Observations and implications of artificial vegetation on suspended sediment capture in laboratory flume experiments

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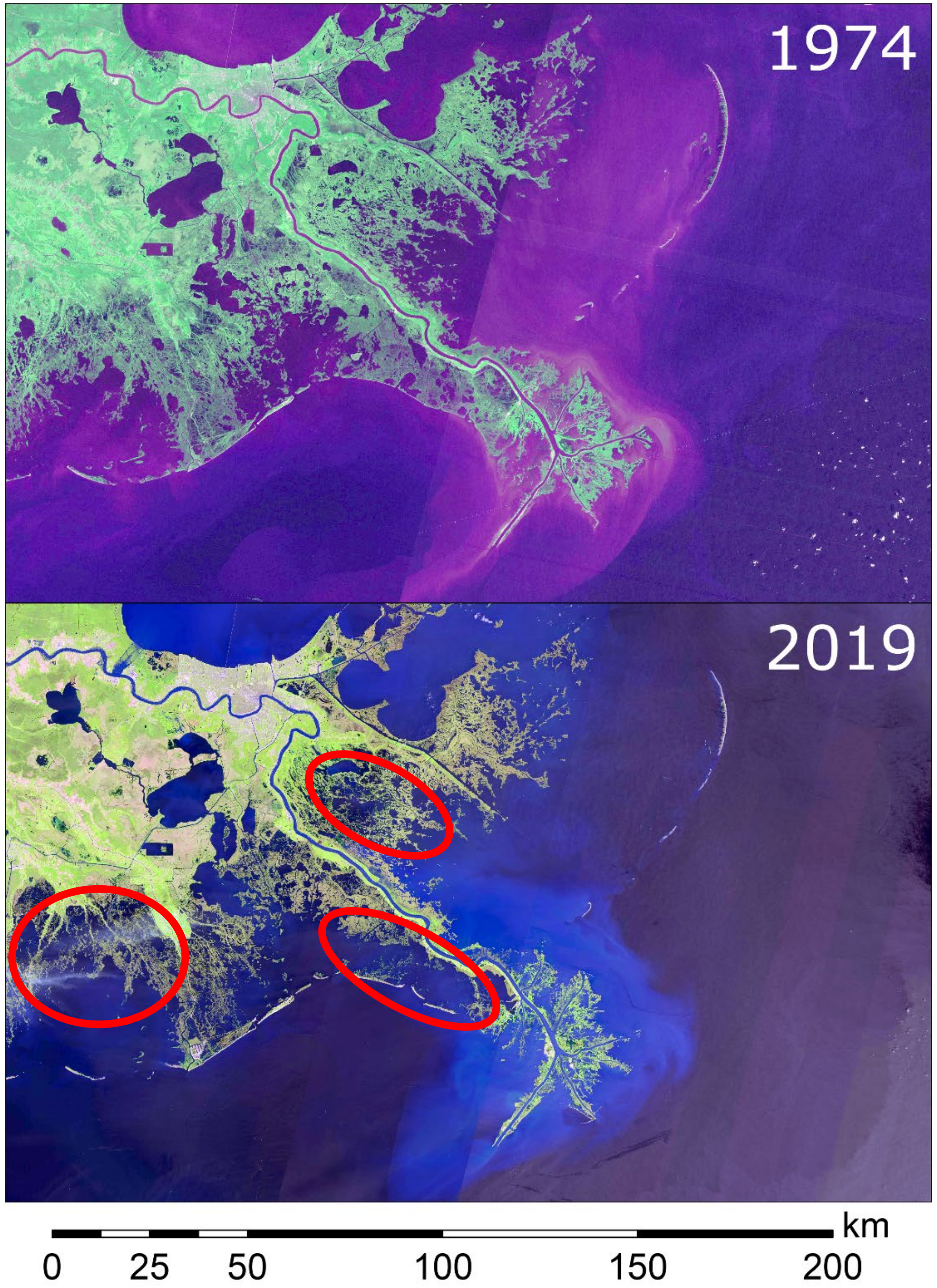
Motivation

- Coastal wetlands are facing historically rapid land loss
- Mississippi River Delta has lost over 5000 km^2 of wetlands since 1930s
- Relative sea level rise accelerates loss



Motivation

- Strategy: vegetation enhances retention of transported sediment load
  - Based on previous studies [Palmer et al., 2004; Wu et al., 2011; Fauria et al., 2015]

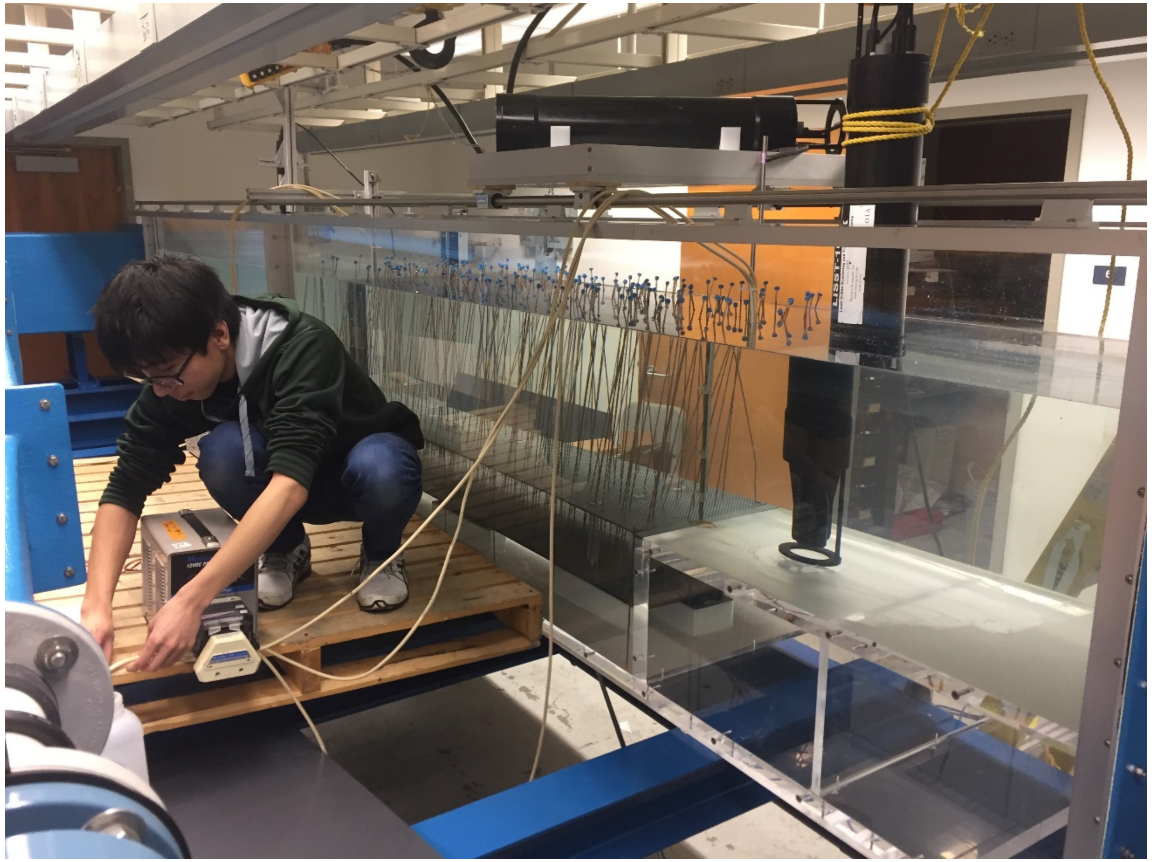
- Mathematical models to predict particle capture are valuable tools for wetland management
  - Empirical models of Palmer et al. [2004] and Fauria et al. [2015]

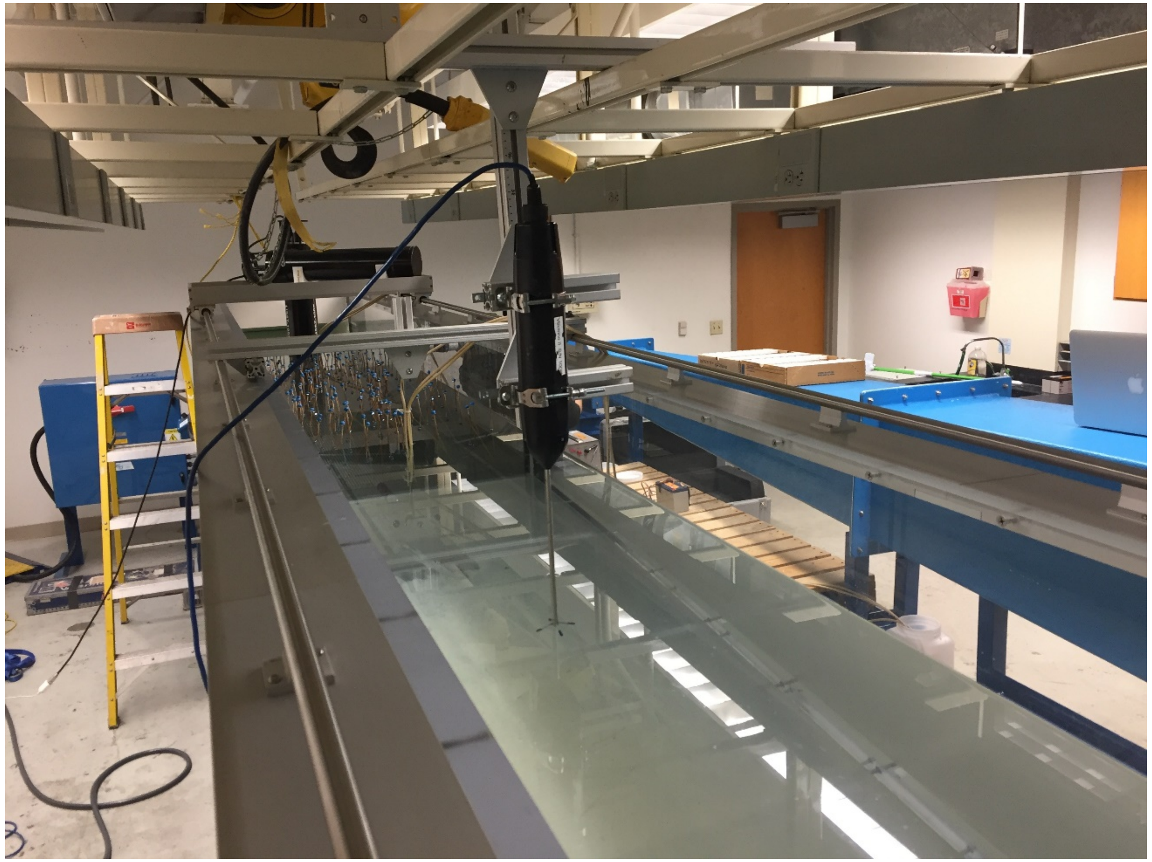
Research Questions

1. How well do existing models of suspended particle capture by vegetation stems perform?
    - Are there important but unaccounted parameters?

2. Through flume experiments, what is the influence of vegetation on suspended particle capture in wetlands?

One method: Flume experiments



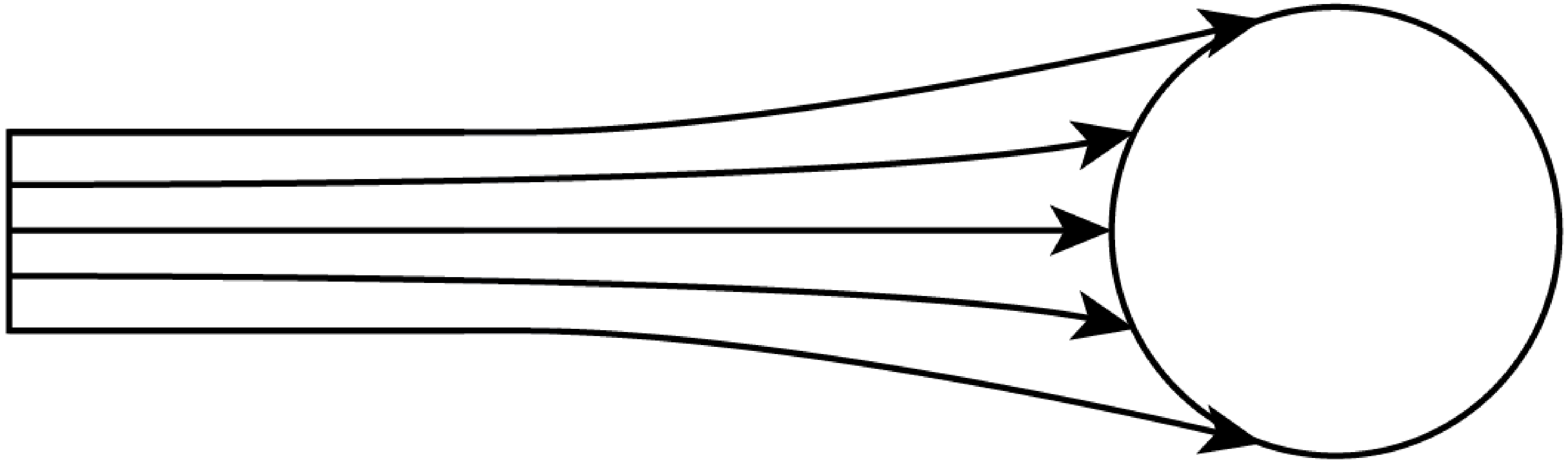


General Terms

- **Particle capture** – general removal of sediment particles from transport in the flow
- **Collectors** – vegetation stems (or stem-like objects) in the flow; their surfaces “collect” particles from the flow
- **Suspended load** – sediment transported in a flow in suspension

Particle capture mechanisms

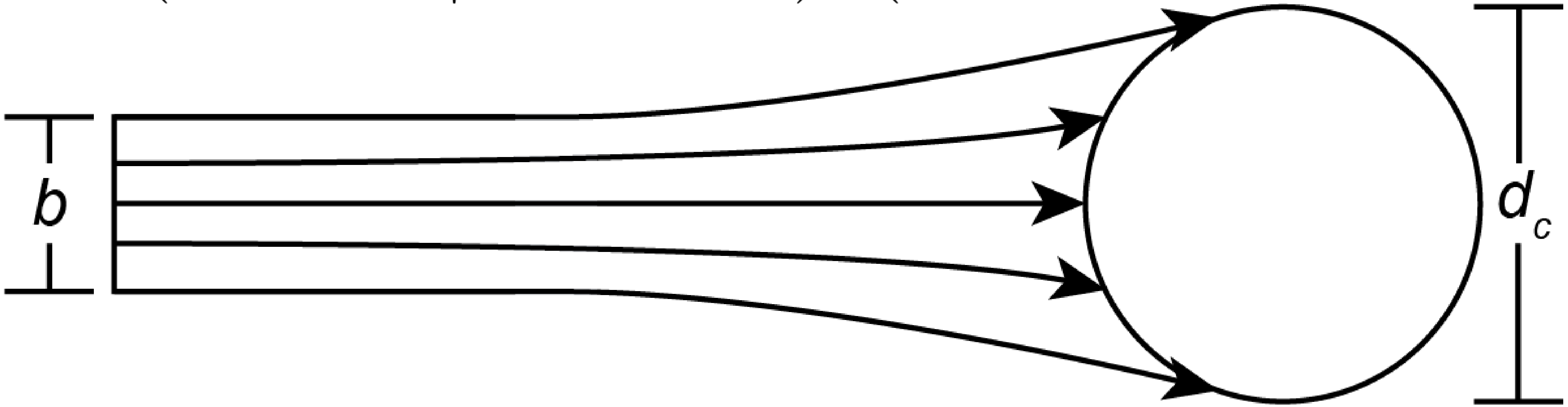
- Gravitational settling
- Direct interception
- Diffusional deposition – turbulence, Brownian motion
- Inertial impaction – divergence from flowlines



Effective capture efficiency

- Quantifies overall rate of particle capture by collectors

$$
\begin{aligned}
\eta' &= p_r \frac{b}{d_c} \\
&= P(\text{retention}|\text{interaction}) P(\text{interaction with collector})
\end{aligned}
$$



Suspended load model

- In practice, fit an exponential model, a solution of an advection-diffusion equation [Fauria et al., 2015]

$$\phi(t) = \phi_0 e^{-kt}$$

where

$$\phi = \text{sediment concentration as a function of time}$$

$$\phi_0 = \text{initial sediment concentration}$$

$$\boxed{k = \text{particle capture rate}}$$

$$t = \text{time}$$

Particle capture rate

- Particle capture rate *k* quantifies **how fast** suspended sediment concentration declines with time
- May be decomposed as

$$k = k_s + k_c$$

where $k_s = \text{particle capture rate due to gravitational settling}$

$k_c = \text{particle capture rate due to collectors}$

- Key: separate effects of settling and collectors

Parameter Estimation Summary

1. Suspended load model

$$\phi(t) = \phi_0 e^{-kt}$$

Estimate k using data

2. Decomposition

$$k = k_s + k_c$$

Partition k into contributions of settling and capture on collectors

3. Estimated effective capture efficiency

$$\eta' = \frac{k_c}{u d_c l_c}$$

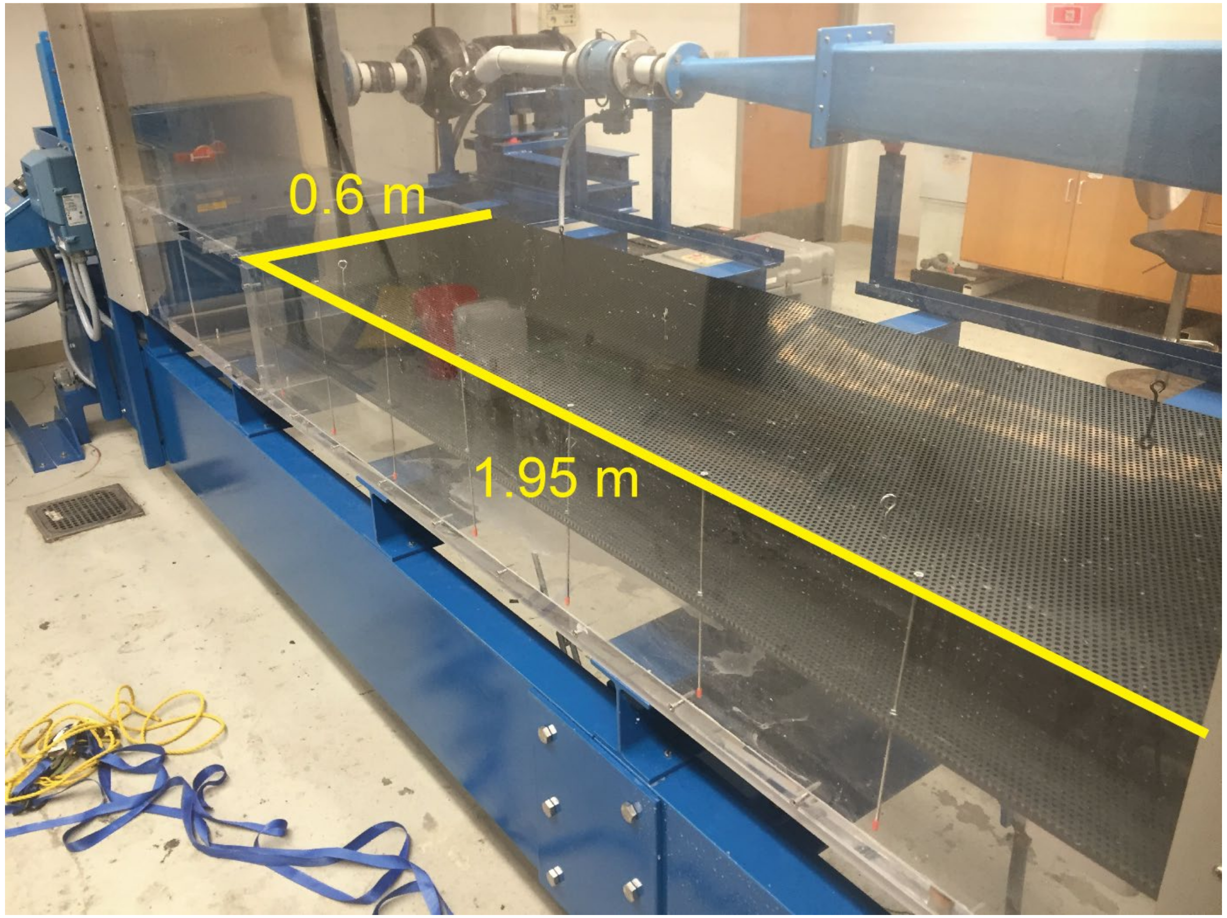
Estimate effective capture efficiency using k_c

Methods

- Flume experiments (~100 min)
  - Two experiments: with dowels, without dowels
- Model vegetation stems using array of wooden dowels
- Sediment added to flume at start of experiment
- Instruments:
  - Peristaltic pumps
  - Acoustic Doppler velocimeter (ADV)
  - Sediment traps

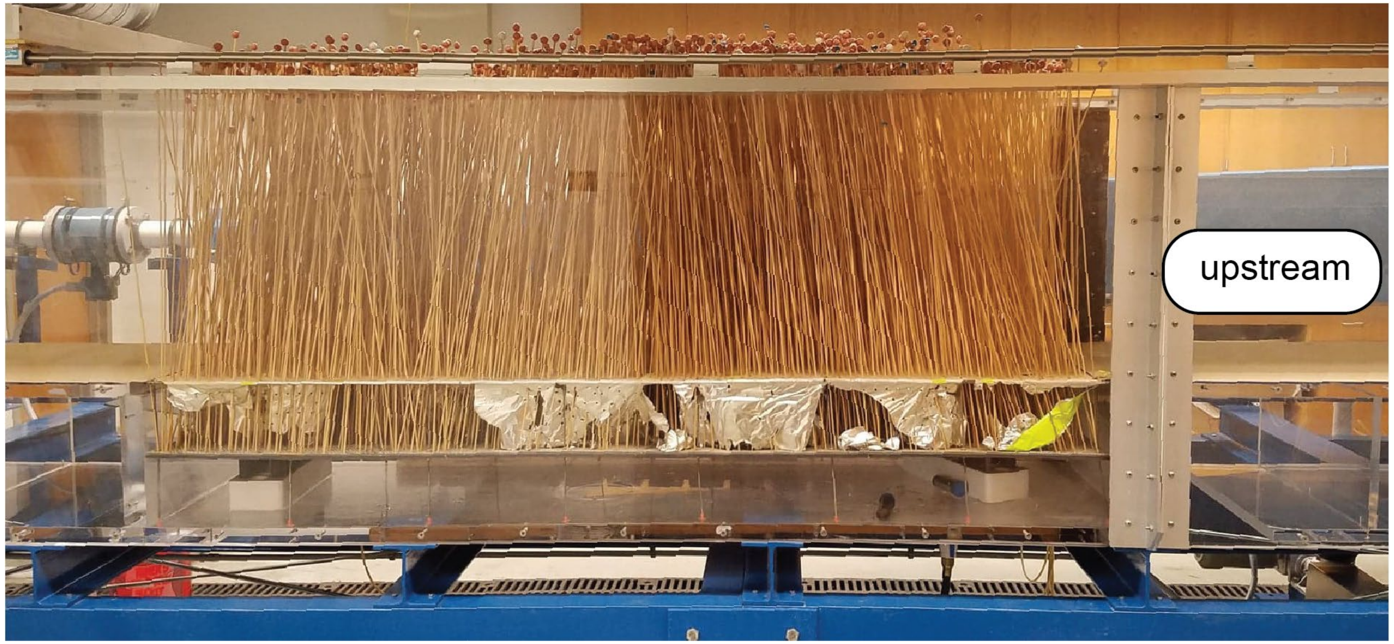
Recirculating Flume

- average flow velocity 5-6 cm/s
- Transitional flow
- 5.25 m long x 0.6 m wide channel
- 0.4 m water depth
- False bed converted into “test section” for dowels



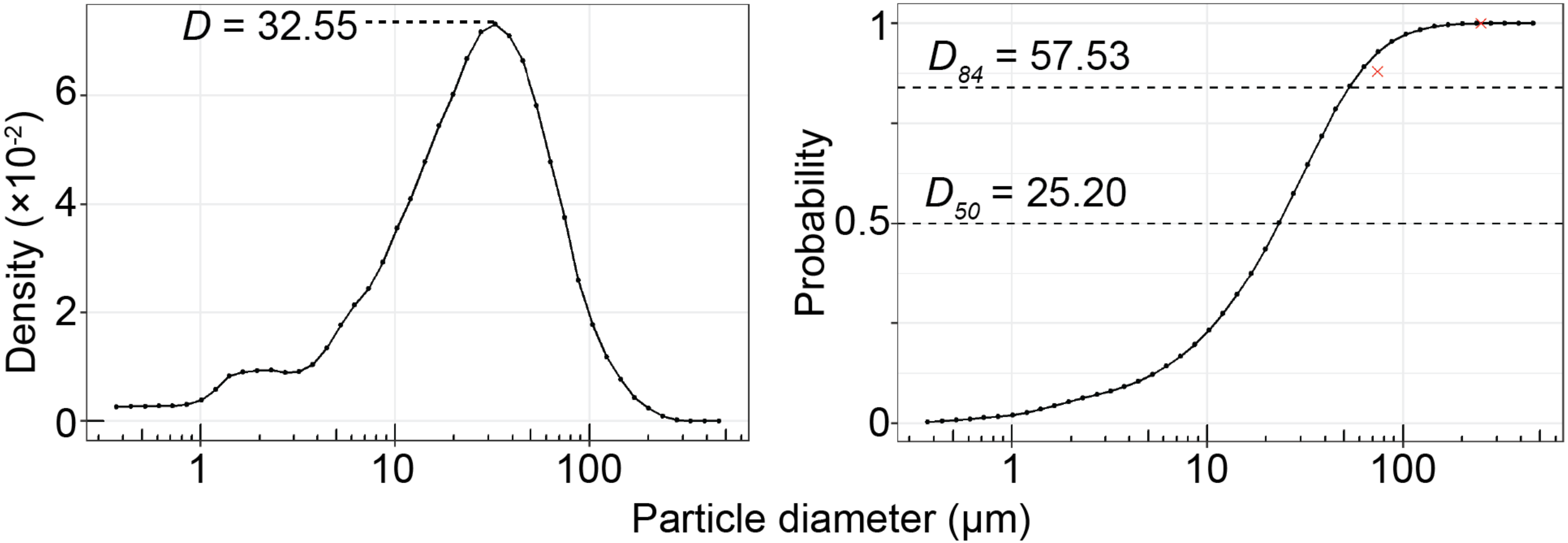
Dowels

- Coat with silicone grease as biofilm analogue
- Install in test section in a roughly uniform pattern
- Approximate dowel density in the test section of 1450 dowels/m^2 in dowel treatment



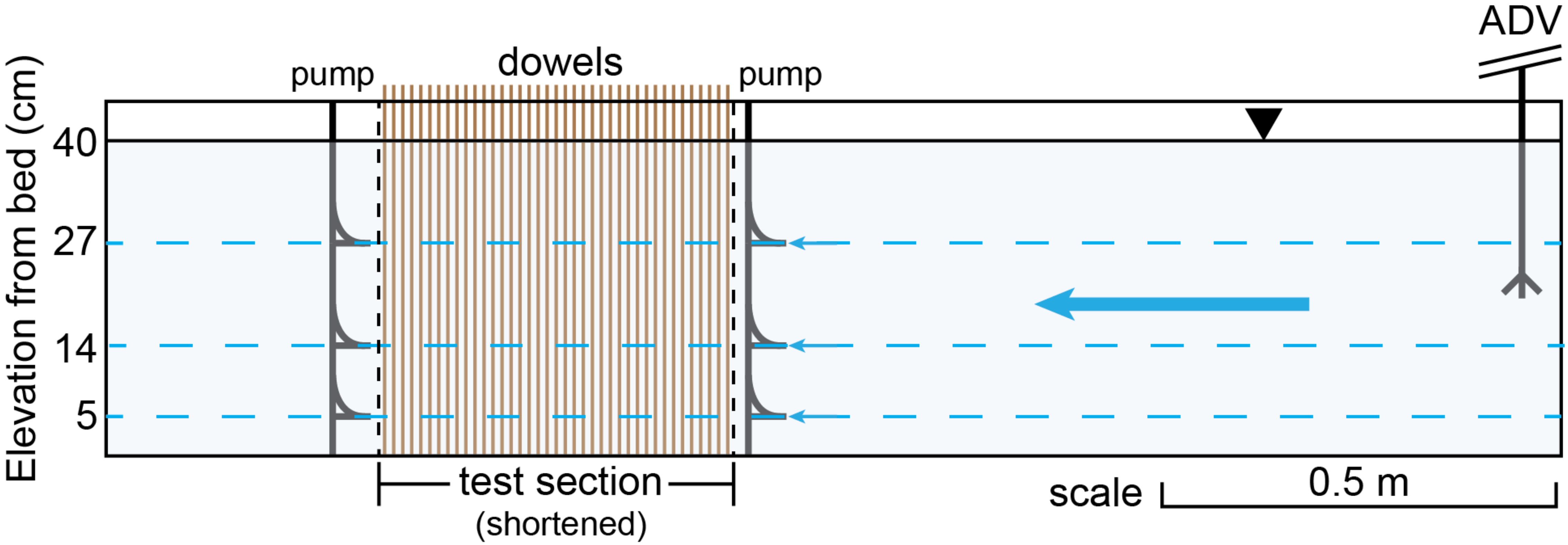
Sediment

- Crushed walnut shell (~silt)
- 200 g added at start of each experiment



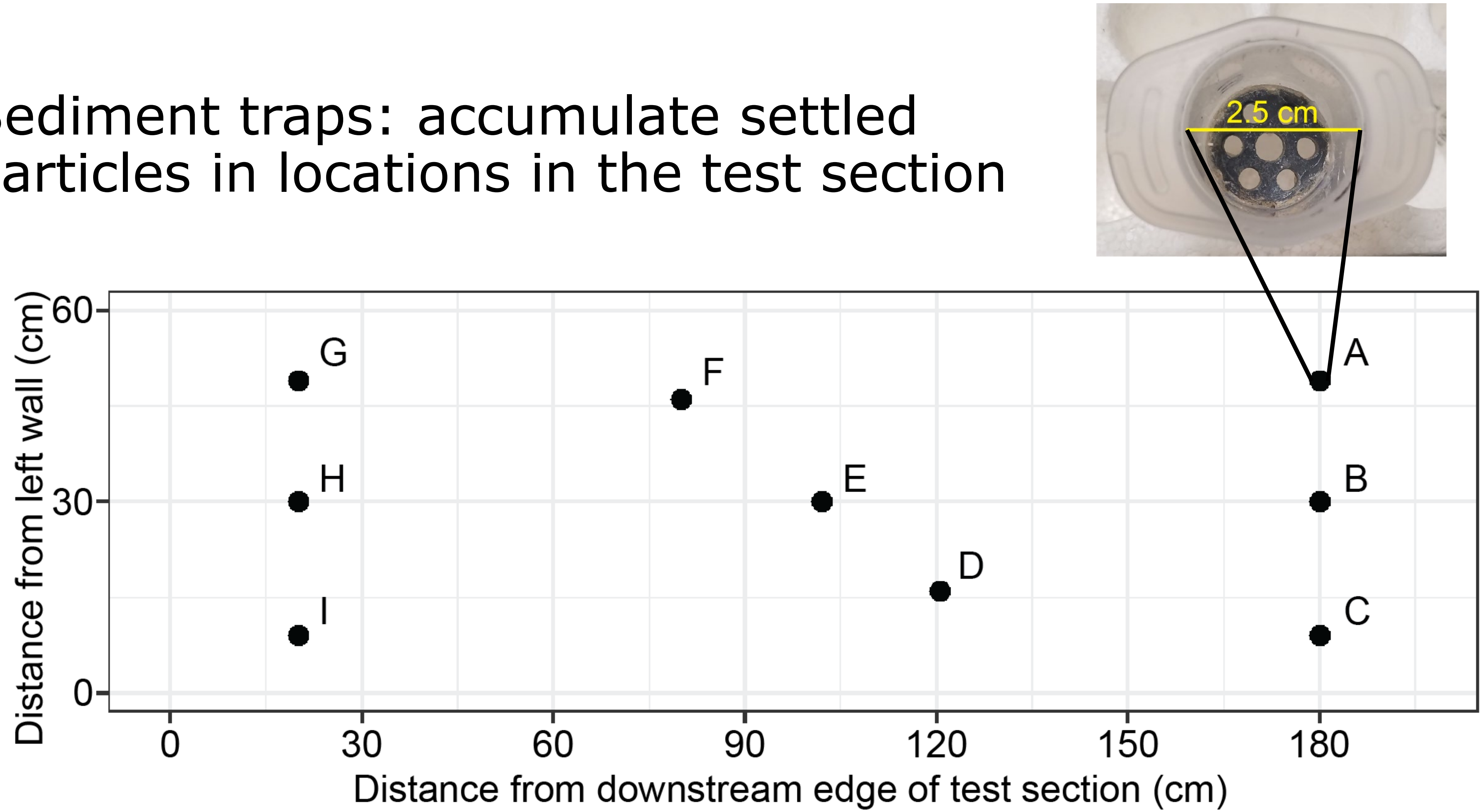
Instruments

- Peristaltic pumps: sample water at 5-min intervals
- ADV: measure flow velocity during experiments



Instruments

- Sediment traps: accumulate settled particles in locations in the test section



Filtering Protocol

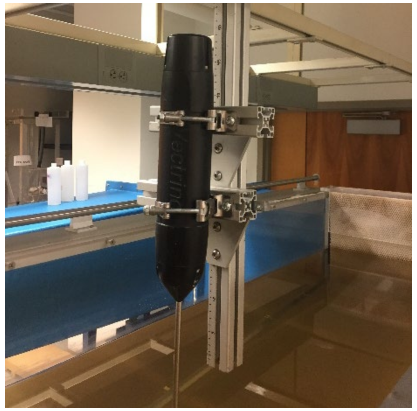
- Samples from peristaltic pumps were filtered through glass microfiber filters, dried, and weighed
- Sediment mass/sample volume = mass concentration

Experiment Protocol Summary

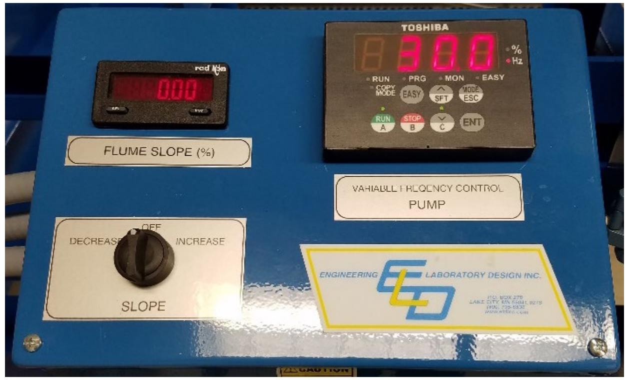
1. Install dowels (if necessary)

2. Fill flume

3. Set up instruments, sediment traps



4. Input settings, turn on flume

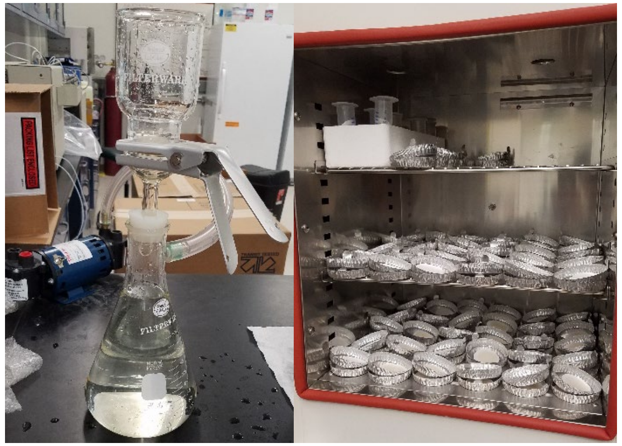


5. Add sediment

6. Collect data

7. Clean flume (sometimes)

8. Filter, dry, and weigh



Results

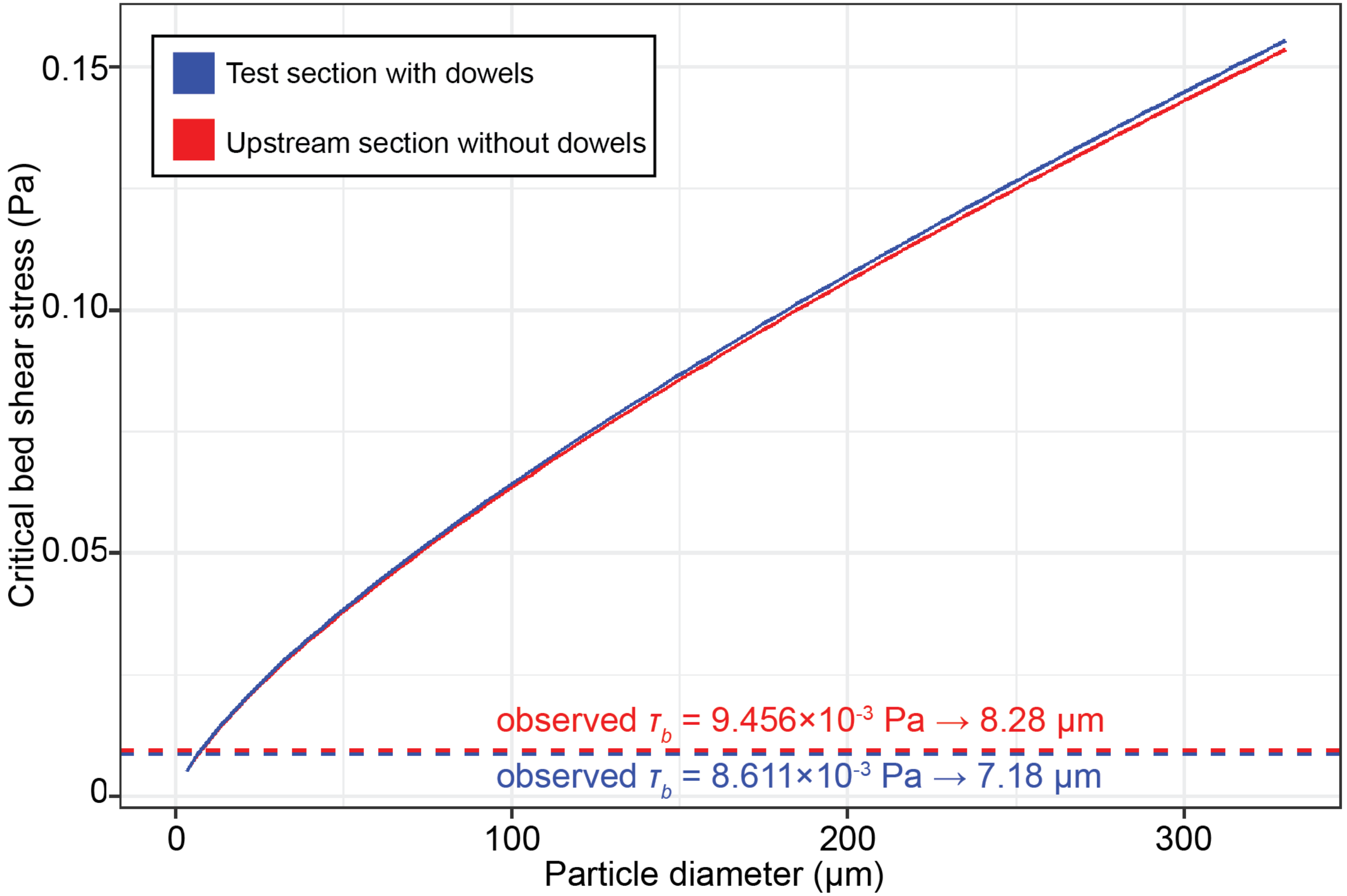
- Flume sediment transport description
  - Shields criterion

- Treatment comparison
  - Particle capture rates
  - Effective capture efficiency

- Predicted vs actual effective capture efficiency

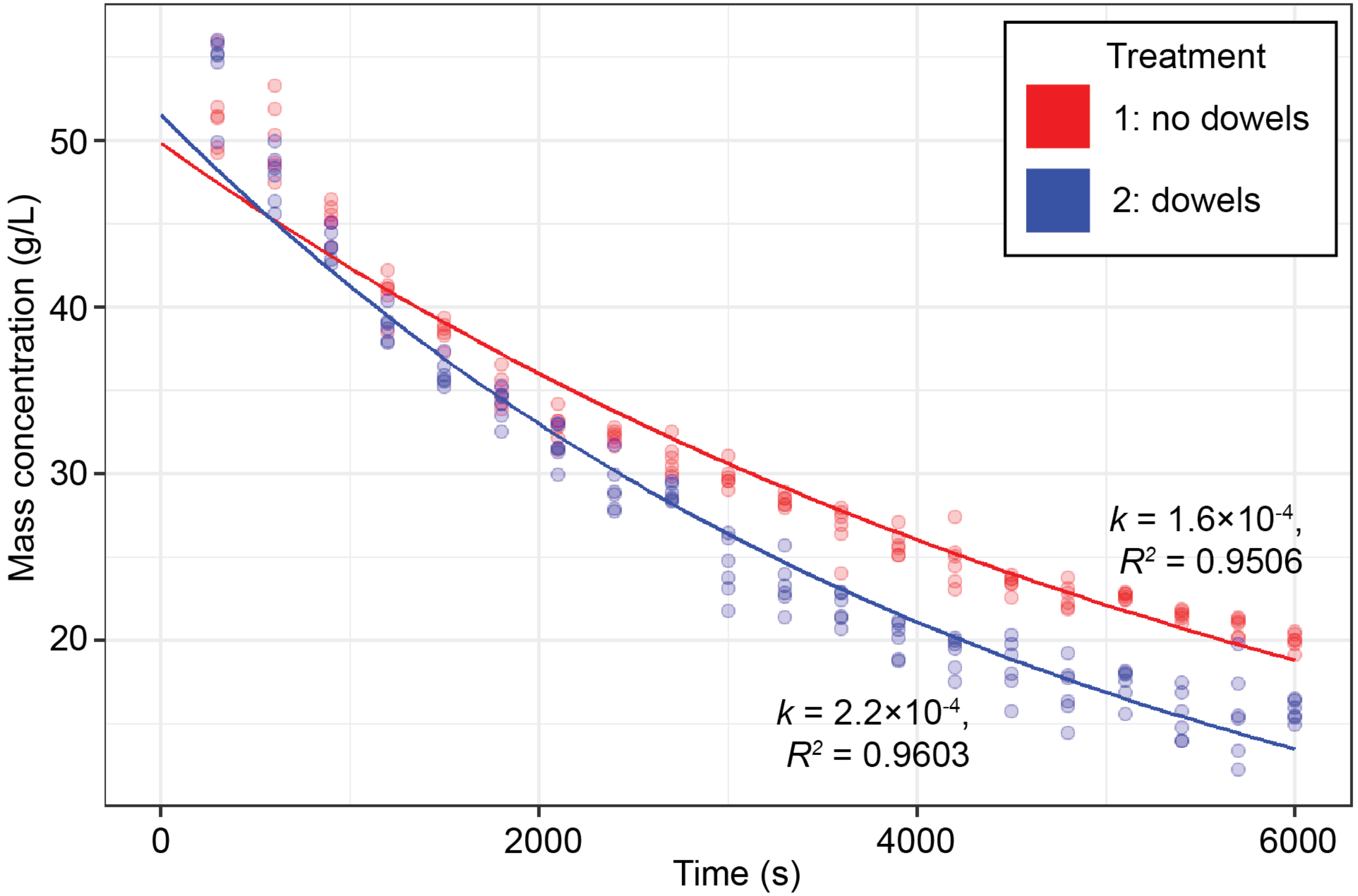
Sediment transport regime

- Shields criterion for initial particle motion
- Conclusion: particles travel in suspension, negligible bed load and resuspension
  - Supports application of background theory



Treatment Comparison

- For each experiment, model fitted to all peristaltic pump data points
  - Insignificant upstream/downstream contrast



Model: $\phi(t) = \phi_0 e^{-kt}$

Treatment Comparison

Treatment	k (x10^{-4} s^{-1})	k_s (x10^{-4} s^{-1})	k_c (x10^{-4} s^{-1})	η' (%)
1. No dowels	1.620 ± 0.0601	1.620 ± 0.0601	NA	NA
2. Dowels	2.229 ± 0.0924	0.4213 ± 0.0092	1.808 ± 0.102	0.0689 ± 0.0039

- Compare: particle capture rates due to settling
- Compare: particle capture rates due to settling versus capture on collectors
  - Order of magnitude differences

Predicted vs actual η'

- Compare predicted effective capture efficiency by two existing power law models to calculated value

Palmer et al. [2004]: $\eta' \sim Re_c^{-1.14} R^{0.65} = 0.142\%$

Fauria et al. [2015]: $\eta' \sim Re_c^{0.718} R^{2.08} = 0.0261\%$

actual η'
0.0689%

where $Re_c = \text{collector Reynolds number}$

$R = \text{ratio of particle and collector diameters}$

What do the results imply?

- Particle capture mechanisms
  - Through comparison of experiments

- Predictive models
  - Potential for improved accuracy in effective capture efficiency prediction?

Particle capture mechanisms

- Two primary mechanisms:
  - Gravitational settling
  - Direct interception
- Interaction of mechanisms with the presence of dowels due to flow instabilities

Treatment	k_s **(x10^{-4} s^{-1})**	k_c **(x10^{-4} s^{-1})**
1. No dowels	1.620 ± 0.0601	NA
2. Dowels	0.4213 ± 0.0092	1.808 ± 0.102

Predictive models

- Comparable Re_c and R for experiments in this study, Palmer et al. [2004], and Fauria et al. [2015]
- Different experimental conditions
  - Palmer: single cylindrical collector with smooth & rough greased surface
  - Fauria: array of emergent collectors with biofilm coating

Model	**η' (%)**
Palmer et al. [2004]	0.142
Fauria et al. [2015]	0.0261
Dowel treatment	0.0689

Predictive models

- Alternative model

$$\eta'(Re_c, R, \text{stem density}, \text{stem surface})$$

- Add information on vegetation characteristics to kinematic and geometric parameters (Re_c & R)
  - Interference between many collectors with wake generation
  - Particles interact directly with stem surface

Conclusion

- In the two experiments, dowel collectors augment overall particle capture rate
  - Interactions of dowels and particle settling
- Possible additions to predictive models for effective capture efficiency (stem density and surface)
  - Better fit of experiment data to model with similar collector characteristics

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