Is the White Clay Creek a Threshold Channel? Evaluating Bed Mobility at a Gravel-Bed River in Pennsylvania, U.S.A.

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Abstract

Gravel-bed rivers are often interpreted as equilibrium, near-threshold channels (Parker, 1979), where channel morphology is adjusted to transmit the supply of coarse bed material with the given discharge. Theoretical analyses based on this concept predict bank sediments at the threshold of motion with bankfull Shields stresses on the bed (based on the D50) slightly in excess of this threshold, such that the bed material is fully mobile at bankfull stage. Surveys of 13 sites around the White Clay Creek, however, provide observations that are inconsistent with this concept. Bedrock is exposed along the channel and the longitudinal profile is controlled by migrating knickpoints, suggesting that the slope is imposed by bedrock erosion. Moreover, up to 50% of the bed material is immobile at bankfull stage. These observations suggest an alternate hypothesis to threshold channel theory: immobile cobble-boulder bed material is supplied locally by colluvial processes and bedrock incision, with a throughput load of sand-pebble-sized sediment readily transported by the river that is primarily stored in bars rather than on the bed. An approximate threshold condition based on the D50 of the streambed arises by averaging the grain size distribution over the immobile bed material and the finer throughput load, but this averaged bankfull Shields stress does not provide a useful measure of the mobility of all size fractions on the bed. These observations suggest that the channel morphology of the study site is decoupled from the supply of bed material, and that the White Clay Creek should not be considered an equilibrium, near-threshold channel. To test our hypothesis, we attached radio frequency identification (RFID) tags to 50 clasts in a 100 m reach. The RFID tags were installed with the gravel in situ on the bed at randomized locations in the channel; the distribution of tagged grains mirrors the grain size distribution of the bed. Since the deployment of tagged clasts in June 2019, six surveys have been accomplished and four significant flow events have occurred with the gage height reaching 2/3 of bankfull stage. Afterwards, 77% of tagged gravel remained in place during a given event, supporting our hypothesis. Numerical modeling of bed mobility under a variety of sediment supply scenarios allows us to generalize our field observations.

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I. Introduction

Background

Gravel-bed rivers are often interpreted as alluvial, equilibrium, near-threshold channels [*Parker*, 1979] with the following characteristics:

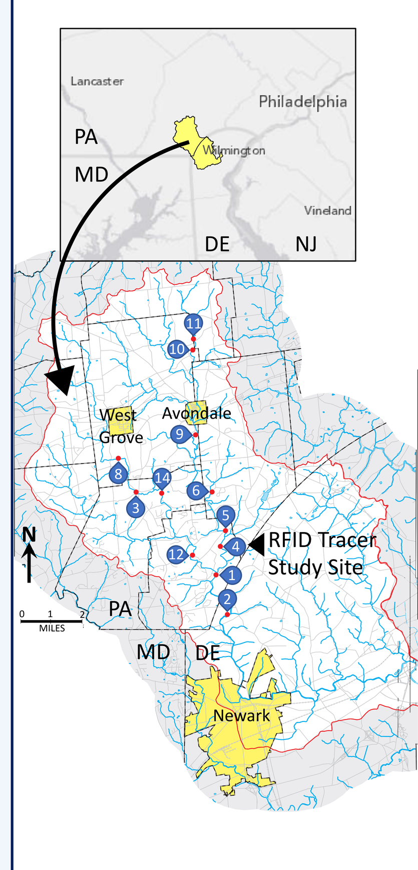
1. Bankfull Shield's stress over the bed is slightly in excess of critical;
2. All grain sizes of bed material are mobile at bankfull stage;
3. Bed material is supplied by fluvial transport from upstream;
4. Grain size distribution of the bed material and channel morphology are adjusted to the supply of sediment and water from upstream. *The bed material therefore consists of material supplied from upstream and the grain size distribution of the bed material is adjusted to this supply.*
5. Changes in sediment supply cause commensurate changes in reach-averaged bankfull morphology and bed material grain size.

Hypothesis

The White Clay Creek only clearly meets the 1st criterion listed above.
It is not an alluvial, near-threshold, gravel-bed river!

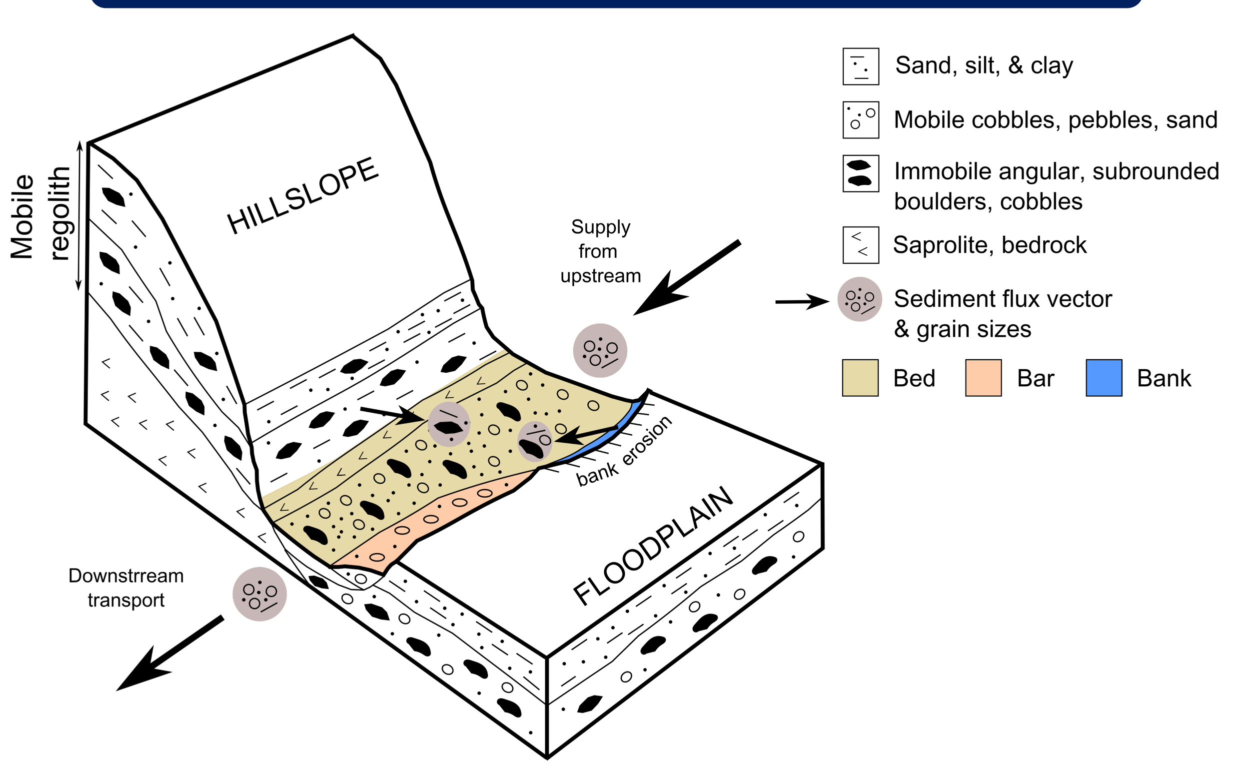
II. Location & Geomorphic Setting

Location



Geomorphic Setting

III. Fluvial Process Conceptual Model



Interpretation & Hypotheses

1. Immobile cobbles and boulders are supplied locally through bank erosion;
2. Fluvial supply from upstream consists of sand and pebbles stored in bars;
3. The streambed is anchored by immobile cobbles and boulders, with a sparse covering of "throughput load" consisting of sand and pebbles.

IV. Experimental Design to Test Hypotheses

Panel No. and Activity	Where hypothesis is presented	Hypothesis to be tested
V. RFID tracer study	Panel I, hypothesis 2	All bed material grain sizes are mobile at bankfull stage for near-threshold channels
VI. Compute bankfull Shield's stress based on D_{50}	Panel I, hypotheses 1 & 2	Bankfull Shield's stress is slightly above critical for near-threshold channels
VII. Determine mobile fraction of bed and bar sediment based on Shield's stress analysis	Panel III, hypotheses 1 & 2	Bar sediment is mobile, bed sediment is partially mobile
VIII. Evaluate mobility of bed and bar sediment based on the Wilcock-Crowe bedload transport equation	Panel III, hypotheses 1 & 2	Bar sediment is mobile, bed sediment is partially mobile
IX. Compare bed material flux of existing bed with theoretical flux if bar material covered the bed using the Wilcock-Crowe equation	Panel I, hypotheses 3 & 4	Bed material is supplied from upstream and its size distribution reflects both morphology and supply
X. Compute sensitivity of bed material grain size distribution to changes in sediment supply	Panel I, hypothesis 5	Changes in sediment supply cause commensurate changes in bed material grain size

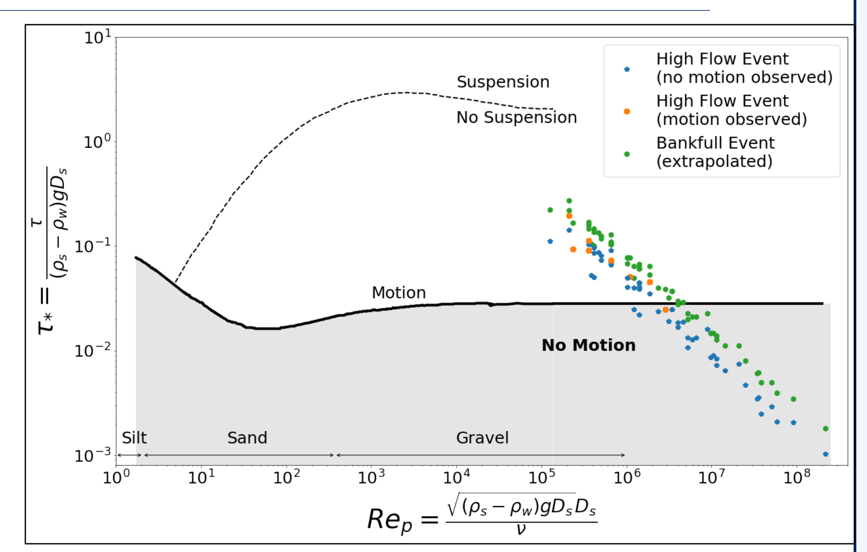
V. RFID Tracer Study

Methodology

- 56 clasts with Radio Frequency Identification (RFID) tags
- Tags installed at randomized locations along a 100*m* riffle
- Tags installed *in situ* on the bed
- Grain size distribution of tagged clasts reflects GSD of reach

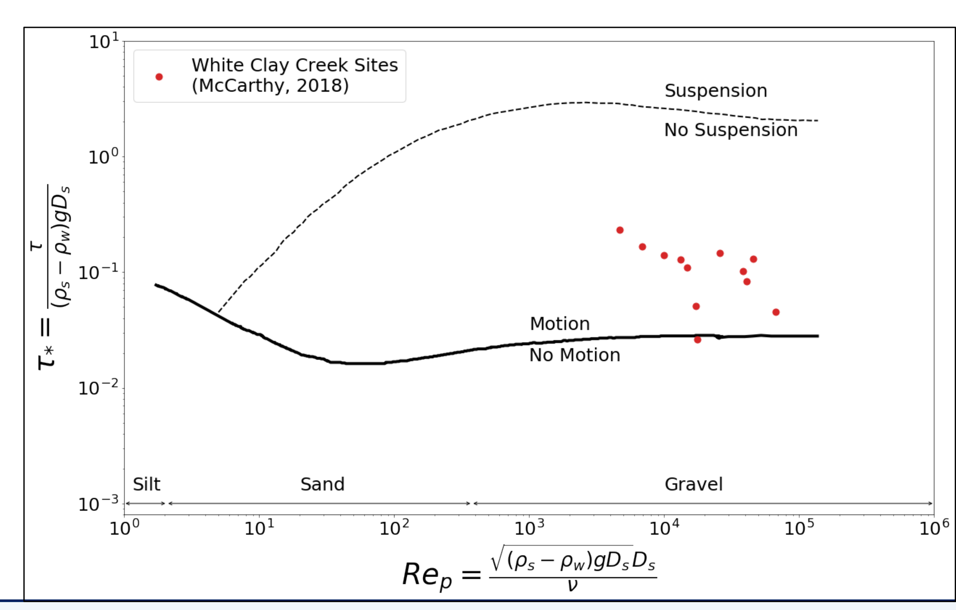
Results

- 6 events observed with flows up to 2/3 of bankfull stage
- **80% of tagged grains observed to be immobile**
- Only smaller clasts (< 8*cm*) are mobile
- Similar results expected at bankfull stage



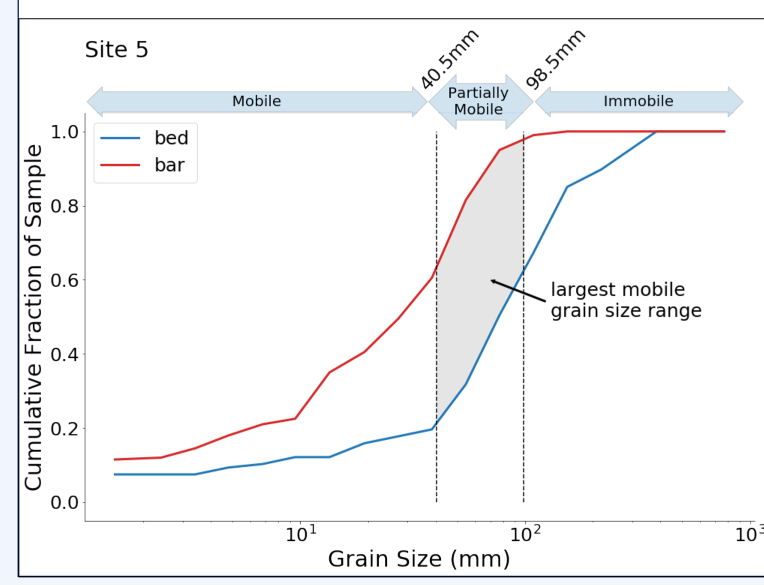
VI. Is Bankfull Shield's Stress Based on D_{50} Slightly Above Critical?

Based on surveys and pebble counts taken at each of the study sites, the bankfull Shield's stress over the bed is slightly in excess of critical for the mean grain size (D_m). **Thus, 11 of the 12 sites at the White Clay Creek satisfy these criteria (Panel I, hypothesis 1 & 2) for near-threshold, gravel-bed rivers.**



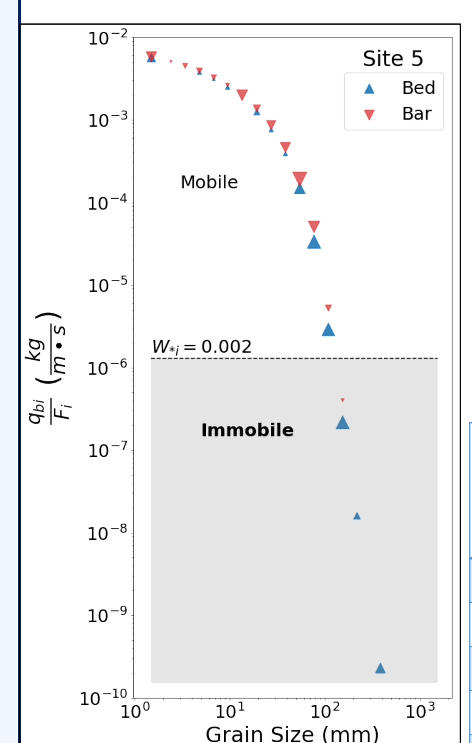
VII. Mobile Fraction of Bed and Bar Sediment Based on Shield's Criterion

- Pebble count of bed and bar sediment
- Evaluate mobility using critical Shield's parameter ($\tau_* = 0.03\text{-}0.073$) during bankfull conditions [*Montgomery & Buffington*, 1997]
- **Bar sediment is nearly 100% mobile, while approximately 20-90% of bed material is mobile at bankfull stage**



Site No.	Largest mobile grain size (mm)	Percent mobile–bed	Percent mobile–bar
1	68.9-167.7	61-85%	93-100%
2	9.6-23.4	23-37%	94-100%
3	35.2-85.5	55-79%	57-97%
4	18.4-44.8	41-55%	45-74%
5	40.5-98.5	21-62%	63-98%
6	62.7-152.6	47-81%	91-100%
8	39.1-95.2	53-85%	82-97%
9	35.5-86.3	71-93%	*NA*
10	32.6-79.2	71-93%	*NA*
11	36.0-87.5	59-87%	*NA*
12	53.3-129.9	46-67%	85-100%
14	91.2-221.8	54-83%	87-100%

VIII. Flux Criteria for Bed and Bar Sediment Based on Wilcock-Crowe Bedload Transport Equation



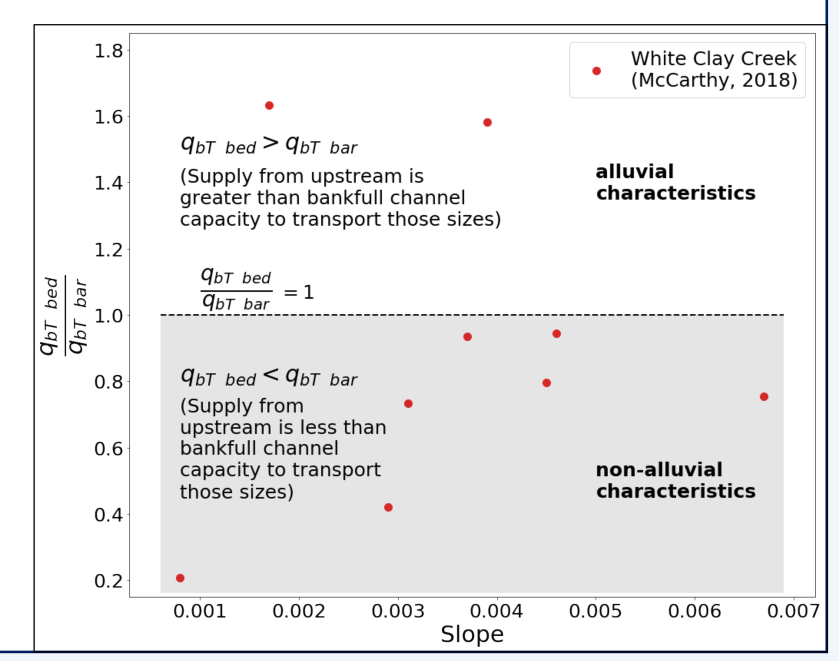
▲ Data points are scaled based on the fraction of sediment in each size bin.

- Evaluate mobility using the uncalibrated Wilcock-Crowe transport equation, where $W_{i*} > 0.002$ indicates that clasts are mobile [*Parker, et al.*, 1982]
- At Site 5 (see left), the largest mobile grain size is 136*mm*, with 78% of the bed material mobile and 100% of the bar material mobile
- **Bar sediment is typically 100% mobile while approximately 50-95% of bed material is mobile at bankfull stage**

Site No.	Largest mobile grain size (*mm*)	Percent mobile-bed	Percent mobile-bar	Site No.	Largest mobile grain size (*mm*)	Percent mobile-bed	Percent mobile-bar
1	293.4	92%	100%	8	136.3	92%	100%
2	35.5	52%	100%	9	111.2	96%	*NA*
3	136.4	92%	100%	10	105.6	96%	*NA*
4	68.0	62%	85%	11	108.6	94%	*NA*
5	135.8	78%	100%	12	181.5	75%	100%
6	213.7	85%	100%	14	368.0	96%	100%

IX. Documenting "Undersupply" of Alluvial Bed Material from Upstream

- Flux of the bar material ($q_{bT\ bar}$) reflects the theoretical flux of alluvial bed material supplied from upstream at bankfull stage, where the upstream bed is covered by material with the same grain size distribution as the bar
- We utilized the bar grain size distribution to estimate the alluvial supply because the bar material is shown to be mobile during bankfull conditions (Panels VII & VIII)
- Flux of bed material ($q_{bT\ bed}$) reflects the actual transport of bed material at bankfull stage



IX. Documenting "Undersupply" of Alluvial Bed Material (cont.)

- The ratio of bed and bar fluxes describes whether the channel is experiencing an oversupply or undersupply of alluvial material
  - $q_{bT\ bed} > q_{bT\ bar}$: the channel is currently transporting more than the expected alluvial supply, suggesting that enough material is being supplied to the reach
  - $q_{bT\ bed} < q_{bT\ bar}$: the channel is transporting less than the expected alluvial supply, suggesting that not enough material is being supplied from upstream
- As $q_{bT\ bed}/\ q_{bT\ bar} < 1$ for most sites, we can say that the White Clay Creek tends to be undersupplied
- **This indicates that the White Clay Creek is not a fully alluvial river**

X. Is White Clay Creek Bed Texture and Elevation Sensitive to Changes in Sediment Supply?

In Progress

- Near-threshold, equilibrium, alluvial channels should be adjusted to and sensitive to changes in bed material supply
- To assess this hypothesis, we used a numerical model to predict changes in bed elevation and grain size distribution given an input bed material flux
- We used the Wilcock-Crowe (2003) bedload transport equation and Parker's (1991) approach to determine changes in bed material grain size and elevation
- Similar to the analysis presented in Panel IX, we can specify an input bed material flux to simulate an over or undersupply of alluvial material from upstream
- We can then evaluate the resulting change in bed elevation and grain size distribution, where aggradation and a bed grain size distribution that matches the input GSD indicate that the channel is developing alluvial characteristics

XI. Conclusion

Observations, calculations, and a model of the White Clay Creek study sites indicate that:

- A significant proportion of the bed is immobile during bankfull flows–
  - RFID tags: 80% of tagged clasts were immobile during significant flow events
  - Shield's criterion: 10-80% of bed material is immobile during bankfull conditions
  - Uncalibrated Wilcock-Crowe bedload transport equation: 5-50% of the bed material is immobile at bankfull stage
    - Shield's criterion and Wilcock-Crowe bedload transport equations likely overestimate sediment flux
- This immobile fraction is supplied locally from colluvial hillslopes or exhumed from the underlying bedrock
- In addition to the supply of immobile material from the channel, mobile material is supplied from upstream and is stored on the bar
- There is an undersupply of alluvial material from upstream, producing non-alluvial characteristics

So is the White Clay Creek a Threshold Channel?

The observations from the field and modeling results do not agree with all criteria of the threshold channel concept proposed by Parker (1979). Thus, we believe that the White Clay Creek is not an alluvial, near-threshold, gravel-bed river.

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