Predictions of bedload transport in vegetated channels: uncertainties and steps forward

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- https://earthengine.google.org/#timelapse/v=-9.69993,-74.13468,9.148,latLng&t=2.73

Vegetation can affect floodplain deposition rates

Vegetation is used to increase bank stability and aquatic habitat for river restoration

Invasive vegetation can degrade natural channel conditions, particularly downstream of dams

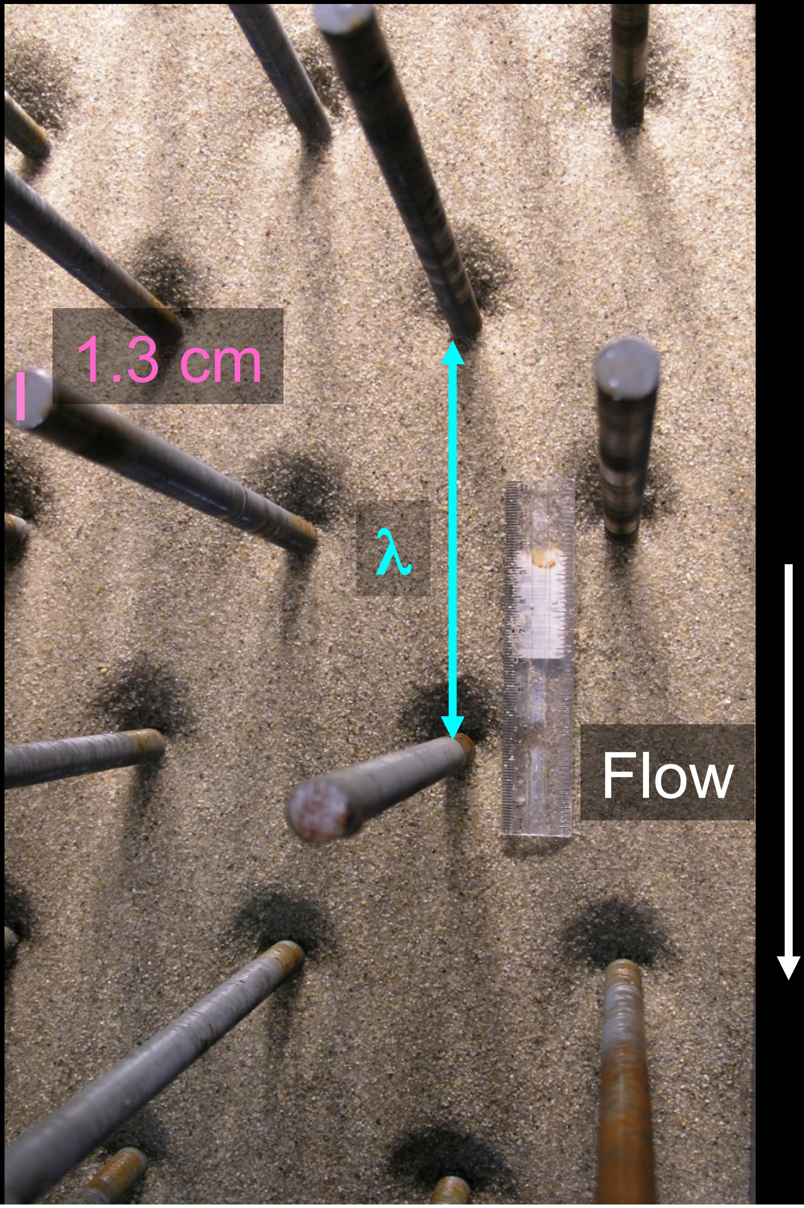
The influence of vegetation on sediment transport is not well understood

Questions

How does vegetation affect flow and sediment transport?

How can we accurately predict bedload transport through vegetation?

Experiments to determine the effects of vegetation on flow and sediment transport



-hold mean flow velocity constant
-0.5 mm sand transported through regular cylinders
-scaled to field conditions in natural rivers

Vary the vegetation density between experiments

Flow

0%

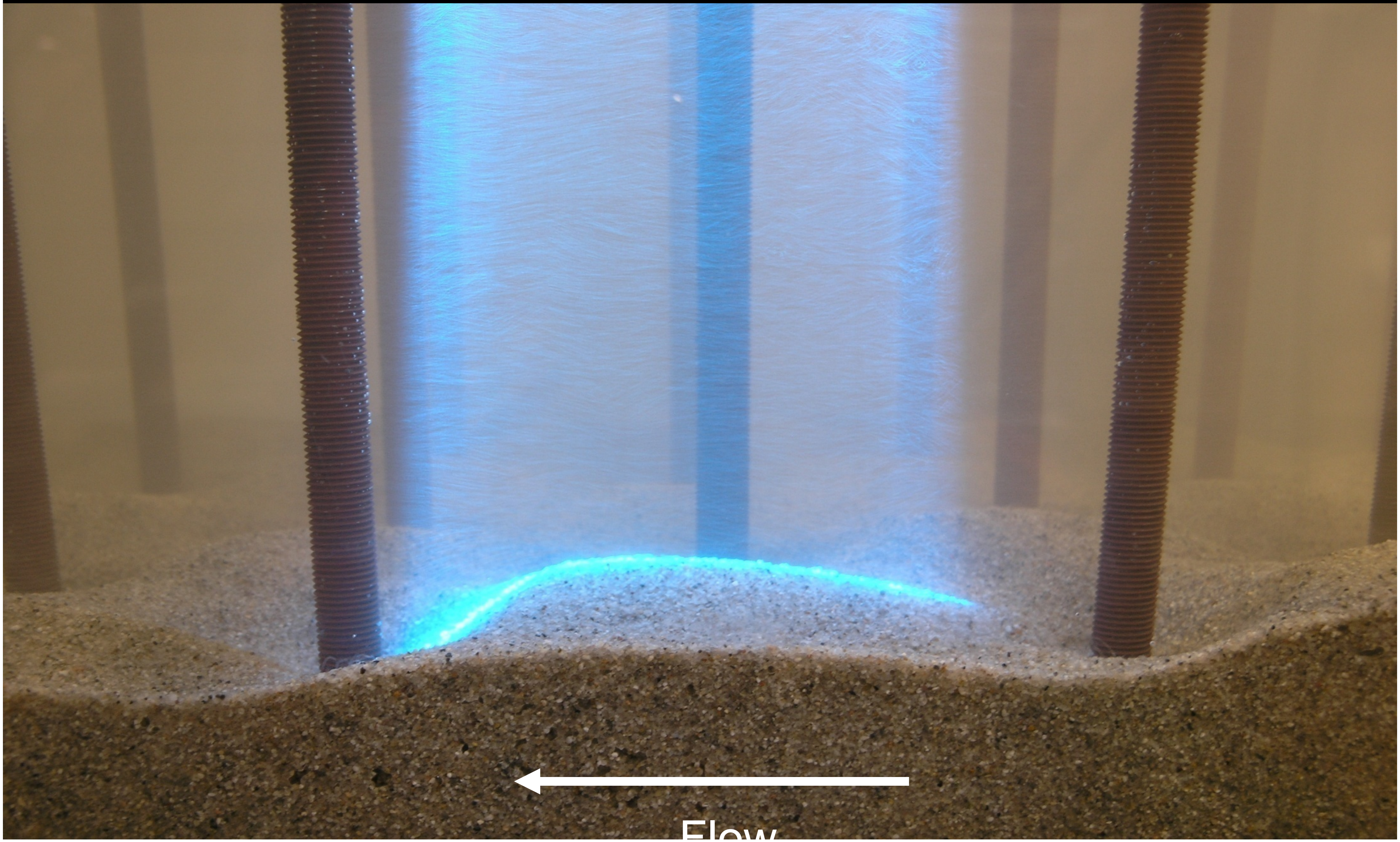
0.8%

1.7%

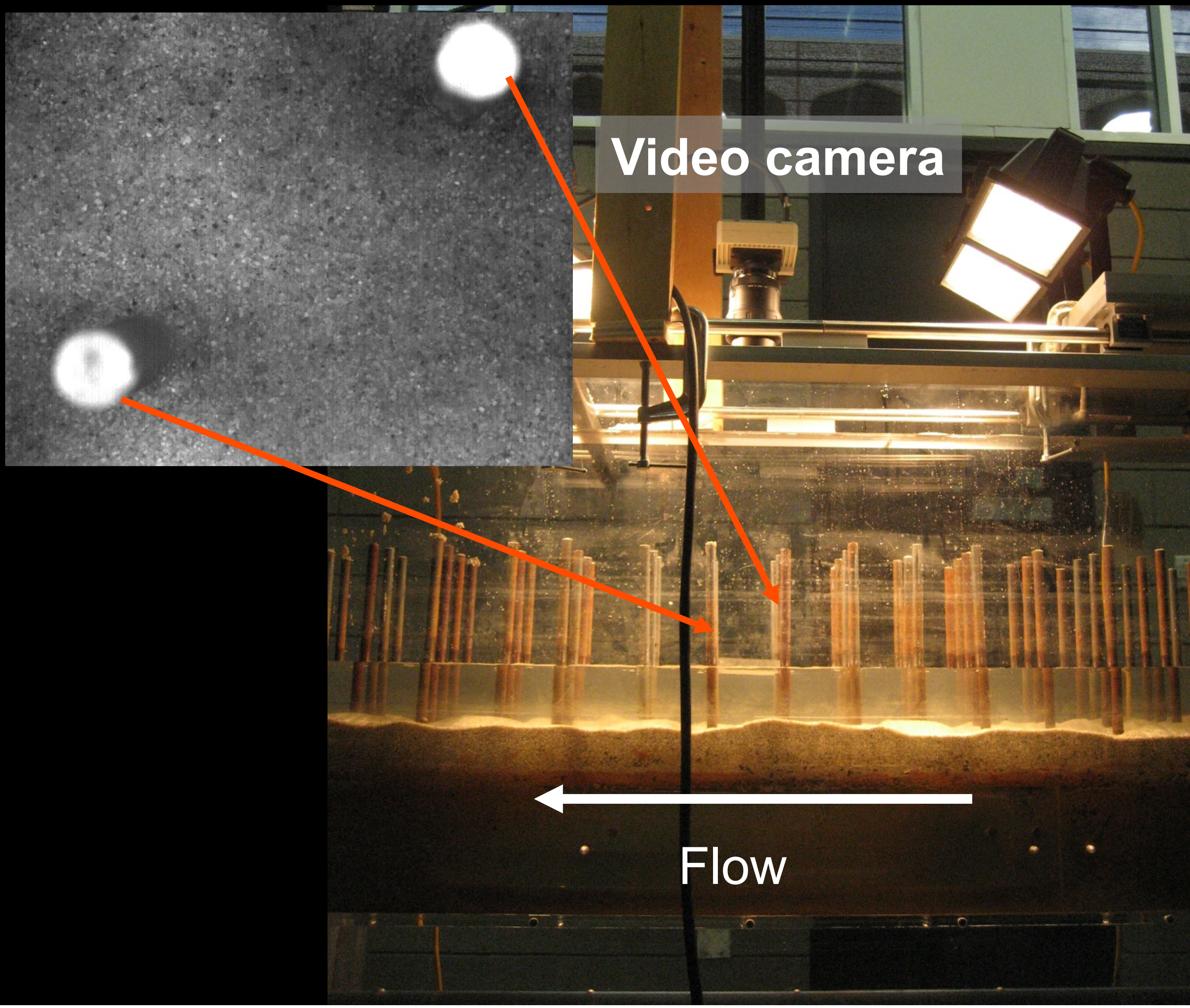
4.0%

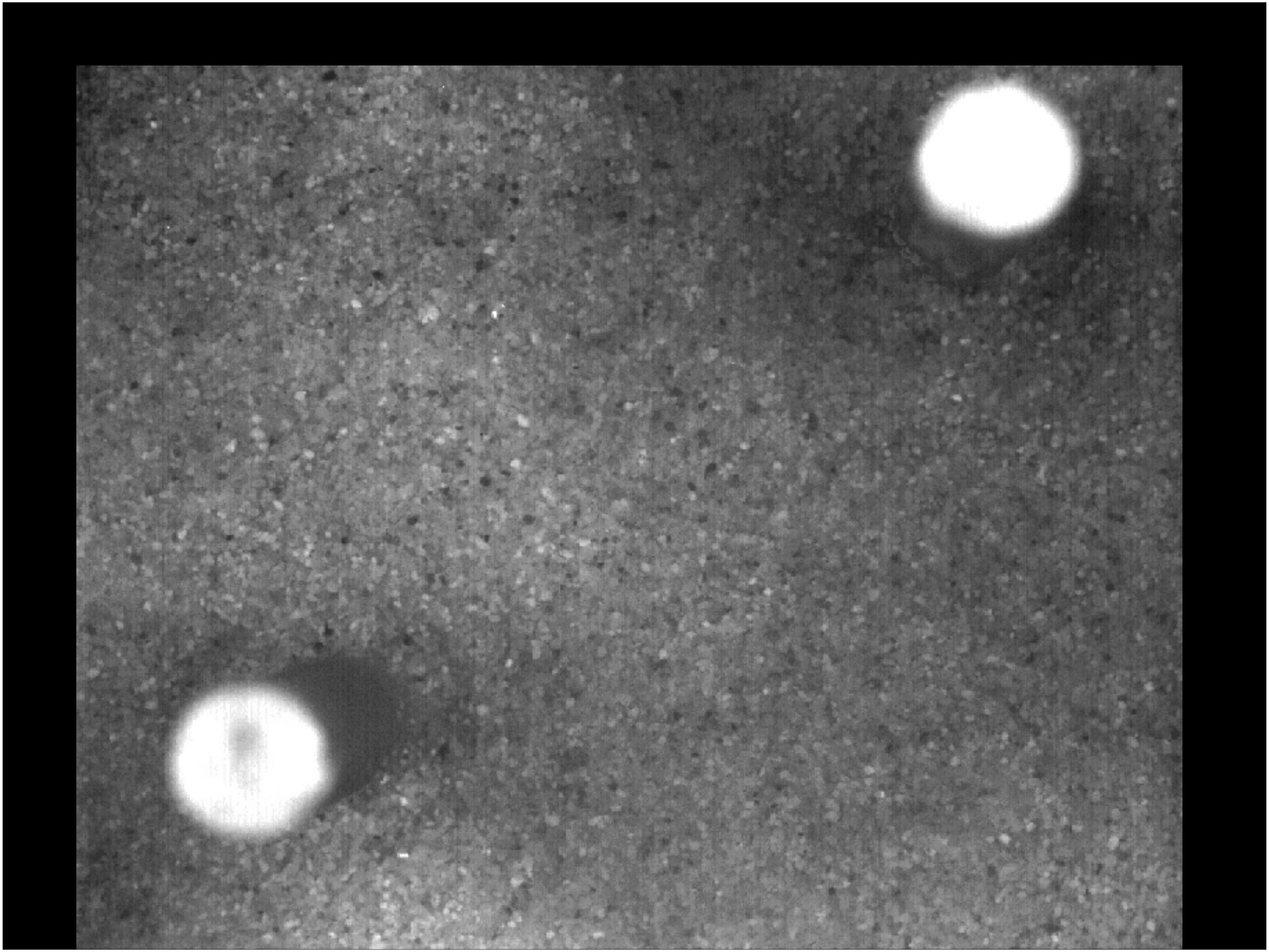
Vegetation density by area

Particle imaging velocimetry records spatial and temporal variations in downstream and vertical velocities



High-speed video records spatial and temporal variations in the sediment transport rate

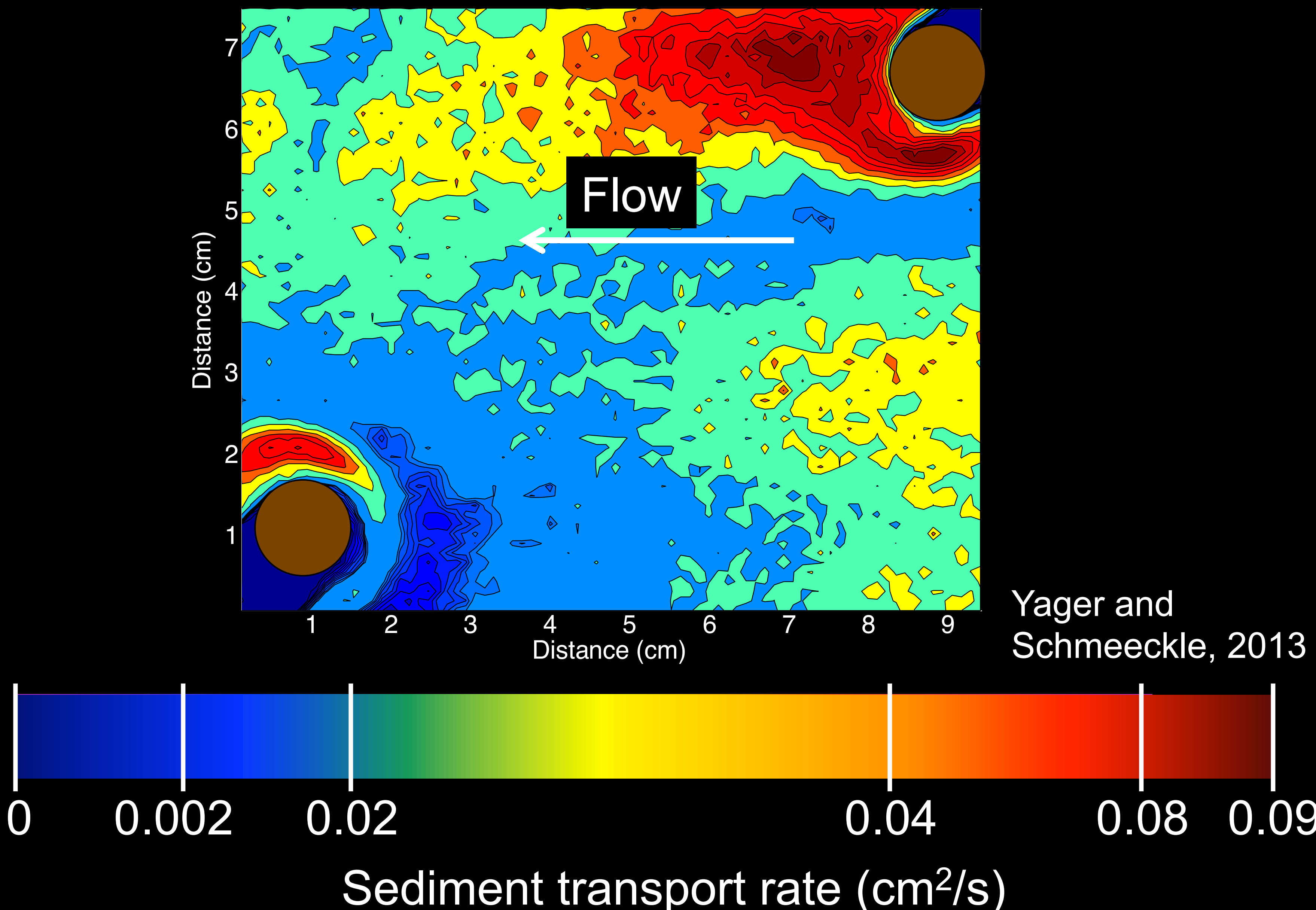


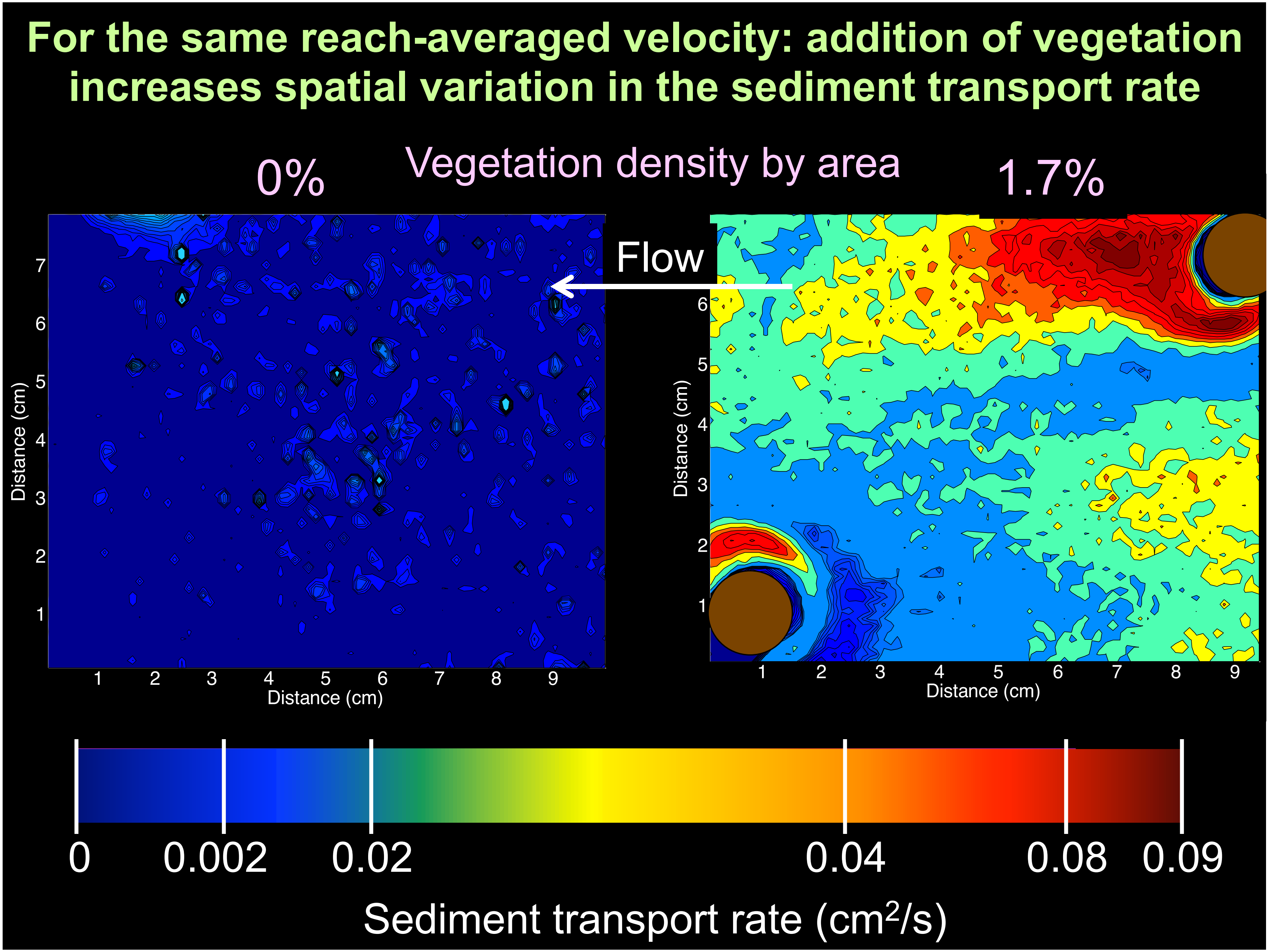


Difference between images to obtain relative transpor rates

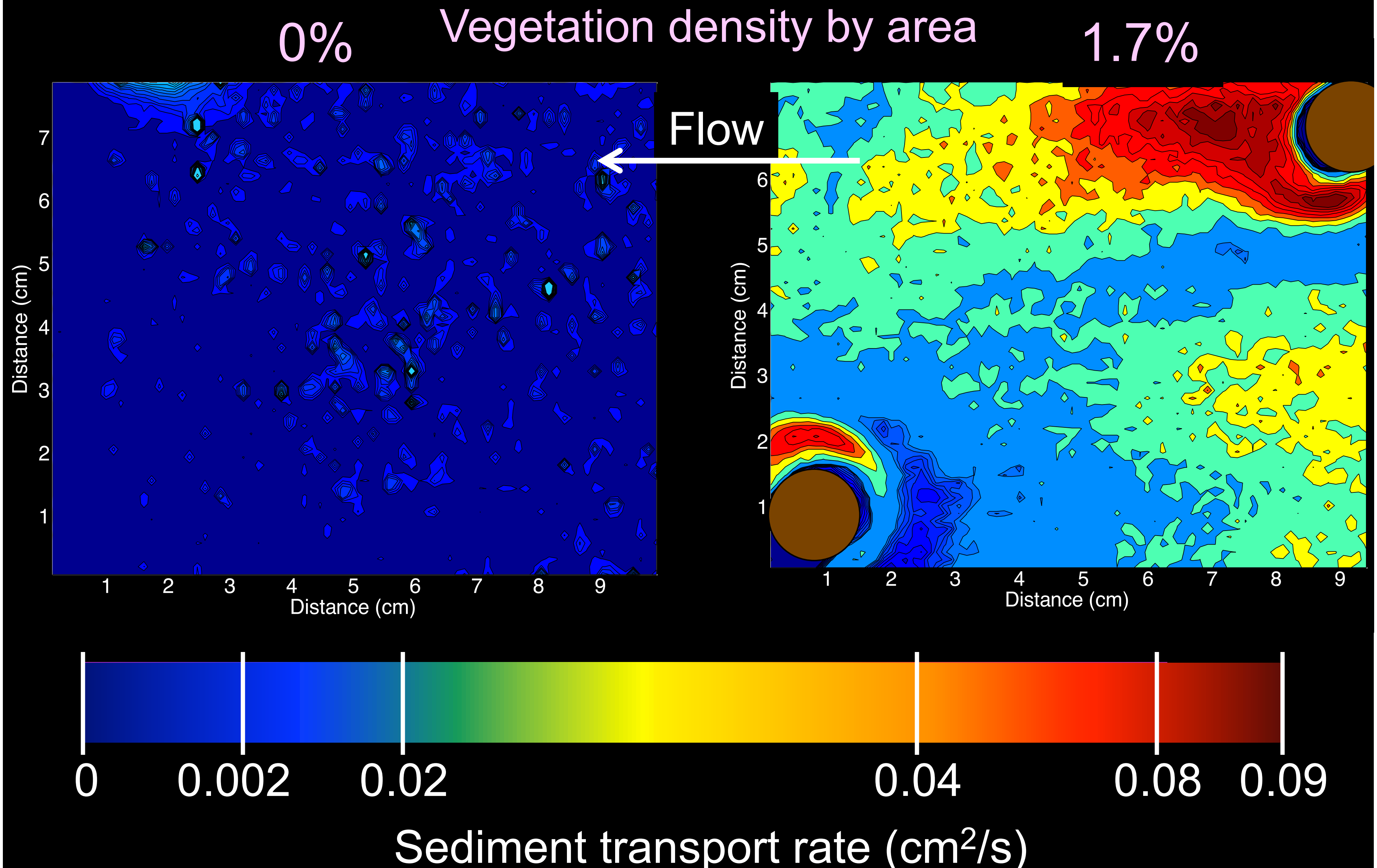
Calibrate each transport rate to individual counts of mobilized grains in videos

Obtain detailed map of sediment transport rates around vegetation

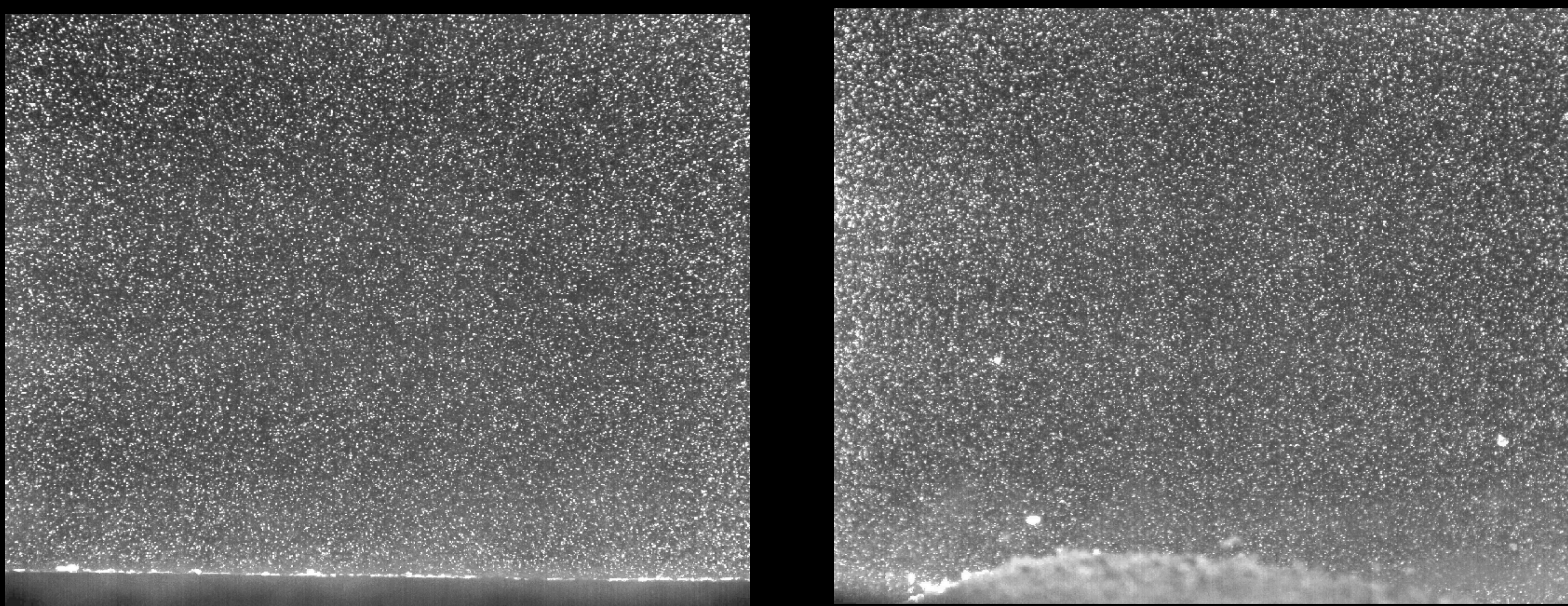



For the same reach-averaged velocity: addition of vegetation increases spatial variation in the sediment transport rate
Vegetation density by area
0%
1.7%
Flow
Distance (cm)
Distance (cm)
Distance (cm)
Distance (cm)
1 2 3 4 5 6 7
1 2 3 4 5 6 7 8 9
1 2 3 4 5 6
1 2 3 4 5 6 7 8 9
0
0.002
0.02
0.04
0.08
0.09
Sediment transport rate (cm^2/s)

For the same reach-averaged velocity: addition of vegetation generally increases mean sediment transport rates



Addition of vegetation increases turbulence

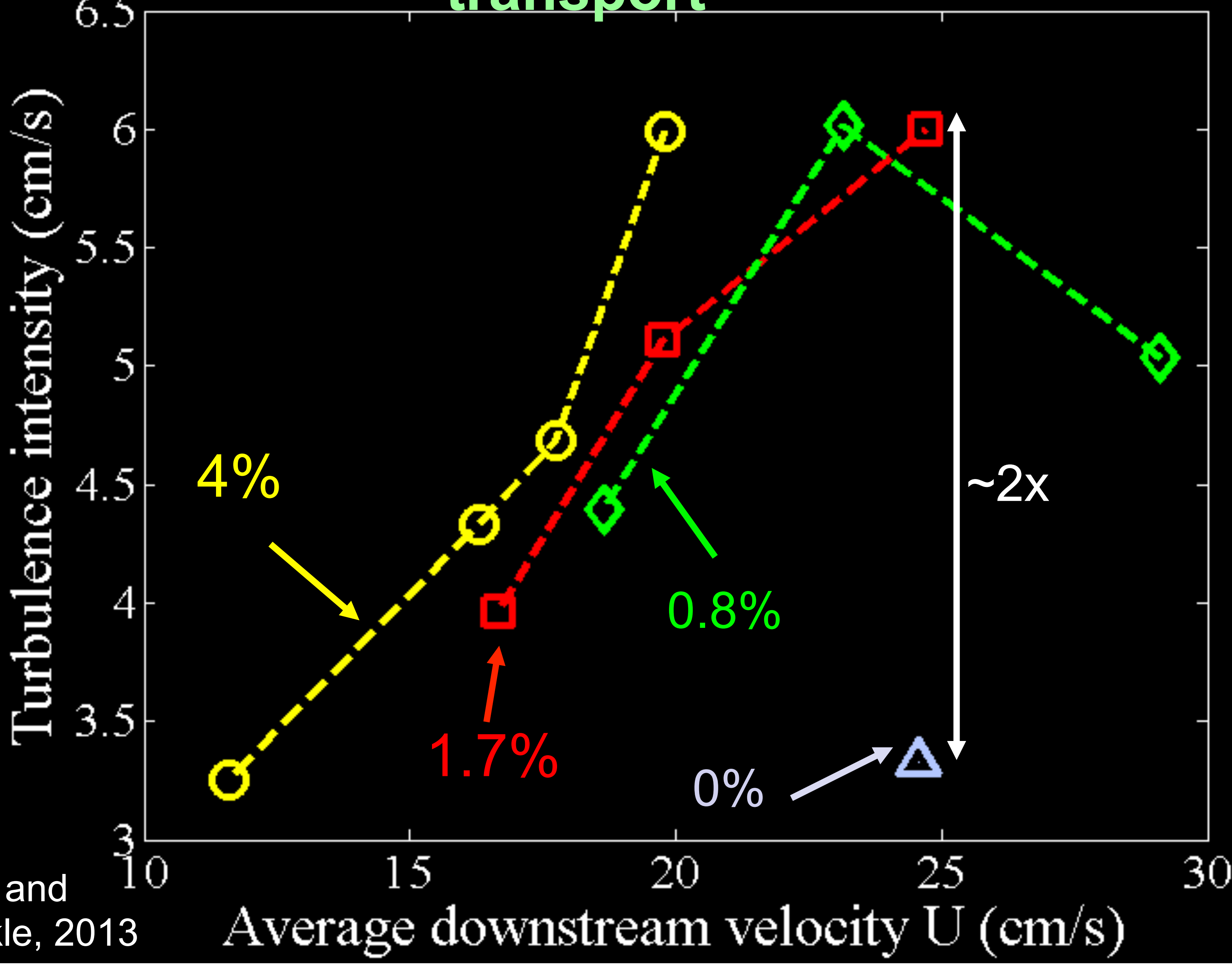


Without vegetation

With vegetation

Flow

Addition of vegetation increases near-bed turbulence intensities, which can increase sediment transport



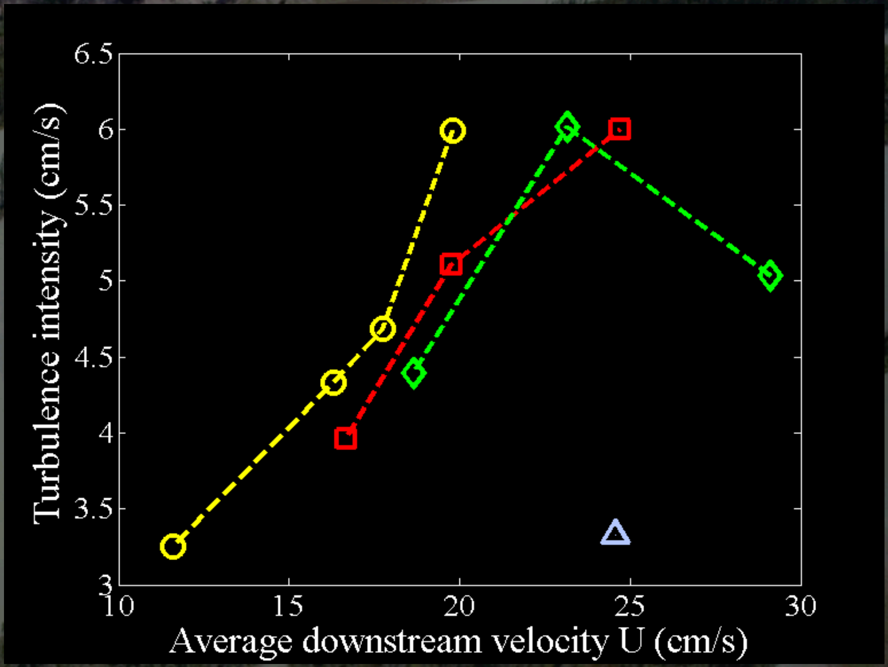
Yager and Schmeeckle, 2013

Conclusions of indoor experiments

- For a constant velocity, addition of rigid emergent vegetation increases:

  turbulence intensities
  sediment transport rates

- Predicting sediment flux through vegetation patches will require some measure of turbulence

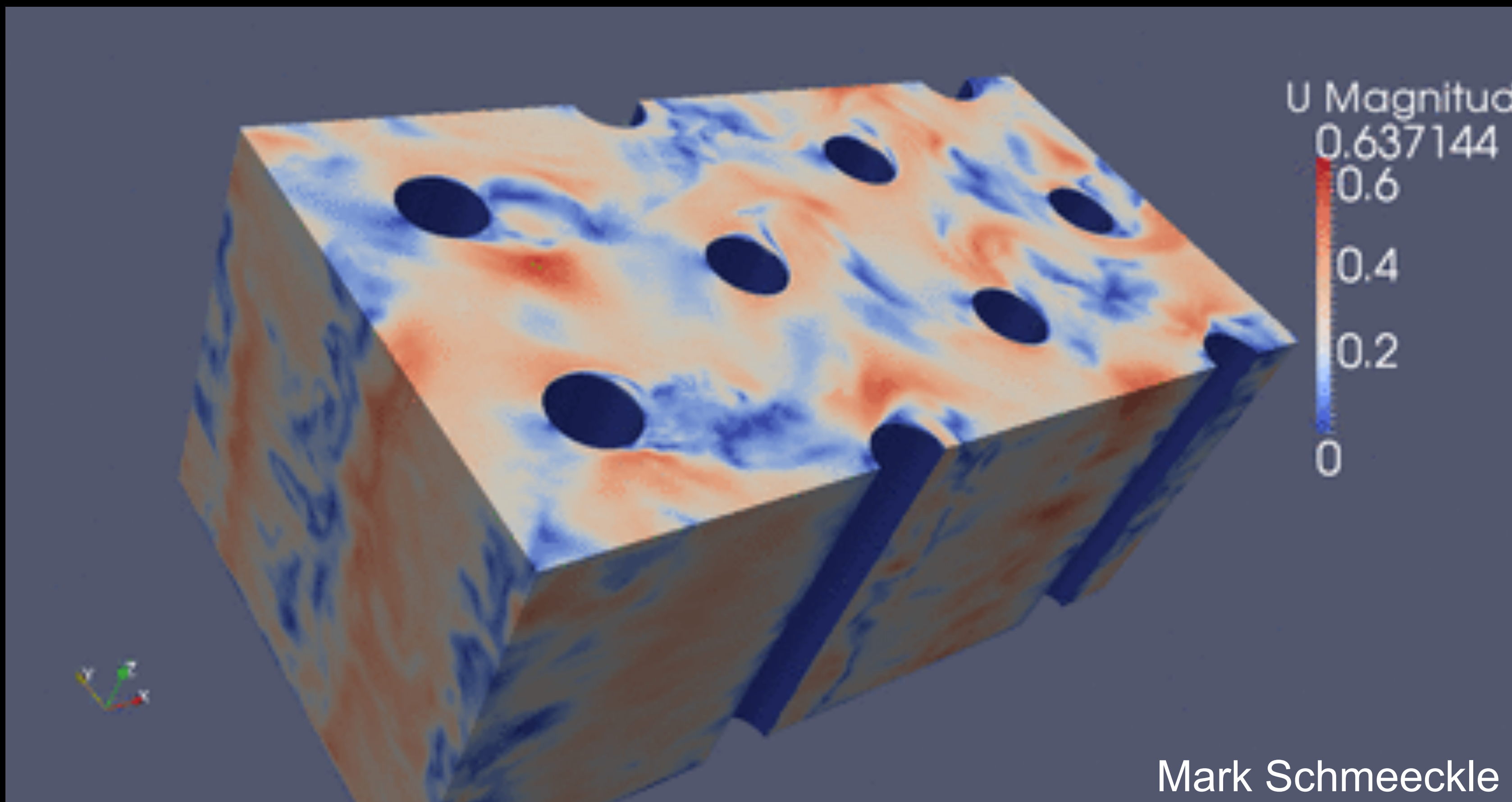


Questions

How does vegetation affect flow and sediment transport?

How can we accurately predict bedload transport through vegetation?

LES coupled with DEM would provide accurate predictions, but is computationally expensive and not currently practical for very large reaches or long-term landscape evolution



Use simple sediment transport equation to start

Sediment transport rate

$$q_s^* = 5.7\left(\tau_t^* - \tau_c^*\right)^{1.5}$$

Luque and Van Beek equation (1976)

Total shear stress

Critical shear stress

Total shear stress does not account for effects of increased drag and turbulence

Sediment transport rate

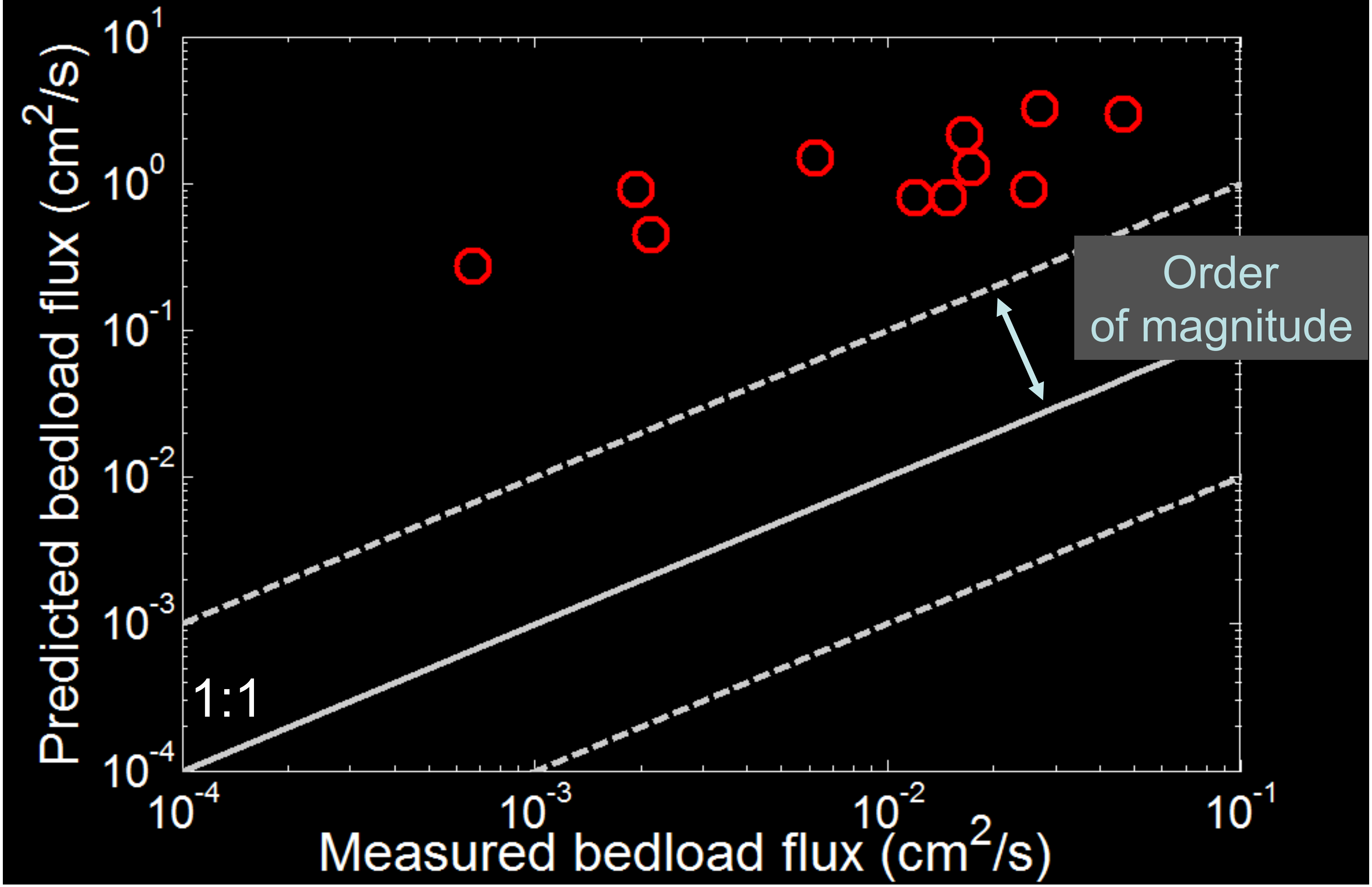
$$q_s^* = 5.7\left(\tau_t^* - \tau_c^*\right)^{1.5}$$

Luque and Van Beek equation (1976)

Total shear stress

Critical shear stress

Use of the total shear stress over-predicts sediment flux, as expected



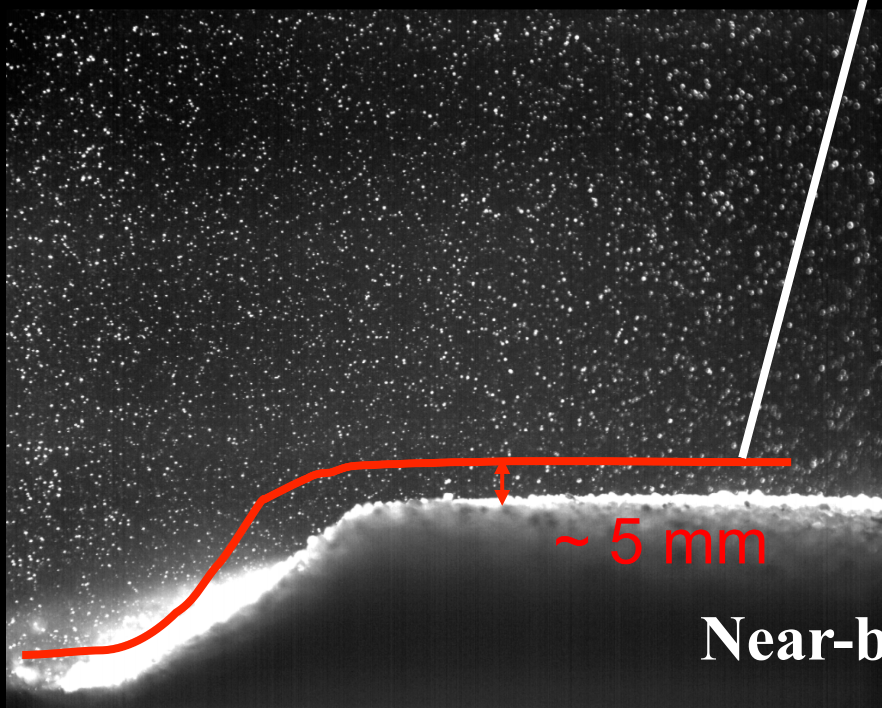
Use average near-bed Reynolds stress to account for vegetation induced drag and ~turbulence

Sediment transport rate

$$q_s^* = 5.7\left(\tau_s^* - \tau_c^*\right)^{1.5}$$

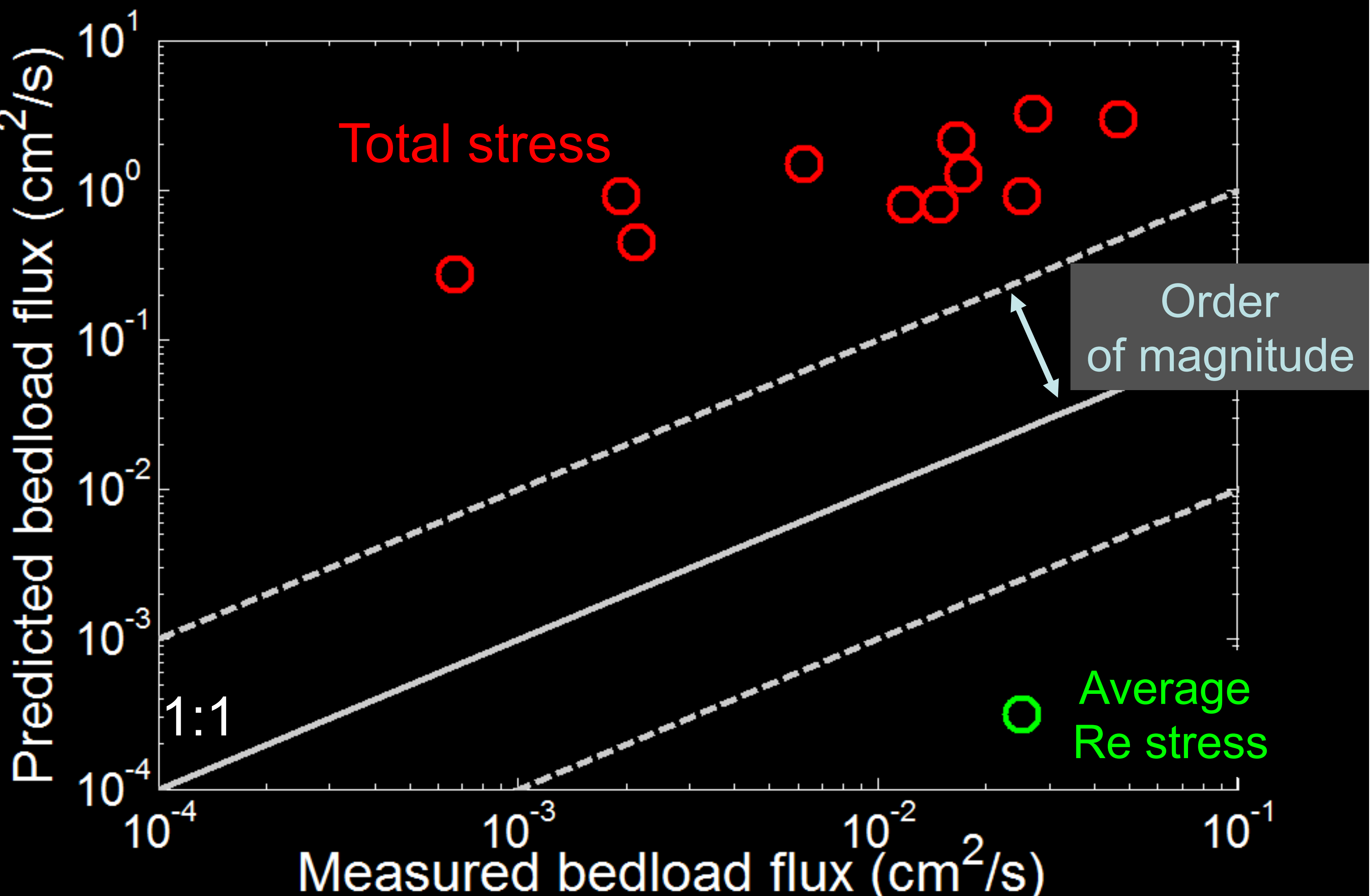
Luque and Van Beek equation (1976)

Critical shear stress

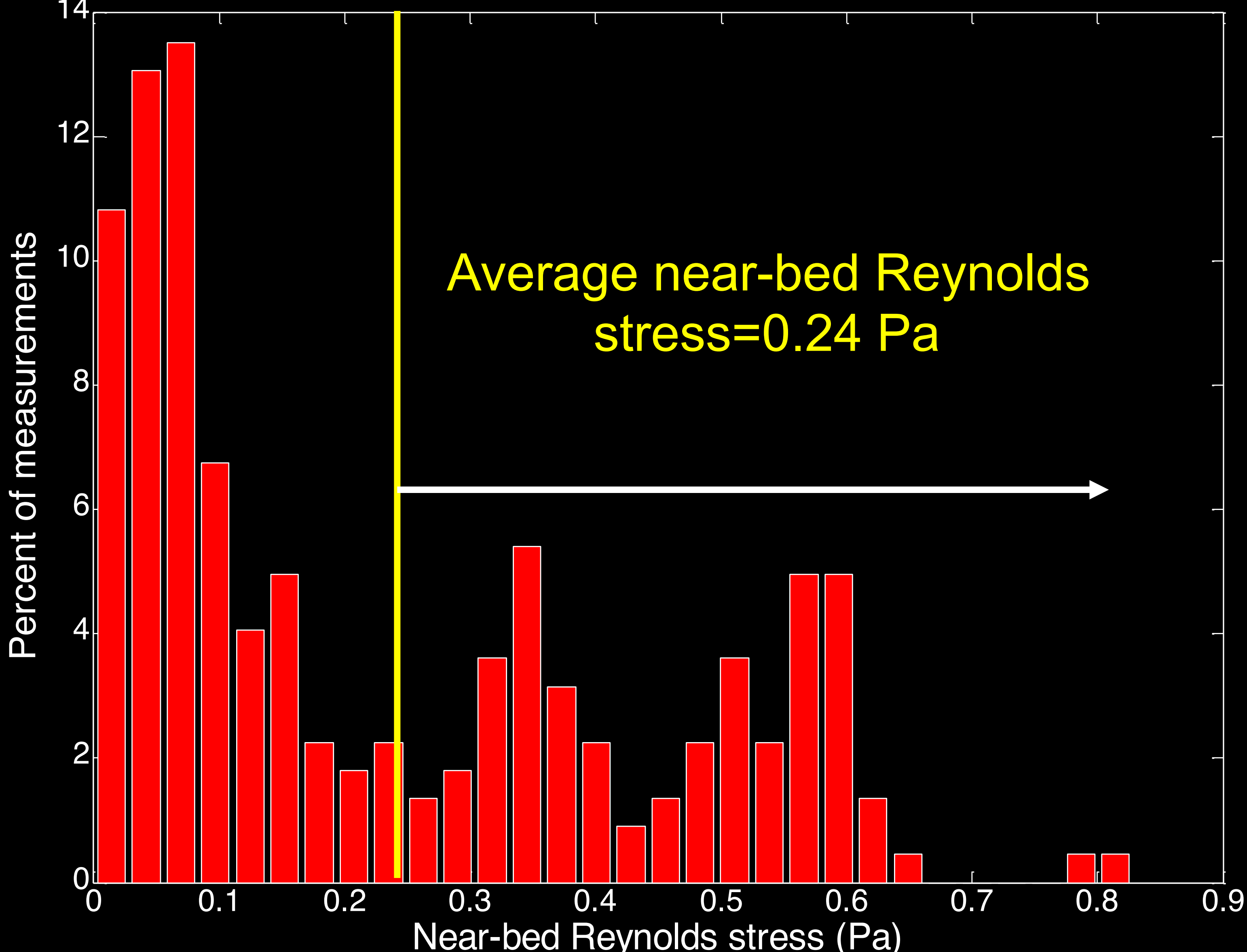


Near-bed Reynolds stress $-\rho\overline{u'w'}$

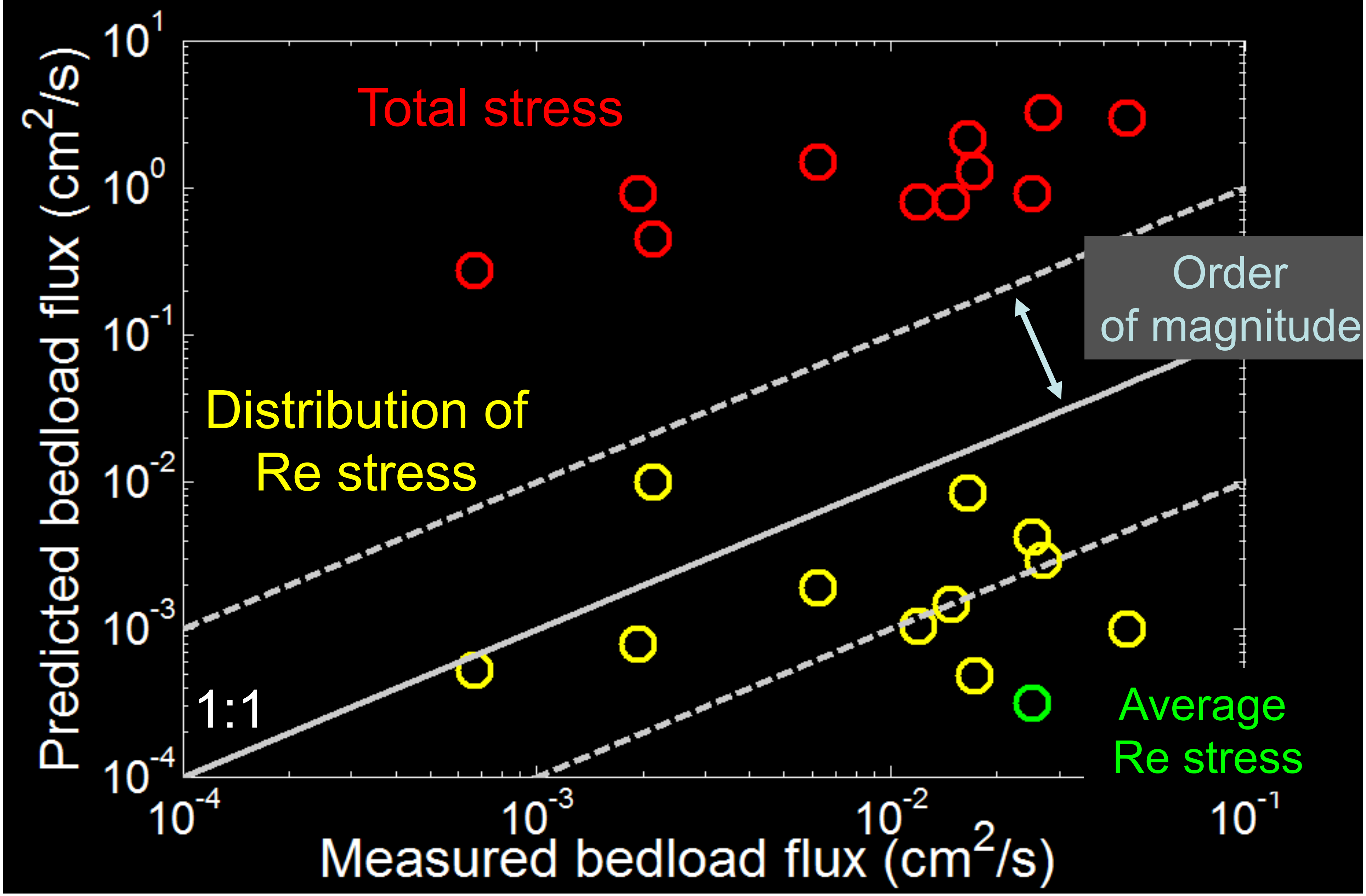
Use of the average Reynolds stress under-predicts sediment flux (11 points with 0 flux)



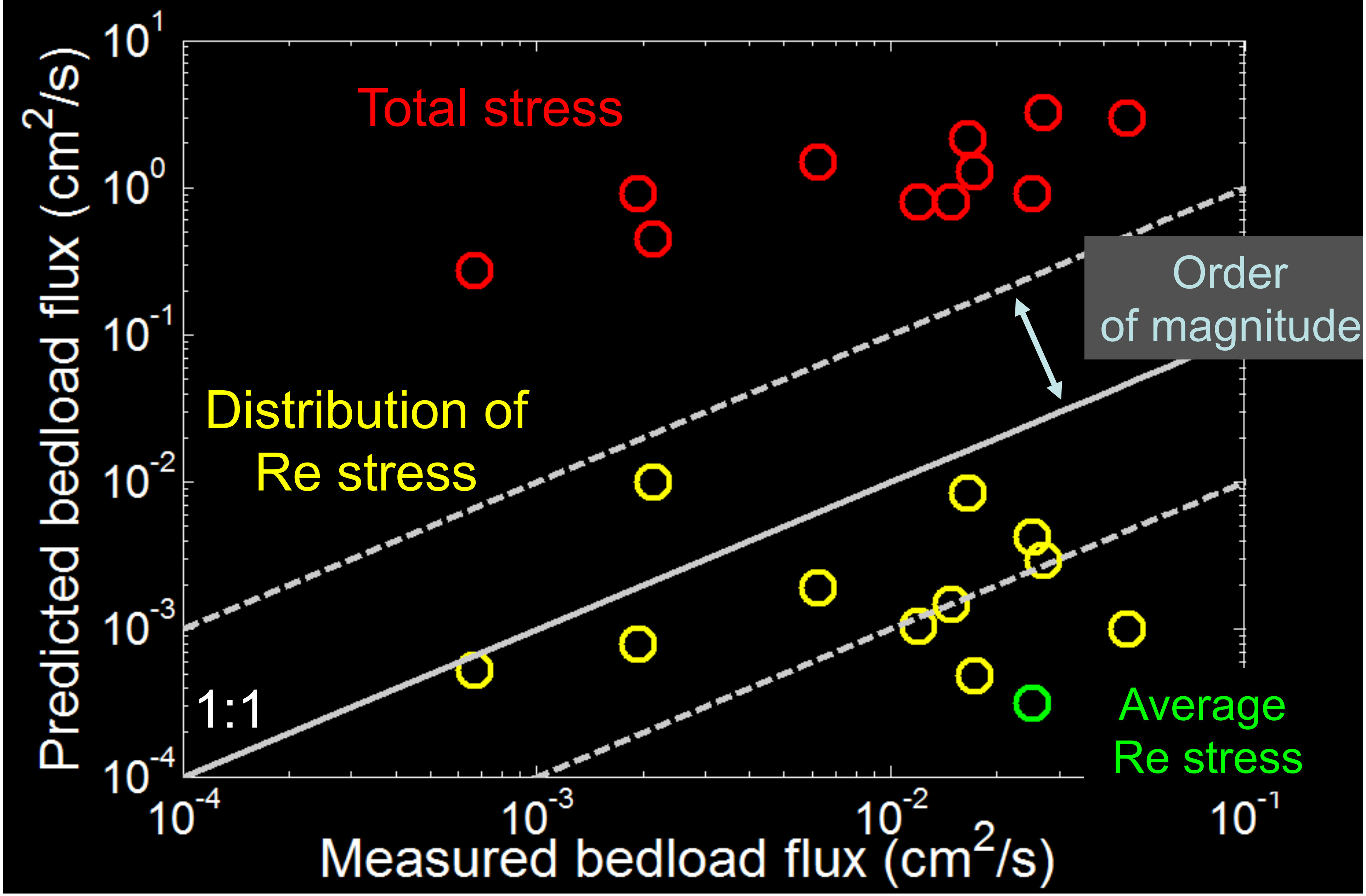
Stresses greater than the mean will cause much greater local sediment transport rates



Use of the distribution of Reynolds stresses improves sediment flux predictions



Only 70% of predictions were within an order of magnitude of measured values

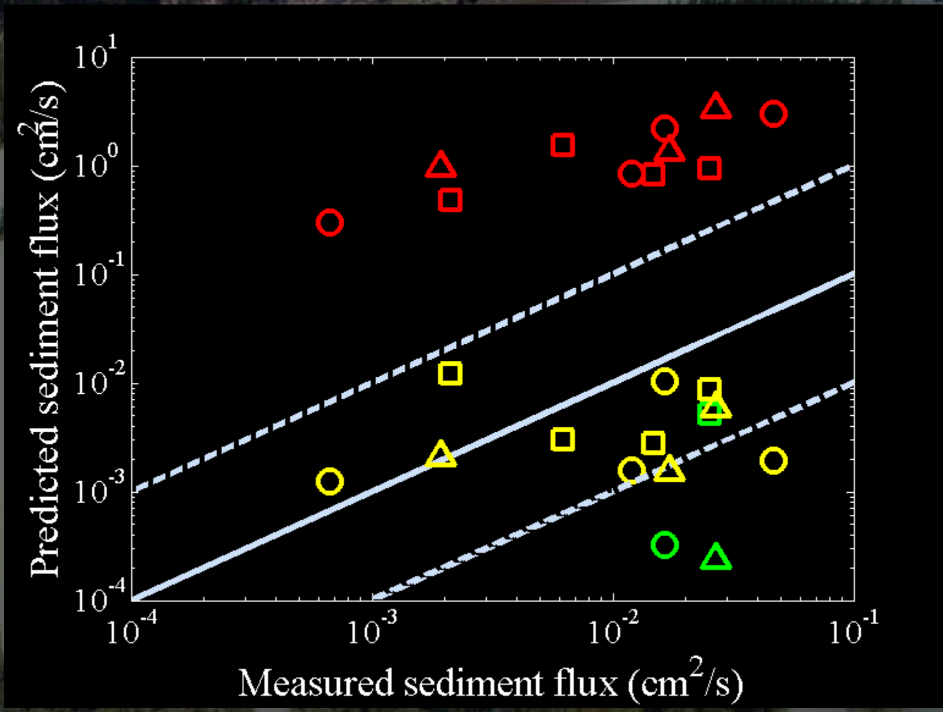


Conclusions for flux predictions

Sediment transport equations need to account for:

- Spatial variation in stress (or velocity) and sediment flux around vegetation

Even with a spatial distribution of shear stress, bedload predictions are still not very accurate



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How can we accurately predict bedload transport through vegetation?

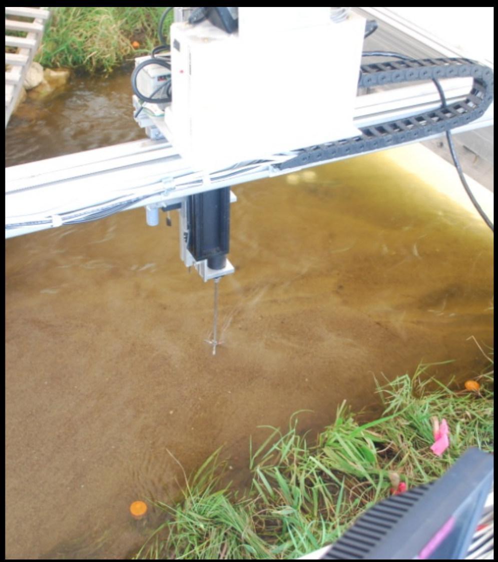
Experiments-Outdoor Stream Lab

Photo: Anne Lightbody

Experiments-Outdoor Stream Lab

Experiments-Outdoor Stream Lab

Vary vegetation frontal area (cm^2)



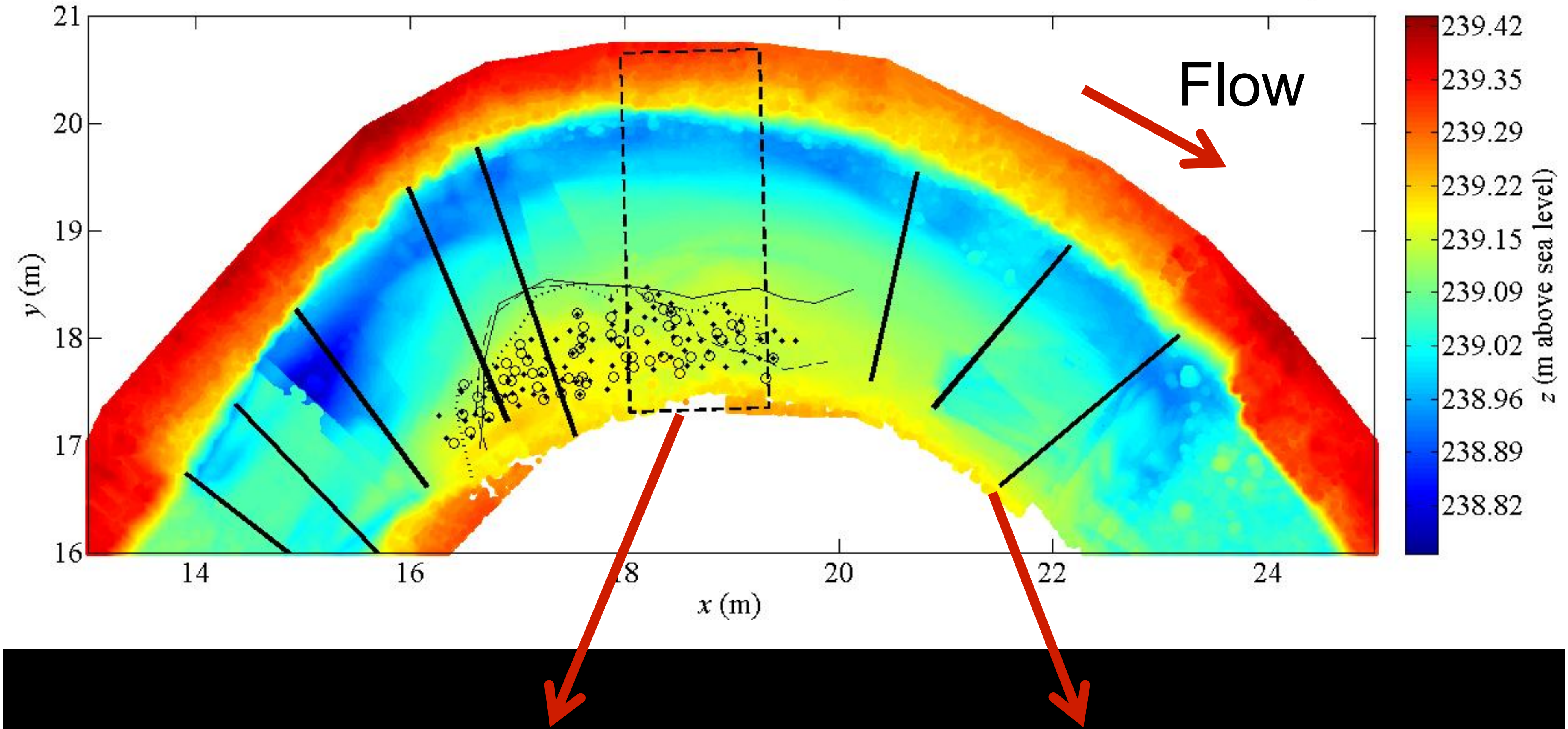
0

6000 ± 600

4500
± 500

Measure-near bed turbulence (3D) and sediment transport rates

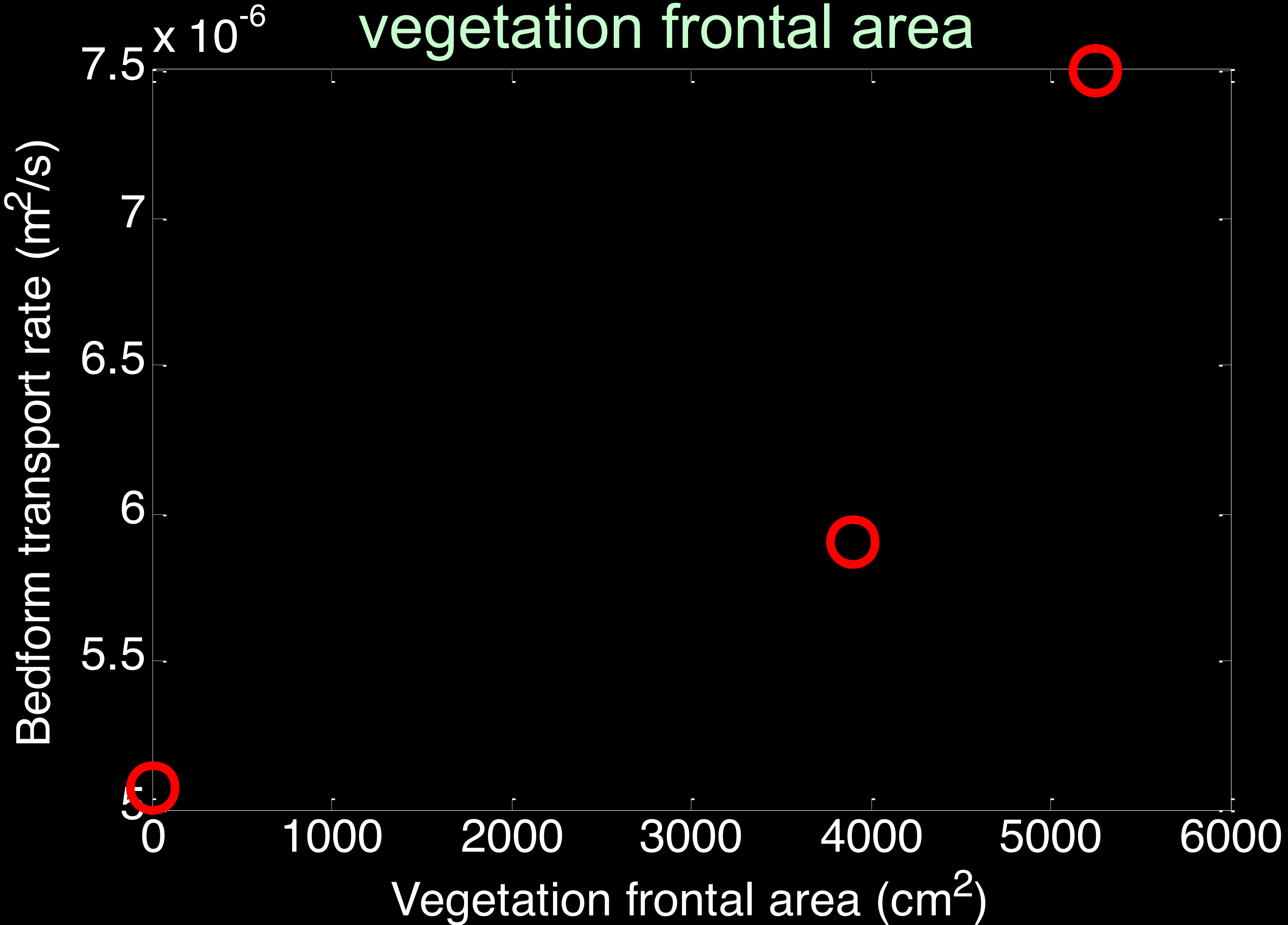
Measure bar topography and dune migration rates



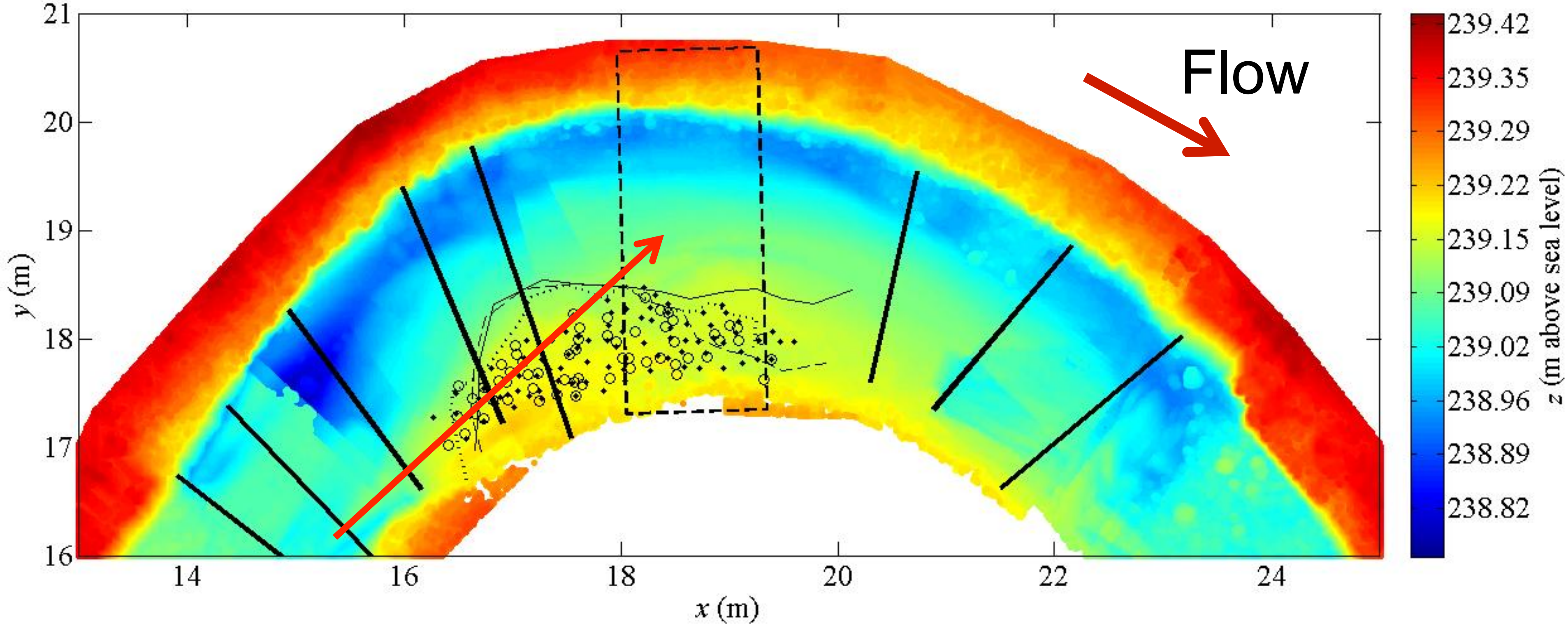
Sonar scans of bar topography

Cross sections

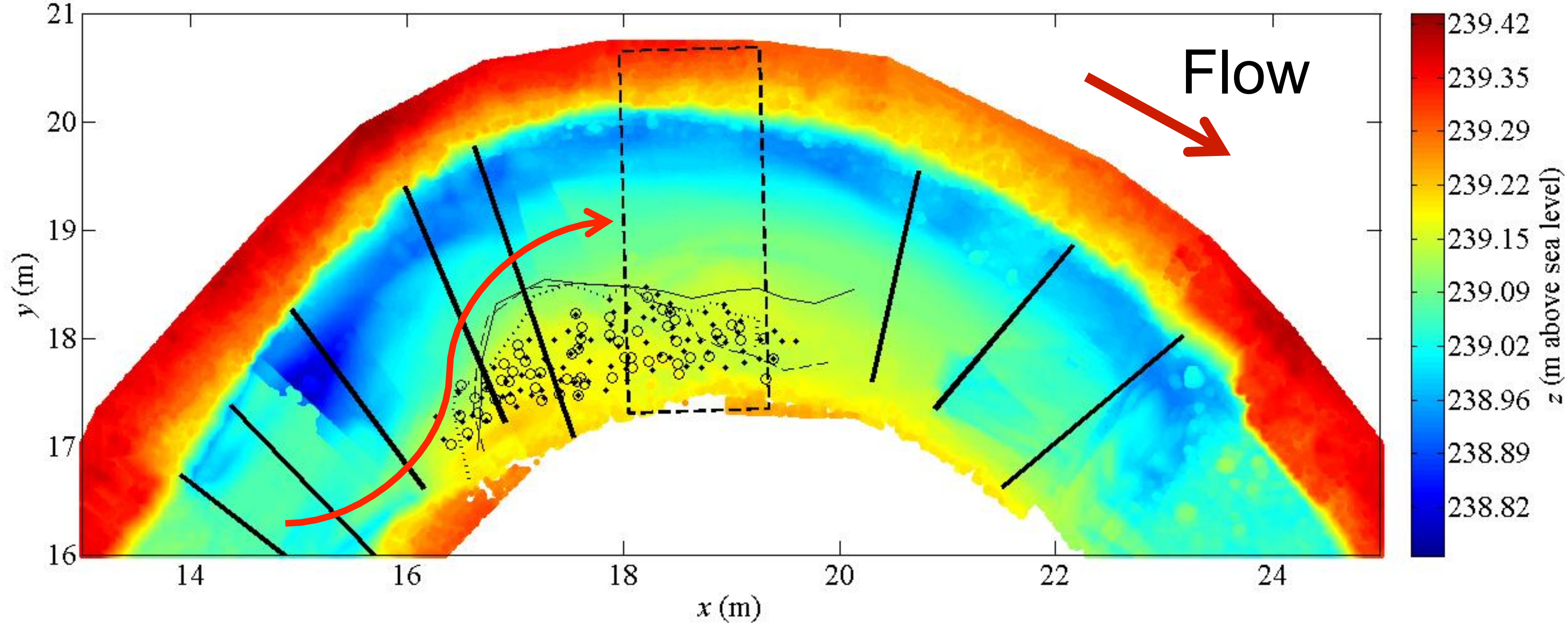
Dune transport rates increased with greater vegetation frontal area



Without vegetation and with distributed vegetation, sand dunes migrate over entire channel width



With dense vegetation, dunes no longer migrate over bar and move faster over a smaller bed area



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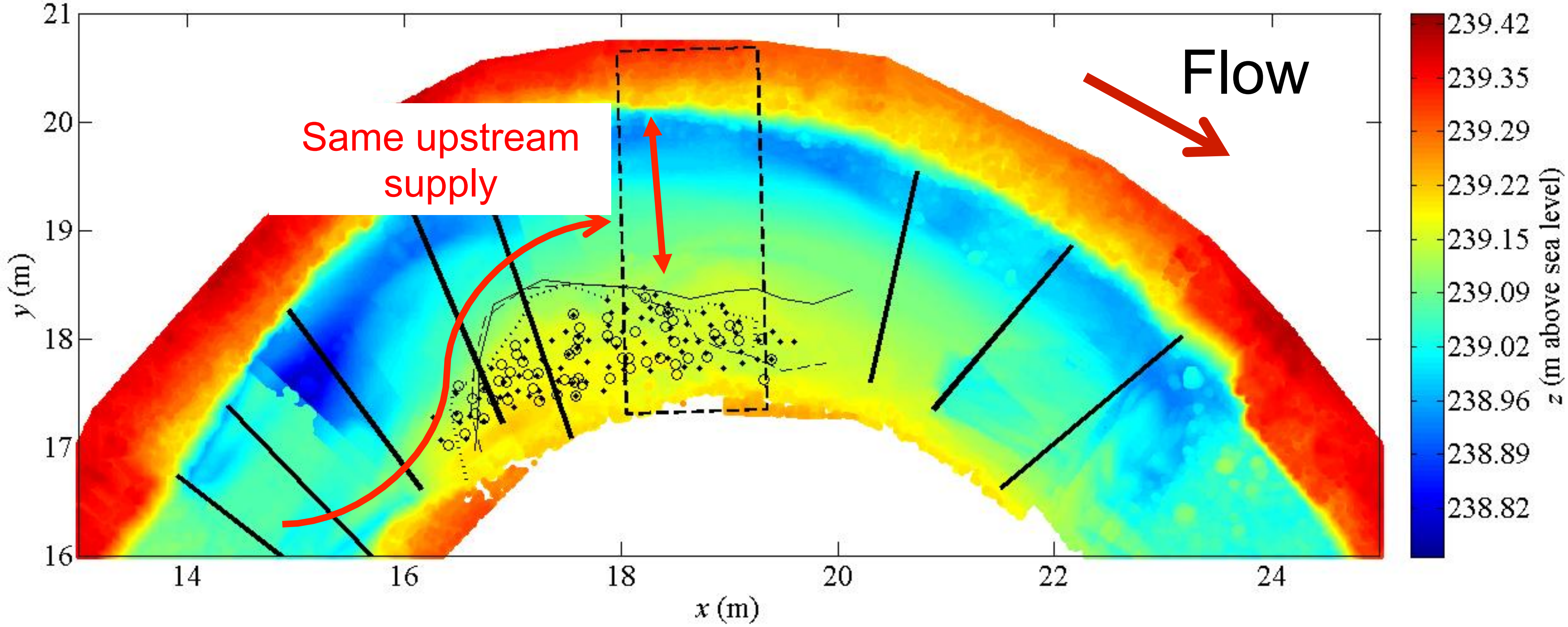
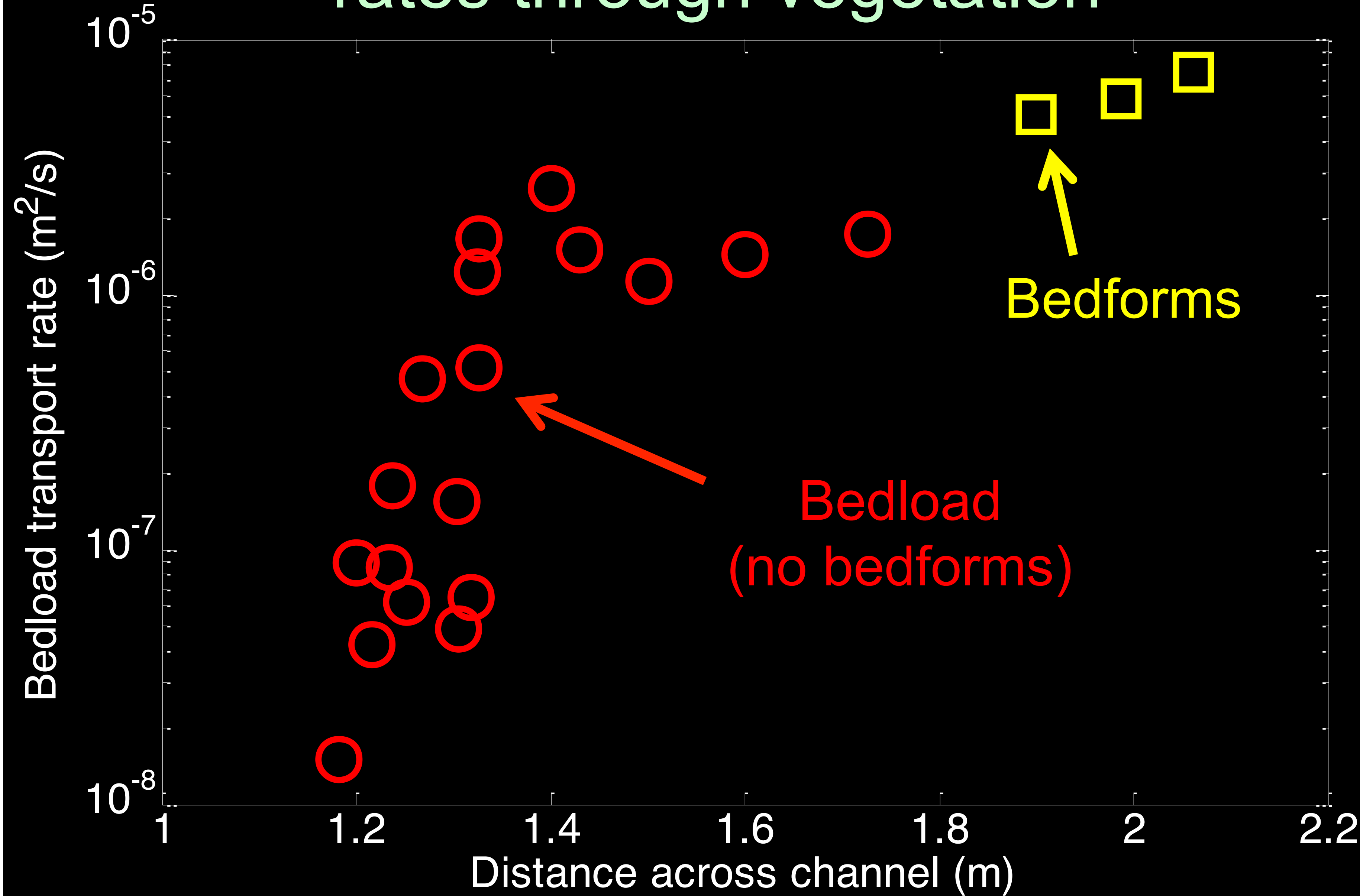
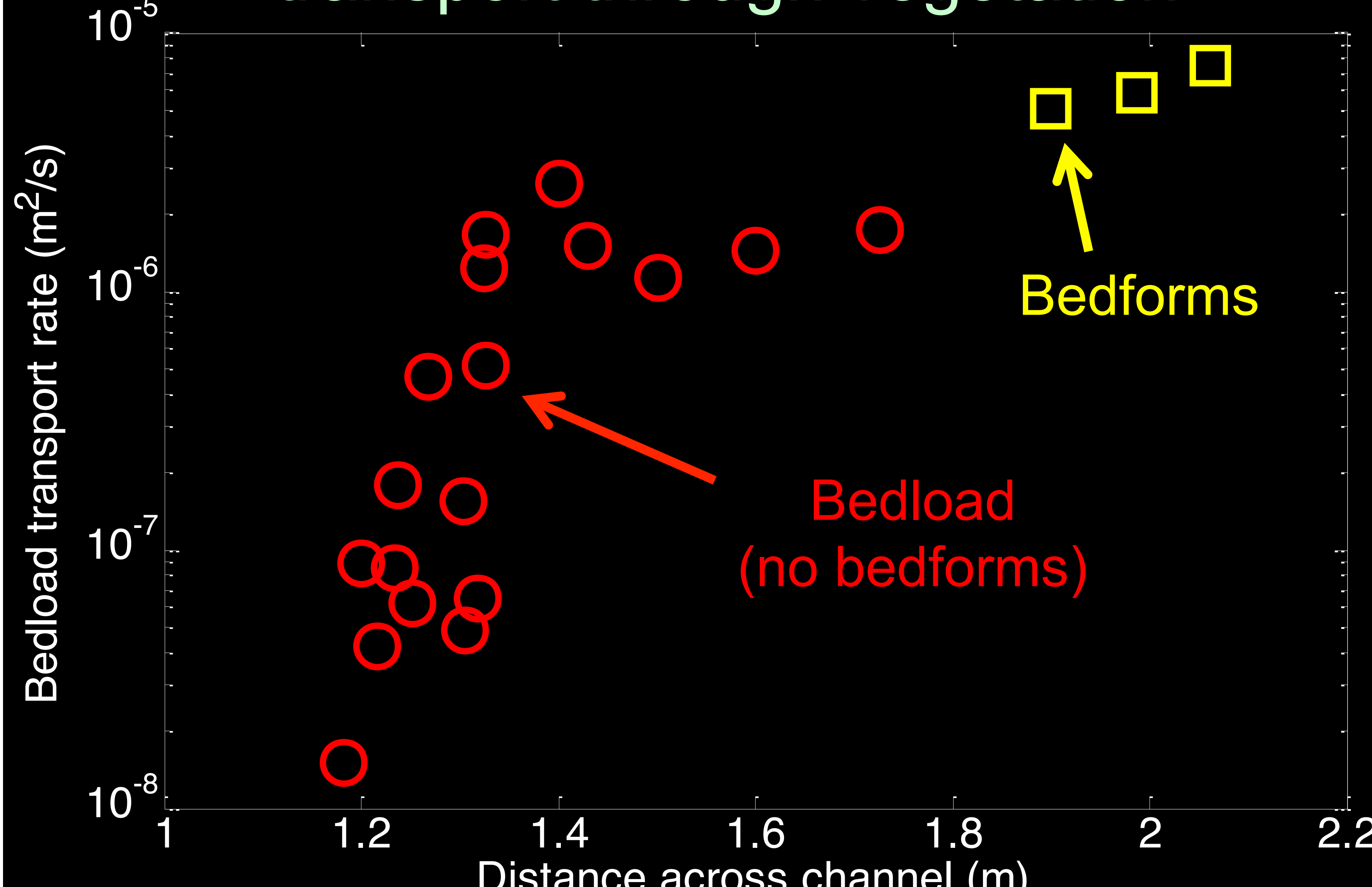


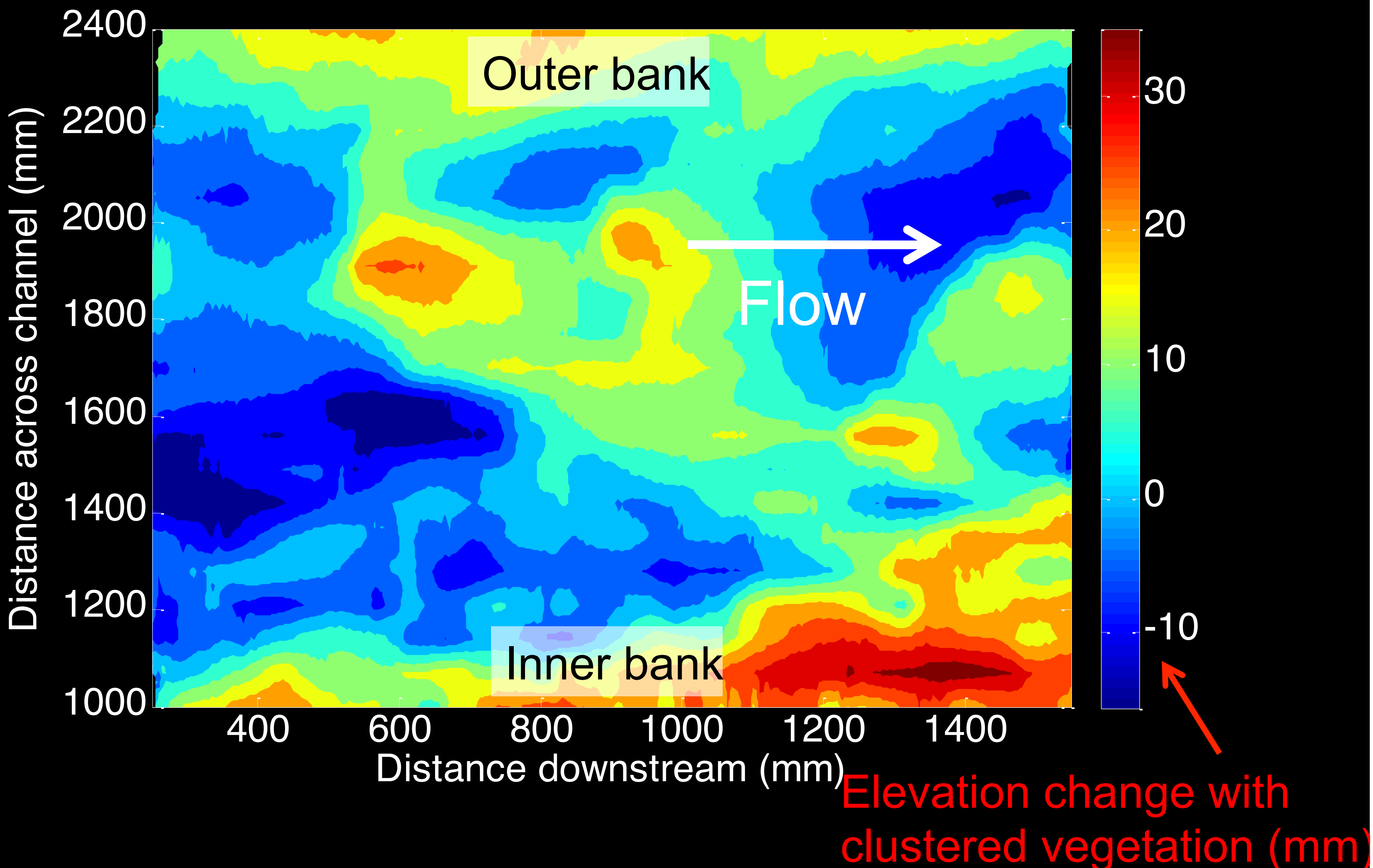
Bedform transport rates>>bedload transport rates through vegetation



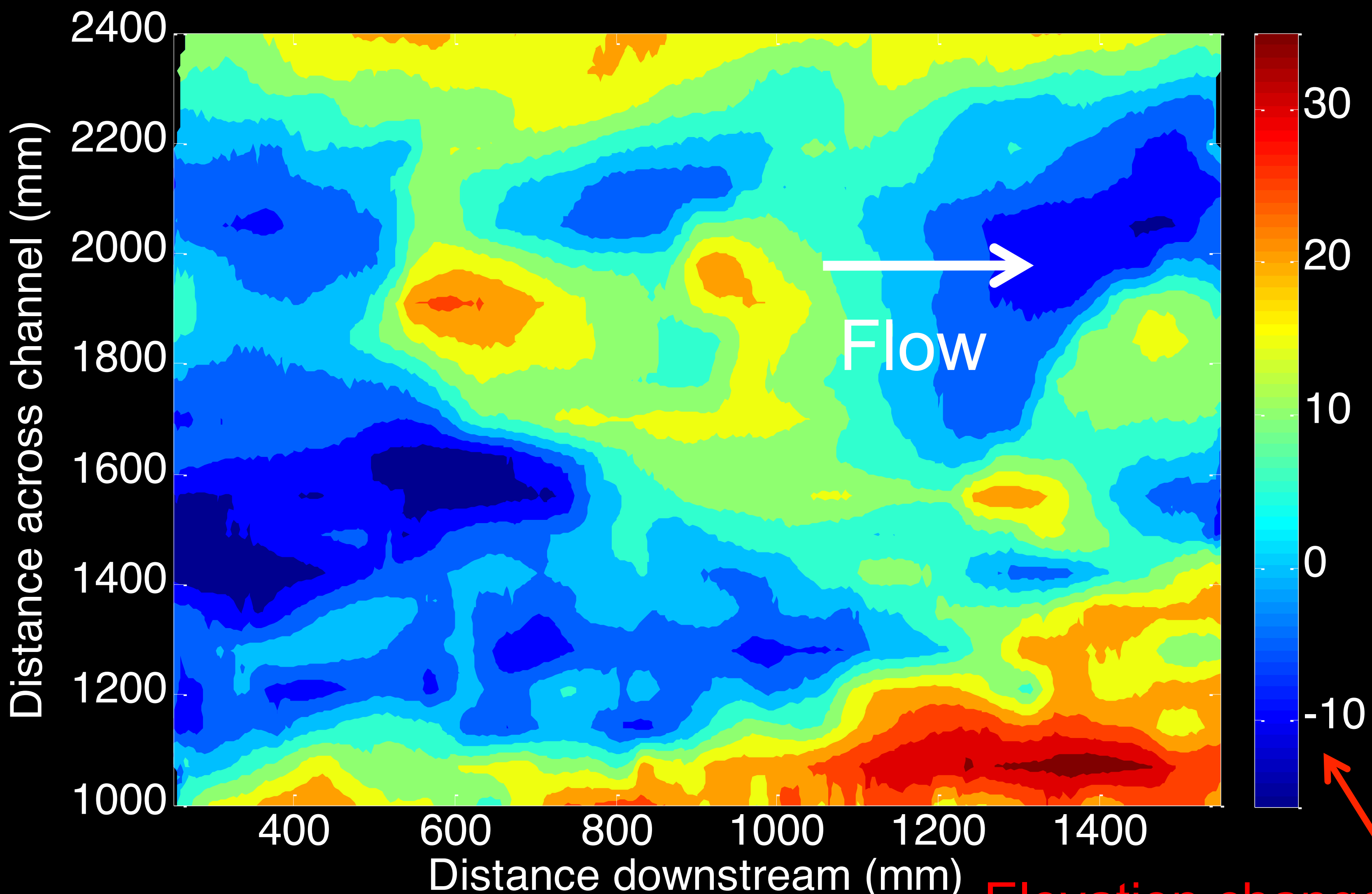
Lack of dune migration causes much lower transport through vegetation



Vegetation generally caused erosion of upstream end of bar



Erosion likely due to lack of dune migration and enhanced turbulence at edge of vegetation patch



Elevation change with clustered vegetation (mm

Distinct scour holes developed immediately adjacent to the stems with areas of deposition downstream of stems

Clustered vegetation may alter the near-bed turbulence and bedload transport patterns similarly to rigid simulated vegetation

Questions

How does vegetation affect flow and sediment transport?

How can we accurately predict bedload transport through vegetation?

Use of distribution of near-bed velocities in bedload transport equation (Ackers and White) results in prediction of 0 flux through vegetation

Use of distribution of near-bed velocities in bedload transport equation results in prediction of 0 flux through vegetation

Even with correct near-bed velocities or shear stresses (measured or predicted from numerical models), current bedload equations may not perform well in vegetation patches

Develop simple bedload transport equation using rigid vegetation data: based on near-bed velocity, turbulence intensity and vegetation density

Predict mean flux through vegetation in OSL:

Measured bedload flux: 0.01 cm2/s

Predicted bedload flux: 0.015 cm2/s

What is missing?

Bedload equations developed for reach-averaged, not local conditions

Flow turbulence effects are missing

Probabilistic equations may perform better

But…larger –scale feedbacks between vegetation and bedform dynamics also must be considered.

Conclusions from outdoor experiments

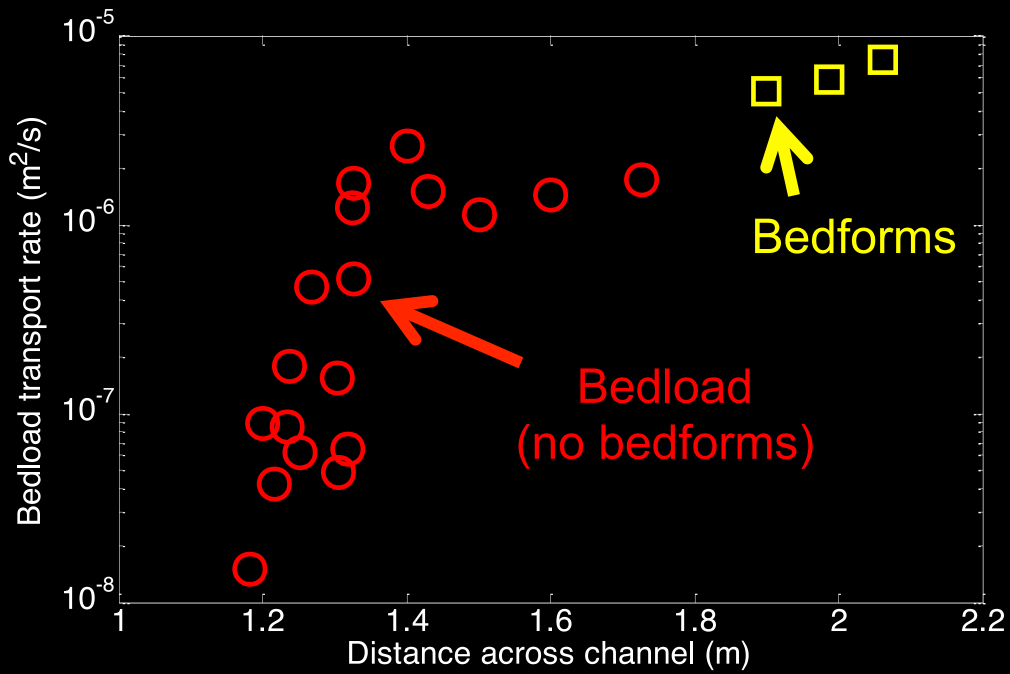
A dense and clustered arrangement of vegetation may significantly alter sediment transport processes by

- halting bedform migration over the point bar top

Conclusions from outdoor experiments

A dense and clustered arrangement of vegetation may significantly alter sediment transport processes by

- halting bedform migration over the point bar top
- increasing bedform transport rates at the outer bank



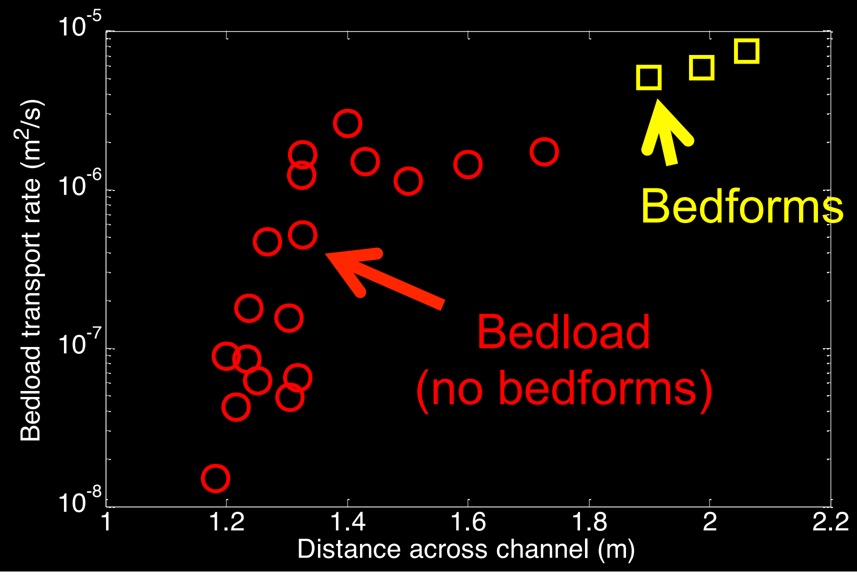
Conclusions from outdoor experiments

A dense and clustered arrangement of vegetation may significantly alter sediment transport processes by

•halting bedform migration over the point bar top

•increasing bedform transport rates at the outer bank

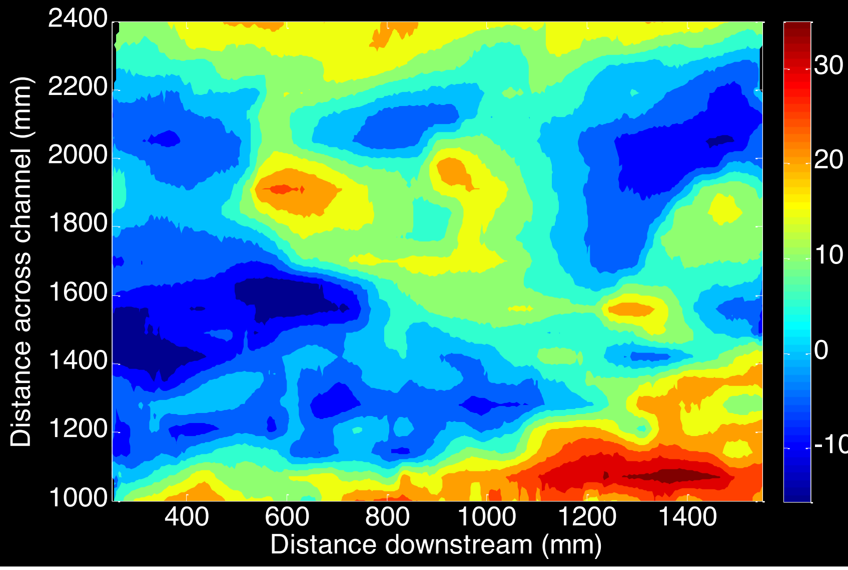
•decreasing bedload transport rates on the point bar



Conclusions from outdoor experiments

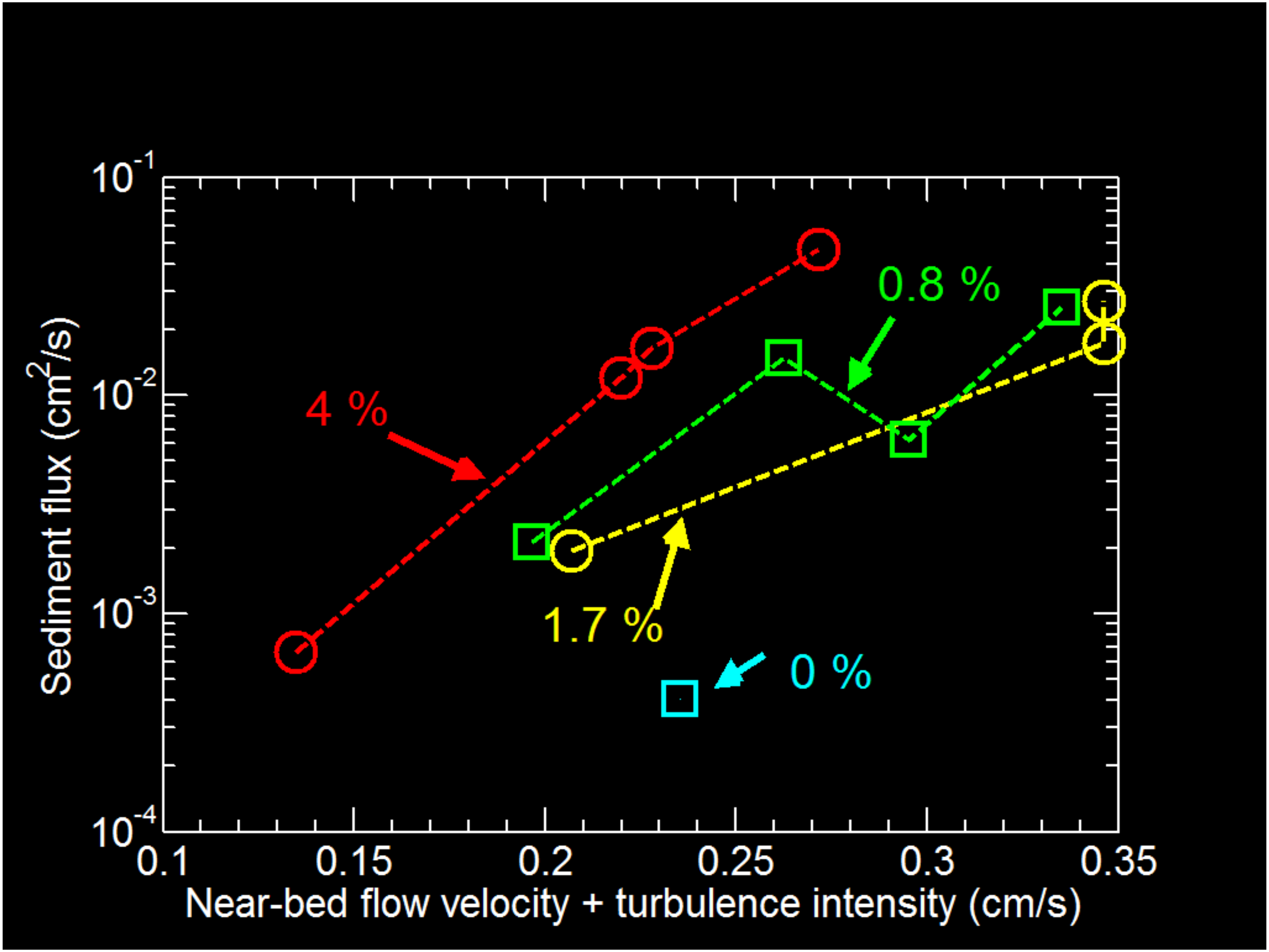
A <u>dense</u> and <u>clustered</u> arrangement of vegetation may significantly alter sediment transport processes by

- halting bedform migration over the point bar top
- increasing bedform transport rates at the outer bank
- decreasing bedload transport rates on the point bar
- reducing point bar width and elevation

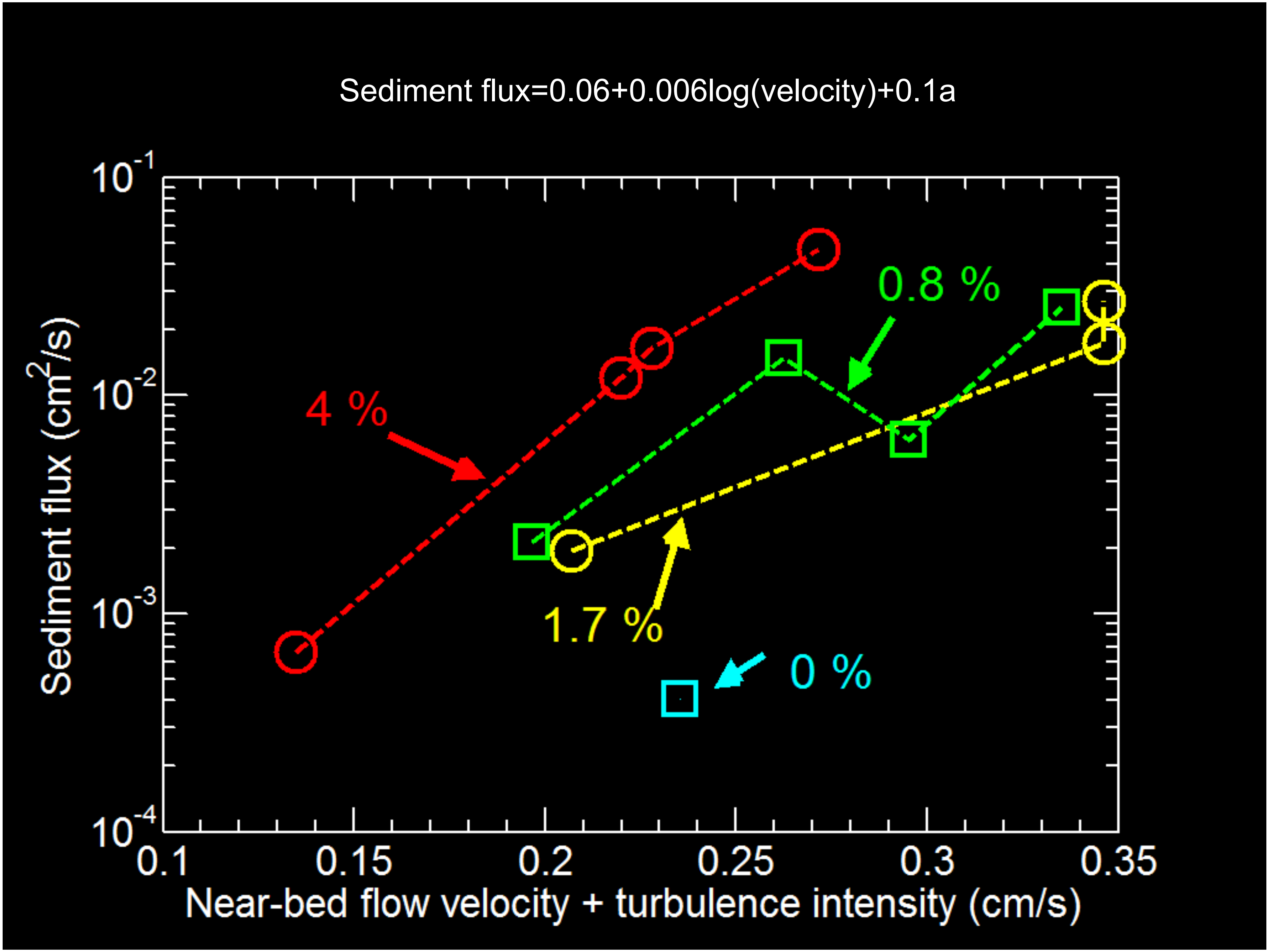


Test new eqn-first OSL description

6 near-bed velocities in vegetation
9 bedload samples



Sediment flux (cm^2/s)
Near-bed flow velocity + turbulence intensity (cm/s)
4 %
0.8 %
1.7 %
0 %



Sediment flux=0.06+0.006log(velocity)+0.1a
Sediment flux (cm²/s)
10⁻¹
10⁻²
10⁻³
10⁻⁴
4 %
0.8 %
1.7 %
0 %
0.1
0.15
0.2
0.25
0.3
0.35
Near-bed flow velocity + turbulence intensity (cm/s)

Test new eqn

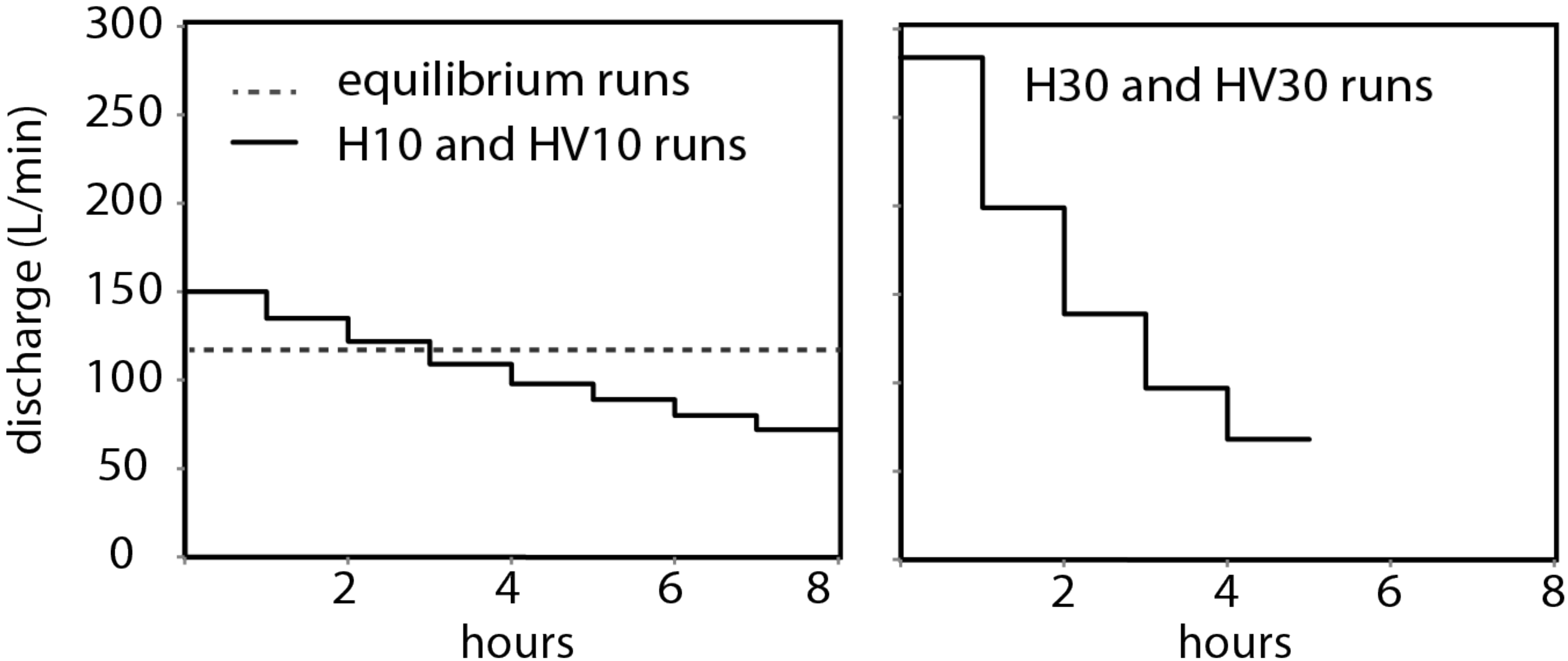
Measured 0.01 cm2/s
Predicted 0.015
Ackers and White 0

Even when current eqns use actual near-bed flow conditions (or assuming these would be corrrectly predicted from 2D model/drag) current sediment transport equations do not perform well. Part of this is likely that these eqns:

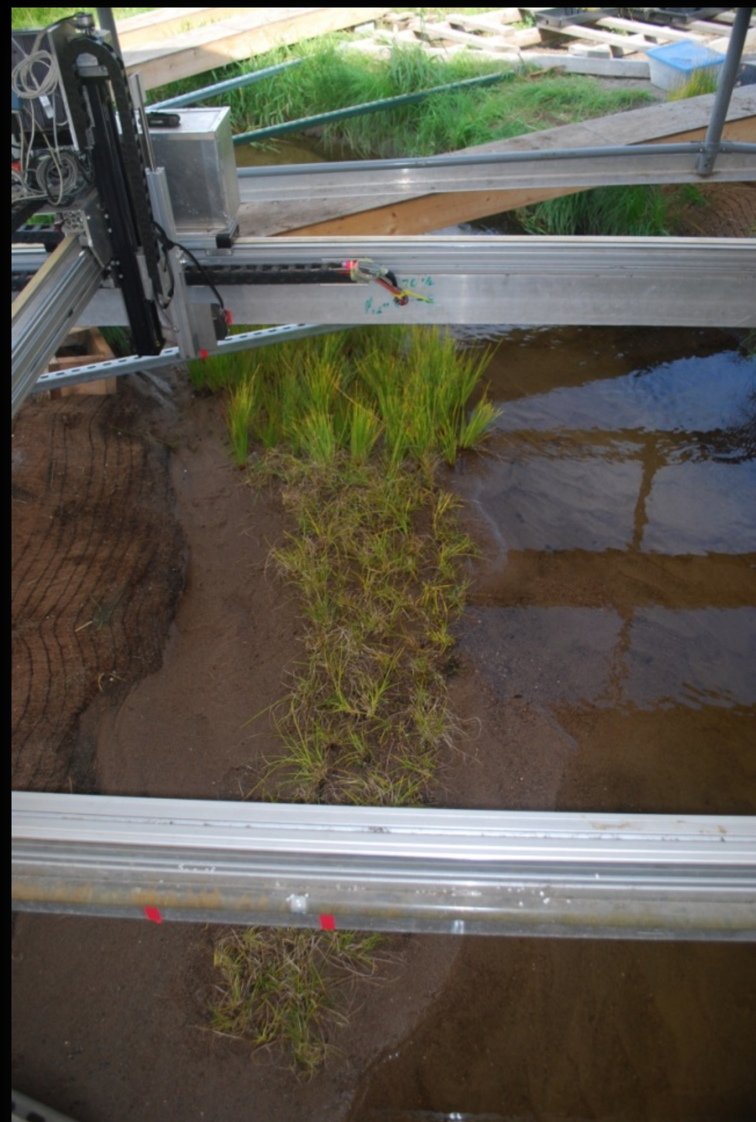
Have been calibrated to mean flow conditions rather than near-bed conditions and therefore will underpredict because some assumption of drag may be implicit in coefficients etc. and therefore using mean actual bed flow will under-predict

Have not been developed for highly spatially variable flow and sediment transport conditions that occur around vegetation

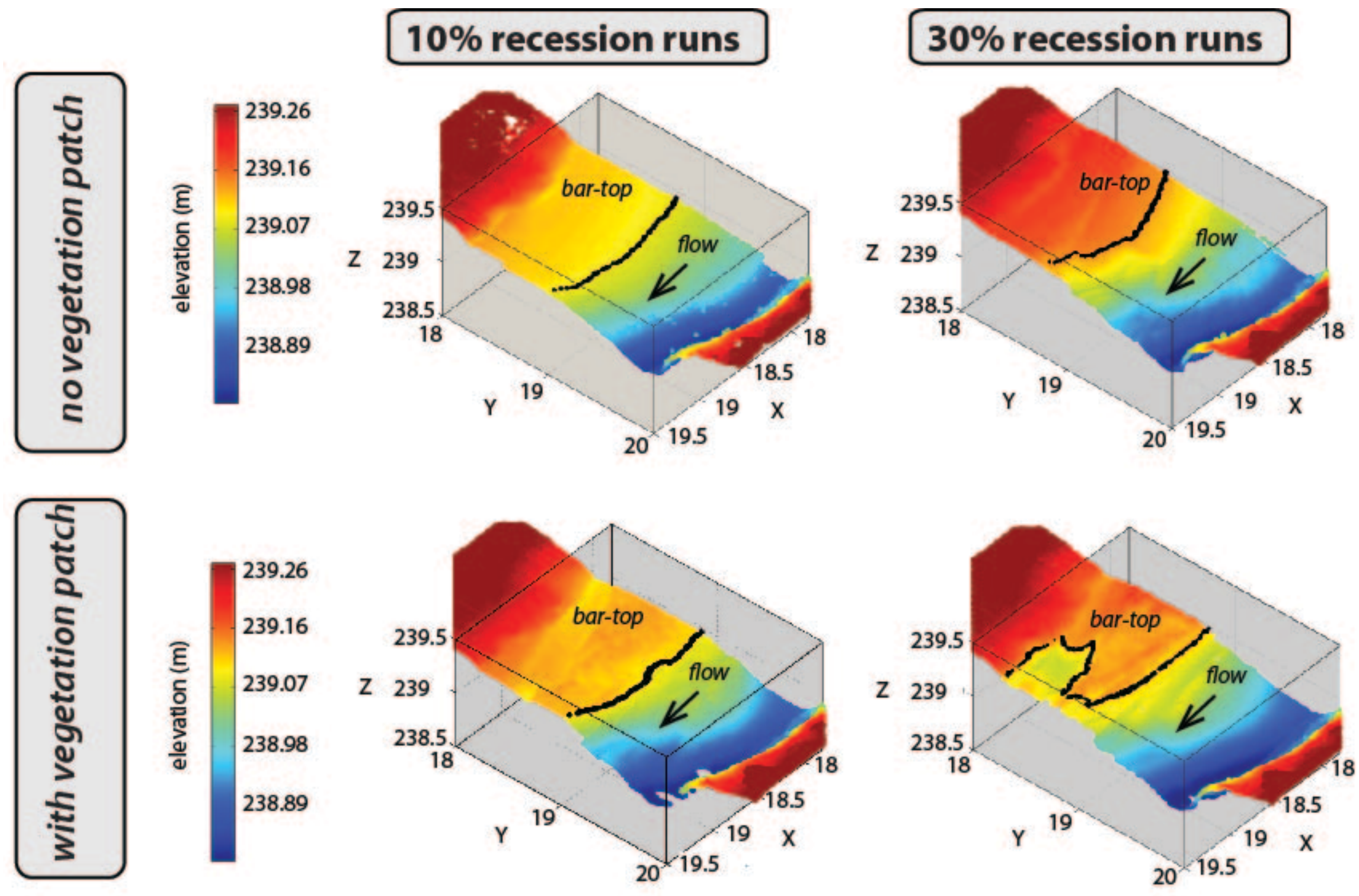
Add in the influence of flow hydrographs, which are more representative of natural conditions!



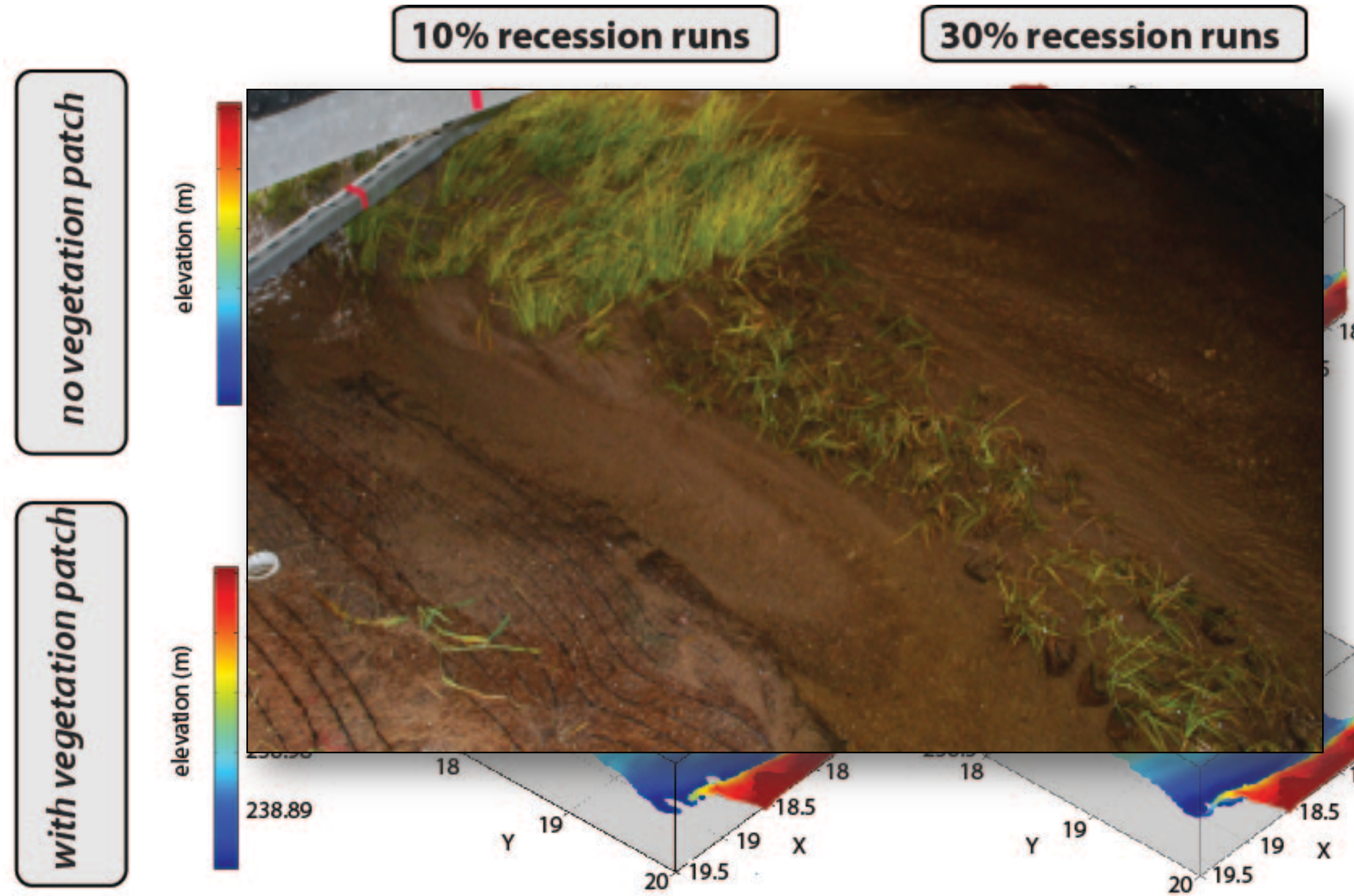
Run each hydrograph with and without vegetation planted on bar



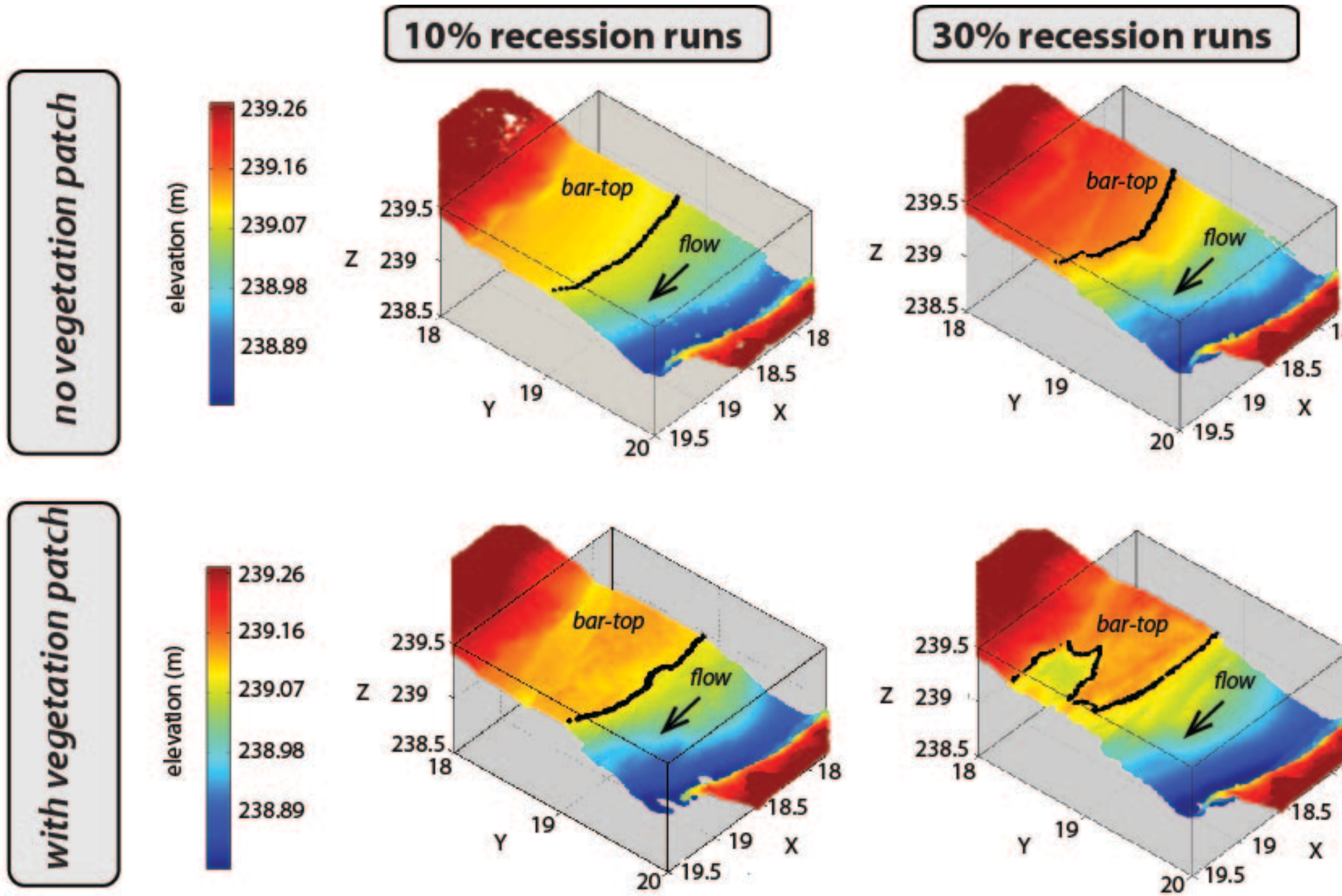
Hydrograph shape influences bar form



Vegetation combined with a flow hydrograph results in the formation of a side channel



Side channel persists with more rapid hydrograph recession rate



Such a side channel could provide habitat for fish but also could decrease bar stability