Science, Service, Stewardship

Fish Passage Design for Boulder Weirs

Aaron Beavers

Hydraulic Engineer

Northwest Region

E.I.T.
M.S.C.E.

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Boulder Weirs

Background

In the Beginning

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- Rock weirs in use since early 1900's.
- Rosgen pushed the design to the forefront.
- **NO** formal hydraulic design guidance.
- Wide range of design methods.

In the Beginning

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- Design methods based on designer experience.
  - This varies greatly!
- Design performance has been anecdotal.
  - Until recently! (more on this later).

Comments

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- Its understood that project "failure" is in the eye of the beholder.
- Failed weirs may provide more habitat and passage than when first installed.
- BUT…experience has shown that when a design fails to meet project goals/application…passage is inherently impaired at some point.

Comments

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- The less stable the weir the more stream side "*modification*" it will require.
- In-stream modifications.
  - Personnel and machinery in the creek.
  - Use of wood, plastic, pushup dams, etc.
- Modifications often prevent fish passage.

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Design Application

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Applications

1) Develop head for irrigation diversion.
2) Mitigate scour/erosion at culverts/bridges/banks.
3) Anchor lateral channel movement.
4) Control streambed slope.
5) Provide fish habitat.

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Small and Large System Projects

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"Smaller" System

Image: CDFG

"Larger" System

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Image: USBR

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Design Stability

First…Some Considerations

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- We'll be taking a look at several studies.
- Studies have evaluated failure of "in-stream" structures.
- Some studies looked at structures "other" than boulder structures.

First…Some Considerations

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- "Other" structures also use rock anchor/ballast.
- Rock sizing and placement methods are similar.
- General failure mechanisms scour, piping, and flanking are also similar.
- Failure modes and mechanics of in-stream structures are synonymous with the failure of boulder weirs

Frissell & Nawa (1992)

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- OR and WA.
- 161 fish habitat structures in 15 streams.
- Evaluated for physical impairment or failure.
- Flood magnitudes 2-10 year flood event.

Frissell & Nawa (1992)

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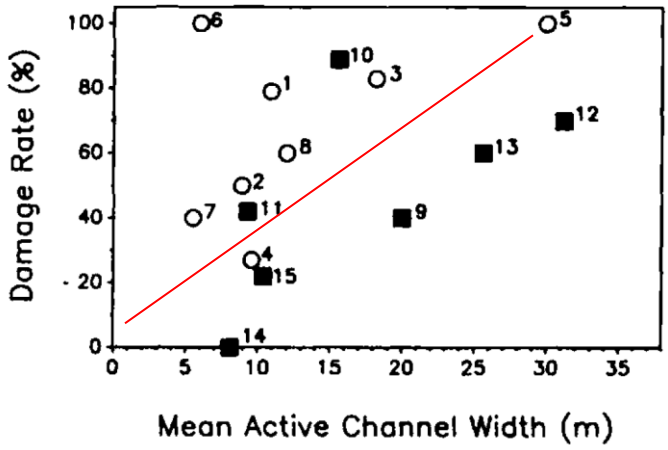

Image: Frissell & Nawa (1992)

Roper et. al. (1998)

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- OR and WA study evaluated in-stream structure durability 1996-97 floods.
- 3,946 structures evaluated in 94 streams.
- Return intervals: 5-150 year flood events.

Review of Stream Order

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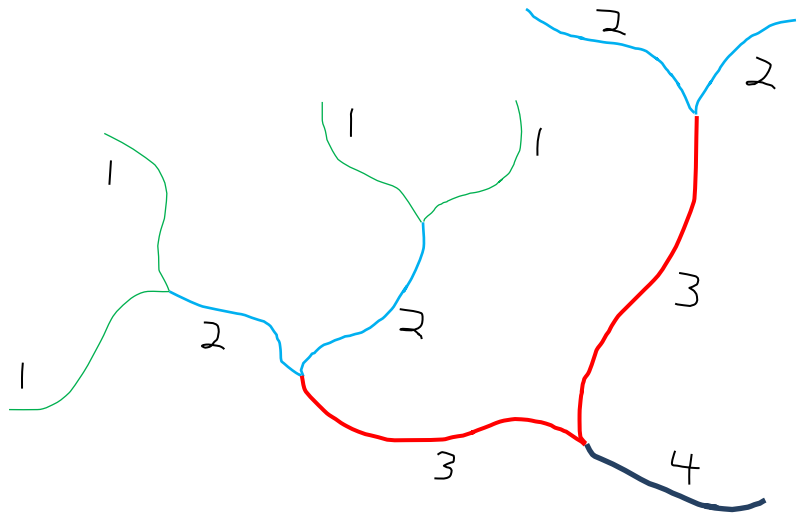

Roper et. al. (1998)

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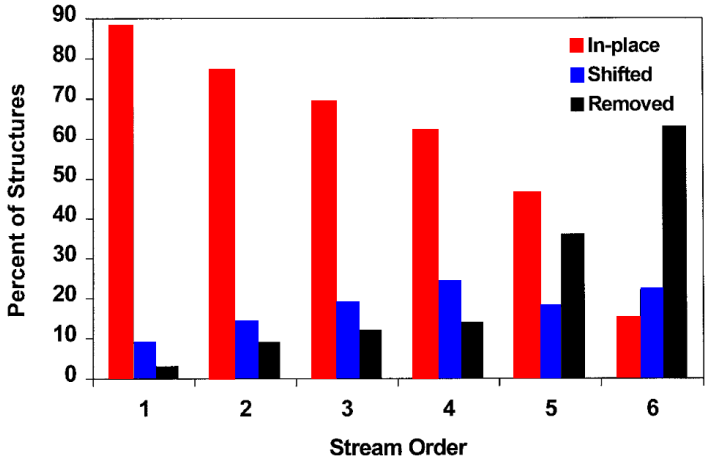

Image: Roper et. alt. (1998)

Modified Roper et. al. (1998)

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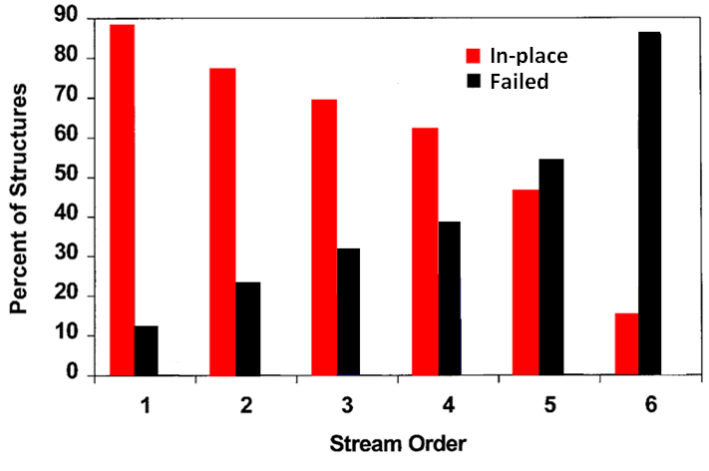

Image: Modified Roper et. alt. (1998)

Design Implications?

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- Methods and techniques which work well for small system design don't translate well to large system design.
- Many reasons and issues which make large system design difficult.
- We need to know more about morphology and sediment transport relative to these designs.

UDOT (2009)

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- Evaluated boulder weirs and J-hooks.
- Scour protection of bridge abutments and stream banks.

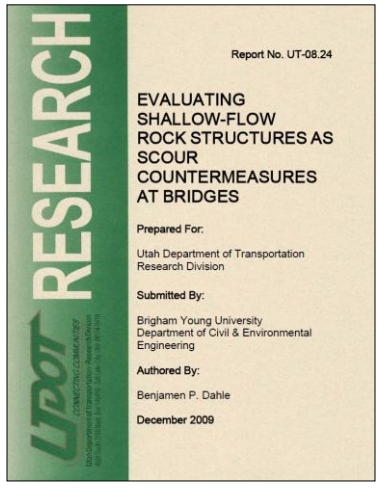

Image: UDOT

UDOT (2009)

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- 98 structures observed.
- Rate of failure was 83%.
- Definition of failure:
  - Did not protect from erosion or scour.

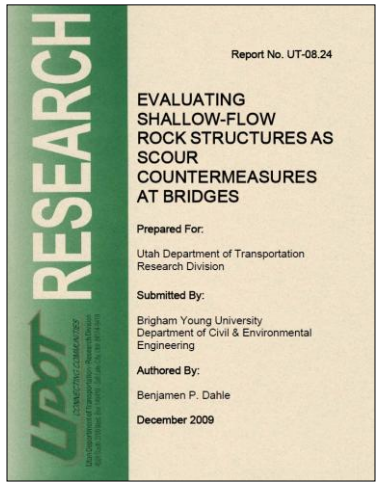

Image: UDOT

UDOT (2009)

NOAA FISHERIES SERVICE

Image: UDOT

UDOT (2009)

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Image: UDOT

USBR (2007)

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- Evaluated failure of rock weirs.
- 127 sites visited.
- 74% failed partially or completely.

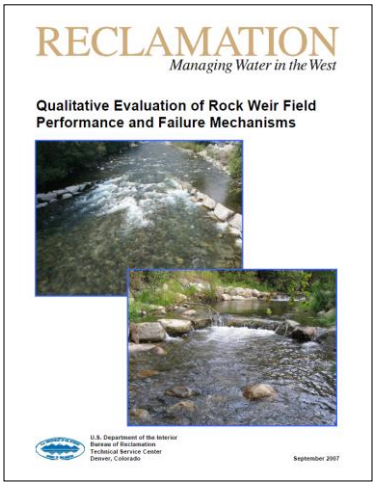

Image: USBR

Take Home

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- Damage and failure rates are proportional to the size of the system.
- Processes of failure are dominated by changes in channel morphology.
- Morphologic failure mechanisms are NOT anticipated by designers.

Take Home

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- Rock structures often induced scour where its unintended.
- Often direct flow toward the stream bank.
- #1 cause of boulder weir failure is scour pool development…NOT initial motion due to force of flow!

Take Home

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- Designs fail at a higher rate than anticipated.
- MUST understand stream processes.
- MUST anticipate channel response.
- Long-term maintenance is required/critical to projects requiring specific head for irrigation.

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Hydraulics

Weir Hydraulics

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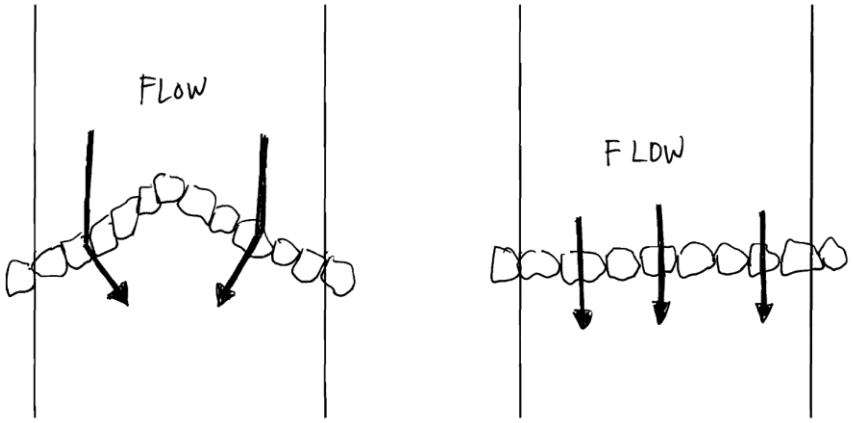
Flow moves perpendicular across the crest



Weir Hydraulics

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- Plunging flow…
  - occurs at lower flows.
  - forms and maintains scour pools.

Forms/Maintains Scour Pool

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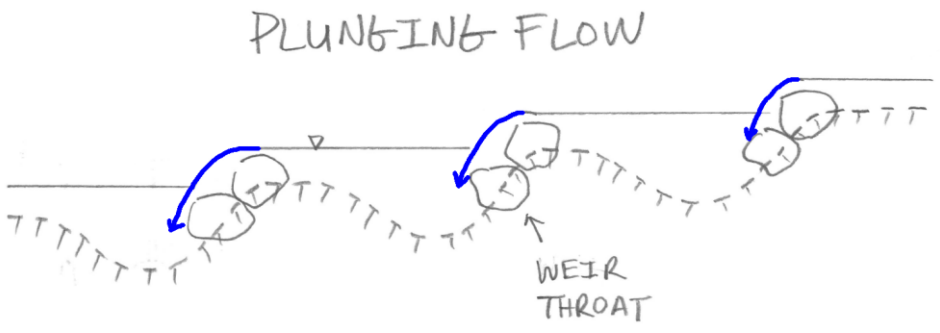

Weir Hydraulics

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- Streaming flow…
  - occurs at higher flows.
  - forms and maintains pool tail outs.

Forms/Maintains Tail out

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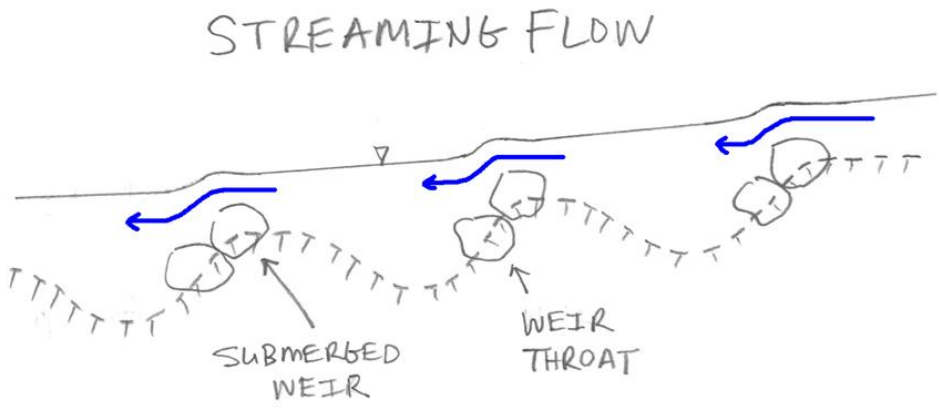

Weir Hydraulics

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- For triangular shaped weirs streaming and plunging flow often exist simultaneously.

Weir Hydraulics

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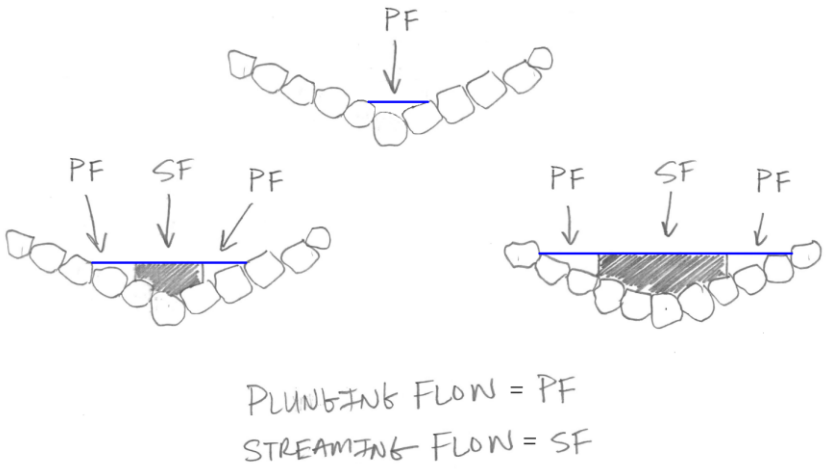

Weir Hydraulics

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- Weir shape
  - Most designs advocate a triangular weir face.
  - Directs flow away from banks.
  - Concentrates flow toward center of the channel.

Weir Hydraulics

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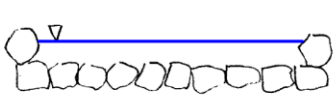

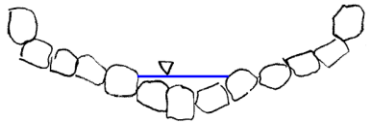

Weir Shape & Scour

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- Weir shape effects…
  - magnitude and location of scour.
  - scour pool geometry.

Deepest Scour Location

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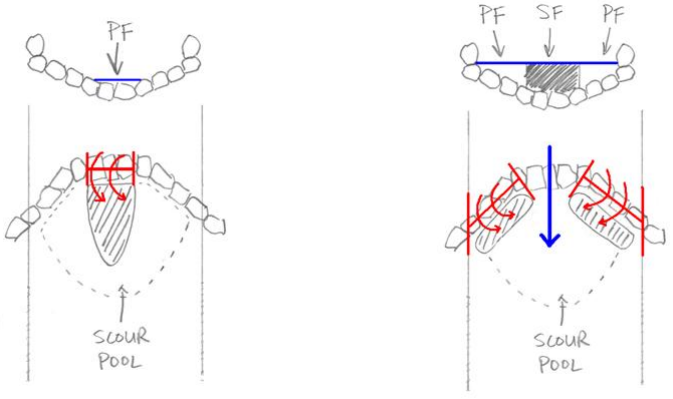

Weir Shape & Scour

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- Scour pool depth and location change relative to the flow rate.

Deepest Scour Location

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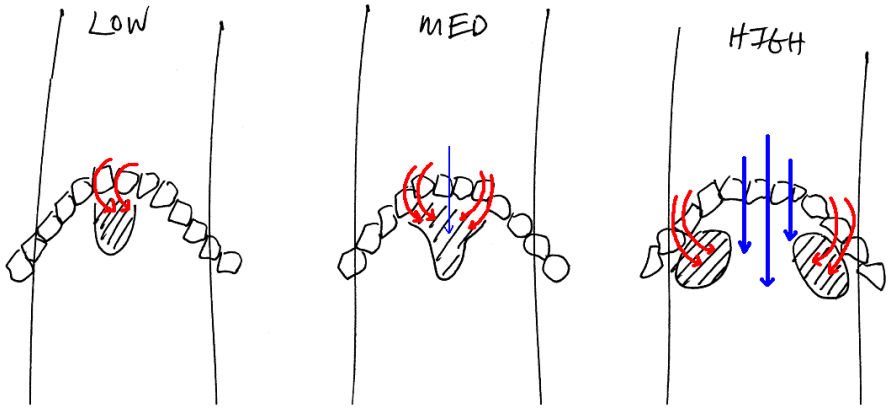

Throat Width

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- Narrow weir throat constricts flow toward the adjacent weir arm.
  - Undermines footer rocks.
  - Jet impacts directly on weir arm.

Throat Width

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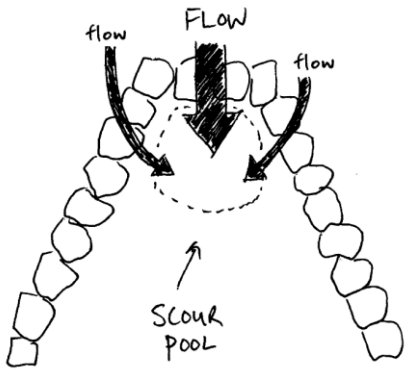
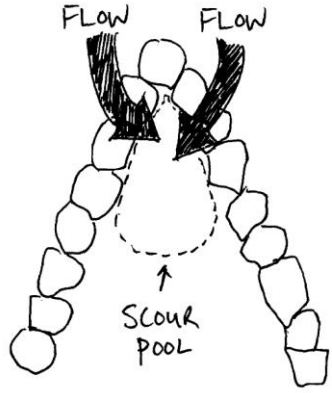
Lower Failure Rate



Higher Failure Rate



Throat Width

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- Constriction can cause adverse backwater effects.
- Upstream velocity is reduced and sediment depositions form.
- Deposits can redirect flow toward streambank causing erosion and flanking (failure).
- Narrower throat increases the magnitude of flow over the arms.

Throat Width

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Image: USBR

Throat Width

NOAA FISHERIES SERVICE

Image: USBR

Scour

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- #1 FAILURE MECHANISM: Development of scour pool.
- Contrary to common belief.
- Common belief is that #1 failure mechanism is mobilization of rocks is due to the force of flow.

Scour

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- Maximum scour is located in one of two areas.
  - At the throat or along the structure arms.
  - Location may change with respect to discharge and sediment load.

Scour

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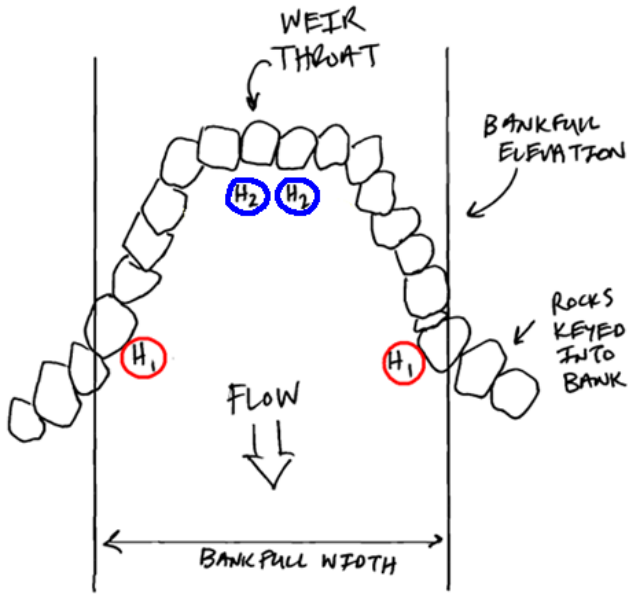

Assumed

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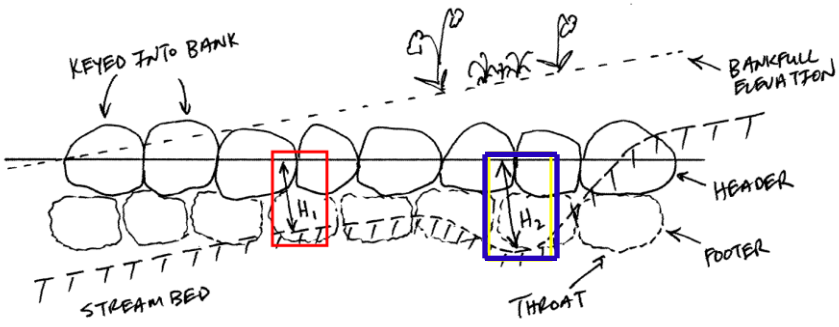

Actual

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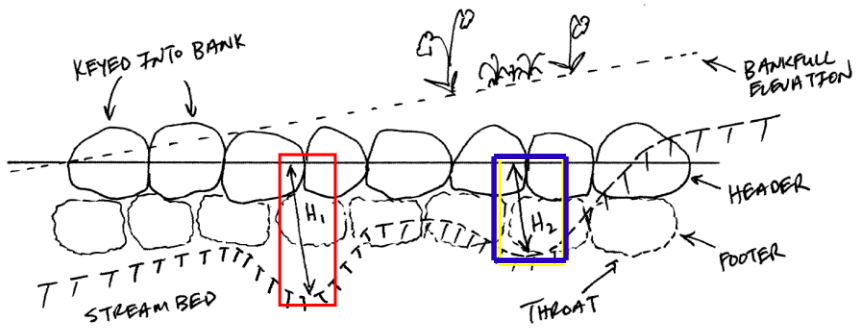
Deepest scour occurs where head drop is greatest and footer protection is least.



Scour

NOAA FISHERIES SERVICE

Image: USBR

Scour

NOAA FISHERIES SERVICE

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Scour

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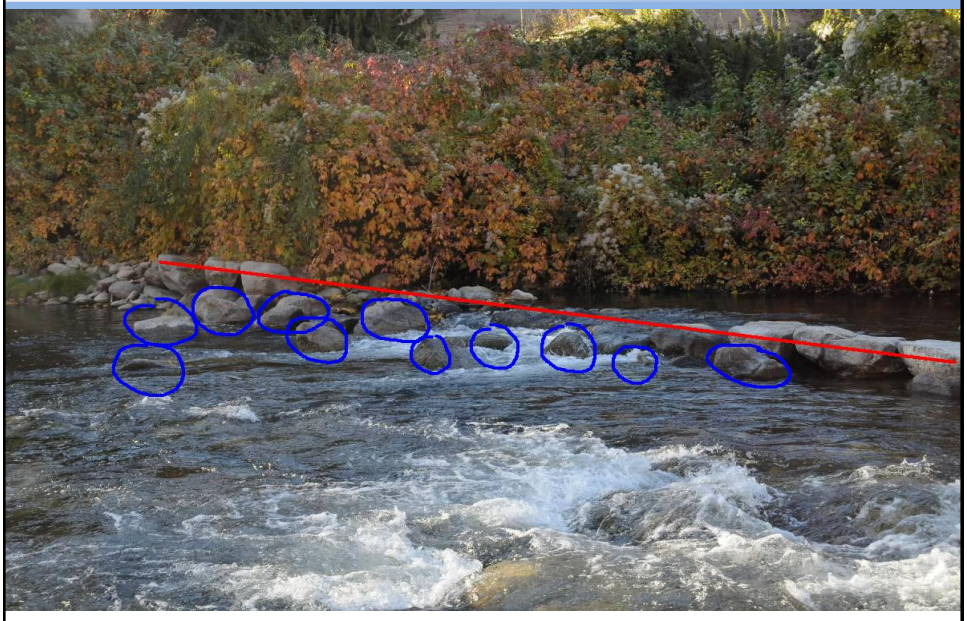

Image: USBR

Channel Hydraulics

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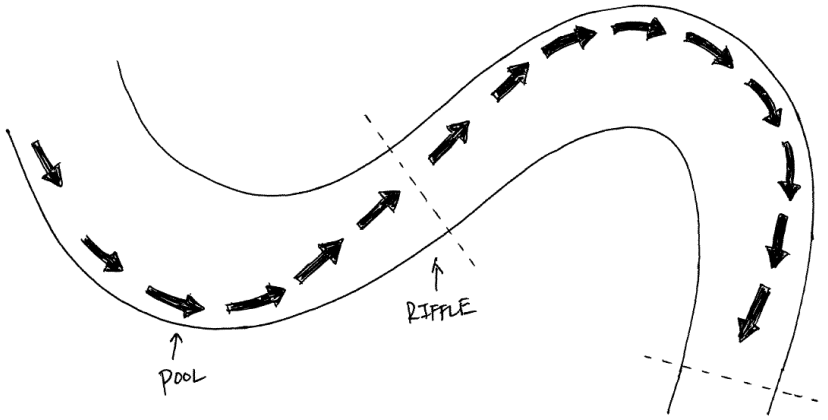

Channel Hydraulics

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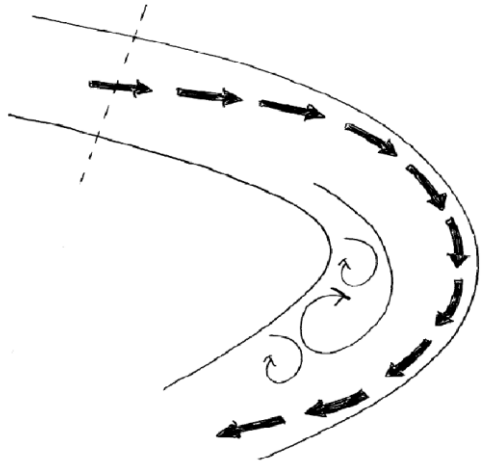

Channel Hydraulics

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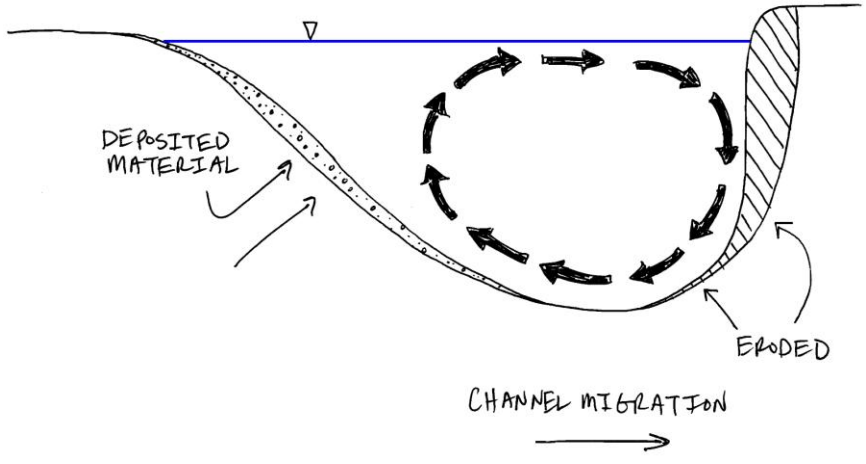

Channel Hydraulics

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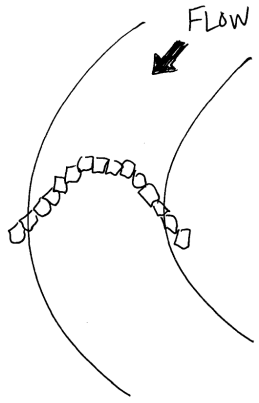
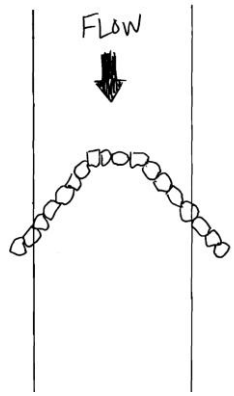
Higher Rate of Failure



Lower Rate of Failure



Channel Migration

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- As channel migrates structure is flanked.
  - Less risk: Confined channel with higher slope.
  - More risk: Unconfined channel with lower slope.

Channel Hydraulics

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- Flow on weir arms in unequal “asymmetrical” in channel bends.
- Asymmetrical orientations shifts flow over the arm instead of through the throat.
- These designs have a higher risk of failure.

Channel Hydraulics

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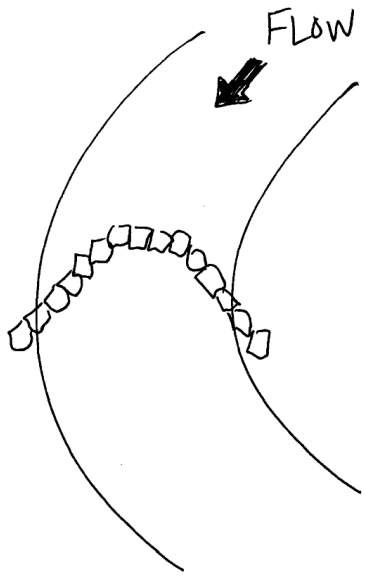

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Boulder Weirs

Designs & Methods

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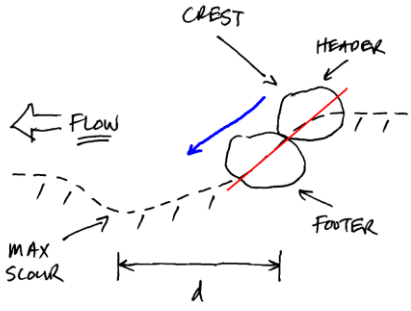
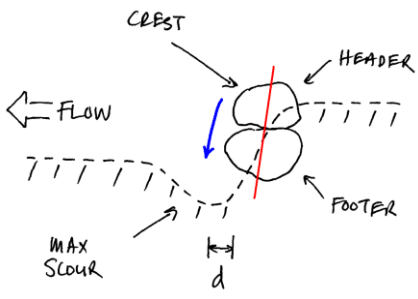
Design: Header Orientation

Lower Failure Rate



Higher Failure Rate



Design: Header Orientation

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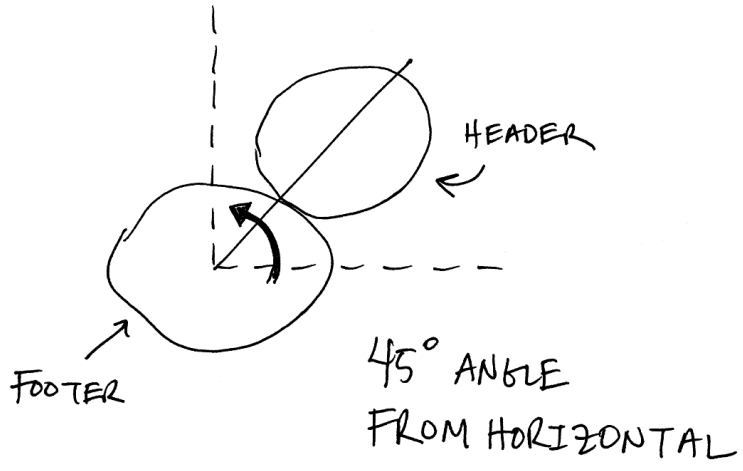

Design: Spacing

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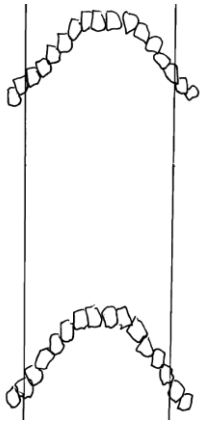
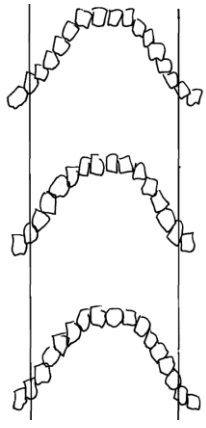
Higher Rate of Failure



Lower Rate of Failure



Design: Spacing

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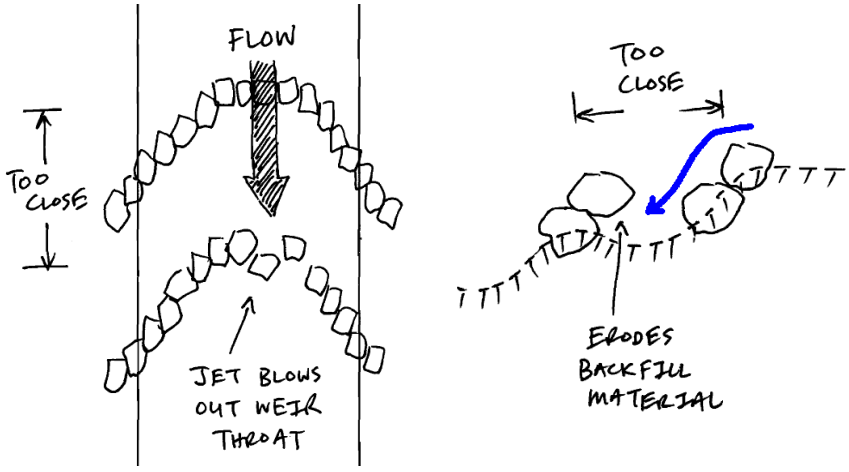

Design: Slope

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- Boulder weir structures can be used effectively hold re-graded slopes up to 4%-5%.
- Beyond this weirs are spaced too close.
- Other options…
  - Complete restorations of channel.
  - Rigid weirs (cement)
  - Roughened channel

DESIGN: Planform Shape

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- Apex should face upstream.
- Throat should be in-line with thalwag.
- Plan view shape should concentrate flows away from the banks…towards the center of the channel.

DESIGN: Planform Shape

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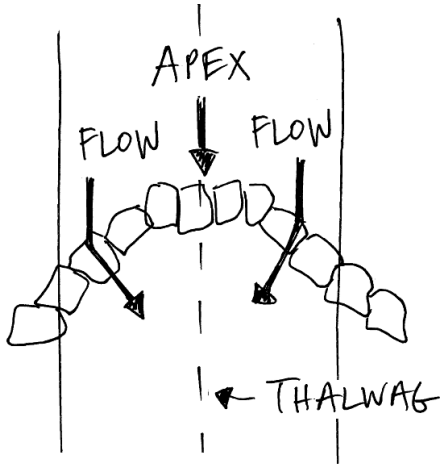

DESIGN: Weir Crest Slope

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- Weir arms should be sloped to focus flows away from streambanks toward the center of the channel.
  - Slope is normally 3 to 7 degrees along the arm from the throat to .
  - USBR found higher rates of failure beyond 7 degrees.

DESIGN: Weir Crest Slope

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Image: USBR

Design: Vertical Placement

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- Elevated risk of flanking when weir elements encroach on the bankfull elevation.
- Floodplain inundates at a much higher frequency.
- Over bankfull flow depths are artificially increased over the weir arms…increasing scour power at lower discharges.

Design: Vertical Placement

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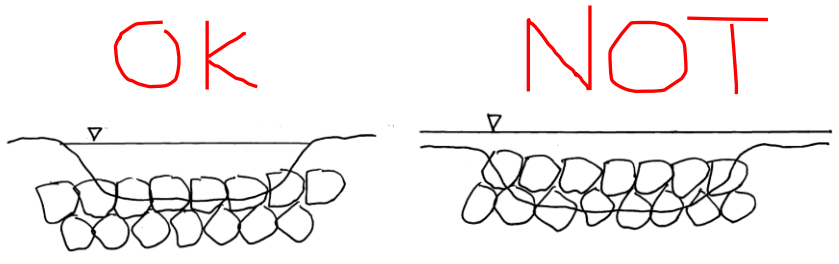

Design: Open Angle

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- Planform shape of U or V apex pointing upstream.
- Open angle should be between an angle between 90 and 120 degrees.

Design: Open Angle

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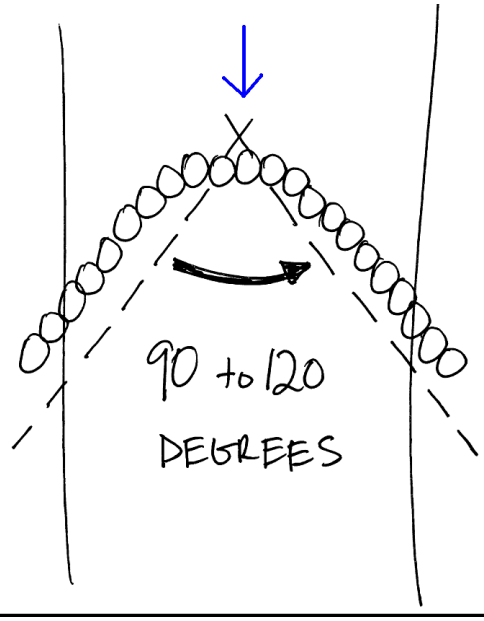

Design: Rock Size

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- Rocks sizing methods are adequate.
- Weirs designed with conservatively sized rock STILL FAIL AT MUCH LOWER FLOWS than anticipated.
- Scour pattern and max depth location will still fail the biggest rocks you can design.

Design: Rock Size

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- Don't use riprap calculations to size rock.
  - Rock is too small.
  - This method assumes a cohesive "matrix" which is lacking in a boulder weir.
- Minimum rock diameter should be on the order of 2-3 ft.

Design: Rock Selection

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- Use angular rock.
  - If rounded rock is used increase the calculated size.
  - Rocks should be “beefy” not flat.
  - Uniform in size and durable (no cracks and defects).

Design: Rock Placement

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- Requires…
  - Skilled operator and attention to detail.
- Rocks should be placed tightly together.
  - Minimum of three contact points.
- Gaps and voids should be filled with well-graded material.
  - Placed by hand, washed, and rodded into position.

Design: Footing Depth

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- Scour depths along weir arm can be significantly deeper than at the throat.
- Footing depth should be sufficient to protect from slumping due to undermining.
- Scour depth is generally 2.5 - 3.0 times the hydraulic drop (Castro 2000).
  - Drop = difference in water surface elevation.

Design: Footing Depth

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- Love & Bates (2009)
  - Minimum footing depth = D100 rock size of the natural channel.
  - Measured from the downstream weir crest to the bottom of the upstream footer.

Design: Footing Depth

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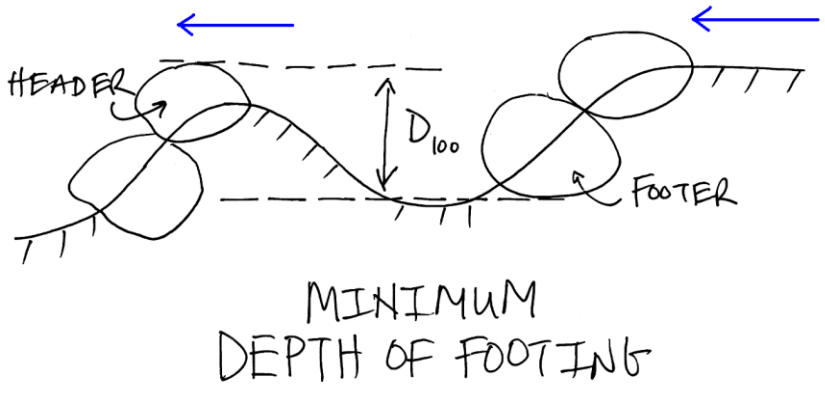

Design: Tie-in

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- Footers should be keyed into the bank the same distance as headers.
- Quantify lateral movement of channel and key weir arms sufficiently into bank.
- **This is-non trivial and should be an in-depth discussion.**

Design: Tie-in

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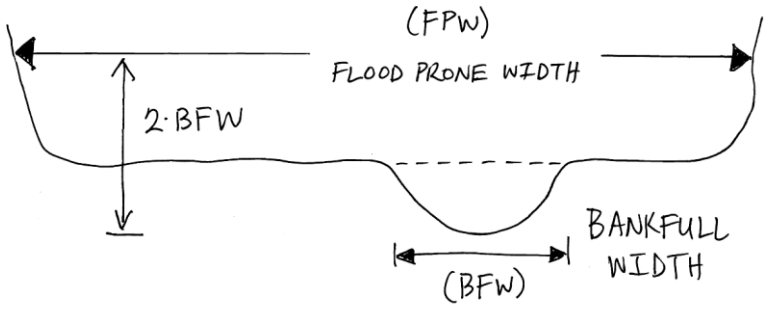

$$\text{ENTRENCHMENT RATIO} = \frac{FPW}{BFW}$$

Entrenchment Ratio

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- **> 2.2**
  - **Greatest risk of channel migration and flanking.**
- 1.4 – 2.2
  - Median risk of channel migration and flanking.
- < 1.4
  - Least risk of channel migration and flanking.

Design: Tie-in

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- Instable streambanks will require weirs to be keyed farther into the streambank.
  - Bank height ratio should be evaluated.

Entrenchment Ratio

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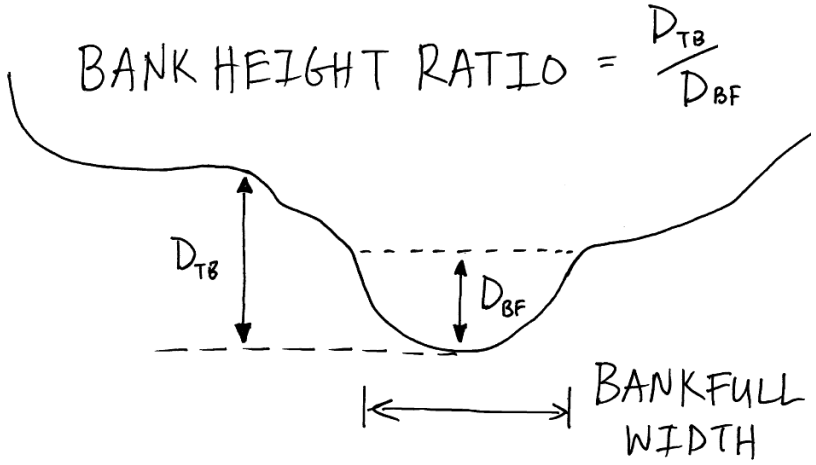

Bank Height Ratio

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- Stable 1.0 – 1.05
- Moderately unstable 1.06 – 1.3
- **Unstable 1.3 – 1.5**
- **Highly unstable > 1.5**

Design: Tie-in

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- Highly mobile channels will require weirs to be keyed farther into the streambank.
  - Meander width ratio should be evaluated.
  - If greater than 3 or 4 there is a increased risk of channel migration and flanking.

Meander Width Ratio

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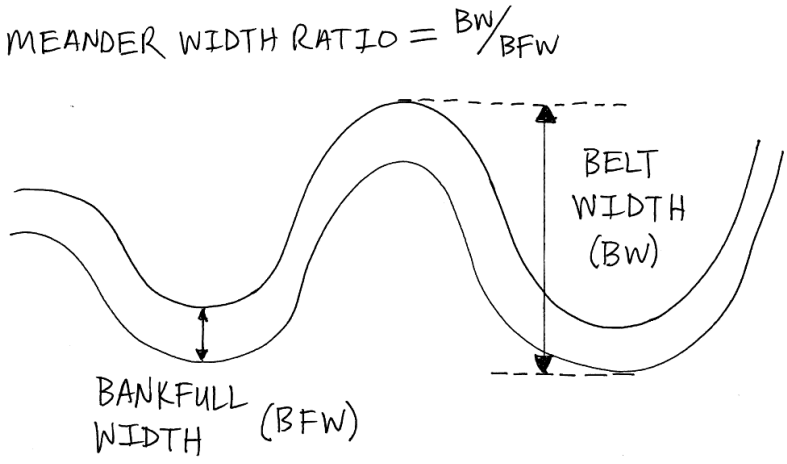

Design: Weir Seal

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- Weir requires entrainment of alluvial material upstream of the throat to maintain prevent porous flow through the weir.
- Insufficient bedload may reduced the amount and/or porosity of the material over time.
- Structure is “starved” of upstream sediment.

Design: Weir Seal

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- Sediment slug just upstream of the header may be entirely removed and replaced over the course of a flood event exposing/removing the fabric.
- Where insufficient sediment recruitment or bedload is anticipated clay has been successfully used to fill voids.

Design: Weir Seal

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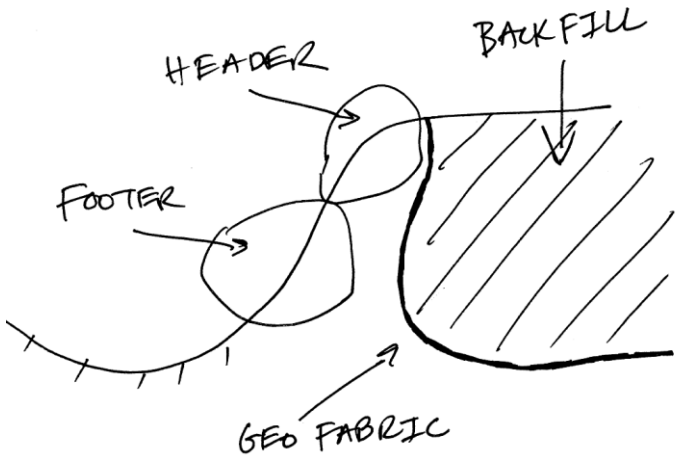

Design: Turbulence

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- Pool volume should be hydraulically sized.
- Pool is rock lined or made of other non-erodible material.
- Or streambanks are very erodible.

Design: Turbulence

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- If pool is armored and sized too small…
- “Extra” energy is now available for unexpected erosion downstream .
- Condition may also create passage barrier due to excessive turbulence .

Design: Turbulence

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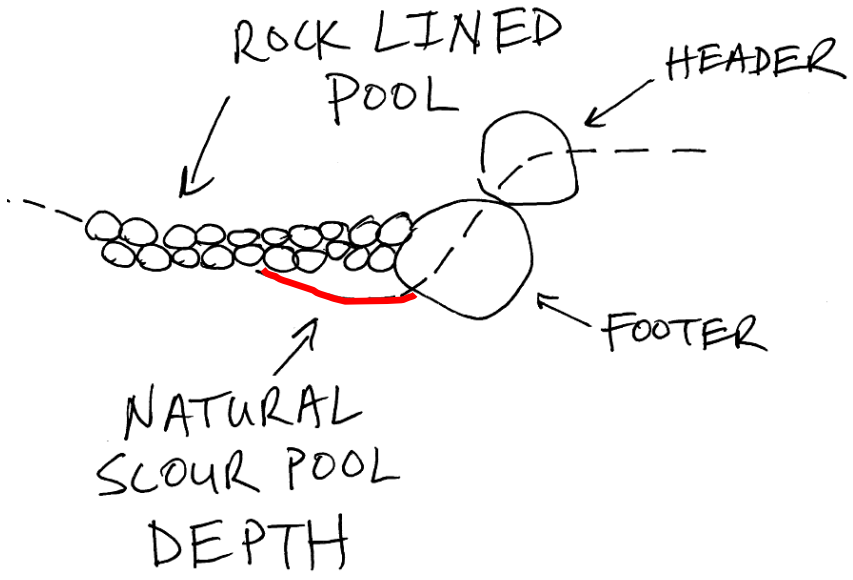

Design: Location

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- Flanking failures are nearly synonymous with placement in river bends.
- Need to assess channel conditions.
  - What is historic channel migration?
  - Beef up design at streambank (tie-in).
- Don't place them in channel bends if you absolutely don't have to.

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Rosgen Method

A Critical Look at a Method Many Designers Use

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Rosgen Method

- "Cookbook" method.
  - "If you build it…it will work" (false).
- The vast majority of designers are not familiar with Rosgen boulder weir design limitations and assumptions.

Rosgen Method

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- Design is not keyed into bank sufficiently.
- Method does not take into account…
  - Upstream disturbances.
  - Channel stability.
  - Channel migration.
- USBR work indicates that understanding these conditions are critical to successful designs.

Rosgen Method

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- Method does not take into account…
  - Channel morphology.
  - Stream processes.
- USBR work indicates that understanding these conditions and concepts are critical to successful designs.

Rosgen Method (2001)

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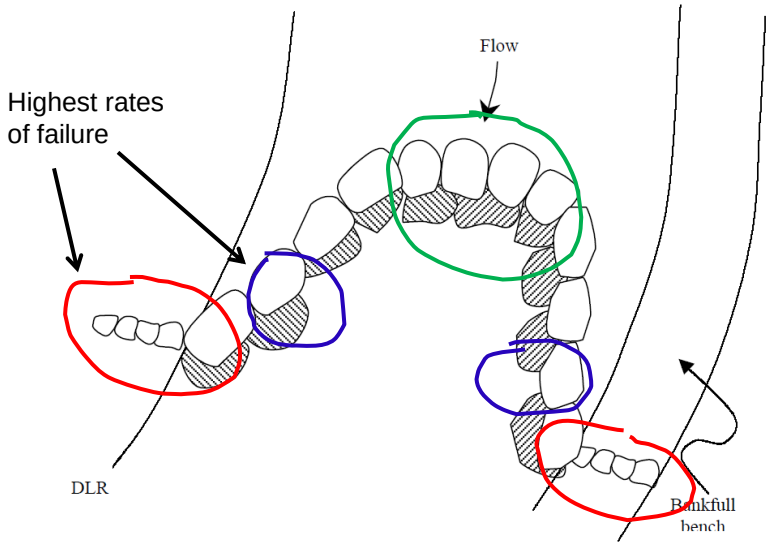

Image: Rosgen 2001

Rosgen Method (2006)

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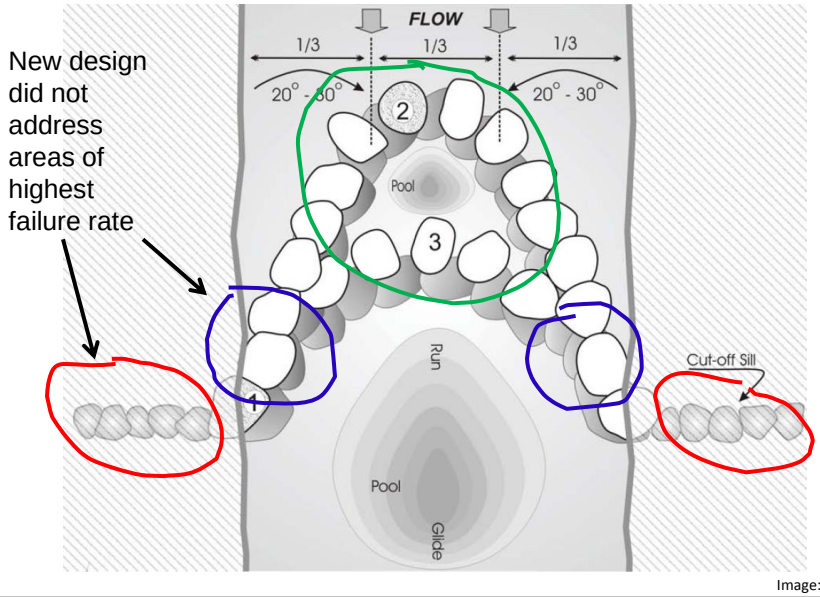

Image: Rosgen 2006

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Fish Passage Criteria

Boulder Weirs

Fish Passage Criteria

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- Concentrate flow into the center of the downstream pool.
- Direct flow toward the downstream thalweg.
- Providing a slight weir crest elevation decrease from each bank to the center (flow notch).
- Low flow notch will be designed to pass the minimum in-stream flow.

Fish Passage Criteria

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- Max hydraulic drop between adjacent weir crests or sills.
  - 1 ft upstream adult passage.
  - 0.5 ft upstream juvenile passage.

Fish Passage Criteria

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- If pools are rock lined or composed of non-erodible material minimum pool depth is 4 feet of depth.
- Tailrace area should be protected from scour.
- Design should anticipate and mitigate the lowering of streambed.

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Project Review & Assessment

General Guidelines…NOT CRITERIA!!!

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Project Review & Assessment

- Review Checklist
  - For several weirs in series slope does not exceed 5% (measured from crest to crest).
  - Weir apex should face upstream.
  - Throat should be in-line with thalweg.
  - Weirs should not be placed in bends.

Project Review & Assessment

NOAA FISHERIES SERVICE

- Review Checklist
  - Planform shape should concentrate flows away from the banks…towards the center of the channel .
  - Side slope should focus flows away from streambanks toward the center of the channel.
    - Side slope should be between 3 to 7 degrees.
  - Structure should be entirely below the bankfull elevation.

Project Review & Assessment

NOAA FISHERIES SERVICE

- Review Checklist
  - Open angle should be between 90 and 120 degrees.
  - Header should rests upstream at a 45 degree angle to footer rock.
  - Minimum rock size should be between 2-3 ft diameter.
  - Maximum rock size should be less than 1/3rd the bankfull width.

Project Review & Assessment

NOAA FISHERIES SERVICE

- Review Checklist
  - Spacing
    - Regular pools should be sequenced between 0.5 to 2 channel widths.
    - Large pools (energy dissipation) should be sequenced at 2 to 4 channel widths.
    - Grade control weirs should be spaced no closer drop between weir crests divided by stream slope.
  - Weir should be designed with at least one header and one footer element.

Project Review & Assessment

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- Review Checklist
  - Weir drop should be 1ft between successive weir crests.
  - Depth of footing protection should be constant throughout the structure.
  - Min scour depth should be 2.5 to 3.0 times the height of the drop OR size of channel D100 rock size (whichever is greater).

Project Review & Assessment

NOAA FISHERIES SERVICE

- Review Checklist
  - Angular rock should be used.
    - Uniform in size and durable (no cracks and defects).
  - Rocks should be placed tightly together.
    - Minimum of three contact points.
  - Gaps and voids should be filled with well-graded material.

Project Review & Assessment

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- Review Checklist
  - Weir arms should extend into the stream bank…
    - As far as the banks are tall
    - Two footer rock diameters
    - Four times the channel D^{100}
    - Minimum eight feet
    - **Whichever is greater**
  - Footers should be keyed into the bank the same distance as headers

Project Review & Assessment

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- Review Checklist
  - Bank keyed footers should extend below predicted scour depth for channel.
  - Geo-synthetic sheets should be installed as deep as the footings.
  - Weirs should be located at least 35 feet upstream of culvert .
  - Weirs should be placed no closer than 20 feet downstream of the outlet .

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Data for Review

Large Boulder Weir Projects

Data for Review

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- Target species, life stages and migration timing at project site.
- Calculations of lower and upper fish passage stream flows for each life stage and species and 100-year flow.
- Calculations of weir depths and velocities.
- Calculations of depths and velocities within low flow notches.

Data for Review

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- Weir, channel, and/or bed material gradations (% finer graph) and calculations.
- Weir rock sizing calculations.
- Hydraulic calculations showing boulder weirs provide sufficient head to divert maximum diversion flow + bypass flow at minimum stream flow considering head losses at flow measurement devices, fish screens, pipes, open ditches, headgates, etc.

Data for Review

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- Engineering drawings
  - Project plan view.
  - Project longitudinal view.
  - Weir cross section in stream wise direction.

Data for Review

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- Engineering drawings/plans show or call out…
  - Water surface profiles at existing and proposed conditions for upper and lower fish passage stream flows and 100-year flow (at a minimum must be shown in the longitudinal profile view).
  - Details and construction notes on placement of bed material and boulders.
  - Delineated floodplains for the lower and upper fish passage flows as well as the 100-year flow.

Data for Review

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- Engineering drawings/plans show or call out…
  - Thalwag (existing and proposed).
  - Locations of bankfull width measurements and their individual values.
  - Open angle of weirs (in degrees).
  - Keyed length (embedded length) of weir arm into the streambank.
  - Size of designed header and footer rock.
  - Size of D100 rock size from natural channel.

Data for Review

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- Engineering drawings/plans show or call out…
  - Distance of weir spacing (distance between successive weir crests).
  - Delineate historic channel and call out historic migration paths.
  - Distance between weir crests (drop).
  - Distance of weir spacing (distance between successive weir crests).
  - Pool depths (all design flows).

Data for Review

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- Engineering drawings/plans show or call out…
  - Stream depth in tail water section of pool .
  - Material gradations (pool lining, stream bed/bank, weir, or other).
  - Weir footing depth.
  - Stream slope (existing and proposed conditions).
  - Show orientation of geo-synthetic sheets.
  - Depth of geo-synthetic sheets.

Data for Review

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- Engineering drawings/plans show or call out…
  - Show weir cross section (include low flow notch and WSE's for the several design flows).
  - Keyed length (embedded length) of weir arm into the streambank.
  - Weir side slope (in degrees).
  - Bank height ratio for existing and proposed conditions.
  - Meander width ratio for existing and proposed conditions.

Data for Review

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- Engineering drawings/plans show or call out…
  - Channel entrenchment ratio for both existing and proposed conditions.

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Monitoring

Boulder Weirs

Monitoring

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- Designs should perform their intended designed function.
- Irrigation applications should be monitored on a regular basis.
  - Flood events on the scale of the 5-10 year flood can require significant maintenance.

Monitoring

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- All applications…
  - Should not become porous during low flow conditions (summer/fall).
  - Should provide concentrated flow during the lowest flow condition of the year.

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Maintenance

Boulder Weirs

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Maintenance

- USBR observed that a high level of maintenance was required to provide irrigators with their water right at boulder weir structures used for water diversions.
- Boulder weir designs often induce the same channel instability as push-up dams.
- Anticipate annual and semi-annual intrusions into the creek with machinery.

Maintenance

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- Irrigation applications will result in additional in-stream work producing continuous fish and habitat impacts.
- Anticipated maintenance efforts should reflect the size of the system designed for and the necessary “elevation” accuracy of the design.

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END

Thank you!

Contact Info

NOAA FISHERIES SERVICE

Contact INFO:

aaron.beavers@noaa.gov

503-231-2177