LARGE EDDY SIMULATION OF SEDIMENT TRANSPORT AND HYDRODYNAMICS AT RIVER BIFURCATIONS

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EXECUTIVE SUMMARY:

A fundamental morphological element present in most river systems is a bifurcation. A diversion is a special kind of bifurcation in which one of the post-bifurcation channels continues along the direction of the original un-bifurcated channel. Previous studies have shown that a larger percentage of near-bed sediments at diversions tend to enter the new channel, even in cases where the opposite trend is exhibited by the water discharge. This study attempts to bolster fundamental understanding of this and related phenomena, such as secondary flows and vorticity-driven sediment transport.

Our simulations resolved all the relevant turbulent eddies of the flow, which not only provided an accurate description of the dynamics of the flow, but also helped model sediment transport accurately when coupled with a Lagrangian particle model for the sediment. We ran computational fluid dynamics simulations using the incompressible Navier–Stokes solver Nek5000. The maximum bulk Reynolds (Re) number of the completed simulations was 7,000; more simulations with higher Re and different diversion angles are planned.

INTRODUCTION

Most river systems contain one or more bifurcations, where a river divides into two channels that each carries part of the water and sediment. Most bifurcations form naturally, like the dendritic networks in deltas, the in-stream bifurcations in braided rivers, etc. Bifurcations have also been built for various engineering purposes, like river connectivity, flood protection, etc. The engineered bifurcations are more commonly referred to as diversions. In a diversion, a lateral channel comes out from the side of the original channel, which continues along the original stream path.

In order to understand the division of flow and near-bed sediment between the main and the diverted channels, H. Bulle conducted the first systematic study of the division of near-bed sediment between bifurcating channels [1]. Through his laboratory experiments, Bulle showed that the near-bed sediment discharge distribution tends to favor the lateral channel, even in cases where water discharge favors the original channel; this nonlinear phenomenon is known as the Bulle Effect.

Interest in fluvial diversions has spiked in the last decade as old diversion channels clog with sediment and engineers look to diversions as a possible means to maintain deltas in the face of rising sea levels [2]. For example, several designs are being evaluated to mitigate potential loss of coastal land and delta degradation in the Lower Mississippi River in Louisiana [3]. Finding the optimal location and layout of the diversions will be more efficient if the fundamental mechanism that causes the Bulle Effect is well understood. On the other side of the world, the Indian government plans to interconnect several rivers [4], many of which carry huge sediment loads that may be redistributed by fluvial diversions.

Apart from improving fundamental understanding of the fluid dynamics at river diversions and its implications on morphological evolution, the current study will also help improve numerical models of bifurcations used for field-scale simulations. A better understanding of the fundamental mechanism behind the Bulle Effect will help shed light on the related phenomenon of vorticity-driven sediment transport, which affects both natural and man-made systems [5].

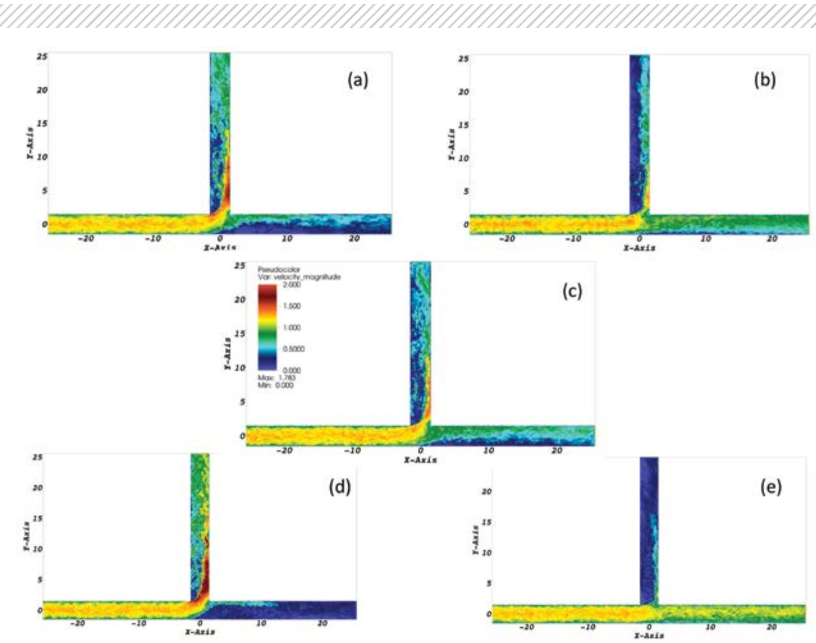

FIGURE 1: Velocity magnitude at a height of 0.75 from the bottom (where channel height is 1.0) for a bulk Reynolds number of 7,000, for different ratios of flows going through each channel: in percentages, (a) 65-35, (b) 35-65, (c) 50-50, (d) 85-15, and (e) 15-85.

METHODS & RESULTS

The simulations had two parts: the fluid portion that was modeled using the 3D incompressible Navier–Stokes equation with the large eddy simulation (LES) approach, and the sediment transport that was modeled as Lagrangian particles [7, 8]. In the LES approach the relevant scales of the flow are resolved and a subgrid stress model simulates the subgrid scales [9]. The simulations are being conducted using Nek5000, an open-source, highly-scalable eddy-resolving incompressible Navier–Stokes solver based on the spectral element method (SEM) [10]. The SEM combines the accuracy of spectral methods and the flexibility of numerical methods based on local approaches, like the finite elements method [11].

The first group of cases that was simulated for the current study was for a 90° diversion angle and bulk Reynolds number of 7,000. Five simulations with different water discharge ratios between the two channels (in percentages: 50-50, 65-35, 35-65, 85-15, and 15-85) were conducted using about 224 million computational points. Velocity magnitudes at a height of 0.75 from the channel bottom (where channel height is 1.0) were plotted for the simulated cases (fig. 1). A distinct and sustained high-velocity zone hugging the right side of the diverted channel was observed in all the cases. The high-velocity zone was expected, but it was surprising to see the relative lack of mixing between the high-velocity and low-velocity zones in the diverted channel, especially for cases where flow in the diverted channel was less than the main channel. The simulations were able to successfully capture the two separation zones in the flow in both channels, though the separation zone in the main channel was more persistent than expected. The structure of the flow clearly indicated the cause of the Bulle Effect. These preliminary results also show how HPC can be used to accurately simulate eddy-resolving river flows at an unprecedented scale.

WHY BLUE WATERS?

The current study pushes the limit of the scale at which eddy-resolving numerical simulations have been used to study complex multi-phase river mechanics. The simulated cases herein required 224 million computational points, and this number can go up to a billion for a Reynolds number of the order 10^4–10^5. Additional computing time would be required to model the sediment using Lagrangian particle tracking; thus, researchers need petascale facilities in order to complete the simulations in a realistic amount of time. Access to the next generation of Track-1 systems will allow us to conduct eddy-resolving simulations of environmental flows at scales and with complexity similar to that of nature. This will allow us to better understand the underlying mechanisms of different environmental flows and help improve predictions of different natural processes.