Numerical Modeling of Turbulence and Sediment Transport in Lateral Recirculation Zones along the Colorado River in Grand Canyon

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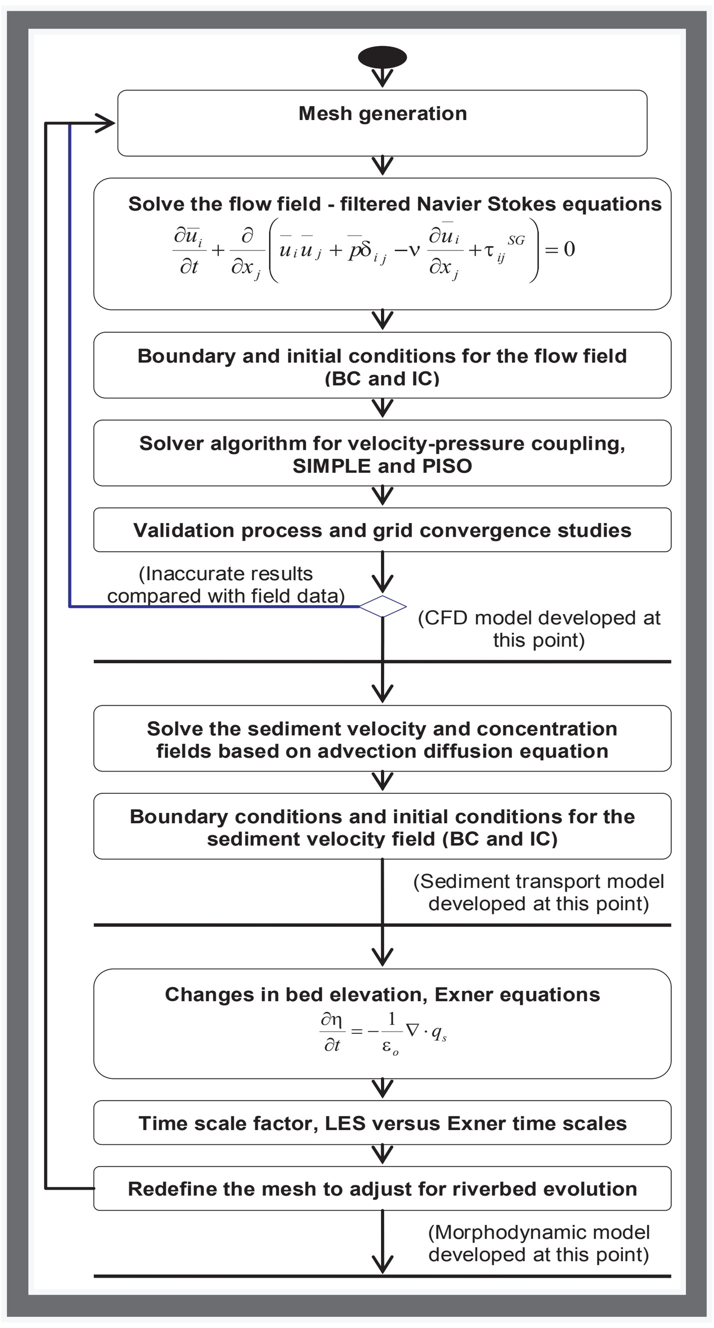
MOTIVATION

A number of two- and three-dimensional models are currently available to calculate sediment transport and channel change in rivers. These three-dimensional models rely on time-averaging and parameterization of the turbulence. Available depth-averaged, two-dimensional models also rely on simple boundary stress closures. In relatively simple channels these models have predictive capability, but they often perform poorly when there is large-scale flow separation or when secondary circulation is strong. Sharp meanders, channel constrictions, many engineering structures, vegetation, and certain types of bedforms all cause flow separation, secondary circulation, and free shear layers. Turbulence-resolving flow and sediment transport models may do better at predicting channel change in complex channels, but at a substantially larger computational cost. With parallelization, turbulence-resolving models can now be developed and applied to refractory fluvial morphodynamic problems.

OBJECTIVE

The general objective is oriented to research the details of turbulent flow structures and their effect on sediment patterns, by means of a high resolution numerical modeling and laboratory experiments. The computational research focuses on applying Large Eddy Simulation techniques to develop three coupled numerical models at the scale of the river: (1) Computational Fluid Dynamic (CFD) model, (2) sediment transport model, (3) morphodynamic model.

METHODOLOGY



1. Mesh Generation: This numerical modeling is developed within OpenFOAM environment. A two-dimensional, depth-averaged flow model, also written in OpenFOAM, determines the local water surface elevation. A separate program was written to automatically construct the block-hexagonal, computational grid between the calculated water surface and a triangulated surface of a digital elevation model of the given river reach. Domain decomposition of the grid is employed to break up the integration between multiple processors, and Open MPI provides communication between the processors.

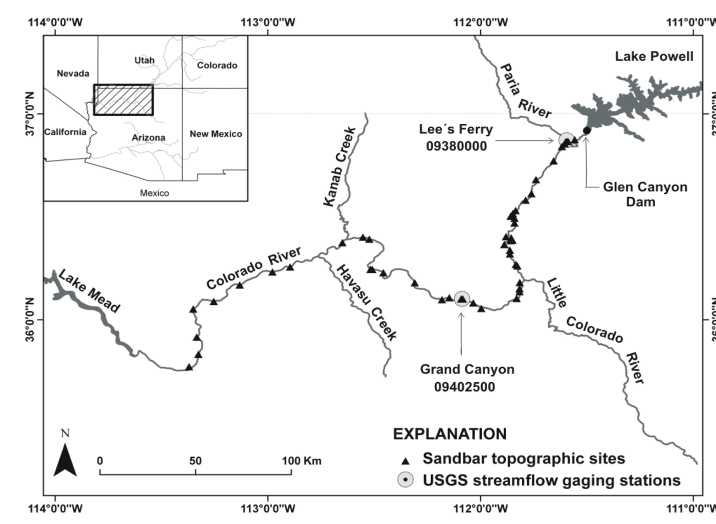
2. Detached-Eddy Simulation (DES) is a hybrid large eddy simulation (LES) and Reynolds-averaged Navier Stokes (RANS) method. RANS is applied to the attached flows at the boundary layer in the near-bed grid cells. LES is applied further from the bed and banks to the flow separation and recirculation regions formed above the boundary layer, which is our research interest. A one equation turbulence closure model with a wall-distance dependence, such as that of Spalart-Allmaras (S-A), is ideally suited for the DES approach.

3. Boundary conditions and initial conditions (BC & IC) for the flow field: . The steady solution (RANS) is used as an input for the initial conditions of the DES model. The boundary conditions for the velocity are no-slip on the bottom, free slip (zero stress) on the top and free slip on all lateral boundaries. The upstream velocity is produced by using a wall at the inlet to guarantee fully developed turbulence. The flow is driven by a uniform pressure gradient. The rough wall extension of the S-A model is utilized herein accounting for the riverbed roughness. It requires an adjustment of the roughness length scale in the bed, ks, to properly mimic the roughness effects of subaqueous ripples responsible of complex turbulent structures generated from the bed.

4. The validation process consists on measuring the accuracy of the resulting velocity field from the CFD model compared with ADCP data from the study region. The score metric to measure such accuracy is the Root Mean Square Error (RMSE) estimator. A grid convergence study is performed to assess the effect of grid resolution based on the grid convergence index (GCI) methodology. The GCI estimator explicitly calculates the accuracy of the grid scheme by measuring the percentage error between the computed values with respect to an asymptotic numerical value (or true solution) comparing the finest grid (reference grid) with coarser grids.

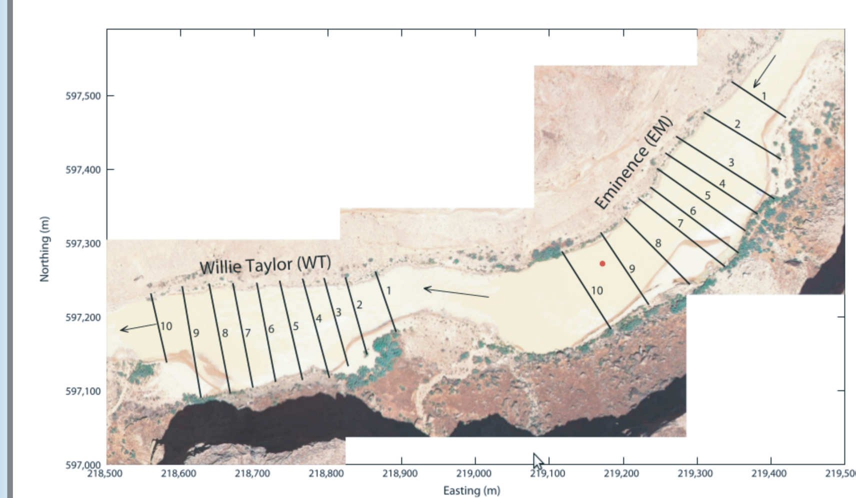
STUDY AREA

The study region comprises the Colorado River transect downstream Glen Canyon Dam spanning the Marble and Grand Canyons. The length of this transect is 446 km (277 miles).



Colorado River and major tributaries between Lake Powell and Lake Mead. Fan-eddy complexes surveyed by U.S. Geological Survey and Northern Arizona University and U.S. Geological Survey gauging stations are represented by the triangles and white circles respectively.

This research work is oriented to study the lateral recirculation zones (eddy) conducive to the formation of eddy sandbars. Results of the modeling system will be shown the flow and suspended sediment model in lateral separation eddies in the Colorado River in Grand Canyon. These recirculation zones formed downstream the channel constriction in the low velocity areas featured by flow separation and secondary flow structures.



On the left side: Aerial photography of Eminence Break (EM) and Willie Taylor (WT) eddy fan complexes.located 97 km downstream from the dam (Wright and Kaplinski, 2011). On the right side: Picture of the study sites taken from EM.

Sandbars provide backwater habitats for endangered species.

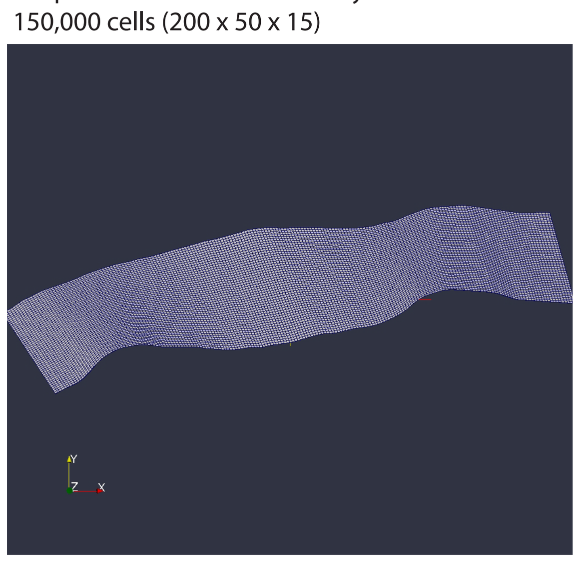
Endangered fishes: Flannelmouth sucker.

Humpback chub (Gila cypha).

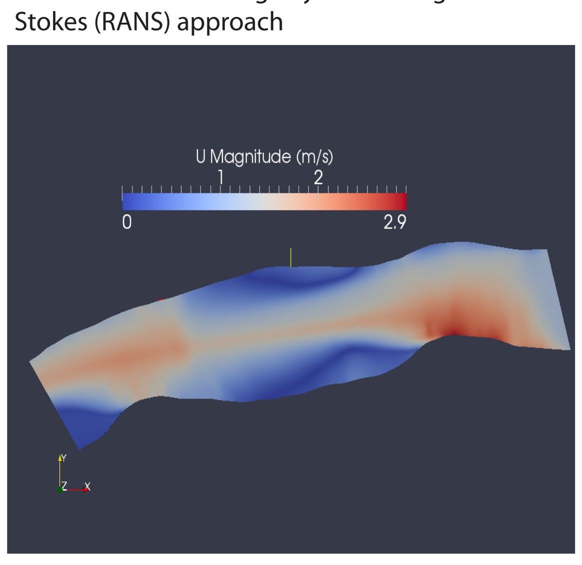
Dam operations resulted in erosion of eddy sandbars formed in the vicinity of the separation and reattachment zones. The Glen Canyon Dam Adaptive Management Program (GCDAMP), established in 1995, to advise the United States Department of Interior on operation of Glen Canyon Dam considers eddy sandbars to be an important resource. Among the most substantial benefits is their capability to provide habitat for native fish species, especially the Humpback chub (Gila cypha), which is listed as endangered by the United States Fish and Wildlife Service. The eddybars also serve as the substrate of riparian vegetation, as an aeolian source of fine sediment that preserves archaeological sites and as campsites for river rafters.

RESULTS

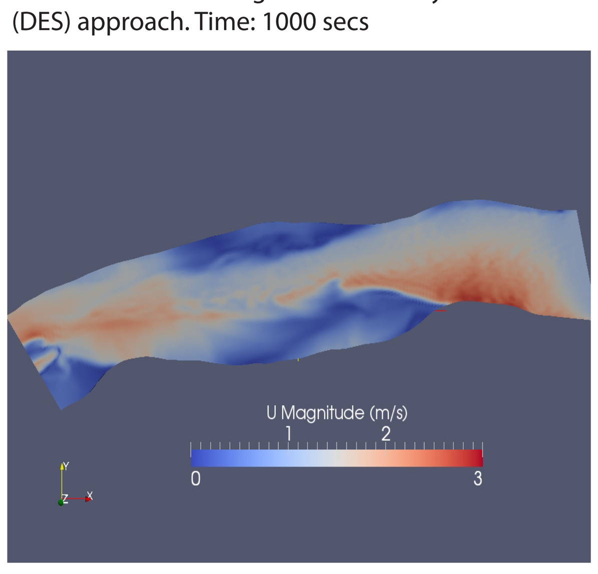
Snapshot of the mesh Willie Taylor.
150,000 cells (200 x 50 x 15)



Flow field solved using Reynols Averaged Navier Stokes (RANS) approach

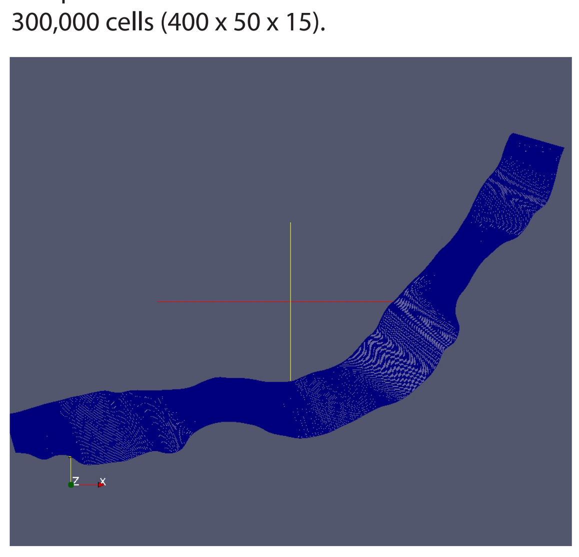


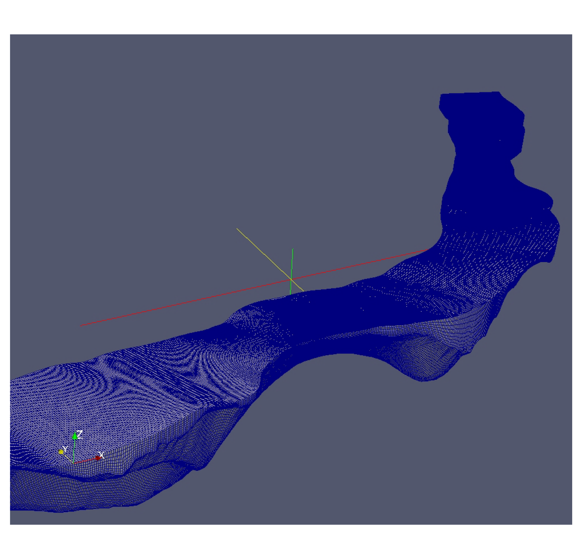
Flow field solved using Detached eddy simulation (DES) approach. Time: 1000 secs

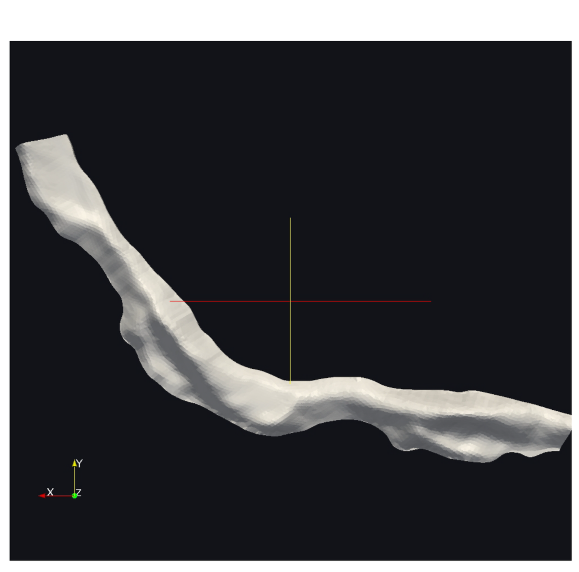


First results from numerical modeling system applied to Willie Taylor eddy fan complex The model does not include topographic boundary conditional at the water surface. No boundary conditions for the upstream velocity.

Snapshots of the block-hexagonal mesh generated for Eminence and Willie Taylor eddy fan complexes.
300,000 cells (400 x 50 x 15).

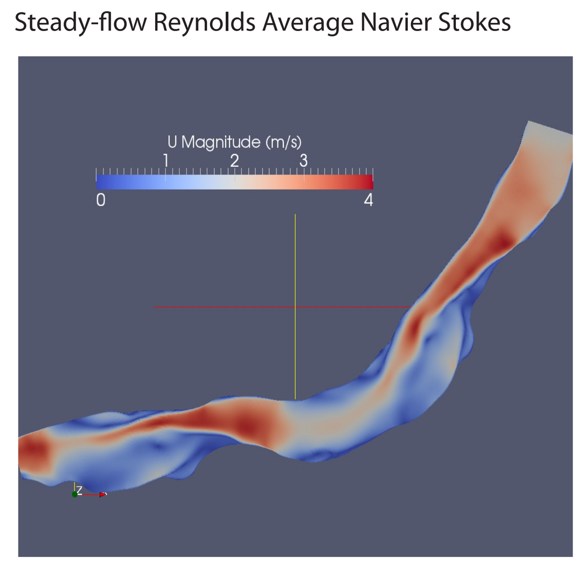




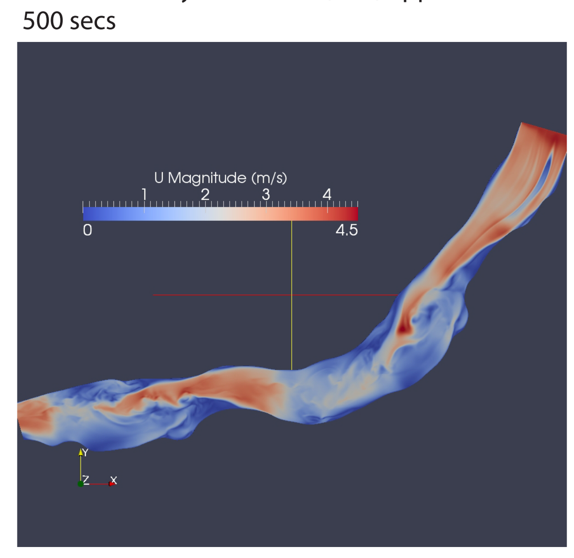


Computational grid between the calculated water surface elevation and the riverbed topography of a digital elevation model from the study region

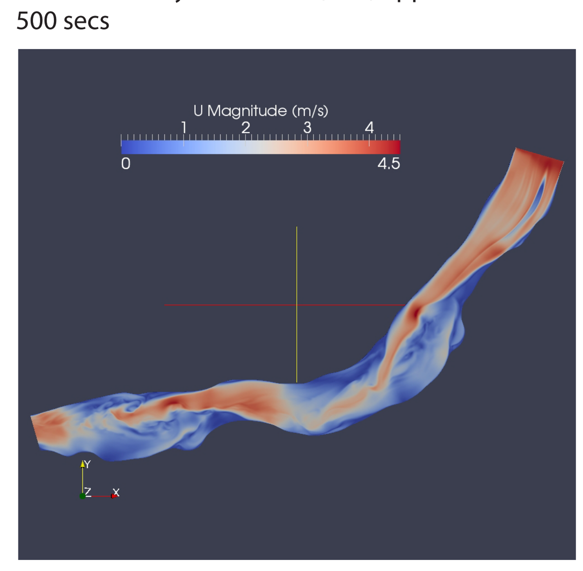
Steady-flow Reynolds Average Navier Stokes



Detached eddy simulation (DES) approach. Time: 500 secs



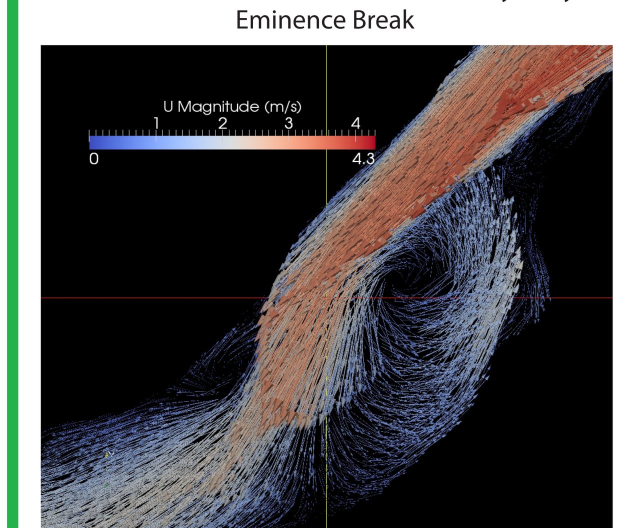
Detached eddy simulation (DES) approach. Time: 500 secs



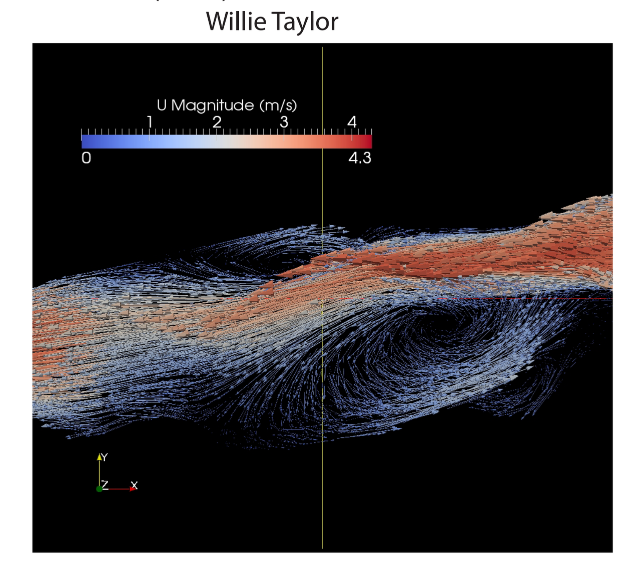
Latest results of the CFD modeling. Eminence Break and Willie Taylor eddy fan complexes. Upstream velocity boundary condition imposed to generate fully developed turbulence at the inlet.

Steady eddy recirculation zone (RANS)

Eminence Break

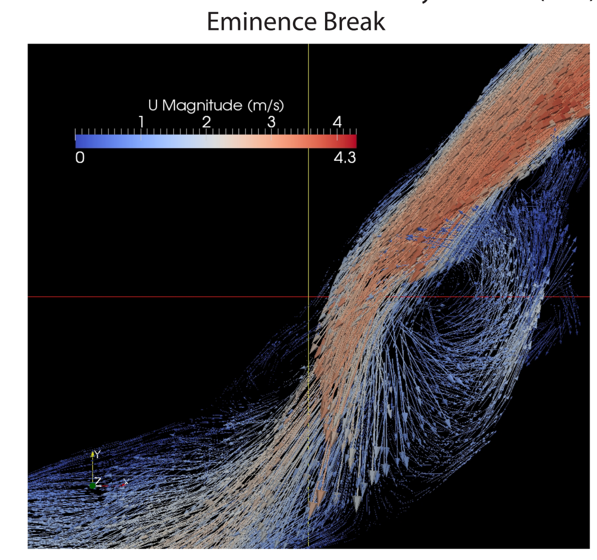


Willie Taylor

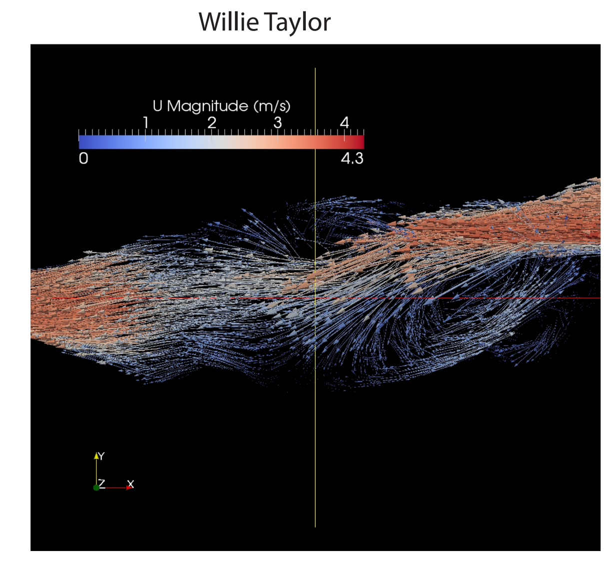


Unsteady solution (DES). Time 500 secs

Eminence Break

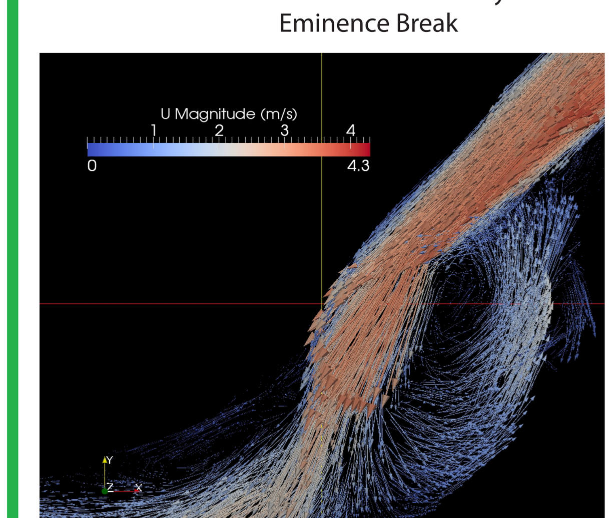


Willie Taylor

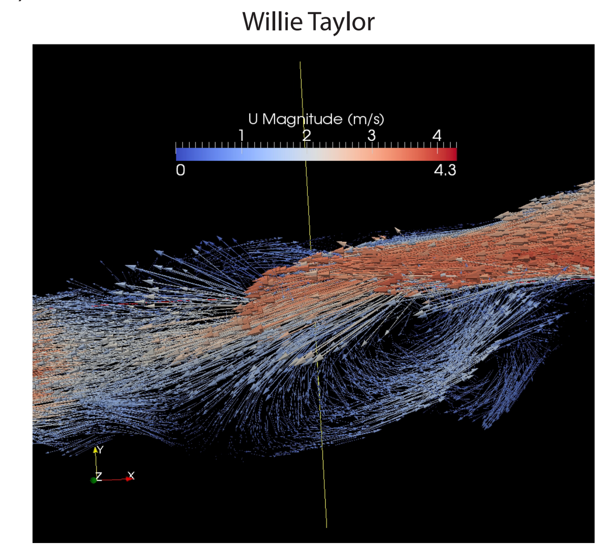


Unsteady solution (DES). Time 1000 secs

Eminence Break



Willie Taylor



Eminence Break and Willie Taylor lateral separation zones. The velocity vector field is displayed (magnitude and direction).

CONCLUSIONS

Our model is one of the first high resolution models at the river channel scale that applies Large Eddy Simulation (LES) techniques. LES models can represent accurately the details of turbulent structures including the nonperiodic pulses of eddy vortices. Nonperiodic eddy pulsations occurring within the eddy recirculation zone are essential in the process of exporting sediment out of the eddy recirculation zone. This nonperiodicity is characterized by low frequency temporal flow variability and can occur due to intrinsic behaviors, such as pulses in vorticity, or due to external forcing, i.e. unsteady flows. Recirculation flow in lateral separation zones is typically weaker than main channel flow providing, in general, an environment appropriated for sediment deposition. Nevertheless, due to these nonperiodic eddy pulsations, once in a while, the flow return zone becomes stronger than the main stem flow, leading to a sediment output from the lateral separation zone causing sediment erosion at the riverbed and eddy bar surfaces.

By using LES approach, a large eddy recirculation zone and one or two secondary smaller eddies are captured at EM and WT fan-eddy complexes. Conversely, the numerical model based on RANS techniques has been inaccurate at representing low frequency temporal flow variability at lateral separation eddies, resulting in one large steady eddy. As a consequence, the time-averaged model will lead to over-supply of sediment within the eddy zone because its limitation to export sediment out of the recirculation zone.

BROADER IMPACTS

Our primary goals are to achieve a deeper understanding of the flow and sediment motions, and how these motions are related to erosion and depositional rates. We are developing one of the first field-scale LES models of turbulence, sediment transport and bed evolution to understand lateral separation zones, a phenomenon that occurs in a variety of river channel configurations, such as, rapid-pool configuration, sharp meander bends and river channel confluences. Broadly, this research work aims to understand flow separation and reattachment zones, which are subaqueous phenomena in river systems taking place at any abrupt changes in channel width and depth (e.g., over river dunes and ripples). This study recognizes the importance of eddy bars and their ecological and economical values. Thus, a deeply understanding of the erosion mechanisms in eddy bars located at the river lateral separation zones is inquired. Eddy bars provide the habitat for the native aquatic and riverine ecosystems, preserve archaeological sites and serve as campsites for river tourists. If our hypothesis, methodology and analysis are successful, they can be used to solve numerically and experimentally the flow field, sediment transport and bed evolution of fluvial environments at the field-scale.