TN

MP

CI

BI

HIGH-RESOLUTION NUMERICAL SIMULATION OF FLOW AND SEDIMENT TRANSPORT THROUGH AQUATIC VEGETATION

Allocation: Illinois/200 Knh
PI: Rafael Tinoco Lopez[1]
Co-PI: Paul Fischer[1]
Collaborators: Som Dutta[1], Pallav Ranjan[1]

[1]University of Illinois at Urbana-Champaign

EXECUTIVE SUMMARY

Aquatic vegetation exerts significant influence in the hydrodynamics of both fluvial and coastal systems. It extracts energy from the flow, which has been found to impede near-bed flow velocities, to modify the structure of the velocity field, and consequently influence sediment erosion and resuspension. Aquatic vegetation influences different processes to such an extent that vegetation has been earmarked as a key component influencing aquatic ecosystems. Our study is geared toward increasing our understanding of the interactions among vegetation, flow, and sediment. We have conducted Direct Numerical Simulations (DNS) and Large Eddy Simulations (LES) through different arrays of idealized vegetation, represented as cylinders, using the higher-order spectral element-based computational fluid dynamics (CFD) solver Nek5000. We simulated different arrangements of cylinders, and the high-fidelity turbulent simulations have shed light on details of the flow features, increasing our understanding of different hydro- and morphodynamic processes.

RESEARCH CHALLENGE

Aquatic vegetation is known to stabilize its environment, thus engineering different aspects of its own ecosystem [1]. Aquatic vegetation provides a wide range of ecosystem services [2], ranging from an increase in water quality through nutrient uptake and oxygen production to creation of habitats through spatial heterogeneity of the flow velocity to dampening erosion. Past computational studies have mainly focused on using CFD models, based on Reynolds Averaged Navier–Stokes equations (RANS), which only provide an averaged approximation of the flow-field. The few studies that have used high-fidelity LES have been limited by the number of vegetation elements. Most of the existing data in this area come from laboratory experiments [3], recreating conditions closer to nature but often lacking the spatial and temporal resolution required to capture some fundamental processes in detail.

The current study is geared to complement experiments being conducted at the Ven Te Chow Hydrosystems Laboratory at the University of Illinois at Urbana-Champaign. The study conducts numerical simulations at an unprecedented scale, resolving details that, in conjunction with the experiments, is providing unforeseen insights into the fundamental dynamics of flow and transport in the presence of aquatic vegetation [4]. These large-scale computations will not only help improve lower-order models of the processes but will also help inform better experimental design and measurement practices.

The scale of the experimental setup to be modeled is a paramount challenge. The number of computation points required to model the whole domain is near 1.2 billion. While such simulations are still tractable on a petascale platform like Blue Waters, the computational cost is high. This results in a reduction in the number of cases that can be run, thus constraining the insights a broader range of parameters could yield.

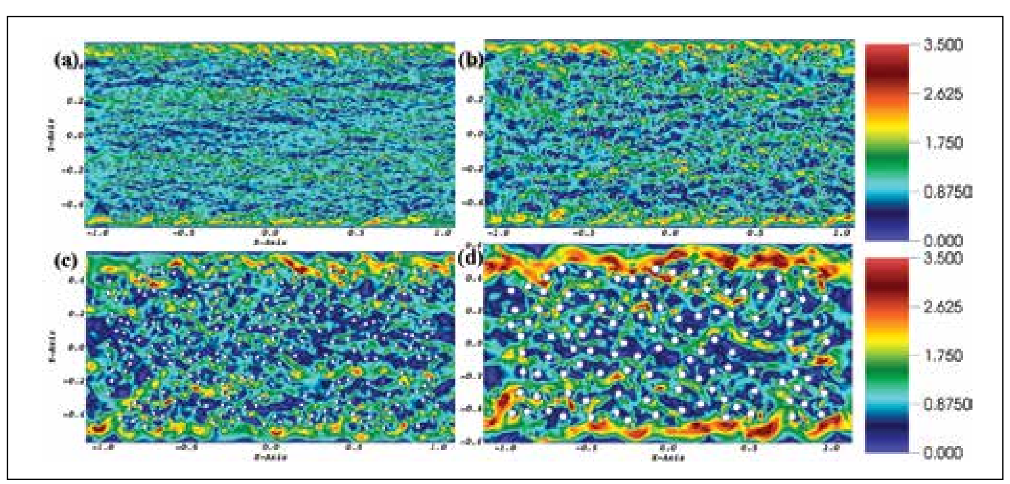

Figure 1: Instantaneous velocity magnitude for flow through random arrays of idealized aquatic vegetation at Reynolds number ~10,000. The arrays have the same volumetric frontal area but different cylinder diameters: (a) 1/8 inch, (b) 1/4 inch, (c) 1/2 inch, and (d) 1 inch. Despite having the same frontal area, the number of high-velocity regions is substantially higher for larger diameters, which also show a more heterogeneous velocity distribution.

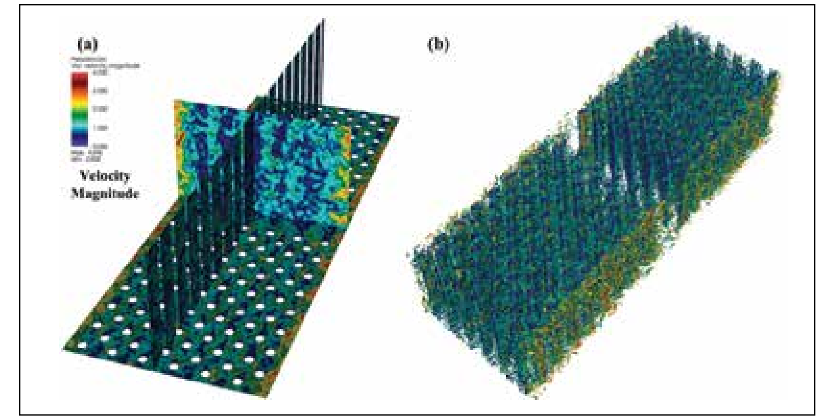

Figure 2: 3D simulation of turbulent flow through a staggered array of emergent cylinders with about 150 million computational points. (a) Plots the instantaneous velocity magnitude at three planes. (b) Visualizes the continuous shedding of vortices using the isosurface of the negative eigenvalue of the vorticity field.

To increase variable space, a wide range of conditions are first simulated in two dimensions for the whole domain (~6 million computational points). This gives an overview of the effect of different parameters such as Reynolds number, vegetation density, and spatial heterogeneity. For a limited set of conditions, we are conducting three-dimensional simulations (~200 million computational points) for only a part of the domain. The conditions to simulate in 3D are informed by the 2D simulations, where the 3D domains are big enough to accurately capture the general dynamics within manageable computational costs.

METHODS & CODES

High-resolution LES and DNS of the flow at different configurations of the idealized vegetation are conducted using the open-source, spectral element-based, high-order incompressible Navier–Stokes solver Nek5000 [5,6]. In the simulations with sediment, sediment transport is modeled under the Eulerian framework using the advection-diffusion equation [7], making our study one of the first to look at the complex interaction between sediment-flow and vegetation using high-fidelity CFD simulations.

RESULTS & IMPACT

We conducted 2D simulations for the full experimental domain for different Reynolds numbers and varying random configurations of vegetation elements for random arrays having the same volumetric frontal area but different cylinder diameters (see Fig. 1). It is evident that, even though the volumetric frontal area is the same, different diameters result in different porosities, thus increasing the heterogeneity in the flow with an increase in diameter of the vegetation elements. We monitored drag on the vegetation arrays and observed that, for the same Reynolds number, the drag in the transverse direction increases with an increase in diameter of the vegetation elements.

We also conducted 3D simulations for different Reynolds numbers, ranging between 12,000 and 20,000, for a staggered array of vegetation elements (see Fig. 2). The simulated setup is similar to experiments currently being conducted at the laboratory. We conducted simulations using up to 200 million computational points, running on 16,384 processors at a time. The simulation results show clear evidence of the dynamics of the flow being driven primarily by the vegetation elements, with clear preferential flow-paths through the array of elements. We visualized the vortices shedding by the cylinders using the isosurface of the negative eigenvalue of the gradient velocity tensor that is decomposed into its symmetric and antisymmetric parts [8]. As expected, the vortex tubes being generated scale to the diameter of the vegetation elements. As part of the analysis, we are investigating the turbulent kinetic energy and turbulence intensity in order to link them to variations in bed shear stresses and intermittent turbulent events altering the sediment transport capacity of the flow.

WHY BLUE WATERS

The study pushes the limits of the scale at which high-resolution simulations are used to study complex multiphase flow in environmental fluid mechanics, requiring computational resources with sustained computing power at an unprecedented scale, such as Blue Waters. We have conducted simulations for up to 200 million computational points, with the code scaling strongly up to 16,384 MPI ranks. Without access to petascale high-performance computing, it would be impossible to complete the simulations within a realistic timeframe. In addition, since visualization of a phenomenon is an effective way to understand and explain its mechanics, we will work with the Blue Waters project staff to create animations of the phenomenon using data from the simulations.

PUBLICATIONS & DATA SETS

Dutta, S., et al., 2D High-Resolution numerical investigation of flow through surrogate emergent vegetation canopies: Part 1. Unidirectional Flow. In preparation for *Environmental Fluid Mechanics* (2018)

Dutta, S., et al., 2D High-Resolution numerical investigation of flow through surrogate emergent vegetation canopies: Part 2. Oscillatory Flow. In preparation for *Environmental Fluid Mechanics* (2018).

Ranjan, P., et al., Flow and sediment transport though aquatic vegetation. In preparation for *Geophysical Research Letters* (2018).