Sediment Transport IV
Mixed-Size Sediment Transport

1. Partial Transport: frequency & implications using field and laboratory evidence

2. Armor layer persistence investigated using a surface-based transport model.

3. Effect of adding sand to a gravel-bed river leading to a two-fraction transport model
The Bed of Many Colors
1. Bed Entrainment & Partial Transport
Partial Transport

- Some grains remain immobile over the course of a transport event
- Implications for benthic disturbance, bed dynamics & subsurface flushing
- but occurrence, prevalence undocumented
Measure partial transport in lab, using time series of bed photographs

When Brian McArdell went blind (and a little nuts)
The domain of partial transport

\[ D[50] \propto (\tau_0)^{3/2} \]

Proportion Active Grains

\begin{align*}
\text{Bed Shear Stress } \tau_0 (\text{Pa}) & \quad 1 \quad 10 \\
\text{Grain Size (mm)} & \quad 0 \quad 1 \quad 10 \\
\text{Proportion Active Grains} & \quad 0 \quad 0.2 \quad 0.4 \quad 0.6 \quad 0.8 \quad 1
\end{align*}

10% active

90% active
Partial transport & the entrainment of benthic invertebrates (Steve Kenworthy)

Proportion of Larvae Recovered in Seed Section(s)
Series B

Proportion of larvae

Proportion of larvae

Hydropsychidae
Psephenidae
Perlidae
Ephemerellidae
Atherix
E

\( \tau_0 \)
Field Observations of Partial Transport (1)
Carnation Ck, BC
3000 magnetically tagged stones

Judy Haschenburger, U. Auckland
Figure 2. Maps for bed area A in upper deployment area. (a) Map indicating mobility of individual tracers for the 24.5 m^3 s^{-1} peak and activity maps for (b) 24.5 m^3 s^{-1} peak, (c) 30.4 m^3 s^{-1} peak, and (d) 36.3 m^3 s^{-1} peak.
Figure 6. Proportional bed activity as a function of scaled peak discharge: (a) upper A area, (b) upper B area, (c) upper D area, and (d) lower E area. \( Q \) is the maximum peak discharge for a given tracer recovery, and \( Q_{bf} \) is the approximate bank-full discharge of 35 m\(^3\) s\(^{-1}\).

Figure 7. Active proportion of surface grains as a function of grain size; (a) upper A area, (b) upper B area, (c) upper D area, and (d) lower E area.
**Field Observations of Partial Transport (2)**
Harris Ck, BC

**Figure 6.** Percent of moved tracers as a function of grain size for three freshet seasons in Harris Creek. Shading denotes the range in the median size of the surface and subsurface material.
• Bed mobilization increases consistently with flow and grain size
• Substantial transport occurs over a partially mobile bed
• Partial transport persists from year to year
  complete disturbance not an annual event
2. Bed surface composition: Armoring & the problem of predicting transport rates
Streambed Armoring

Stream-bed armoring is pervasive in gravel-bed streams

Armor Ratio =

$D_{50}$ (surface) $D_{50}$ (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, so
- 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?*
With no field observations of armor change, we turn to the lab for guidance on armor persistence.

Doing this will sharpen our thinking about how rivers work at different scales of space and time.

- Two ways to run flumes experiments: Feed Sediment, Recirculate Sediment.
Sediment Feed Experiments

As feed (transport) rate increases, bed surface becomes finer

And approaches size of transport (and bed subsurface)
Sediment Recirculation Experiments

As flow (\(\cdot\) transport) increases,

Transport grain size increases, while bed surface grain size remains relatively constant

Approaching the size of the bed subsurface
In both cases, as transport rate increases, the transport coarsens relative to the bed surface.

In the feed flume, this is accomplished via fining of the bed surface.

In the recirculating flume, this is accomplished via coarsening of the transport.
So, does armor stay or go? Does it depend on how you think a river works?

Depends on time & space scale of the problem

Consider the essential “flaws” of the two flume types:

**Feed**
- Transport has constant grain size

**Recirculate**
- Final equilibrium sensitive to initial conditions
To address the armor problem, we have to 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) NOT a good way to build a general model
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 $\text{sed} = \text{other sediment properties}$. We search a transport model of form

$$\frac{q_{bi}}{f_i} = f_{n_1}(\tau, \tau_{ri})$$

$$\tau_{ri} = f_{n_2}(D_m, D_i / D_m, \text{sed})$$

where $\tau_{ri}$ is a reference value of $\tau$ near the onset of sediment motion.

But, what size distribution should we use for $f_i$?

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

- Built five sediments, adding 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, over a wide range of transport rates
- Depth & width held constant, primary variables are sand content & flow strength
- Every run: measure flow, transport rate & grain size, and *bed surface grain size* (point counts of photos of colored grains)
To develop a general transport model, we nondimensionalize in the form of a similarity collapse

\[ \frac{q_{bi}}{F_i} = fn_1(\tau, \tau_{ri}) \]

\[ W_i^* = fn_3\left(\frac{\tau}{\tau_{ri}}\right) \]

where \( W_i^* = \frac{(s - 1)gq_{bi}}{F_i(\tau / \rho)^{3/2}} \)

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

The Point:
The transport function does not contain grain size!
How to make a transport model

(1) Plot $W^*_i$ vs $\tau$; (2) Find $\tau_{ri}$ at $W^*_r$; (3) Plot $W^*_i$ vs. $\tau/\tau_{ri}$; (4) Stand back, admire
All that remains is to explain $\tau_{ri}$ ...
Surface-Based Transport Model

All sizes, All runs, All sediments
Values of $\tau_{ri}$ for all sizes and all sediments

![Graph showing the relationship between $\tau_{ri}$ and Grain Size (mm), with various data points and curves representing different categories such as J06, J14, J21, J27, BOMC, and Shields.](image-url)
Values of $\tau_{ri}$ collapse nicely when divided by values at the mean size $D_{sm}$

The resulting “hiding function” completes the surface-based transport model

Wilcock, P.R. & Crowe, J.C., *J. Hydr. Eng.*, 2003
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
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
3. How does increasing the supply of fines (sand) affect the gravel transport?

Previous Experiments

- Jackson & Beschta (1984)
- Ikeda & Iseyia (1988)

→ Adding sand increases gavel mobility.
Sand content has a huge effect on gravel transport rates – How to generalize?

- Model two fractions:
- Use a similarity collapse
- Use one scaling parameter, the reference shear stress (a surrogate for the critical shear stress for incipient motion)

\[
W^* = \frac{(s - 1) g q_{bi}}{(\tau_o / \rho)^{1.5}} \\
\tau / \tau_r
\]
Gravel transport rate $q_{bi}$ [g/(m$\cdot$s)]

Bed Shear Stress $\tau$ (Pa)

Dimensionless transport rate $W^*$

Bed Shear Stress $\tau$ (Pa)

Dimensionless transport rate $W^*$

$\tau / \tau_r$

J06

J14

J21

J27

BOMC
Include field data to broaden model basis

• Oak Creek, Or (Milhous, Parker et al.)
• Goodwin Creek MS (Kuhnle)
• East Fork River WY (Emmett & Leopold)
• Jacoby Creek CA (Lisle)
Both sand & gravel fractions plotted
Model collapse reasonably good; leaving a single similarity parameter to explain: the reference shear stress, $\tau_r$.

It provides a clean description – and prediction – of the effect of sand on gravel transport.


Wilcock, P.R., 1998. Two-fraction model of initial sediment motion in gravel-bed rivers, Science 280:410-412
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 is required to carry same gravel load and increased sand load

The point?

Adding sand can have a huge effect on gravel transport rates

& there are lots of reasons why sand supply to a gravel-bed river might be increased

  fire, urbanization, reservoir flushing, dam removal

& a two fraction approach captures this effect in a tractable framework
But there are more reasons to like a two-fraction transport model!

Robust!

Mappable!

Captures sand/gravel interaction!

Little Granite CK, nr Bondurant WY
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Summary

Armor layers persist
May be only partially active in a typical flood
↑ sand supply ↑↑ mobility of coarse grains

Surface-based model available for predicting transient transport

2-fraction model available as a robust alternative