Investigating the Fluvial Dynamics of Maine's Penobscot River Using Smoothed Particle Hydrodynamics

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Introduction

- When dams and relict logging structures are removed, the resulting sediment mobilization alters fluvial dynamics and disrupts critical zone processes.
- By adapting smoothed particle hydrodynamics simulations (SPH) to fluvial systems, the sediment mobilization potential associated with dam removal can be investigated for Maine's Penobscot River.

Methods

-Innovative smoothed particle hydrodynamics (SPH) solutions to the Navier-Stokes equations allow interactions between weakly-compressible fluids and solid structures to be resolved in three-dimensional space.
- Adapting SPH to the Penobscot River provides detailed solutions which will be used to simulate the acute impacts of dam removal on the Penobscot River's hydrodynamics and dynamic habitats.
- DualSPHysics, an open source SPH solver which uses parallel processing to simulate millions of particles, was used to produce the SPH models seen here.

Advantages of SPH

- Critical to resolving free-surface flows is the adequate handling of the inertial term of the Navier-Stokes (NS) equations:

$$\rho \; \frac{\partial u}{\partial t} + u * \nabla u = -\nabla p + \nabla * (\theta(\nabla u + (\nabla u)^{T}) - \frac{2}{3}\theta \nabla * u) I) + F$$

- SPH is able to handle fluid accelerations very well, which allows for robust solutions of the intertial NS term and realistic simulation of structure-fluid interaction.
- Simulation of (up to) millions of particles unbound to mesh enables investigation of the energies and kinematics associated with flow past heterogeneous boundaries, which makes it possible to draw conclusions about the effect of heterogeneities such as substrate texture and bedrock cohesion on the hydrodynamics of river systems.

Flow Obstructions in the Penobscot River Watershed

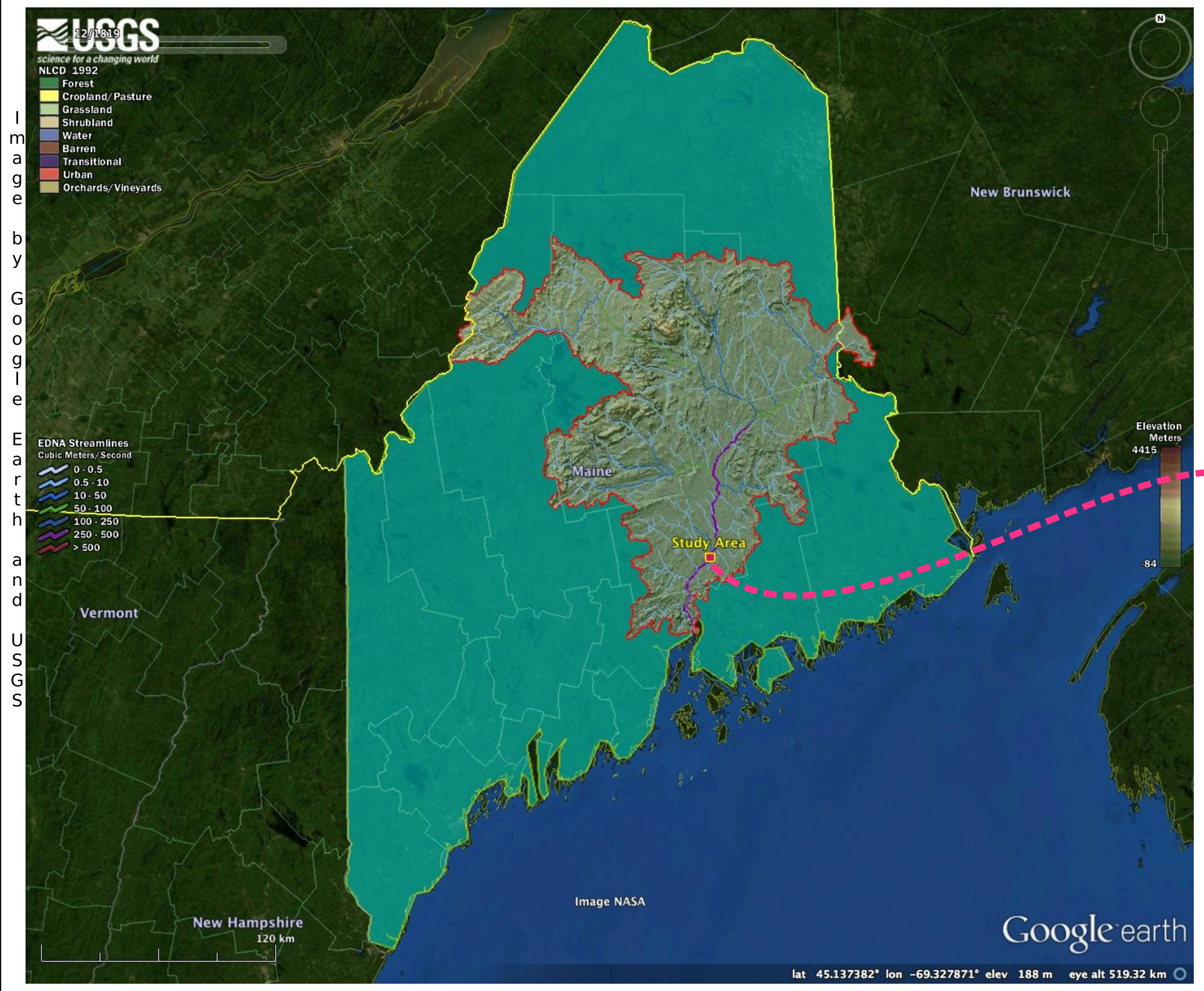


Image Credits: Penobscot River Restoration Project

Veazie Dam was removed in 2013 as part of the Penobscot River Restoration Project. The dam measured 880 feet long with a head height of 19 feet.

Image Credits: Penobscot River Restoration Project

"Boom Islands" (pictured right) are relict structures created to facilitate logging operations on the Penobscot River. These structures impede flow, but their existence may create dynamic habitats that are favorable to protected species such as Atlantic and Shortnose Sturgeon. Logging operations on the Penobscot also added sunken logs to the substrate; these logs may contribute to turbulence at the riverbed.

Image Credits: Bangor Daily News

Models

Figure 1: Cross Section of Flow Over a Saturated Sediment Substrate

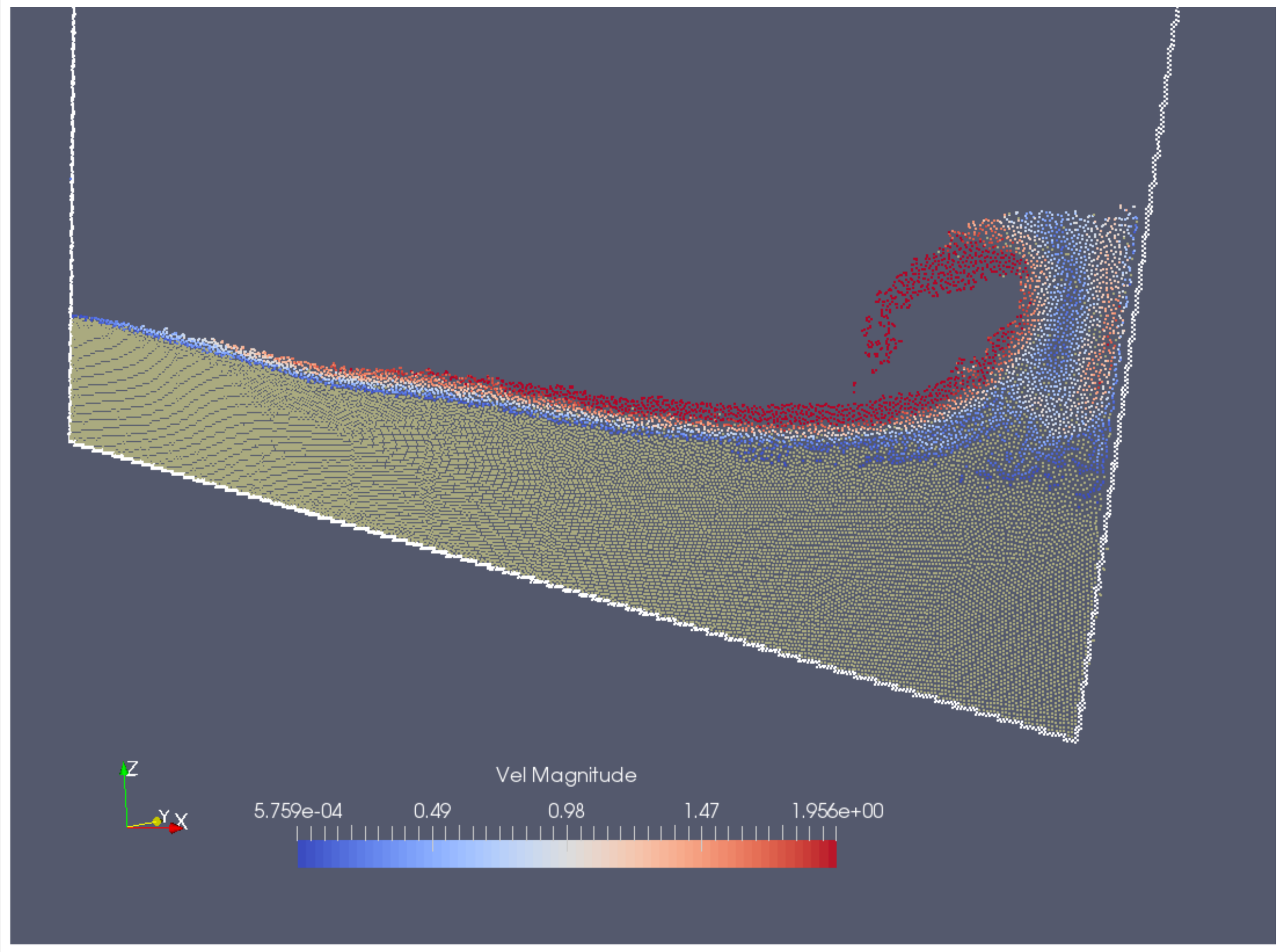
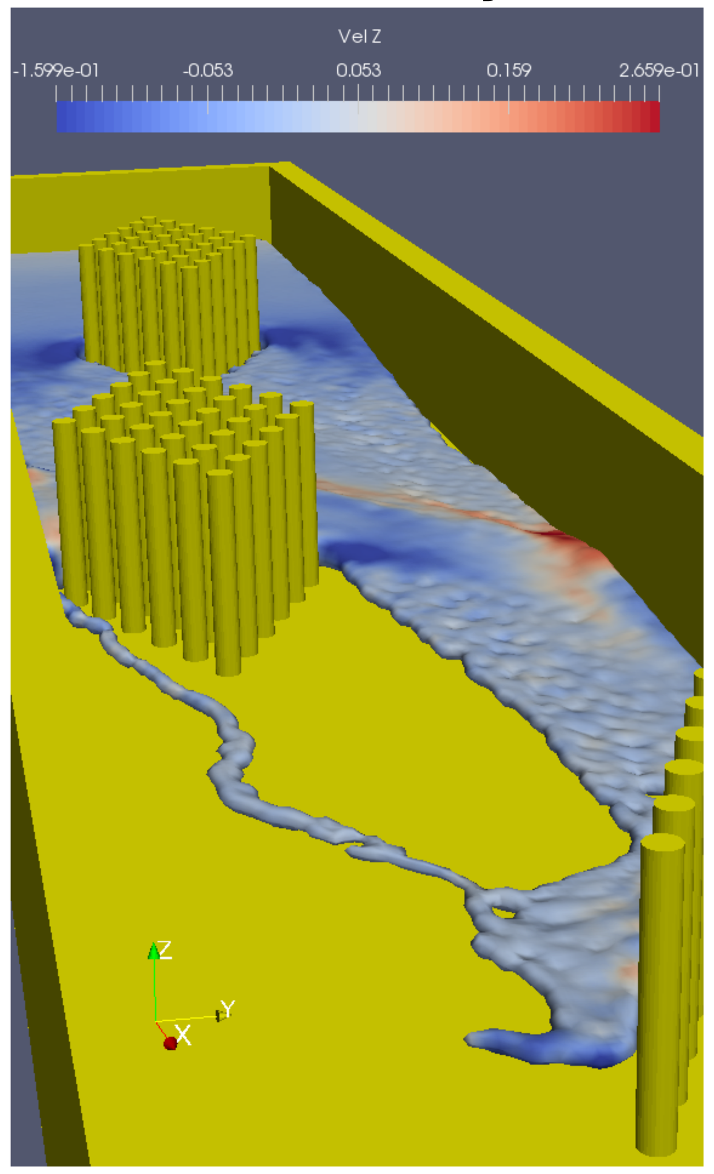


Figure 1 shows water flowing above a saturated sediment substrate. Sediment is advected as the water accelerates from the left side of the tank to the right. Vorticity of the water intensifies sediment advection. This model uses the Drucker-Prager Yield Criterion to describe the plastic yielding of the saturated sediment.

Figure 2 show water moving about clusters of densely-packed cylindrical obstacles. The presence of a standing wave oblique to the right edge of the tank contributes to a high vertical velocity gradient. This observation is made possible by the full three-dimensional solutions provided by SPH method.

Figure 2: Flow About Cylinders



The Importance of Synthetic Environments

In order to adequately describe the behavior of particles in natural systems, it is important to first describe the signal of particles in idealized, predictable settings. Rendering natural environments is made possible by merging LiDAR and bathymetric data, but many interesting descriptions are lost to the low resolution of the boundaries (see Figure 3).

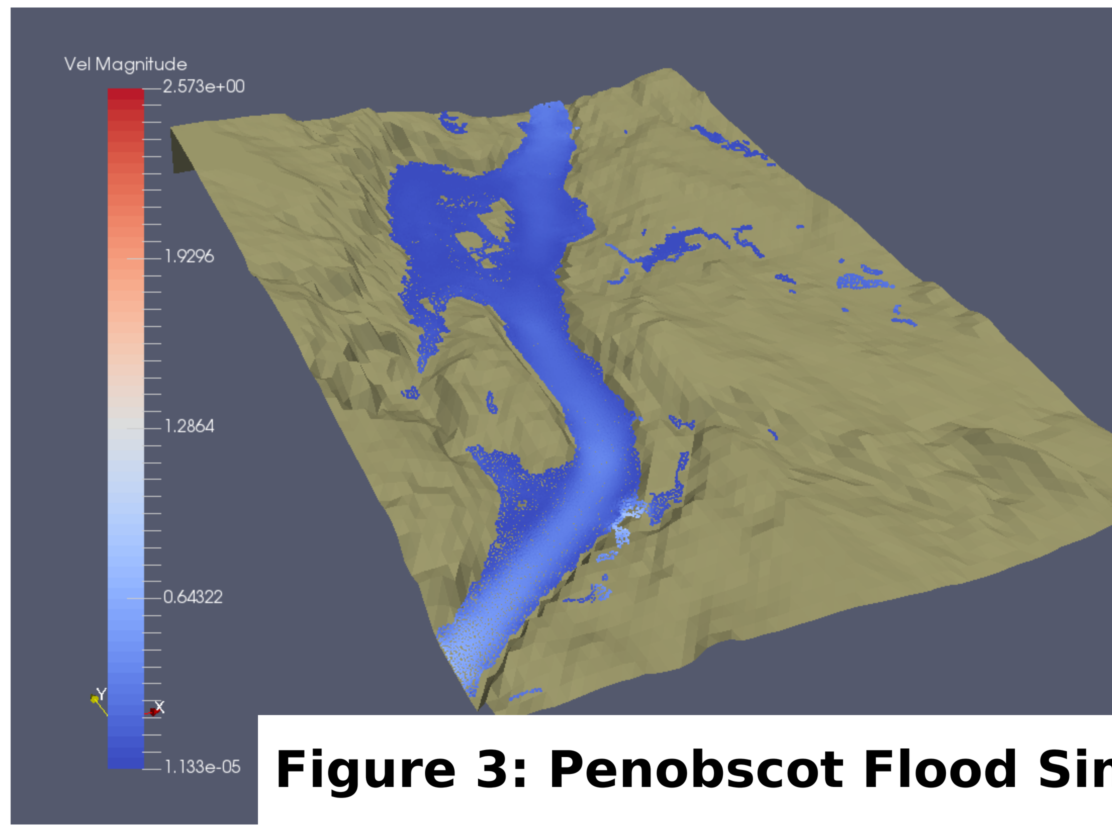


Figure 3 shows a flood scenario for the area around a ~5km long reach just north of the former Veazie Dam. To create a natural environment for use in DualSPHysics, bathymetric data must be appended to digital data for the surrounding floodplain. The digital elevation data joined using a GIS suite is then used to render a scene in Blender.

Figure 3: Penobscot Flood Simulation

Acknowledgements

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Conclusions and Future Work

- SPH provides a solid foundation for numerical simulation of fluvial hydrodynamics in the Penobscot River.
- The changing hydraulics associated with dam removal will be simulated to draw conclusions about the effects of dam removal on the dynamic habitats of protected fish species, particularly Atlantic and Shortnose Sturgeon.
- Boom islands have highly variable geometry. Rendering a wide variety of boom island geometries will be useful when determining their hydrodynamic signature in the Penobscot River.
- Field measurements of substrate texture, boundary structure, and flow conditions will be necessary to calibrate SPH models to the Penobscot River.