10. Sediment Mobility and Stability

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Contributors

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Two big sediment transport questions:

Transport continuity of gravel/cobble at lower flood flows?

Stability of large pieces during design flood?

Presentation Outline

- **BACKGROUND**
  - **Bedload Transport**
  - **Channel Types and Bed Mobility/Stability**
- **WHY DO BED STABILITY-MOBILITY ANALYSIS?**
- **FLOW HYDRAULICS AND SEDIMENT ENTRAINMENT**
- **DESIGN APPLICATION**
  - **Bed Mobility**
    - Modified Critical Shear Stress Approach
    - Unit Discharge Approach Bed Stability
  - **Bed Stability**
    - Modified Critical Shear Stress Approach
    - Unit Discharge Approach
    - Other Equations

Bedload Transport in Brief..

- **Phases of Bedload Transport**
- **Temporal and Spatial Variability**
- **Sediment Supply and Armoring**

Bedload Transport Phases

Phase I Bedload Transport:

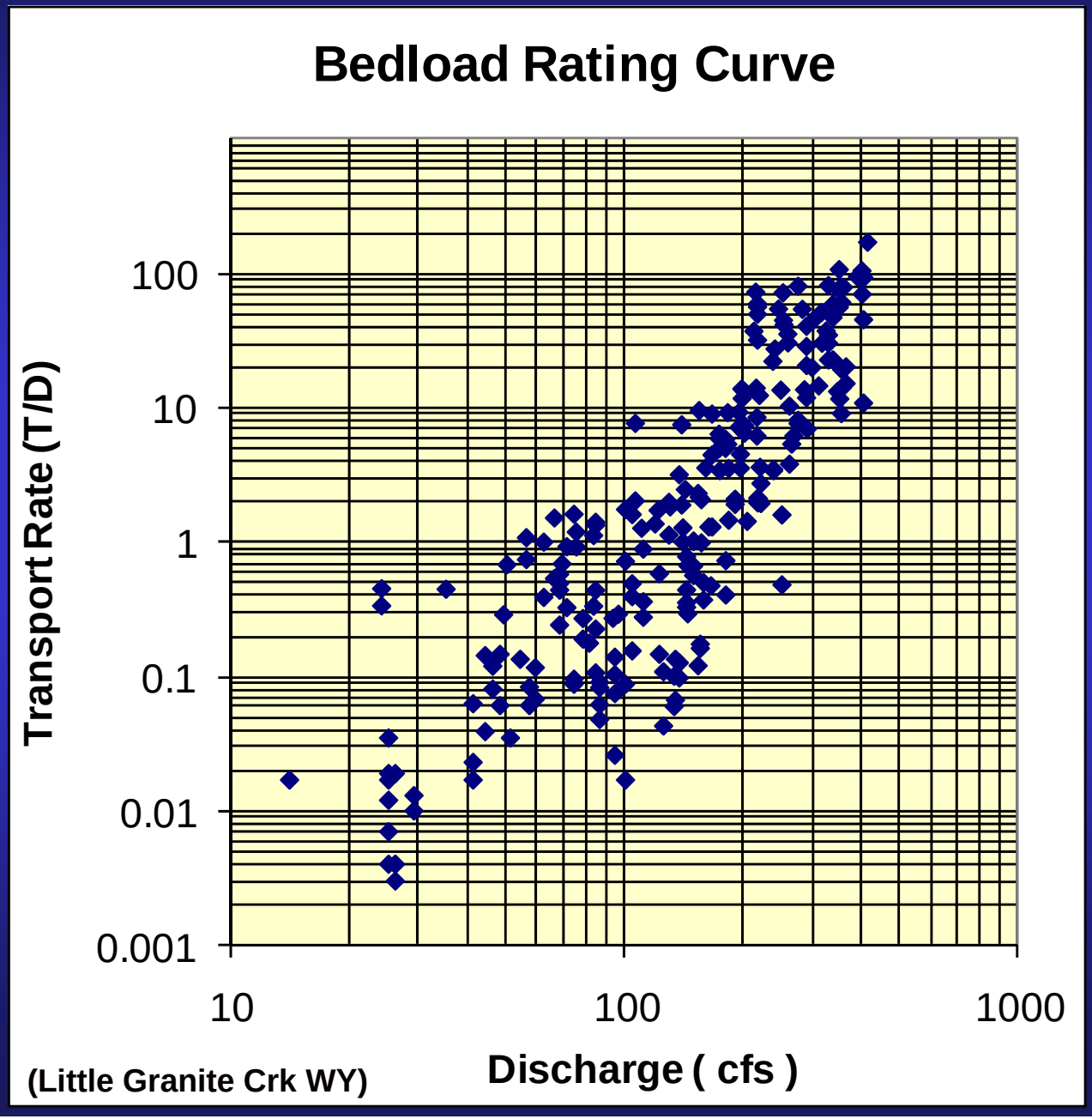
The transport of fine sediment over the immobile armor layer

Phase II Bedload Transport:

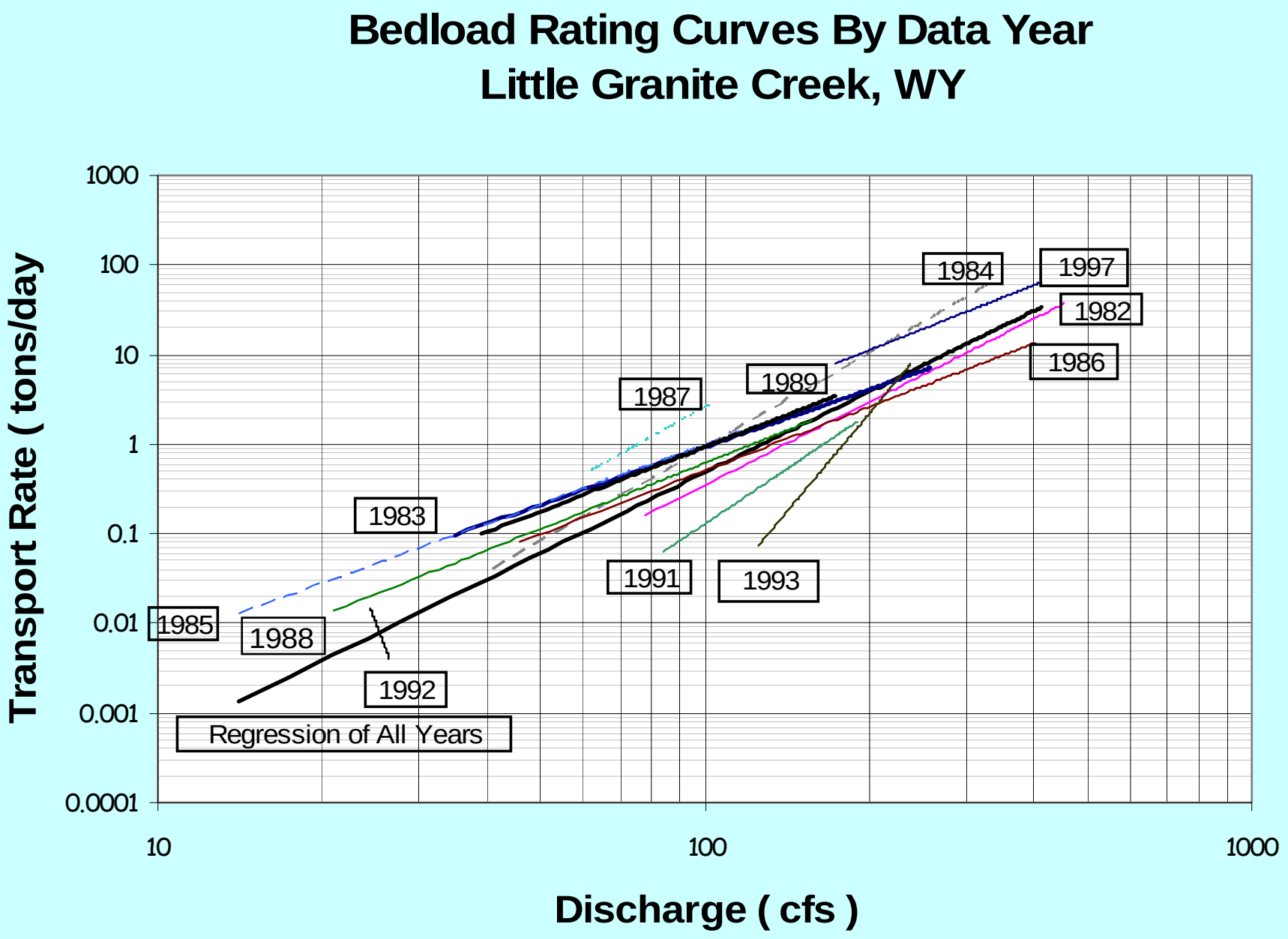
The armor layer is breached and the bed is mobilized

Surface Armor Layer

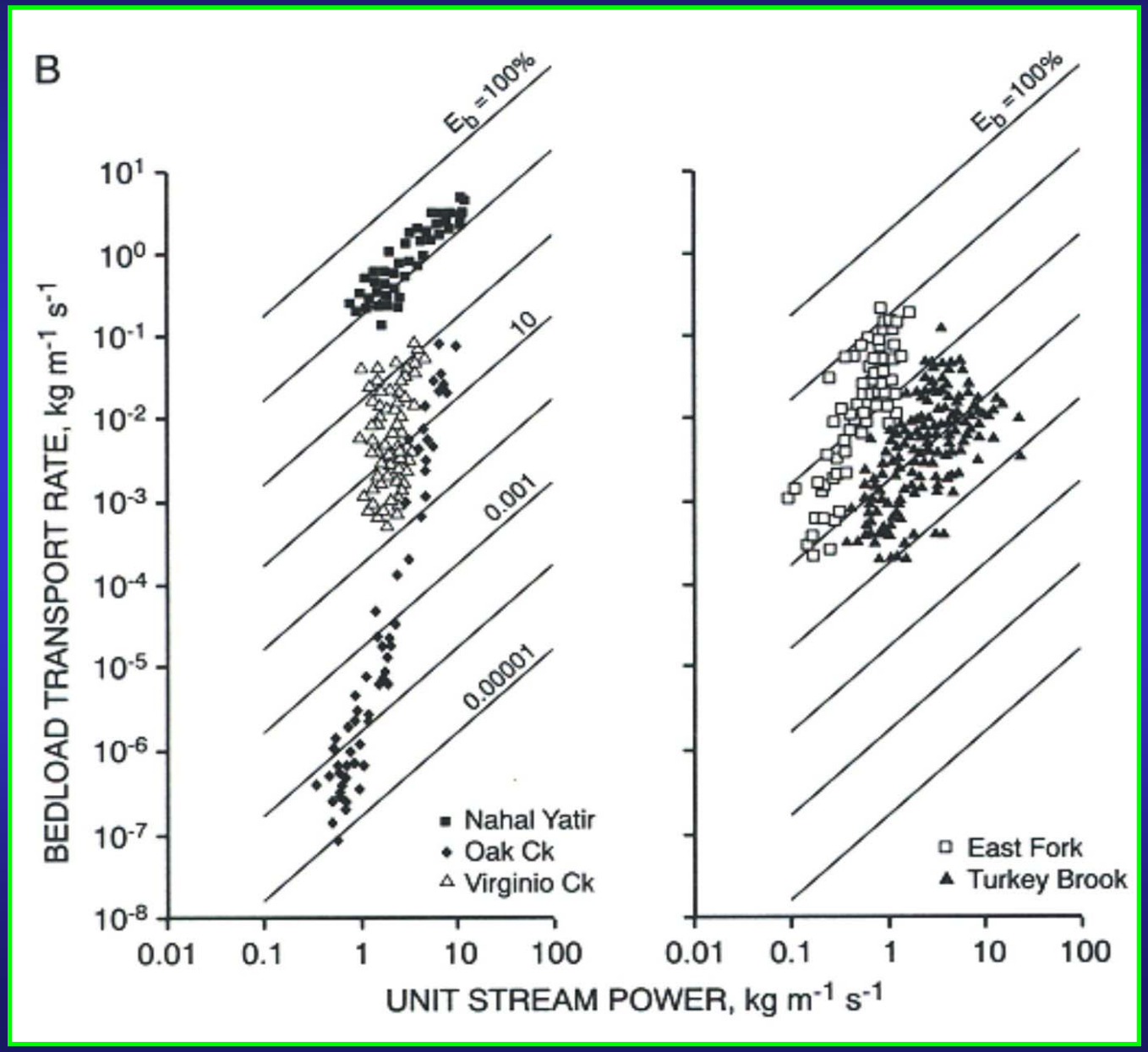
Bedload Temporal Variability



Annual Bedload Temporal Variability

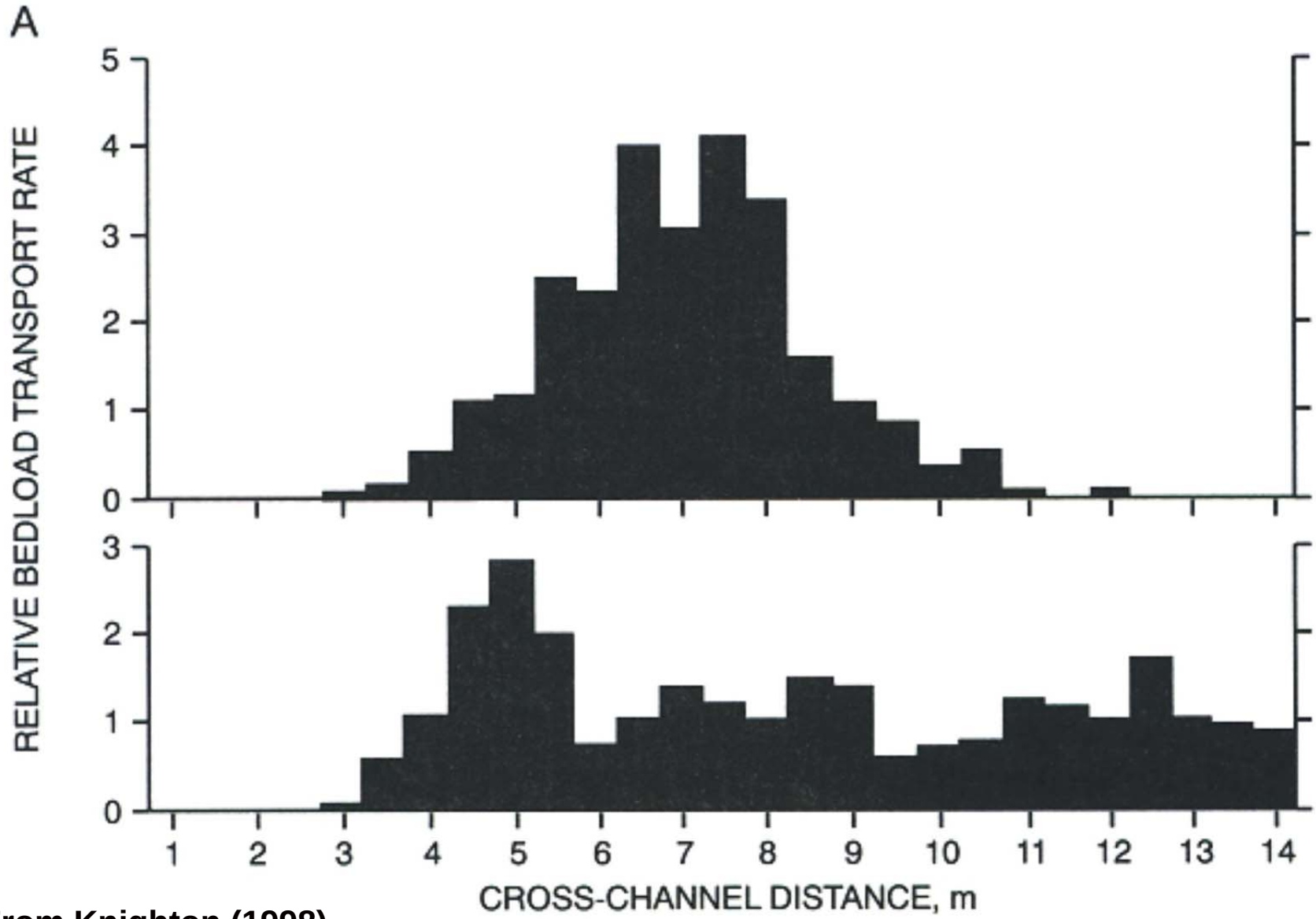


Different Transport Rates for Different Streams



From Knighton (1998)

Bedload Spatial Variability

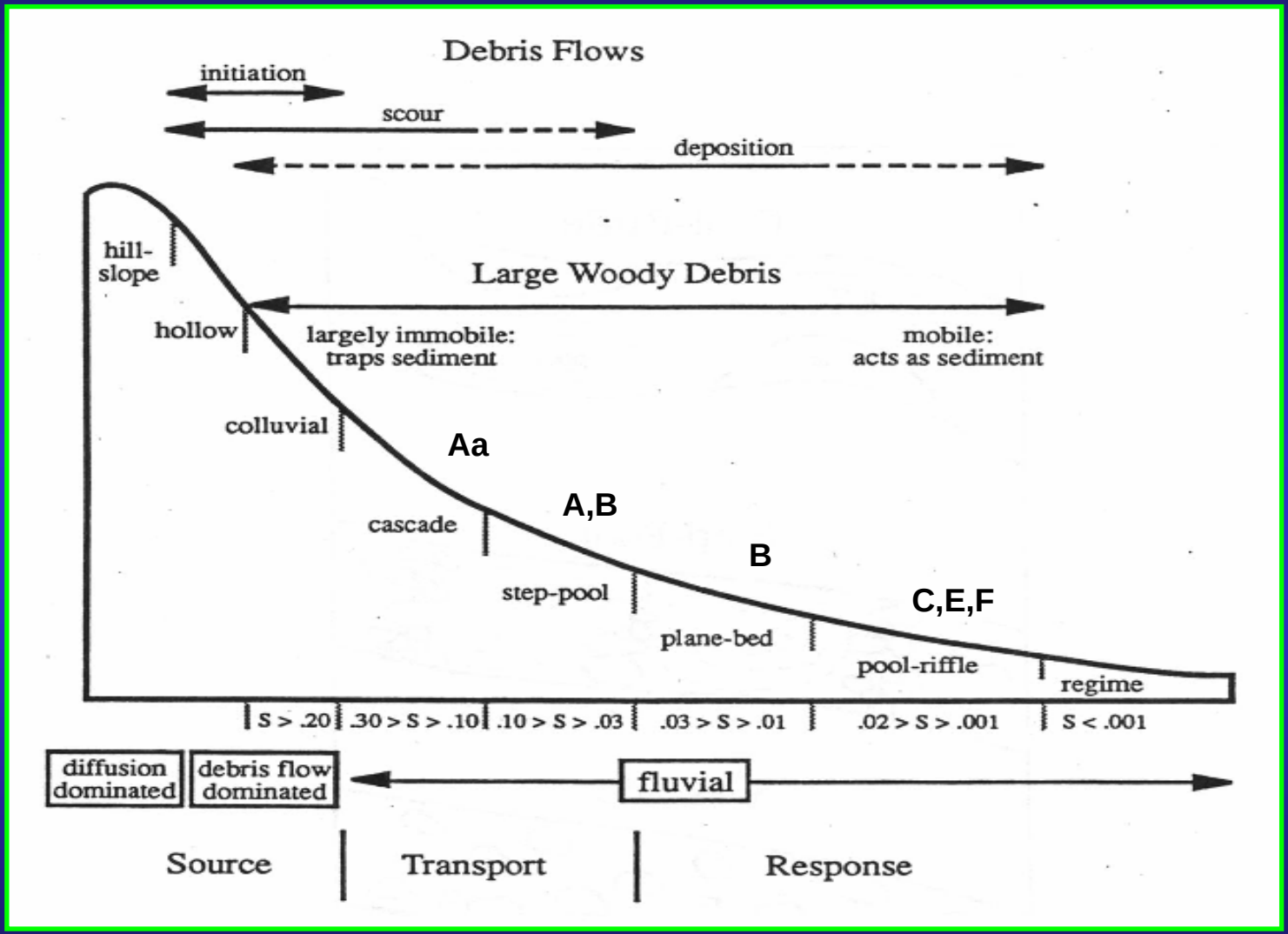


From Knighton (1998)

Relationship Between Channel Type and Sediment Entrainment/Bedload Transport

Channel – Bed Type	Relative Mobility	Typical Transport at Bankfull	Structure	Channel Type
Boulder Cobble	Low	Phase I	Steps	Rosgen A Cascade Step Pool
Gravel Cobble		Phase I Phase II	Particle clusters Armor	Rosgen B C Plane Bed Pool Riffle
Sand	High	Phase II	Bed Forms	Rosgen C Regime

Channel Type, Sediment Entrainment, Bedload Transport



(From: Montgomery & Buffington, 1993)

Bedload Transport Summary

Sediment entrainment and bedload transport have considerable uncertainty in prediction – uncertainty increases with gradient

- Sand bed streams – D_{84} may move constantly
- Low gradient gravel bed pool-riffle - D_{84} may move every few years
- High gradient boulder step-pool - D_{84} may not move for decades

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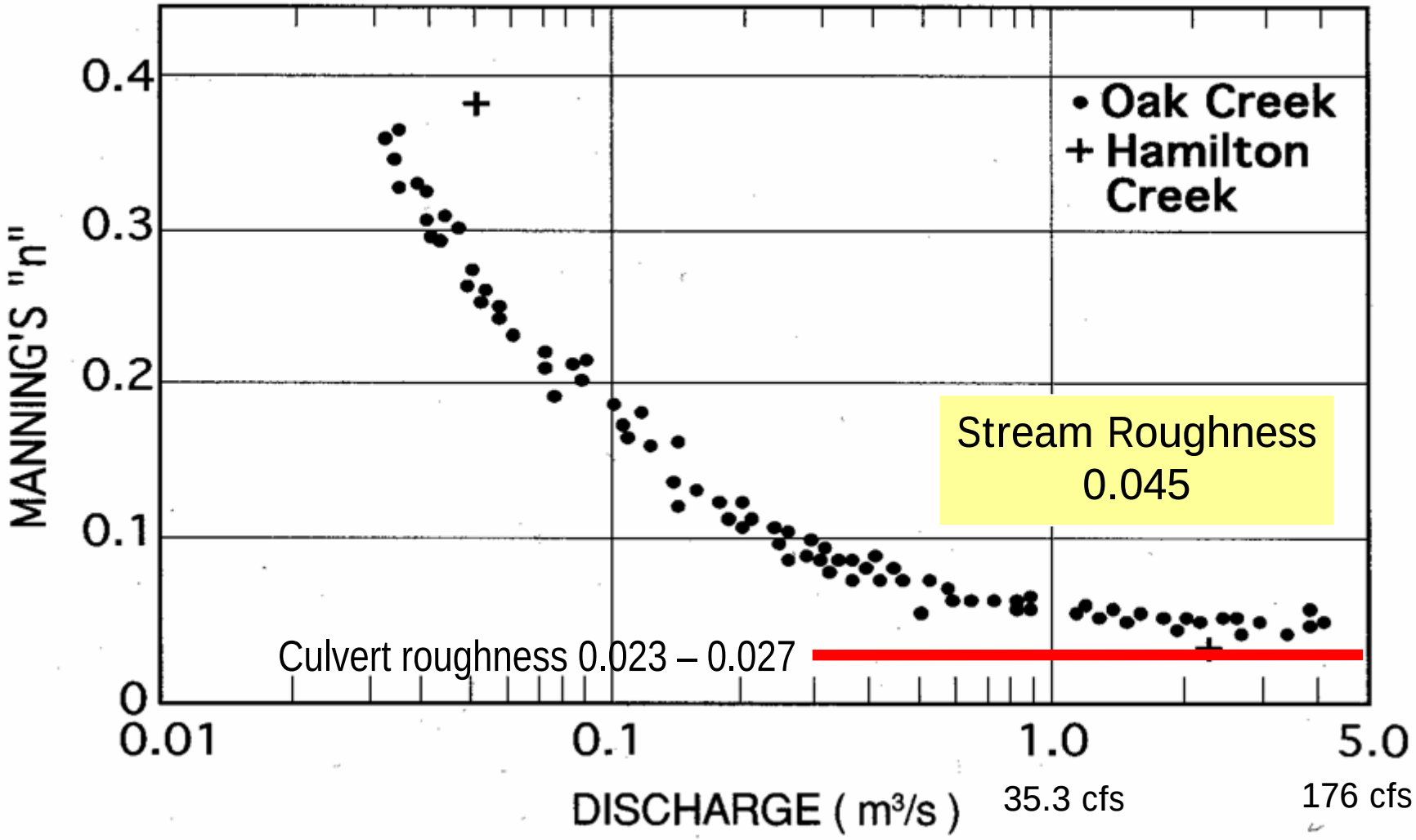
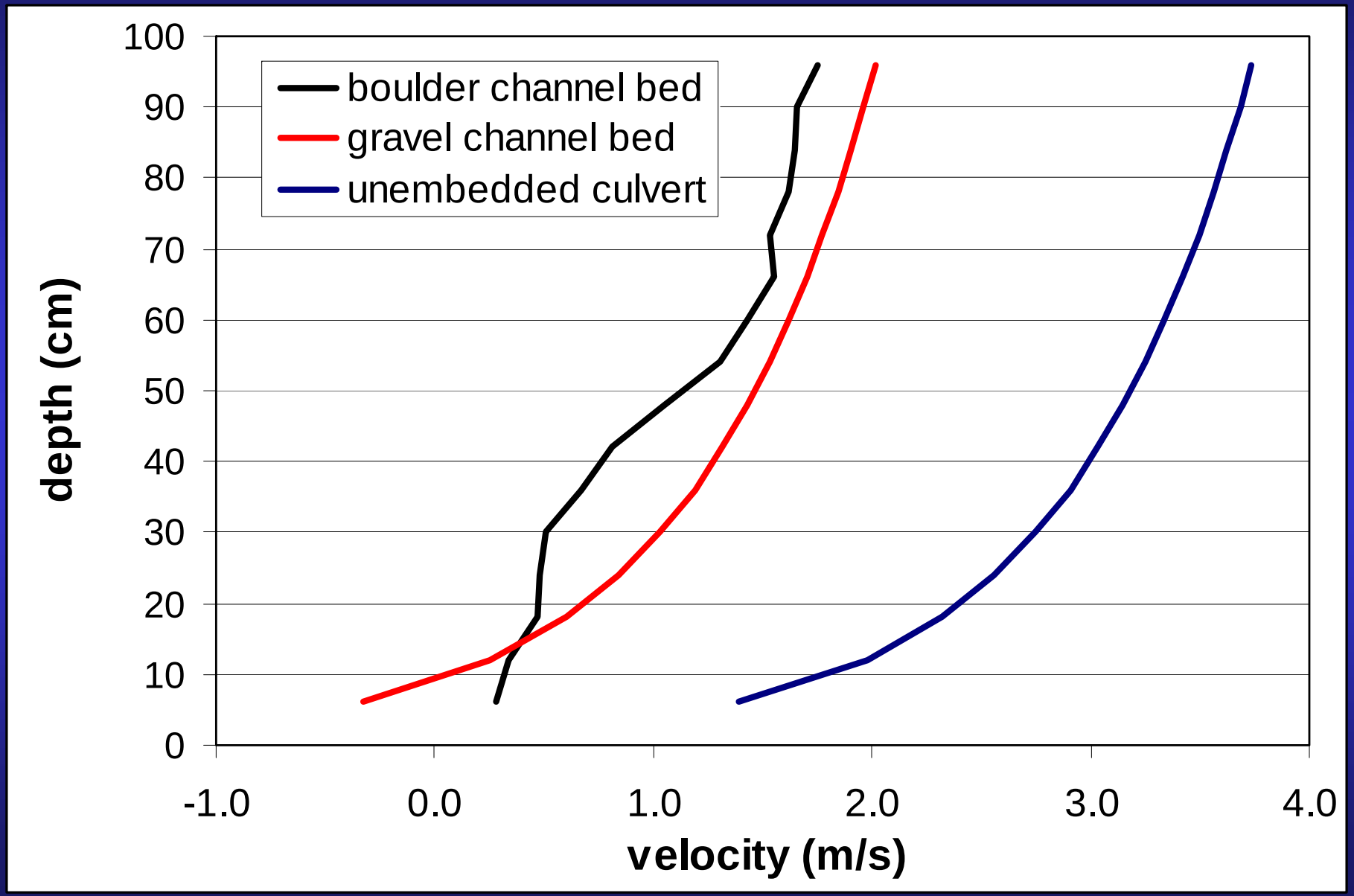
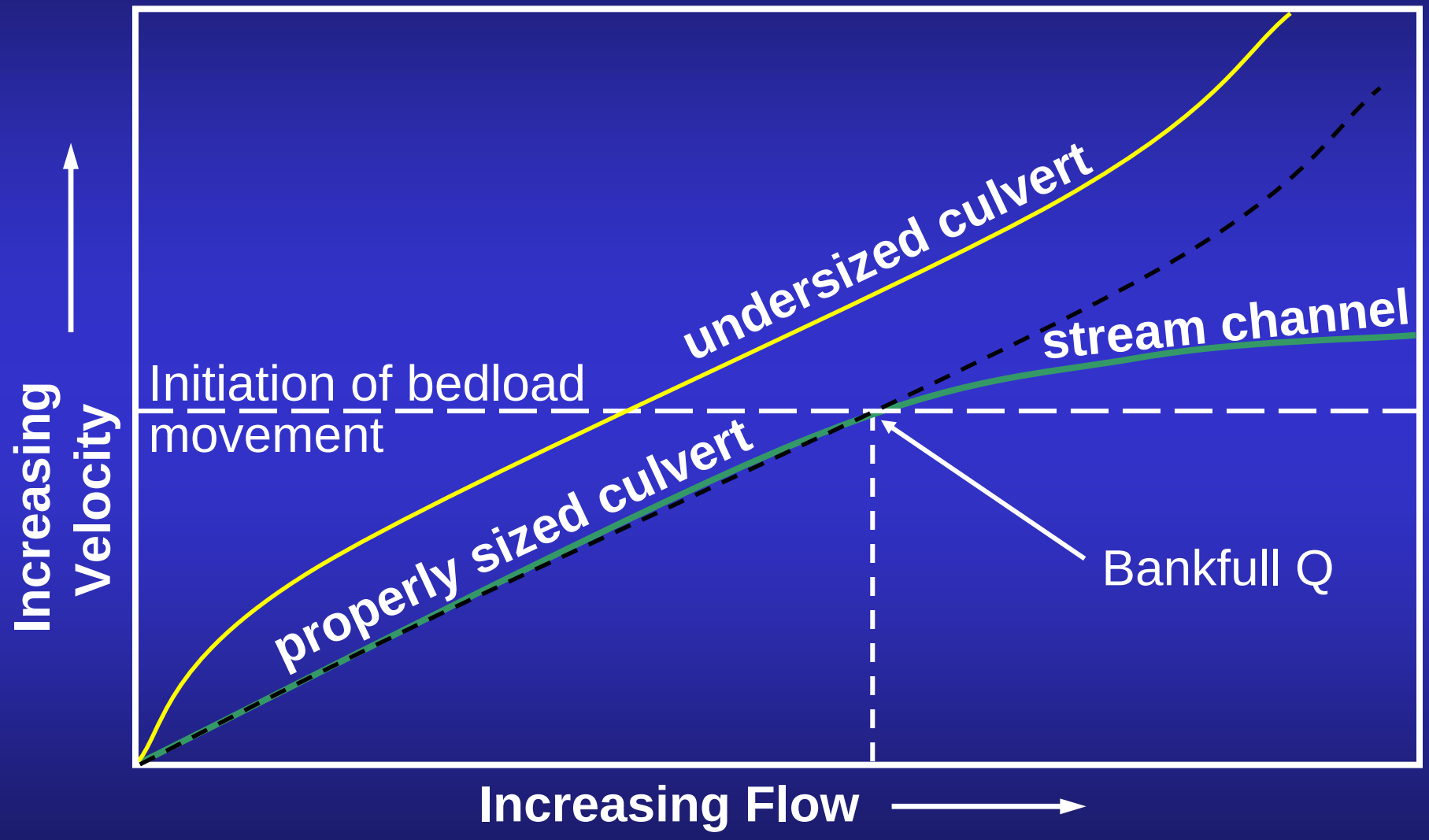
Variation of "n" with Flow



Typical velocity profiles



Bedload and Culverts



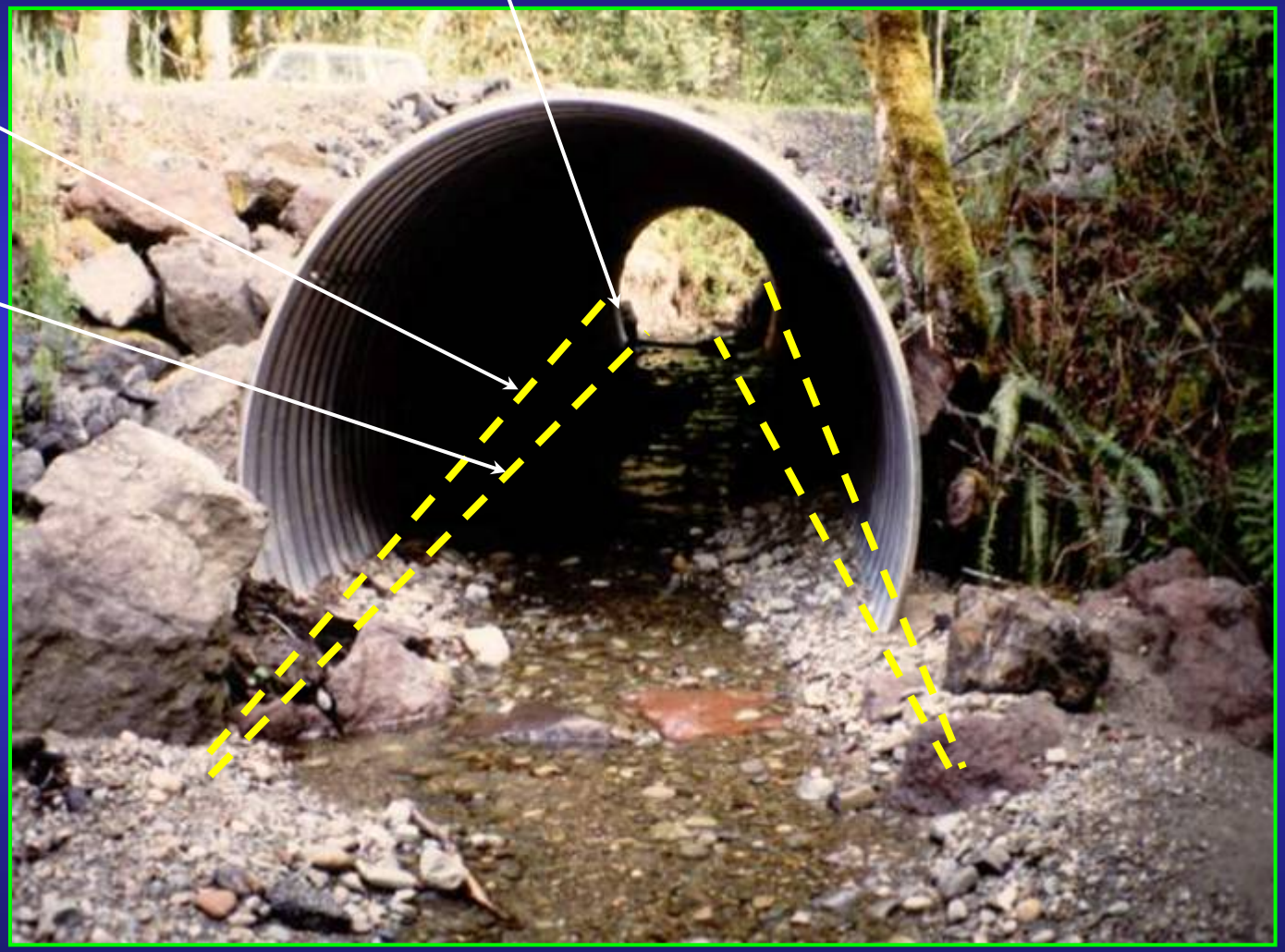
Bed Failure

Stimson Ck.
Width ratio = 1.0
Slope = 2.2% (5%)

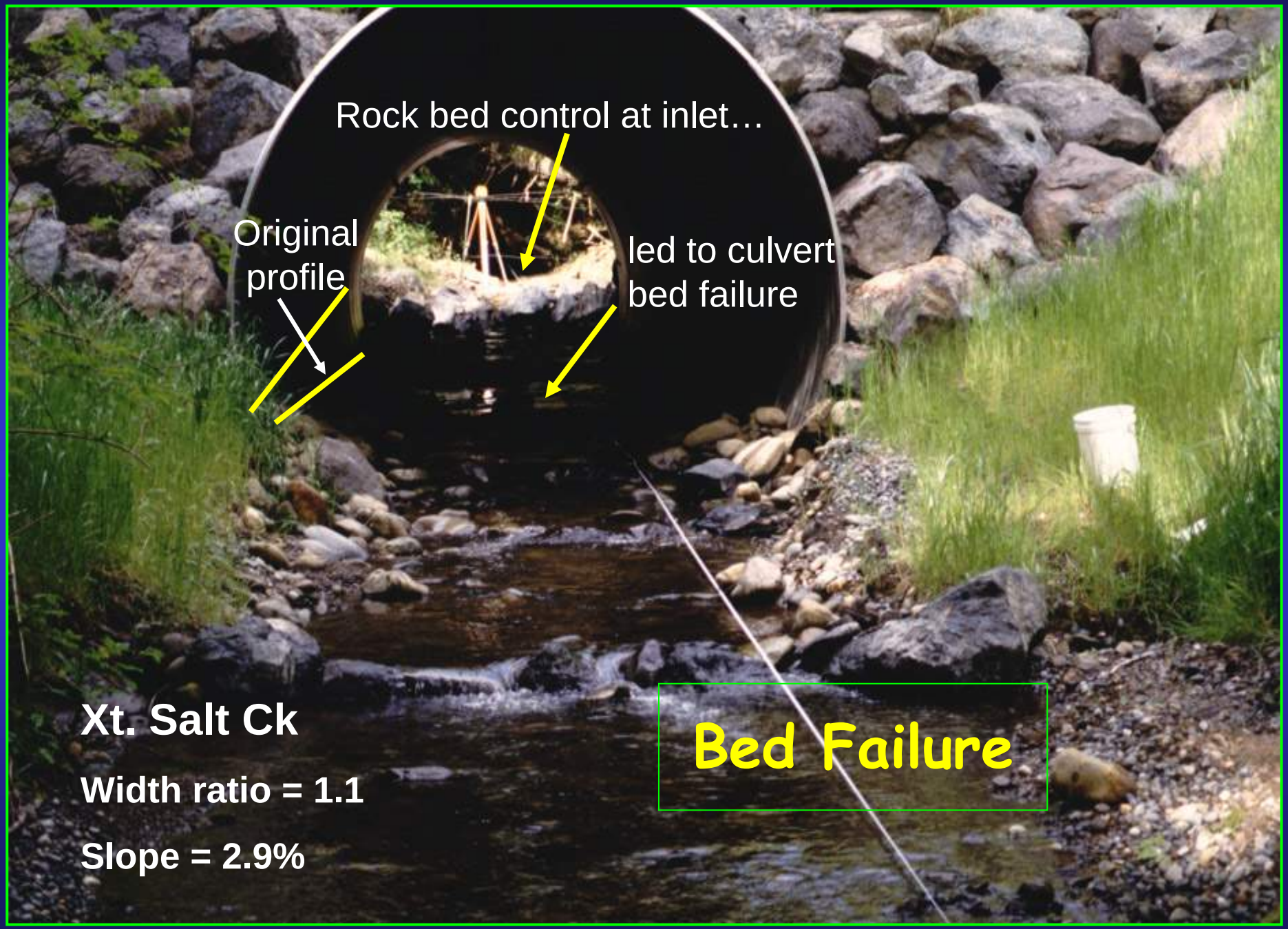
Note regrade

Original profile

Resulting profile



Culvert too narrow, bed material too small.

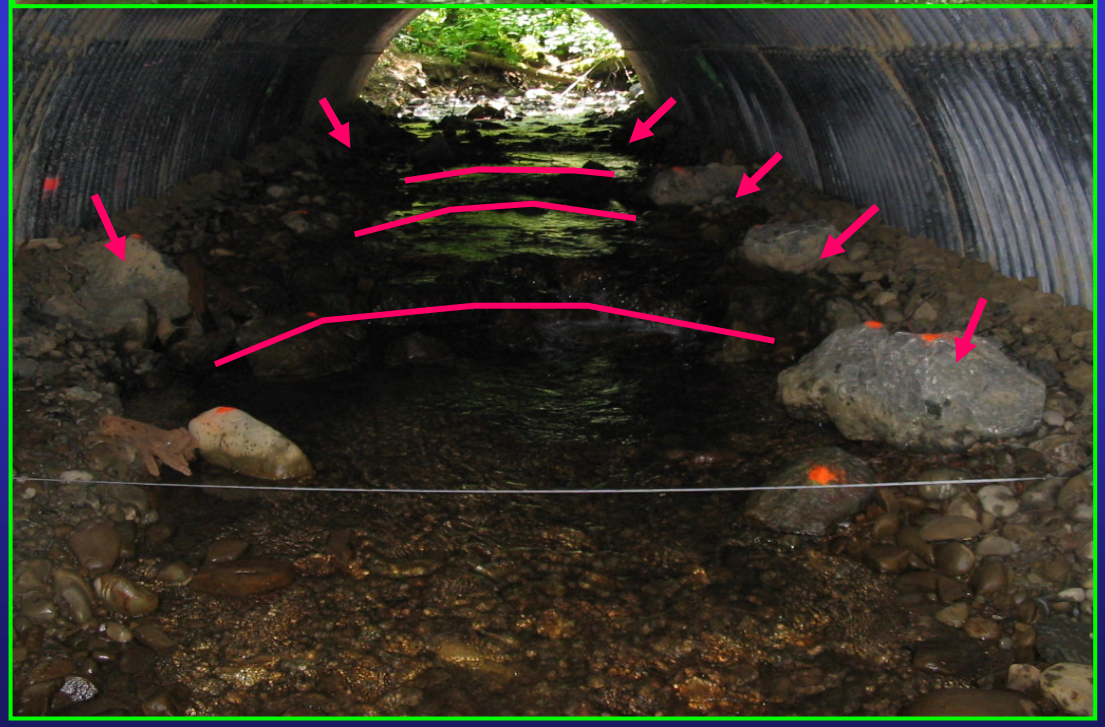

Rock bed control at inlet…
Original profile
led to culvert bed failure
Xt. Salt Ck
Width ratio = 1.1
Slope = 2.9%
Bed Failure

Bed Mobility and Stability Considerations?

- Key bed or grade control features
  - steps, particle clusters
- Bank material
- Floodplain contraction
  - entrenchment ratio high
  - floodplain conveyance high

The big questions:

- Is the mobility of sediment in the design channel similar to the mobility of sediment in the reference reach channel?
- Is sediment transport continuity occurring through the channel at low/moderate floods?
- Are key pieces and grade controls stable for the design flow and large floods?



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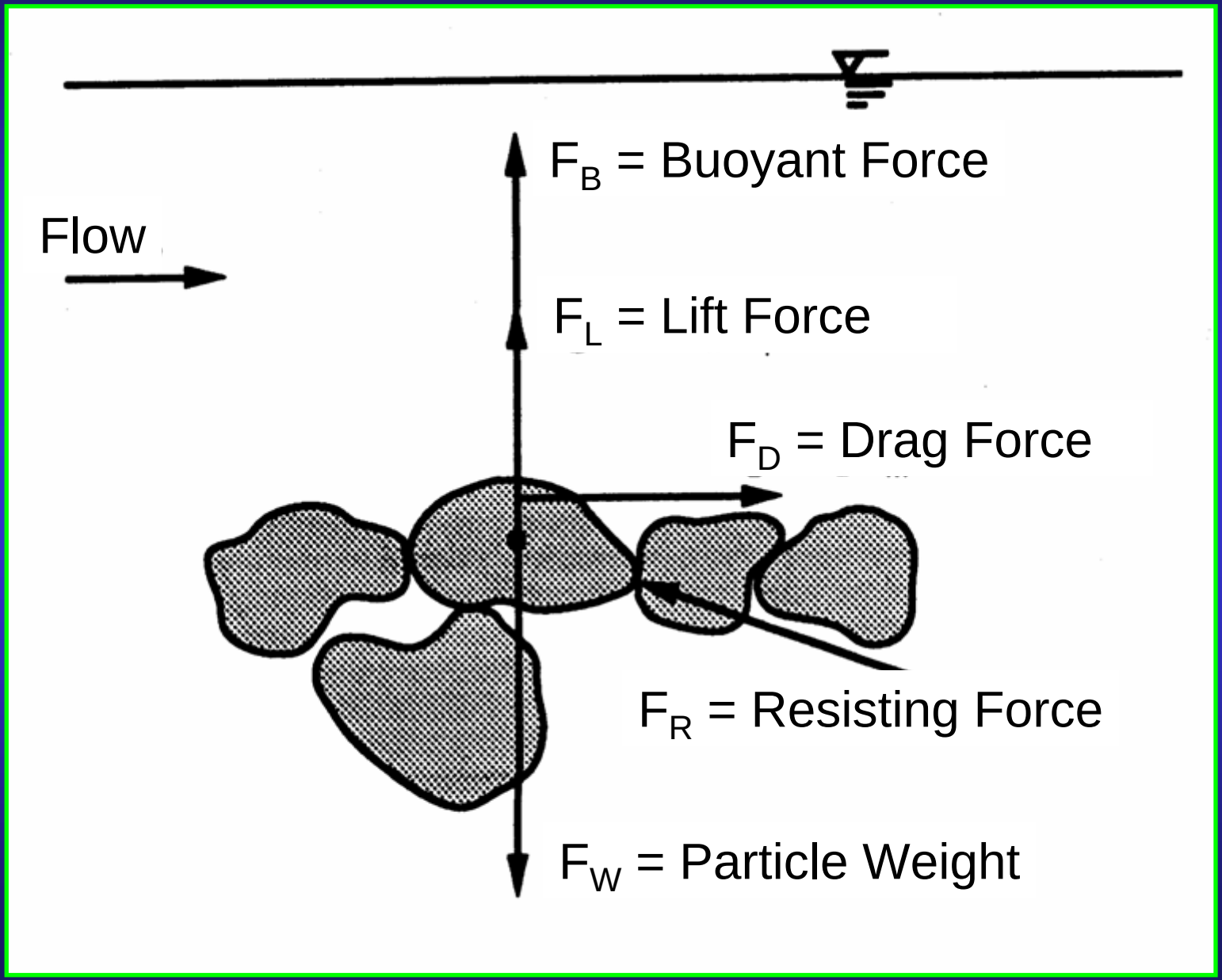
Entrainment = Incipient Motion



Factors Affecting Motion

1) Sediment Properties

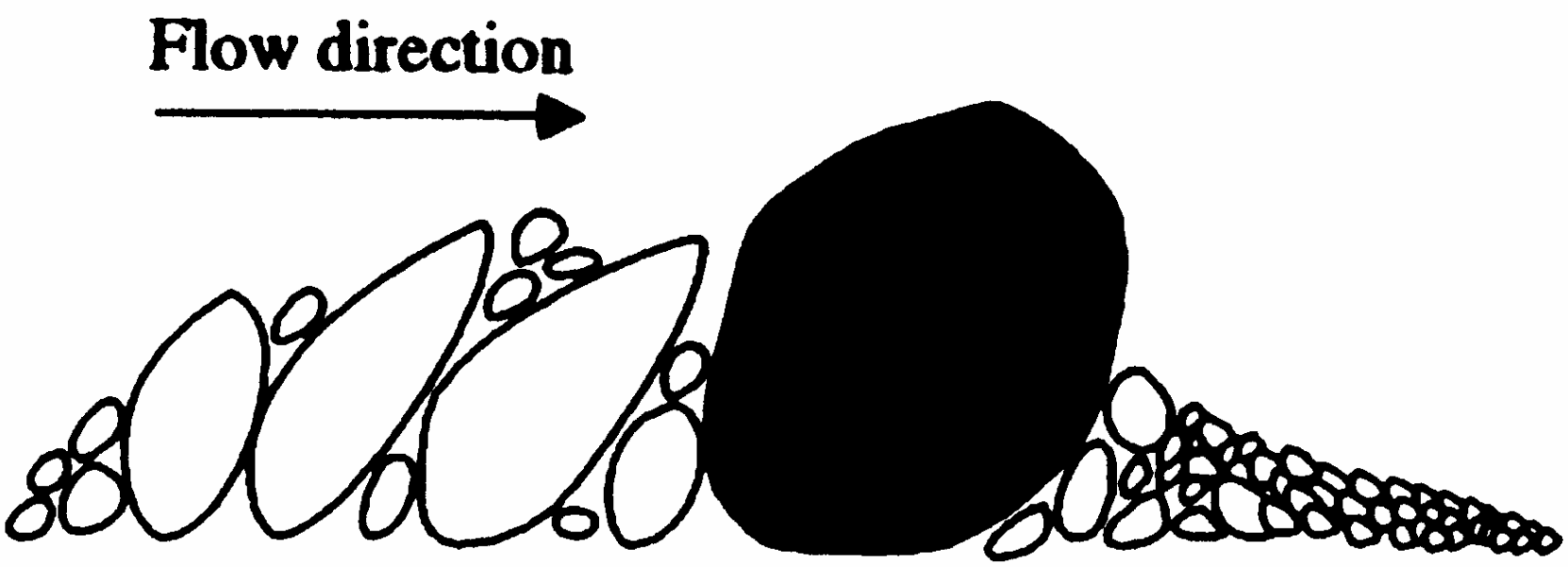
- particle size
- particle shape
- particle density
- pivot angle

2) Channel-bed

- packing of particles
- orientation of particles
- sorting of sediments
- distribution of bedforms
- exposure to flow

3) Flow hydraulics

- velocity
- flow depth
- slope
- turbulence



Quantifying Hydrodynamic Forces

Total bed shear stress:

$$\tau = \gamma \cdot R \cdot S$$

Stream power:

$$\Omega = \gamma \cdot Q \cdot S$$

Unit Discharge:

$$q = Q / w$$

Variables:

τ is total bed shear stress (N/m^2)

γ is sp weight of fluid (N/m^3)

R is hydraulic radius (m)

S is energy slope

Ω is stream power (W/m^2)

Q is discharge (m^3/s)

q is unit discharge (m^2/s)

w is flow width (m)

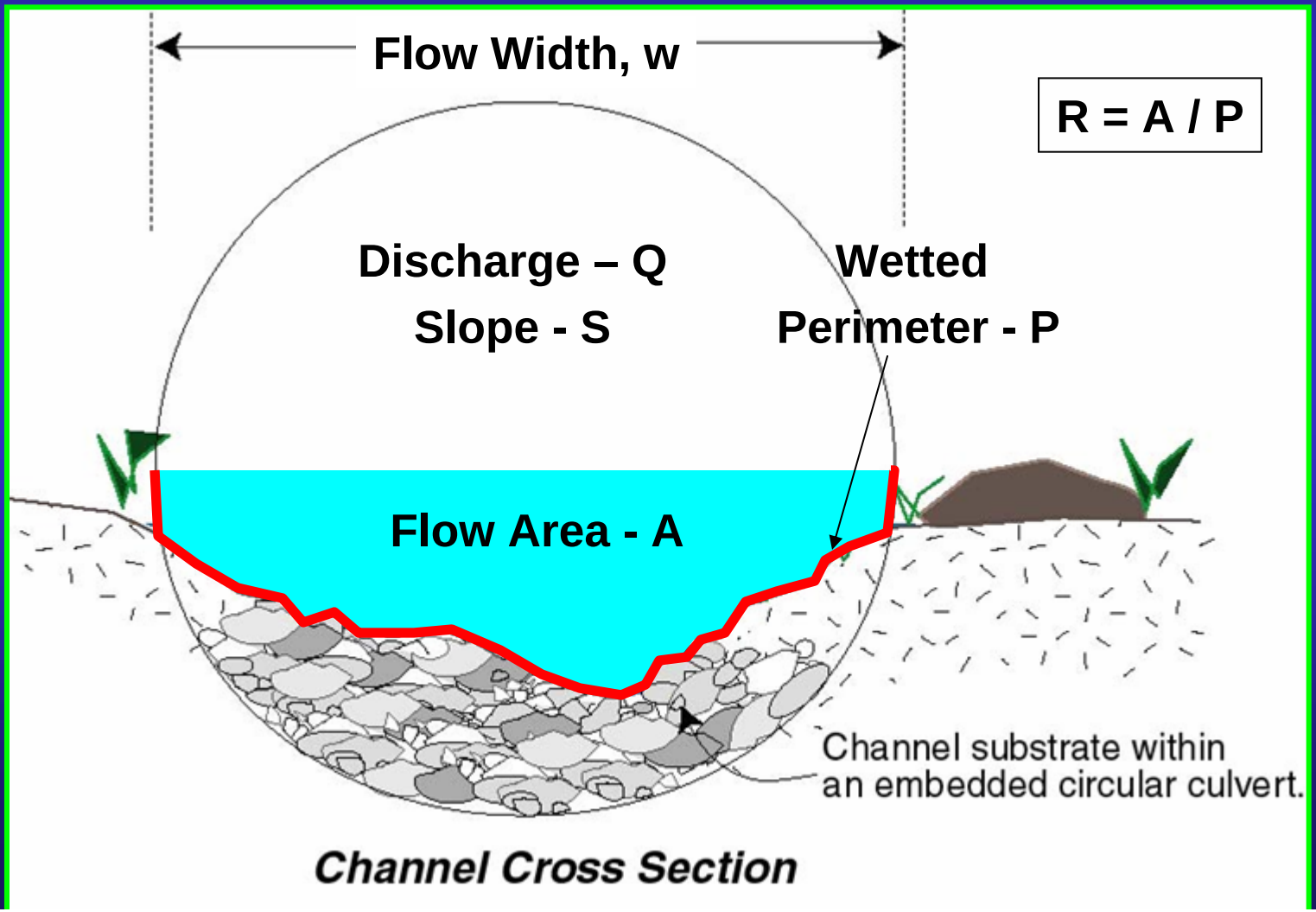
Quantifying Hydrodynamic Forces

Unit Discharge:

$$q = Q / w$$

Total bed shear stress:

$$\tau = \gamma \cdot R \cdot S$$



Early Effort to Define Motion

Shields (1936) for UNIFORM grains on flat bed

$$\tau^* = \frac{\tau_c}{\gamma(G-1)D_i} = \frac{\gamma RS}{\gamma(G-1)D_i} = \frac{RS}{(G-1)D_i}$$

τ^* = Shields parameter

τ_c = critical shear stress - particle begins to move

γ = unit weight of water

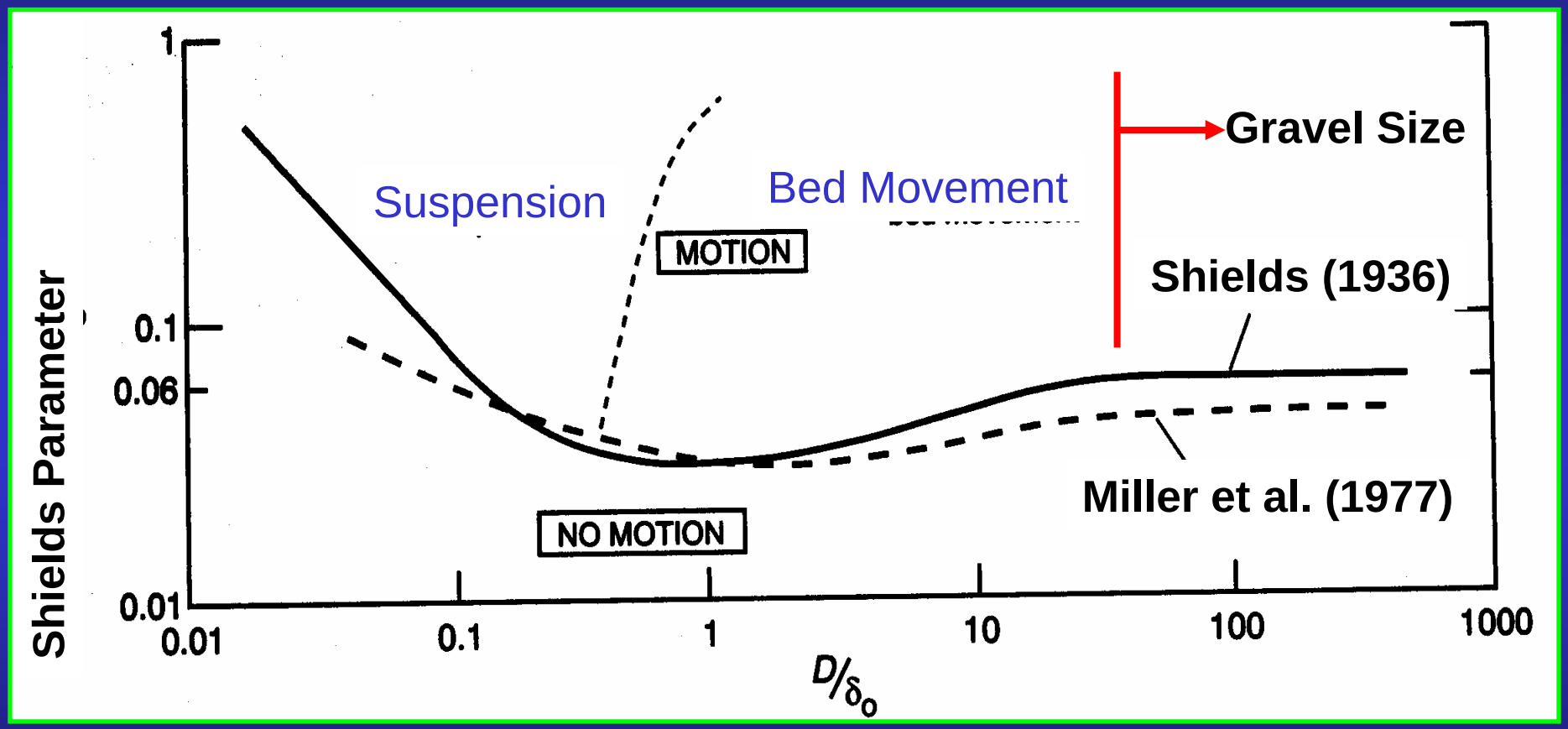
R = hydraulic radius

S = stream slope

G = specific gravity of sediment

D_i = sediment particle size of interest

Shield's Parameter vs Particle Size



Entrainment Threshold Table

Table 2. Entrainment thresholds for different particle sizes (modified from Julien, 1995). The Shields parameter and critical shear stress values are for the smallest number in the particle-size interval.

Particle size classification	Particle size, D_s (mm)	angle of repose, ϕ (degrees)	Shield's parameter[a], τ_*	critical shear stress, τ_{cr} (N/m^2)
very large boulders	> 2048	42	0.054	1789
large boulders	1024-2048	42	0.054	895
medium boulders	512-1024	42	0.054	447
small boulders	256-512	42	0.054	224
large cobbles	128-256	42	0.054	112
small cobbles	64-128	41	0.052	54.0
very coarse gravels	32-64	40	0.050	26.1
coarse gravels	16-32	38	0.047	12.1
medium gravels	8-16	36	0.044	5.64
fine gravels	4-8	35	0.042	2.72
very fine gravels	2-4	33	0.039	1.26
very coarse sands	1-2	32	0.029	0.48
coarse sands	0.5-1.0	31	0.033	0.27
medium sands	0.25-0.50	30	0.048	0.19
fine sands	0.125-0.25	30	0.072	0.15
very fine sands	0.0625-0.125	30	0.109	0.11
coarse silt	0.0313-0.0625	30	0.165	0.084
medium silt	0.0156-0.0313	30	0.250	0.063

a. equations used to determine Shield's parameter:

$\tau_* = 0.25\,(25296D)^{-0.6}\tan\phi$ when 0.012 mm < D < 0.75 mm (medium silt to coarse sand)

$\tau_* = 0.013\,(25296D)^{0.4}\tan\phi$ when 0.75 mm < D < 2 mm (coarse sand to very coarse sand)

$\tau_* = 0.06\tan\phi$ when D > 2 mm (gravels, cobbles, and boulders)

Application

Threshold:

$$\tau^* = \frac{\tau_c}{\gamma(G-1)D_i}$$

$$\tau_c = \tau^* \gamma (G-1) D_i$$

Driving Force:

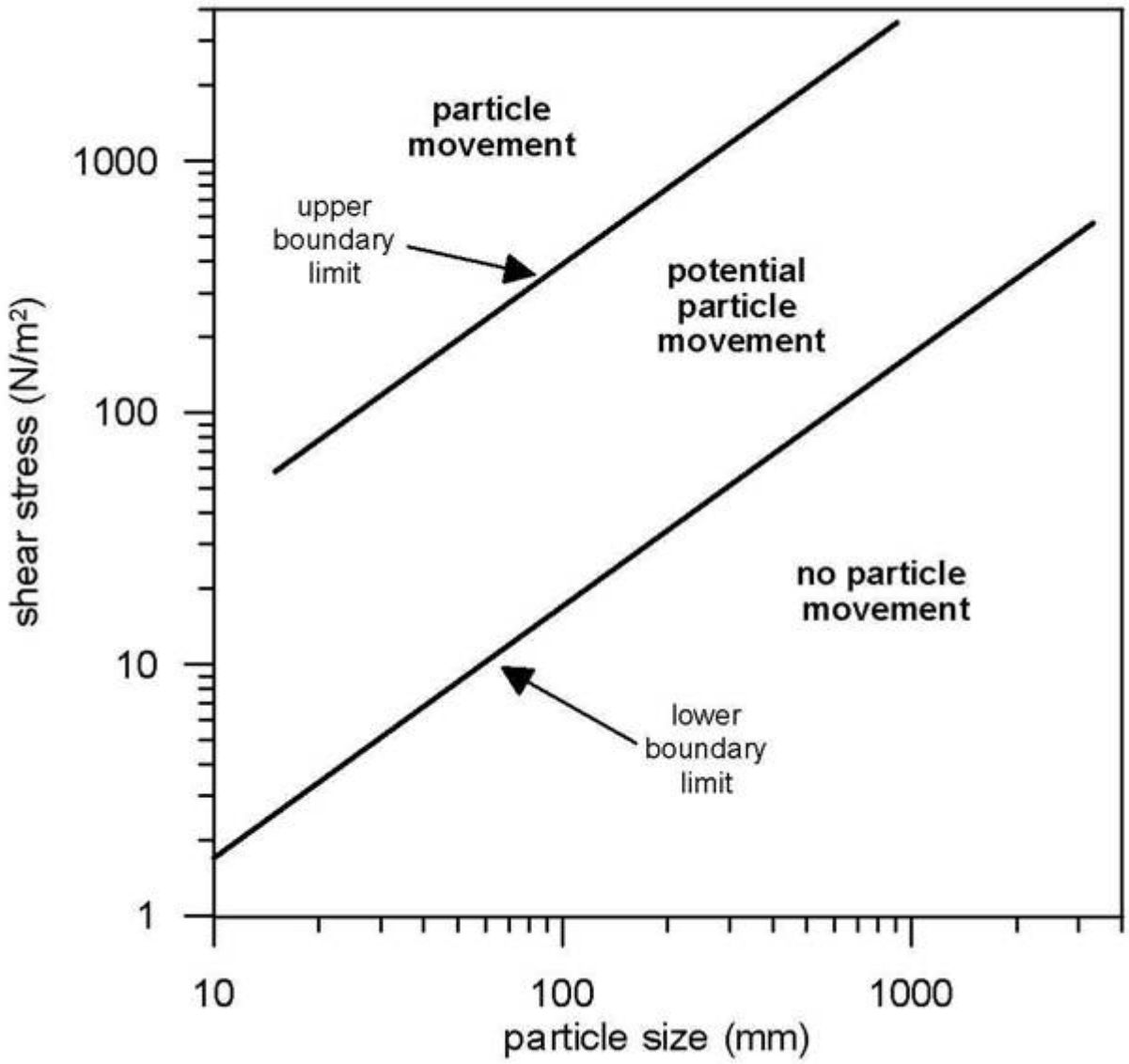
$$\tau = \gamma \cdot R \cdot S$$

If $\tau > \tau_c$, particle will move
If $\tau < \tau_c$, particle will not move

Most Stream Beds are NOT UNIFORM

Some are FAR FROM UNIFORM

Empirical - Williams (1983)

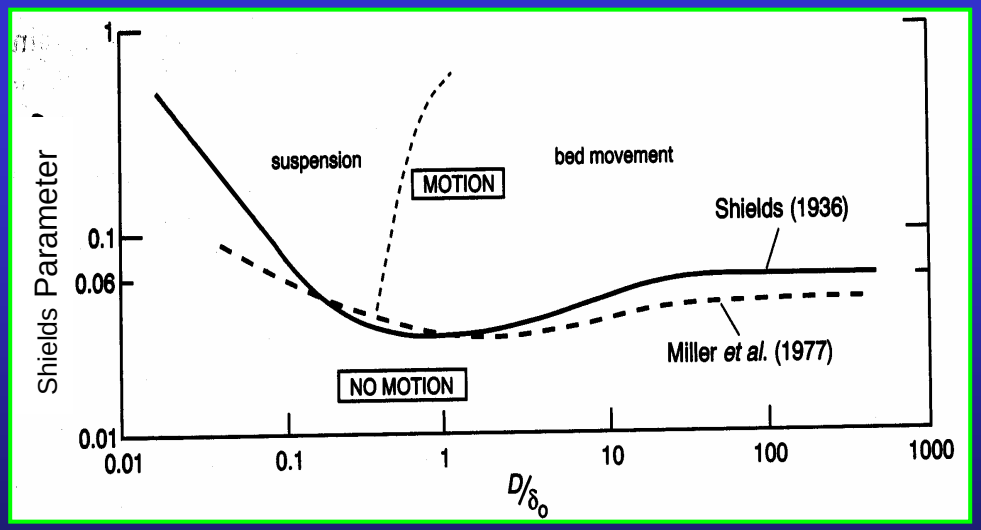


Real Stream Beds:

- **Not Uniform**
- **Variable Density**

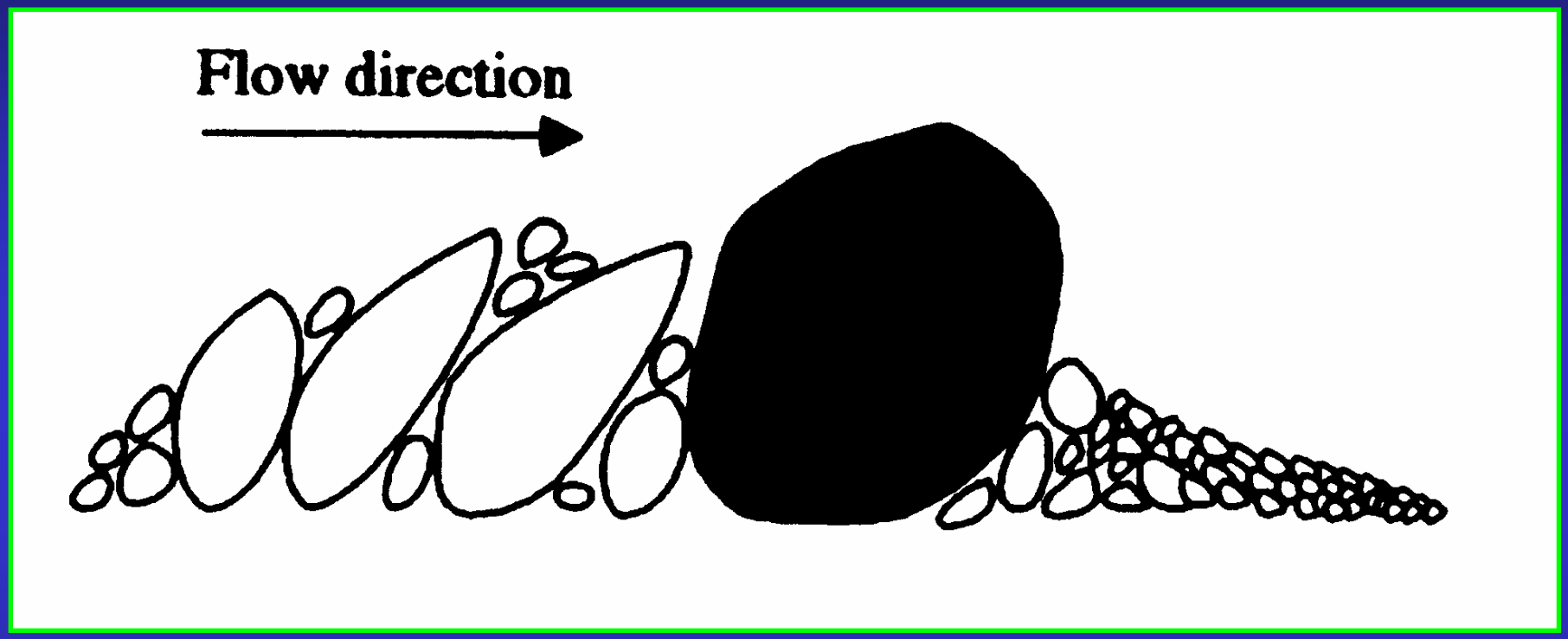
Density of Sediment Mixture

For gravel sized grains and larger, the critical Shields parameter varies an order of magnitude depending on if the bed is loosely packed ($\tau^* = 0.010$) or tightly packed ($\tau^* = 0.080$)



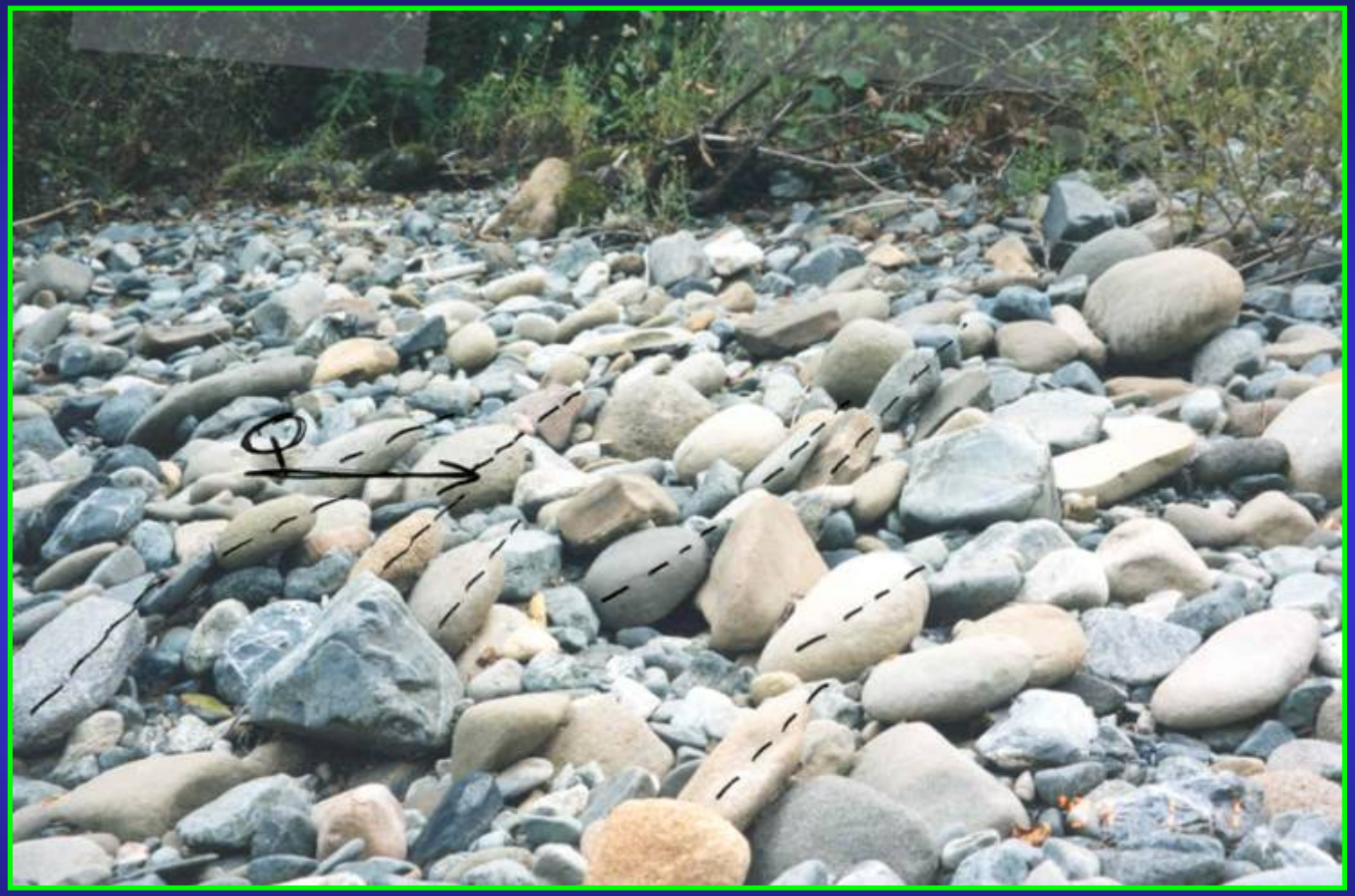
This is a big deal if trying to predict when particle size d_i begins to move.

Hiding/Exposure for Mixed Grain Sizes



- **Smaller particles shielded behind larger particles**
  (less mobile than uniform bed)
- **Larger particles project into flow**
  (more mobile than uniform bed)

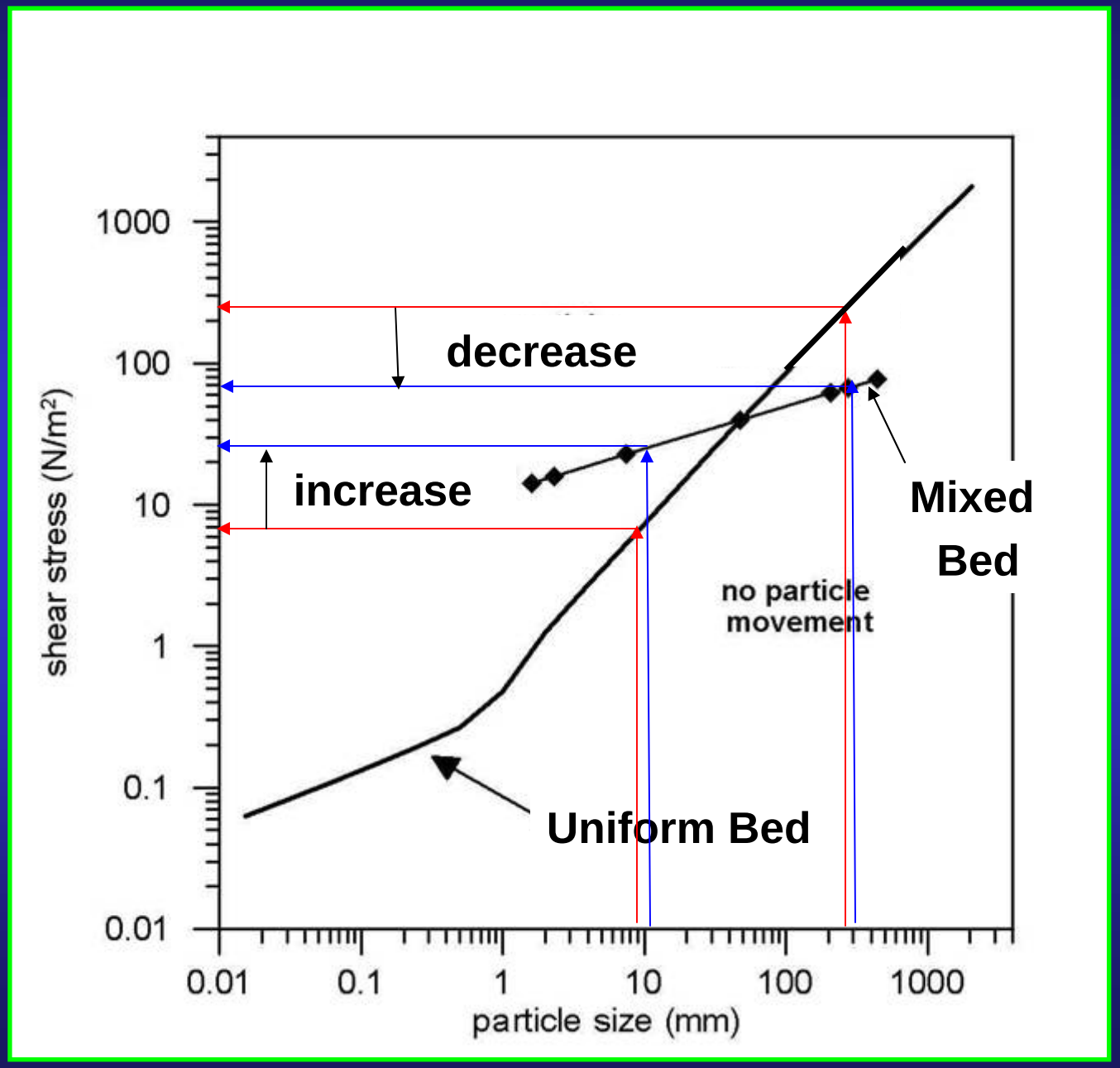
Hiding/Exposure for Mixed Grain Sizes



Smaller particles shielded behind larger particles.

Larger particles project into flow.

Effects of the Hiding/Exposure Factor



Modification of Shields by Komar (1987,1996)

Hiding/Exposure Factor for Beds of Mixed Sizes

$$\tau_c = f\left(\frac{D_i}{D_{50}}\right)$$

How big is my particle size compared to the median size on bed?

Modification of Shields (Komar 1987 and 1996)

Threshold:

$$\tau_c = \gamma(G-1)\tau^*_{D50} D_i^{0.3} D_{50}^{0.7}$$

$$\gamma(G-1) = 16{,}170$$

Driving force:

$$\tau = \gamma \cdot R \cdot S$$

If $\tau > \tau_c$, particle will move
If $\tau < \tau_c$, particle will not move

(Most applicable on slopes <5%, R/D_{84}>5, D_i/D_{50} ratios <25, and particles 10-250 mm)

Critical Unit Discharge (Bathurst 1987)

Threshold

$$q_{ci} = q_{c50}[D_i / D_{50}]^{b}$$

$$q_{c50} = 0.15\, g^{1/2}\, D_{50}^{3/2}\, S^{-1.12}$$

$$b = 1.5\, [D_{84} / D_{16}]^{-1}$$

- q is unit discharge (m^2/s)
- Q is discharge (m^3/s),
- W is active flow width (m),
- q_{ci} is critical discharge of the i particle (typically d_{84}) (m^2/s),
- q_{cr} is critical discharge of d_{50} particle size,
- g is gravitational acceleration (9.81 m/s^2)

Driving Force

$$q = Q / w$$

- S is slope,
- d_{50} is 50th percentile particle size (m),
- d_{84} is 84th percentile particle size, and
- d_{16} is 16th percentile particle size (m)

Critical Unit Discharge (Bathurst 1987)

Threshold:

$$q_{ci}(m^2/s) = q_{cr}[D_i / D_{50}]^{b}$$

$$q_{cr} = 0.15\, g^{1/2}\, D_{50}^{3/2}\, S^{-1.12}$$

$$b = 1.5\, [D_{84} / D_{16}]^{-1}$$

Driving force:

$$q = Q / w$$

If $q > q_{ci}$, particle will move

If $q < q_{ci}$, particle will not move

(Most applicable on slopes 2-5%, D_{50} 70-140 mm, D_{84} 150-250 mm, $R/D_{84}<5$ and $R/D_{50}<10$)

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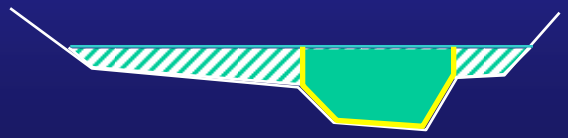
Bed Mobility Analysis - Concepts

- Compares design channel bed to reference reach
- D_{84} and D_{95} particle sizes should mobilize at the same flow in both channels
- Channel roughness, channel form, and bed mobility are controlled by D_{84} and D_{95} particles sizes
- Comparative analysis based on reference reach calibrates the model; therefore analysis is not sensitive to hydrology, hydraulics and model inputs or assumptions

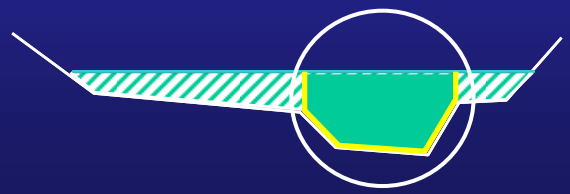
Procedure for Bed Mobility Analysis: Reference Reach

1. **Determine flow hydraulics**
   - Calculate shear stress and/or unit discharge
   - Active channel
   - Range of discharges: Q_{bf}, $Q_{1.5}$-Q_{100}
2. **Calculate critical shear stress and/or unit discharge**
   - D_{84} (or D_{95}) particle size
   - Entire particle size distribution
3. **Determine when particle mobility occurs**



Procedure for Bed Mobility Analysis: Design Channel

4. **Determine flow hydraulics**
   - Calculate shear stress and/or unit discharge
   - Range of discharges: Q_{bf}, $Q_{1.5}$-Q_{100}
5. **Calculate critical shear stress and/or unit discharge**
   - D_{84} (or D_{95}) particle size
   - Entire particle size distribution
6. **Determine when particle mobility occurs**



Procedure for Bed Mobility Analysis: Adjust Design Bed as Needed

7. Compare reference and design beds

- Does D_{84} mobility occur at the same discharge?
- If yes, proceed to stability analysis
- If no, adjust particle sizes in the design channel until mobility occurs at the same discharge as in the reference reach

8. If the particle size adjustment exceeds 25%, reevaluate design and make further adjustments

Bed Stability Analysis - Concepts

- Key pieces provide stable banks and bed forms
- Key pieces are critical for bank stability and form due to lack of vegetation in culverts and under bridges
- Key pieces are permanent - up to stability design flow
- What is stability design flow? Q_{100} or higher

Procedure for Bed Stability Analysis

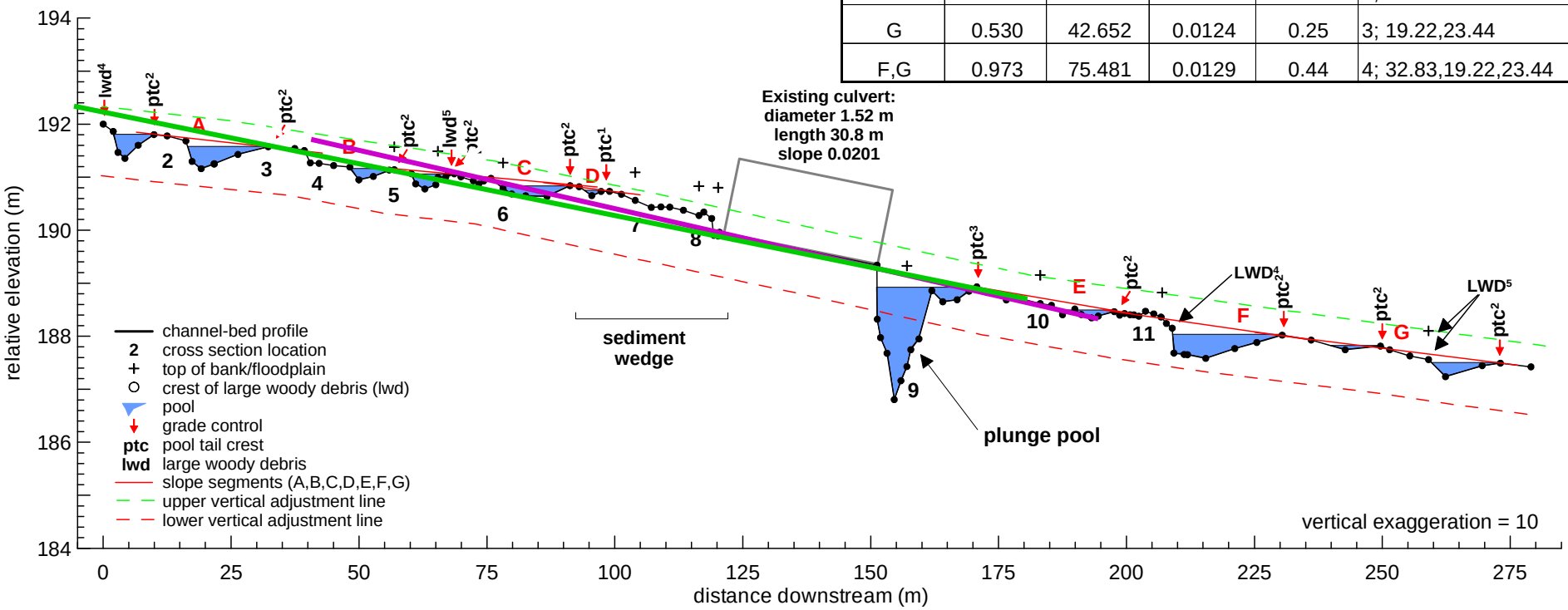
- **Use same procedures as for mobility analysis**
  - Shear Stress
  - Unit Discharge
- **Except use D_{84} (or D_{95}) from key pieces (10 largest particles) in reference reach**

Hydraulics, Sediment Mobility (D_{84}) and Sediment Stability (key pieces)

Example: Schafer Trib

Schafer Tributary Longitudinal Profile

slope segment	elevation difference (m)	segment length (m)	slope	segment maximum residual pool depth (m)	number of and distance between grade controls (m)
A	0.230	22.338	0.0103	0.41	2; 22.34
B	0.433	24.643	0.0176	0.19	2; 24.64
C	0.301	34.334	0.0088	0.30	3; 11.71,22.62
D	0.108	7.728	0.0140	0.08	2; 7.73
culvert	0.619	30.800	0.0201	2.13	
E	0.467	26.865	0.0174	0.12	2; 26.87
F	0.443	32.829	0.0135	0.44	2; 32.23
G	0.530	42.652	0.0124	0.25	3; 19.22,23.44
F,G	0.973	75.481	0.0129	0.44	4; 32.83,19.22,23.44



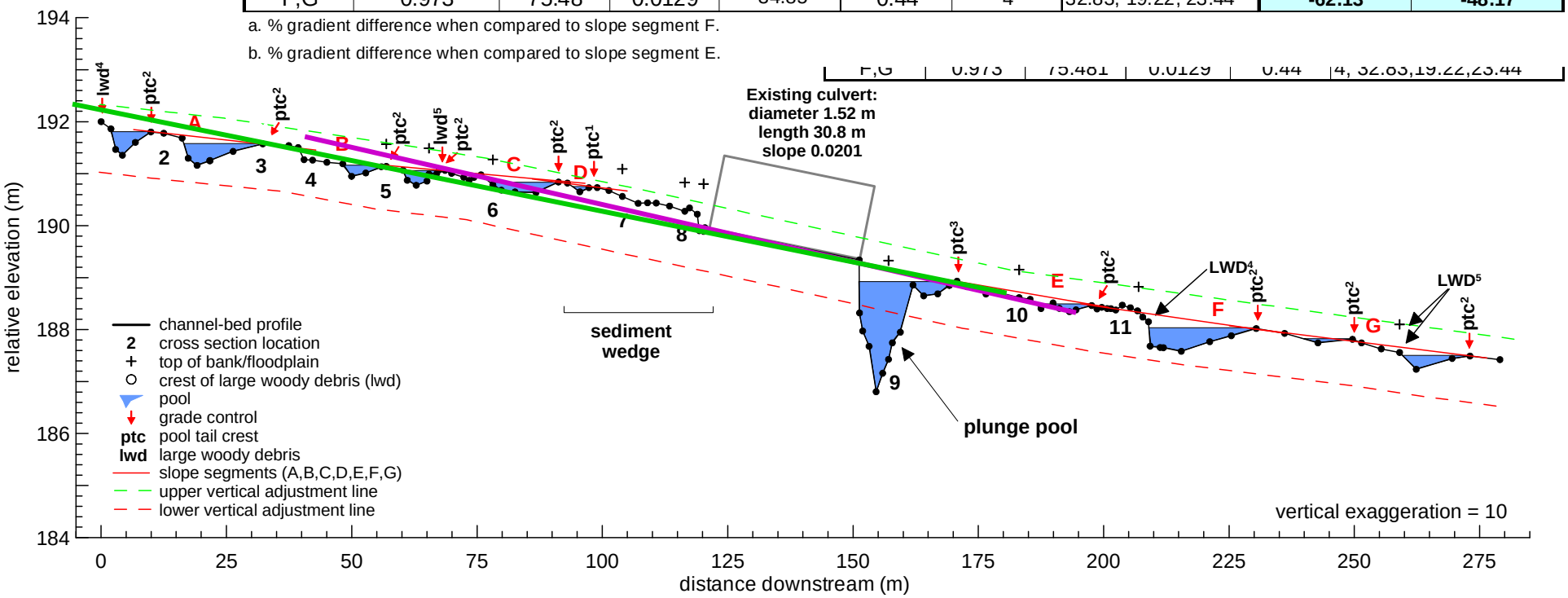
ptc[1]: pool-tail crest, channel spanning, loosely embedded gravels and small cobbles (LOW STABILITY)
ptc[2]: pool-tail crest, channel spanning, well embedded cobbles and coarse gravels (MODERATE STABILITY)
ptc[3]: pool-tail crest, channel spanning, well embedded cobbles, small boulders, coarse gravels (HIGH STABILITY)
lwd[4]: large woody debris, channel spanning, competent, diameter > 0.60 m, deeply embedded into channel and banks (HIGH STABILITY)
lwd[5]: large woody debris, channel spanning, competent, diameter 0.30-0.60 m, minimal embedment into channel and banks (MODERATE STABILITY)

Schaf
Longit

segment	elevation change (m)	segment length (m)	gradient	% gradient difference between successive segments	maximum residual pool depth (m)	number of grade controls	distance between grade controls (m)	design 1 (0.0209), ref B percent slope difference with slope segment	design 2 (0.0191), ref E percent slope difference with slope segment
A	0.230	22.34	0.0103	n/a	0.41	2	22.34	**-102.98**	**-85.50**
B	0.433	24.64	0.0176	41.4	0.19	2	24.64	**-18.95**	**-8.70**
C	0.301	34.33	0.0088	-100.4	0.30	3	11.71, 22.62	**-138.40**	**-117.87**
D	0.108	7.73	0.0140	37.3	0.08	2	7.73	**-49.55**	**-36.67**
culvert	0.619	30.80	0.0201		2.13				
E	0.467	26.87	0.0174	n/a	0.12	2	26.87	**-20.23**	**-9.88**
F	0.443	32.83	0.0135	-28.8	0.44	2	32.23	**-54.88**	**-41.54**
G	0.530	42.65	0.0124	-8.59[a]	0.25	3	19.22, 23.44	**-68.19**	**-53.71**
F,G	0.973	75.48	0.0129	-34.85[b]	0.44	4	32.83, 19.22, 23.44	**-62.13**	**-48.17**

a. % gradient difference when compared to slope segment F.

b. % gradient difference when compared to slope segment E.



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ptc[2]: pool-tail crest, channel spanning, well embedded cobbles and coarse gravels (MODERATE STABILITY)
ptc[3]: pool-tail crest, channel spanning, well embedded cobbles, small boulders, coarse gravels (HIGH STABILITY)
lwd[4]: large woody debris, channel spanning, competent, diameter > 0.60 m, deeply embedded into channel and banks (HIGH STABILITY)
lwd[5]: large woody debris, channel spanning, competent, diameter 0.30-0.60 m, minimal embedment into channel and banks (MODERATE STABILITY)

Shafer Trib, Channel-Bed Design

Tributary to Shafer Creek Culvert Replacement

Figure 1. Plan view drawing of channel-bed configuration. The gray shaded rocks represent larger obstacle particles.

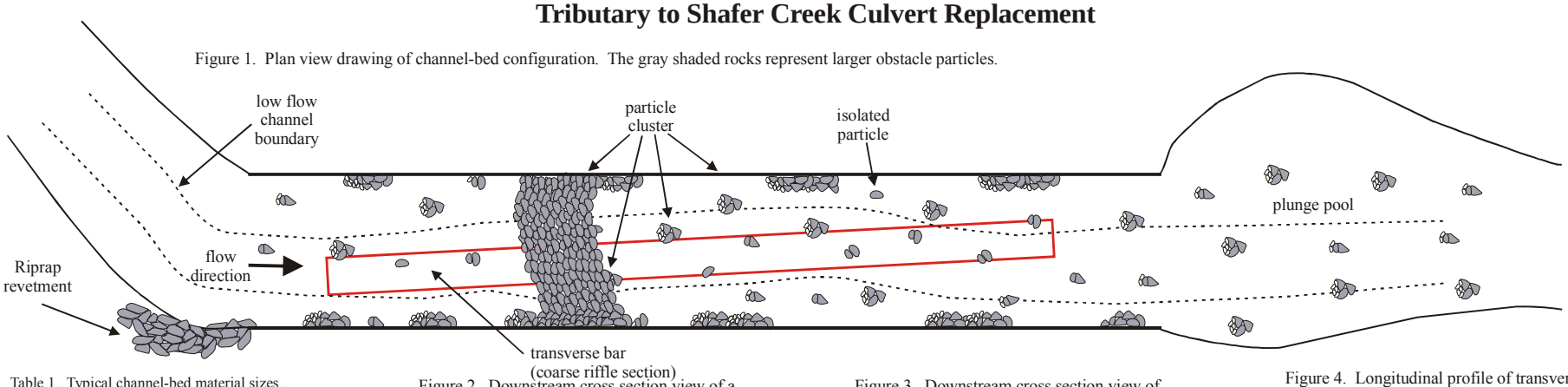


Table 1. Typical channel-bed material sizes.

Percent Mass or Volume	Particle Diameter (mm)
1	256 to 362
15	128 to 256
38	64 to 128
38	16 to 64
8	0.5 to 16

Table 2. Size and quantity of large, obstacle particles.

Quantity	Particle Diameter (mm)	Particle Length (mm)
140	250 to 350	375 to 525

Figure 2. Downstream cross section view of a transverse bar. The gray shaded rocks represent larger obstacle particles. The upper dashed line is bankfull flow and lower dashed line represents typical low flow width.

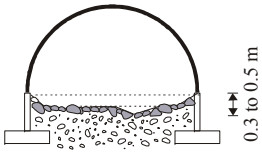


Figure 3. Downstream cross section view of the channel. The gray shaded rock represents an obstacle particle. The upper dashed line is bankfull flow and lower dashed line represents typical low flow width.

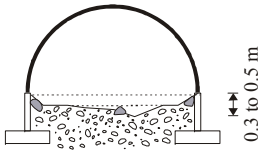
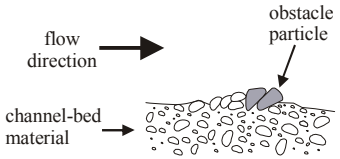


Figure 4. Longitudinal profile of transverse ribs and particle clusters showing the imbrication of the larger particles and embeddedness of the larger particles into the underlying channel sediment.
Note: This diagram is not to scale.



NOTES:

1) The width of the structure is at or slightly less than bankfull width making it difficult to construct channel bank and bed features without compromising hydraulic conveyance. The above design is not the preferred channel configuration, but is an attempt to create channel complexity within the constraints or limitations of the engineering design.

2) The engineering design plans do not indicate the depth of the footing/stem wall with regard to the surface of the channel bed. Therefore, the relationship between the footing/stem wall with regard to the channel-bed surface depicted in these diagrams are independent of the engineering design; this needs to be confirmed before constructing the channel bed.

3) Once the new culvert is installed, if the excavated material below the old culvert has similar particles shapes and size distributions as the reference channel reach [particle shapes: subrounded to rounded; particle sizes of the armor layer: d5=7 to 14 mm, d16=24 to 42 mm, d50=50 to 86 mm, d84=80 to 158 mm, d95=101 to 208 mm; particle sizes of the subarmor layer: a higher percentage of fine gravels (2 to 16 mm) and coarse sands (0.5 to 2 mm) than the armor layer], place material at an elevation just above the stem wall. Compact the material and be sure that the voids between the larger particles are filled with coarse sands and fine gravels. Refer to Table 1 for the percent mass or volume and particle size ranges needed to construct the channel bed.

4) Construct a low flow channel and banks as shown in Figures 1, 2, and 3. The low flow channel has a width of about 2.0-3.5 m and the maximum depth of the channel should be about 0.30-0.50 m lower than the channel-bed surface at the margins of the structure (i.e., the top of the stem wall). The low flow channel and bankfull channel margins constructed through the structure should be connected to or tied into the low flow channel and bankfull channel margins upstream and downstream from the structure.

5) At the locations identified in Figure 1, construct the transverse bar, particle clusters, and isolated boulders as depicted (Figures 1, 2, 3, and 4). The transverse bar should be placed at an angle of 15 degrees upstream from the right bank stemwall. Approximately 145 particles having subrounded to rounded shapes, intermediate axis sizes of 250 to 350 mm, and long axis sizes of 375 to 525 mm will be needed to construct the transverse bar, particle clusters, and isolated boulders (Table 2). The particles of these structures should be 25 to 50 percent buried into the channel bed (Figures 3 and 4).

6) Fill in the plunge pool with the sediment sizes described in note 3 and Table 1. Construct the channel bed as described in note 4.

7) Recommend constructing riprap revetment to protect bank and footing from scour at the right bank inlet (Figure 1). Class 4 riprap should be used to construct the revetment. The riprap revetment should be keyed into the bank, extend about 6 m upstream from the right bank inlet, and placed at the same depth as the base of the footing.

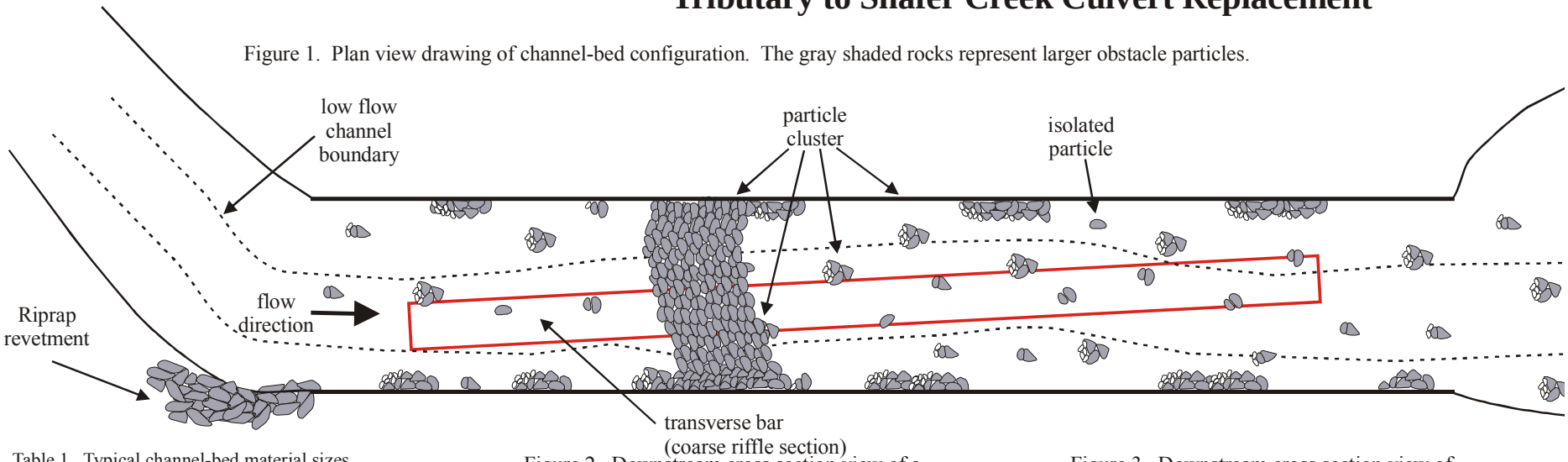
0 10 m

USDA Forest Service
Olympic National Forest
Hood Canal Ranger District

Project: Tributary to Shafer Creek Culvert Replacement
Subject: Channel-bed Design
Date: 9/19/2003
Design by: Dan Cenderelli

Tributary to Shafer Creek Culvert Replacement

Figure 1. Plan view drawing of channel-bed configuration. The gray shaded rocks represent larger obstacle particles.



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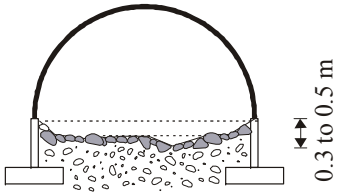

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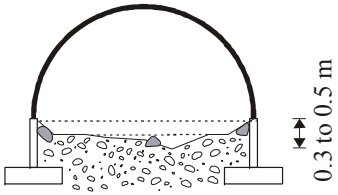

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5) At the locations identified in Figure 1, construct the transverse bar, particle clusters, and isolated boulders as depicted (Figures 1, 2, 3, and 4). The transverse bar should be placed at an 15 degrees upstream from the right bank stemwall. Approximately 145 particles having subrounded to rounded shapes, intermediate axis sizes of 250 to 350 mm, and long axis sizes of 37 mm will be needed to construct the transverse bar, particle clusters, and isolated boulders (Table 2). The particles of these structures should be 25 to 50 percent buried into the channel bed (Figures 3 and 4).

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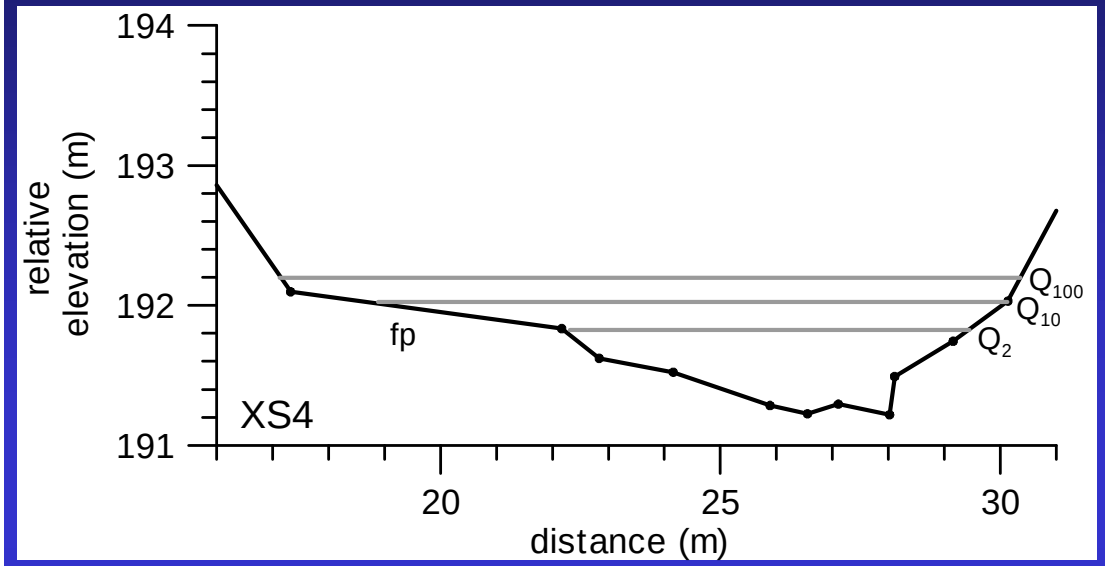
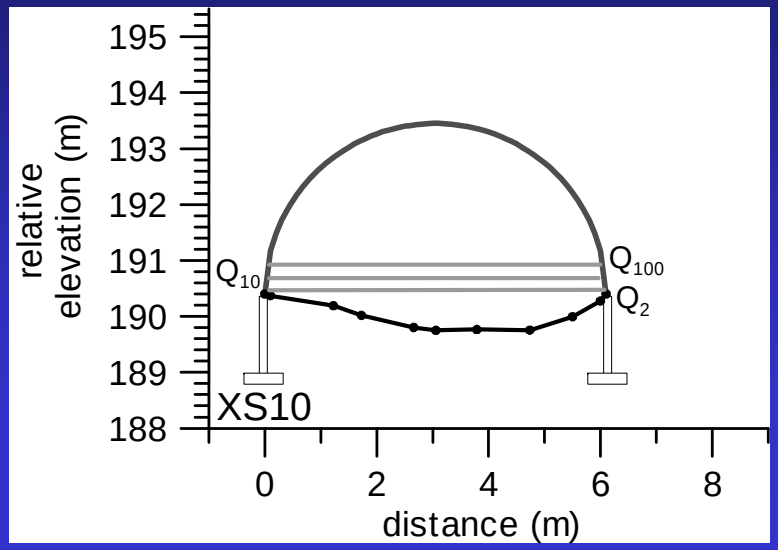
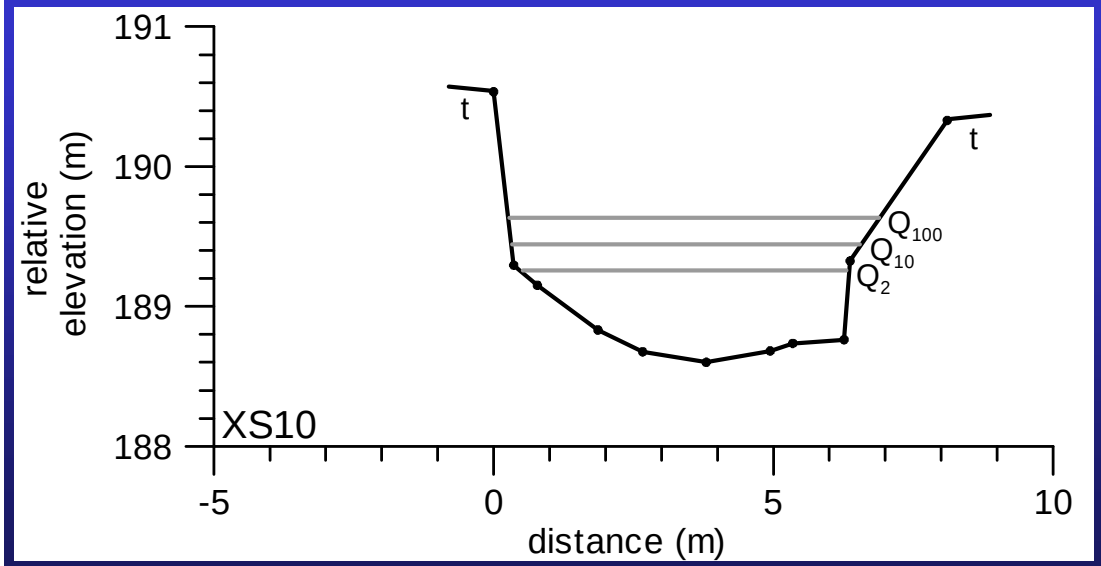
Example: Schafer Trib







Explanation

—	Q_2, Q_{10}, Q_{100} water surfaces
fp	floodplain
t	terrace

Hydraulics and Sediment Mobility

(excel example – shear stress – XS 10 Ref Reach)

Hydraulics												Particle Mobility/Stability					
Recur-rence Interval	Dis-charge, Q (m^3/s)	Flood-plain n value	Chan-nel n value	Chan-nel slope, S_c	Energy slope, S_e	Total flow width, W_t (m)	Chan-nel flow width, W_c (m)	Total hydraulic radius, R_t (m)	Channel Hydraulic Radius, R_c (m)	Total boundary shear stress, τ_t (N/m^2)[a]	**Channel boundary shear stress, τ_c (N/m^2)[b]**	D_{50} (mm)	D_{84} (mm)	Angle of repose ϕ	Shield's entrain-ment for τ^*_{D50} [c]	**Critical Shear Stress to Entrain D_{84} Particle Size, $\tau_{c\text{-}D84}$ (N/m^2) [d]**	D_{84} Particle Mobile (yes/no)
A. Reference reach cross section: XS10																	
	2.00	0.150	0.050	0.0174	0.0161	5.22	5.22	0.31	0.31	49.17	49.17	86	159	42	0.054	**90.34**	no
bf	3.00	0.150	0.050	0.0174	0.0170	5.56	5.56	0.37	0.37	62.10	62.10	86	159	42	0.054	**90.34**	no
	4.00	0.150	0.050	0.0174	0.0173	5.81	5.81	0.43	0.43	72.56	72.56	86	159	42	0.054	**90.34**	no
2	4.20	0.150	0.050	0.0174	0.0174	5.86	5.86	0.44	0.44	74.45	74.45	86	159	42	0.054	**90.34**	no
	5.00	0.150	0.050	0.0174	0.0176	6.01	6.01	0.47	0.47	81.47	81.59	86	159	42	0.054	**90.34**	no
	6.00	0.150	0.050	0.0174	0.0173	6.11	6.01	0.52	0.53	88.03	90.08	86	159	42	0.054	**90.34**	no
10	6.70	0.150	0.050	0.0174	0.0172	6.19	6.01	0.55	0.57	91.82	95.58	86	159	42	0.054	**90.34**	yes
	7.00	0.150	0.050	0.0174	0.0171	6.22	6.01	0.56	0.58	93.35	97.84	86	159	42	0.054	**90.34**	yes
25	7.80	0.150	0.050	0.0174	0.0169	6.31	6.01	0.59	0.62	97.16	103.57	86	159	42	0.054	**90.34**	yes
	8.00	0.150	0.050	0.0174	0.0169	6.34	6.01	0.59	0.63	98.06	104.95	86	159	42	0.054	**90.34**	yes
50	8.80	0.150	0.050	0.0174	0.0167	6.42	6.01	0.62	0.67	101.48	110.26	86	159	42	0.054	**90.34**	yes
	9.00	0.150	0.050	0.0174	0.0166	6.44	6.01	0.63	0.68	102.29	111.54	86	159	42	0.054	**90.34**	yes
100	9.90	0.150	0.050	0.0174	0.0164	6.54	6.01	0.66	0.73	105.73	117.08	86	159	42	0.054	**90.34**	yes
	10.00	0.150	0.050	0.0174	0.0164	6.55	6.01	0.66	0.73	106.10	117.68	86	159	42	0.054	**90.34**	yes
	11.00	0.150	0.050	0.0174	0.0162	6.65	6.01	0.69	0.78	109.54	123.40	86	159	42	0.054	**90.34**	yes

Hydraulics and Sediment Mobility

(excel example – shear stress – 6.1 Arch Initial)

Hydraulics												Particle Mobility/Stability					
Recur-rence Interval	Dis-charge, Q (m^3/s)	Flood-plain n value	Chan-nel n value	Chan-nel slope, S_c	Energy slope, S_e	Total flow width, W_t (m)	Chan-nel flow width, W_c (m)	Total hydraulic radius, R_t (m)	Channel Hydraulic Radius, R_c (m)	Total boundary shear stress, τ_t (N/m^2)[a]	**Channel boundary shear stress, τ_c (N/m^2)[b]**	D_{50} (mm)	D_{84} (mm)	Angle of repose ϕ	Shield's entrain-ment for τ^*_{D50} [c]	**Critical Shear Stress to Entrain D_{84} Particle Size, $\tau_{c\text{-}D84}$ (N/m^2) [d]**	D_{84} Particle Mobile (yes/no)
B. Preliminary stream simulation design channel for bottomless arch (span 6.1 m, height 3.05 m) with a channel-bed gradient of 2.09% (XS8.3D)																	
	2.00	0.028	0.050	0.0209	0.0212	4.67	4.67	0.31	0.31	64.52	64.52	86	159	42	0.054	**90.34**	no
bf	3.00	0.028	0.050	0.0209	0.0211	5.49	5.47	0.36	0.36	74.33	74.75	86	159	42	0.054	**90.34**	no
	4.00	0.028	0.050	0.0209	0.0212	6.02	5.90	0.40	0.41	82.92	85.09	86	159	42	0.054	**90.34**	no
2	4.20	0.028	0.050	0.0209	0.0212	6.08	5.90	0.41	0.42	84.48	87.51	86	159	42	0.054	**90.34**	no
	5.00	0.028	0.050	0.0209	0.0211	6.09	5.90	0.45	0.47	92.17	96.90	86	159	42	0.054	**90.34**	yes
	6.00	0.028	0.050	0.0209	0.0211	6.07	5.90	0.49	0.52	101.12	107.89	86	159	42	0.054	**90.34**	yes
10	6.70	0.028	0.050	0.0209	0.0210	6.06	5.90	0.52	0.56	106.51	114.81	86	159	42	0.054	**90.34**	yes
	7.00	0.028	0.050	0.0209	0.0210	6.06	5.90	0.53	0.57	108.90	117.87	86	159	42	0.054	**90.34**	yes
25	7.80	0.028	0.050	0.0209	0.0209	6.05	5.90	0.56	0.61	114.77	125.59	86	159	42	0.054	**90.34**	yes
	8.00	0.028	0.050	0.0209	0.0209	6.05	5.90	0.57	0.62	116.08	127.38	86	159	42	0.054	**90.34**	yes
50	8.80	0.028	0.050	0.0209	0.0209	6.04	5.90	0.59	0.66	121.55	134.79	86	159	42	0.054	**90.34**	yes
	9.00	0.028	0.050	0.0209	0.0209	6.04	5.90	0.60	0.67	122.80	136.53	86	159	42	0.054	**90.34**	yes
100	9.90	0.028	0.050	0.0209	0.0208	6.02	5.90	0.63	0.71	128.40	144.40	86	159	42	0.054	**90.34**	yes
	10.00	0.028	0.050	0.0209	0.0208	6.02	5.90	0.63	0.71	129.02	145.28	86	159	42	0.054	**90.34**	yes
	11.00	0.028	0.050	0.0209	0.0208	6.01	5.90	0.66	0.75	134.92	153.78	86	159	42	0.054	**90.34**	yes

Hydraulics and Sediment Mobility

(excel example – shear stress – 6.1 Arch Adjustment Pct)

Ref Reach (XS10): D_{84} mobile at 6.7 cms (Q_{10})
Initial Bed: D_{84} mobile at 5.0 cms (~Q_5)

D_{50} (mm)	D_{84} (mm)	Angle of repose ϕ	Description
86	159	42	initial reference reach particle size
103.2	190.8	42	adjusted particle sizes in design channel
		20	**percent particle size adjustment**

Hydraulics and Sediment Mobility

(excel example – shear stress – 6.1 Arch Adjusted)

Hydraulics												Particle Mobility/Stability					
Recur-rence Interval	Dis-charge, Q (m^3/s)	Flood-plain n value	Chan-nel n value	Chan-nel slope, S_c	Energy slope, S_e	Total flow width, W_t (m)	Chan-nel flow width, W_c (m)	Total hydraulic radius, R_t (m)	Channel Hydraulic Radius, R_c (m)	Total boundary shear stress, τ_t (N/m^2)[a]	**Channel boundary shear stress, τ_c (N/m^2)[b]**	D_{50} (mm)	D_{84} (mm)	Angle of repose ϕ	Shield's entrain-ment for τ^*_{D50} [c]	**Critical Shear Stress to Entrain D_{84} Particle Size, $\tau_{c\text{-}D84}$ (N/m^2) [d]**	D_{84} Particle Mobile (yes/no)
C. Adjusted stream simulation design channel for bottomless arch (span 6.1 m, height 3.05 m) with a channel-bed gradient of 2.09% (XS8.3D)																	
	2.00	0.028	0.050	0.0209	0.0212	4.67	4.67	0.31	0.31	64.52	64.52	103	191	42	0.054	**108.40**	no
bf	3.00	0.028	0.050	0.0209	0.0211	5.49	5.47	0.36	0.36	74.33	74.75	103	191	42	0.054	**108.40**	no
	4.00	0.028	0.050	0.0209	0.0212	6.02	5.90	0.40	0.41	82.92	85.09	103	191	42	0.054	**108.40**	no
2	4.20	0.028	0.050	0.0209	0.0212	6.08	5.90	0.41	0.42	84.48	87.51	103	191	42	0.054	**108.40**	no
	5.00	0.028	0.050	0.0209	0.0211	6.09	5.90	0.45	0.47	92.17	96.90	103	191	42	0.054	**108.40**	no
	6.00	0.028	0.050	0.0209	0.0211	6.07	5.90	0.49	0.52	101.12	107.89	103	191	42	0.054	**108.40**	no
10	6.70	0.028	0.050	0.0209	0.0210	6.06	5.90	0.52	0.56	106.51	114.81	103	191	42	0.054	**108.40**	yes
	7.00	0.028	0.050	0.0209	0.0210	6.06	5.90	0.53	0.57	108.90	117.87	103	191	42	0.054	**108.40**	yes
25	7.80	0.028	0.050	0.0209	0.0209	6.05	5.90	0.56	0.61	114.77	125.59	103	191	42	0.054	**108.40**	yes
	8.00	0.028	0.050	0.0209	0.0209	6.05	5.90	0.57	0.62	116.08	127.38	103	191	42	0.054	**108.40**	yes
50	8.80	0.028	0.050	0.0209	0.0209	6.04	5.90	0.59	0.66	121.55	134.79	103	191	42	0.054	**108.40**	yes
	9.00	0.028	0.050	0.0209	0.0209	6.04	5.90	0.60	0.67	122.80	136.53	103	191	42	0.054	**108.40**	yes
100	9.90	0.028	0.050	0.0209	0.0208	6.02	5.90	0.63	0.71	128.40	144.40	103	191	42	0.054	**108.40**	yes
	10.00	0.028	0.050	0.0209	0.0208	6.02	5.90	0.63	0.71	129.02	145.28	103	191	42	0.054	**108.40**	yes
	11.00	0.028	0.050	0.0209	0.0208	6.01	5.90	0.66	0.75	134.92	153.78	103	191	42	0.054	**108.40**	yes

Hydraulics and Sediment Stability

(excel example – shear stress – XS 4 Ref Reach)

Hydraulics												Particle Mobility/Stability					
Recur-rence Interval	Dis-charge, Q (m^3/s)	Flood-plain n value	Chan-nel n value	Chan-nel slope, S_c	Energy slope, S_e	Total flow width, W_t (m)	Chan-nel flow width, W_c (m)	Total hydraulic radius, R_t (m)	Channel Hydraulic Radius, R_c (m)	Total boundary shear stress, τ_t $(N/m^2)^a$	**Channel boundary shear stress, τ_c $(N/m^2)^b$**	D_{50} (mm)	D_{95} (mm)	Angle of repose ϕ	Shield's entrain-ment for τ^*_{D50} [c]	**Critical Shear Stress to Entrain D_{84} Particle Size, $\tau_{c\text{-}D95}$ (N/m^2) [d]**	D_{95} Particle Stable (yes/no)
A. Reference reach cross section (key pieces): XS4																	
	2.00	0.150	0.050	0.0176	0.0186	6.41	6.41	0.27	0.27	48.47	48.47	135	166	42	0.054	**125.48**	yes
bf	3.00	0.150	0.050	0.0176	0.0183	6.98	6.84	0.32	0.33	57.66	58.79	135	166	42	0.054	**125.48**	yes
	4.00	0.150	0.050	0.0176	0.0178	7.77	6.99	0.35	0.39	61.52	67.62	135	166	42	0.054	**125.48**	yes
2	4.20	0.150	0.050	0.0176	0.0177	8.05	6.99	0.35	0.40	61.11	69.26	135	166	42	0.054	**125.48**	yes
	5.00	0.150	0.050	0.0176	0.0174	9.09	6.99	0.36	0.45	60.78	75.89	135	166	42	0.054	**125.48**	yes
	6.00	0.150	0.050	0.0176	0.0172	10.28	6.99	0.37	0.50	61.59	83.70	135	166	42	0.054	**125.48**	yes
10	6.70	0.150	0.050	0.0176	0.0170	11.07	6.99	0.37	0.53	62.29	88.54	135	166	42	0.054	**125.48**	yes
	7.00	0.150	0.050	0.0176	0.0169	11.39	6.99	0.38	0.55	62.70	90.59	135	166	42	0.054	**125.48**	yes
25	7.80	0.150	0.050	0.0176	0.0167	12.16	6.99	0.39	0.58	64.06	95.67	135	166	42	0.054	**125.48**	yes
	8.00	0.150	0.050	0.0176	0.0167	12.35	6.99	0.39	0.59	64.43	96.90	135	166	42	0.054	**125.48**	yes
50	8.80	0.150	0.050	0.0176	0.0165	12.94	6.99	0.41	0.63	66.26	101.15	135	166	42	0.054	**125.48**	yes
	9.00	0.150	0.050	0.0176	0.0164	12.96	6.99	0.42	0.64	67.24	102.13	135	166	42	0.054	**125.48**	yes
100	9.90	0.150	0.050	0.0176	0.0161	13.08	6.99	0.45	0.67	71.40	106.37	135	166	42	0.054	**125.48**	yes
	10.00	0.150	0.050	0.0176	0.0161	13.10	6.99	0.46	0.68	71.84	106.83	135	166	42	0.054	**125.48**	yes
	11.00	0.150	0.050	0.0176	0.0158	13.22	6.99	0.49	0.72	76.05	111.19	135	166	42	0.054	**125.48**	yes

Hydraulics and Sediment Stability

(excel example – shear stress – 6.1 Span Initial)

Hydraulics												Particle Mobility/Stability					
Recur-rence Interval	Dis-charge, Q (m^3/s)	Flood-plain n value	Chan-nel n value	Chan-nel slope, S_c	Energy slope, S_e	Total flow width, W_t (m)	Chan-nel flow width, W_c (m)	Total hydraulic radius, R_t (m)	Channel Hydraulic Radius, R_c (m)	Total boundary shear stress, τ_t $(N/m^2)^a$	**Channel boundary shear stress, τ_c $(N/m^2)^b$**	D_{50} (mm)	D_{95} (mm)	Angle of repose ϕ	Shield's entrain-ment for $\tau^*_{D50}{}^c$	**Critical Shear Stress to Entrain D_{84} Particle Size, $\tau_{c\text{-}D95}$ $(N/m^2)^d$**	D_{95} Particle Stable (yes/no)
B. Key Pieces. Preliminary stream simulation design channel for bottomless arch (span 6.1 m, height 3.05 m) with a channel-bed gradient of 2.09% (XS8.3D)																	
	2.00	0.028	0.050	0.0209	0.0212	4.67	4.67	0.31	0.31	64.52	64.52	135	166	42	0.054	**125.48**	yes
bf	3.00	0.028	0.050	0.0209	0.0211	5.49	5.47	0.36	0.36	74.33	74.75	135	166	42	0.054	**125.48**	yes
	4.00	0.028	0.050	0.0209	0.0212	6.02	5.90	0.40	0.41	82.92	85.09	135	166	42	0.054	**125.48**	yes
2	4.20	0.028	0.050	0.0209	0.0212	6.08	5.90	0.41	0.42	84.48	87.51	135	166	42	0.054	**125.48**	yes
	5.00	0.028	0.050	0.0209	0.0211	6.09	5.90	0.45	0.47	92.17	96.90	135	166	42	0.054	**125.48**	yes
	6.00	0.028	0.050	0.0209	0.0211	6.07	5.90	0.49	0.52	101.12	107.89	135	166	42	0.054	**125.48**	yes
10	6.70	0.028	0.050	0.0209	0.0210	6.06	5.90	0.52	0.56	106.51	114.81	135	166	42	0.054	**125.48**	yes
	7.00	0.028	0.050	0.0209	0.0210	6.06	5.90	0.53	0.57	108.90	117.87	135	166	42	0.054	**125.48**	yes
25	7.80	0.028	0.050	0.0209	0.0209	6.05	5.90	0.56	0.61	114.77	125.59	135	166	42	0.054	**125.48**	no
	8.00	0.028	0.050	0.0209	0.0209	6.05	5.90	0.57	0.62	116.08	127.38	135	166	42	0.054	**125.48**	no
50	8.80	0.028	0.050	0.0209	0.0209	6.04	5.90	0.59	0.66	121.55	134.79	135	166	42	0.054	**125.48**	no
	9.00	0.028	0.050	0.0209	0.0209	6.04	5.90	0.60	0.67	122.80	136.53	135	166	42	0.054	**125.48**	no
100	9.90	0.028	0.050	0.0209	0.0208	6.02	5.90	0.63	0.71	128.40	144.40	135	166	42	0.054	**125.48**	no
	10.00	0.028	0.050	0.0209	0.0208	6.02	5.90	0.63	0.71	129.02	145.28	135	166	42	0.054	**125.48**	no
	11.00	0.028	0.050	0.0209	0.0208	6.01	5.90	0.66	0.75	134.92	153.78	135	166	42	0.054	**125.48**	no

Hydraulics and Sediment Stability

(excel example – shear stress – 6.1 Arch Adjustment Pct)

Ref Reach (XS4): key pieces stable at all flows

Initial Bed: key pieces not stable $\geq$ 7.8 cms (Q_{25})

D_{50} (mm)	D_{95} (mm)	Angle of repose ϕ	Description
135	166	42	initial reference reach particle size
168.8	207.5	42	adjusted particle size in design channel

25	**percent particle size adjustment**

Hydraulics and Sediment Stability

(excel example – shear stress – 6.1 Span Adjusted)

Hydraulics												Particle Mobility/Stability					
Recur-rence Interval	Dis-charge, Q (m^3/s)	Flood-plain n value	Chan-nel n value	Chan-nel slope, S_c	Energy slope, S_e	Total flow width, W_t (m)	Chan-nel flow width, W_c (m)	Total hydraulic radius, R_t (m)	Channel Hydraulic Radius, R_c (m)	Total boundary shear stress, τ_t $(N/m^2)^a$	**Channel boundary shear stress, τ_c $(N/m^2)^b$**	D_{50} (mm)	D_{95} (mm)	Angle of repose ϕ	Shield's entrain-ment for τ^*_{D50} [c]	**Critical Shear Stress to Entrain D_{84} Particle Size, $\tau_{c\text{-}D95}$ (N/m^2) [d]**	D_{95} Particle Stable (yes/no)
C. Key Pieces. Adjusted stream simulation design channel for bottomless arch (span 6.1 m, height 3.05 m) with a channel-bed gradient of 2.09% (XS8.3D)																	
	2.00	0.028	0.050	0.0209	0.0212	4.67	4.67	0.31	0.31	64.52	64.52	169	208	42	0.054	**156.85**	yes
bf	3.00	0.028	0.050	0.0209	0.0211	5.49	5.47	0.36	0.36	74.33	74.75	169	208	42	0.054	**156.85**	yes
	4.00	0.028	0.050	0.0209	0.0212	6.02	5.90	0.40	0.41	82.92	85.09	169	208	42	0.054	**156.85**	yes
2	4.20	0.028	0.050	0.0209	0.0212	6.08	5.90	0.41	0.42	84.48	87.51	169	208	42	0.054	**156.85**	yes
	5.00	0.028	0.050	0.0209	0.0211	6.09	5.90	0.45	0.47	92.17	96.90	169	208	42	0.054	**156.85**	yes
	6.00	0.028	0.050	0.0209	0.0211	6.07	5.90	0.49	0.52	101.12	107.89	169	208	42	0.054	**156.85**	yes
10	6.70	0.028	0.050	0.0209	0.0210	6.06	5.90	0.52	0.56	106.51	114.81	169	208	42	0.054	**156.85**	yes
	7.00	0.028	0.050	0.0209	0.0210	6.06	5.90	0.53	0.57	108.90	117.87	169	208	42	0.054	**156.85**	yes
25	7.80	0.028	0.050	0.0209	0.0209	6.05	5.90	0.56	0.61	114.77	125.59	169	208	42	0.054	**156.85**	yes
	8.00	0.028	0.050	0.0209	0.0209	6.05	5.90	0.57	0.62	116.08	127.38	169	208	42	0.054	**156.85**	yes
50	8.80	0.028	0.050	0.0209	0.0209	6.04	5.90	0.59	0.66	121.55	134.79	169	208	42	0.054	**156.85**	yes
	9.00	0.028	0.050	0.0209	0.0209	6.04	5.90	0.60	0.67	122.80	136.53	169	208	42	0.054	**156.85**	yes
100	9.90	0.028	0.050	0.0209	0.0208	6.02	5.90	0.63	0.71	128.40	144.40	169	208	42	0.054	**156.85**	yes
	10.00	0.028	0.050	0.0209	0.0208	6.02	5.90	0.63	0.71	129.02	145.28	169	208	42	0.054	**156.85**	yes
	11.00	0.028	0.050	0.0209	0.0208	6.01	5.90	0.66	0.75	134.92	153.78	169	208	42	0.054	**156.85**	yes