LARGE-EDDY SIMULATION OF SEDIMENT TRANSPORT AND HYDRODYNAMICS AT RIVER BIFURCATIONS: USING A HIGHLY SCALABLE SPECTRAL ELEMENT-BASED CFD SOLVER

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EXECUTIVE SUMMARY

Bifurcations are fundamental features of all river systems. This study focuses on a specific class of bifurcations called diversions. Experiments have shown that the distribution of near-bed sediment between the downstream channels at a diversion is not proportional to the water flow distribution, with a disproportionately higher amount of sediment going into the lateral channel. A better understanding of the aforementioned non-linear phenomena will help in efficient design of river diversions. Diversions are used for navigation and flood mitigation, and have also been put forth as a solution for reclaiming deltas going under the sea due to increasing sea level. The current study investigates the mechanisms behind this phenomenon through Large Eddy Simulations (LES) and Direct Numerical Simulations (DNS) of the flow in idealized diversions of different configurations, with the sediment being modeled as Lagrangian particles. The simulations have been conducted using a highly scalable spectral element based incompressible Navier-Stokes solver, Nek5000. The simulation conditions are comparable to the laboratory experiments, which make these simulations large enough to require the use of Blue Waters. The simulation results provide new insight into the mechanism behind the phenomenon, and has identified yet unexplored parameters that influences the distribution of sediment at a diversion.

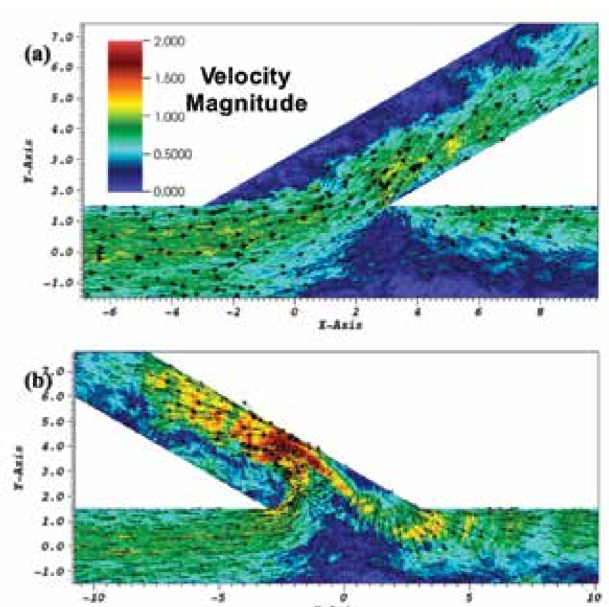

Figure 1: Instantaneous velocity magnitude at the bottom of the channel for diversion angle of (a) 30-degrees and (b) 150-degrees. For both cases, the Reynolds number of the flow is 25,000, and the flow is divided equally between the two channels. One can clearly observe that most of the flow near the bottom enters the lateral channel, even though the total flow is equally divided between the two channels.

RESEARCH CHALLENGE

Bifurcations are fundamental features found in river systems. This current study focuses on a specific class of bifurcations called diversions, where one source channel splits into two: a main channel and a lateral branch. Laboratory experiments conducted by Bulle in 1926 [1,2] and later by other investigators, have shown that the distribution of near-bed sediment between the downstream channels is not proportional to the flow distribution, with a disproportionately higher amount of sediment going into the lateral channel. This non-linear phenomenon is often referred to as the Bulle Effect. The current study investigates the mechanisms behind this phenomenon through high-resolution numerical simulations of the flow and sediment transport at the scale, and for the configurations similar to Bulle's experiments.

A better understanding of the aforementioned phenomenon will help in efficient design of river diversions, which among uses like navigation and flood-mitigation have also been put forth as a solution for reclaiming deltas sinking under the sea due to rise in sea level, which is a consequence of anthropogenic climate change [3]. A prime example is the Mississippi River delta, for which different potential diversion designs are being studied for diverting water and sediment from the Mississippi River [4]. Better understanding of the phenomenon will eventually help in more accurate prediction of the short and long-term geomorphological evolution of river bifurcations, thus furthering the state of art in the field of river mechanics. It will also provide insights that will help improve reduced-order models of flow and sediment transport at bifurcations. Better understanding of the fundamental mechanism behind Bulle-Effect will also help shed light on vorticity-driven transport at bifurcations in human body (e.g. the carotid bifurcation [6]) and manmade systems (e.g. grit chambers in water reclamation plants [5]).

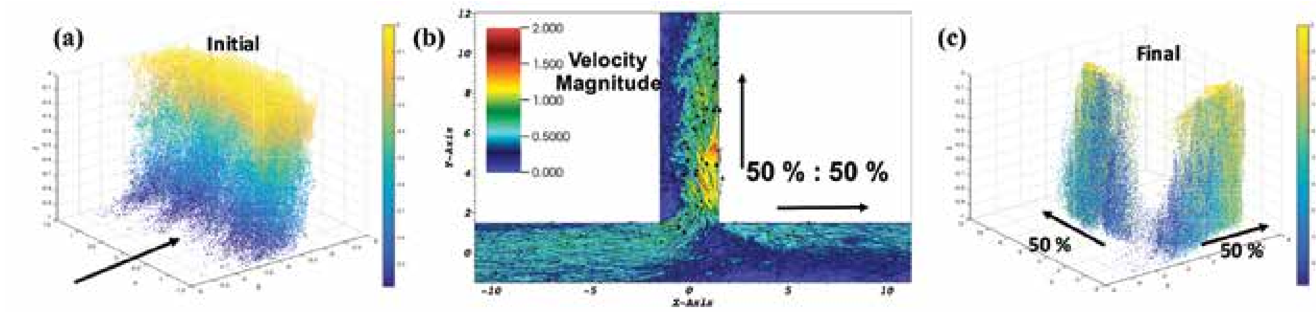

Figure 2: The figure illustrates the division of uniformly distributed (in the water column) neutrally buoyant fine particles between the two channels, for Reynolds number of 25,000 and 50:50 flow division. The particles in the panels (a, b) are colored according to their position in the water column. Particles near the bottom are blue and those near the top are yellow. (c) shows that most of the blue particles have moved into the lateral channel and most of the yellow particles have continued into the main channel.

RESULTS & IMPACT

High-resolution Large Eddy Simulations (LES) and Direct Numerical Simulations (DNS) of the flow at different configurations of the idealized diversions have been conducted, with sediment being modeled as Lagrangian particles. A simulation being LES or DNS depended on the Reynolds number of the flow, as simulations were conducted for a range of Reynolds numbers 10–25,000. For the cases with Reynolds number of 25,000 the conditions are comparable to the laboratory experiments. The simulations have been conducted using the open-source, spectral element based higher-order incompressible Navier-Stokes solver Nek5000 [7]. The Spectral Element Method (SEM) combines the accuracy of spectral methods and the flexibility of Finite Elements Method [8]. Sediment transport in the flow has been modeled using Lagrangian particle tracking. For simulating transport of poly-disperse sediment particles efficiently, a semi-implicit Lagrangian particle algorithm was developed for the current study [1].

Initial results had shown that for a 90-degree diversion, and the flow being equally divided between the channels, the simulation was able to capture the preferential movement of bedload sediment into the lateral-channel [2]. Hence, simulations were conducted for a range of Reynolds number and flow divisions, further confirming the primary driver of the phenomenon that is preferential movement of the flow near the bottom of the channel into the lateral-channel [3,4]. This characteristic of the flow was also observed for different diversion angles (e.g. for 30,150 degrees see fig. 1).

Simulations were also conducted for sediment with different diameters, which made them travel at different depths in the water column. It was found that the phenomenon was not just valid for sediment traveling as bedload, but for any sediment traveling at the lower 30 percent of the water column. To illustrate that, thousands of neutrally buoyant fine particles were released and their paths monitored. These particles by design will follow the flow, thus providing a sense of how the flow divides between the two channels. Figure 2 illustrates one of the above-mentioned cases, where most of the particles starting near the bottom of the channel can be observed to primarily move into the lateral-channel. This study not only provides new insights into the hydrodynamics and sediment transport at bifurcations, it also shows that high-resolution LES can be used to study complex river-mechanics problems.

WHY BLUE WATERS

The current study pushes the limit of the scale at which high-resolution LES have been used to study complex multi-phase river mechanics problems, warranting the use of a computational resource that can provide sustained computing power at an unprecedented scale, thus the need to use Blue Waters. For the current study simulations have been conducted for up to 243.648 million computational points, with the code scaling strongly up to 32,768 MPI ranks. Without access to supercomputers like Blue-Waters, completing the study within a realistic timeframe would be impossible. Visualization of a phenomenon is an effective way to understand (and explain) it's mechanics, thus we are currently working with Blue Waters project staff to create an animation of the phenomenon, using data from one of the simulations.

PUBLICATIONS AND DATA SETS

S. Dutta, P. Fischer, M.H. Garcia, A novel semi-implicit Lagrangian particle tracking model for efficient computation of particle transport at low Stokes number, under preparation for Journal of Scientific Computing, Springer.

S. Dutta, P. Fischer, M.H. Garcia, Large Eddy Simulation (LES) of flow and bedload transport at an idealized 90-degree diversion: insight into Bulle-Effect. In River Flow 2016, CRC Press (2016).

S. Dutta, P. Fischer, M.H. Garcia, Direct Numerical Simulation of flow at a 90-degree asymmetric bifurcation for different flow splits, under preparation for Journal of Fluid Mechanics.

S. Dutta, P. Fischer, M.H. Garcia, Flow dynamics and fine particle transport at an asymmetric 90-degree bifurcation: insights into the Bulle-Effect under laminar inflow, under preparation for Physical Review Fluids.