3D Bedrock Channel Evolution with Smoothed Particle Hydrodynamics Coupled to a Finite Element Earth

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Abstract

An enduring obstacle to reliable modeling of the short and long-term evolution of the stream channel-hillslope ensemble has been the difficulty of estimating stresses generated by stream hydrodynamics. To capture the influence of complex three-dimensional (3D) flows on bedrock channel evolution, we derive the contribution of hydrodynamic stresses to the stress state of the underlying bedrock through a Smoothed Particle Hydrodynamics (SPH) approximation of the Navier-Stokes equations as calculated by the DualSPHysics code (Crespo et al., 2015). Coupling the SPH flow solutions to the stress-strain formulation of the Failure Earth Response Model (FERM) (Koons et al., 2013) provides three-dimensional erosion as a function of the strength-stress ratio of each point in the computational domain. From the coupling of SPH and FERM we gain a 3D physics-based erosion scheme and a two-way link between complex flows and hillslope dynamics in a finite element framework.

Motivating Questions

1.) What are the hydraulic stresses generated in bedrock channels, and how do they vary in time and space?

2.) What is the geomorphic response to the hillslope stresses and hydraulic stresses in a bedrock channel with heterogeneous rock strength?

3.) Can SPH be used to support decisions related to dam removal and fish habitat rehabilitation activities in river locations where conditions are affected by remnant structures from past industrial operations??

Methods

Smoothed Particle Hydrodynamics (SPH)

The physics of motion for fluids (Navier-Stokes [N-S] equations) are solved for each particle at every timestep. SPH is able to handle the fluid accelerations very well, which allows for realistic simulation of natural flows and fluid-structure interaction.

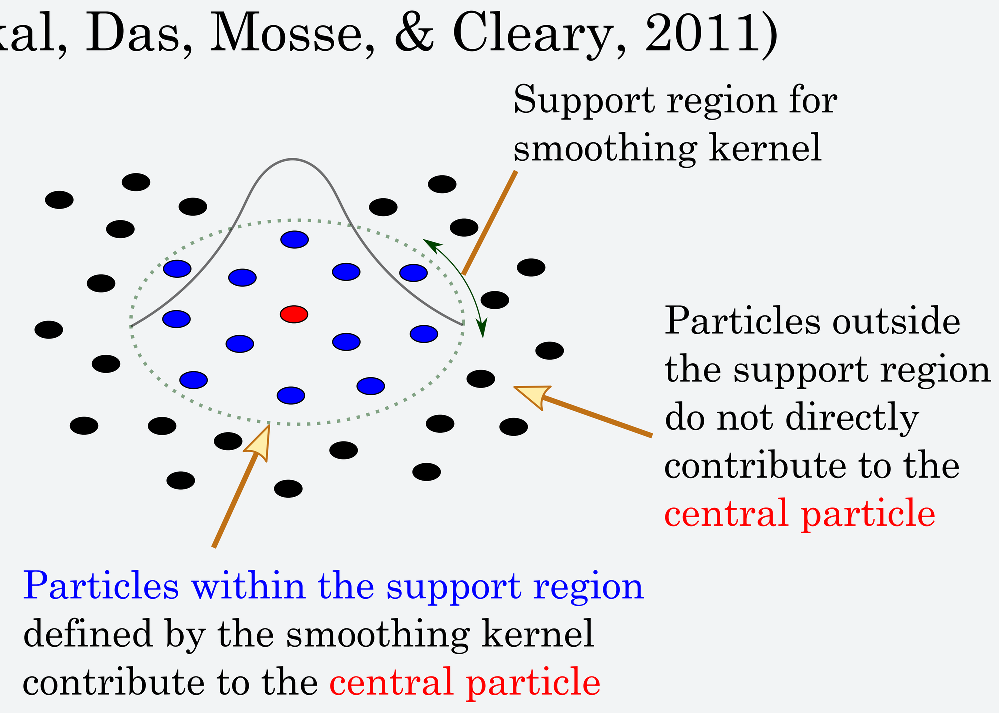
A Basic SPH Smoothing Kernel

(after Karekal, Das, Mosse, & Cleary, 2011)

Navier-Stokes (Simplified Notation)

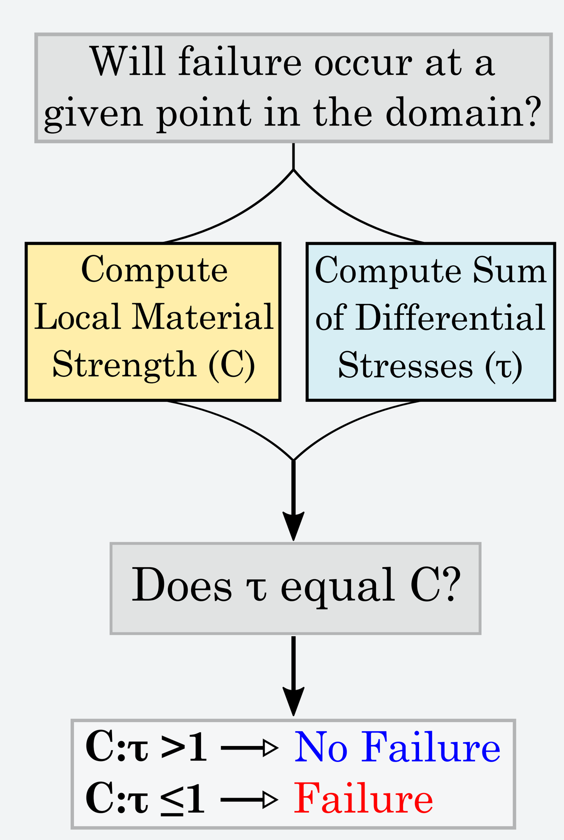
$$\rho\frac{\partial \vec{v}}{\partial t} = \nabla P - \rho g + \mu \nabla^2 \vec{v}$$

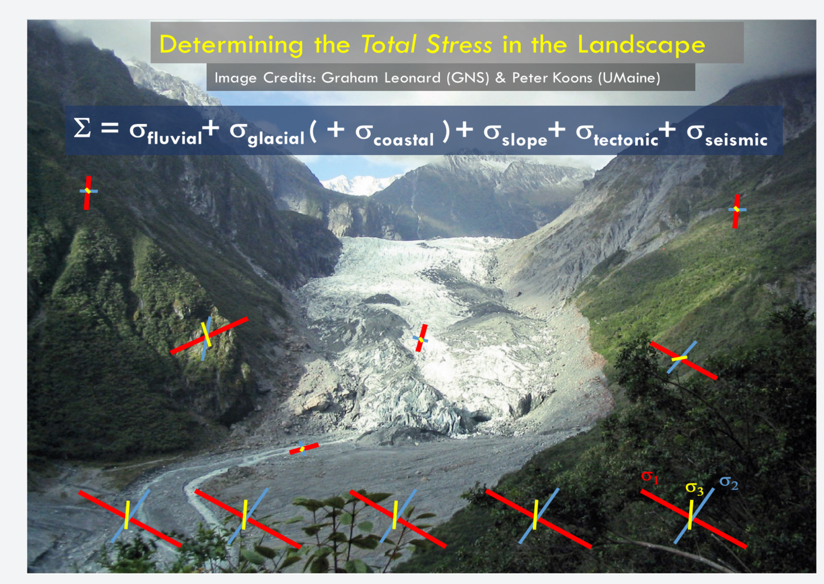
For a given particle, (such as the central particle shown right), the N-S equations are locally integrated using the position and motion information of neighbor particles.



Failure Earth Response Model (FERM)

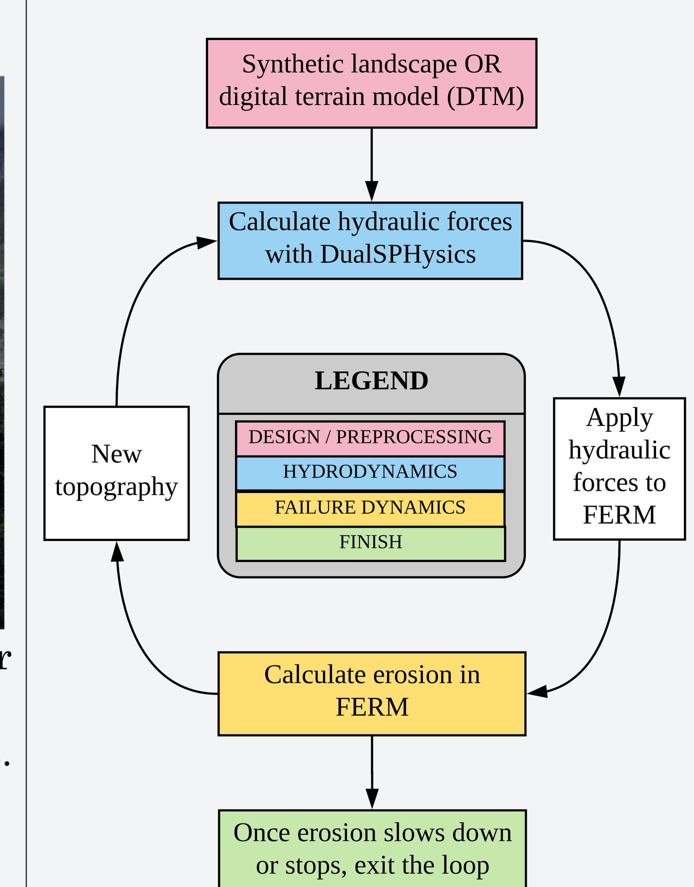
FERM uses a Mohr-Coulomb approach to failure of Earth materials wherein failure occurs if the local differential stress (τ) exceeds the local strength (C) of the Earth material.



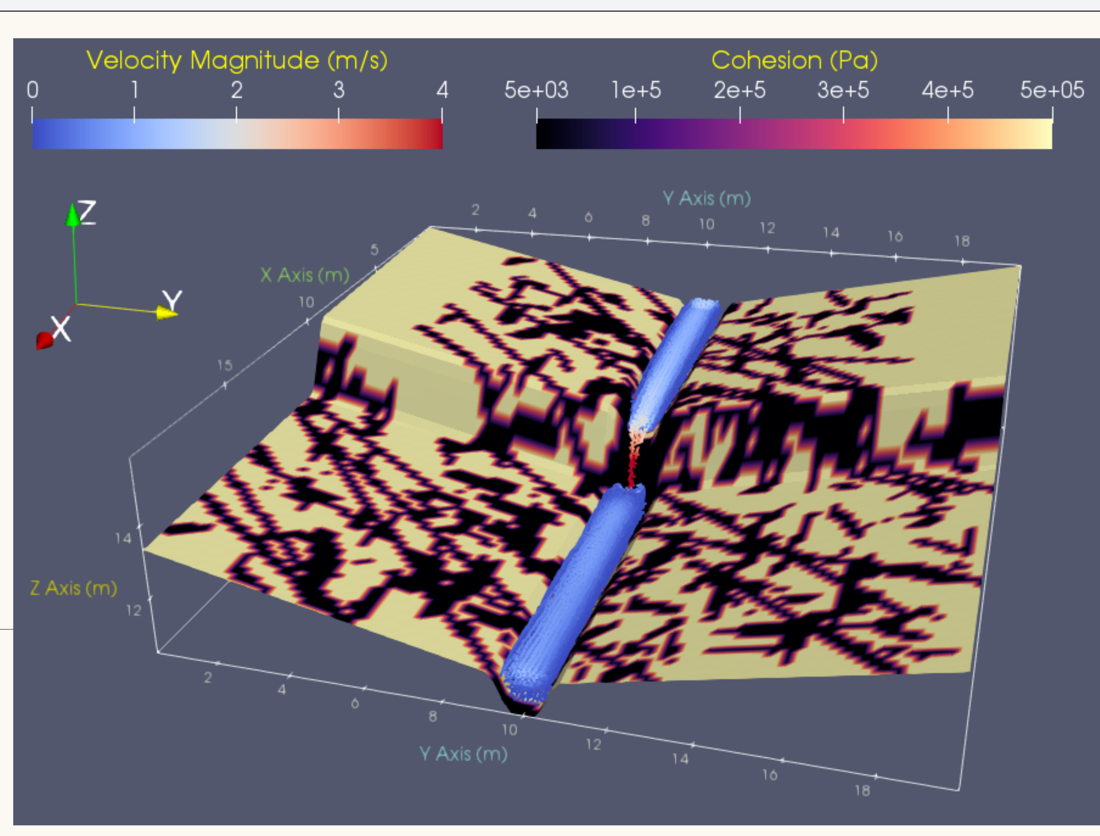


The above photograph of Franz Josef Glacier (NZ) shows that differential stress varies by orders of magnitude over short spatial scales. Approximate principal stresses (shown with glyphs) reflect the contribution of many stresses acting on the landscape.

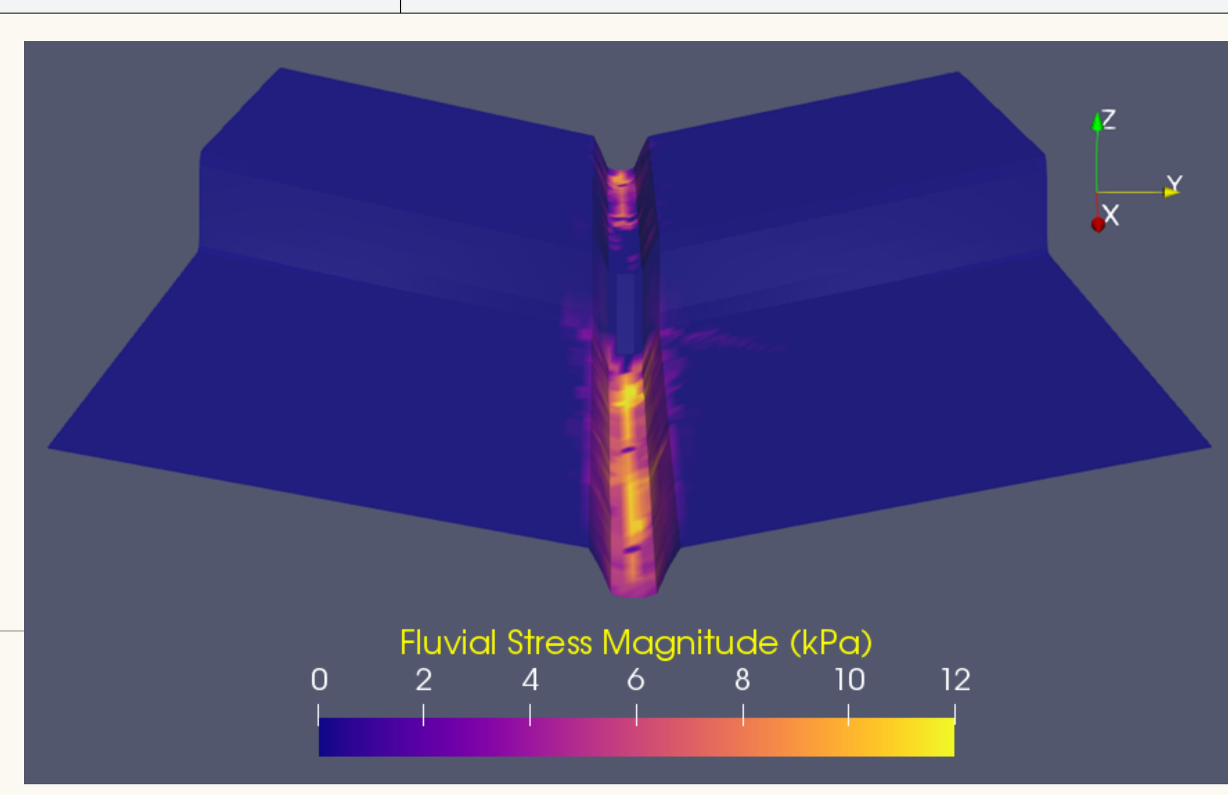
Coupling SPH With FERM



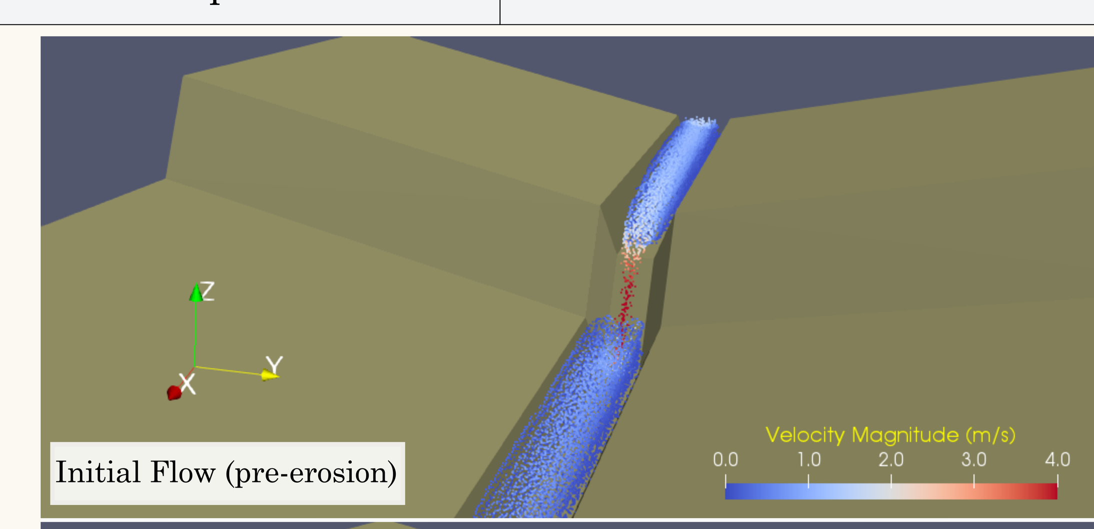
Flows + Failure

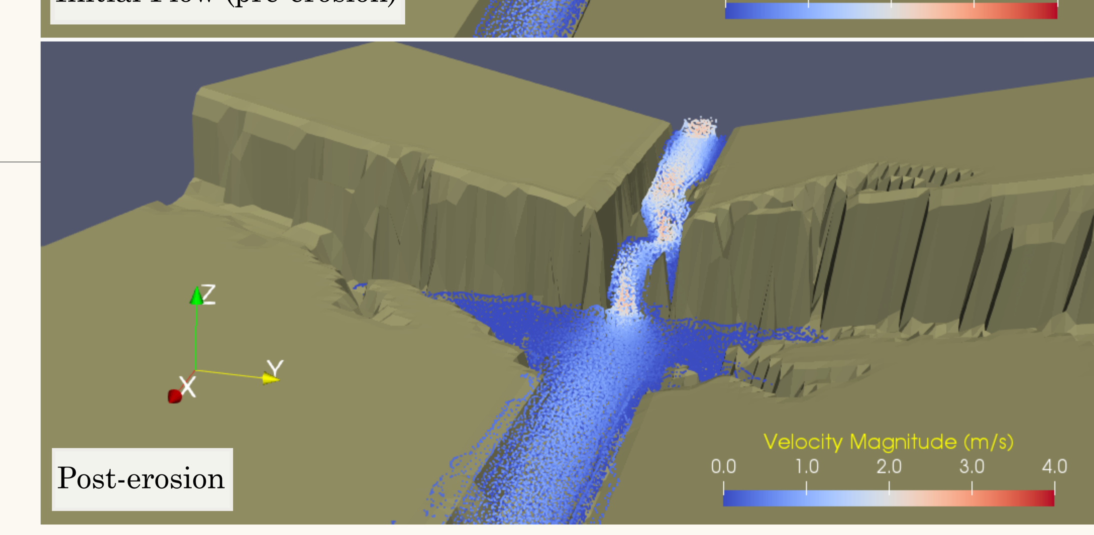


In the above synthetic bedrock channel (20 m * 20 m with a 2 m vertical drop at the knickpoint), water flows over bedrock with strength heterogeneities which are defined in space by a power law fracture distribution. The small waterfall marks a transition in hydraulic stresses from shear-dominant to normal-dominant.



Up to 12 kPa of hydraulic stress is generated in the channel and is highest where the water impacts normal to the channel bed. This suggests that the capacity for bedrock channel incision is high where local flow accelerations dominate.

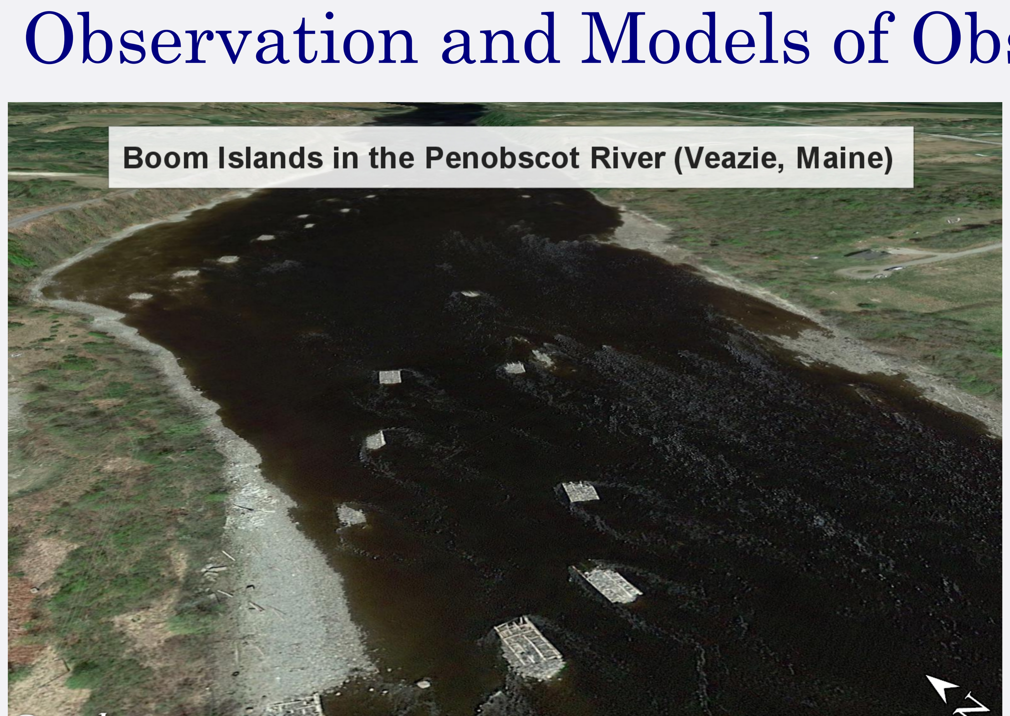




Erosion via coupled FERM-DualSPHysics modeling shows a reorganization of the channel's velocity structure as weak material is preferentially removed from the domain.

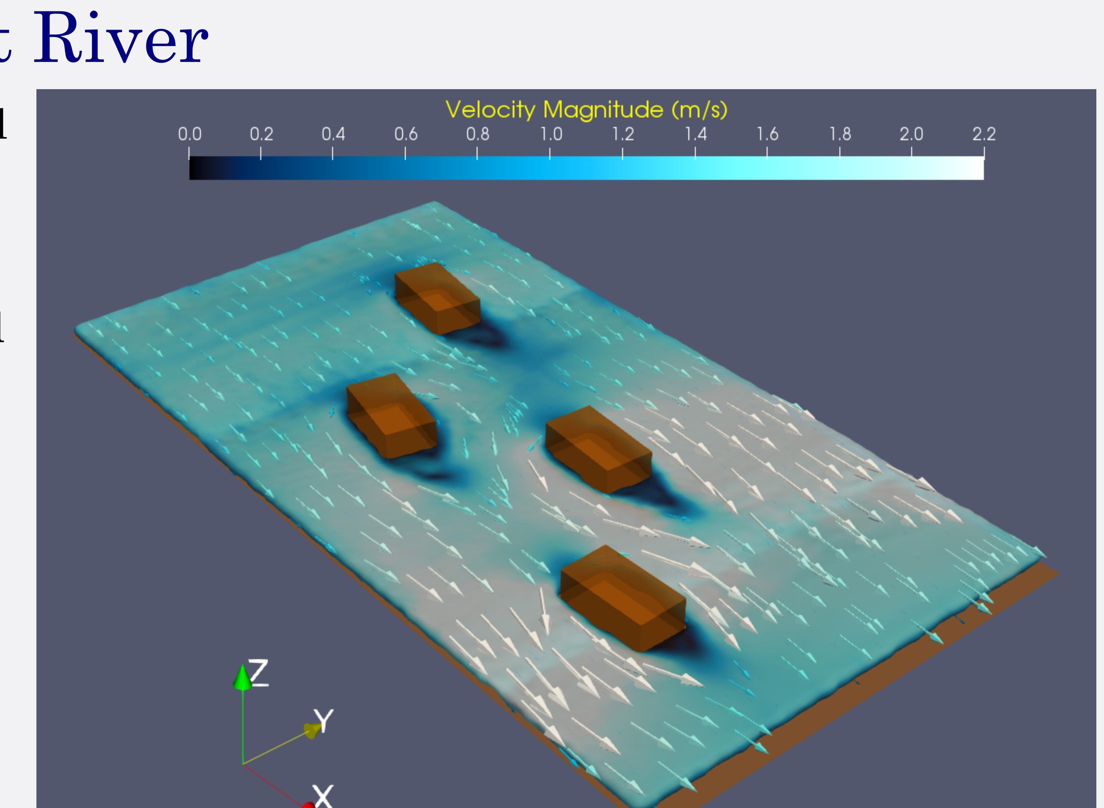
Model Verification: Observation and Models of Obstructions in Maine's Penobscot River

"Boom islands" are relict structures used for past industrial logging operations in Maine's Penobscot River. Recent large dam removal projects have restored access to extensive river segments that contain the remnant log drive era structures. Questions remain about the cumulative effect of the structures on habitat for fish such as Shortnose Sturgeon that is partly governed by water flow depth and velocity in the river.



Shown right is a SPH flow past a cluster of artificial boom islands arranged to reflect the real boom island clusters shown on the map shown left.

By scaling up numerical flow simulations calibrated with field measurements we will evaluate the zone of influence from boom island structures and estimate their cumulative effects over a range of flow conditions in the river. The information is framed around the development of decision tools for dam removal and fish habitat rehabilitation projects in locations with legacy structures and debris that may affect modern hydraulic conditions.



Conclusions and Future Work

The coupling of a particle-based flow solution with a finite element geomorphic solution is a novel approach to bedrock channel incision which robustly approximates the 3D stresses and geomorphic response of bedrock channels with complex geometries and lithologies. Future development of this model will focus on real-time cosimulation of failure and flows in order to capture the complex dynamics of sediment transport and the erosional effects of mobile sediment in bedrock channels and surrounding hillslopes. Acoustic Doppler velocimetry will be performed in June 2018 will be used to constrain and validate the flow modeling around relict logging structures in the Penobscot River.

Acknowledgements

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