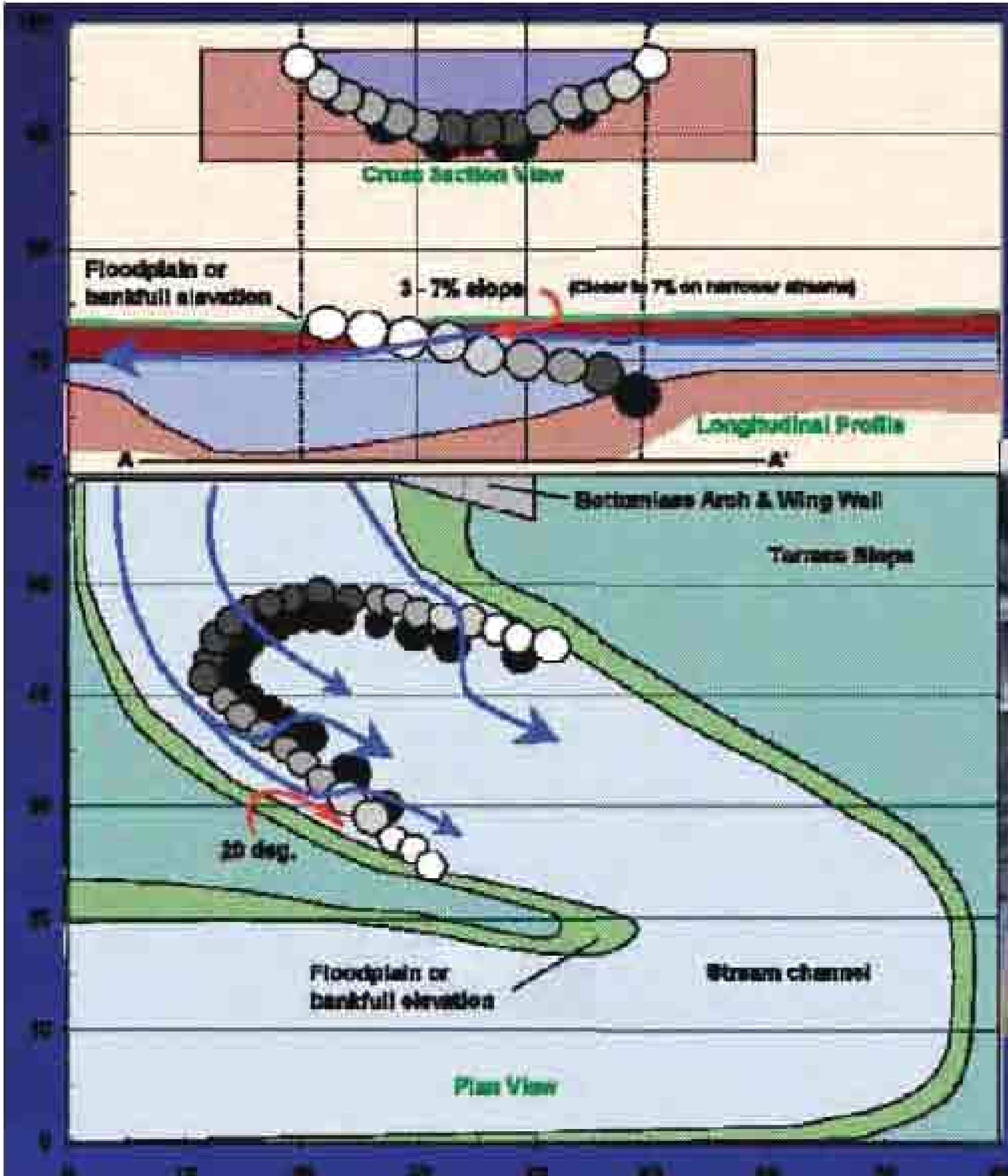

DEQ 22, UnNamed Tributary to Middle Bayou
looking downstream.

This crossing is sometimes a velocity and jump barrier to adult salmonids and a jump barrier to juveniles. Just after this picture was taken, downstream weirs were built to backwater the structure.

Perched, 12 ft.-wide wooden box culvert replaced with 18 ft. Bottomless Arch Culvert



Smith Creek
Blandin Paper Co.
So. of Grand Rapids MN



Specification for a rock cross vane structure in a [illegible] channel. Cross vane is eccentric to route water around the first bend (Longer leg on stream right).

Blowouts tend to occur in deep valleys
with a low valley width/depth
when the road fill approach 10 feet?

~ 75-yr level ?

as stream culvert.
Set same as
floodplain slope

Stream culvert sized
To bankfull width.
Set same as
thalweg riffle slope

New Bridge and Flood Relief Culverts on the Dark River St. Louis County, MN DNR, And Superior Nat. Forest

Fisheries Division DNR Policy & Procedure	Program **Field Operation**	
	Chapter **Construction Impact Assessment**	Date Approved: **4/22/2005**
	Responsible Program **Habitat Management Unit**	
Title **Stream Crossings (Bridges, Culverts, and Pipelines)**		Number 02.01.007

LEGAL REFERENCES

Michigan, acting through its Department of Natural Resources, has an obligation to preserve and protect its resources as prescribed by Article 4, § 52 of the Michigan Constitution. Fish and other aquatic organisms in the public waters of Michigan are entrusted to the State for the use and enjoyment of the public, present and future.

Part 301, Inland Lakes and Streams, of the Natural Resources and Environmental Protection Act (NREPA), 1994 PA 451, as amended.

Stream crossings over State designated Natural Rivers are also subject to the respective Natural Rivers Plan (available on the MDNR web site under Forest, Land and Waters, http://www.michigan.gov/dnr) and accompanying zoning ordinances administered by the local zoning review board, or the Michigan Department of Natural Resources, Fisheries Division. The Natural Rivers Program is established pursuant to NREPA, Part 305.

Projects which obstruct or alter navigable waters of the United States require federal review by the U.S. Army Corps of Engineers under Section 10 of the Rivers and Harbors Act of 1899 (33 U.S.C. 403). The following projects are subject to Section 10 permit review: 10,000 cubic yards or more of wetland fill; stream enclosures of 100 feet or more; stream channelization of 500 feet or more; work in Section 10 (navigable) waters; projects which involve federal or state lands or rivers (e.g. federally designated wild and scenic rivers, federal parks, national lake shores, wildlife sanctuaries); projects that would impact federal endangered species.

For all construction related projects, refer to the following Soil Erosion and Sedimentation Control guidance documents:

- Department of Management and Budget Soil Erosion and Sedimentation Control Guidebook, February 2003 http://dnrintranet/pdfs/divisions/fish/seso/DMB_handbook.pdf
- MDNR Soil Erosion and Sedimentation Control Procedures, July 2003 http://dnrintranet/pdfs/divisions/fish/seso/SESCProcedure7-22-03.pdf
- MDNR Fisheries Division Process for Soil Erosion and Sedimentation Control, March 2003 and Addendum, September 2003

POLICY

The Michigan Department of Environmental Quality (MDEQ) Land and Water Management Division has regulatory authority over the construction of stream crossings. Fisheries Division will review proposed activities and provide comments and concerns to MDEQ in a timely manner.

The most important objective when considering a new, replacement, or temporary stream crossing structure is to maintain a free-flowing, natural stream channel. Fisheries, hydrology, recreation, water quality, and aesthetics can all be significantly degraded by poorly designed, constructed, or maintained stream crossings. Fisheries Division will recommend alternatives that avoid construction of new stream crossings and removal of unnecessary or abandoned crossings. Whenever possible, pipeline and utility crossings should use existing stream crossings and bore/jack or directional drill installation methods. When a new stream crossing is necessary, Fisheries Division will recommend crossings that retain or restore the natural stream bottom, such as bridges or clear-span structures, in lieu of culverts. When culverts are used, single, large capacity culverts that match the bankfull channel width are preferred over multiple culverts of lower capacity. Stream crossings should be constructed with Best Management Practices (BMPs) that minimize erosion and disturbance of the stream, wetlands, floodplains, and riparian vegetation.

EXPLANATION

Stream channels are continuously shaped by variable flow patterns, the character of the soil and sediment particles in the channel, and the adjacent vegetation. In an undisturbed stream, processes of natural erosion, sediment transport

Economics ?

- **The initial cost of designing for fish passage is higher, because the culvert is bigger. However, . .**
- **Failure risks are reduced**
- **Structural life is optimized**
- **Maintenance levels are reduced, and . . .**
- **Replacement frequency declines**
- **Creating opportunities for work at other sites**

Reality Check

- **Having the least expensive crossing alternative and still maintaining fish passage, stream function, maximized structural life, and minimum maintenance cost is unrealistic**
- **Integrating culverts, streams, and fish passage is a win-win scenario that leads to more viable fish populations, healthier streams, and engineering maintenance budgets that can focus resources elsewhere**
- **Do it for the big picture, for the long haul, first**
- **With a little luck, you won't need to come back!**

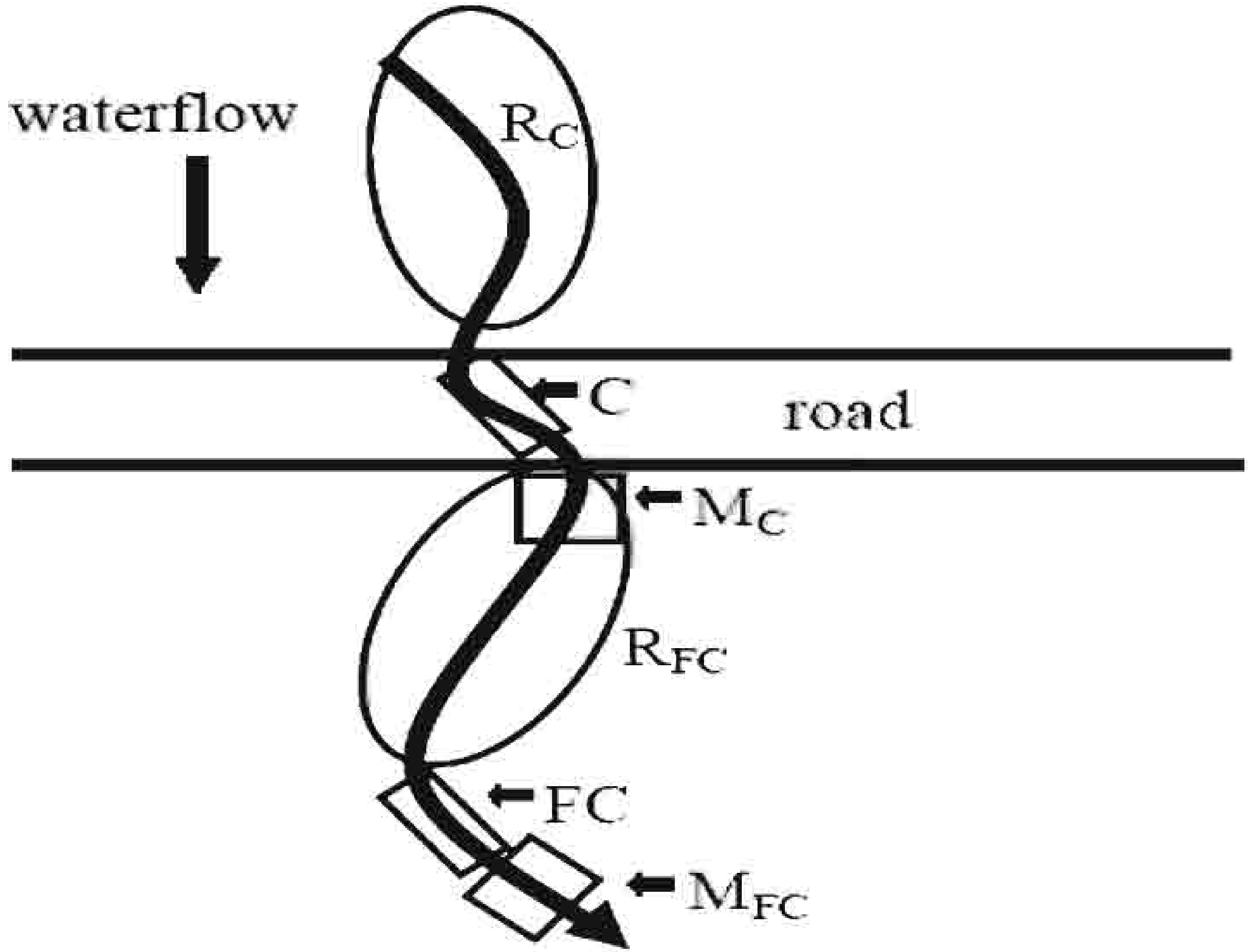
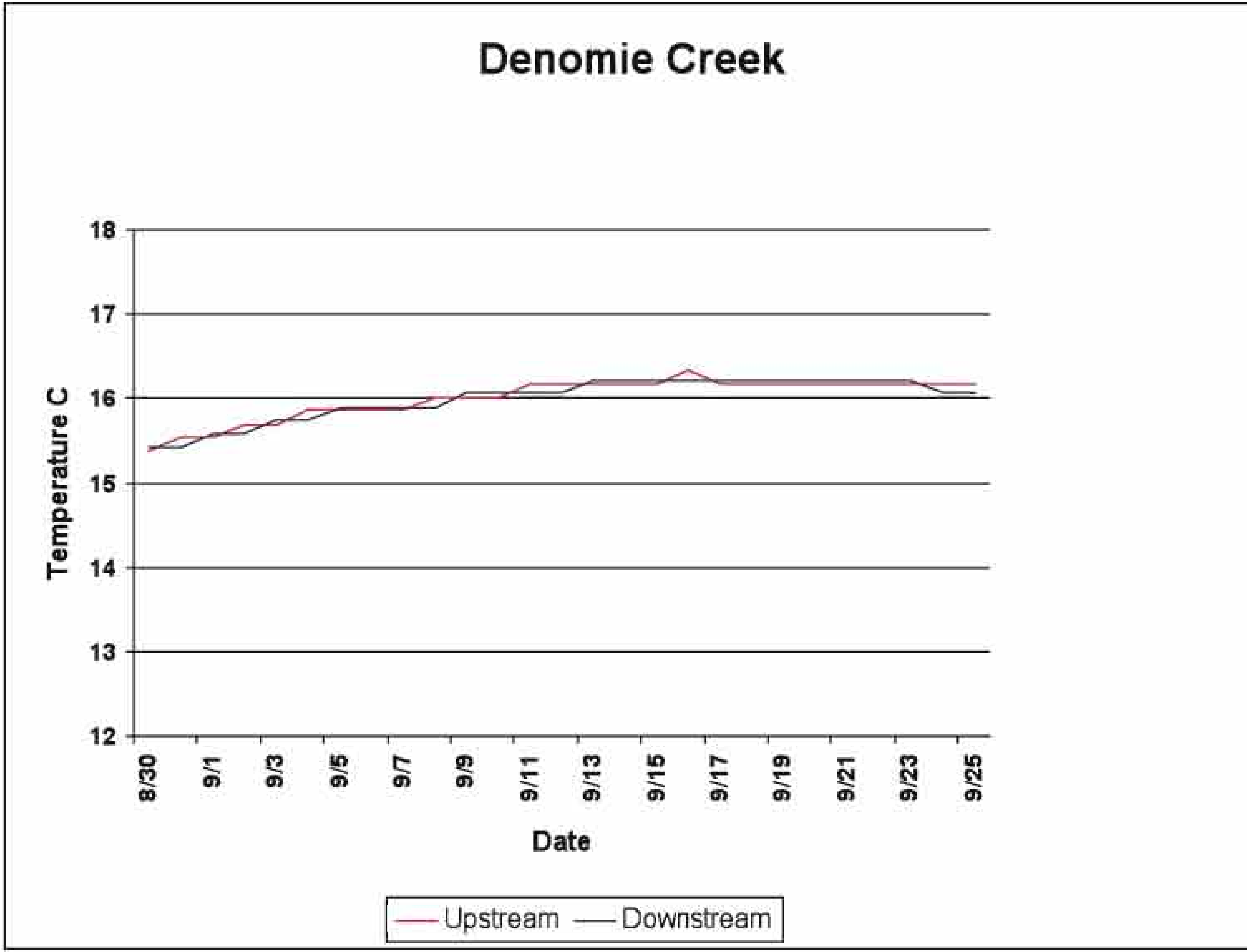
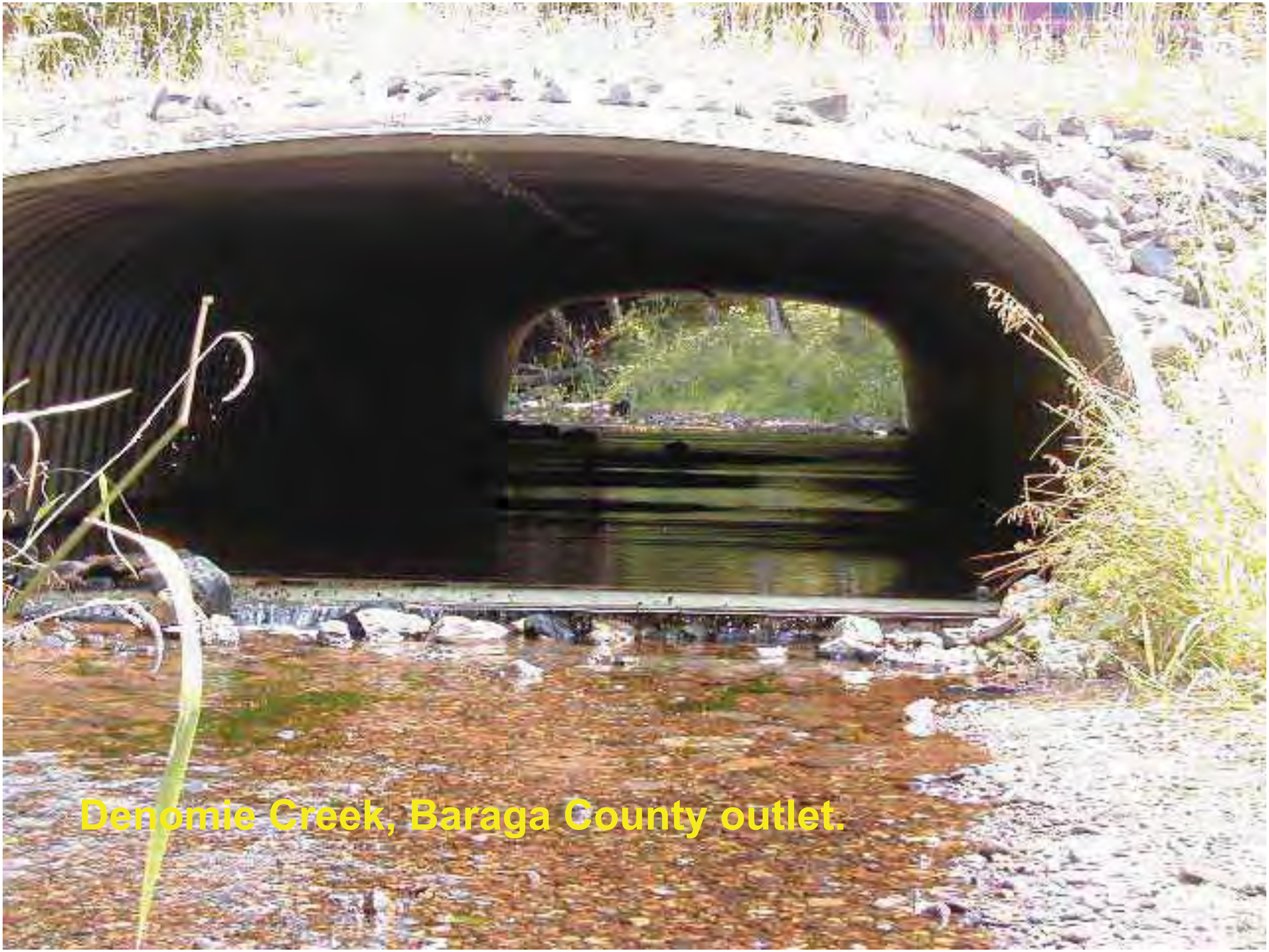
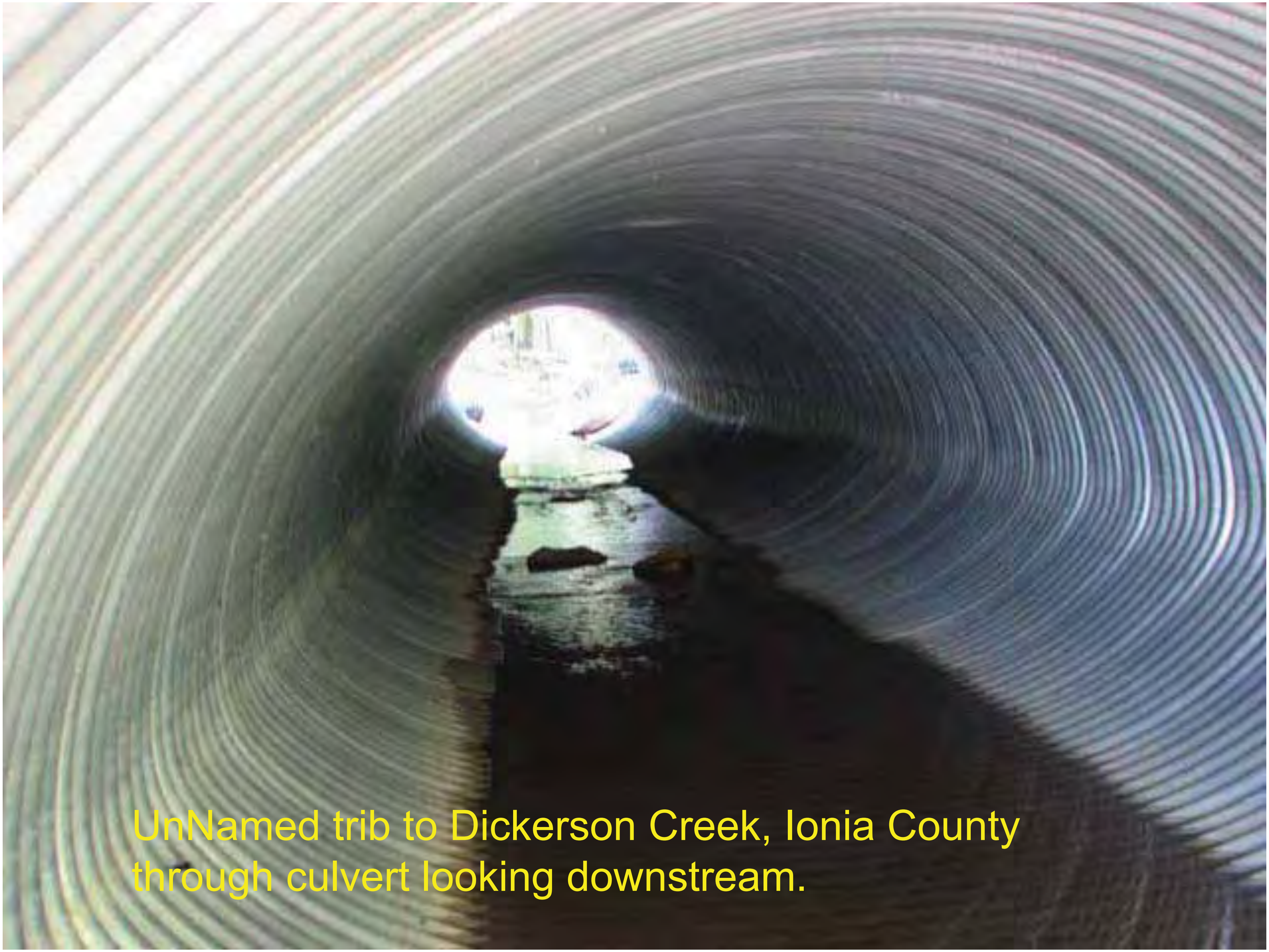


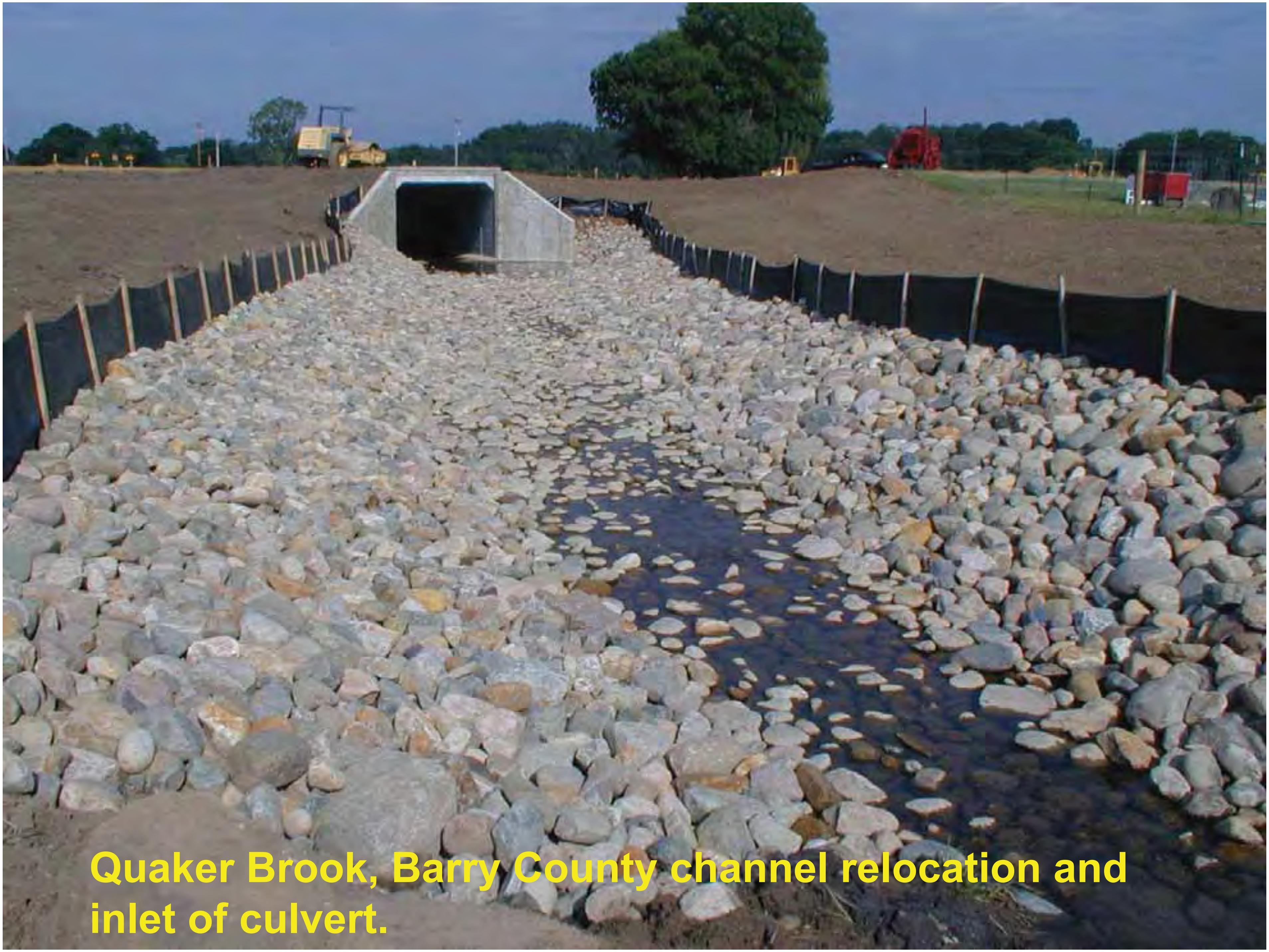
Figure 2.3. Study design for validating fish passage predictive models. M_{FC} and M_C are sections of stream where fish were initially marked. R_{FC} is the recapture section for fish from M_{FC} and R_C is the recapture section for fish from M_C. C is the culvert at the road crossing and FC is a section of undisturbed stream equal in length to C. Distances of each section are as follows: $M_{FC} = M_C =$ 5 times channel width or 50 m minimum, $R_{FC} = R_C = 4$ times M_{FC} or 200 m minimum, and FC = C = culvert length.


Denomie Creek
18
17
16
15
14
13
12
Temperature C
8/30
9/1
9/3
9/5
9/7
9/9
9/11
9/13
9/15
9/17
9/19
9/21
9/23
9/25
Date
Upstream
Downstream


Denomie Creek, Baraga County outlet.

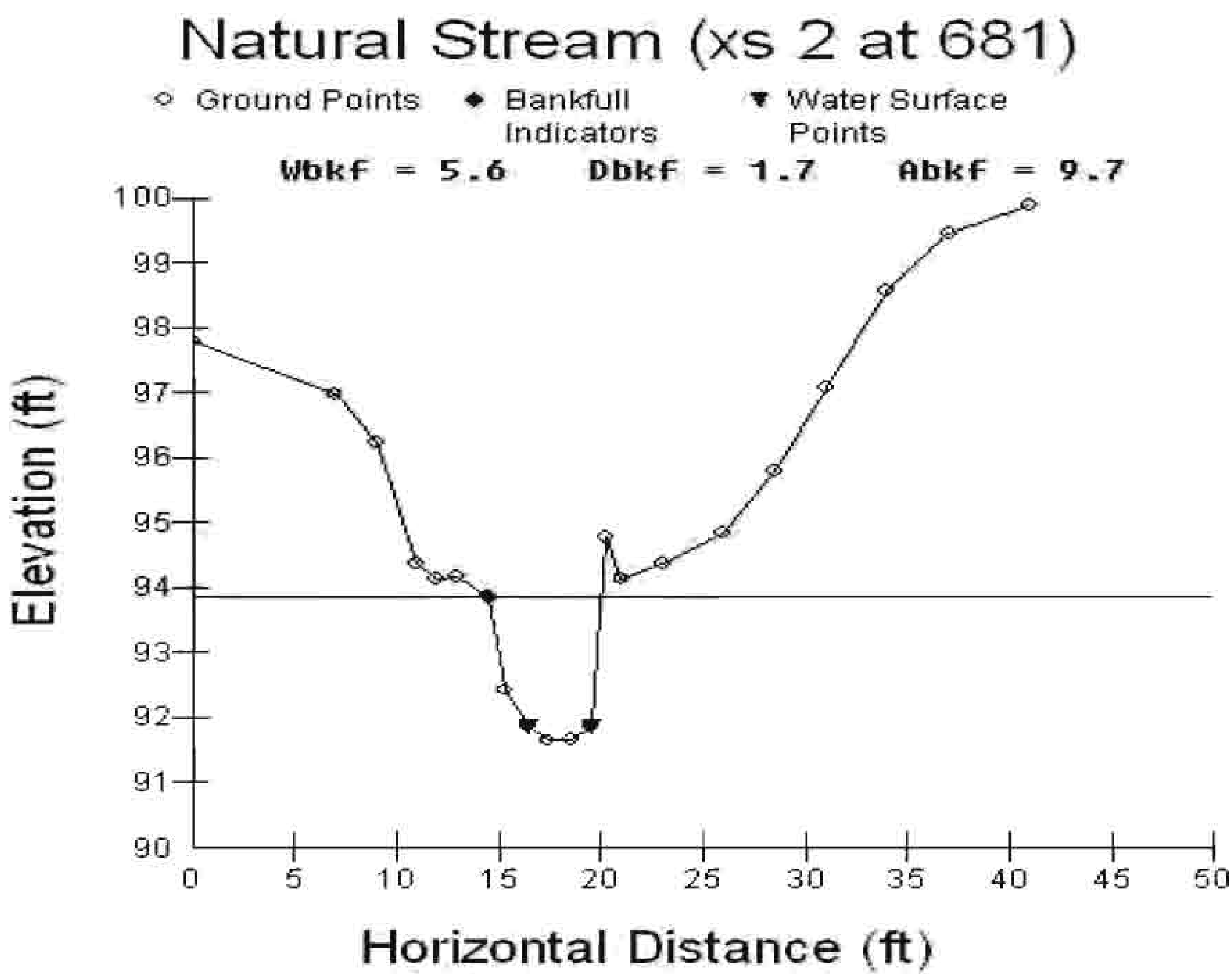

Pekkala Creek through culvert looking downstream.

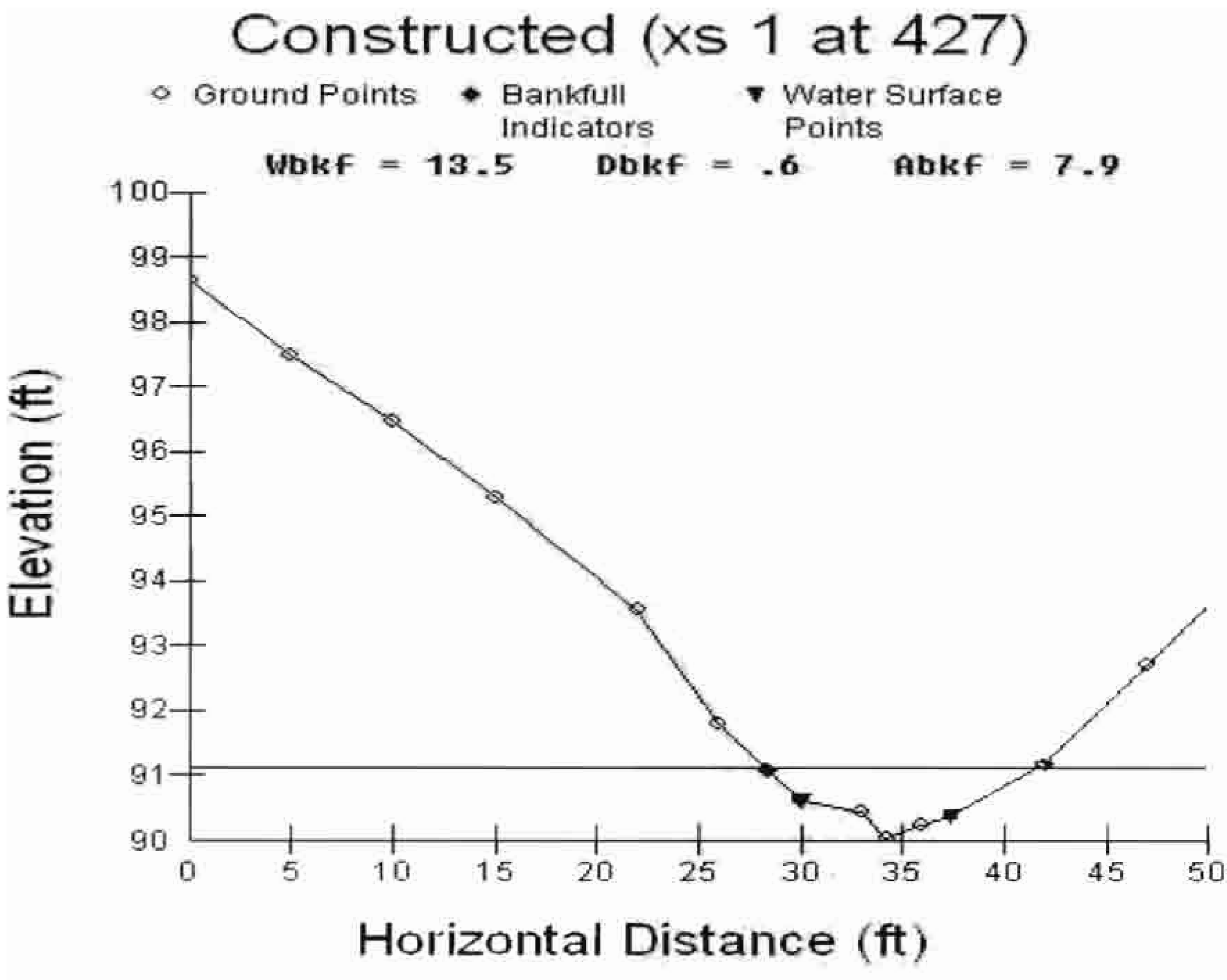

UnNamed trib to Dickerson Creek, Ionia County
through culvert looking downstream.

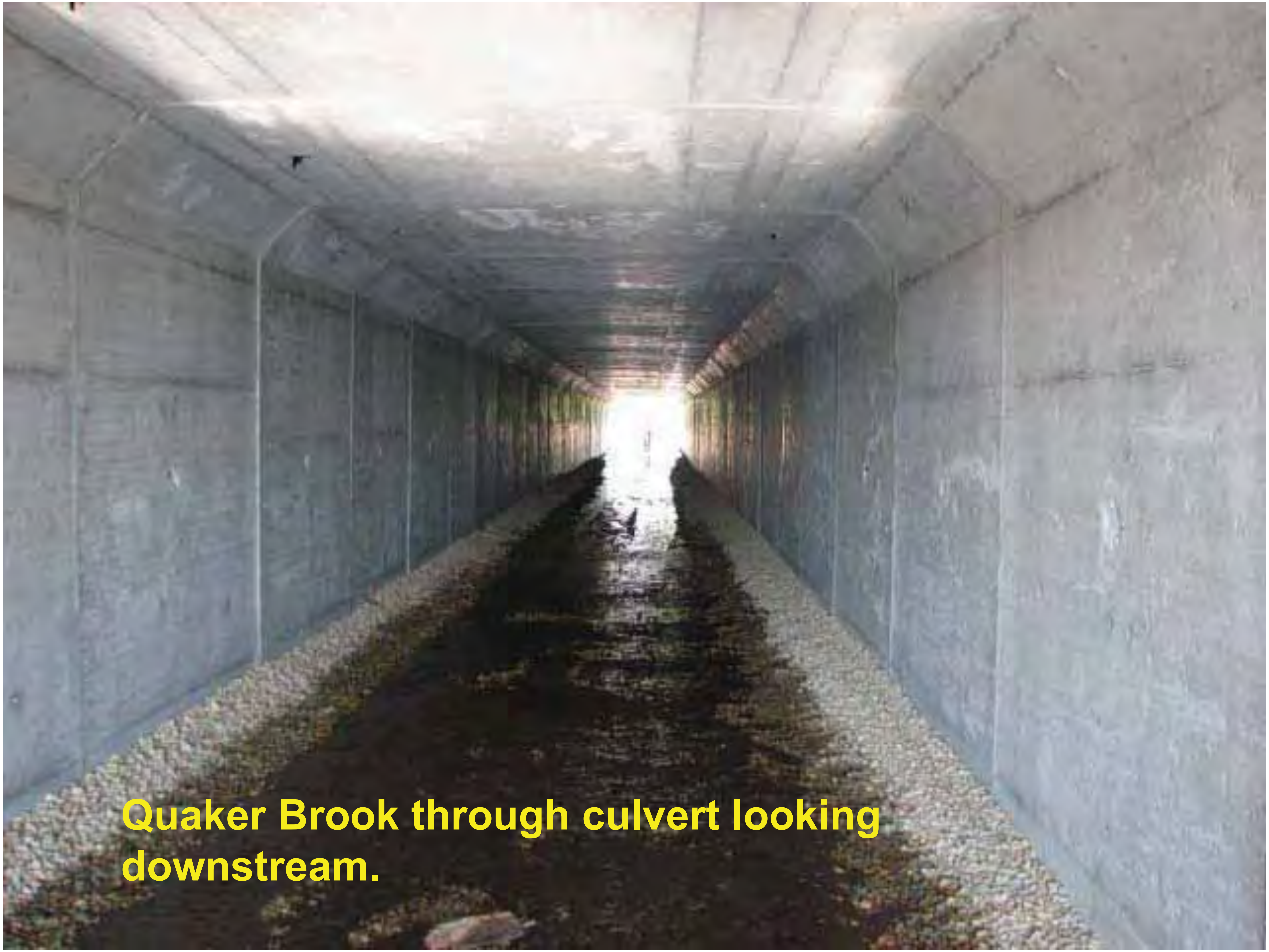


Quaker Brook, Barry County channel relocation and inlet of culvert.


Quaker Brook looking upstream from stream relocation to natural channel.


Natural Stream (xs 2 at 681)
Ground Points
Bankfull Indicators
Water Surface Points
Wbkf = 5.6
Dbkf = 1.7
Abkf = 9.7
Elevation (ft)
100
99
98
97
96
95
94
93
92
91
90
0
5
10
15
20
25
30
35
40
45
50
Horizontal Distance (ft)

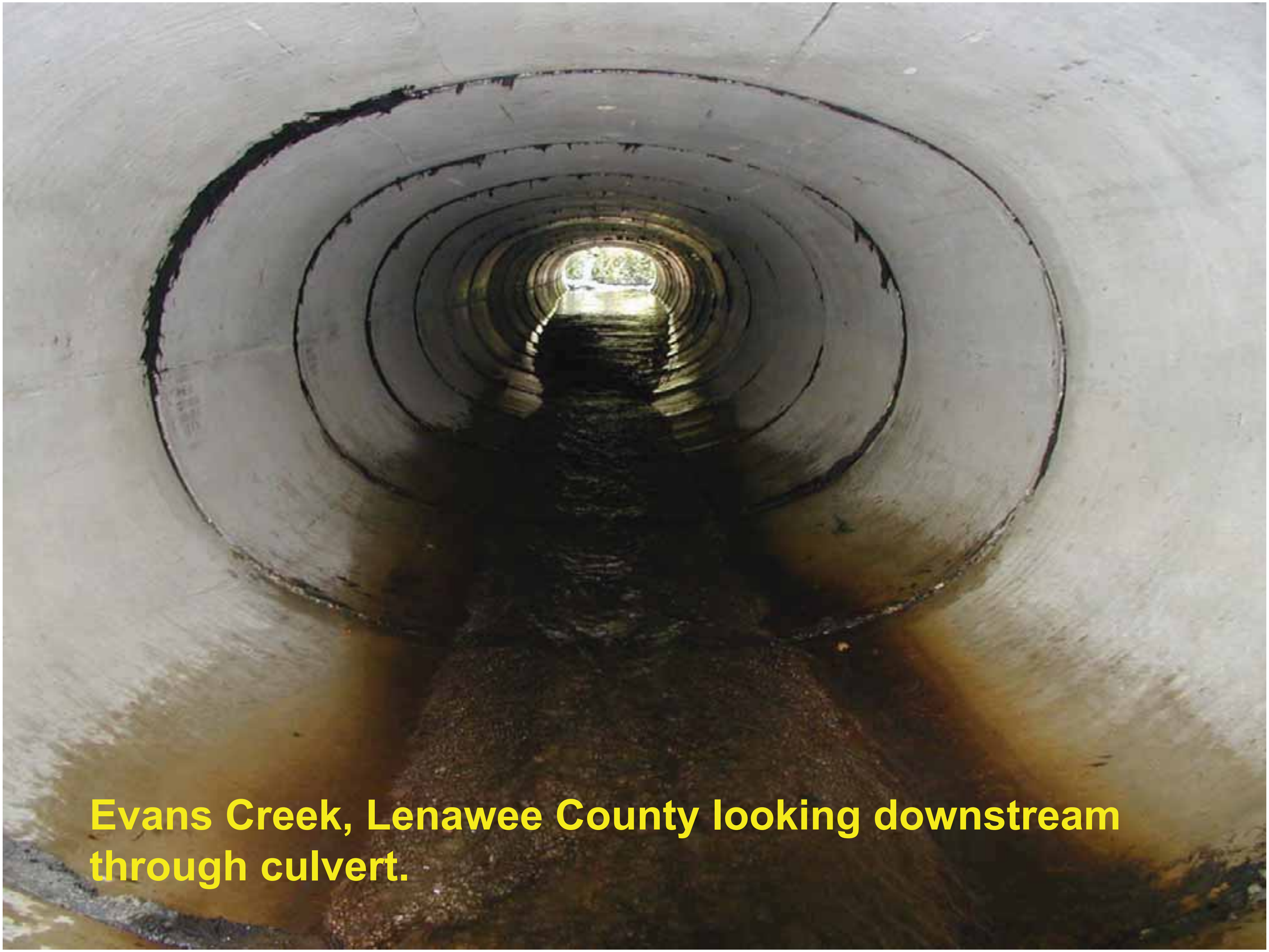

Constructed (xs 1 at 427)
Ground Points
Bankfull Indicators
Water Surface Points
Wbkf = 13.5
Dbkf = .6
Abkf = 7.9
Elevation (ft)
100
99
98
97
96
95
94
93
92
91
90
0
5
10
15
20
25
30
35
40
45
50
Horizontal Distance (ft)


Quaker Brook through culvert looking downstream.


McBride Drain, Shiawassee County outlet.


McBride Drain, Shiawasee County inlet.

Sweet & S'Mine Drain looking upstream through culvert.



Evans Creek, Lenawee County looking downstream through culvert.


Indian Creek, Monroe County inlet.


McIntyre Drain, Washtenaw County inlet.


Arner Creek, Manistee County outlet.


Second Creek, Manistee County outlet.


Larson Creek, Marquette County inlet.


Gomanche Creek, Baraga County inlet.