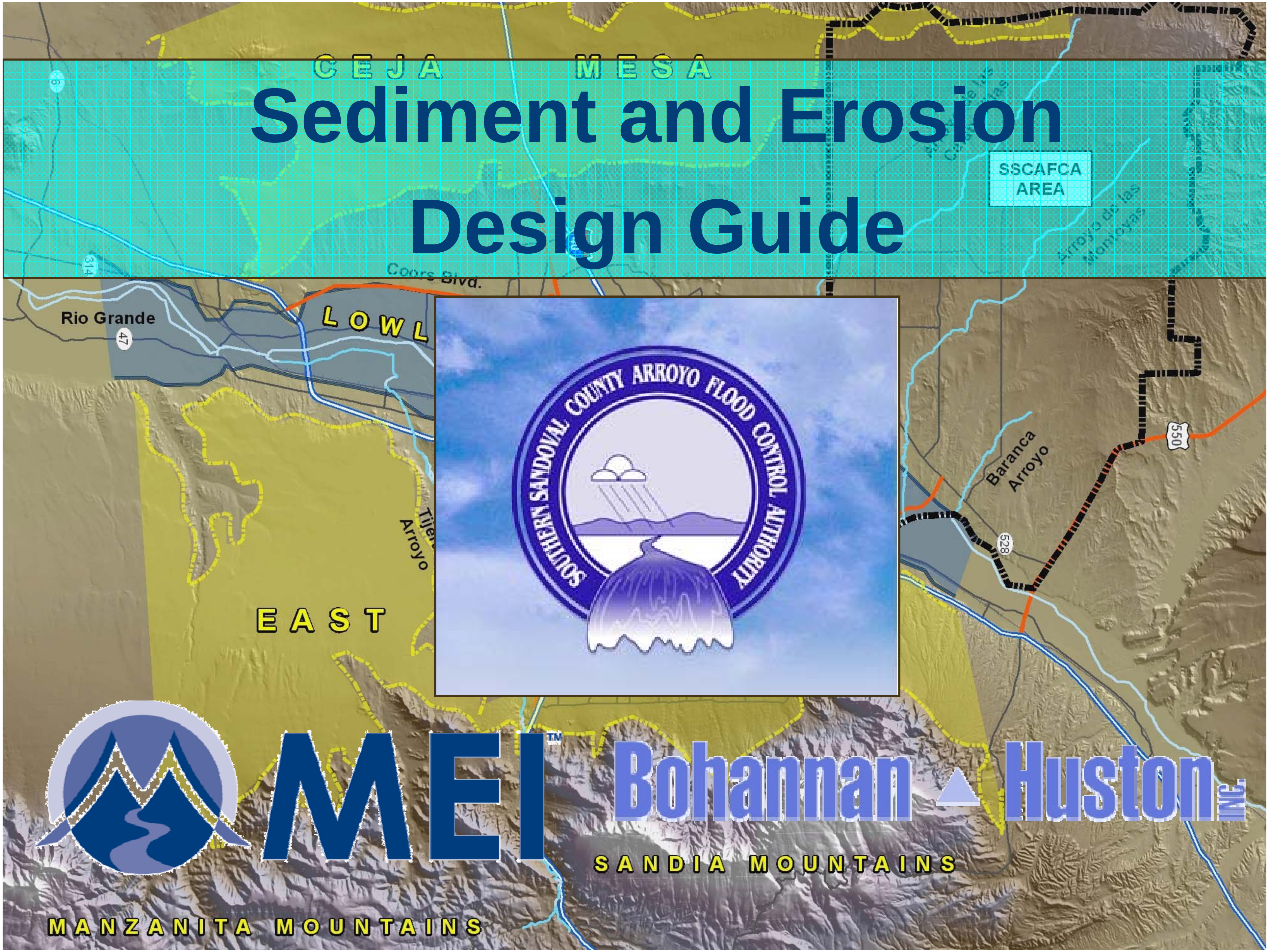
Sediment and Erosion Design Guide



SOUTHERN SANDOVAL COUNTY ARROYO FLOOD CONTROL AUTHORITY

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Bohannan ▲ Huston INC.

Evaluation of Channel Adjustments

Section 3.4

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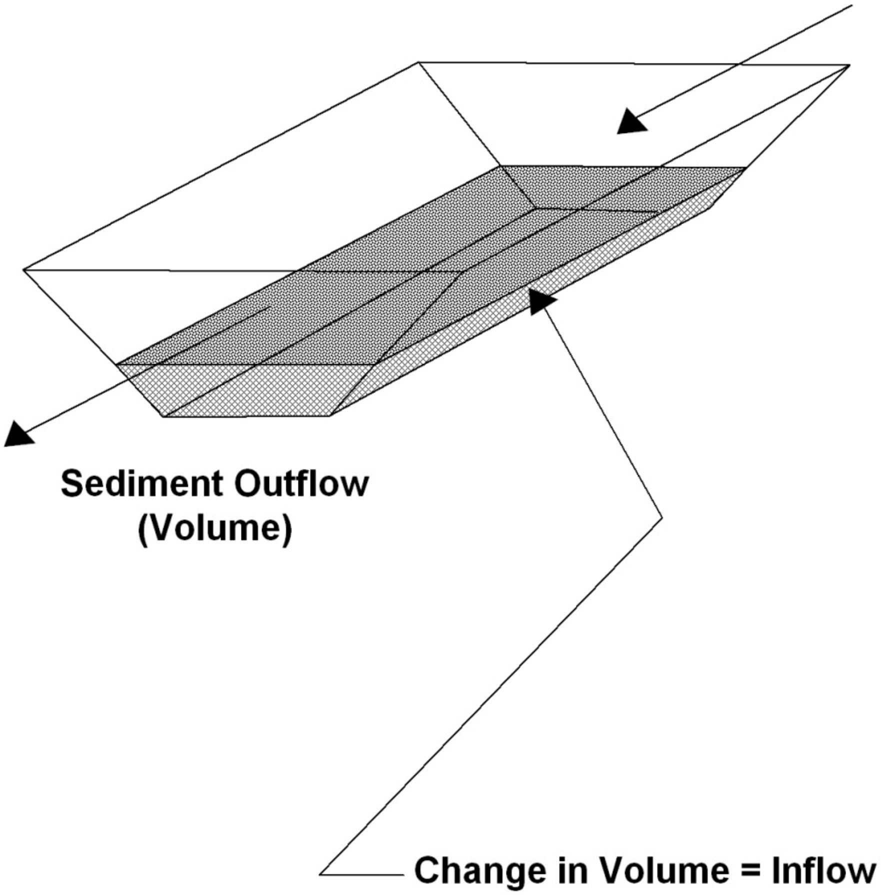
Objectives

1. Evaluation of Channel Adjustments
   Sediment Continuity
   Equilibrium Concept
   Evaluation of Vertical Stability (incl. equilibrium slope)

2. Rio Grande Project Example

3. Sample Problems

Sediment-Continuity Concept



Sediment Intflow
(Volume)

Sediment Outflow
(Volume)

Change in Volume = Inflow - Outflow

If negative, erosion will occur
If positive, sedimentation will occur

Sediment Continuity

$$\Delta V = V_{s(inflow)} - V_{s(outflow)} \quad (3.25)$$

Where

ΔV = volume of sediment stored (+) or lost (-) in the reach

$V_{s(inflow)}$ = volumetric sediment-transport rate into the reach from upstream and material sources

$V_{s(outflow)}$ = volumetric sediment-transport rate out of the reach

Sediment Continuity

Vertical adjustments occur in stream channels:

(1) due to the removal of sediment from the channel bed (degradation), or

(2) deposition of sediment on the channel bed (aggradation)

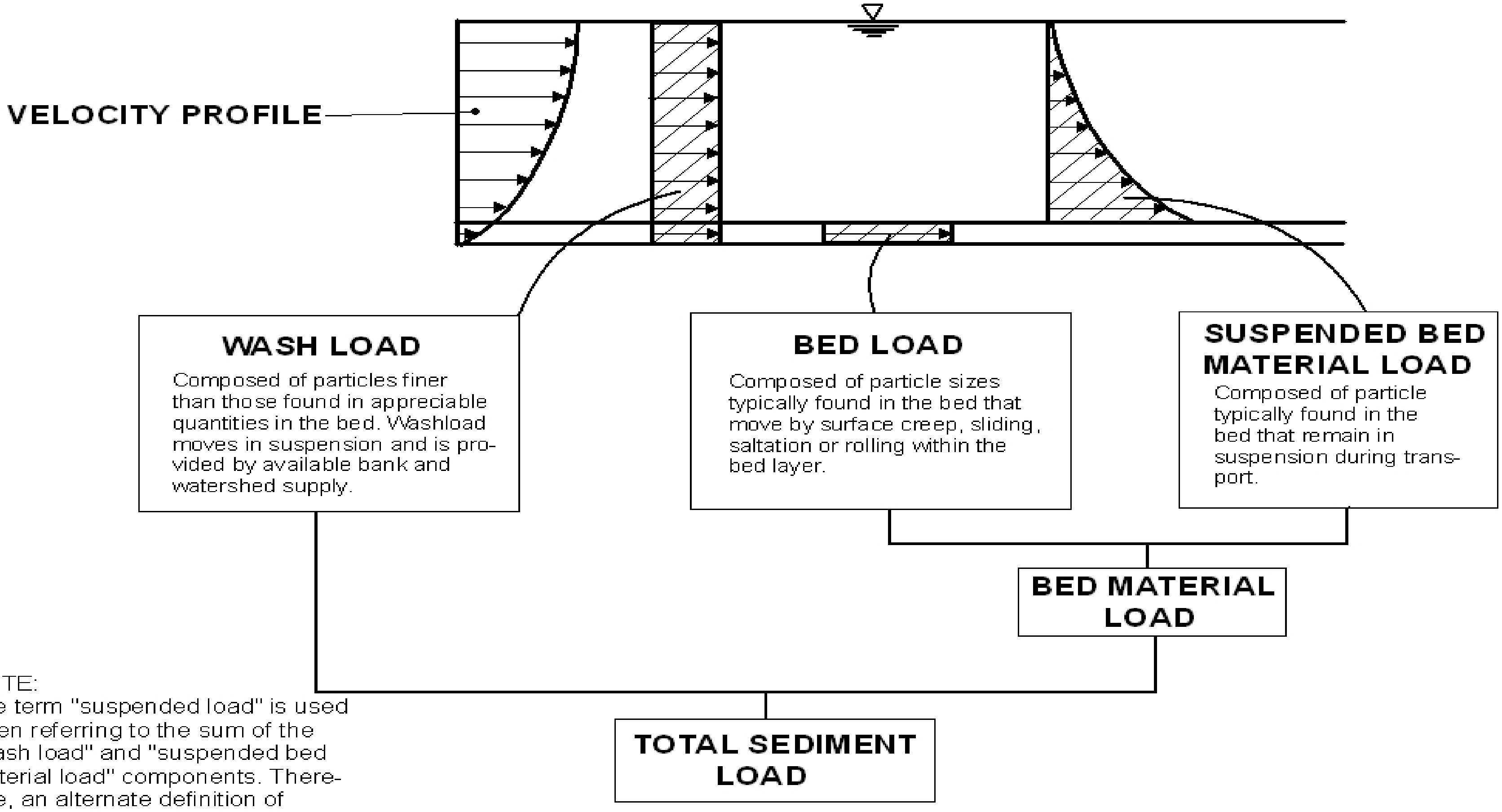
Sediment Continuity

$$\Delta V = V_{s(inflow)} - V_{s(outflow)} \qquad (3.25)$$

Sediment transport and sediment volume (Eqn. 3.25) relate only to the bed material load when applied to the aggradation/degradation estimates.

Wash load is assumed to pass through the reach since it is carried in suspension and has little interaction with the channel bed.

Modes of Sediment-load Transport



WASH LOAD

Composed of particles finer than those found in appreciable quantities in the bed. Washload moves in suspension and is provided by available bank and watershed supply.

BED LOAD

Composed of particle sizes typically found in the bed that move by surface creep, sliding, saltation or rolling within the bed layer.

SUSPENDED BED MATERIAL LOAD

Composed of particle typically found in the bed that remain in suspension during transport.

BED MATERIAL LOAD

TOTAL SEDIMENT LOAD

NOTE:
The term "suspended load" is used when referring to the sum of the "wash load" and "suspended bed material load" components. Therefore, an alternate definition of total sediment load is the sum of the suspended load and bed load.

Sediment Continuity

Dynamic Equilibrium

$$V_{s(\inf low)} = V_{s(outflow)}$$

Equilibrium Concept

- Stream channel tend to adjust toward a state of dynamic equilibrium

- Ability of the channel to carry water and sediment is in balance with the amount of water and sediment delivered from upstream and lateral sources

- Concept applies to the condition to which the channel tends over along period of time, and is the accumulated result of all the flows to which the channel is subjected.

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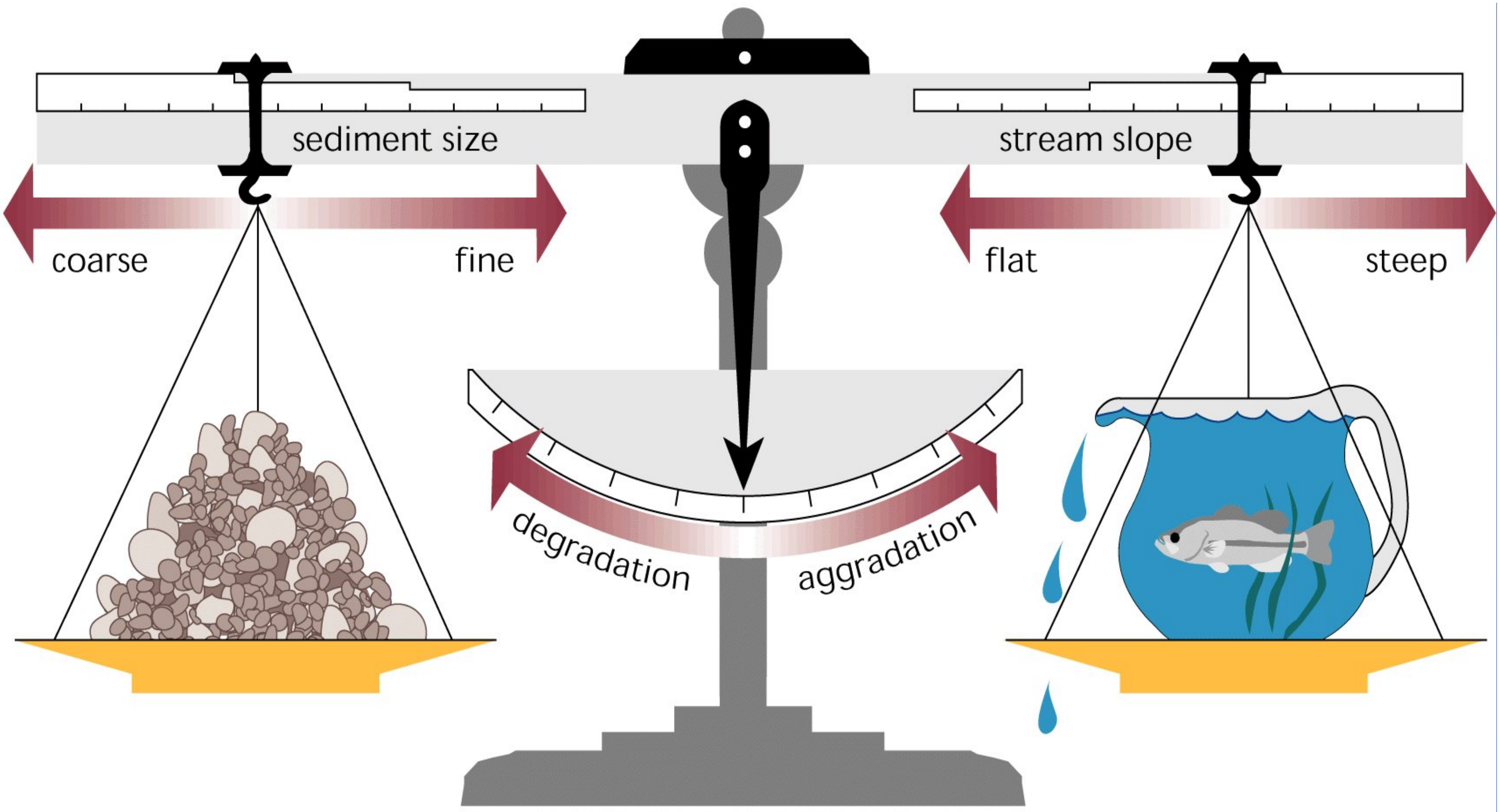

$$Q_s \cdot D_{50} \propto Q_w \cdot S$$

From Rosgen (1996), from Lane, Proceedings, 1955.
Published with the permission of American Society of Civil Engineers.

Fig. 1.13 – Factors affecting channel degradation and aggradation: Concept of "Stream Balance.".
In Stream Corridor Restoration: Principles, Processes, and Practices, 10/98.
Interagency Stream Restoration Working Group (15 Federal Agencies of the US).

Equilibrium Slope

From Lanes' equation $QS \sim Q_s \; D_{50}$

When sediment to reach is reduced (less than the transport capacity), channel will flatten

When sediment is increased (greater than the transport capacity), the channel will steepen

Ultimate condition is referred to as the equilibrium slope

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Equilibrium Concept

Adjustments to the channel can occur in different ways:

Changes in cross-section shape (primarily width)
Changes in gradation of the bed material
Changes in slope

Equilibrium Concept

Adjustments to the channel can occur in different ways:

Changes in cross-section shape (primarily width)
Changes in gradation of the bed material
Changes in slope

Typically, the adjustments are a combination of all three
The relative importance depends on the specific characteristics of the channel

Evaluation of Vertical Stability

If channel width remains unchanged:

$$\Delta Z = \frac{\Delta V}{WL(1-\eta)}$$

where Δz = average change in bed elevation in the reach

ΔV = average change in sediment volume in the reach

W = average width of the channel bed

L = length of the reach

η = porosity of the bed material (~0.4)

Equilibrium Slope

How do we estimate it?

Equilibrium Slope

Use hydraulic and sediment-transport relationships (and assumptions regarding the channel geometry) to estimate the equilibrium slope for a specific discharge and sediment inflow conditions.

Analysis is performed using the dominant discharge

Dominant Discharge

Increment of discharge that carries the most sediment over a long period of time

In ephemeral streams, the dominant discharge tends to be associated with larger, less frequent floods than perennial streams.

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For design purposes:
lightly developed watersheds - dominant discharge will be in the 5-10-year peak flood event
highly developed watersheds - dominant discharge will be in the 3-5-year peak flood event

Dominant Discharge

If bed-material transport rating curves and storm hydrographs are available, then

Dominant discharge can be estimated as the peak storm event that will produce a bed-material sediment yield equal to the mean-annual sediment yield.

Dominant Discharge

Mean annual sediment yield can be estimated by integrating the sediment yield frequency curve (Chang, 1988):

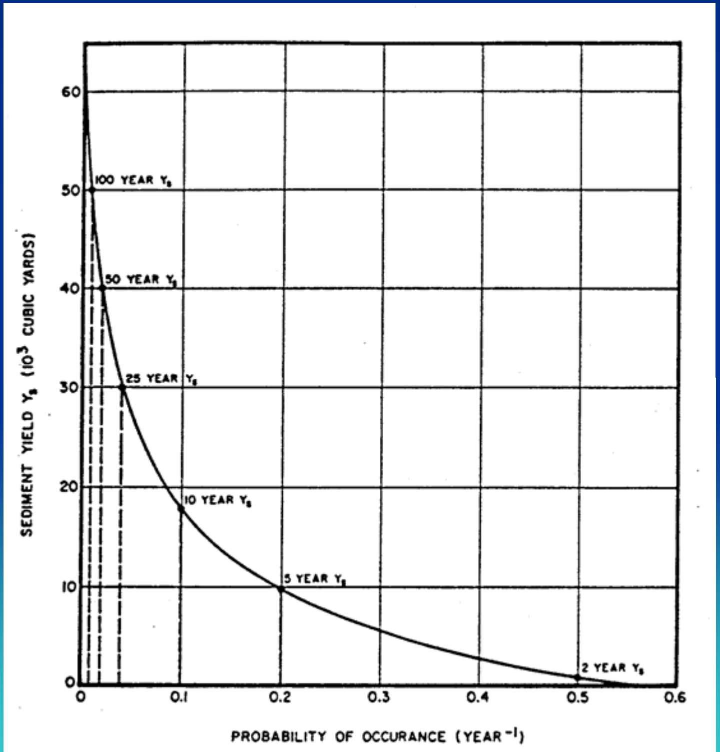
$$Y_{sm} = \int_0^1 Y_s \, dP$$

where Y_s = individual storm sediment yield
P = the probability of occurrence of that flood in one year.

Dominant Discharge

$$Y_{sm} = .055Y_{s100} + 0.245Y_{s10} + 0.4Y_{s2}$$

$$Y_{sm} = .015Y_{100} + .015Y_{50} + .04Y_{25} + .08Y_{10} + .2Y_{5} + .4Y_{2}$$



Equilibrium Slope

$$q_w = \frac{1.49}{n} Y^{\frac{2}{3}} S^{\frac{1}{2}}$$

$$q_s = a\,V^b\,Y^c$$

Where:

q_w = water discharge per unit width of channel

s = friction slope

n = Manning’s n roughness coefficient

y = channel depth

V = channel velocity

q_s = bed-material supply per unit width of channel

a, b, c = coefficient and exponents of the power function bed-material transport capacity relationship

Equilibrium Slope

$$S_{eq} = \left(\frac{a'}{q_s}\right)^{\frac{10}{3(c-b)}} \quad q^{\frac{2(2b+3c)}{3(c-b)}} \quad \left(\frac{n}{1.49}\right)^{2} \qquad (3.30)$$

where S_{eq} = equilibrium slope
q_s = bed-material supply per unit width of channel
q = water discharge per unit width of channel
n = Manning's roughness coefficient
a’, b, c = coefficient and exponents of the power function bed-material transport capacity relationship

Equilibrium Slope

Comments:

Results of the equilibrium slope calculations are used to calculate long-term bed changes

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Important to note presence of vertical controls (natural and man-made).

Natural controls include:
Bedrock, clay or caliche outcrops (may be temporary)

Equilibrium Slope

Comments:

Results of the equilibrium slope calculations are used to calculate long-term bed changes

Important to note presence of vertical controls (natural and man-made).

Natural controls include:
Bedrock, clay or caliche outcrops (may be temporary)

Man-made controls include:
Grade-control structures
Detention ponds
Roadways
Culverts

Equilibrium Slope

Comments:

Vertical controls act as a pivot point

Consider the height the banks that would develop as the channel flattens, or steepens.

Equilibrium Slope

For cases where the equilibrium slope of a series of reaches having similar roughness, discharge and channel geometry is of interest:

$$S_{eg} = S_{ex}\left(\frac{Q_{s(\text{supply})}}{Q_{s(\text{existing})}}\right)^{\left(\frac{2}{b-x}\right)} \qquad \textbf{(3.31)}$$

where

$$x = (3/5)(2b/3 + c) \qquad \textbf{(3.32)}$$

and S_{ex} is the existing channel slope

Equilibrium Slope

Comments:
Equilibrium slope depends on magnitude of upstream bed-material supply

Obtaining estimate of upstream supply is difficult or impractical due to:

- Uncertainty in timing and magnitude of sediment from overland sources
- Inability to define long-term condition of upstream channel
- Imprecision of bed-material transport relationships

Alternative Approximation of the Equilibrium Slope

Alternative Approximation of the Equilibrium Slope

Based on observation that stable alluvial channels rarely, if ever, sustain super critical flows for extended periods.

Average Froude numbers in stable sand-bed stream rarely exceed 0.7 to 1.0.

Alternative Approximation of the Equilibrium Slope

Therefore, maximum stable channel slope for a given geometry and dominant discharge can be computed by combining the relationship for Froude number with the uniform flow formula

$$q_w = \frac{1.49}{n} Y^{\frac{2}{3}} S^{\frac{1}{2}} \qquad Fr = \frac{V}{\sqrt{gY}}$$

Where:

q_w = water discharge per unit width of channel

s = friction slope

n = Manning's n roughness coefficient

y = channel depth

V = channel velocity

Fr = Froude Number

Alternative Approximation of the Equilibrium Slope

For arroyos with wide rectangular channel:

$$S_s = CQ_D^{-0.133} \qquad (3.33)$$

$$C = 18.28\, n^2 F^{0.133} F_r^{2.133} \qquad (3.34)$$

In the above equations,

S_s = maximum stable slope
n = Manning's roughness coefficient
F_r = maximum Froude Number (0.7 to 1.0)
Q_D = dominant discharge
F = width-depth ratio of the flowing water

Alternative Approximation of the Equilibrium Slope

Dominant width of the channel (W_D)

$$W_D = 0.5F^{0.6}F_r^{-0.4}Q_D^{0.4} \quad (3.35)$$

In the above equations,

W_D = width of the channel
F_r = maximum Froude Number (0.7 to 1.0)
Q_D = dominant discharge
F = width-depth ratio of the flowing water

Alternative Approximation of the Equilibrium Slope

Special Case:
Width-depth ratio ~40 for channel at or near dominant discharge.
Critical flow conditions can be assumed (Fr=1)

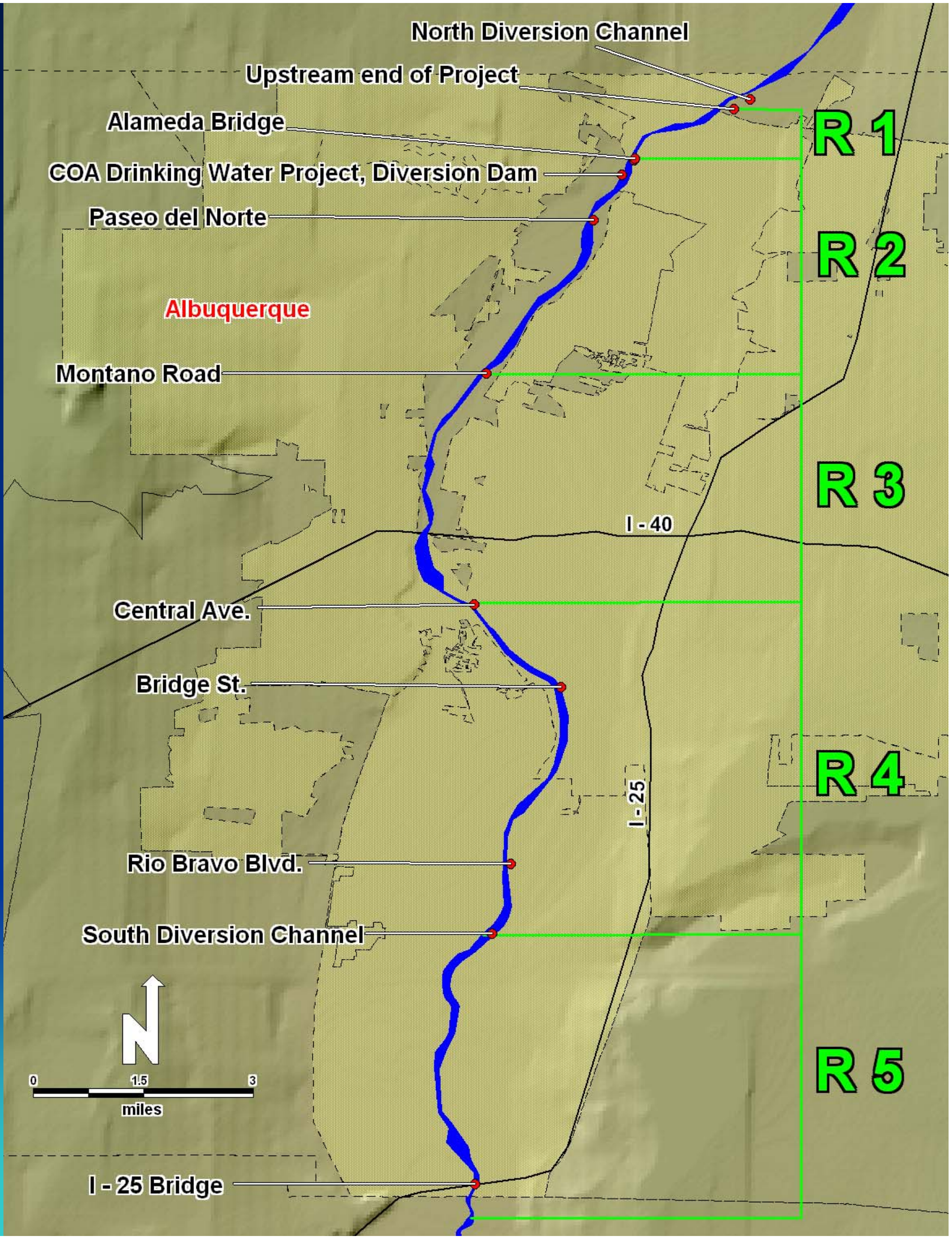
Equation 3.35 reduces to:

$$W_D = 4.6\ Q_D 0.4 \qquad (3.36)$$

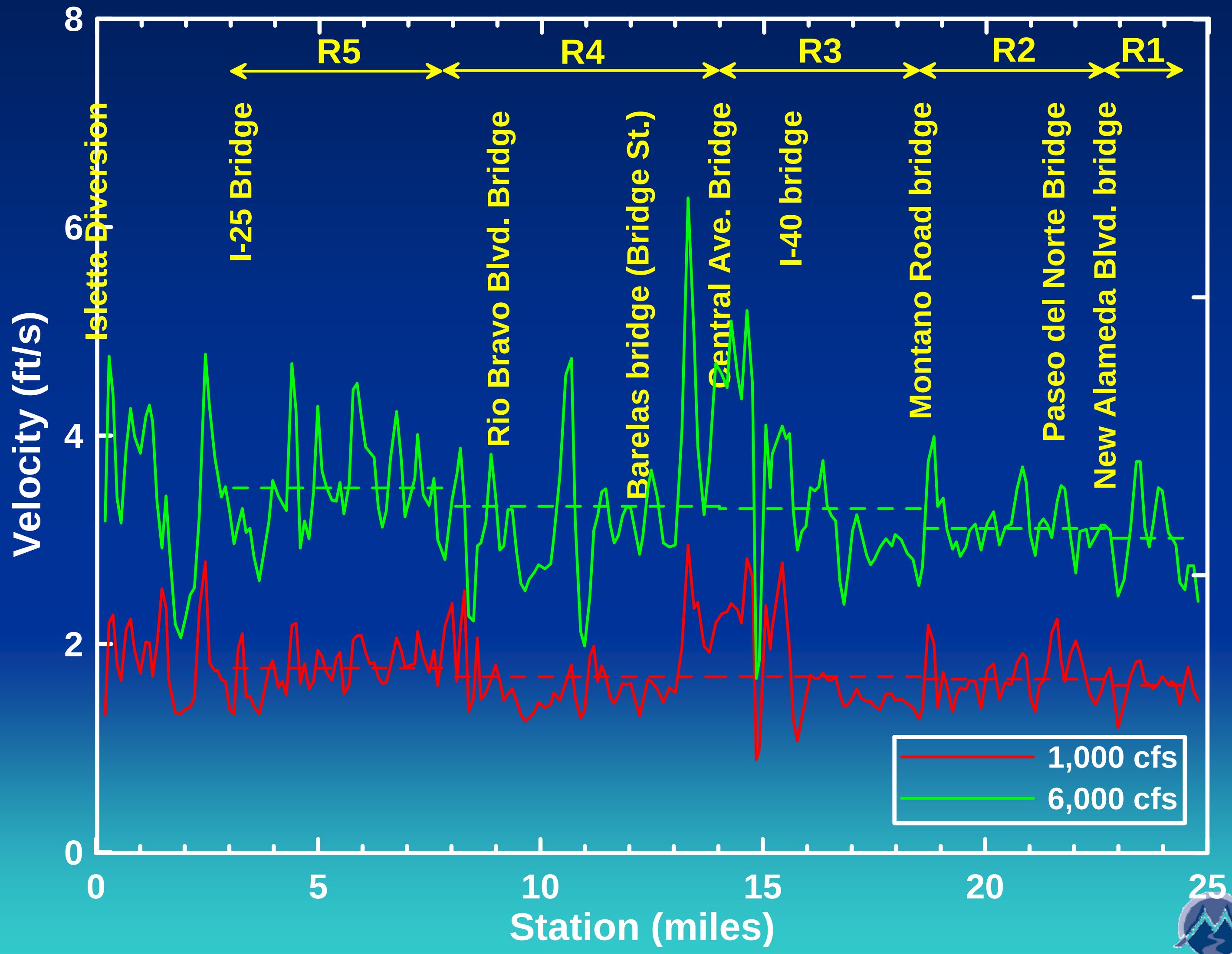
Project Example

Rio Grande Channel Stability Analysis

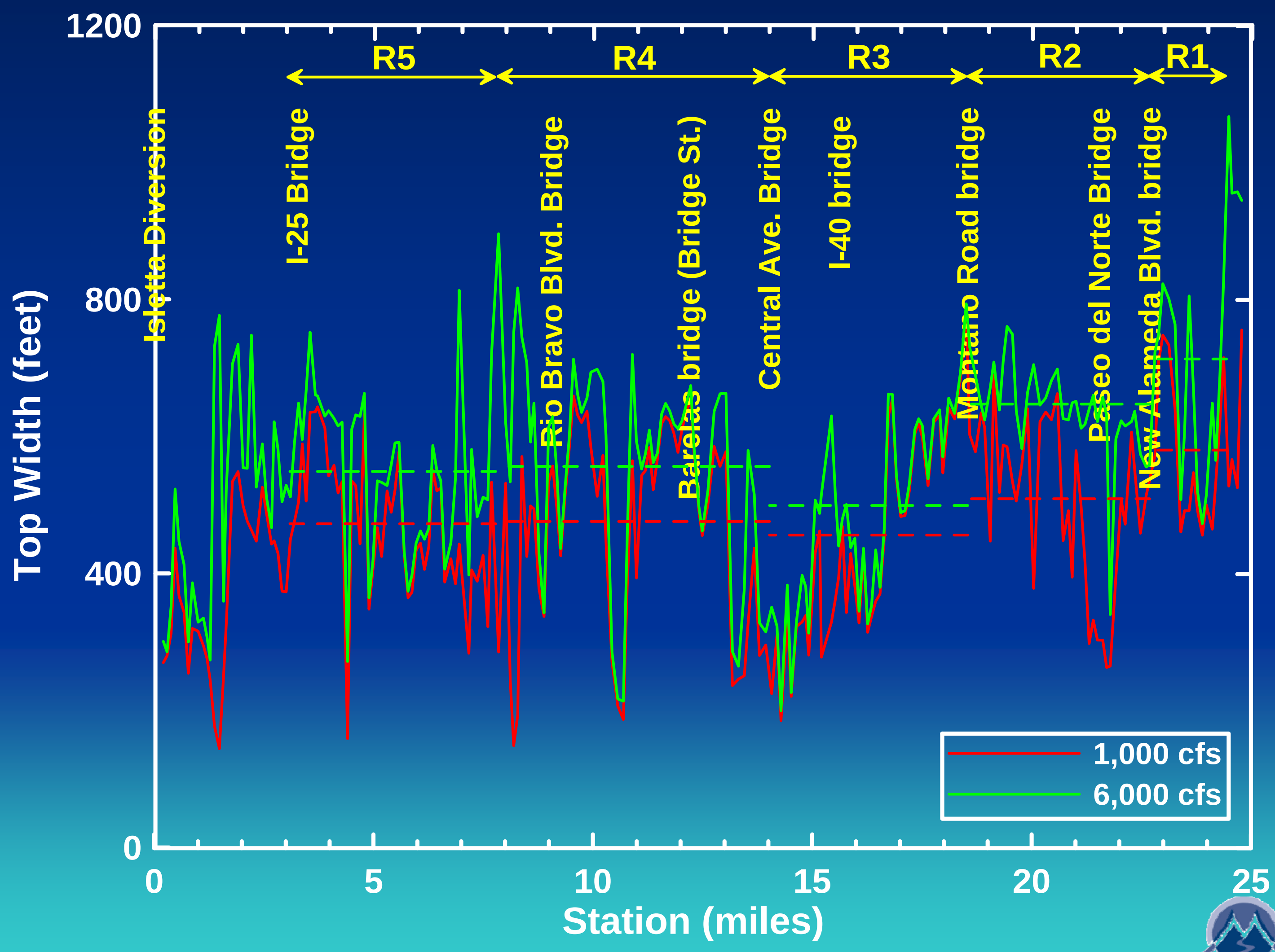
Subreach Definitions for Sediment Continuity Analysis



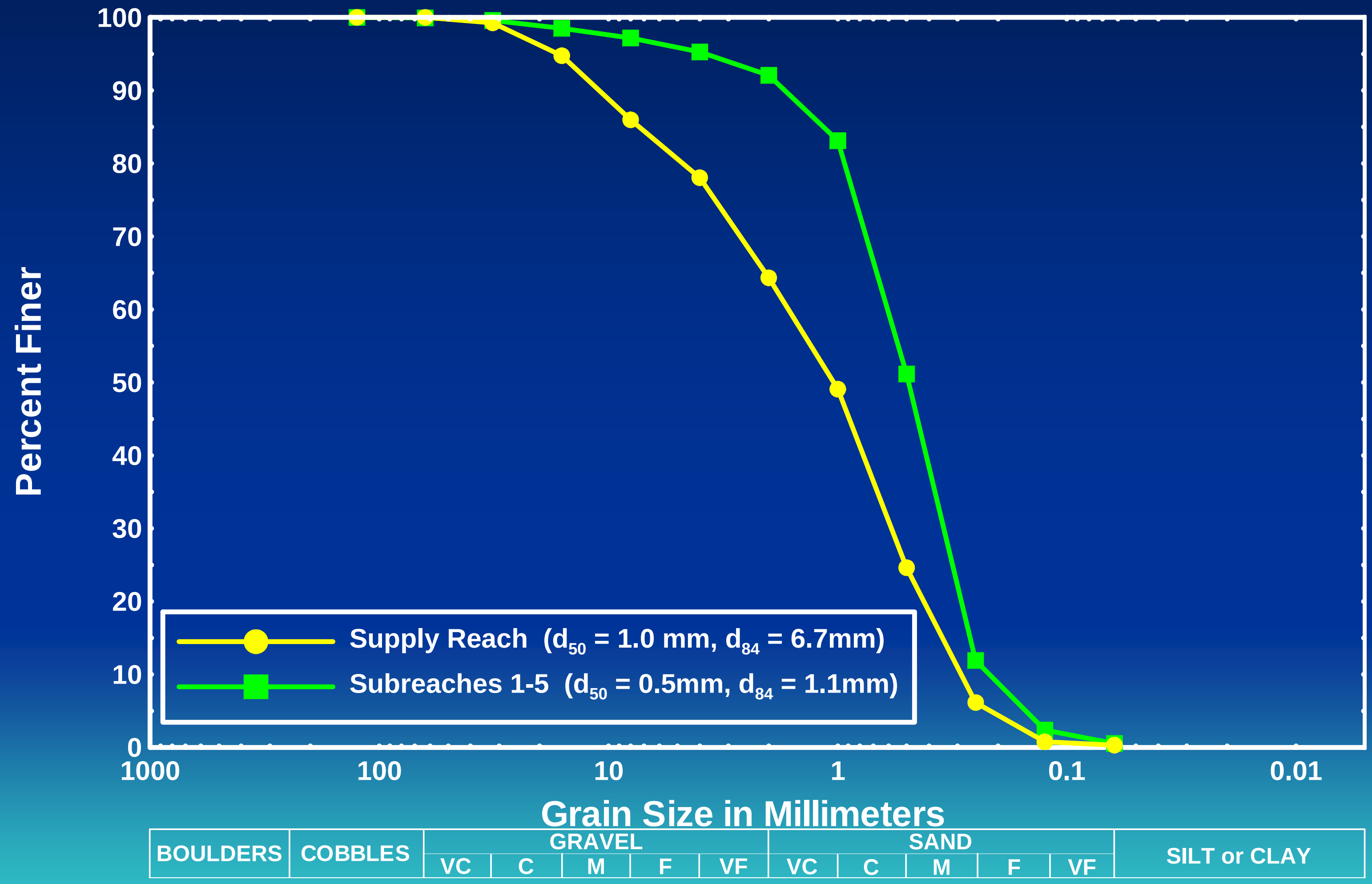
Subreach-Averaged Velocity



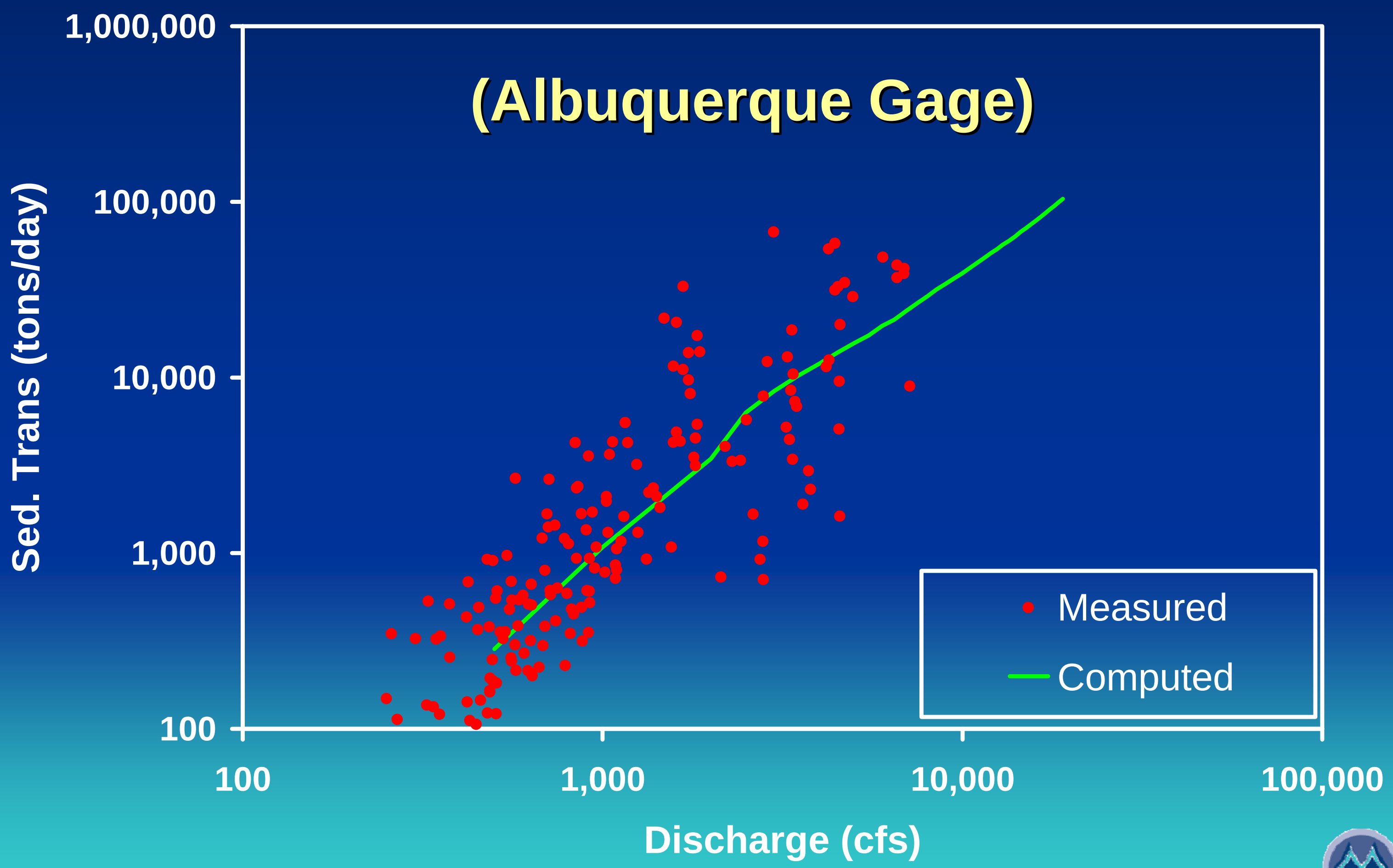
Subreach-Averaged Topwidth



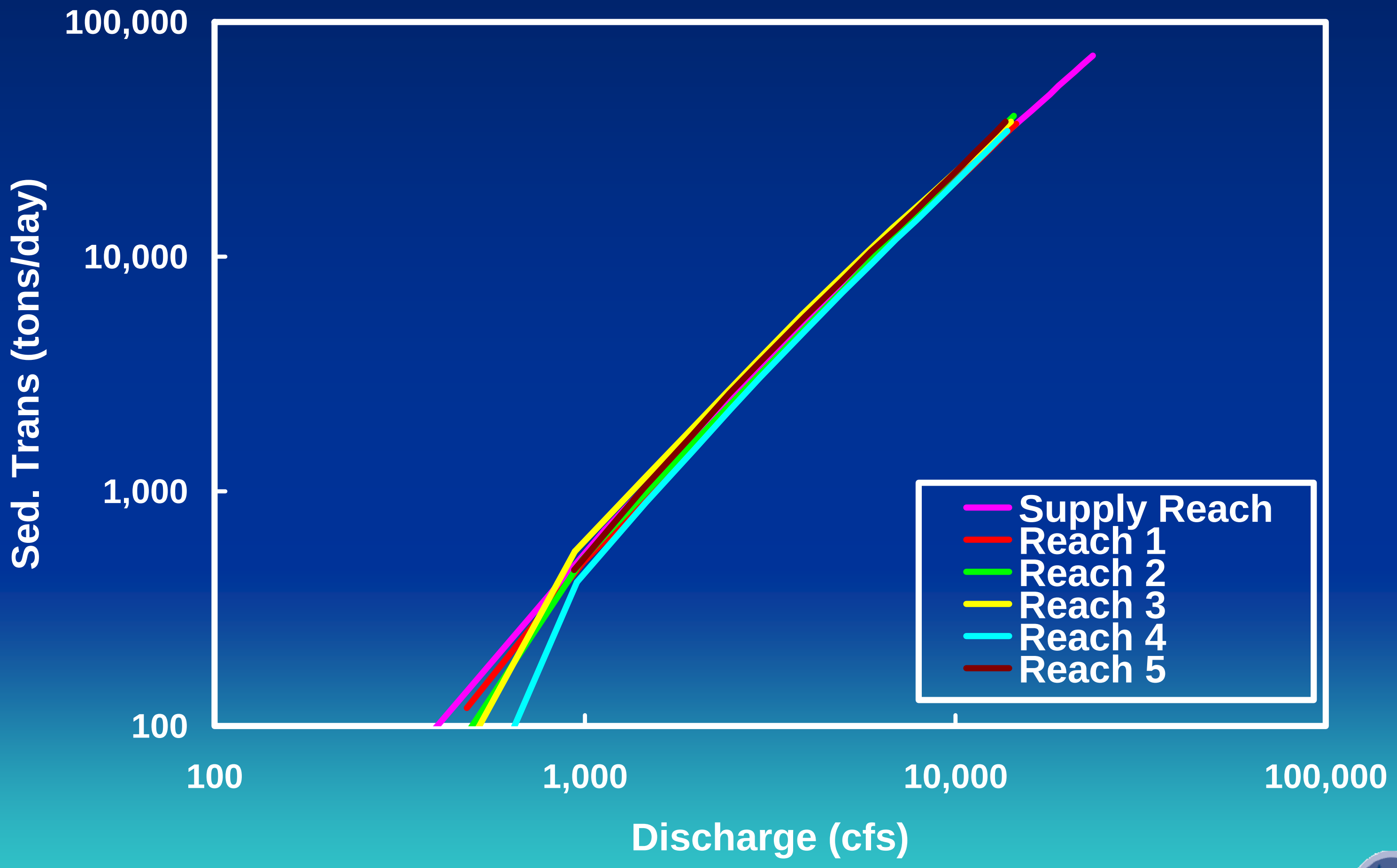
Bed Material Gradation Curve



Bed Material Rating Curve
Yang (sand)



Sediment Rating Curves



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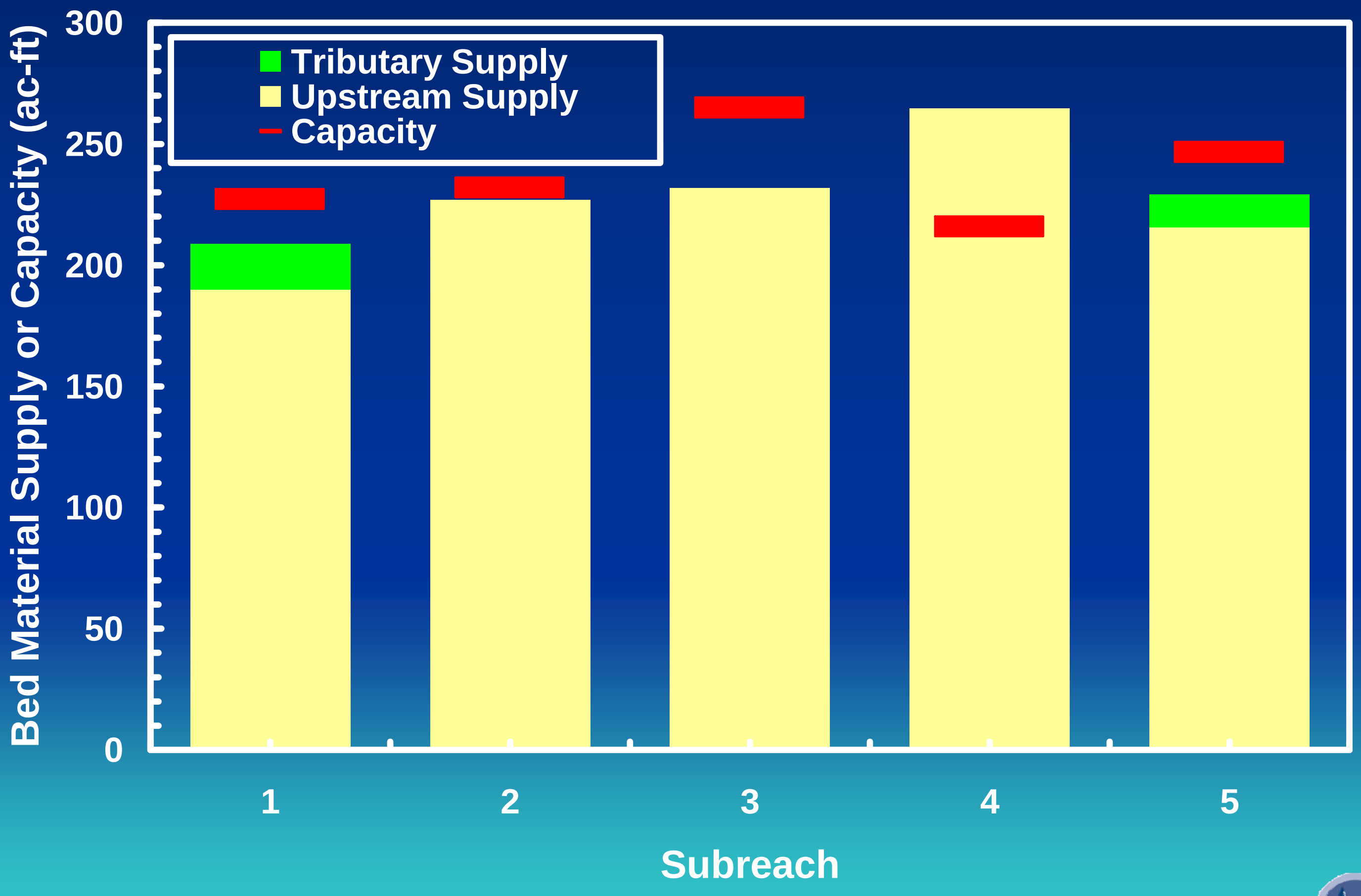
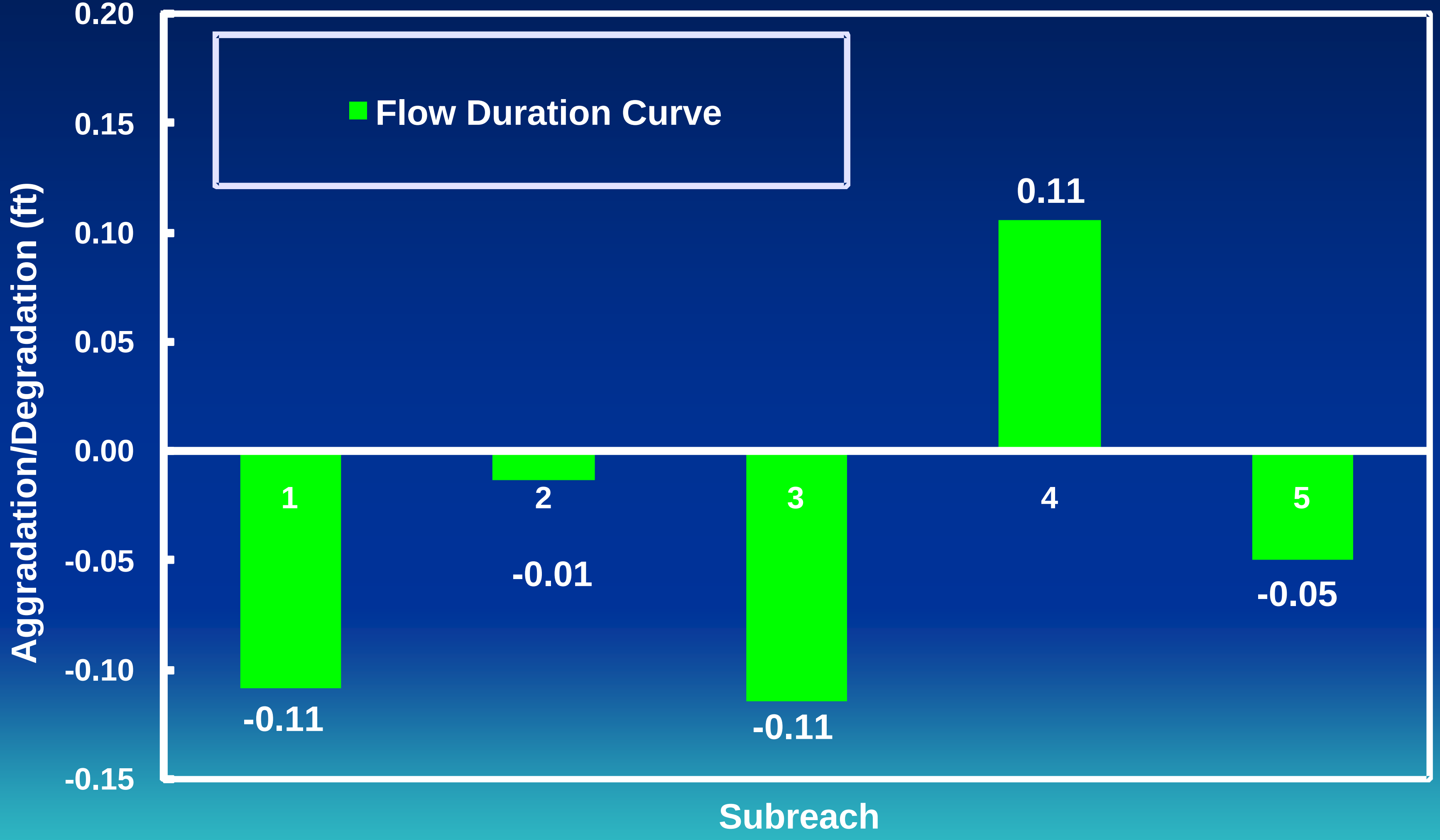
Sediment Continuity

Flow Duration Curve



Sediment Continuity Results



Questions?

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Example Problems

Annual Sediment Yield

The following total sediment yield results were obtained by integrating the bed-material transport capacity and adding the fine sediment for each storm.

Return Period (years)	Water Yield (ac-ft)	Total Sediment Yield (tons)	Unit Sediment Yield (tons/acre)
100	40.2	6,142	16.6
50	33.8	4,863	13.1
25	27.5	3,774	10.2
10	19.4	2,413	6.5
5	13.7	1,559	4.2
2	7.1	668	1.8

Compute the mean annual water and sediment yields.

Annual Sediment Yield Example Problem

From Equation 3.26:

$$Y_{x\ Annual} = 0.015\ Y_{x\,100} + 0.015\ Y_{x\,50} + 0.04\ Y_{x\,25} + 0.08\ Y_{x\,10} + 0.20\ Y_{x\,5} + 0.40\ Y_{x\,2}$$

where x = Either the total sediment or water yield.

(1) Water yield:

$$Y_{w\,a} = 0.015\,(40.2) + 0.015\,(33.8) + 0.04\,(27.5) + 0.08\,(19.4) + 0.2\,(13.7) + 0.4\,(7.1)$$

$$= 9.34\ ac - ft$$

Sediment yield:

$$Y_{s\,a} = .015\,(6142) + 0.015\,(4863) + 0.04\,(3774) + 0.08\,(2413) + 0.2\,(1559) + 0.4\,(668)$$

$$= 1088\ tons$$

Annual Sediment Yield Example Problem

Unit sediment yield:

$$Y_{sa} = \frac{1088}{370} = 2.94 \text{ tons/acre}$$

$$= 2.94/3.4^{*} = 0.86 \text{ ac-ft/ mi}^{2}$$

(*assuming bulked unit weight of 100 pcf, see Constants and Conversions)

Equilibrium Slope
Example Problem #1

For the given arroyo, estimate the equilibrium slope for the dominant discharge.

1. Estimate the dominant discharge (Q_D) from Equation 3.46:

$$Q_D = 0.2\,Q_{100} = (.2)(1045) = 209\ cfs$$

Equilibrium Slope Example Problem #2

2. Estimate the hydraulic conditions for Q_D.

Using procedures in the hydraulic example problem, the following results are obtained:

Velocity = 7.1 fps
Hydraulic depth = 0.76 feet

Equilibrium Slope Example Problem #3

3. **If the bed material supply at this discharge is 3.2 cfs (from similar analysis of the supply reach) estimate the equilibrium slope.**

Method 1 - Use Equation 3.30:

$$S_{eq} = \left(\frac{a}{q_{s\,supply}} \right)^{\frac{10}{3(c-b)}} q^{\frac{2(2b+3c)}{3(c-b)}} \left(\frac{n}{1.486} \right)^{2}$$

where a, b, c are given by Equation C.3:

Equilibrium Slope Example Problem #3

$$Q_s = a' V^b Y^c (1 - (C_f)^d$$

a' = 1.5 x 10^{-6}
b = 5.8
c = -0.7
d = -1.9

$$q = Q/W = 210/39 = 5.38 \text{ cfs/ft}$$

$$q_{ssupply} = Q_{ssupply} / W = \frac{3.2}{39} = 0.082 \text{ cfs/ft}$$

Equilibrium Slope
Example Problem #3

If the fine sediment concentration for (Cf) Qd is 10,000 ppm

$$a = a'\left(1-\left(C_f/10^6\right)\right)^d = 1.5\ x\ 10^6\left(1-\frac{10{,}000}{10^6}\right)^{-1.9} = 1.53\ x\ 10^{-6}$$

$$S_{eq} = \left(\frac{1.53\ x\ 10^{-6}}{0.082}\right)^{\frac{10}{3(-0.7-5.8)}}(5.38)^{\frac{[2(2(5.8)+3(-0.7))]}{3(-0.7-5.8)}}\left(\frac{0.035}{1.486}\right)^2$$

$$= 0.029$$

Equilibrium Slope
Example Problem #3

Method 2 - Use Equation 3.31

$$S_{eq} = S_{existing}\left(\frac{Q_{s\ Supply}}{Q_{s\ Existing}}\right)^{\left(\frac{2}{(b-x)}\right)}$$

where

$$X = \left(\frac{3}{5}\right)\left(\frac{2b}{3} + c\right) = \left(\frac{3}{5}\right)\left[\frac{2(5.8)}{3} + (-0.7)\right] = 1.9$$

$$Q_{s\ Existing} = a' V^{b} Y^{c} \left(1 - \left(C_f / 10^6\right)\right)^{d} W$$

$$= \left(1.5\ x\, 10^{-6}\right)(7.1)^{2.8}\,(.76)^{-0.7}\left(1 - \frac{10{,}000}{10^6}\right)^{-1.9}(39) \quad = \quad 6.25\ cfs$$

Equilibrium Slope Example Problem #3

$$S_{eq} = 0.04\left(\frac{3.2}{6.25}\right)^{\left(\frac{2}{(5.8-1.9)}\right)} = 0.028$$

What is the required spacing (L) of a series of grade control structures if the maximum drop height over one structure is 3 feet?

$$L = \frac{H_{max}}{\Delta S}$$

$$= \frac{3}{(0.04 - 0.028)} = 250\ feet$$

Equilibrium Slope Example Problem #3

Method 3 – Use Equation 3.33.

An alternative method for estimating the equilibrium slope is suggested in Chapter 3 that is based on the anticipated Froude number in the channel after the degradation has occurred. The Froude number for the existing channel in the above example is:

$$F_r = \frac{V}{\sqrt{gY}} = \frac{7.1}{\sqrt{32.2 * 0.76}} = 1.4$$

and the Froude Number for the equilibrium channel would be about 1.2, assuming rigid boundary conditions. Supercritical flow typically occurs only over relatively short distances and short timeframes in erodible natural channels. Based on this factor alone, the bed slope should eventually adjust so that the Froude Number does not exceed 1. Use Equations 3.33 and 3.34 to estimate the slope for this condition:

$C = 18.28n^2F^{0.133}F_r^{2.133} = 18.28(0.035)^2(40)^{0.133}(1)^{2.133} = 3.66$

$S_s = CQ_D^{-0.133} = 3.66(209)^{-0.133} = 0.018$