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 3D flows on bedrock channel evolution, we derive the contribution of hydrodynamic stresses to the stress state of surrounding bedrock through a Smoothed Particle Hydrodynamics (SPH) approximation of the Navier-Stokes (N-S) equations. Coupling the flow solutions to the stress-strain formulation of the Failure Earth Response Model (FERM) provides three-dimensional erosion as a function of the strength-stress ratio of each point in the computational domain. This novel approach allows the resulting geomorphic response to be quantified for bedrock channels with bends, knickpoints, plunge pools, and other geometric and hydrodynamic complexities. From the coupling of SPH and FERM we gain 3D physics-based erosion and a dynamic link between complex flows and hillslope dynamics in a finite element framework.

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.

$C:\tau > 1 \longrightarrow$ No Failure

$C:\tau \leq 1 \longrightarrow$ Failure

Fluvial stresses calculated with SPH are added to the other components of the total stress state, such as slope-generated and tectonically-generated stresses. Together, these differential stresses represent the total stress tensor (Figure 1). Strength parameters used in FERM (tensile strength, cohesion, and friction angle) are readily constrained with field observations.

Figure 1

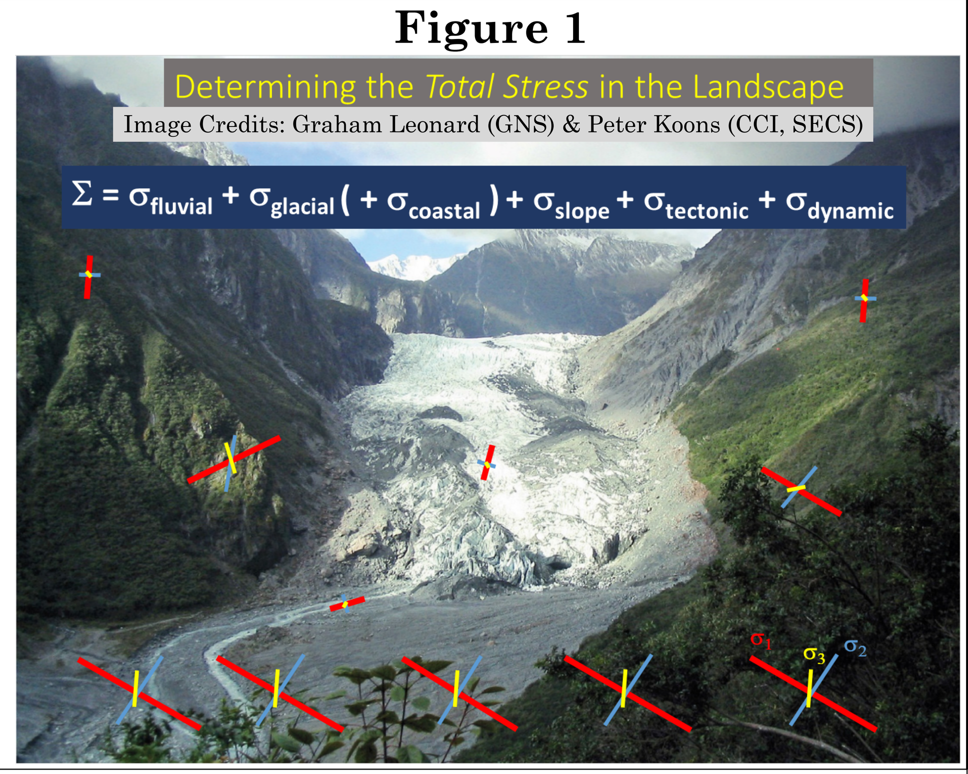


Figure 3

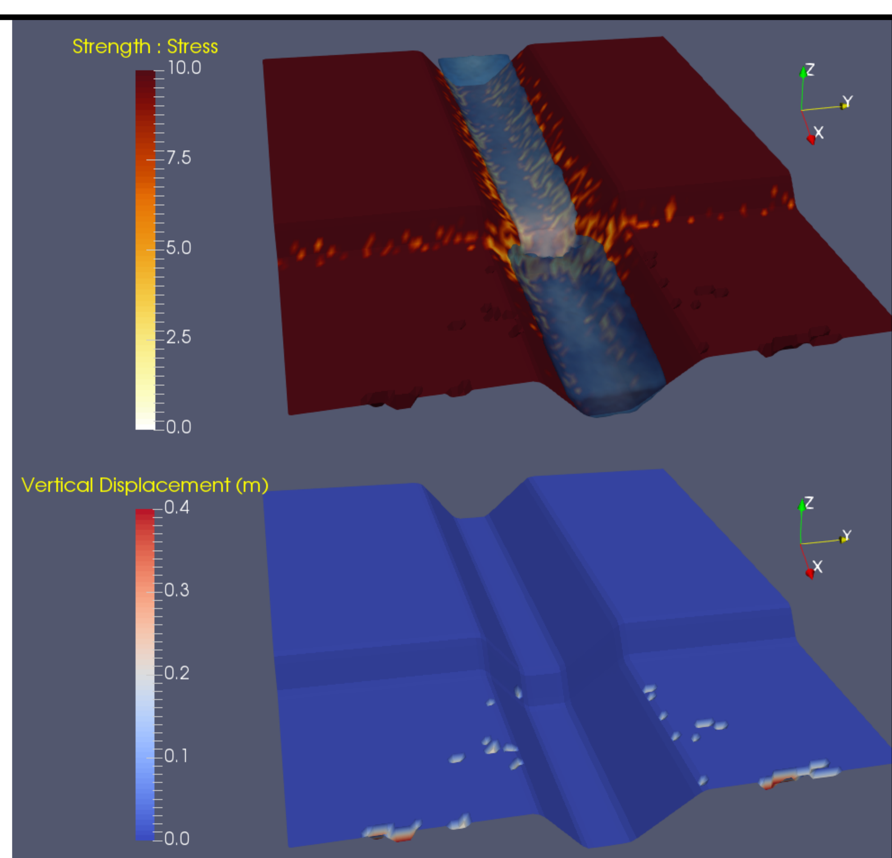


Figure 4

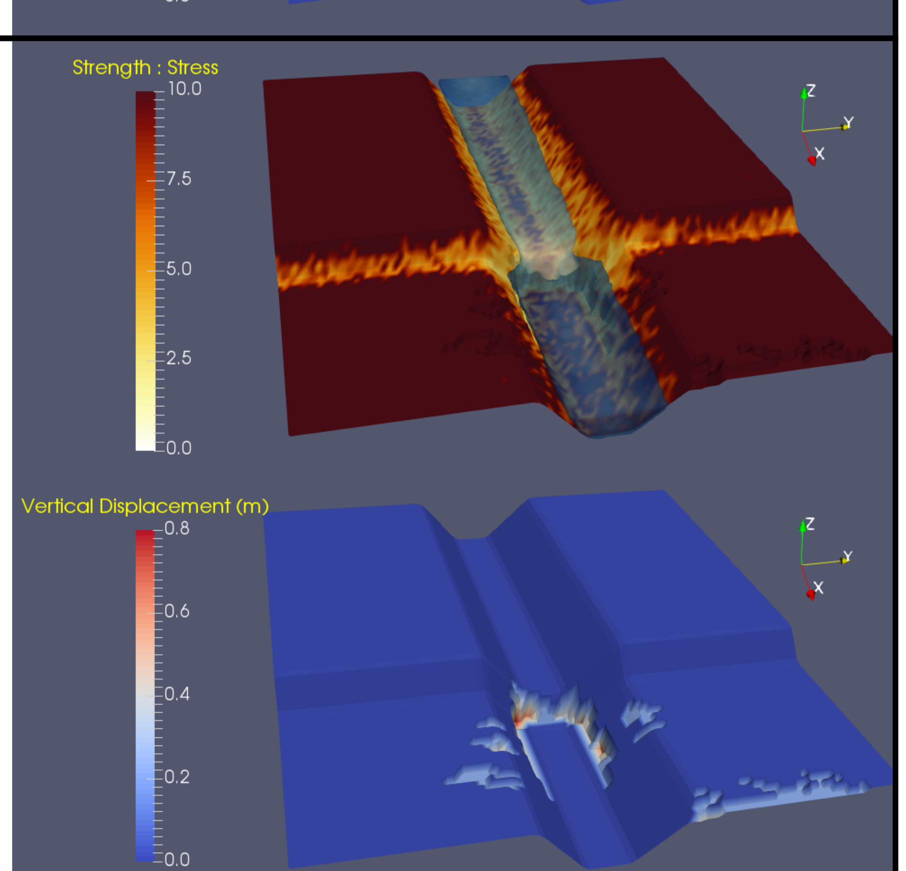
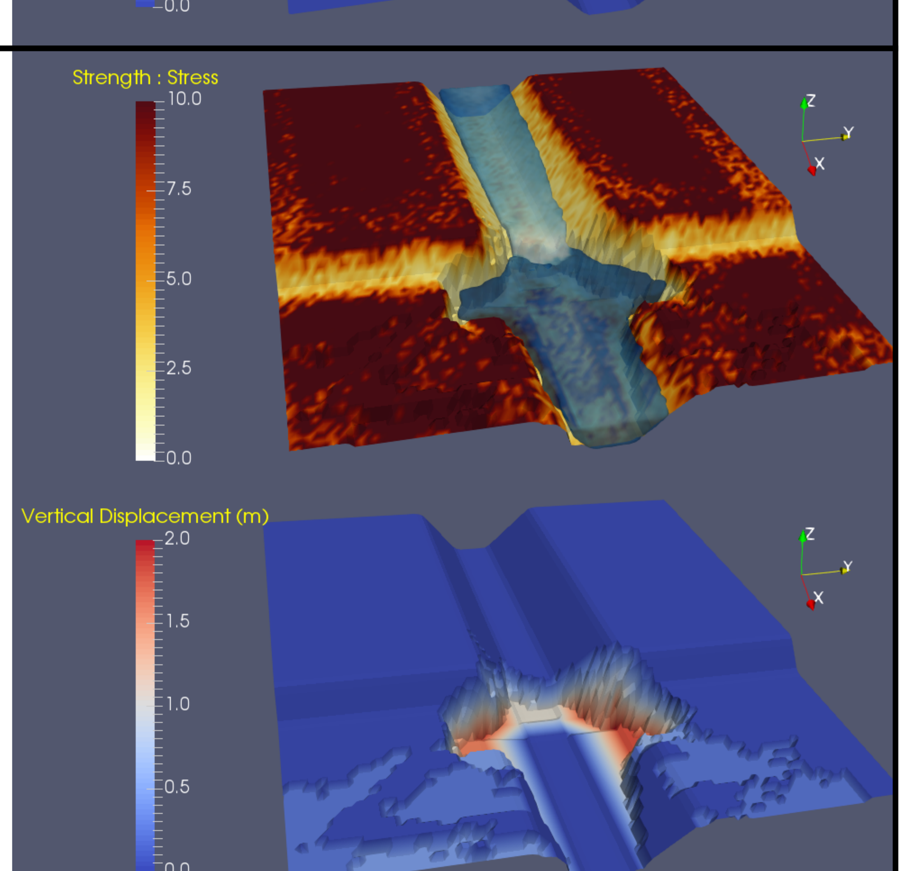
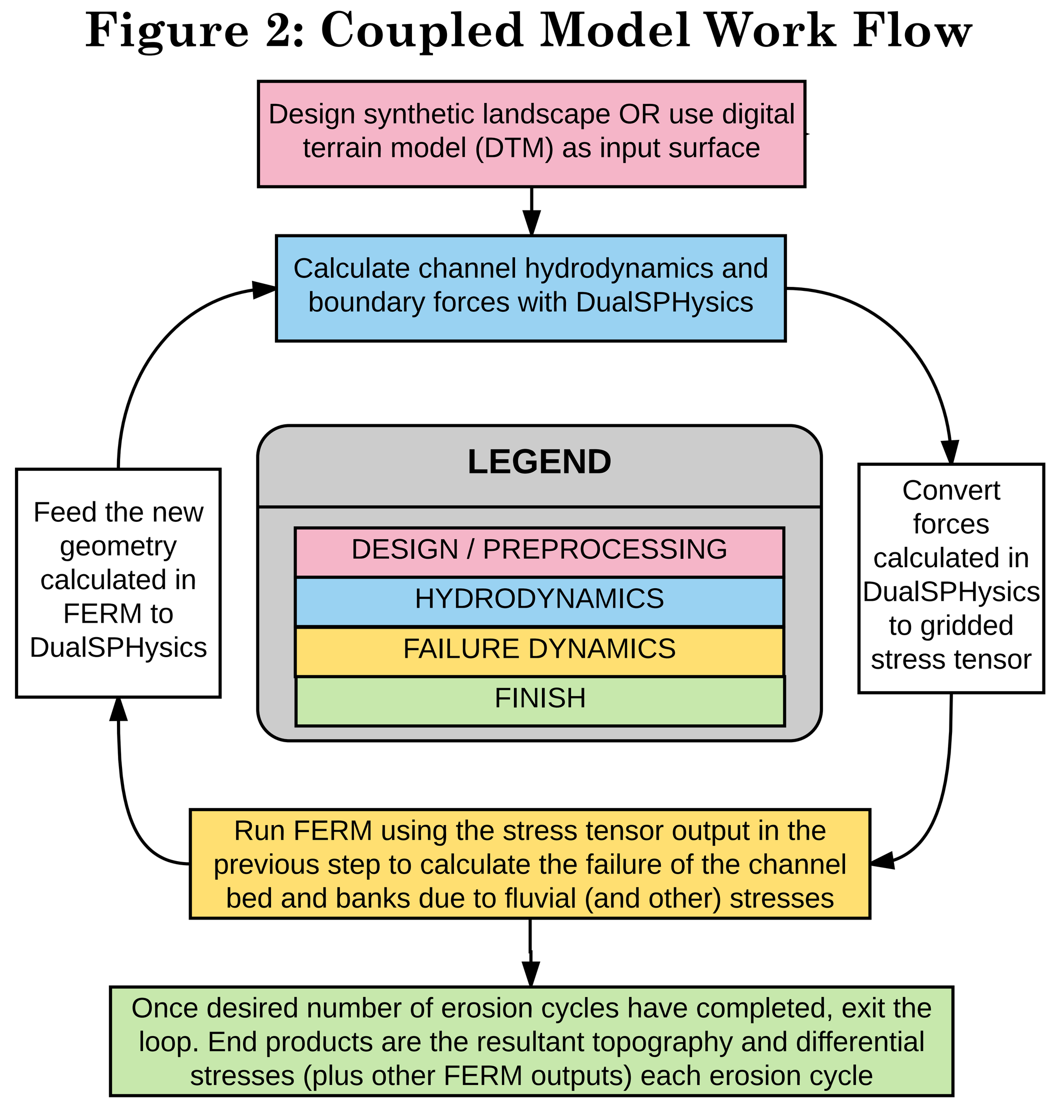


Figure 5



Coupled FERM-SPH

Figure 2: Coupled Model Work Flow



Figures 3-5 show the effects of 300 FERM cycles using SPH fluvial stresses acting on a knickpoint (20m x 20m, 1m drop, 1° slope). Capturing the inertial forces with SPH and the 3D erosive potential of complex flows with FERM provides a comprehensive description of the stream channel-hillslope ensemble.

Figure #	Tensile Strength (Pa)	Cohesion (Pa)	Friction Angle (°)
3	1E4	1E5	30
4	5E3	5E4	30
5	2.5E3	2.5E4	30

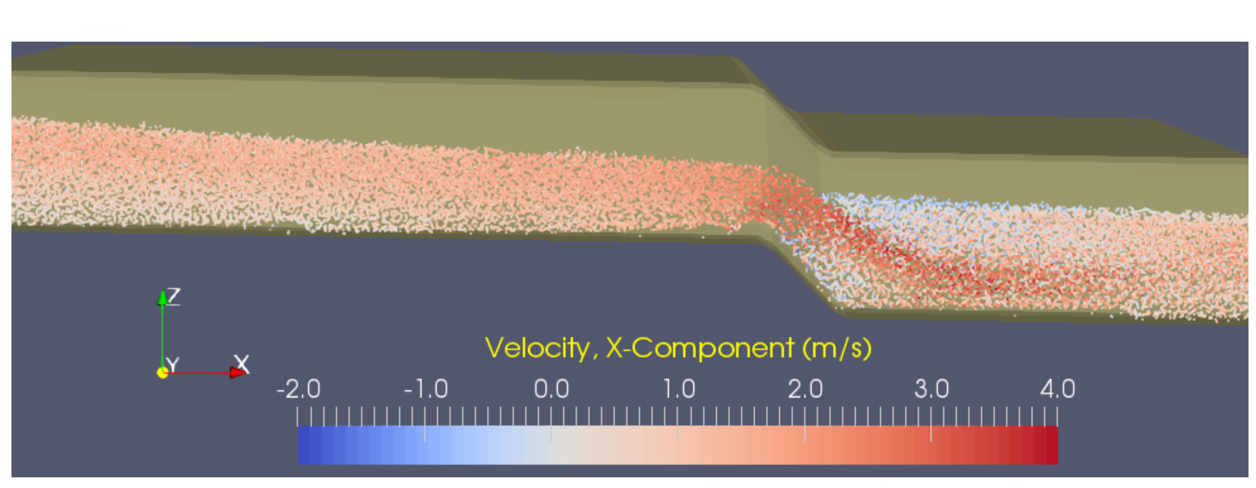


Figure 6 shows the velocity structure of the flow field across the knickpoint, which was calculated using 104,154 SPH particles. There is a strong return flow (up to 2 m/s) at the knickpoint.

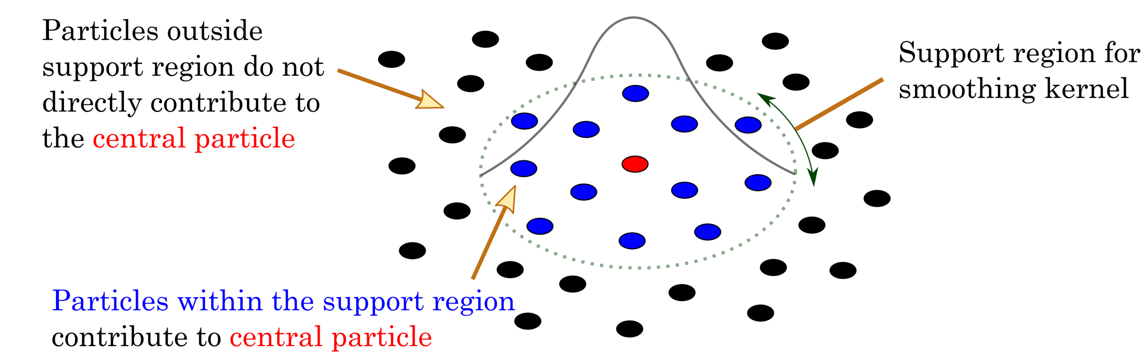
How Does SPH Work?

The physics of motion for fluids (Navier-Stokes equations, below) are solved for each particle at every timestep.

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

For a given particle (shown below as the red "central particle," the N-S equations are locally integrated using the position and motion information of neighbor particles. A smoothing kernel weights the influence of the neighbor particles on the central particle such that the closest neighbors have the greatest influence on the central particle.

Figure 7: A Basic SPH Smoothing Kernel (after Karekal, Das, Mosse, & Cleary, 2011)

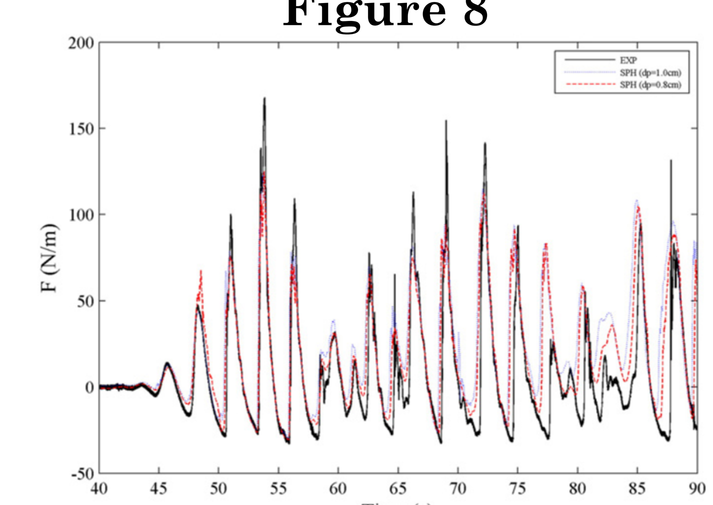


SPH is able to handle the fluid accelerations very well, which allows for robust solutions of the inertial N-S term and realistic simulation of fluid-structure interaction. Simulation of millions of particles with DualSPHysics (Crespo et al., 2015) enables investigation of the forces and kinematics associated with flow past hetergeneous boundaries in three dimensions.

Are SPH Force Outputs Reliable?

Figure 8 compares experimental and numerical (DualSPHysics) force calculations for waves acting on a 1:25 scale coastal defense structure shows good agreement between the SPH solution and values collected using force sensors in the experimental flume (Altomare et al., 2015).

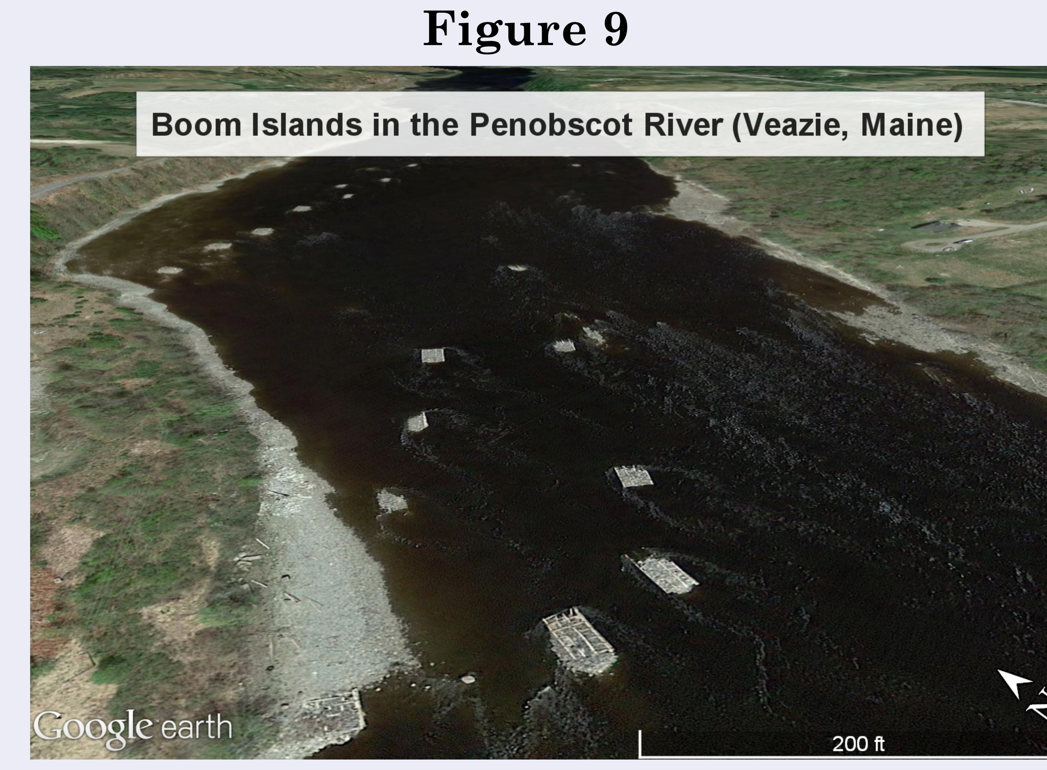
Figure 8



What Else Can We Investigate With SPH?

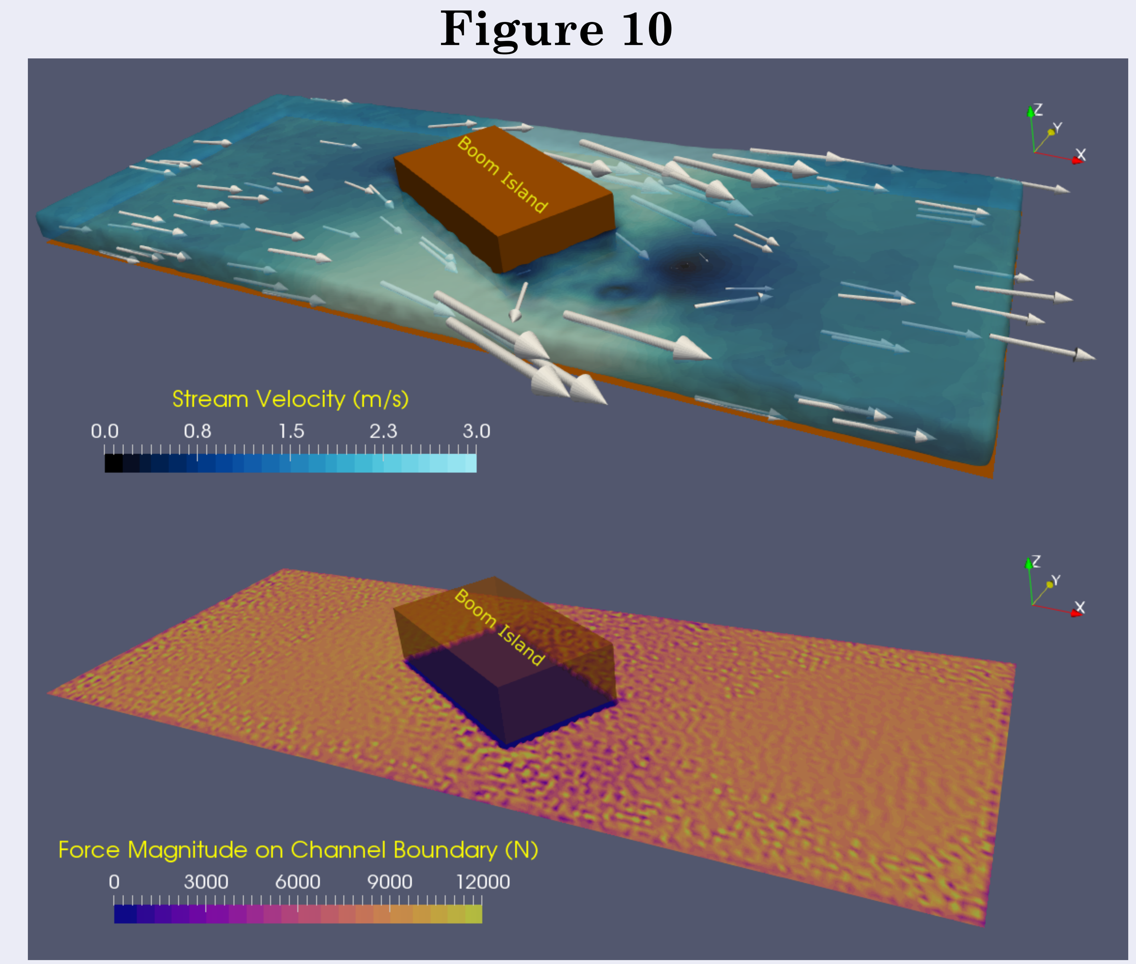
"Boom Islands" (Figure 9) are relict structures used for logging operations on Maine's Penobscot River. These structures became unsubmerged after the 2013 removal of Veazie Dam, and the flow obstruction may create dynamic habitats which are favorable to protected species such as Shortnose Sturgeon. Field observations will be compared to SPH model results to evaluate the role of Boom Islands and substrate texture on the velocity structure of the Penobscot River.

Figure 9



Shown below is an SPH solution for flow past an idealized boom island. A distinct low-velocity zone (top panel) and zone of low forces acting on the channel bed (bottom panel) on the down-stream end of the boom island may provide favorable breeding conditions for shortnose sturgeon.

Figure 10



Acknowledgements

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