Bedload traps for sampling gravel/cobble bedload

and what we learned from them

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Most commonly used sampler in US:

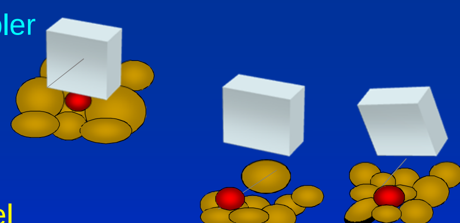
3-inch (7.6 x 7.6 cm) Helley-Smith sampler, flared body

- Availability

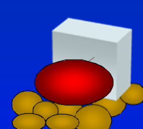
HS: ease of use…

…but not always

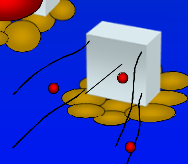
Challenges posed by HS sampler



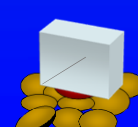
- perched on large gravel
  → undersampling gravel
- dislocating or scooping gravel
  → oversampling gravel



- opening too small for cobbles
  → undersampling cobbles



- hydraulic efficiency > 1
  → oversampling sand and pea gravel



- short sampling time
  → oversampling at low, undersampling at high Q_B

Motivation for a new bedload sampler

US Forest Service needed to identify **initiation of bedload movement** in gravel/cobble mountain streams for channel maintenance flows

This required measurement of:

1. **Transport capacity**: How much coarse gravel is transported
2. **Flow competence**: Critical flows for transport of channel-forming gravels (i.e., bed surface D_{50} to D_{84})

Desired features: Low cost, technologically simple, portable for use at remote sites, easy to install, and usable by a two-person team in wadeable flows

Challenges for sampler design:

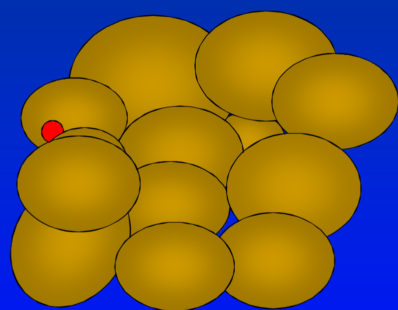
Characteristics of bedload transport in coarse-bedded streams during a highflow event

- Gravel transport occurs over a wide range of flows (10 to >150% of bankfull)

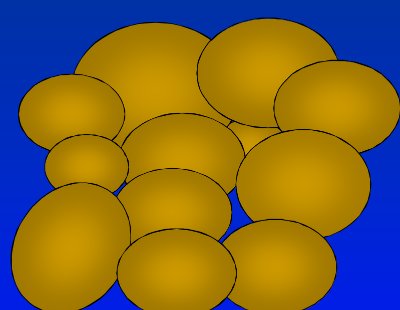
  ↳ Device needs to function in wide range of (wadeable) flows

- **Different transport modes** that extend to different depth of the bed:

  Onset of gravel motion:
  Sand and pea gravel move over stable gravel bed



  Partial transport:
  Mid- to large gravel surface particles move intermittently.
  Particle sizes at incipient motion move infrequently.



Full bed mobility:
Gravel sheet several particles thick moves as grain flow

➯ Device needs to provide accurate samples in all transport modes

- **Large range of transport rates**

Gravel bedload transport rates range over 6-7 orders of magnitude




in 3 hrs
1 E-6 g/s

in 1 hour
0.1 - 1 g/s

in 5 minutes
100 -1000 g/s

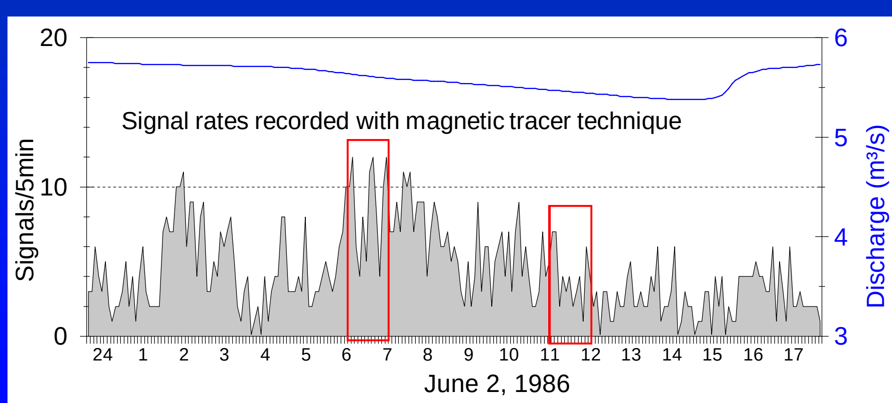
➯ Device needs to provide accurate samples at all transport rates

- **Large range of bedload particle sizes**
  pea gravel - cobbles.

➯ Device needs to collect all transported gravel/cobble sizes.

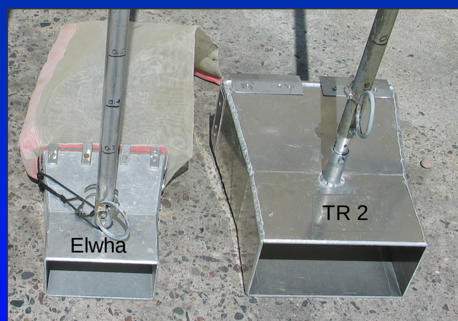
- **Transport rates fluctuate over time**

➯ Sufficiently long sampling interval to integrate over short-term fluctuations of transport



Helley-Smith type samplers larger than 3” x 3”

- 6-inch Helley-Smith (6” x 6”),
- Toutle River sampler (6” x 12”)
- Elwha sampler (4” x 8”)



solve opening size problem, but difficult to hold at high flows; need tethers or crane; scoop particles, and sample for only 30 - 120 s

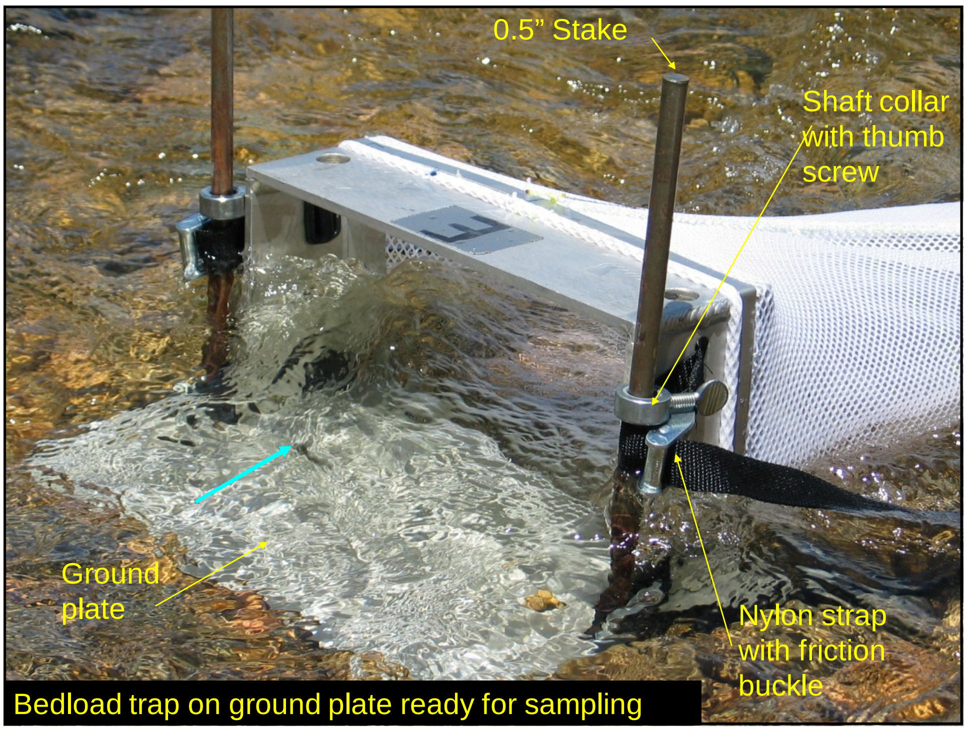
A new bedload sampler was needed

for more accurate sampling of gravel and cobble bedload in wadeable coarse-bedded mountain streams

Design of bedload traps

Bedload trap design criteria

- **Large opening** to sample particles from 2 to 256 mm (gravel to cobbles)
- **Long sampling times** to integrate over fluctuating transport rates
- **Large capacity** to allow collection of large volumes of gravel and cobble bedload
- **Satisfactory hydraulic efficiency**
  good through-flow rate with little retardation or acceleration of flow
- **Satisfactory sampler efficiency**
  no involuntary particle pick-up or hindrance of particle entry
- Ability to sample a large percentage of stream width



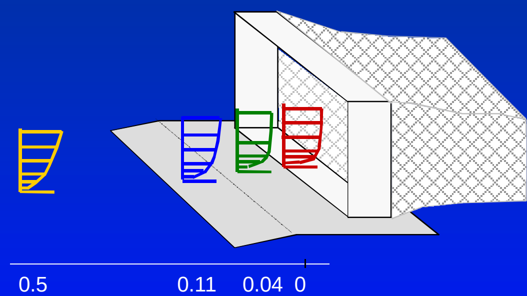
Bedload trap on ground plate ready for sampling

- **Large opening size** to accommodate large gravel and cobbles
- **Mounted on ground plates** to avoid involuntary particle pick up

- **4-mm mesh width**
  - lets sand, fine organics, and water pass freely but limits sampling to gravel transport;
  - avoids the need for a flared opening
- 0.5-mm mesh unsuitable (clogs, bulges, and ponds upstream flow)

Field and flume measurements of velocity profiles:

Net retards flow velocity in the middle and upper part of trap entrance…



Distance upstream from trap entrance (m)

…but smooth ground plates increase near-bottom flow velocity

→ particles on the plate will enter the trap

Combination of:

- **Long sampling times** (strapped to stakes)
- **Large net**

↳ permits collection of large sample volumes

Large sample volumes needed:

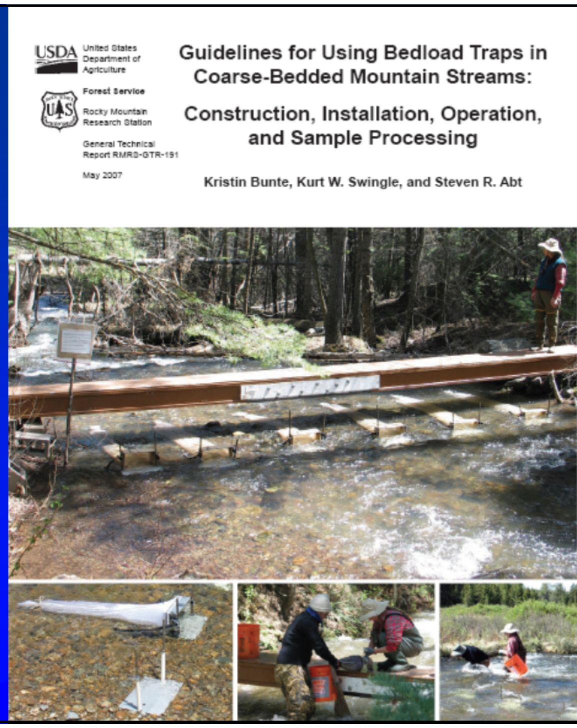
- to average over fluctuating Q_B
- to obtain representative samples, particularly of the largest mobile particles that move infrequently

Deployment of bedload traps

in mountain gravel-bed streams

Several ground plates are installed over the cross-section to sample the lateral variability

Bedload traps set on the ground plates at approx. 60% of bankfull flow.



Freely available on the internet

Emptying bedload traps


Without a footbridge (Halfmoon Creek 2004)


With footbridge (Halfmoon Creek 2004)


HOMER'S ALL-PURPOSE BUCKET
WARNING AVISO


HOMER'S ALL-PURPOSE BUCKET 3
5 Gallons
HOMER'S ALL-PURPOSE BUCKET 4
5 Gallons

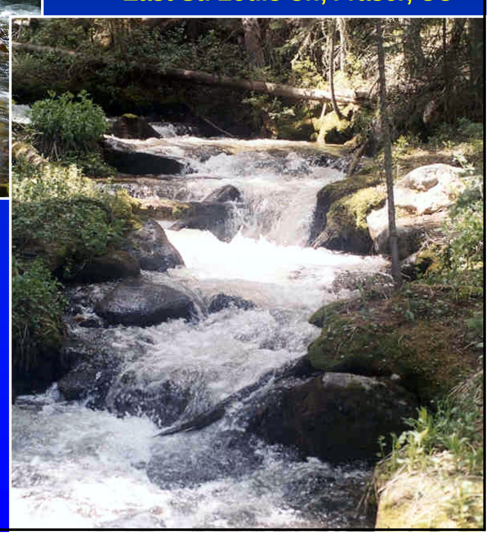

HOMERS ALL-PURPOSE BUCKET


HOMERS ALL-PURPOSE BUCKET

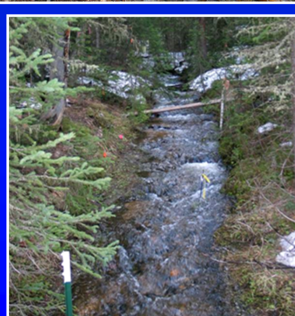
Washing samples to separate coarse organic material from bedload

Step-pool streams

Hayden Creek, CO



East St. Louis Cr., Fraser, CO



Fool Cr., CO

Plane-bed streams

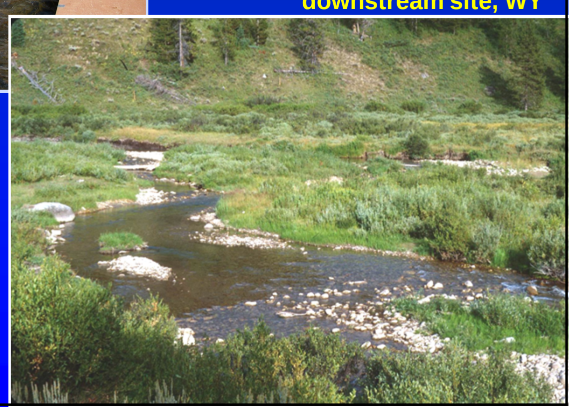
Little Granite Cr., upper site, WY

St. Louis Cr., CO

East Dallas Cr., CO

Streams with isolated pool-riffle sequences

Little Granite Cr., downstream site, WY



Halfmoon Creek, CO

Bedload traps are also used in Alpine steep streams:

Swiss WSL: Johannes Schneider, Bastian Schmidt, Jens Turowski


Foto: J. Schneider


Foto: J. Turowski

Freie Univ. Bozen: Francesco Comiti, Luca Mao

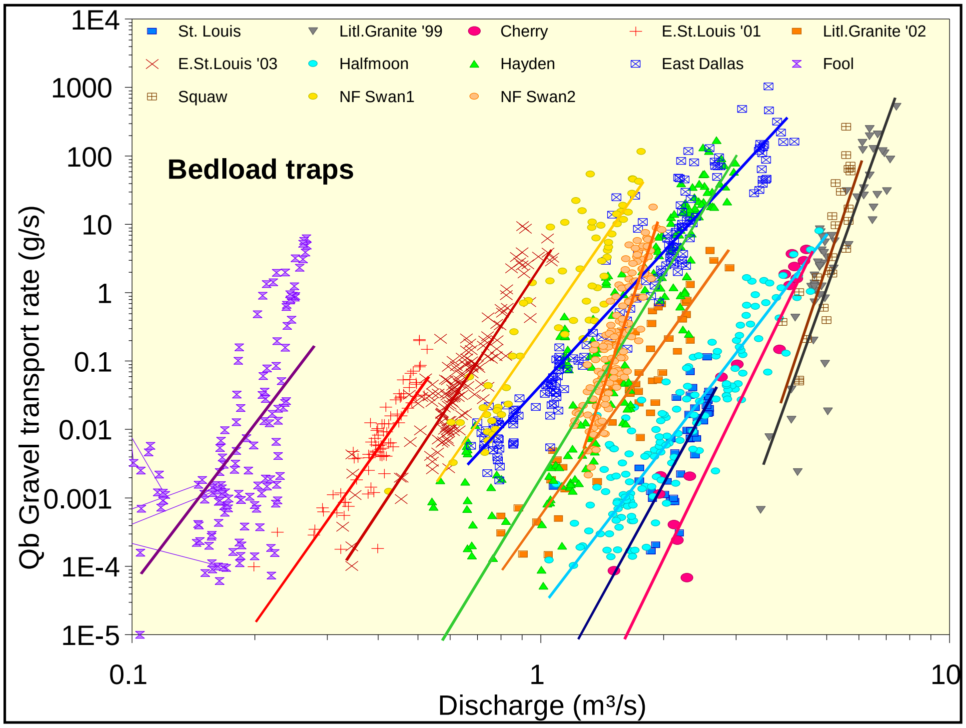

Foto: F. Comiti

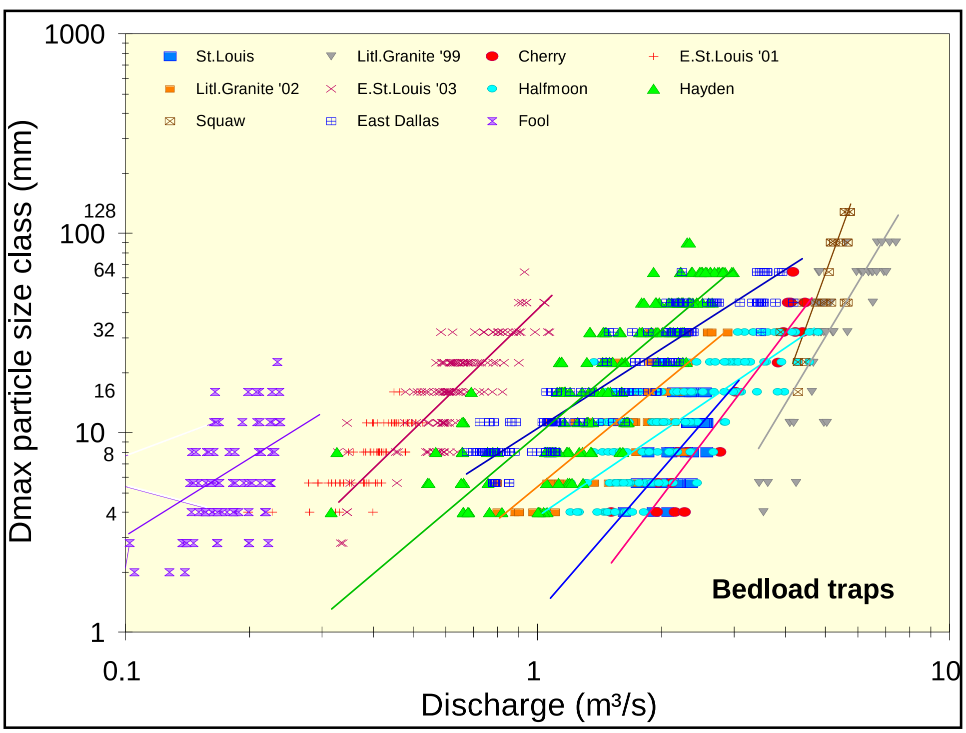
Univ. BOKU Wien: Hugo Seitz, Helmut Habersack


Foto: H. Seitz

Conditions required for use of bedload traps

- Wadeable flows
- Non-wandering bed
- Stable bed that can withstand wading impacts
- Gravel transport rates < ≈100 g/s
- No excessively high amount of organic material
- 2-person sampling team
- Ability to tend to traps and empty them before they overfill


St. Louis
Litl.Granite '99
Cherry
E.St.Louis '01
Litl.Granite '02
E.St.Louis '03
Halfmoon
Hayden
East Dallas
Fool
Squaw
NF Swan1
NF Swan2
Bedload traps
Qb Gravel transport rate (g/s)
1E4
1000
100
10
1
0.1
0.01
0.001
1E-4
1E-5
0.1
1
10
Discharge (m³/s)


St.Louis
Litl.Granite '99
Cherry
E.St.Louis '01
Litl.Granite '02
E.St.Louis '03
Halfmoon
Hayden
Squaw
East Dallas
Fool
Bedload traps
Dmax particle size class (mm)
1000
128
100
64
32
16
10
8
4
1
0.1
1
10
Discharge (m³/s)

What have we learned?

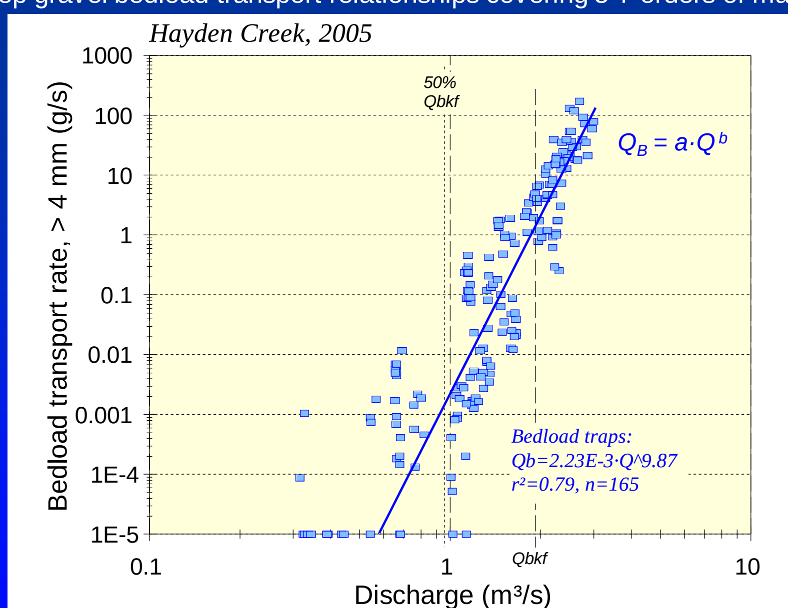
Characteristics of bedload trap sampling results

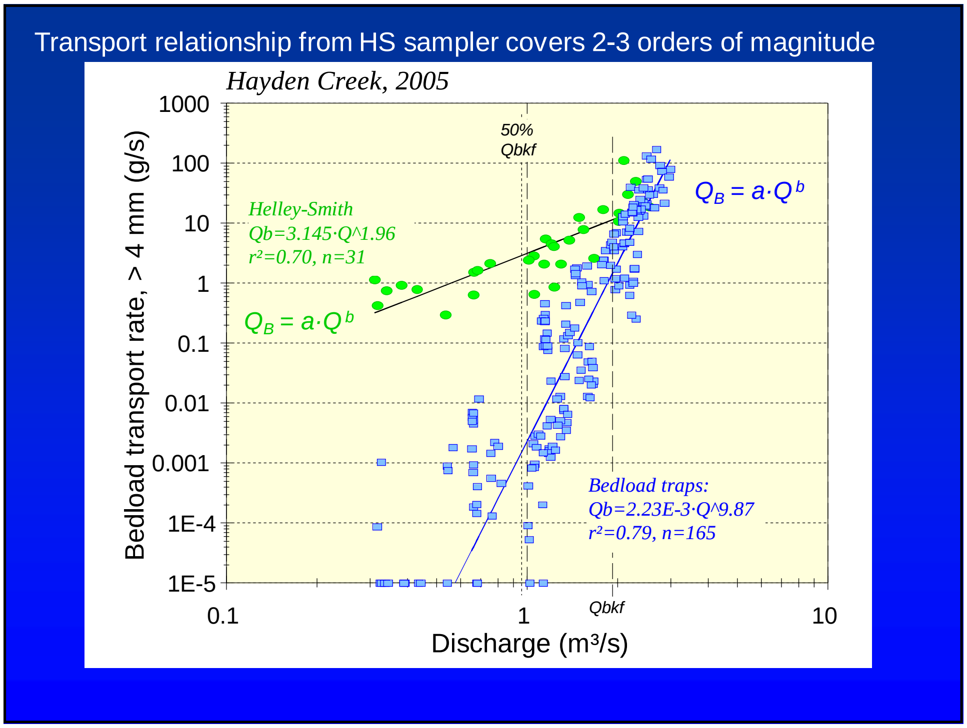
Sampling results

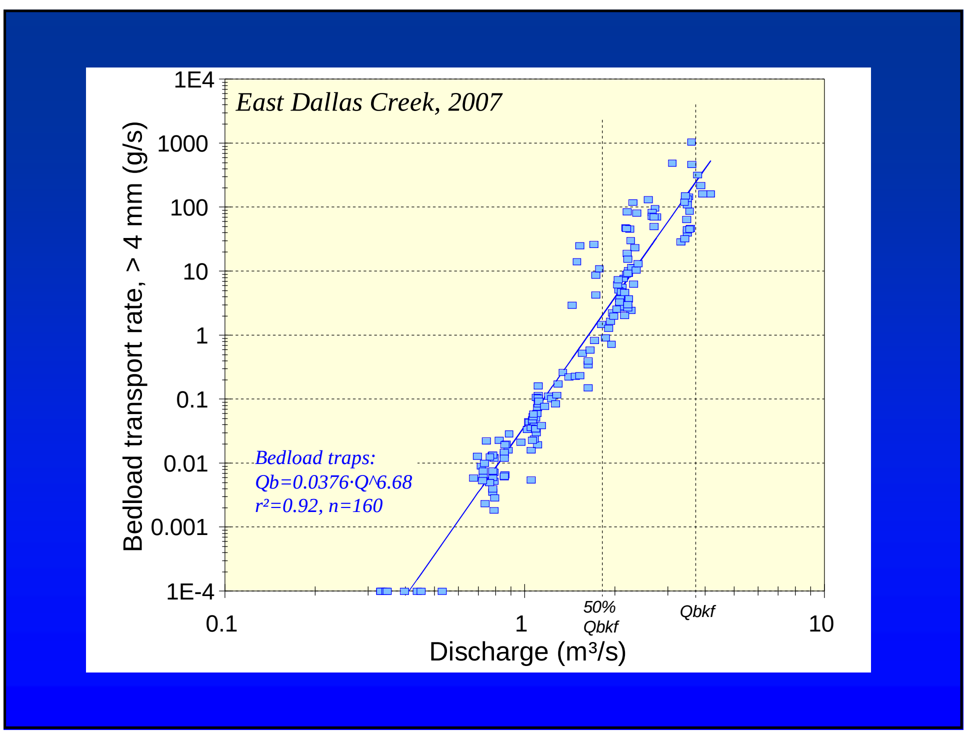
from bedload traps are best explained in comparison to bedload samples collected with a Helley-Smith sampler.

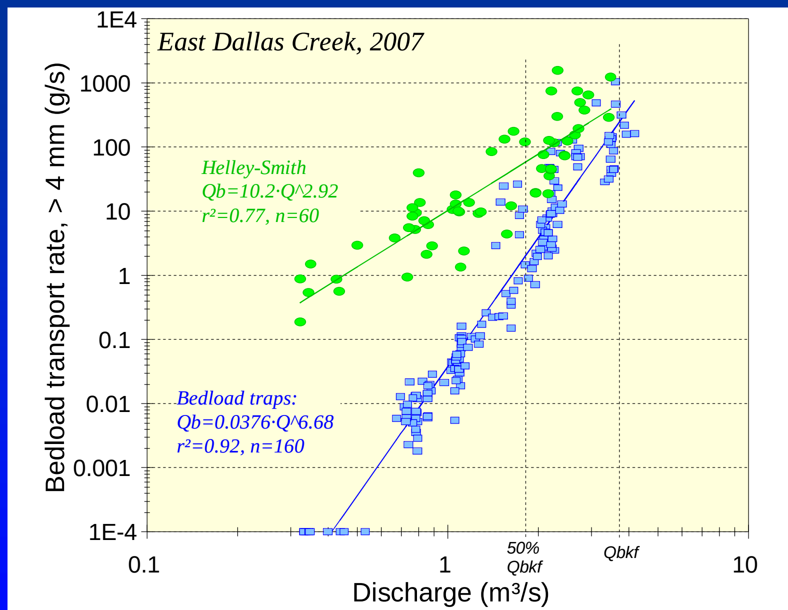
A Helley Smith sampler was deployed together at the same field sites

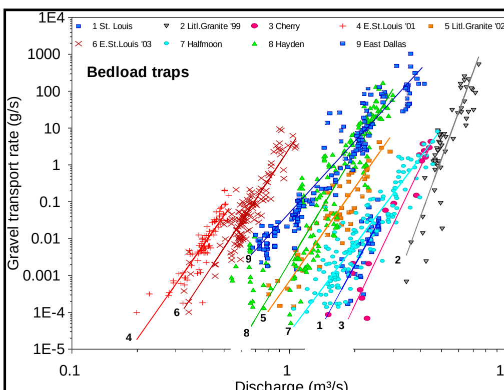
Steep gravel bedload transport relationships covering 5-7 orders of magnitude




Transport relationship from HS sampler covers 2-3 orders of magnitude
Hayden Creek, 2005
Bedload transport rate, > 4 mm (g/s)
Discharge (m³/s)
50% Qbkf
Qbkf
Helley-Smith
Qb=3.145·Q^1.96
r²=0.70, n=31
$Q_B = a \cdot Q^b$
$Q_B = a \cdot Q^b$
Bedload traps:
Qb=2.23E-3·Q^9.87
r²=0.79, n=165
1000
100
10
1
0.1
0.01
0.001
1E-4
1E-5
0.1
1
10


East Dallas Creek, 2007
Bedload transport rate, > 4 mm (g/s)
Discharge (m³/s)
Bedload traps:
Qb=0.0376·Q^6.68
r²=0.92, n=160
50% Qbkf
Qbkf
1E4
1000
100
10
1
0.1
0.01
0.001
1E-4
0.1
1
10

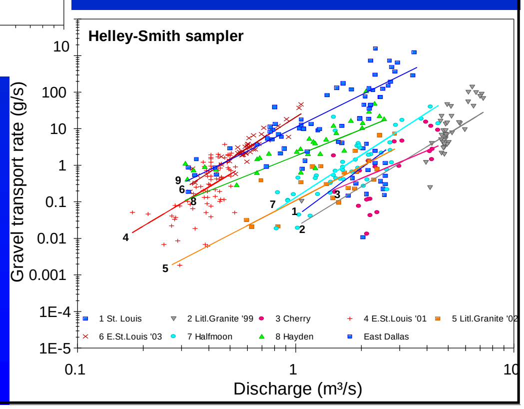




$Q_b = a\ Q^b$

Bedload traps:

Exponents *b*: 6.8 – 16.2



Helley-Smith sampler:

Exponents *b*: 2.0 – 4.2

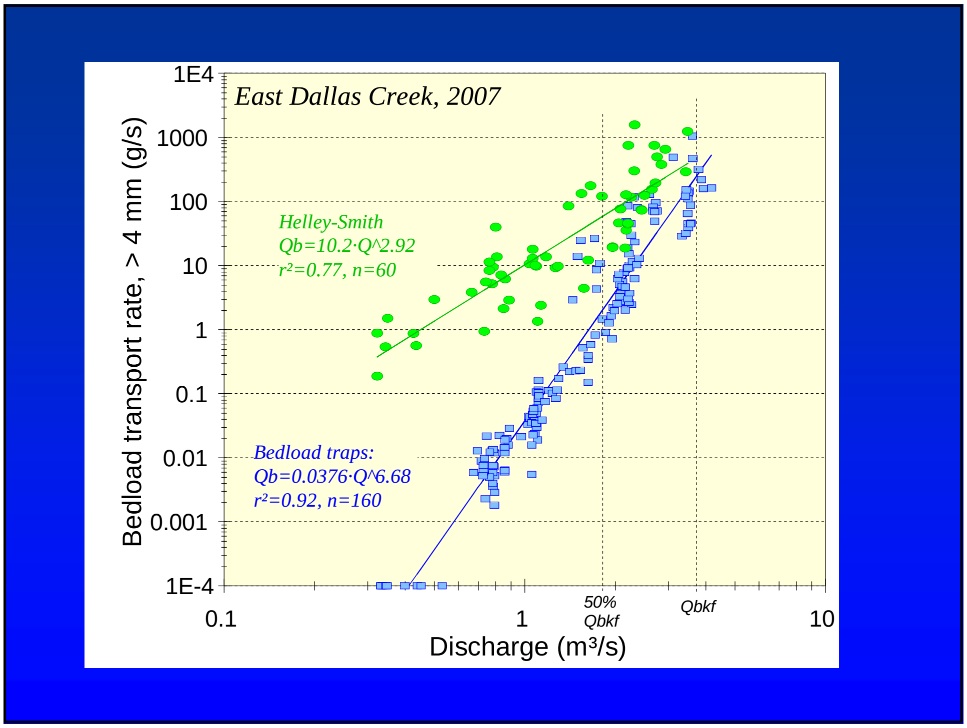
What causes the difference
between bedload trap and HS sampling results?

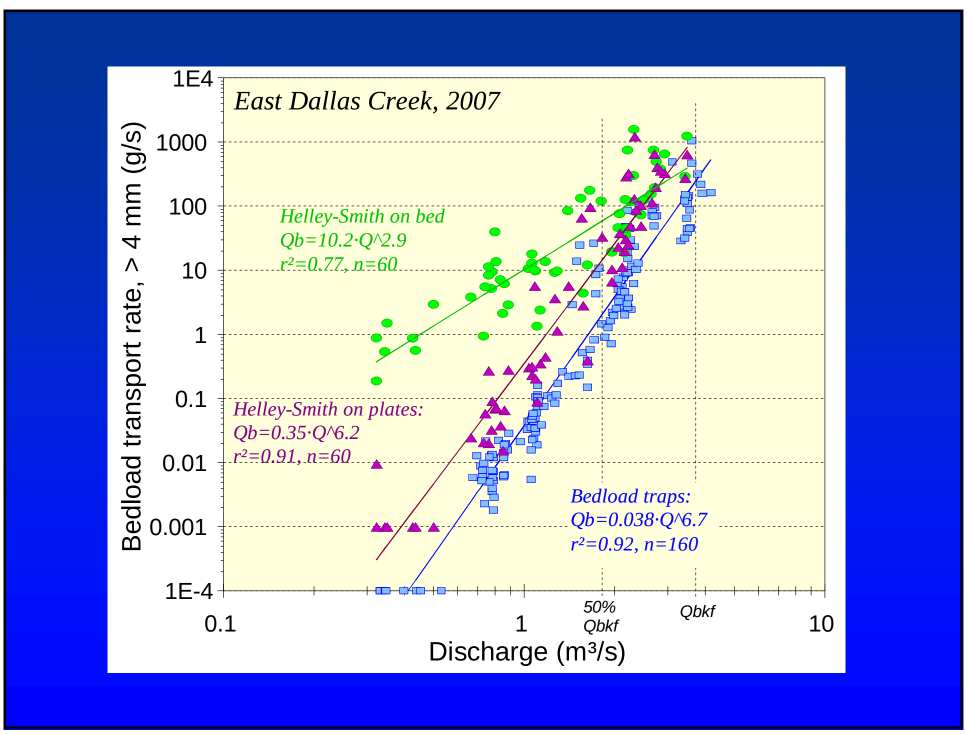
Most important:

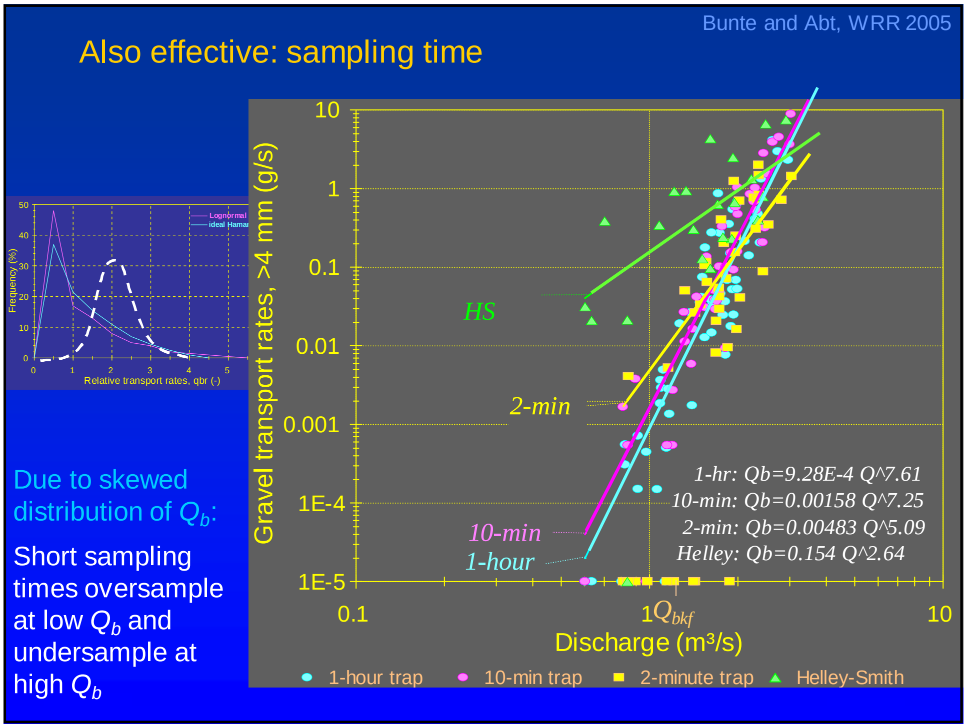
Effects of Ground plates

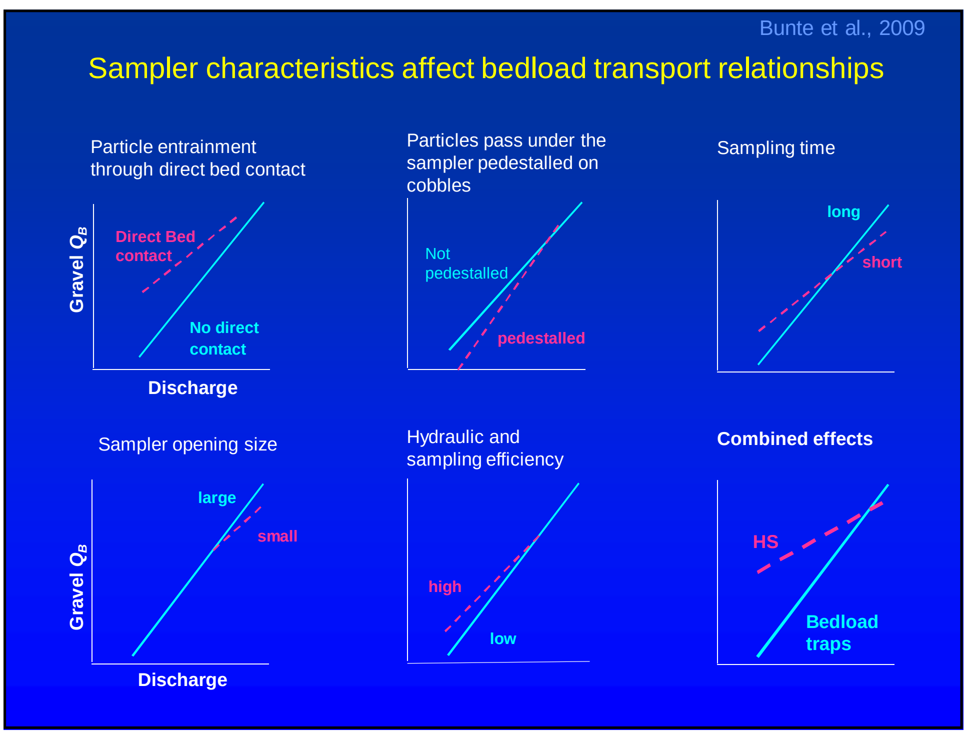
Helley-Smith on bed

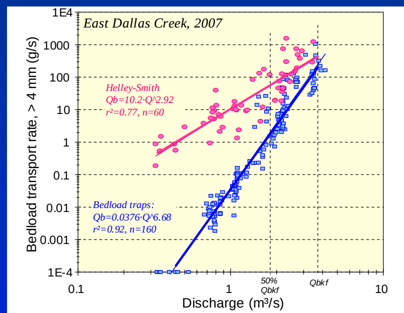
Helley-Smith on ground plates

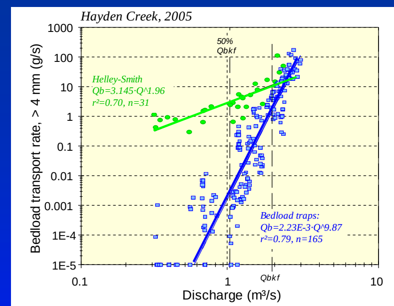

East Dallas Creek, 2007
Helley-Smith
Qb=10.2·Q^2.92
r²=0.77, n=60
Bedload traps:
Qb=0.0376·Q^6.68
r²=0.92, n=160
Bedload transport rate, > 4 mm (g/s)
1E4
1000
100
10
1
0.1
0.01
0.001
1E-4
0.1
1
50%
Qbkf
Qbkf
10
Discharge (m³/s)


East Dallas Creek, 2007
Helley-Smith on bed
Qb=10.2·Q^2.9
r²=0.77, n=60
Helley-Smith on plates:
Qb=0.35·Q^6.2
r²=0.91, n=60
Bedload traps:
Qb=0.038·Q^6.7
r²=0.92, n=160
Bedload transport rate, > 4 mm (g/s)
1E4
1000
100
10
1
0.1
0.01
0.001
1E-4
0.1
1
50%
Qbkf
Qbkf
10
Discharge (m³/s)


Bunte and Abt, WRR 2005
Also effective: sampling time
Frequency (%)
Relative transport rates, qbr (-)
Lognormal
Due to skewed distribution of Q_b:
Short sampling times oversample at low Q_b and undersample at high Q_b
Gravel transport rates, >4 mm (g/s)
10
1
0.1
0.01
0.001
1E-4
1E-5
HS
2-min
10-min
1-hour
1-hr: Qb=9.28E-4 Q^7.61
10-min: Qb=0.00158 Q^7.25
2-min: Qb=0.00483 Q^5.09
Helley: Qb=0.154 Q^2.64
0.1
1
Q_{bkf}
10
Discharge (m³/s)
1-hour trap
10-min trap
2-minute trap
Helley-Smith


Bunte et al., 2009
Sampler characteristics affect bedload transport relationships
Particle entrainment through direct bed contact
Gravel Q_B
Direct Bed contact
No direct contact
Discharge
Particles pass under the sampler pedestalled on cobbles
Not pedestalled
pedestalled
Sampling time
long
short
Sampler opening size
Gravel Q_B
large
small
Discharge
Hydraulic and sampling efficiency
high
low
Combined effects
HS
Bedload traps





Difference between bedload trap and HS sampler gravel transport rates → implications for subsequent computations

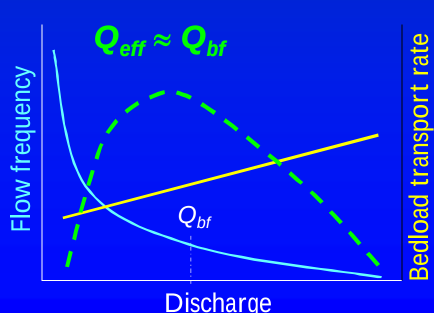
- magnitude frequency analysis
- annual gravel loads
- flow competence and critical flow for incipient motion

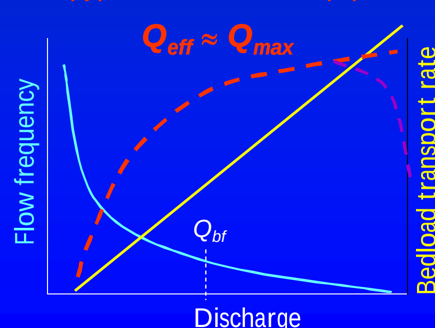
Magnitude – frequency analysis of effective discharge Q_{eff}
to determine which flow transports the majority of all bedload

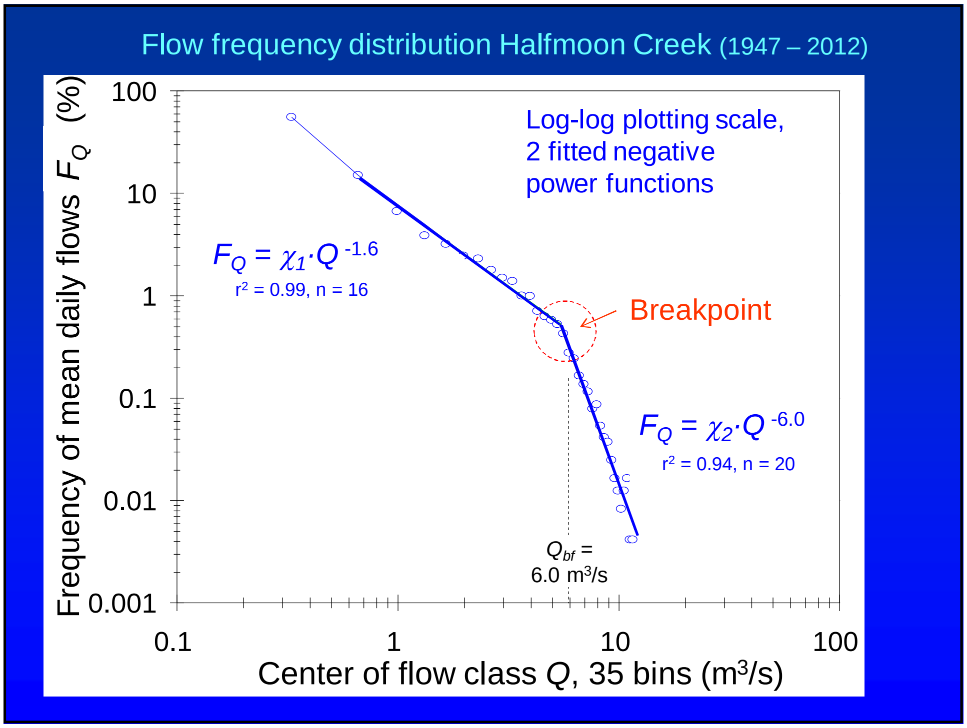
Q_{eff} for gravel bedload in mountain streams:
- Typically believed to be near bankfull flow (based on HS samples)
- More accurate bedload samples indicate that $Q_{eff} \approx \boldsymbol{Q_{max}}$

For bedload rating curve exponents of 2 - 4
(typical of HS sampler)

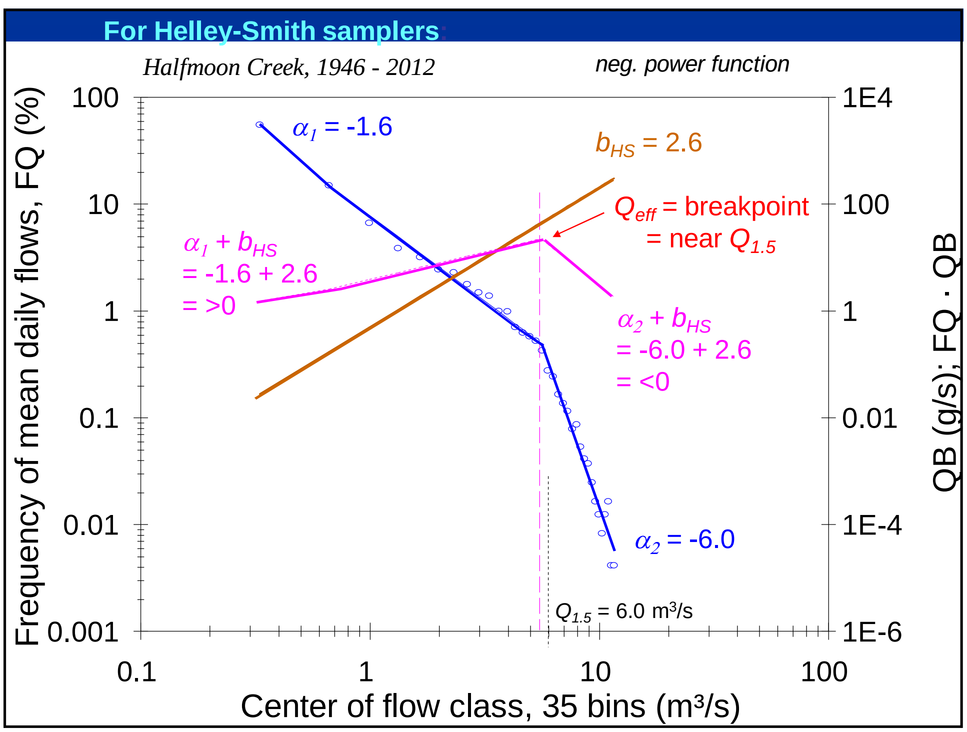
For bedload rating curve exponents of 5 - 16
(typical of bedload traps)





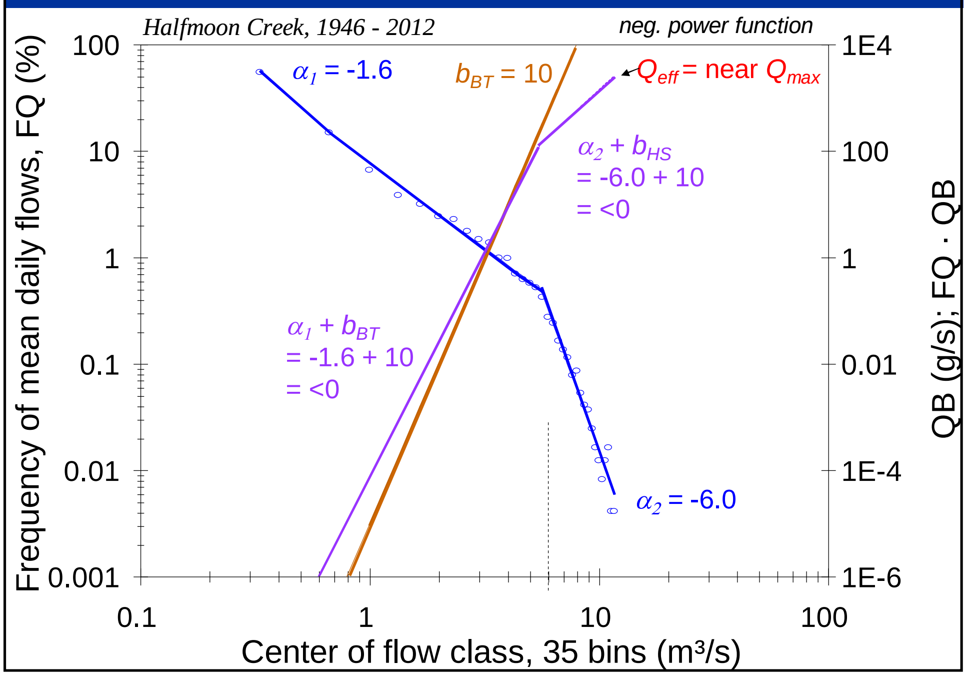


Flow frequency distribution Halfmoon Creek (1947 – 2012)
Log-log plotting scale,
2 fitted negative
power functions
$F_Q = \chi_1 \cdot Q^{-1.6}$
$r^2 = 0.99$, n = 16
Breakpoint
$F_Q = \chi_2 \cdot Q^{-6.0}$
$r^2 = 0.94$, n = 20
Q_{bf} =
6.0 m³/s
Frequency of mean daily flows F_Q (%)
100
10
1
0.1
0.01
0.001
0.1
1
10
100
Center of flow class Q, 35 bins (m³/s)

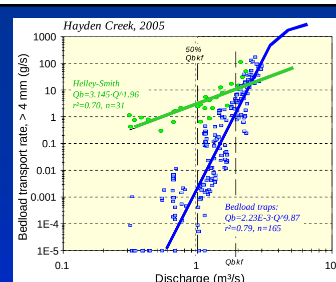


For Helley-Smith samplers
Halfmoon Creek, 1946 - 2012
neg. power function
α_1 = -1.6
b_{HS} = 2.6
Q_{eff} = breakpoint
= near $Q_{1.5}$
$\alpha_1 + b_{HS}$
= -1.6 + 2.6
= >0
$\alpha_2 + b_{HS}$
= -6.0 + 2.6
= <0
α_2 = -6.0
$Q_{1.5}$ = 6.0 m³/s
Frequency of mean daily flows, FQ (%)
100
10
1
0.1
0.01
0.001
1E4
100
1
0.01
1E-4
1E-6
QB (g/s); FQ · QB
0.1
1
10
100
Center of flow class, 35 bins (m³/s)

For bedload traps: Bunte et al., J Hydrol. 2014



Annual sediment load Q_{ba}



Bedload trap results indicate:

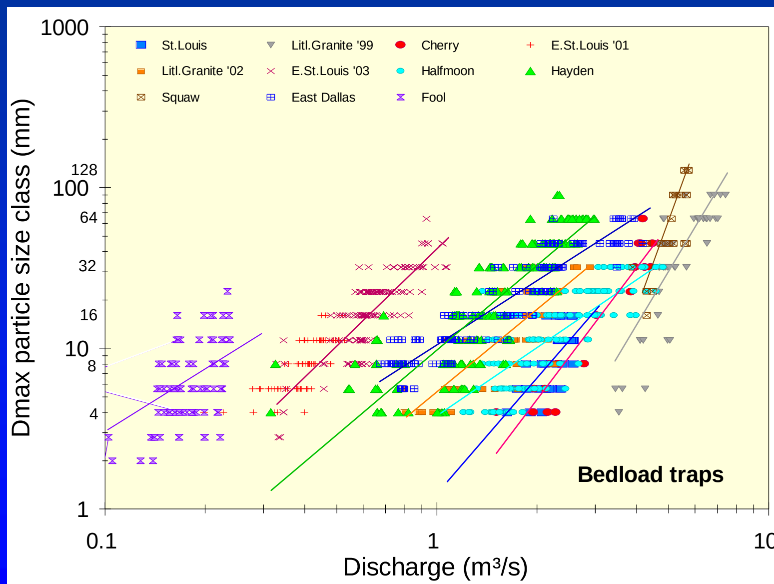
- Smaller Q_{ba} in low flow years and
- Higher Q_{ba} in high flow years than from Helley-Smith data

→ Gravel and cobble transport is more episodic and annually more variable than previously thought

→ high flow years play a more important role in long-term annual gravel yield

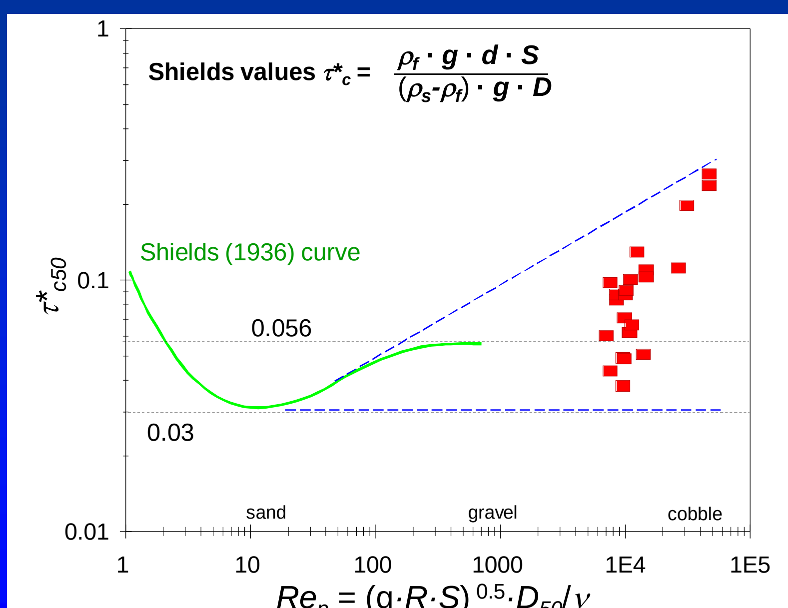
→ L o n g time series needed to establish mean Q_{ba}

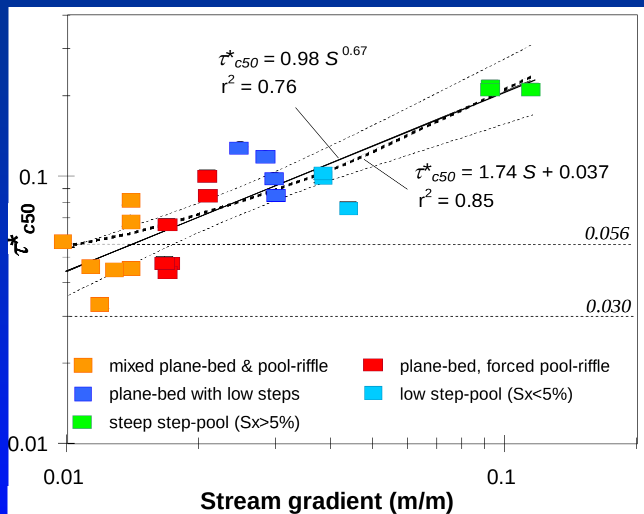
Flow competence curves from bedload traps provide insight into incipient motion:



Bunte et al., WRR. 2013

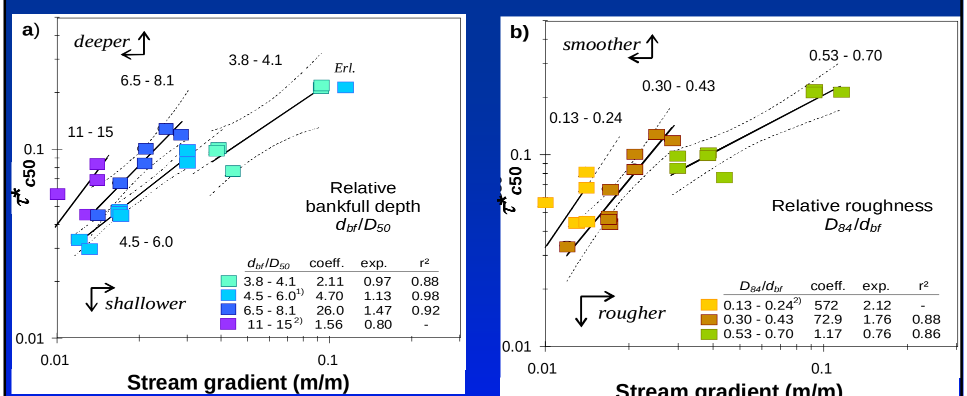
Incipient motion computations…





$$\tau^*_c = \frac{\rho_f \cdot g \cdot d \cdot S}{(\rho_s - \rho_f) \cdot g \cdot D_{50}}$$

- τ^*_c is strongly affected by stream gradient (10 fold diff. btw. streams)
- range of τ^*_c may be estimated for stream types

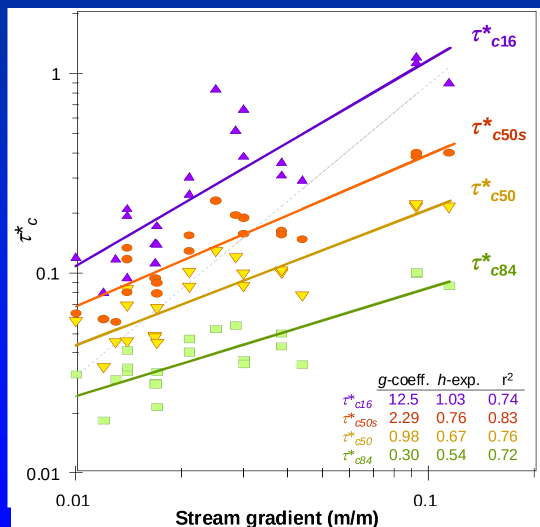


Scatter in relation of τ^*_c vs. stream gradient is reduced by stratification with:

- relative bankfull flow depth d_{bf}/D_{50}
- relative bankfull roughness D_{84}/d_{bf}

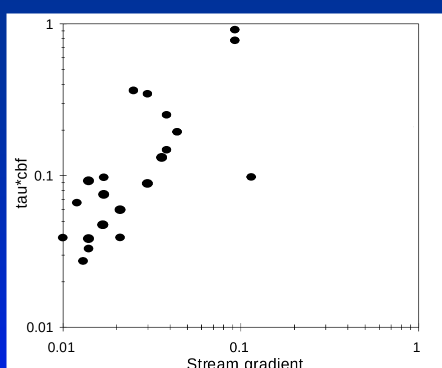
τ^*_c high for small particles and large for small particle sizes…perhaps simple numerical explanation

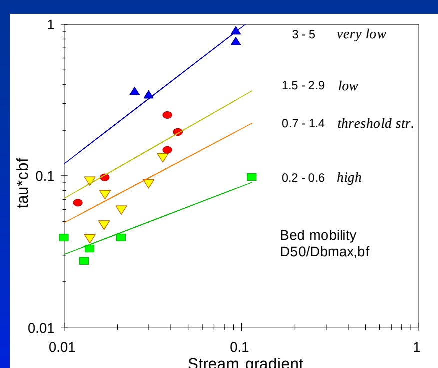
$$\tau^*_c = \frac{\rho_f \cdot g \cdot d \cdot S}{(\rho_s-\rho_f) \cdot g \cdot D}$$



Flow depth *d* varies little btw. moderate and high flows (factor of ≈ 2)

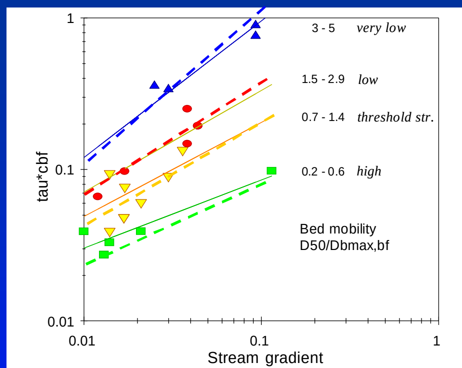
D_{16} to D_{84} sizes differ about 6-10 fold in mountain streams

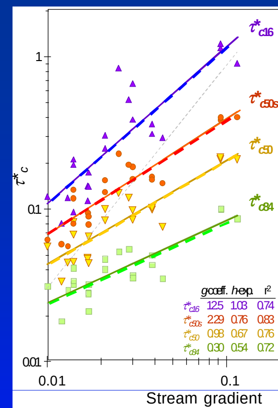




Critical Shields values for bankfull flow τ^*_{cbf} also increase with stream gradient, but scatter

τ^*_{cbf} is well stratified by bed mobility $D_{50}/D_{Bmax,bf}$





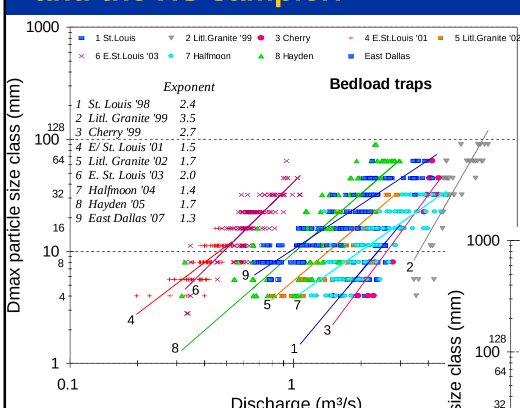
Stratification of τ^*_{cbf} by bed mobility $D_{50}/D_{Bmax,bf}$ …

…mirrors variability of τ^*_c for different particle sizes

τ^*_{cbf} corresponds approx. with mobility of:

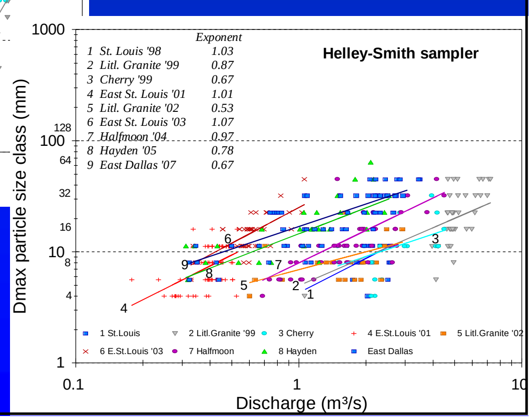
- surface D_{16} size	in **poorly** mobile streams
- subsurface D_{50sub} size	in **low** mobile streams
- surface D_{50} size	in **threshold** streams
- surface D_{84} size	in **highly** mobile streams

Flow competence curves also differ between bedload traps and the HS sampler:



Bedload traps:

Exponents: 1.3 – 3.5



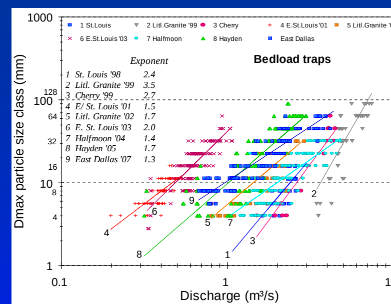
Helley-Smith sampler:

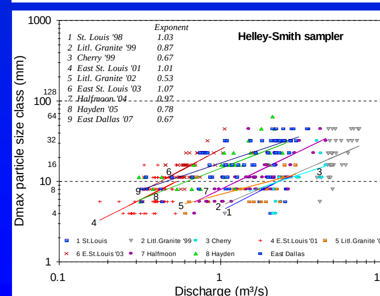
Exponents: 0.53 – 1.1

Difference between bedload traps and HS sampler affects incipient motion computations

Bedload traps **(large openings, long sampling times)** can collect coarse gravel and cobbles

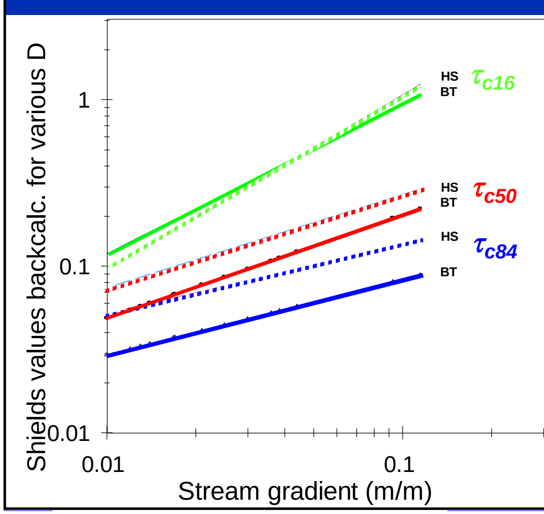
At the same flow depth, the HS sampler **(small opening, short sampling times)** collects smaller particles than bedload traps.





Differences in τ^*_c between HS and bedload traps:

$$\tau^*_c = \frac{\rho_f \cdot g \cdot d \cdot S}{(\rho_s - \rho_f) \cdot g \cdot D}$$

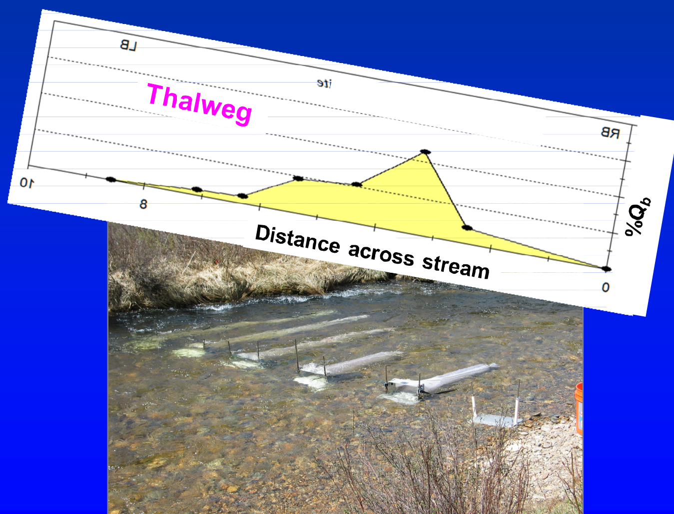


➯ because HS collects smaller ***D*** at the same depth ***d*** than traps,

HS samples indicate a higher critical τ^*_c for a given particle size than bedload traps

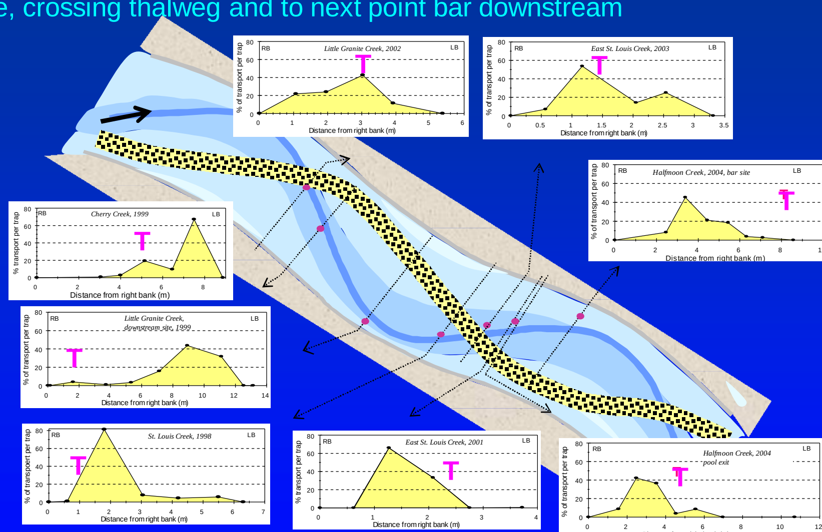
Other things we learned from bedload trap results:

Patterns of lateral variability



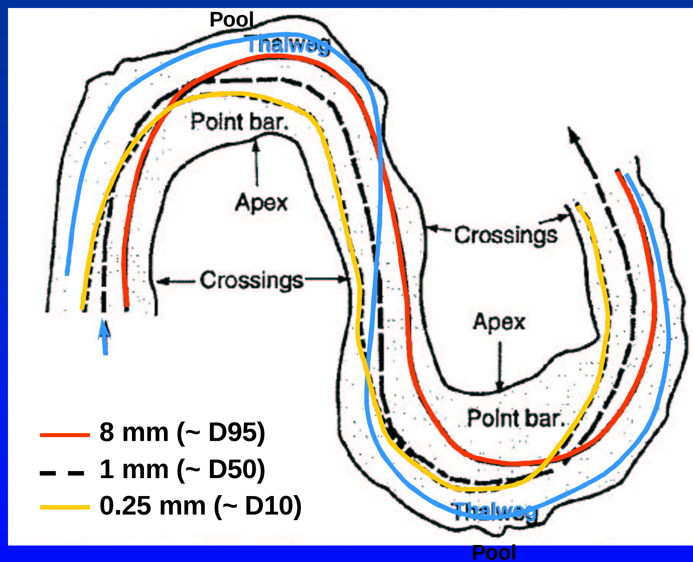
Transport path of coarse gravel

Typically not along thalweg; meandering path from head of point bar to bar toe, crossing thalweg and to next point bar downstream



→ Head of point bar receives high Q_b and may remain wadeable in otherwise unwadable streams

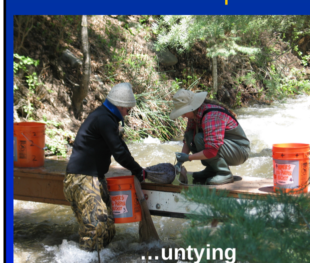
Transport paths for coarse and fine bedload in a meander bend

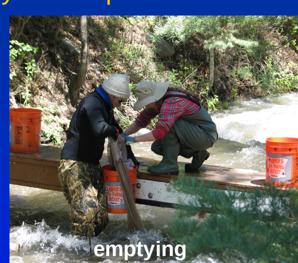


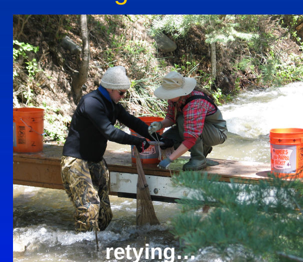
From: Julien and Anthony (2002), slightly altered

Temporal variability

Intensive back-to-back sampling with bedload traps provides 8-10 continuous samples a day and a quasi time series over the high flow season







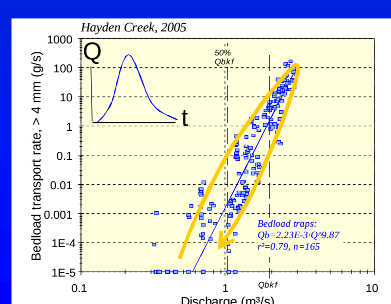
sampling…

sampling…

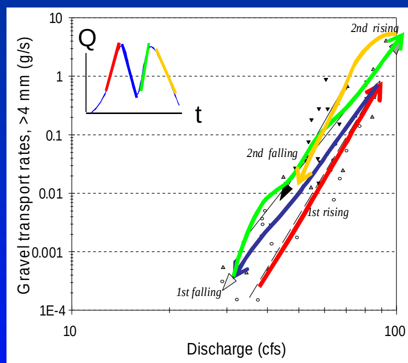
Hysteresis

daily and seasonal pattern

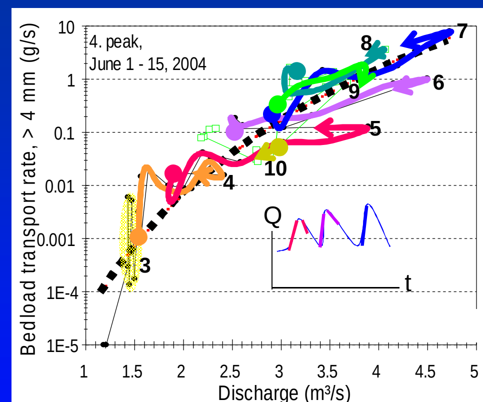
Here: clockwise seasonal hysteresis due to depletion of sediment supply



Counterclockwise seasonal hysteresis indicates delayed availability of sediment supply



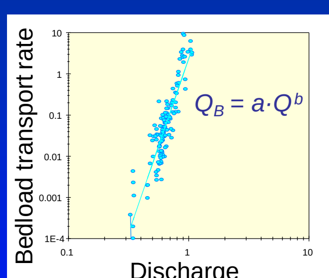
Clockwise daily hysteresis indicates increasing availability of sediment supply



→ dynamics of sediment supply (supply exhaustion, sudden sed. release)

→ emphasizes need to sample entire highflow season to determine transport relationship

Transport eqs. are notoriously poor at predicting gravel transport in mountain streams.
If bedload rating and flow competence curves is described by power functions…can ***coeff.*** and ***exp.*** be predicted?



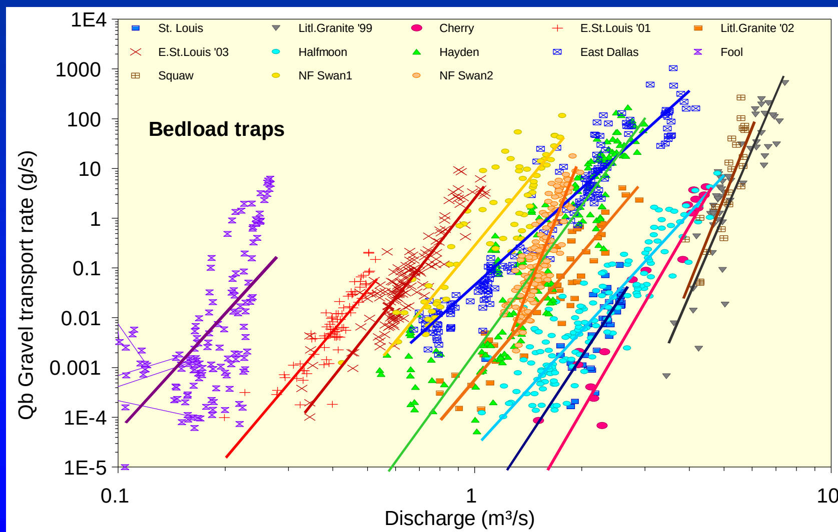
Bedload transport rate
coefficient
discharge
exponent

bedload transport rating curve: $Q_B = a \cdot Q^b$

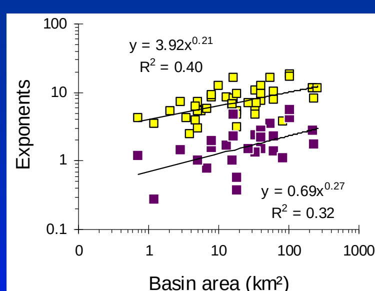
flow competence curve: $D_{max} = f \cdot Q^g$

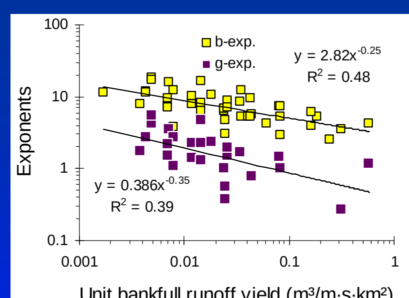
Exponents and coefficients

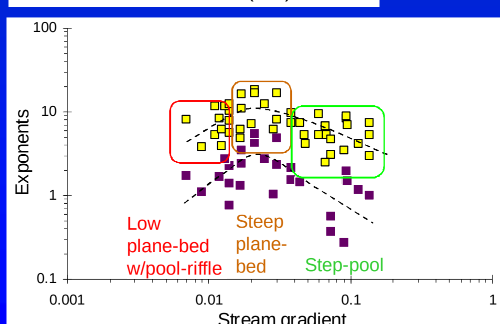
of bedload rating and flow competence curves
and their relationship to stream and channel parameters

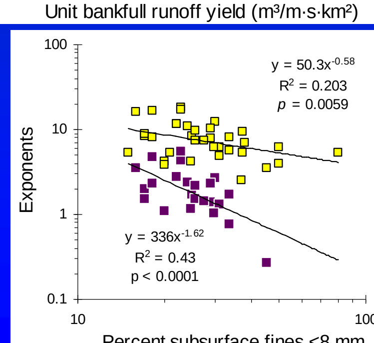


Exponents systematically to watershed and channel parameters

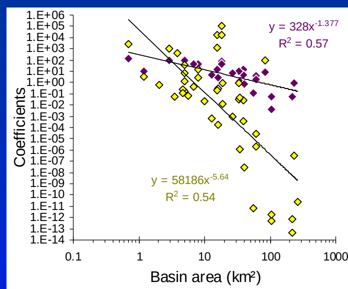


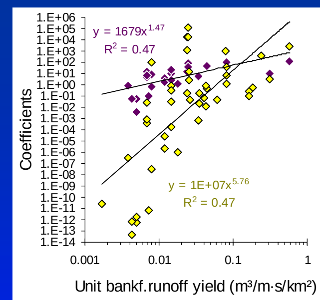


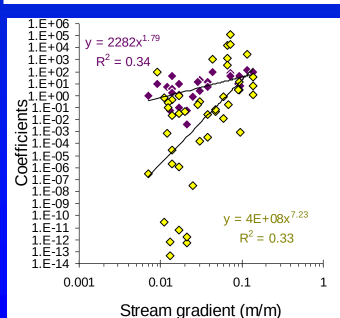


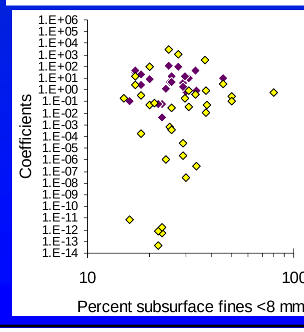


Coefficients ***a*** of transport and ***f*** of flow competence also related to watershed and channel parameters

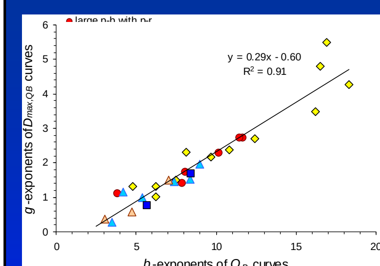




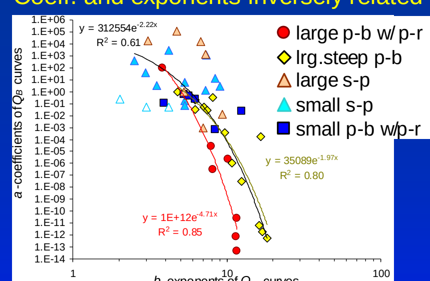




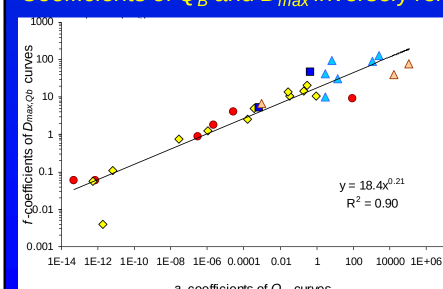
Exponents of bedload transport and flow competence positively related



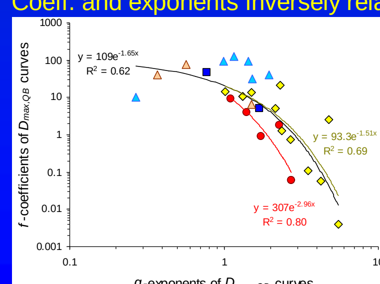
Bedload transport curves: Coeff. and exponents inversely related



Coefficients of Q_B and D_{max} inversely rel.



Flow competence curves: Coeff. and exponents inversely related



Summary and conclusions

Why bedload traps?

- Challenges posed by gravel bedload characteristics
- Challenges caused by handheld samplers
- Design criteria of bedload traps
- (large opening, large net, large mesh size, long sampling time, large vol.)

What have we learned from using bedload traps?

1. Rating and flow comp. curves are steep (and rel. well defined except at lowest Q_b)

2. Rating and flow comp. curves differ between traps and HS
   - Can attribute differences to sampler attributes

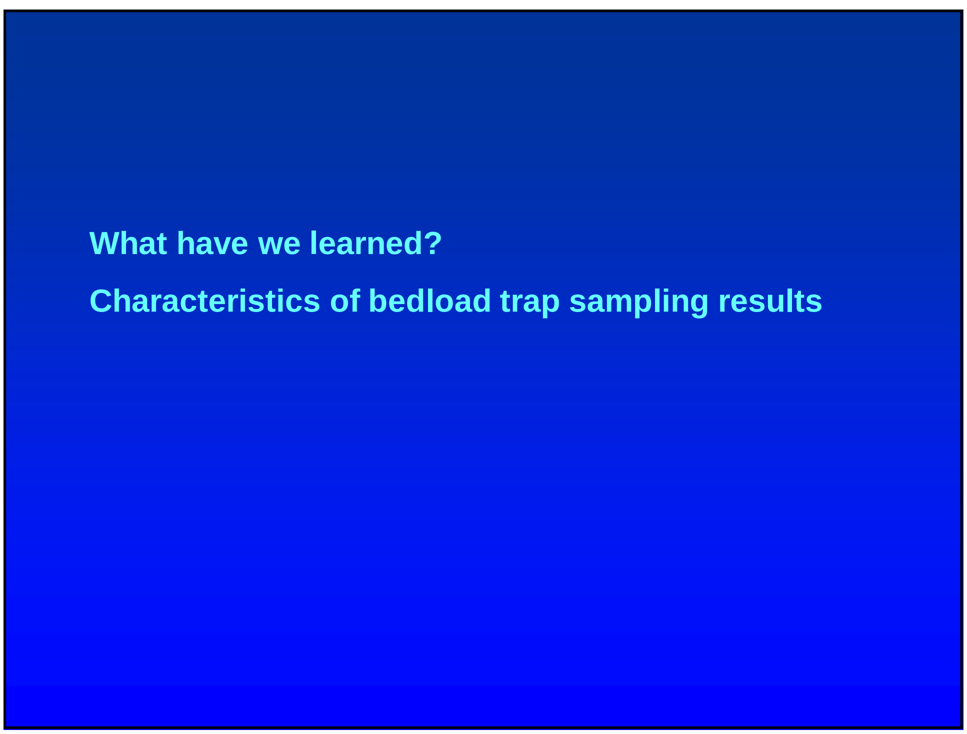
3. Differences btw. trap and HS results have implications on:
   - Magn.- freq. analysis: Q_{eff} shifts from Q_{bkf} (HS) toward Q_{max} (traps)
   - Annual load: less interannual variability for HS
   - Shields values: shifts τ_{*c} for given D from higher (HS) to lower (traps)

4. Lateral and temporal variability
   - Thalweg Not typically location of max. transport rates
   - Downstream transp. path in gravel-bed streams similar to that in sand bed streams
   - daily and seasonal hysteresis (availability or depletion of sed. supply)

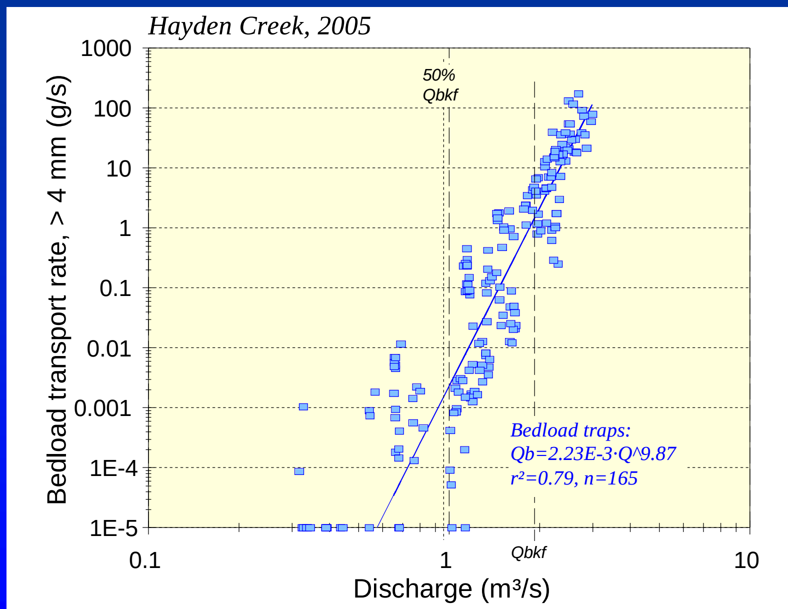
   → Sampling needs to cover entire highflow season to determine transport relationship

5. Incipient motion
   - τ^*_c strongly increases with stream gradient
   - τ^*_{cbf} depends on bed mobility

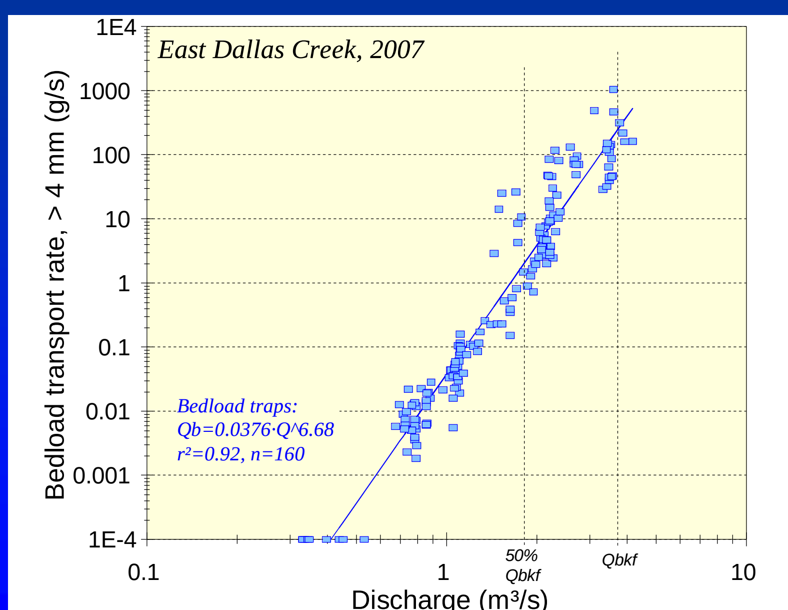
6. Exponents and coeff. of rating and flow comp. curves follow some trends
   - exponents increase with stream size (w_{bf}, Q_{bf}, ω_{bf}, A_d);
   - exponents decrease with % subsurface fine gravel
   - exponents highest for plane-bed streams, lower for pool-riffle and step-pool streams
   - exponents of bedl. rating und flow compet. curves closely related
   - exponents and coefficients neg. related but with much scatter


What have we learned?
Characteristics of bedload trap sampling results

Steep gravel bedload transport relationships covering 5-7 orders of magnitude



Relatively well defined transport relationships permit recognizing changes in transport rates

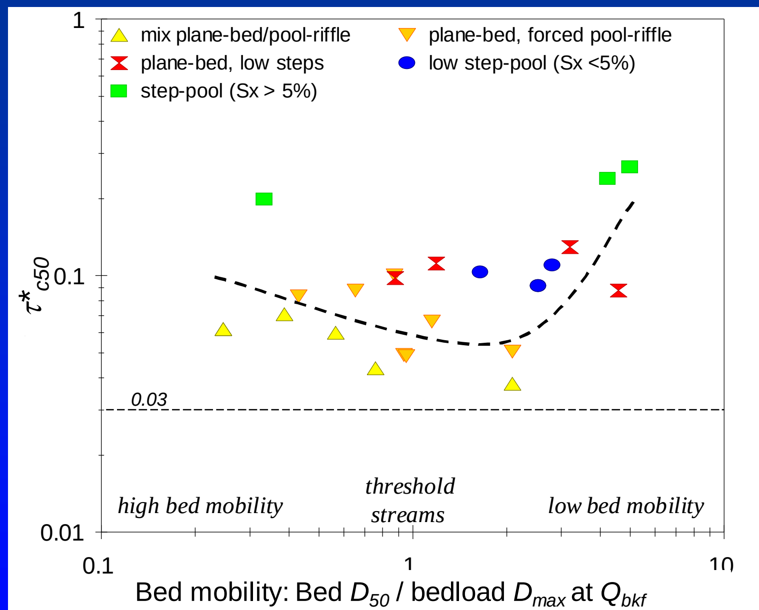


Bedload traps can be deployed over a range of wadeable flows to sample throughout a highflow season.

Flows of 20 – 130% of bankfull at East Dallas Creek

Samples can become large ….

…. and bags can add up
(1,000 bags and 1 ton of sampled bedload in one highflow season)



→ Implications for incipient motion criteria