Sediment Transport & Channel Design

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Discharge

Rate of Sediment Transport (tons / day)

Frequency of Discharge (days / yr)

transport * frequency (tons / yr)

Wolman and Leopold, 1953

Leopold & Maddock 1953

Kilpatrick & Barnes, 1964

Leopold, Wolman, Miller 1964

Williams, 1978

Leopold & Maddock 1953

Phillips et al., 2022

Wolman and Miller, 1960

Fig. 1.—Relations between rate of transport, applied stress, and frequency of stress application.

75% of obs within box

19% of obs: 1.36<RI<2.2 yr

1.06

5

ALL n = 107

Wolman and Leopold, 1957

WY, MT, MD, NC, SC

Kilpatrick & Barnes, 1964

AL, GA, NC, SC

Leopold, Wolman, Miller 1964

IN, NB, MS, MD

Williams, 1978

CO, UT, NM, OR

Phillips et al., 2022

Return Period of Bankfull Flow (years)

Width (m)

Discharge m³ s⁻¹
The width of channels increases consistently with the square root of discharge.

The flow that moves the most sediment, over time, tends to just fill the channel and occurs ever year or two.
The stable channel
The regime channel
The hydraulic geometry

A basis for natural channel design?
The width of channels increases consistently with the square root of discharge.

The flow that moves the most sediment, over time, tends to just fill the channel and occurs ever year or two.

At the core of these observations is a correlation between channel geometry, flow, and sediment supply.

The correlation requires that the channels have adjusted to their water and sediment supply.

But what if channel is currently adjusting, or perpetually adjusting?
Using "the stable channel" or "the equilibrium channel" for design?
→ Streams are never in equilibrium!
   Especially in Southern Ontario.
   Especially those we judge to be unacceptably “out of adjustment”
→ How do we connect with specific, local, non-sediment objectives?
   (if we build it like this ... good things will happen. | | how do we balance?)
→ A “rational” approach: break problem down into its pieces:
   specify drivers, quantify channel response.
→ A “design approach”: specify objectives and design to meet them
   (rather than specify design and hope that it solves the problem)
→ Connect goals to objectives to actions, through specific mechanisms

**Unfortunately, for a rational design approach ...**
(A) We can never forecast future conditions (e.g. water & sediment supply)
   with a high degree of accuracy
(B) We will never know the exactly correct channel geometry for a river channel
   *(because there probably isn’t one)*

**Can we develop a design approach that**
(1) Specifies desired channel behavior
(2) Incorporates sediment transport with uncertainty
(3) Accommodates “typical” conditions
What is the supply of water and sediment? and
What do you want to do with them?

(1) Do you want the bed and banks to be static at a design flow?
(2) Do you need to match transport capacity to sediment supply?
(3) Both of the above
(I) Mixed-size sediment transport I: Response to fines content
(II) Threshold Channel Design Under Uncertainty
(III) Mixed-sized Sediment Transport II: Size sorting and the Armoring Problem
(IV) Alluvial Channel Design
(V) Threshold & Alluvial Channel Design: Together at last!
(VI) Channel Design Strategy
(I) Mixed-sized Sediment Transport I: The basics ... and response to fines content
Absolute size has two effects on transport:
(i) Grain mass increases faster than area, bigger grains harder to move
(ii) Viscous effects dampen fluctuations, tiny grains harder to move

Relative size has two effects on transport:
(i) Little grains “hidden”, harder to move
(ii) Bigger grains “exposed”, easier to move

What if the absolute and relative size effects exactly cancel?

\[ \tau_c \propto \text{const} \]

\[ \tau^* = \frac{\tau_c}{(s-1)\rho g D} \propto \frac{1}{D} \]

---

**Graphical Data**

- **X-axis**: Grain Size \(D\) (mm)
- **Y-axis**: Shear stress \(\tau_c\) (Pa)
- **Legend**: Quartz in water
  - No Motion
  - Motion
  - Viscous effects

**Shields Diagram**

Fig. 2.18. Shields diagram for initiation of motion (source Vanoni, 1964).
There are many reasons why sand supply to a gravel-bed river might be increased: fire, urbanization, reservoir flushing, dam removal.

What is the effect on transport rates? Channel dynamics? Stream ecology?

Previous Experiments

• Jackson & Beschta (1984)
• Ikeda & Iseya (1988)

→ Adding sand increases gravel mobility
Some experimental evidence

- 5 sediments, add sand to gravel
- Sand: 0.5 – 2.0 mm
- Gravel: 2.0 – 64 mm
- Sand Content: 6, 14, 21, 27, & 34%
- 9 or 10 runs with each sediment, wide range of transport rates
- Depth & width held constant, primary variables are sand content & flow strength
Effect of sand content on gravel transport rate

How do we capture effect of sand content on gravel transport rates?

Transport increases even though proportion of gravel in bed decreases.
The sand effect on transport is captured by a reduced critical shear stress for incipient motion of the gravel.

\[
\tau^* = \frac{\tau_c}{(s-1) \rho g D} \approx 0.03
\]

For \( D > 4 \) mm
We have captured the effect of sand on gravel transport by reducing the critical shear stress for the gravel.

Reducing $\tau_C^*$ by a factor of four increases the transport rate by much, much more.
This changes our approach to predicting sediment transport rates:

A fundamental parameter depends on bed grain size

(also found in the many fraction surface-based model)


Test sand effect in a sediment feed flume
Feed gravel (2-32 mm) at same rate in each run; Increase sand feed rate from much less to much more than gravel

Results
As sand feed increases, bed gets sandier & slope decreases: less stress required to carry same gravel load & increased sand load

Pay attention to this slide
The point?

Adding sand can have a huge effect on gravel transport rates. Most of this is captured in a changed critical Shields Number.

There are a number of ways to increase sand supply to a gravel-bed river: fire, urbanization, reservoir flushing, dam removal.

A two fraction approach captures this effect in a tractable framework.
The first transport problem: incipient motion

The transport model is a defined value of critical Shields Number

For a gravel-bed river, a reasonable choice of $D$ is the median size of the gravel portion of the bed (the framework), measured with a pebble count. For clean, loose gravel,

$$\tau_c^* = \frac{\tau_c}{(s-1)\rho gD} \approx 0.03$$

For a gravel bed that has not been entrained for some time, the grains can become weakly cemented, and they can also become arranged into subtle structures that increase their resistance to movement. This can more than double $\tau_c^*$. 

Church, Hassan, Wolcott Water Res Res 1998
(II) Threshold Channel Design Under Uncertainty
Example problem: Threshold channel design

*Given:*
Valley slope = 0.007 (this is the maximum possible slope)
Bed material \( D_{50} = 45 \text{ mm} = 0.148 \text{ ft} \)
Bed material \( D_{75} = 55 \text{ mm} = 2.17 \text{ in} \)
Bed material \( D_{84} = 60 \text{ mm} = 0.197 \text{ ft} \)
Channel side slope = 3H:1V
Specific weight of sediment = 165 lb/ft\(^3\)
Water temperature = 68 °F
Design discharge is 25-year storm = 400 ft\(^3\)/s

*Problem:*
Design a threshold channel to convey the design discharge.

Note: There is no unique solution with the given design constraints.
Step 1 Determine design bed-material gradation/channel boundary.

Step 2 Determine preliminary width.

Step 3 Estimate critical shear stress/velocity.

Step 4 Determine flow resistance (Manning’s $n$).

Step 5 Calculate depth and slope.

Step 6 Determine planform.

Step 7 Assess for failure and sediment impact.
For a ‘real’ channel...
we have choices to make
Design discharge
\(\tau^*\)
Roughness model
Drag partition?
Channel Geometry

Given discharge \(Q\), grain size \(D\),
critical Shields Number \(\tau^*_c\),
Pick a roughness model & channel geometry
find slope \(S\) and depth \(h\) producing incipient motion.

**Finding Normal Depth - Trapezoidal Channel**

Manning’s eqn: 
\[
Q = \frac{\sqrt[3]{nS}}{n} \left[ \frac{h(B_o + mh)}{B_o + 2h\sqrt{1 + m^2}} \right]^{2/3}
\]

where

\[
B = B_o + 2mh, \quad A = B_o h + mh^2 = h(B_o + mh), \quad P = B_o + 2h\sqrt{1 + m^2}
\]

Finding \(n, Q,\) or \(S\) is easy; to find \(h\) requires iteration

Try Manning arranged as 
\[
h_{n+1} = \left( \frac{nQ}{\sqrt[3]{S}} \right)^{3/5} \left[ \frac{B_o + 2h_n\sqrt{1 + m^2}}{B_o + mh_n} \right]^{2/5}
\]

where \(n\) and \(n+1\) subscripts indicate successive approximations

**GENERAL SOLUTION STRATEGY for SLOPE and**
**DIMENSION for INCIPIENT MOTION in a TRAPEZOIDAL CHANNEL**

Given \(Q, B_o, m, \tau^*_c, D_{50}, D_{84}\),
find \(\tau^*_c, n, R, U\) and \(S\) from

\[
\tau^*_c = \left( (s-1)\rho gD_{50} \tau^* \right) \quad \text{(definition of } \tau^*_c \text{)}
\]

Determine \(n\) (Limerinos, Lotter, or just specify it)

\[
h_{n+1} = \left( \frac{n\rho gQ}{\sqrt[3]{S}} \right)^{3/5} \left[ \frac{B_o + 2h_{n}\sqrt{1 + m^2}}{B_o + mh_{n}} \right]^{2/5}
\]

\{Recursive calculation for depth \(h\), showing steps \(l\) and \(l+1\)\}

\[
R = \frac{A}{P} = \frac{h(B_o + mh)}{B_o + 2h\sqrt{1 + m^2}} \quad \text{(definition of hydraulic radius)}
\]

\[
U = \frac{Q}{A} \quad \text{ (continuity)}
\]

\[
S = \frac{\tau^*_c}{\rho gh} \quad \text{ (momentum)}
\]
Use trapezoid with user specified bank angle and bank roughness

<table>
<thead>
<tr>
<th>Roughness</th>
<th>Drag Partition</th>
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<tbody>
<tr>
<td>Limerinos (1970)</td>
<td>No – For wide channel with only grain roughness</td>
</tr>
<tr>
<td>Lotter (1936)</td>
<td>Yes, w/ Strickler grain roughness</td>
</tr>
<tr>
<td>Different bed and bank roughness</td>
<td></td>
</tr>
<tr>
<td>Sum flows across panels</td>
<td></td>
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</tbody>
</table>

\[ \frac{PR^{5/3}}{n_c} = \sum_i \frac{P_i R_i^{5/3}}{n_i} \]

User specified \( n \)  |  Yes, w/ Strickler grain roughness  |

Finding Normal Depth - Trapezoidal Channel

Manning’s eqn: \( Q = \sqrt{\frac{n}{S}} \left[ \frac{h(B_0 + mh)^{5/3}}{B_0 + 2h\sqrt{1 + m^2}} \right]^{2/3} \)

where

\( B = B_0 + 2mh \), \( A = B_0h + mh^2 = h(B_0 + mh) \), \( P = B_0 + 2h\sqrt{1 + m^2} \)

Finding \( n, Q, \) or \( S \) is easy; to find \( h \) requires iteration

Try Manning arranged as \( h_{n+1} = \left( \frac{nQ}{\sqrt{S}} \right)^{3/5} \left[ \frac{B_0 + 2h_n\sqrt{1 + m_n^2}}{B_0 + mh_n} \right]^{2/5} \)

where \( n \) and \( n + 1 \) subscripts indicate successive approximations
Given discharge $Q$, grain size $D$, Limerinos roughness & trapezoidal channel shape, find slope $S$ producing incipient motion.

Specify $B = 12.5\ m$ and $\tau_c^* = 0.047$,
solution is $S = 0.0064$ with depth $h = 0.54\ m$

Find velocity, boundary stress, depth, and **slope** from continuity, momentum, flow resistance, and definition of $\tau_c^*$
Given discharge $Q$, grain size $D = 45$ mm, Limerinos roughness & trapezoidal channel shape, find slope $S$ producing incipient motion.

Specify $B = 12.5$ m and $\tau^*_C = 0.047$,
solution is $S = 0.0064$ with depth $h = 0.54$ m

a: $D = 64$ mm
b: $D = 32$ mm (or $\tau^*_C = 0.3$)
Strategy

What is probability of failure? What probability are you willing to accept?

\[ P(\text{failure}) = P(Q_D)P(Q_D > Q_c) \]

Choose width, slope combination to match acceptable risk.

For example, for a 25yr \( Q_D \) and a channel design with 10% failure probability,

\[ P(\text{failure}) = P(Q_D)P(Q_D > Q_c) = (0.04)(0.1) = 0.004 \]

giving a 0.4% chance of failure in any year.
(III) Mixed-sized Sediment Transport II: Size sorting and the Armoring Problem
1. Stream-bed armoring

*surface composition & the problem of predicting transport rates*
Streambed armoring is pervasive in gravel-bed steams

Armor Ratio = \( \frac{D_{50} \text{ (surface)}}{D_{50} \text{ (subsurface)}} \)

Bed surface composition determines:
- grains available for transport
- hydraulic roughness
- bed permeability
- living conditions for bugs & fish
The armor problem

- We can measure the bed surface size at low flow, but not at flows moving sediment
- We don’t know what the bed surface looks like at the flows that create it
- *Does the armor layer stay or go during floods?*
Flume studies do not resolve the issue

Sediment Feed

Sediment Recirculation

Both Cases

Mobility – driven armoring

Zero divergence

Kinematic sorting

Grain Size

Flow, Transport Rate

D50

Flow, Transport Rate

D50
To address the armor problem, we first tackle the transport problem

• Transport rates depend on transport of grains available for transport on bed surface

• But nearly all transport data provide composition of the bed *subsurface*, *not surface*!

• This means that the resulting transport models must somehow implicitly account for surface sorting (armoring)
Transport Modeling Basics - 1

Given fully rough flow with boundary stress \( \tau \), sediment of mean size \( D_m \), with individual fractions of size \( D_i \) and proportion \( f_i \). Transport rate \( q_{bi} \) depends on

\[
q_{bi} = f_n(f_i, D_i, D_m, \tau, \text{sed})
\]

where \( \text{sed} = \) other sediment properties. We search a transport model of form

\[
\frac{q_{bi}}{f_i} = f_{n1}(\tau, \tau_{ri})
\]

\[
\tau_{ri} = f_{n2}(D_m, D_i / D_m, \text{sed})
\]

But, what size distribution should we use for \( f_i \)?

ans: surface
There were essentially no surface-based transport observations, so we made some:

- 5 sediments, add sand to gravel
- Sand: 0.5 – 2.0 mm
- Gravel: 2.0 – 64 mm
- Sand Content: 6, 14, 21, 27, & 34%
- 9 or 10 runs with each sediment, wide range of transport rates
- Depth & width held constant, primary variables are sand content & flow strength
To develop a general transport model, we nondimensionalize in the form of a similarity collapse

\[
\frac{q_{bi}}{F_i} = f_{n_1}(\tau, \tau_{ri})
\]

\[
W_i^* = f_{n_3}\left(\frac{\tau}{\tau_{ri}}\right)
\]

where

\[
W_i^* = \frac{(s - 1) g q_{bi}}{F_i(\tau / \rho)^{3/2}}
\]

\(F_i\) surface proportion;
\(g\) gravity;
\(\rho\) water density;
\(s\) sed spec. gr.

**The Point:**
The transport function does not contain grain size!
Building a surface-based transport model

\[ W_i^* \]

\[ W_r^* \Rightarrow \]

\[ \tau \text{ (Pa)} \]

\[ \tau / \tau_{ri} \text{ (Pa)} \]
It remains to explain $\tau_{ri}$...
Surface-Based Transport Model
All sizes, All runs, All sediments

\[ W_i^* \]

\[ \tau / \tau_{ri} \]
Values of $\tau_{ri}$ for all sizes and all sediments

![Graph showing values of $\tau_{ri}$ for different grain sizes and sediments](image)
Values of $\tau_{ri}$ collapse nicely when divided by values at the mean size $D_{sm}$

Relative size effect weaker for larger sizes (absolute size effect makes $\tau_{ri}$ increase with $D_i$)

Wilcock, P.R. & Crowe, J.C., J. Hydr. Eng., 2003
It remains to explain $\tau_{rm} \ldots$

Sand Interaction Function

The sand interaction function completes the surface-based transport model.
Surface-based transport model can be used in both forward & inverse forms

- **Forward**: predict transport rate & grain size as function of $\tau$ and bed surface grain size
- **Inverse**: predict $\tau$ and bed surface grain size as function of transport rate & grain size

*Don’t try this with a subsurface – based model!*

The **inverse** model provides a useful tool for considering **armor persistence** – because we do have good transport data from the field

*To the field!*
Transport grain size increases with flow!

iSBTM not only predicts a persistent armor layer, it also predicts the surface grain size observed in the field!
Again, transport grain size increases with flow!

Again, iSBTM predicts a persistent armor layer. This time it overpredicts the surface grain size observed in the field!

Reason: *dunes*!
At “reach” and “storm” scales of space and time

- Armor layer grain size appears to be persistent – a real advantage for predicting roughness & transport during floods: a low flow measurement of bed composition may suffice (unless dunes develop).

Increasing transport grain size balances change in grain mobility to produce a constant bed surface.

A SBTM needed to model transients.
(IV) Alluvial Channel Design
Connecting sediment supply to the design problem

1. **Reconnaissance phase**: What is the trajectory of the stream? How has it responded to changes in water and sediment supply over the years? \( \text{Henderson relation} \rightarrow \text{mixed-size seds} \)

2. **Develop flood series, specify flood frequency** \( \rightarrow Q_{bf} \).
   \{Select \( Q_{bf} \) for flood frequency specified to maintain riparian ecosystem & prevent vegetation encroachment\}

3. **Estimate sediment supply**

4. **Planning phase**: What slope \( S \) is needed to carry the sediment supply with the available flow?
   \{How does \( S \) vary with \( Q_s \) and width \( b \)\}

5. **Develop flow duration curve**

6. **Design phase**: Evaluate trial designs. Will the sediment supply be routed through the reach over the flow duration curve?
   \{Build 1-d hydraulic model for trial design. Calculate cumulative transport over flow duration curve at each section; evaluate sediment continuity.\}
The Lane Balance, quantified almost 40 yrs ago by Henderson (1966, Open Channel Flow)

Einstein-Brown depth-slope continuity Chezy

\[ q^* \propto (\tau^*)^3 \]
\[ \tau \propto RS \]
\[ q \propto UR \quad U \propto \sqrt{RS} \]

\[ q_b \propto \frac{\tau^3}{D^3/2} \]
\[ q_b \propto \frac{(RS)^3}{D^3/2} \]

\[ R^3 \propto \frac{q^2}{S} \]

or

\[ q_b \propto \frac{q^2 S^2}{D^3/2} \]

\[ S \propto \sqrt{\frac{q_b D^3/4}{q}} \]

or for two cases

\[ \frac{S_2}{S_1} = \sqrt{\frac{q_{b2}}{q_{b1}}} \left( \frac{D_2}{D_1} \right)^{3/4} \left( \frac{q_1}{q_2} \right) \]

What if \( q_b \) increases and \( D \) decreases?
Lane’s balance is indeterminate.
A mixed-size transport model can be used in both forward & inverse forms

- **Forward**: Given $\tau$ and bed surface grain size $\Rightarrow$ predict transport rate & grain size
- **Inverse**: Given transport rate & grain size $\Rightarrow$ predict $\tau$ and bed surface grain size

**Forward**: predict transport rate & grain size as a function of $\tau$ and bed surface grain size

Hydraulic Model
\[ q, U, h, S \Rightarrow \tau \]

Transport Model
\[ \tau, \text{bed grain size} \Rightarrow q_b, \text{transport grain size} \]

**Inverse**: predict $\tau$ and bed surface grain size as function of transport rate & grain size

Hydraulic Model
\[ U, h, S \leftarrow q, \tau \]

Transport Model
\[ \tau, \text{bed grain size} \leftarrow q_b, \text{transport grain size} \]

We can use an inverse transport model to forecast, or design, a steady state channel that will transport a specified sediment supply rate and grain size with the available flow (!)
Presenting ….

**iSURF**

1. **State Diagram I** –
   transport v. discharge, lines of constant slope
2. **State Diagram II** –
   transport v. slope, lines of constant discharge
3. **Channel Stability Diagram**

- **Inverse Model**: predict $\tau$ and bed surface grain size as fn(transport rate & grain size)
- Specify discharge and basic channel geometry and solve for slope (& depth)
Stream State Diagrams

"Given": \( q, \dot{q}, \rho_i, \rho, \rho_s, g \)
"Find": \( U, h, \tau, S, F_i, n \)

\[
q^* = \frac{q_t}{\sqrt{(s-1)gD_s^{3/2}}}
\]
\[
q^* = \frac{q_w}{\sqrt{(s-1)gD_s^{3/2}}}
\]

We are working per unit width ...

The iSBTM routine calculates bed shear stress and bed surface grain size for a specified transport rate and transport grain size. Each transport rate and grain size and, therefore, shear stress and bed surface grain size, can be produced by different combinations of unit discharge \( q \) and slope \( S \). The state diagrams present families of curves giving either transport rate and water discharge for specified values of \( S \), or transport rate and \( S \) for specified values of water discharge.

Conservation Relations

Water Mass \( q = Uh \)
Momentum \( \tau = \rho ghS \)

• Constitutive Relations

Roughness relation \( n = f(F_i) \)
Sediment transport \( iSBTM \) gives \( \tau, F_i \)
Flow resistance \( U = \frac{\sqrt{S} h^{2/3}}{n} \)
Sediment Transport Rate per unit width $q_T$ (kg/m/s)

Water Discharge per unit width $q_W$ (m²/s)

Lines of constant slope

- $S=0.001$
- $S=0.002$
- $S=0.005$
- $S=0.01$
- $S=0.02$
- $S=0.05$

$G_1=25.07, G_2=25.07$

$G_1=16.85, G_2=16.85$

$G_1=2.79, G_2=2.79$

Lines of constant unit water discharge

- $qw=0.10$ m²/s
- $qw=0.32$
- $qw=1.0$
- $qw=3.2$
- $qw=10.0$

High flow

Low flow

More armored

Less armored

High slope

Low slope

Less armored

More armored

Reconnaissance
Given
Water discharge and sediment supply

Find
channel slope, depth & width (& velocity & shear)

We have enough general relations to solve for all but one of these unknown variables.

If we specify channel width, we can solve for the rest of the variables.

What slope is needed to transport the supplied sediment with the available water?
For a specified supply of water and sediment, what is the slope needed to transport the supplied sediment with the available flow?
Sometimes, sediment supply does not matter

Sometimes, it does
So, there must be a boundary between cases where sediment supply matters or not

<table>
<thead>
<tr>
<th>Threshold</th>
<th>Alluvial</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bed &amp; banks immobile</td>
<td>Active transport</td>
</tr>
<tr>
<td>Easier to model &amp; design</td>
<td>Harder to design</td>
</tr>
<tr>
<td>Bed &amp; banks must only be strong enough</td>
<td>Requires a balance between transport capacity &amp; sediment supply</td>
</tr>
<tr>
<td>Extend Threshold definition to include small sediment supply rates requiring a slope negligibly larger than the zero supply case</td>
<td>Focus on cases in which slope is sensitive to supply</td>
</tr>
</tbody>
</table>

Nothing new under the sun ... see SCS in the ’30s
Why we can ‘neglect’ small sediment supply rates

1. Small sediment supply rates → many storms (and many decades) req’d to produce significant aggradation and degradation.

2. Small sediment supply rates → channel morphology and slope required to transport the supplied sediment can be negligibly larger than that of a threshold channel.
So, what is a SMALL sediment supply rate?

That sounds dangerously like a real question, so first, let's deal with real sediments, which contain a mixture of sizes.

But for mixed-size sediment, there are complications ...

- Grain size of bed ≠ grain size of transport
- Bed is sorted spatially and vertically
- Transport is a function of the changing population of grains on the bed surface
iSURF Channel Stability Diagram
what slope is needed to transport a specified sediment supply of
specified size distribution
with a specified discharge?

Find velocity, boundary stress, depth, slope, and bed surface grain size
from continuity, momentum, flow resistance, and the
Wilcock-Crowe Surface-Based Mixed-Size Sediment Transport Model
As a bonus, you find out how armored the bed becomes!

And get a measure of where you are relative to the threshold/alluvial channel boundary!
Is an accurate sediment supply estimate needed?

If your sediment supply is safely below the boundary between “low” slope and “high” slope, channel slope is relatively insensitive to sediment supply – you are less likely to accumulate sediment given an error in estimating sediment supply.

**Threshold Design Approach**

Just make the channel strong enough to stand up to high flows.
Design steps incorporating sediment supply

1. **Reconnaissance phase**: What is the trajectory of the stream? How has it responded to changes in water and sediment supply over the years?

   \[
   \frac{S_2}{S_1} = \left( \frac{q_{b2}}{q_{b1}} \right)^{3/4} \left( \frac{D_2}{D_1} \right) \]

   *ISURF State Diagrams*

2. **Develop flood series, specify flood frequency → Design Q.**
   
   \{Select\ \( Q_{bf} \)\ for flood frequency specified to maintain riparian ecosystem & prevent vegetation encroachment\}

3. **Estimate sediment supply**

4. **Planning phase**: What slope \( S \) will transport the sediment supply with the available \( Q_{bf} \)?
   
   Calculate \( (b, S) \) combination \{S and valley slope determine sinuosity\}

   Check if alluvial \( v. \) threshold channel

5. **Develop flow duration curve**

6. **Design phase**: Evaluate trial designs. Will the sediment supply be routed through the reach over the flow duration curve?
   
   \{Build 1-d hydraulic model for trial design. Calculate cumulative transport over flow duration curve at each section; evaluate sediment continuity.\}

7. **Bottlenecks or blowouts?** Adjust for sediment continuity
Alluvial Channel Design Example
Example 2: Stable channel analytical method

Objective: Determine stable channel dimensions for a diversion channel. Upstream natural stream is coming out of a hillside watershed.

1. Supply reach
   Estimate sediment transport rate

2. Design reach
   Given discharge and sediment supply rate and grain size, calculate slope needed to transport supplied sediment at a specified channel width
1. Find stress in upstream “supply” channel

<table>
<thead>
<tr>
<th>$Bo$ m</th>
<th>$nc$ composite n</th>
<th>$h$ m</th>
<th>$B$ m</th>
<th>$A$ $m^2$</th>
<th>$R$ m</th>
<th>$U$ m/s</th>
<th>$\tau_0$ Pa</th>
<th>$\tau'$ Pa</th>
<th>$u''$ m/s</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.71</td>
<td>0.0369</td>
<td>2.97</td>
<td>16.2</td>
<td>34.0</td>
<td>1.90</td>
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<td>total</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$Bo$ ft</td>
<td>$nc$</td>
<td>$h$ ft</td>
<td>$B$ ft</td>
<td>$A$ $ft^2$</td>
<td>$R$ ft</td>
<td>$U$ ft/s</td>
<td>boundary stress</td>
<td>grain stress</td>
<td>as a shear velocity</td>
</tr>
<tr>
<td>22.0</td>
<td>0.0369</td>
<td>9.74</td>
<td>53.2</td>
<td>366.3</td>
<td>6.23</td>
<td>6.83</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Given: Dimensions of the upstream natural channel reach are:
- Base width = 22 ft
- Side slopes
  - Left bank = 2.2H:1V
  - Right bank = 1.1H:1V
- Side slope roughness coefficient = 0.07
- Channel slope = 0.0025
- Bed material — sandy gravel
  - $D_{84} = 22$ mm
  - $D_{50} = 3.7$ mm
  - $D_{16} = 0.43$ mm
- Channel-forming discharge = 2,500 $ft^3/s$
2. Find transport rate in upstream “supply” channel

**SBTM - calculate transport rate and transport grain size from specified shear velocity and bed surface grain size**

### RULES, CONVENTIONS, AND UNITS
1. Cells for input data are highlighted in GREEN, cells for output data are ORANGE
2. Grain-diameters must be in millimeters (mm)
3. Cumulative percentiles, not fractions, are used
4. Cumulative grain-size distribution percentiles must span from 0 to 100 %
5. Shear velocity must be in meters-per-second (m/s)
6. The 0 and 100 % must be EXACTLY 0 and 100

### INSTRUCTIONS
1. In table below, enter grain size and cumulative % in order of decreasing grain size
2. Enter your bed shear velocity
3. Check input for errors, press **Enter**, and then click once on the **Run SBTM** button

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Description</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>u*</td>
<td>1.45E-01</td>
<td>Bed shear velocity</td>
<td>m/s</td>
</tr>
<tr>
<td>qT</td>
<td>8.17E-04</td>
<td>Total transport rate</td>
<td>m$^2$/s</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>D (mm)</th>
<th>Surface CDF GSD (% Finer)</th>
<th>Transport CDF GSD (% Finer)</th>
</tr>
</thead>
<tbody>
<tr>
<td>64.00</td>
<td>100.00</td>
<td>100.00</td>
</tr>
<tr>
<td>32.00</td>
<td>93.00</td>
<td>98.86</td>
</tr>
<tr>
<td>16.00</td>
<td>77.00</td>
<td>93.03</td>
</tr>
<tr>
<td>8.00</td>
<td>65.00</td>
<td>84.94</td>
</tr>
<tr>
<td>4.00</td>
<td>53.00</td>
<td>72.39</td>
</tr>
<tr>
<td>2.00</td>
<td>45.00</td>
<td>62.51</td>
</tr>
<tr>
<td>1.00</td>
<td>35.00</td>
<td>49.35</td>
</tr>
<tr>
<td>0.50</td>
<td>20.00</td>
<td>28.82</td>
</tr>
<tr>
<td>0.25</td>
<td>10.00</td>
<td>14.65</td>
</tr>
<tr>
<td>0.13</td>
<td>0.00</td>
<td>0.00</td>
</tr>
</tbody>
</table>
3. Enter transport rate and grain size from upstream “supply” channel as input to the channel stability code.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Description</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Q₁</td>
<td>70.8</td>
<td>Case 1 water discharge</td>
<td>m³/s</td>
</tr>
<tr>
<td>Q₉₁</td>
<td>0.005478475</td>
<td>Case 1 sediment supply rate</td>
<td>m³/s</td>
</tr>
<tr>
<td>Q₂</td>
<td>70.8</td>
<td>Case 2 water discharge</td>
<td>m³/s</td>
</tr>
<tr>
<td>Q₉₂</td>
<td>0.01095695</td>
<td>Case 2 sediment supply rate</td>
<td>m³/s</td>
</tr>
<tr>
<td>b⁻¹⁰⁻⁰</td>
<td>3.00</td>
<td>Minimum bottom width</td>
<td>m</td>
</tr>
<tr>
<td>b⁻¹⁰⁻¹</td>
<td>35.00</td>
<td>Maximum bottom width</td>
<td>m</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>D (mm)</th>
<th>Case 1 Transport Grain Size (% Finer)</th>
<th>Case 2 Transport Grain Size (% Finer)</th>
</tr>
</thead>
<tbody>
<tr>
<td>64.00</td>
<td>100.00</td>
<td>100.00</td>
</tr>
<tr>
<td>32.00</td>
<td>98.86</td>
<td>98.86</td>
</tr>
<tr>
<td>16.00</td>
<td>93.03</td>
<td>93.03</td>
</tr>
<tr>
<td>8.00</td>
<td>84.94</td>
<td>84.94</td>
</tr>
<tr>
<td>4.00</td>
<td>72.39</td>
<td>72.39</td>
</tr>
<tr>
<td>2.00</td>
<td>62.51</td>
<td>62.51</td>
</tr>
<tr>
<td>1.00</td>
<td>49.35</td>
<td>49.35</td>
</tr>
<tr>
<td>0.50</td>
<td>28.82</td>
<td>28.82</td>
</tr>
<tr>
<td>0.25</td>
<td>14.65</td>
<td>14.65</td>
</tr>
<tr>
<td>0.13</td>
<td>0.00</td>
<td>0.00</td>
</tr>
</tbody>
</table>
The iSURF (Wilcock & Crowe) solution including case with 3x sediment supply:

- Discharge 1 = 70.8 cms
- Discharge 2 = 70.8 cms
- Sed Supply 1 = 52265 kg/hr
- Sed Supply 2 = 165275 kg/hr

Potential Aggradation and Potential Degradation are indicated on the graph.
For this design problem, slope is very sensitive to sediment supply rate (because it is large)

\[ Q = 70.8 \text{ cms} \]

*b = 19.0 m*

*iSURF* design module provides this plot of slope vs. sediment supply rate
What happens if we build the channel at a slope other than the graded slope?

\[ S = 0.003 \] for a bottom width \( B_o = 22.5 \text{ m} \)

We will either accumulate sediment (slope too small) or evacuate sediment (slope too large).

How much? Also a measure of consequences of uncertainty.
(V) Threshold & Alluvial Channel: Together at last!
A simple view of channel behavior options
Consider a channel, with bed and bank materials & dimensions,
Specify \textit{water discharge}, \textit{sediment supply}

1. **Threshold channel**
   at what slope does bed material move?

2. **Mobile channel**
   at what slope does capacity to transport sediment match supply of sediment?

\begin{align*}
Q &= 100 \text{ m}^3/\text{s} \\
D_{50} &= 64 \text{ mm} \\
D_{84} &= 128 \text{ mm} \pm 10\% \\
n &= 0.04 \pm 10\% \\
\tau_c^* &= 0.03 \pm 10\%
\end{align*}

\begin{align*}
Q &= 100 \text{ m}^3/\text{s} \{160 \text{ m}^3/\text{s}\} \\
Q_s &= 20 \text{ t/hr} \{60 \text{ t/hr}\} \\
\text{Supply } D_{50} &= 13 \text{ mm} (0.5 \text{ mm} - 128 \text{ mm})
\end{align*}
Failure in a threshold channel = grain entrainment

\[ Q = 100 \text{ m}^3/\text{s} \]
\[ D_{50} = 64 \text{ mm} \]
\[ D_{84} = 128 \text{ mm} \pm 10\% \]
\[ n = 0.04 \pm 10\% \]
\[ \tau_c^* = 0.03 \pm 10\% \]
Mobile channel design = match transport capacity to sediment supply

- $Q = 100 \text{ m}^3/\text{s}$ \{160 m$^3$/s\}
- $Q_s = 20 \text{ t/hr}$ \{60 t/hr\}
- Supply $D_{50} = 13 \text{ mm (0.5 mm - 128 mm)}$
Over-capacity Threshold: combine threshold and alluvial

\[ Q = 100 \text{ m}^3/\text{s} \]
\[ D_{50} = 64 \text{ mm} \]
\[ D_{84} = 128 \text{ mm} \pm 10\% \]
\[ n = 0.04 \pm 10\% \]
\[ \tau^* = 0.03 \pm 10\% \]

Supply vs. Capacity

\[ Q = 100 \text{ m}^3/\text{s} \quad \{160 \text{ m}^3/\text{s}\} \]
\[ Q_s = 20 \text{ t/hr} \quad \{60 \text{ t/hr}\} \]
Supply \( D_{50} = 13 \text{ mm} \) (0.5 mm - 128 mm)
Bottom Line:
specify a width, a channel and its bed material, and a water & sediment supply
Critical Shields Number gives threshold channel slope
Transport Model gives alluvial channel slope
Range of widths gives indication of adjustments with respect to bed material transport
But the watershed, and the water and sediment supply may also be changing aka ‘moving the goalposts’

Arrows indicate response to an INCREASE in each driving variable
(VI) Channel Design Strategy
Strategy

(i) Determine if the sediment supply is a big number or a little number
   (a) if big, invest in more accurate estimate of sediment supply
       be prepared for a dynamic channel
       reserve riparian corridor and let the stream go
       or plan to trap and remove sediment
   (b) if little, design a threshold channel

(ii) Estimate uncertainty and account for the consequences
     esp. potential for aggradation, degradation

![Graph showing sediment supply rate vs. slope]

- \( Q = 70.8 \text{ cms} \)
- \( b = 19.0 \text{ m} \)

Graph labeling:
- \( \Delta \) Your sediment supply
- Big Number
- Little Number
OR, Make your channel
(i) steep enough: transport capacity exceeds supply and
(ii) strong enough: bed material immobile

... an overcapacity threshold channel

<table>
<thead>
<tr>
<th>Design Basis:</th>
<th>Flow Competence</th>
<th>Competence &amp; Capacity</th>
<th>Transport Capacity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Channel Type</td>
<td>Threshold Channel</td>
<td>Overcapacity Threshold</td>
<td>Alluvial Channel</td>
</tr>
<tr>
<td>Topography &amp; Bed Material</td>
<td>Static</td>
<td>Static</td>
<td>Dynamic</td>
</tr>
</tbody>
</table>

Pipe-like channels: an increasingly common & safe design option, may provide acceptable aesthetics. Does not provide anything like native structure & function
Assess magnitude of sediment supply

“small”

Threshold channel design

Use risk assessment and $P$(failure) to guide design

“large”

Alluvial channel design

Overcapacity channel design

Invest in improved sediment estimate

Allow for dynamic stream
Sediment Transport in Channel Design

Environmental Drivers
- Objective
  - sediment & nutrients
  - property & infrastructure
  - biological recovery
  - aesthetics, recreation
  - penance

What needs fixing?
- Nothing
- Stormwater control
- Introduced species
- Channel change

Disturbance Internal or external?
- Internal
- External

Channel Design
- Sediment Objectives
  - Is Sediment Supply Large or Small?
  - Estimate flood frequency
  - Design threshold channel
  - Estimate sediment supply & flow duration
  - Design alluvial channel

Design Threshold AND Alluvial Channel

Alluvial, Threshold, or Overcapacity Threshold Channel?
- Fence out the cows!
- Remove the concrete!
- Template approach can work
We can go beyond equilibrium channel design by specifying **desired channel behavior** and incorporating sediment transport with **uncertainty**, which allows calculation of risk of undesirable behavior while accommodating “typical” channel dimensions.

### Channel Design

<table>
<thead>
<tr>
<th>Specified equilibrium dimensions</th>
<th>Specified channel behavior</th>
</tr>
</thead>
</table>

Account for uncertainty & risk
Accommodate typical dimensions
Midway Transport Observations by Erwin et al.
These are transport observations from the Midway sampling site located just upstream from the design reach.

<table>
<thead>
<tr>
<th>Design Q (cfs)</th>
<th>Design Qs (t/d)</th>
<th>Design Q (m³/s)</th>
<th>Design Qs (m³/s)</th>
<th>kg/hr</th>
</tr>
</thead>
<tbody>
<tr>
<td>800</td>
<td>0.001</td>
<td>22.7</td>
<td>2.18E-09</td>
<td>0.0</td>
</tr>
<tr>
<td>900</td>
<td>0.003</td>
<td>25.5</td>
<td>1.21E-08</td>
<td>0.1</td>
</tr>
<tr>
<td>1000</td>
<td>0.014</td>
<td>28.3</td>
<td>5.59E-08</td>
<td>0.5</td>
</tr>
<tr>
<td>1100</td>
<td>0.056</td>
<td>31.1</td>
<td>2.24E-07</td>
<td>2</td>
</tr>
<tr>
<td>1200</td>
<td>0.200</td>
<td>34.0</td>
<td>7.94E-07</td>
<td>8</td>
</tr>
<tr>
<td>1300</td>
<td>0.64</td>
<td>36.8</td>
<td>2.54E-06</td>
<td>24</td>
</tr>
<tr>
<td>1400</td>
<td>1.88</td>
<td>39.6</td>
<td>7.48E-06</td>
<td>71</td>
</tr>
<tr>
<td>1500</td>
<td>5.1</td>
<td>42.5</td>
<td>2.04E-05</td>
<td>195</td>
</tr>
<tr>
<td>1600</td>
<td>13.1</td>
<td>45.3</td>
<td>5.22E-05</td>
<td>498</td>
</tr>
<tr>
<td>1700</td>
<td>32</td>
<td>48.1</td>
<td>1.26E-04</td>
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<tr>
<td>1800</td>
<td>73</td>
<td>51.0</td>
<td>2.90E-04</td>
<td>2764</td>
</tr>
<tr>
<td>1900</td>
<td>160</td>
<td>53.8</td>
<td>6.36E-04</td>
<td>6071</td>
</tr>
<tr>
<td>2000</td>
<td>338</td>
<td>56.6</td>
<td>1.34E-03</td>
<td>12805</td>
</tr>
<tr>
<td>2100</td>
<td>688</td>
<td>59.5</td>
<td>2.73E-03</td>
<td>26044</td>
</tr>
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<td>2200</td>
<td>1353</td>
<td>62.3</td>
<td>5.37E-03</td>
<td>51248</td>
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<tr>
<td>2300</td>
<td>2583</td>
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<td>1.03E-02</td>
<td>97853</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Grain Size (mm)</th>
<th>% finer than 1000-1300 cfs</th>
<th>% finer than 1300-1600 cfs</th>
<th>% finer than &gt;1600 cfs</th>
</tr>
</thead>
<tbody>
<tr>
<td>128</td>
<td>100</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>90</td>
<td>99.5</td>
<td>99.1</td>
<td>98.7</td>
</tr>
<tr>
<td>64</td>
<td>97.6</td>
<td>93.9</td>
<td>90.0</td>
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<tr>
<td>45</td>
<td>92.0</td>
<td>83.3</td>
<td>74.3</td>
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<td>32</td>
<td>73.1</td>
<td>64.1</td>
<td>53.5</td>
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<td>22</td>
<td>50.4</td>
<td>43.0</td>
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<tr>
<td>16</td>
<td>3.3</td>
<td>11.5</td>
<td>8.2</td>
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<tr>
<td>8</td>
<td>2.1</td>
<td>7.3</td>
<td>3.5</td>
</tr>
<tr>
<td>4</td>
<td>1.1</td>
<td>3.1</td>
<td>1.8</td>
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<tr>
<td>2</td>
<td>0.6</td>
<td>1.3</td>
<td>0.9</td>
</tr>
<tr>
<td>1</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
</tbody>
</table>
**iSURF Channel Stability Diagram for 1200 cfs and 1800 cfs flows**

**CHANNEL STABILITY DIAGRAM FOR GRAVEL-BED RIVERS - INPUT WORKSHEET**

**RULES, CONVENTIONS, AND UNITS**
1. Cells for input data are highlighted in GREEN
2. Grain-diameters must be in millimeters (mm)
3. Cumulative percentiles, not fractions, are used
4. Cumulative grain-size distribution percentiles must span from 0 to 100 %
5. The 0 and 100 % must be EXACTLY 0 and 100

**INSTRUCTIONS**
1. In first table below, enter water discharge and sediment supply rate in units of m$^3$/s and the minimum and maximum channel widths to be evaluated
2. In second table below, enter grain size and cumulative % in order of decreasing grain size
3. In cells to right, enter side slope angle $z$ and side slope roughness $n_s$
4. Check input for errors and then click once on the Run STAB button
5. Results appear on Worksheet "STAB OUTPUT"

**Parameter** | **Value** | **Description** | **Units** | **Parameter** | **Value** | **Description** | **Units**
--- | --- | --- | --- | --- | --- | --- | ---
$Q_1$ | 34 | Case 1 water discharge | m$^3$/s | $z$ | 1 | side slope | $H:V$ | 0
$Q_{ss1}$ | 0.00000397 | Case 1 sediment supply rate | m$^3$/s | $n_s$ | 0.08 | side slope roughness | #&%@$
$Q_2$ | 51 | Case 2 water discharge | m$^3$/s | $Q_{ss2}$ | 0.00145 | Case 2 sediment supply rate | m$^3$/s | $b_{min}$ | 8.00 | Minimum bottom width | m | $b_{max}$ | 50.00 | Maximum bottom width | m

<table>
<thead>
<tr>
<th>$D$ (mm)</th>
<th>Case 1 Transport Grain Size (% Finer)</th>
<th>Case 2 Transport Grain Size (% Finer)</th>
</tr>
</thead>
<tbody>
<tr>
<td>128.00</td>
<td>100.00</td>
<td>100.00</td>
</tr>
<tr>
<td>90.00</td>
<td>99.50</td>
<td>98.70</td>
</tr>
<tr>
<td>64.00</td>
<td>97.60</td>
<td>90.00</td>
</tr>
<tr>
<td>45.00</td>
<td>92.00</td>
<td>74.30</td>
</tr>
<tr>
<td>32.00</td>
<td>73.10</td>
<td>53.50</td>
</tr>
<tr>
<td>22.00</td>
<td>50.40</td>
<td>32.60</td>
</tr>
<tr>
<td>16.00</td>
<td>13.30</td>
<td>10.80</td>
</tr>
<tr>
<td>8.00</td>
<td>9.70</td>
<td>7.10</td>
</tr>
<tr>
<td>4.00</td>
<td>7.50</td>
<td>5.30</td>
</tr>
<tr>
<td>2.00</td>
<td>4.30</td>
<td>4.20</td>
</tr>
<tr>
<td>1.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
</tbody>
</table>

**Input transport size distributions**

**Statistic** | FIRST Transport GSD | SECOND Transport GSD | Units
--- | --- | --- | ---
$D_{min}$ | 1.00 | 1.00 | mm
$D_{max}$ | 128.00 | 128.00 | mm
$D_{50}$ | 21.92 | 30.05 | mm
$D_g$ | 20.52 | 26.85 | mm
$c_0$ | 1.18 | 1.24 | $\psi/\mu$-units
$F_s$ | 4.30 | 4.20 | %
The iSURF Channel Stability Diagram for 1200 cfs and 1800 cfs flows is shown in the image. The diagram includes graphs for slope, depth, sediment supply rate, grain size distribution, armor ratio, and Froude number as functions of channel width.

- **Slope and Depth**
  - Discharge 1 = 34.0 cms
  - Discharge 2 = 51.0 cms

- **Sediment Supply**
  - Sed Supply 1 = 38 kg/hr
  - Sed Supply 2 = 13833 kg/hr

- **Grain Size Distribution**
  - Case 1 Transport
  - Case 2 Transport

- **Armor Ratio Dsm/Dtm**

- **Froude Number**

The diagrams illustrate the stability of the channel under different conditions, with parameters such as side slope, discharge, and sediment supply rate varying as shown.
We have run iSURF-STAB for a range of different discharges and their associated sediment supply.

<table>
<thead>
<tr>
<th>Discharge (cfs)</th>
<th>Fraction of Sediment Delivered</th>
</tr>
</thead>
<tbody>
<tr>
<td>1800</td>
<td>0.93</td>
</tr>
<tr>
<td>1900</td>
<td>0.82</td>
</tr>
<tr>
<td>2000</td>
<td>0.65</td>
</tr>
<tr>
<td>2100</td>
<td>0.51</td>
</tr>
<tr>
<td>2200</td>
<td>0.27</td>
</tr>
<tr>
<td>2300</td>
<td>0.12</td>
</tr>
</tbody>
</table>
(VI) Overtime
Threshold & Alluvial Channel Design from the guys who invented it
Some useful readings

Chapter 7  Basic Principles of Channel Design

Chapter 8  Threshold Channel Design

Chapter 9  Alluvial Channel Design

Part 654 Stream Restoration Design
National Engineering Handbook
654.0701 Overview of channel design

A stable channel is often defined as a channel where the planform, cross section, and longitudinal profile are sustainable over time. While channel migration may not always be acceptable due to project or site constraints, it is important to note that a natural channel can migrate and still be considered stable, in that its overall shape and cross-sectional area do not change appreciably. Design methodologies and approaches may be used to estimate the conditions that may result in such movements. Design features are also often employed to reduce the frequency and magnitude of these changes.

Another common goal for a channel restoration design is that long-term aggradation and/or degradation should be small enough to allow for economical channel maintenance. Ideally, a channel should be self-sustaining and not require any maintenance. Many design methodologies can be used to design a channel which is in balance with the incoming sediment load. However, it is also important for the designer to recognize that manmade, as well as natural channels may aggrade or degrade over time or in response to specific storm events. Sediment impact assessments can be used to quantify what storm events may result in a sediment disequilibrium and to quantify the expected aggradation, so that appropriate maintenance can be budgeted. Design features can also be employed to counteract a tendency for bed degradation.
Table 7-1  Characteristics of threshold and alluvial channels

<table>
<thead>
<tr>
<th>Channel boundary</th>
<th>Threshold channel</th>
<th>Alluvial channel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Immobile at design discharge</td>
<td>Mobile</td>
<td></td>
</tr>
<tr>
<td>Bed-material sediment inflow</td>
<td>Usually small or negligible</td>
<td>Significant</td>
</tr>
<tr>
<td>Dependent variables</td>
<td>Width</td>
<td>Width</td>
</tr>
<tr>
<td></td>
<td>Depth</td>
<td>Depth</td>
</tr>
<tr>
<td></td>
<td>Slope</td>
<td>Slope</td>
</tr>
<tr>
<td></td>
<td>Roughness, if there is a choice of boundary materials</td>
<td>Planform</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Bank roughness</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Roughness due to obstructions or structures</td>
</tr>
<tr>
<td>Independent variables</td>
<td>Design discharge</td>
<td>Design hydrograph</td>
</tr>
<tr>
<td></td>
<td>Channel roughness</td>
<td>Channel-forming discharge</td>
</tr>
<tr>
<td>Design equations</td>
<td>Energy</td>
<td>Momentum</td>
</tr>
<tr>
<td></td>
<td>Momentum</td>
<td>Resistance</td>
</tr>
<tr>
<td></td>
<td>Resistance</td>
<td>Sediment transport</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Geomorphic relationship</td>
</tr>
<tr>
<td>Design goal with respect to channel</td>
<td>Pass the design discharge below the top of bank</td>
<td>Pass the incoming sediment load without significant</td>
</tr>
<tr>
<td>stability</td>
<td>without mobilizing the boundary</td>
<td>aggradation or degradation or planform change</td>
</tr>
</tbody>
</table>

Table 7-2  Hydraulic design philosophies

<table>
<thead>
<tr>
<th>Design discharges</th>
<th>Threshold channels</th>
<th>Alluvial channels</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Maximum design discharge</td>
<td>Channel-forming discharge</td>
</tr>
<tr>
<td></td>
<td>Flow-duration curve and/or long-term</td>
<td></td>
</tr>
<tr>
<td></td>
<td>hydrograph</td>
<td></td>
</tr>
<tr>
<td>Design criteria</td>
<td>Critical velocity/shear stress</td>
<td>Continuity of sediment</td>
</tr>
<tr>
<td>Dependent variables</td>
<td>Width, depth, and slope (roughness</td>
<td>Width, depth, slope, planform, bank roughness, and</td>
</tr>
<tr>
<td></td>
<td>if there is a choice of boundary material)</td>
<td>roughness due to obstructions or structures</td>
</tr>
<tr>
<td>Design equations</td>
<td>Energy, momentum, and hydraulic resistance</td>
<td>Energy, momentum, hydraulic resistance, sediment</td>
</tr>
<tr>
<td></td>
<td></td>
<td>transport, and geomorphic relationship</td>
</tr>
</tbody>
</table>
# Chapter 8  Threshold Channel Design

<table>
<thead>
<tr>
<th>Technique</th>
<th>Significant sediment load and movable channel boundaries</th>
<th>Boundary material smaller than sand size</th>
<th>Boundary material larger than sand size</th>
<th>Boundary material does not act as discrete particles</th>
<th>No baseflow in channel. Climate can support permanent vegetation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Allowable velocity</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Allowable shear stress</td>
<td></td>
<td>X</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tractive power</td>
<td></td>
<td></td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Grass lined/tractive stress</td>
<td></td>
<td></td>
<td></td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Alluvial channel design techniques</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
### Table 8-3  Maximum permissible canal velocities

<table>
<thead>
<tr>
<th>Original material excavated for canals</th>
<th>Mean velocity, for straight canals of small slope, after aging with flow depths less than 3 ft (0.9 m)</th>
<th>[ \frac{V_{ss}}{V_{avg}} = 1.74 - 0.52 \log \left( \frac{R}{W} \right) ]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clear water, no detritus</td>
<td>ft/s</td>
<td>m/s</td>
</tr>
<tr>
<td>Fine sand (noncolloidal)</td>
<td>1.5</td>
<td>0.46</td>
</tr>
<tr>
<td>Sandy loam (noncolloidal)</td>
<td>1.75</td>
<td>0.53</td>
</tr>
<tr>
<td>Silt loam (noncolloidal)</td>
<td>2.0</td>
<td>0.61</td>
</tr>
<tr>
<td>Alluvial silt (noncolloidal)</td>
<td>2.0</td>
<td>0.61</td>
</tr>
<tr>
<td>Ordinary firm loam</td>
<td>2.5</td>
<td>0.76</td>
</tr>
<tr>
<td>Volcanic ash</td>
<td>2.5</td>
<td>0.76</td>
</tr>
<tr>
<td>Stiff clay (very colloidal)</td>
<td>3.75</td>
<td>1.14</td>
</tr>
<tr>
<td>Alluvial silt (colloidal)</td>
<td>3.75</td>
<td>1.14</td>
</tr>
<tr>
<td>Shales and hardpans</td>
<td>6.0</td>
<td>1.83</td>
</tr>
<tr>
<td>Fine gravel</td>
<td>2.5</td>
<td>0.76</td>
</tr>
<tr>
<td>Graded, loam to cobbles (when noncolloidal)</td>
<td>3.75</td>
<td>1.14</td>
</tr>
<tr>
<td>Graded silt to cobbles (when colloidal)</td>
<td>4.0</td>
<td>1.22</td>
</tr>
<tr>
<td>Coarse gravel (noncolloidal)</td>
<td>4.0</td>
<td>1.22</td>
</tr>
<tr>
<td>Cobbles and shingles</td>
<td>5.0</td>
<td>1.52</td>
</tr>
</tbody>
</table>

### Figure 8-3  Allowable velocity-depth grain chart

- Increased Bank Velocity in Bends
- \[ \frac{V_{ss}}{V_{avg}} = 1.74 - 0.52 \log \left( \frac{R}{W} \right) \]
- \( V_{ss} \): depth-averaged velocity at 20% slope length from toe
- \( V_{avg} \): X/S average velocity
- \( R \): bend hydraulic radius
- \( W \): channel top width

### Table 8-2  Suggested minimum radius of curvature in stable soils without bank protection

<table>
<thead>
<tr>
<th>Type of ditch</th>
<th>Slope</th>
<th>Minimum radius of curvature (ft) (m)</th>
<th>Approximate curve (degrees)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Small ditches with maximum top width 15 ft (4.6 m)</td>
<td>&lt;0.00057</td>
<td>300</td>
<td>90</td>
</tr>
<tr>
<td>Medium-sized ditches with top width 15 to 35 ft (4.6–10.7 m)</td>
<td>0.00057 to 0.00114</td>
<td>400</td>
<td>120</td>
</tr>
<tr>
<td>Large ditches with top width &gt;35 ft (10.7 m)</td>
<td>&lt;0.00057</td>
<td>600</td>
<td>180</td>
</tr>
<tr>
<td></td>
<td>0.00057 to 0.00114</td>
<td>800</td>
<td>240</td>
</tr>
</tbody>
</table>
1. Calculate total stress
   (use RAS if flow non-uniform)
2. Calculate grain stress $\tau'$ using
   
   \[ \tau' = \left( \frac{nD}{n} \right)^{3/2} \tau_0 \quad \text{and} \quad n_D = 0.013D^{1/6} \]
   for $D$ in mm
3. Choose critical Shields Number
4. Compare $\tau'$ and $\tau_c$
Step 1 Determine design bed-material gradation/channel boundary.

Step 2 Determine preliminary width.

Step 3 Estimate critical shear stress/velocity.

Step 4 Determine flow resistance (Manning’s n).

Step 5 Calculate depth and slope.

Step 6 Determine planform.

Step 7 Assess for failure and sediment impact.
Example problem: Threshold channel design

*Given:*
Valley slope = 0.007 (this is the maximum possible slope)
Bed material $D_{50} = 45$ mm = 0.148 ft
Bed material $D_{75} = 55$ mm = 2.17 in
Bed material $D_{84} = 60$ mm = 0.197 ft
Channel side slope = 3H:1V
Specific weight of sediment = 165 lb/ft$^3$
Water temperature = 68 °F
Design discharge is 25-year storm = 400 ft$^3$/s

*Problem:*
Design a threshold channel to convey the design discharge.

*Note:* There is no unique solution with the given design constraints.
Step 1 Estimate channel width using hydraulic geometry equation (fig. 9-9, NEH654.09):

\[
W = 2.03Q^{0.55}
\]

\[
W = 2.03(400)^{0.55}
\]

\[
W = 41 \text{ ft}
\]

Note from figure 9-9 in NEH654.09 that widths between 22 and 74 feet are within the 90 percent single response confidence bands. If there are width constraints on the project design they may be applied here. If there are minimum depth requirements, a narrower width may be necessary. It should also be noted that the figure refers to measurements of top width. However, the difference between the top and bottom width is within the error bounds. This example will proceed with the mean width of 41 feet.

<table>
<thead>
<tr>
<th>Table 9-9</th>
<th>Hydraulic geometry width predictors for gravel-bed rivers</th>
</tr>
</thead>
<tbody>
<tr>
<td>( W = aQ^b )</td>
<td>SI units ( m ) and ( m^2/s ) (English units ( ft ) and ( ft^2/s ))</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Data source</th>
<th>Sample size</th>
<th>( a )</th>
<th>90% single response limit for ( a )</th>
<th>95% mean response limit for ( a )</th>
<th>( b )</th>
</tr>
</thead>
<tbody>
<tr>
<td>All North American gravel-bed rivers</td>
<td>34</td>
<td>3.58</td>
<td>(2.03)</td>
<td>(1.12–3.05)</td>
<td>0.5</td>
</tr>
<tr>
<td>All U.K. gravel-bed rivers</td>
<td>86</td>
<td>2.99</td>
<td>(1.65)</td>
<td>(1.02–2.64)</td>
<td>0.5</td>
</tr>
<tr>
<td>&lt;5% tree or shrub cover, or grass-lined banks (U.K. rivers)</td>
<td>36</td>
<td>3.70</td>
<td>(2.94)</td>
<td>(1.46–2.67)</td>
<td>0.5</td>
</tr>
<tr>
<td>≥5% tree or shrub cover (UK rivers)</td>
<td>43</td>
<td>2.46</td>
<td>(1.36)</td>
<td>(1.08–1.70)</td>
<td>0.5</td>
</tr>
</tbody>
</table>
**Given:** Dimensions of the upstream natural channel reach are:
Base width = 22 ft (6.7 m)
Side slopes
  - Left bank = 2.2H:1V
  - Right bank = 1.1H:1V
Side slope roughness coefficient = 0.07
Channel slope = 0.0025
Bed material — sandy gravel
  - $D_{84} = 22$ mm
  - $D_{50} = 3.7$ mm
  - $D_{16} = 0.43$ mm
**Design** discharge = 2,500 ft$^3$/s (70.8 m$^3$/s)

Design values for the bypass channel:
Side slopes = 3H:1V
Side slope roughness coefficient = 0.045
Valley slope = 0.0020 (maximum design slope)

**Objective:** Determine stable channel dimensions for a diversion channel. Upstream natural stream is coming out of a hillside watershed.

**Example 2: Stable channel analytical method**

1. **Supply reach**
   Estimate sediment transport rate
2. **Design reach**
   Given discharge and sediment supply rate and grain size, calculate slope needed to transport supplied sediment at a specified channel width
NRCS (Brownlie, SAM) solution

![NRCS Graph](image-url)

- Channel Width (m)
- Slope

NRCS

S<sub>v</sub>