Simulating turbulence in natural waterways with MHK devices

Recent Advances and Future Challenges

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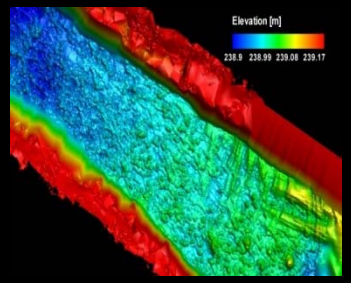
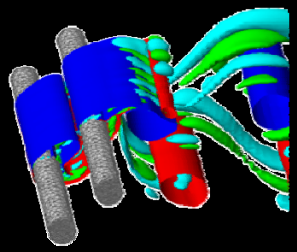
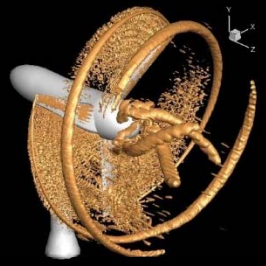
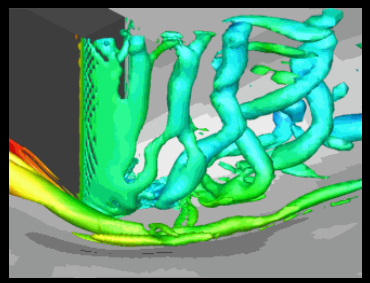
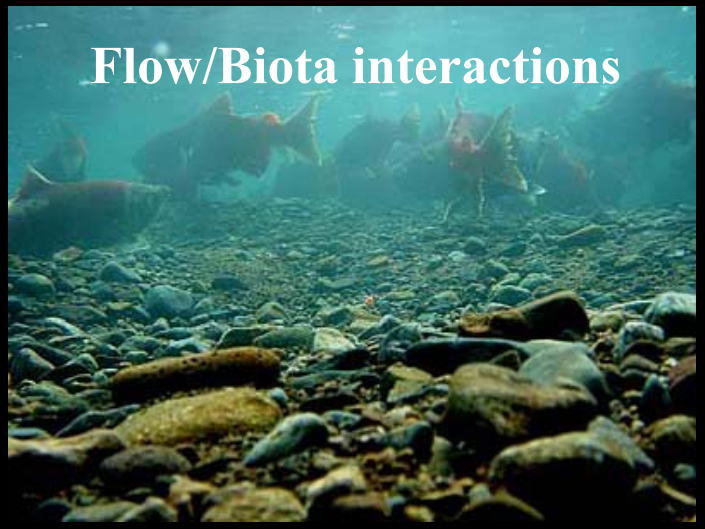


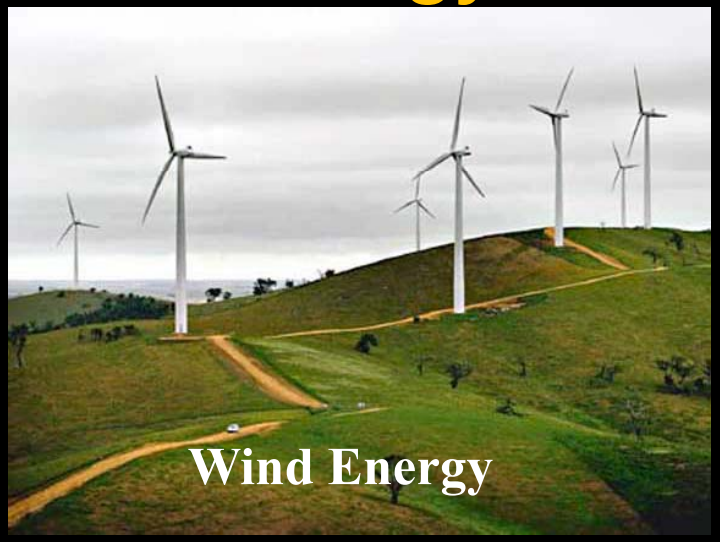


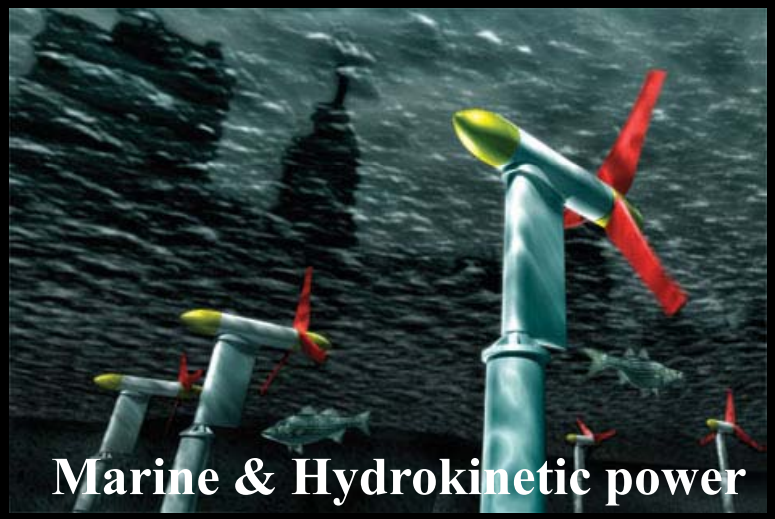



NREL Marine and Hydrokinetic Device Modeling Workshop - March 1, 2011
National Wind Technology Center, Boulder, CO



Fluid Mechanics Challenges in the Energy/Environment Nexus

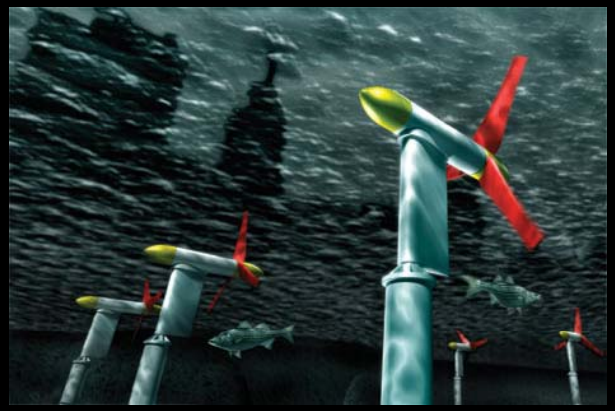




Computational challenges

- Arbitrarily complex geometries with moving boundaries and fluid-structure interaction
- High-Re turbulent flows with energetic coherent structures
- Free-surface effects and wave-device interactions
- Sediment transport and scour
- Device-biota interactions
- Large disparity in scales:

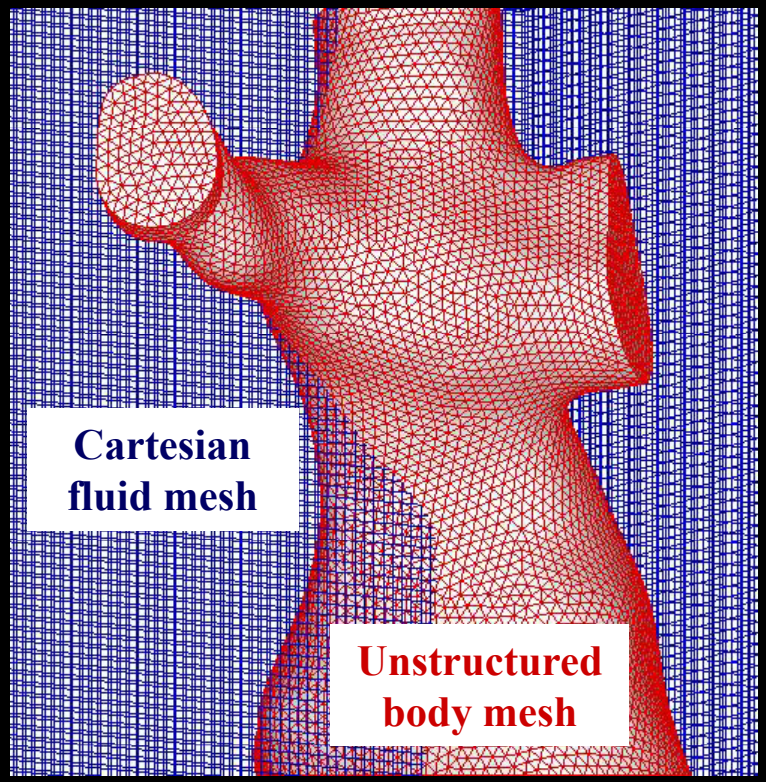
  Waterway – Device – Biota
- Laboratory and field data for model validation



Advances in numerical algorithms

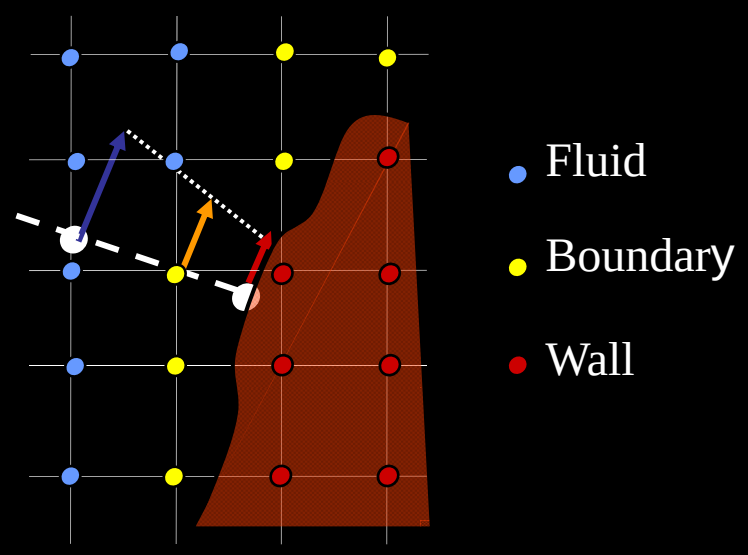
Sharp-Interface Hybrid Cartesian/Immersed Boundary (HCIB) Method

Gilmanov & Sotiropoulos, J. Computational Physics, 2005



Sharp-Interface Hybrid Cartesian/Immersed Boundary (HCIB) Method

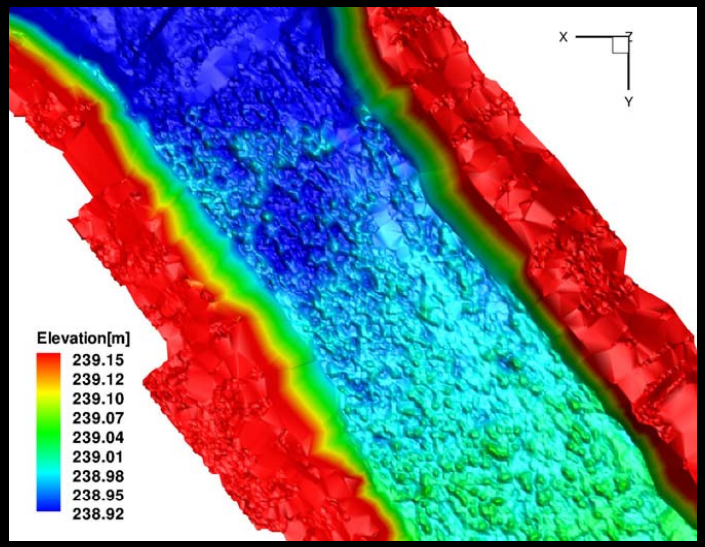
Gilmanov & Sotiropoulos, J. Computational Physics, 2005

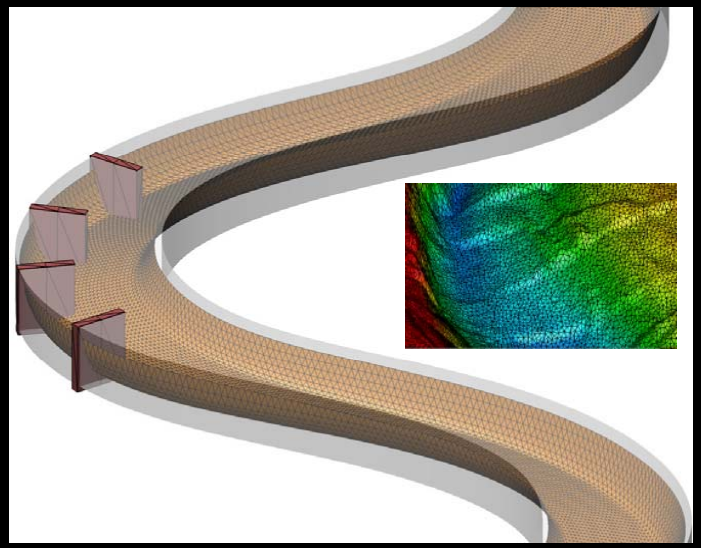


LES of arbitrarily complex flows with the CURVIB method

Kang et al., Adv. in Water Resources, 2011

- Curvilinear Immersed Boundary (CURVIB)
- 2nd order central differencing on a hybrid staggered/non-staggered grid
- Fractional-step algorithm: Jacobian-free Krylov solvers with Algebraic Multigrid
- Turbulence simulation and modeling:
  - ✓ DNS; LES; URANS
- Wall model to reconstruct velocity field at immersed boundary nodes
- Fully parallelized with MPI

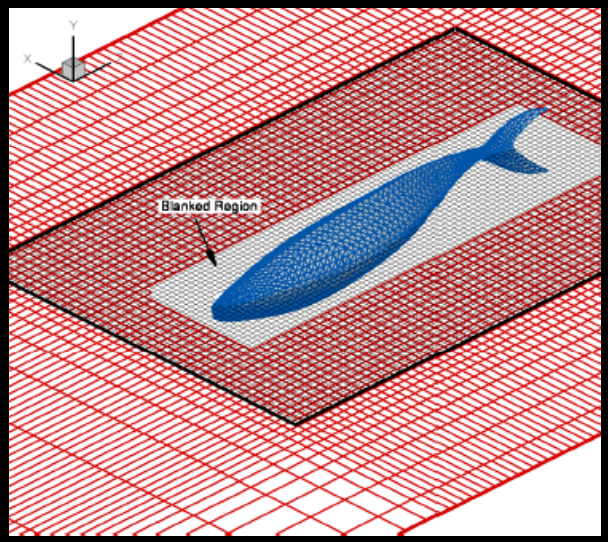


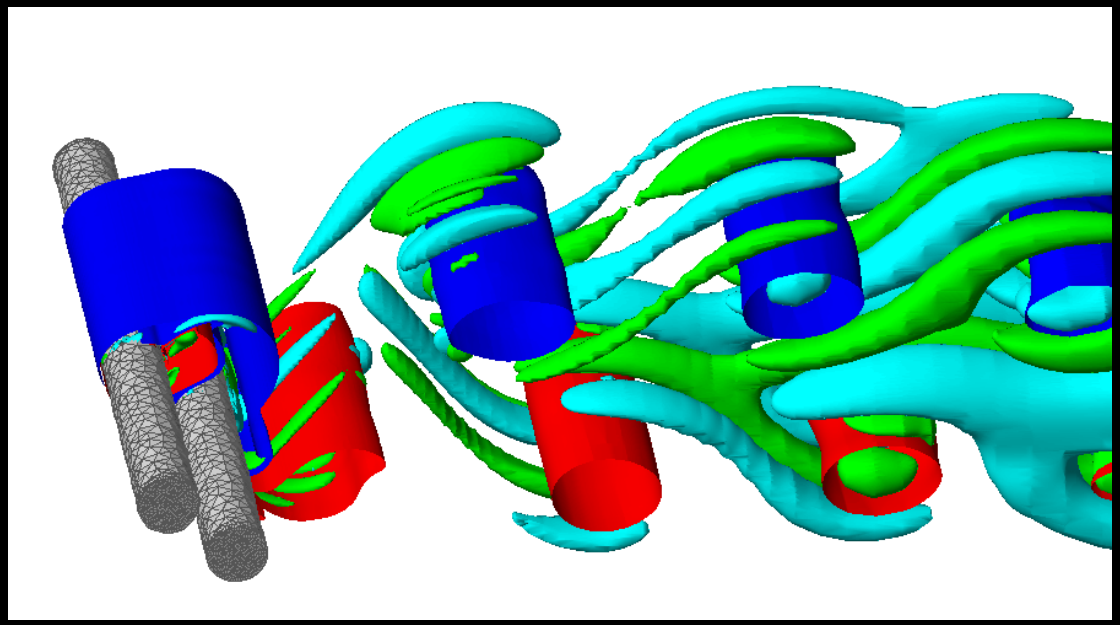


Fluid-Structure Interaction

Borazjani et al, J. Comp. Physics 2008

- Overset CURVIB grid formulation:
  - ✓ Arbitrarily large displacements
  - ✓ Increased resolution near immersed boundaries
- Loose and strong FSI coupling
- Aitken non-linear relaxation for fast convergence of FSI iterations





Vortex-induced vibrations of two cylinders in tandem arrangement in the proximity–wake interference region

Borazjani and Sotiropoulos, JFM, 2009

Free-Surface Modeling with Level-Sets

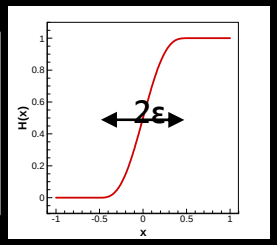
Kang and Sotiropoulos, J. Comp. Physics, in preparation

- CURVIB coupled with level set method for LES in arbitrarily complex free-surface flows
- Interface tracking using distance function

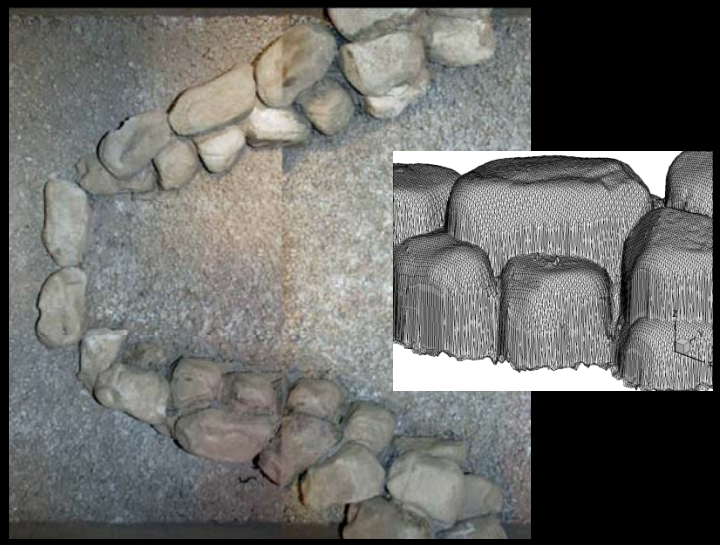
$$\frac{D\phi}{Dt} = \frac{\partial \phi}{\partial t} + u_j \frac{\partial \phi}{\partial x_j} = 0,$$

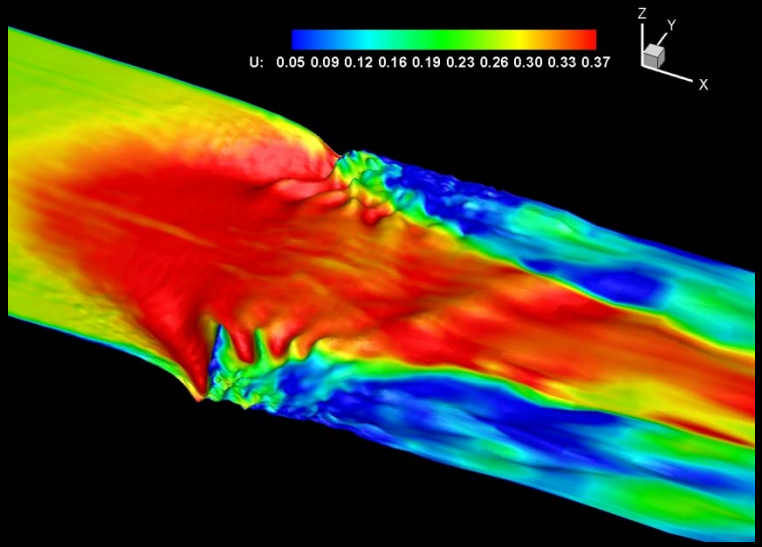
- Air-water phases are solved simultaneously

$$\rho(\phi) = \rho_{air} + (\rho_{water} - \rho_{air})h(\phi)$$
$$\mu(\phi) = \mu_{air} + (\mu_{water} - \mu_{air})h(\phi)$$



- Reinitialization of distance function (Osher & Fedkiw 2002)



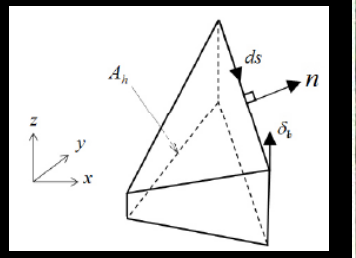


Bed Morphodynamics Modeling

Khosronejad et al., Adv. In Water Res., in press, 2011

- CURVIB method to handle the sediment/water interface
- Solve Exner equation on unstructured mesh

$$z_b^{n+1} = z_b^n - \frac{\Delta t}{(1-\gamma)A_h} \sum_{i_e=1,2,3} [\mathbf{q}_{BL} \cdot \mathbf{n}]_{i_e}$$



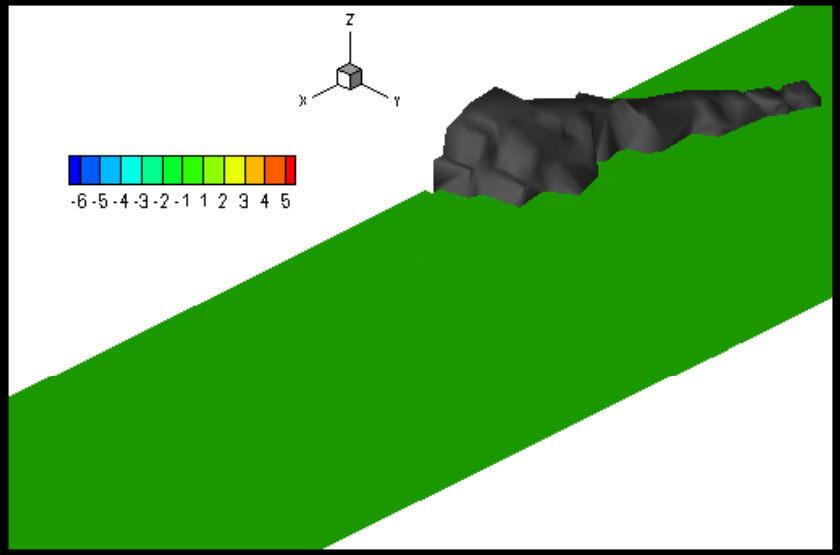
- Bed-load flux:

$$\mathbf{q}_{BL} = \psi \, \|d\mathbf{s}\| \, \delta_{BL} \mathbf{u}_{BL}$$

- Sediment concentration ψ (Van Rijn, 1993):

$$\psi = 0.015 \frac{d_{50}}{\delta_b} \frac{T^{\frac{3}{2}}}{D_*^{\frac{3}{10}}}$$

- Sand-slide algorithm to limit local bed slope to satisfy the material angle-of-repose condition



Applications

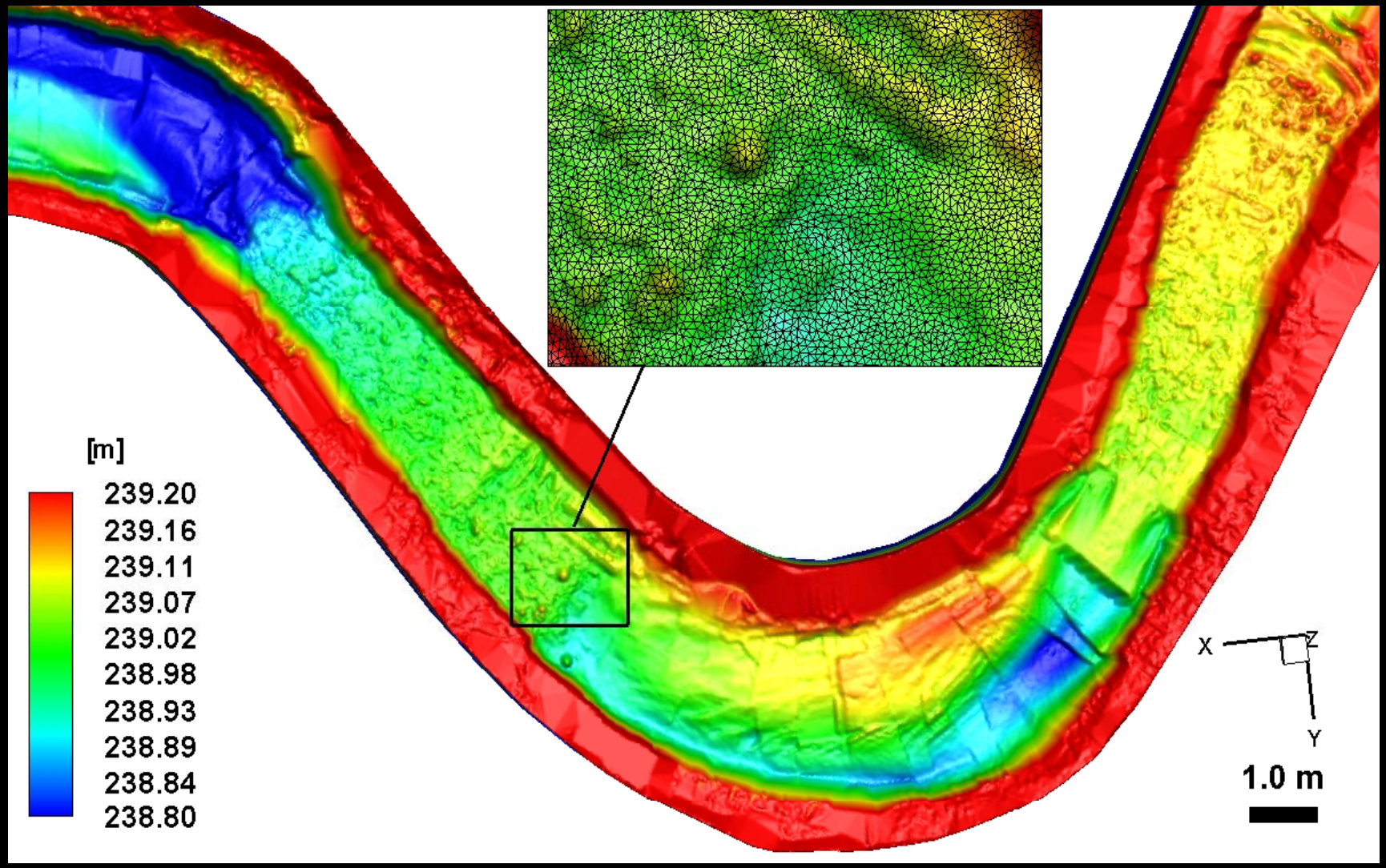
LES of Turbulence in Natural Waterways

Test Case: The SAFL Outdoor StreamLab

Meandering stream dimensions:

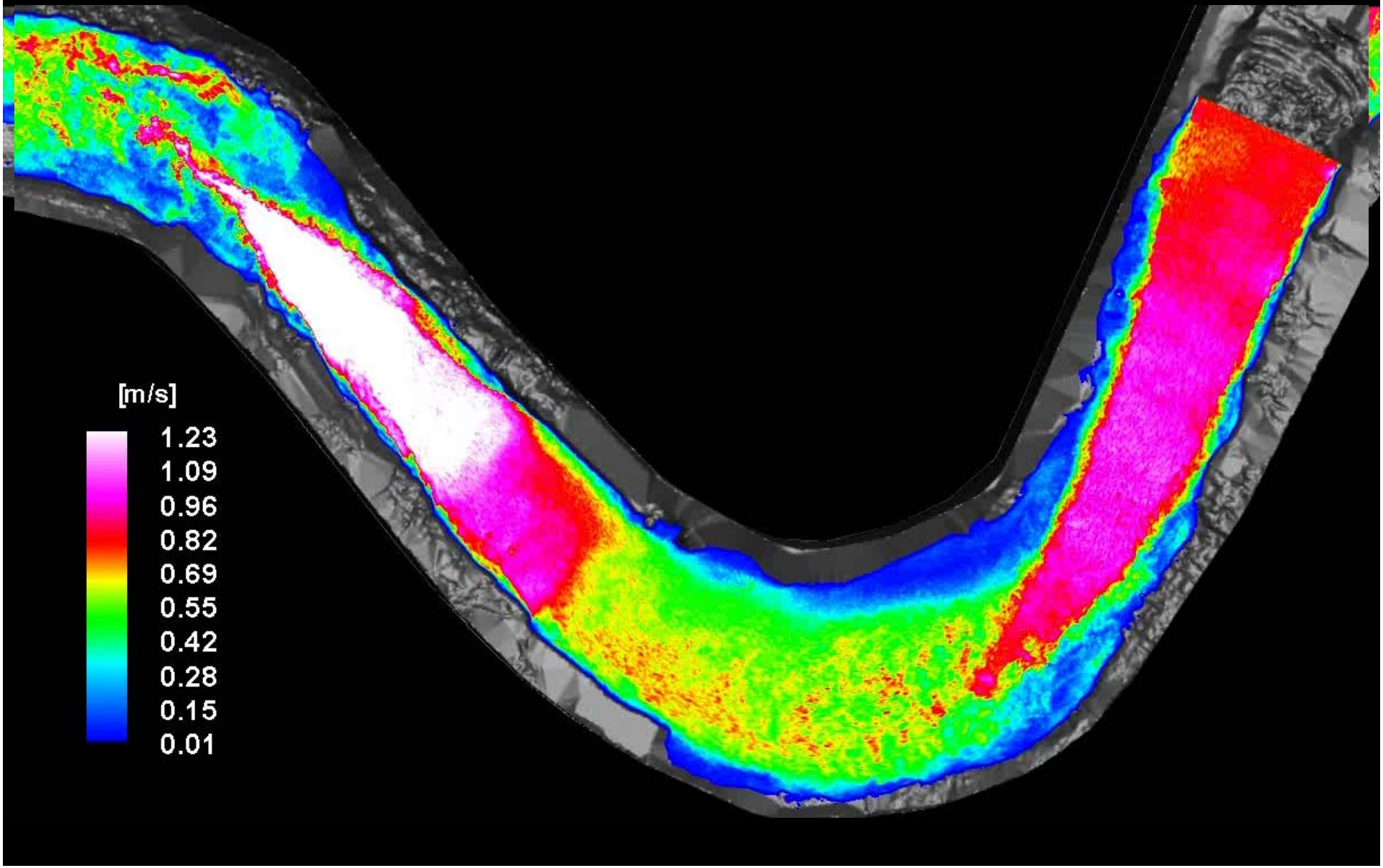
50-m long, 2-m wide, and 0.1-m deep at base flow

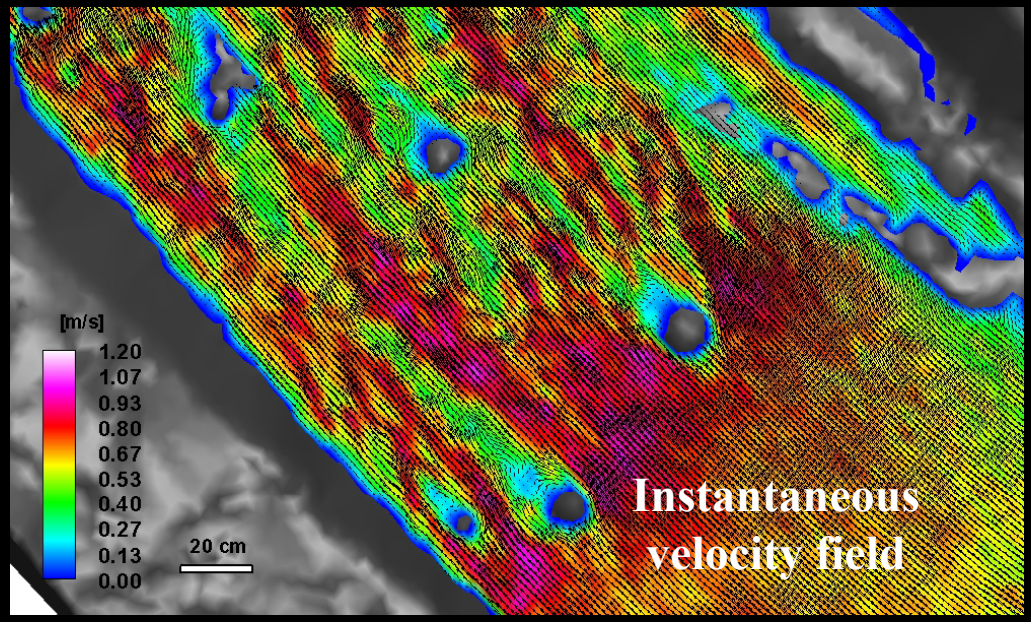
High-resolution bathymetry

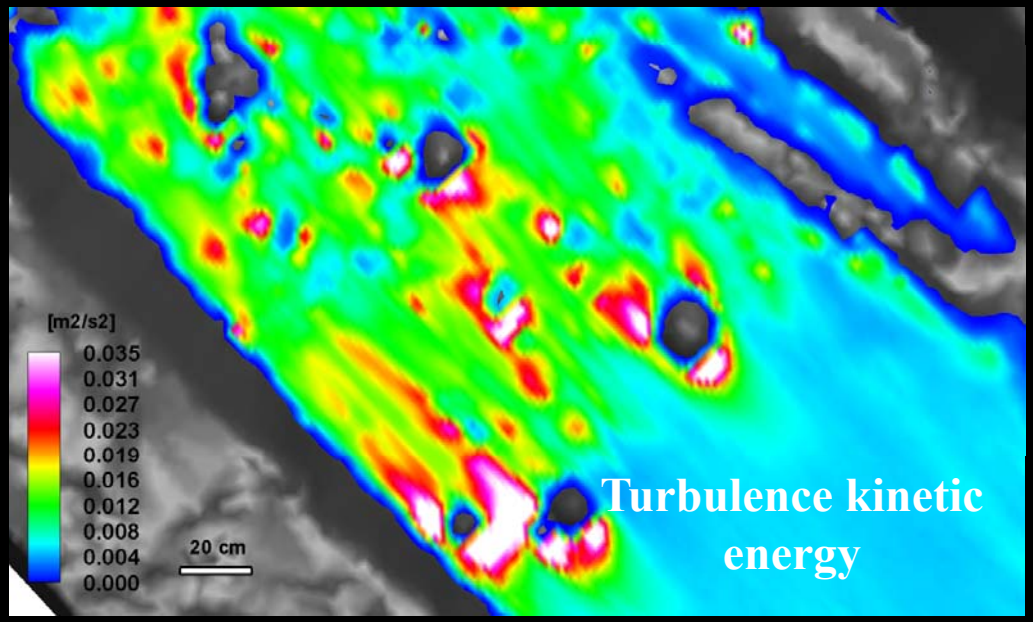


LES of bankfull case – Re = 2×10^4

Kang and Sotiropoulos, J. Geoph. Research, in press, 2011

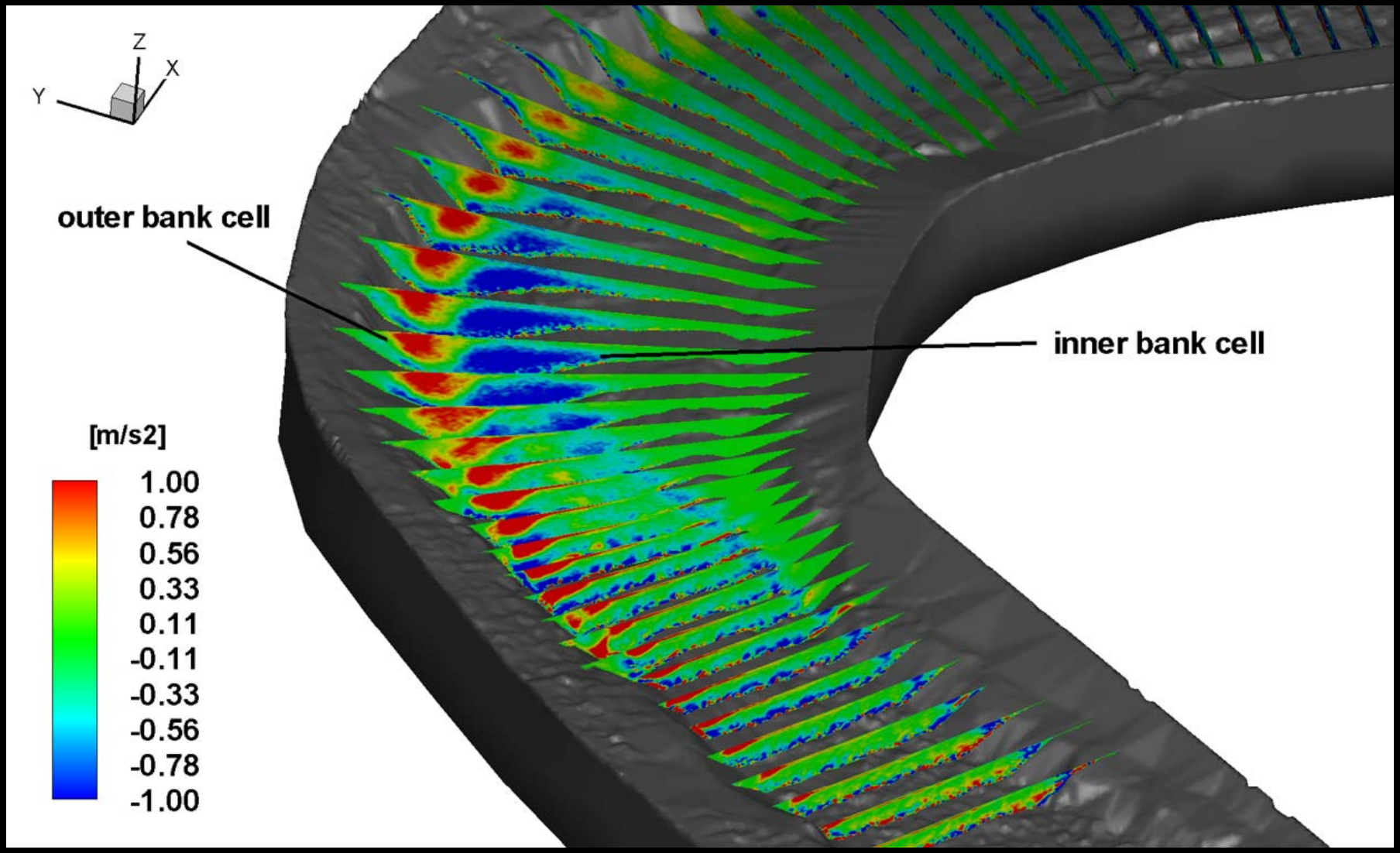






The simulation resolves flow around discrete roughness elements

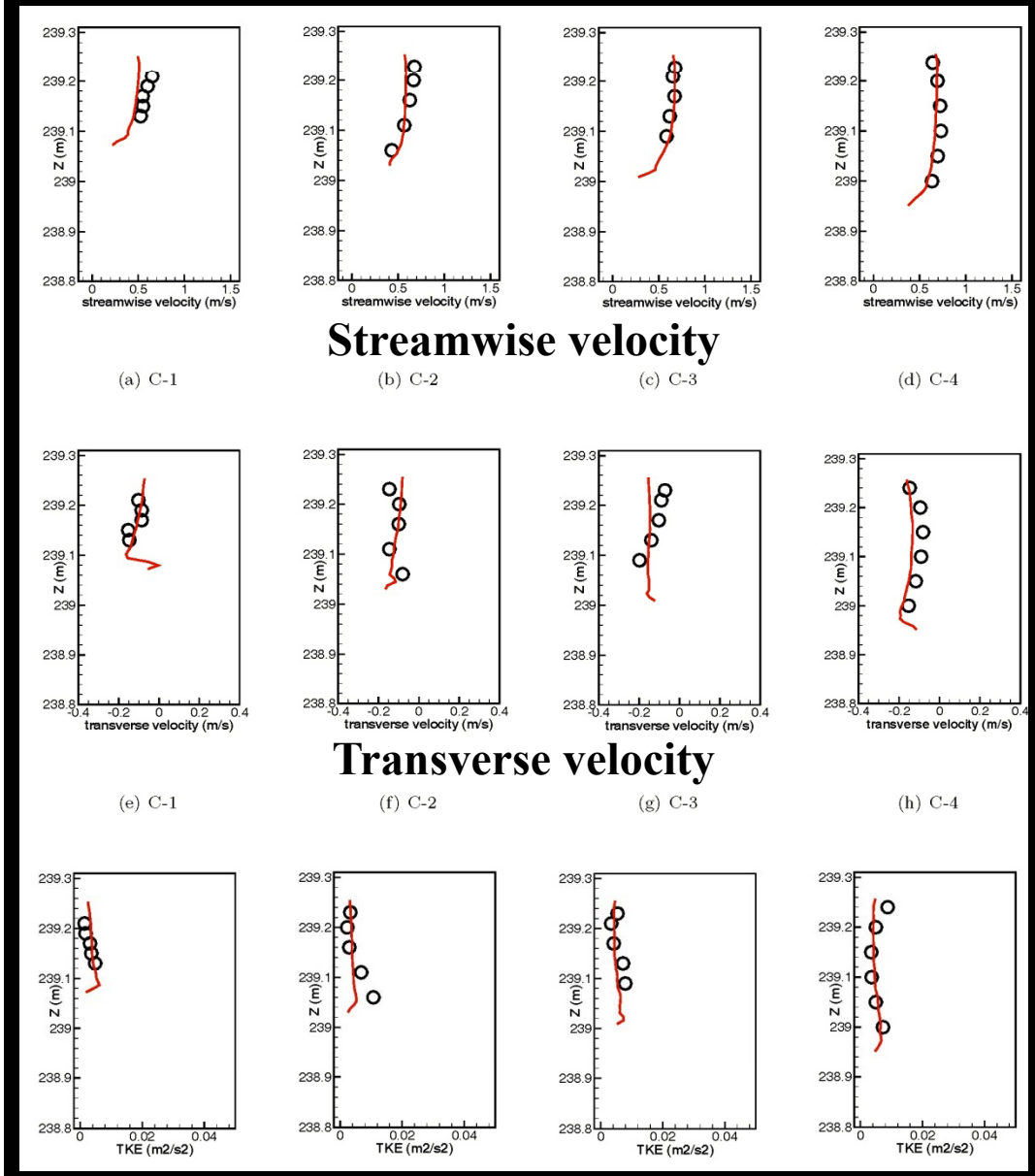
Secondary flow patterns



Helicity = $\mathbf{V} \cdot \mathbf{\Omega}$

Model Validation

Bankfull case



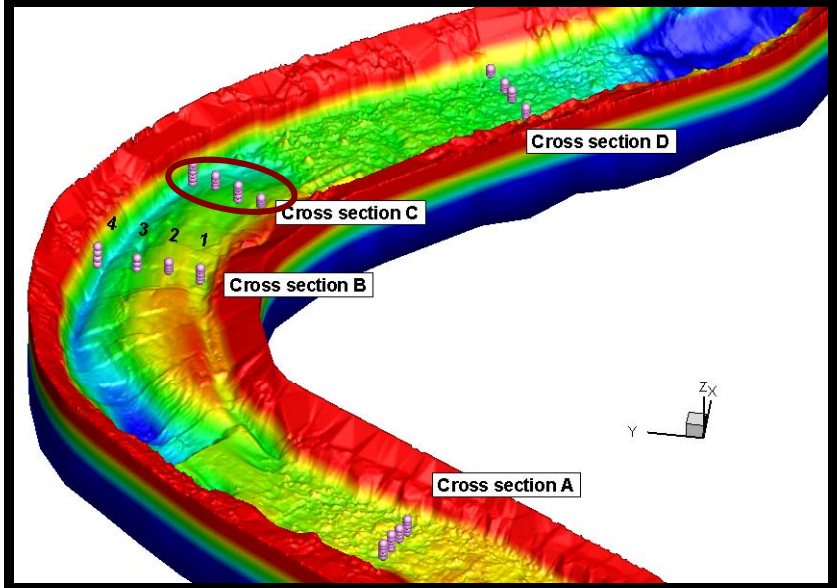
Streamwise velocity

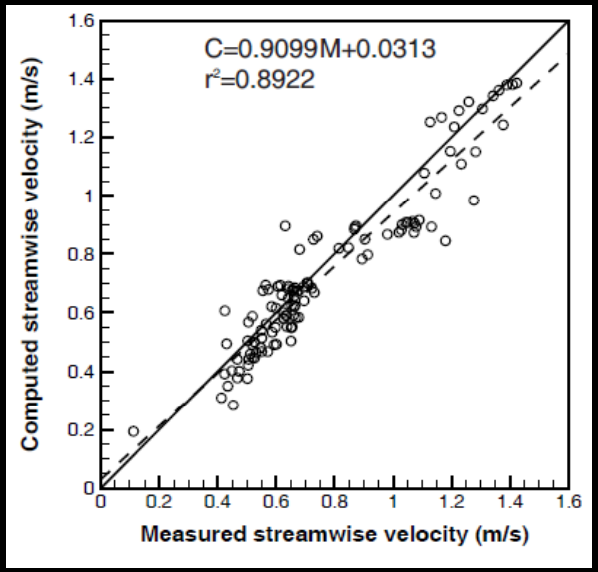
(a) C-1 (b) C-2 (c) C-3 (d) C-4

Transverse velocity

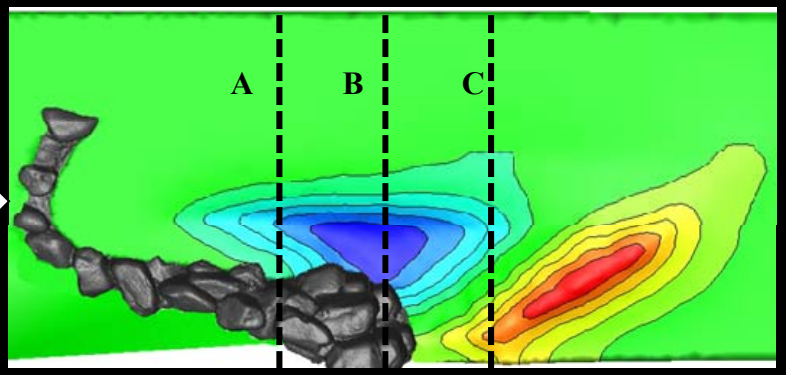
(e) C-1 (f) C-2 (g) C-3 (h) C-4

Turbulence kinetic energy

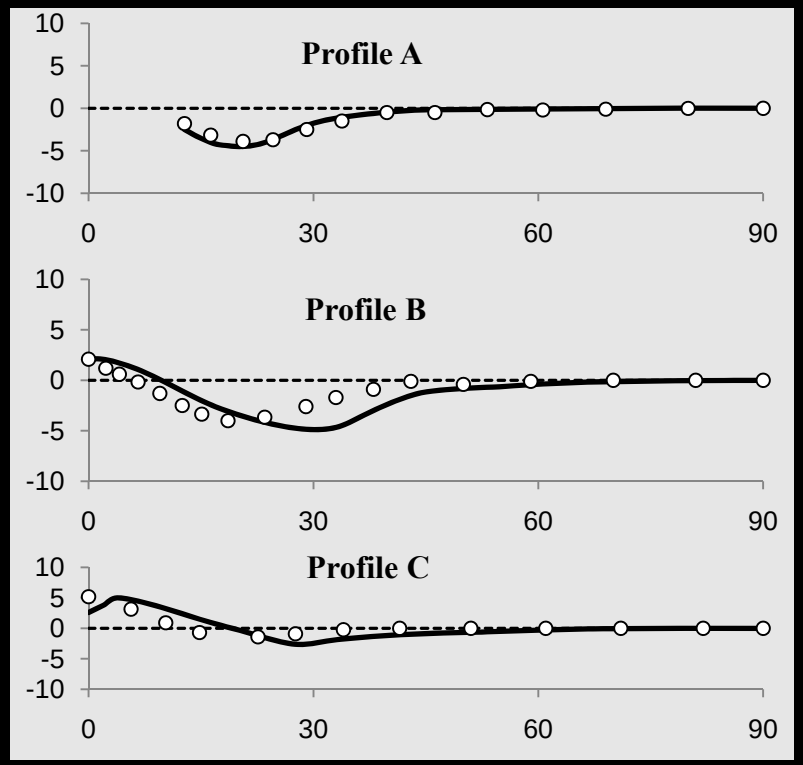


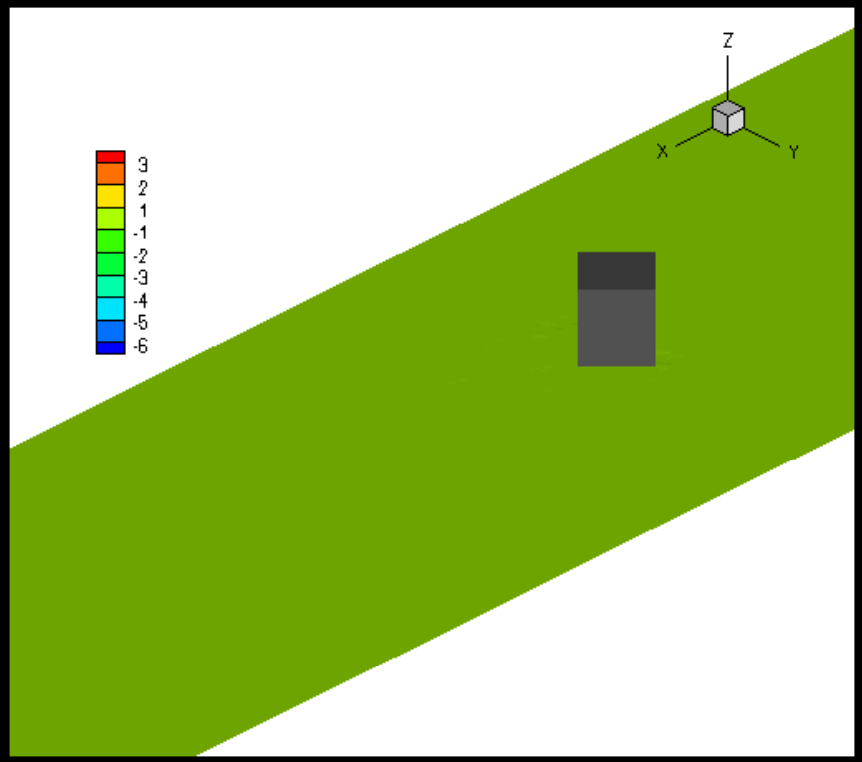


Scour past arbitrarily complex structures



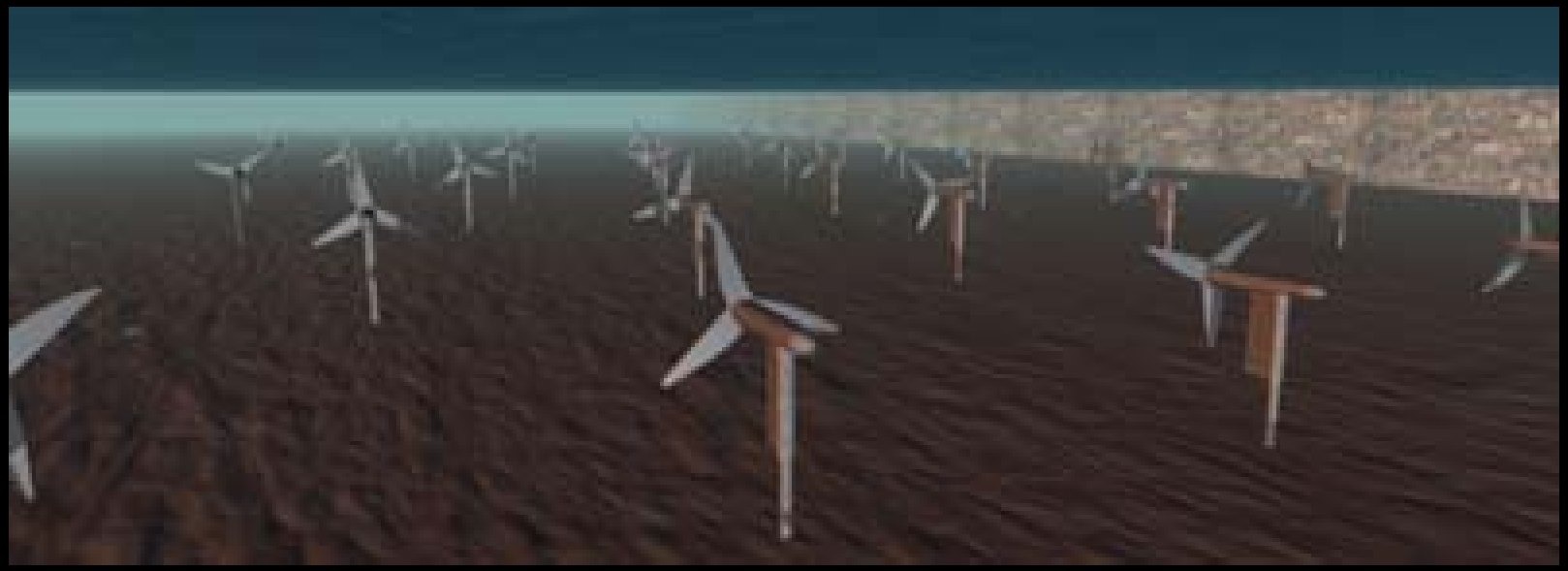
Scour past a J-hook - URANS





Scour past a diamond-shaped pier - LES

Streams with Turbines
Hydrokinetic Power

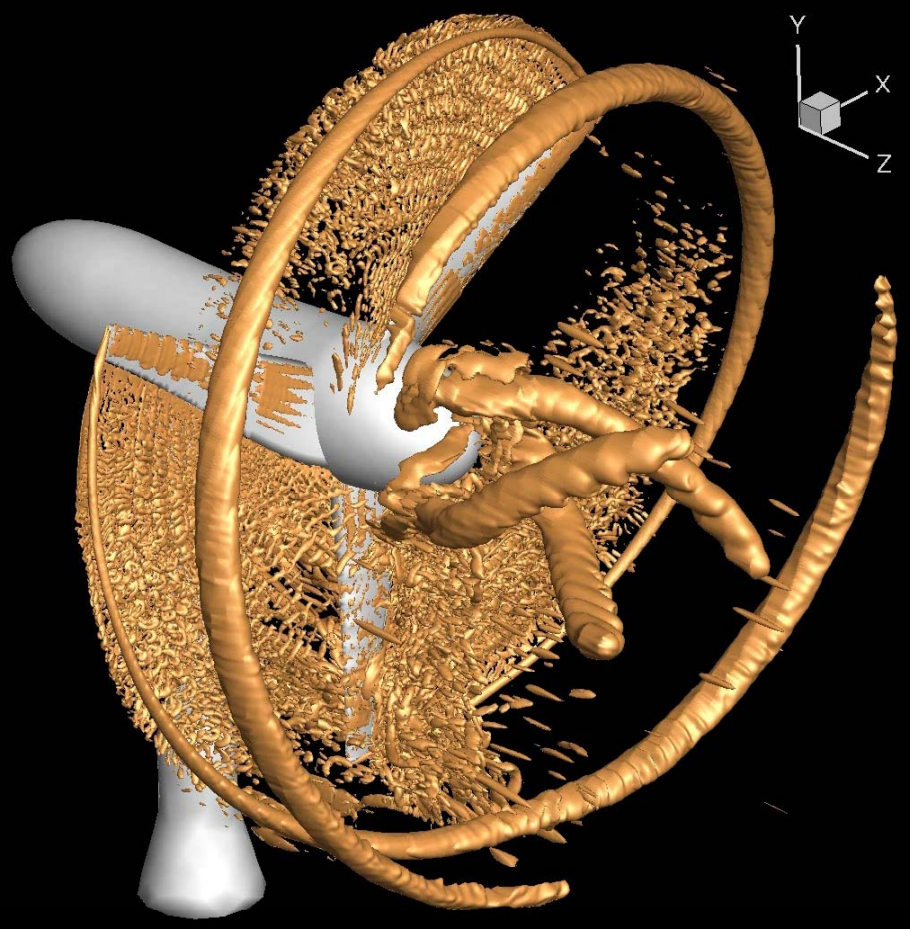


The Verdant Power Roosevelt Island Tidal Project

Laboratory experiments for LES validation

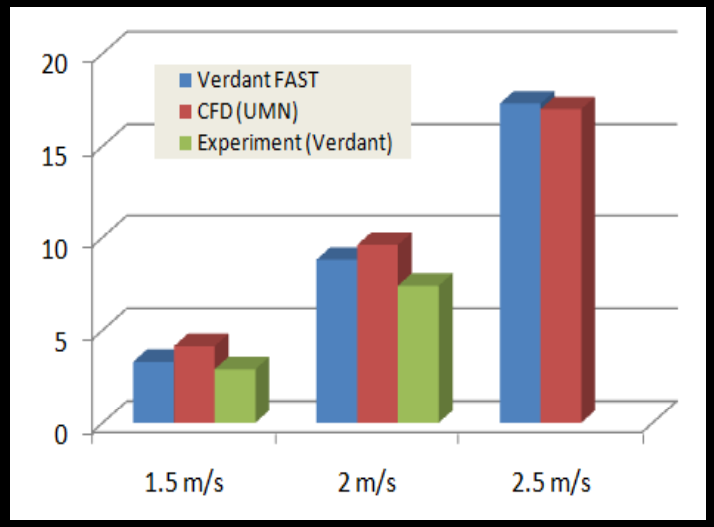
The St. Anthony Falls Laboratory Main Channel

Verdant turbine in uniform approach flow



Vortical structures visualized with q-criterion

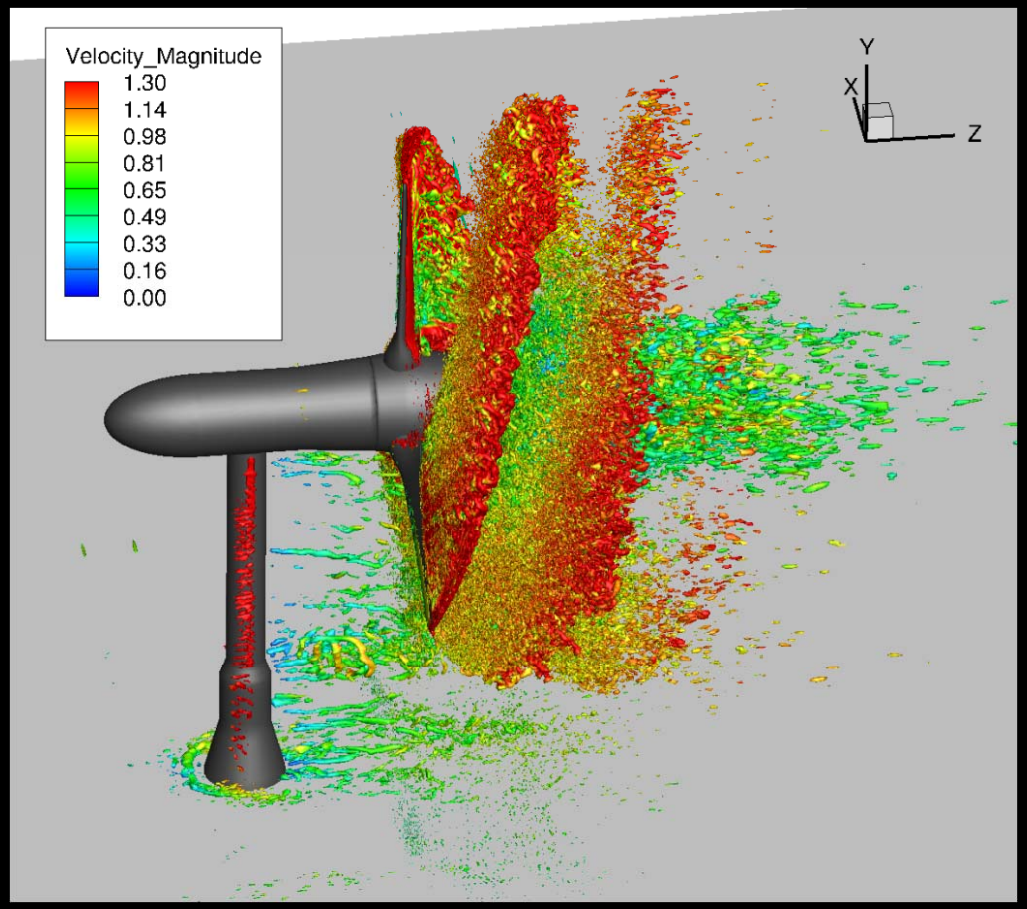
- Uniform approach flow with U=2.5m/s
- Rotor speed = 36 RPM
- Rotor diameter = 5.0m

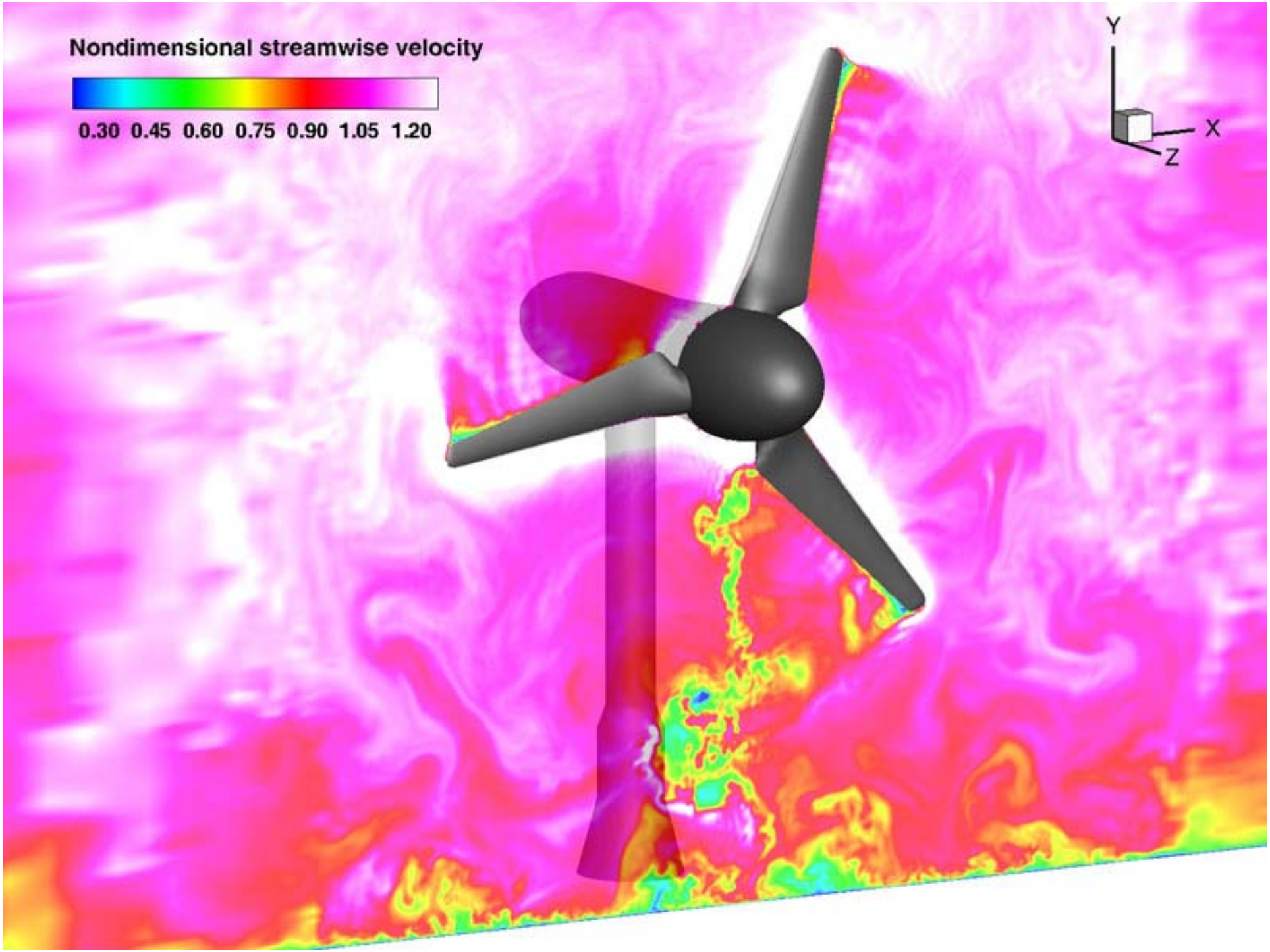


Measured & calculated torque for various approach flow velocities

LES of the Verdant turbine in an open channel

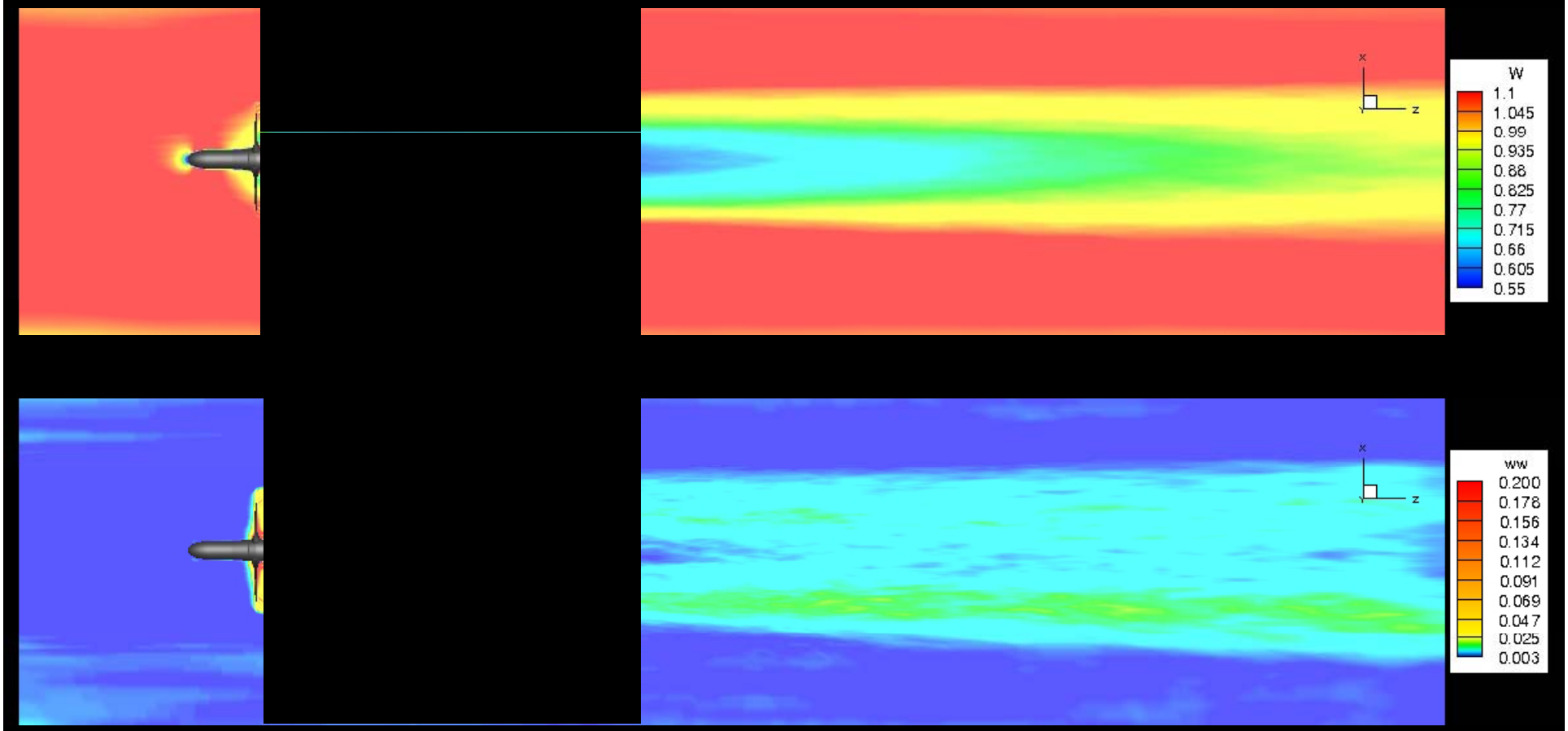
- Bulk U=0.47m/s, Rotor D=0.5m, Re=2.4×10^5
- Tip speed ratio=4.69
- Computational domain: 5.5D×2.3D×12D
- 521×508×568 = 150M grids
- Wall-model for walls and blades.
- Fully-developed turbulent inflow.
- 400 processors were used.




Nondimensional streamwise velocity
0.30 0.45 0.60 0.75 0.90 1.05 1.20
Y
X
Z

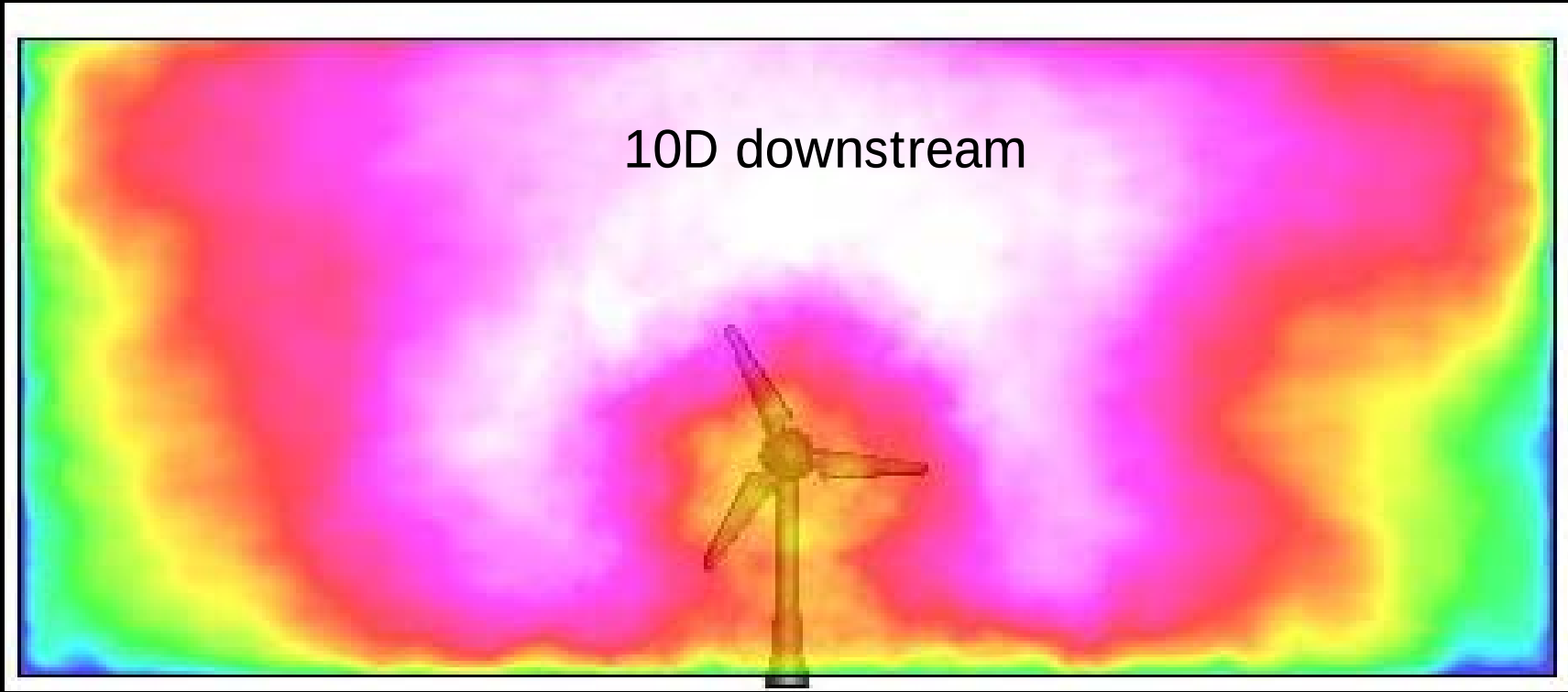
Time-averaged wake recovery

Mean streamwise velocity & turbulence intensity

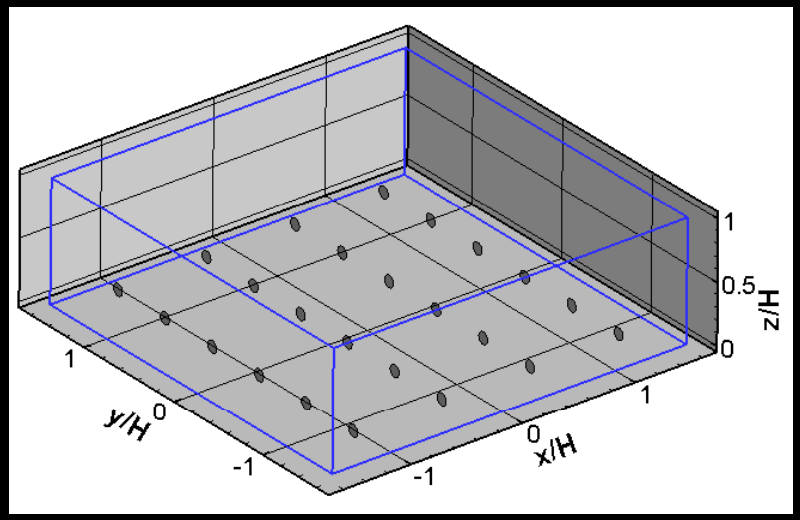


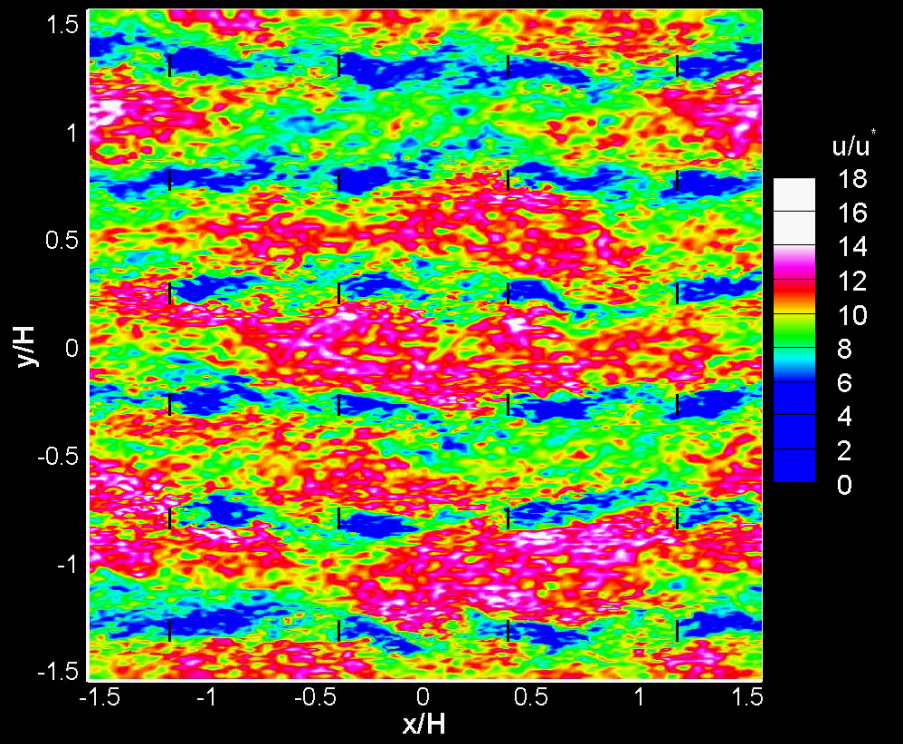
Time-averaged wake recovery

Mean streamwise velocity

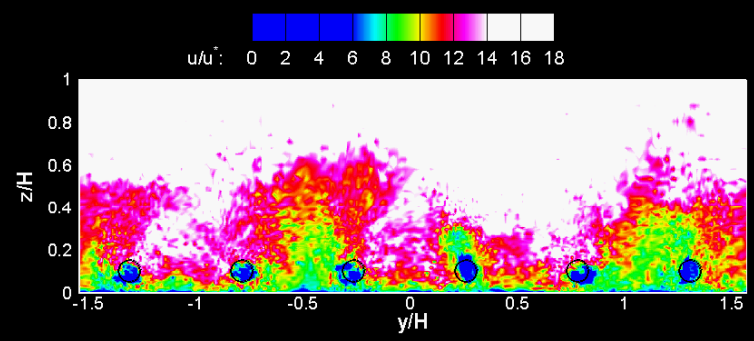


Array-scale LES: Actuator disks

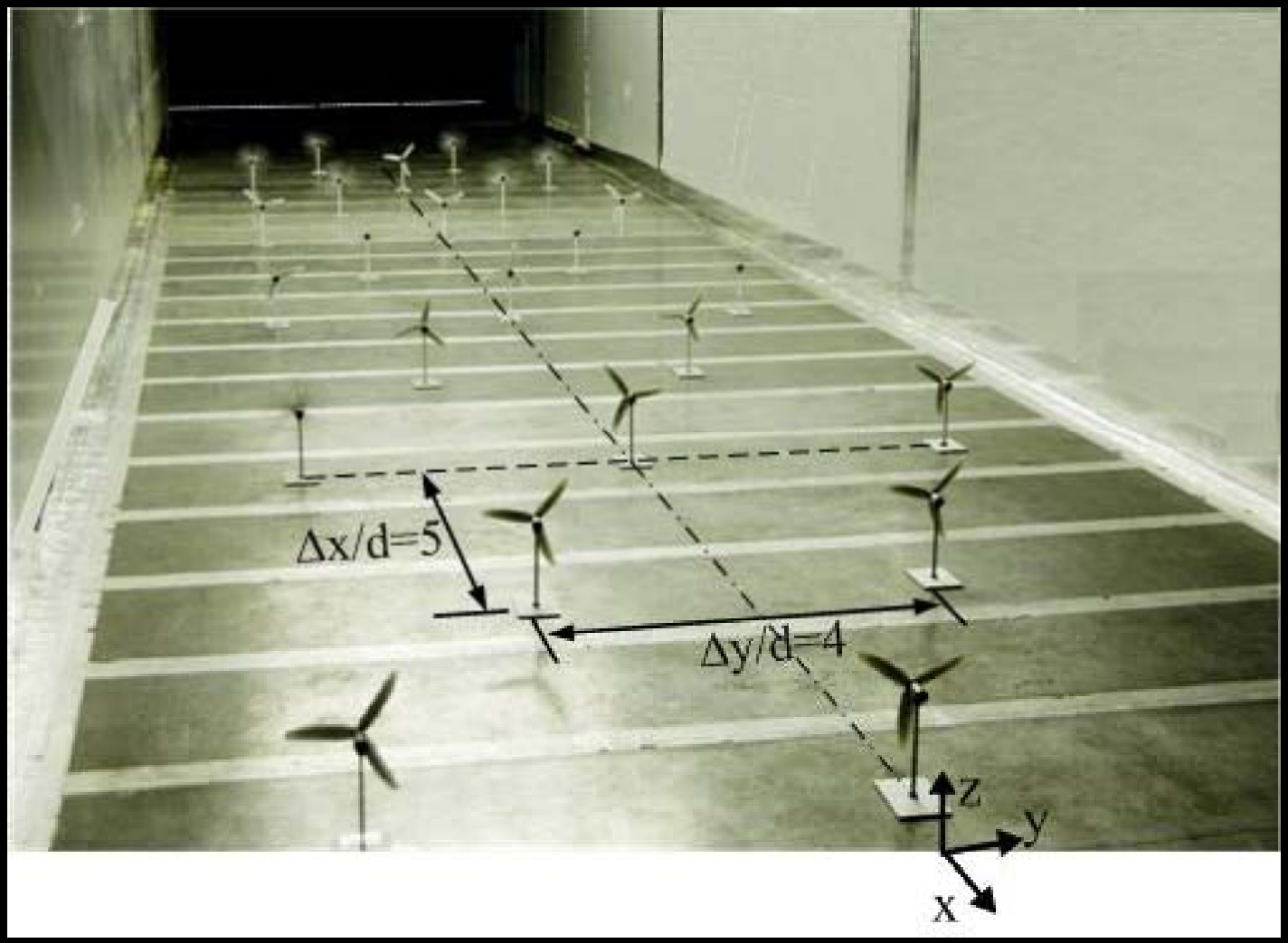




- Actuator disk with discrete delta function to distribute the force
- Re=10^5 based on bulk velocity and domain height H
- Hub height = 0.1H
- LES with dynamic Smagorinski model and wall model for bottom boundary
- Periodic conditions in streamwise and spanwise directions



Experiments for LES validation
SAFL Wind Tunnel



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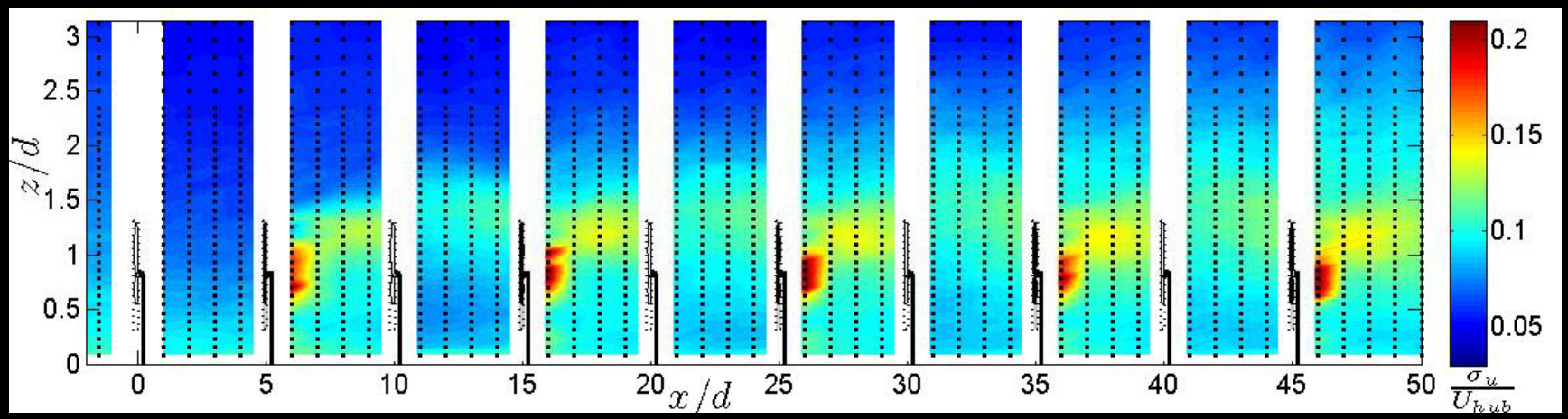
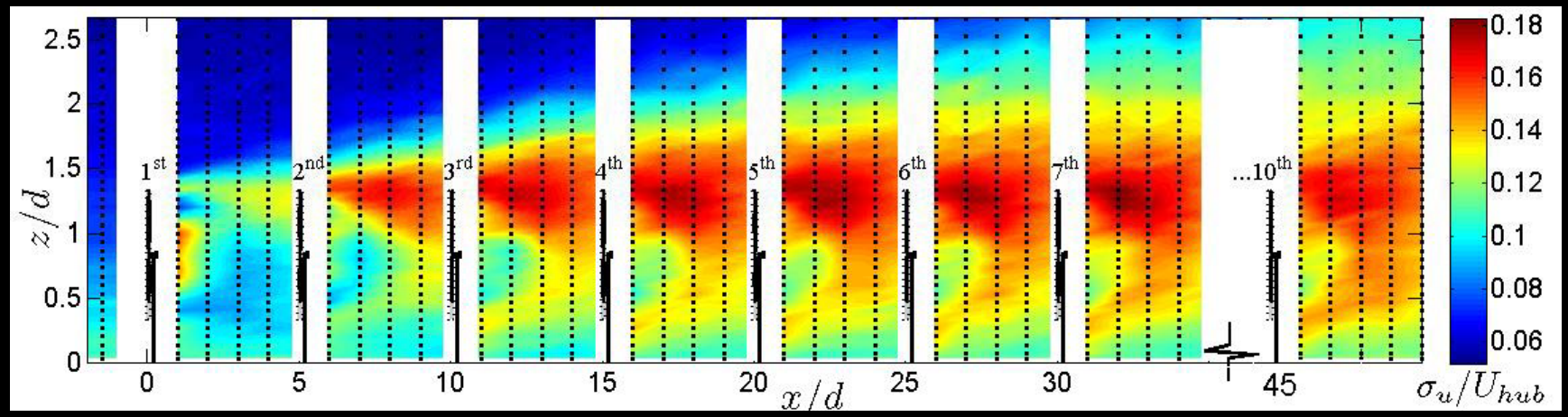
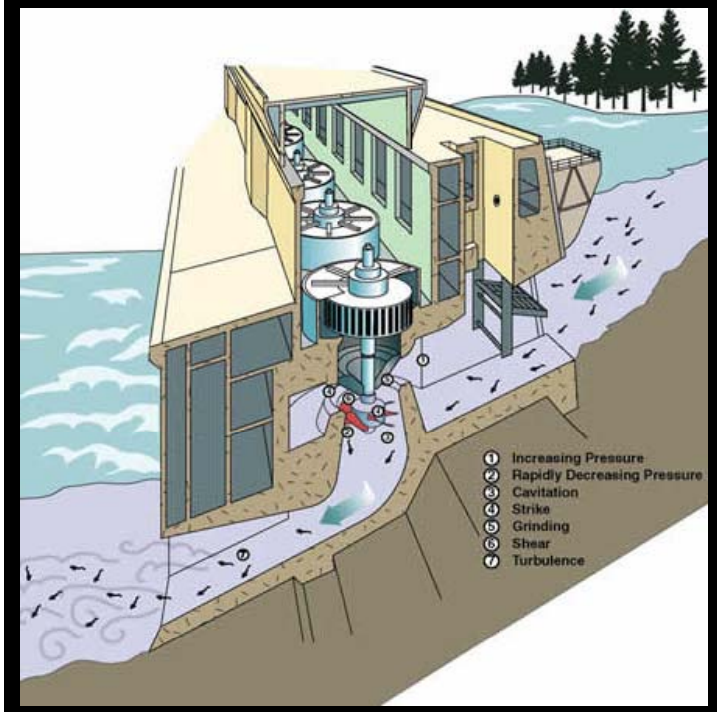




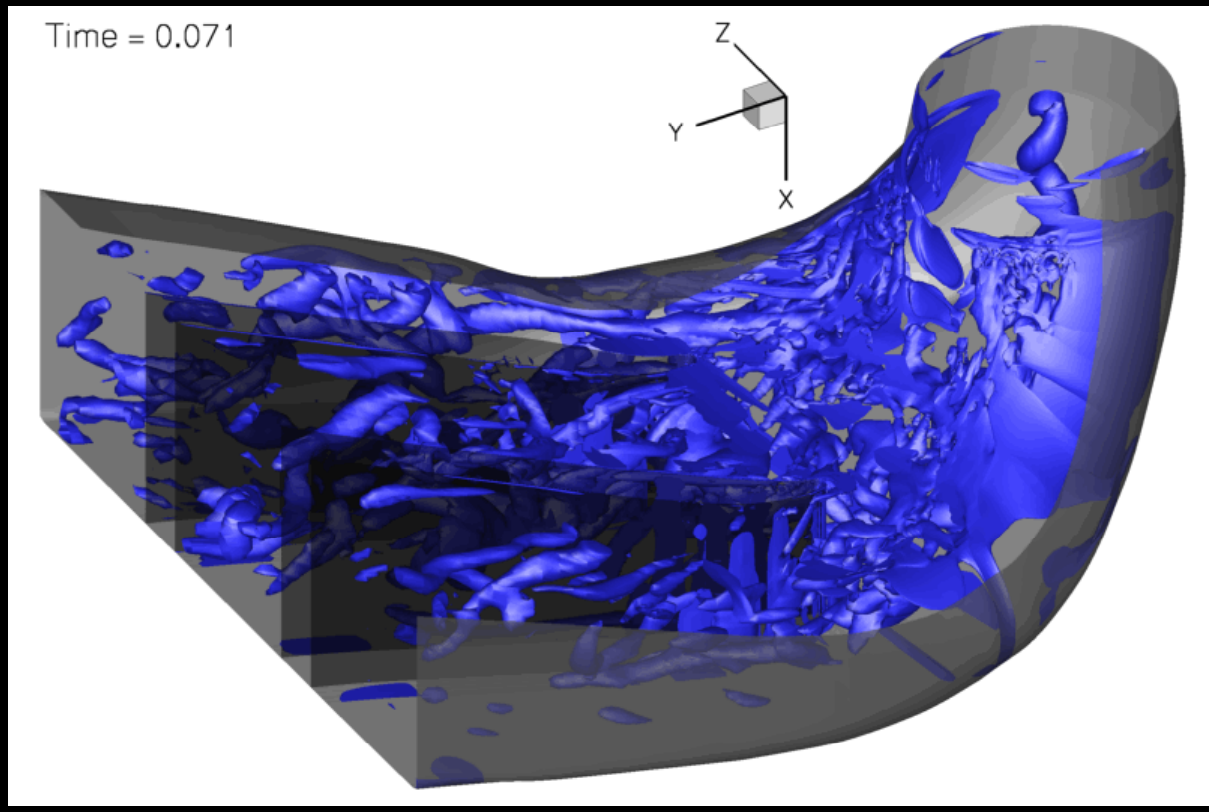
Turbulence intensity: staggered v/s aligned configurations

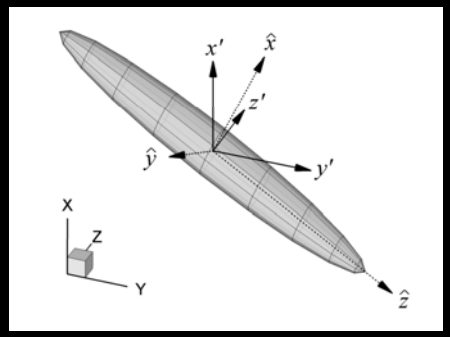
Turbine-resolving LES of arrays

Computational “fish” tracking



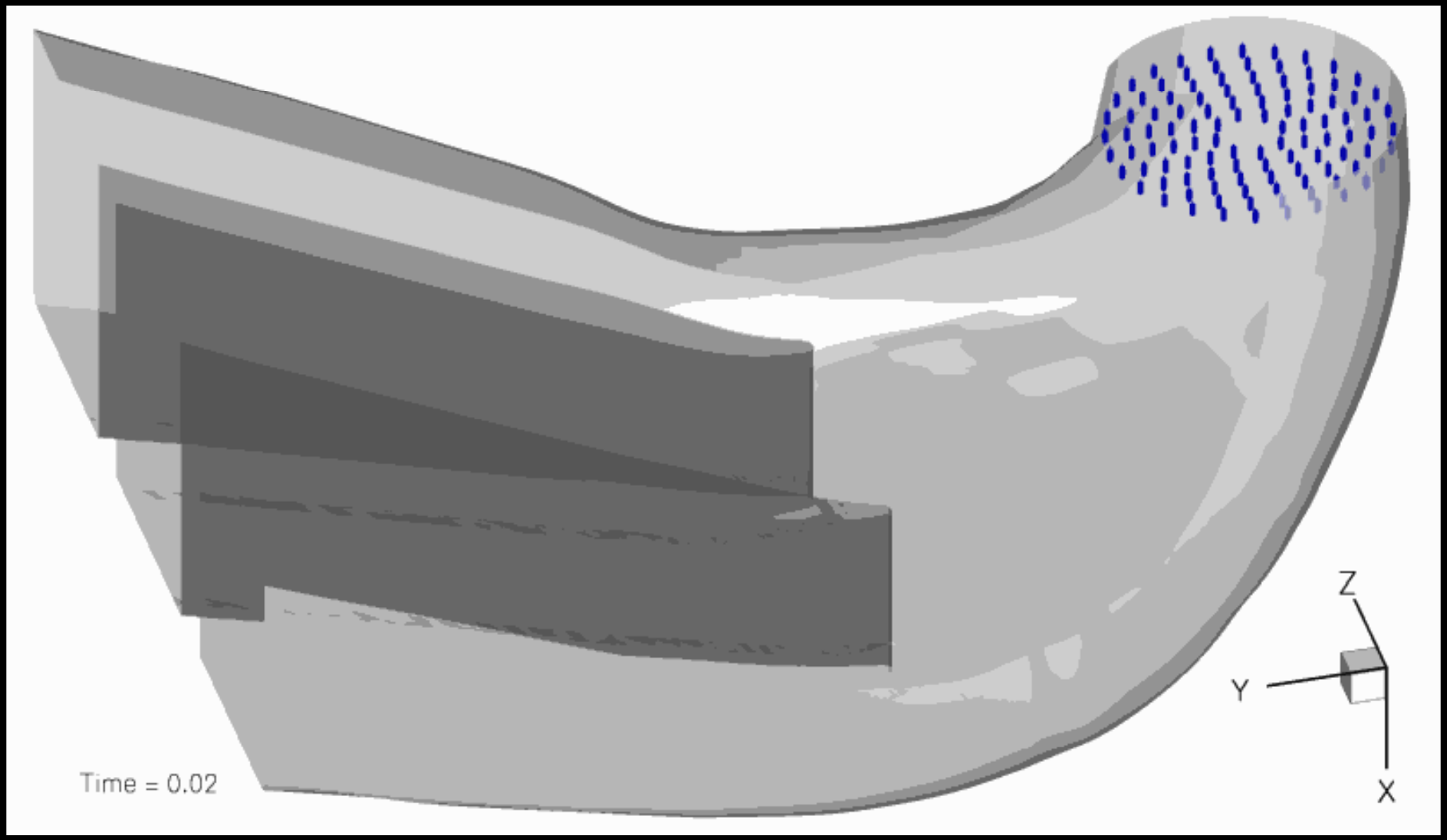
Leverage tools developed for fish friendly hydroturbines





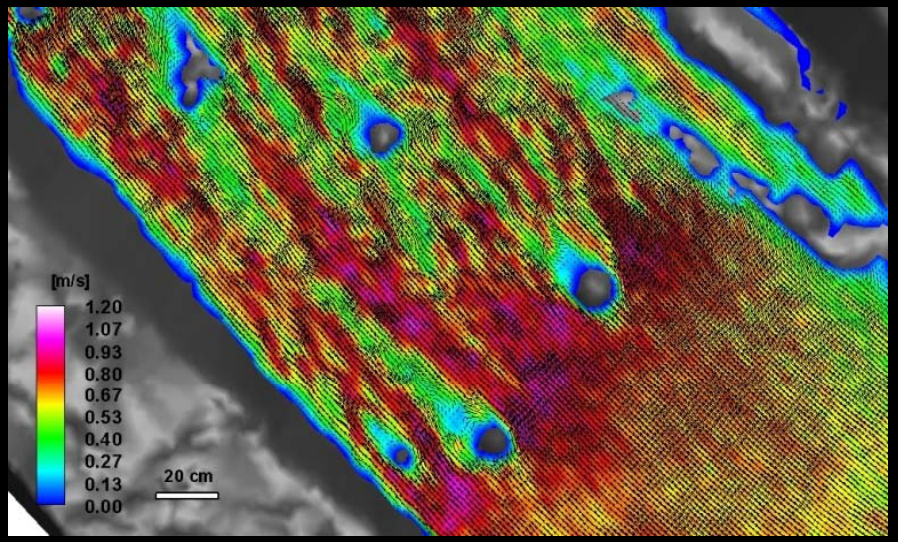
Lagrangian tracking of 6 DOF fish-like bodies: The Virtual Sensor Fish

Computational “fish” tracking



Ongoing & Future work

- Blade design optimization
- Determine structural loads on complete turbine configuration
- Effects of river bathymetry on turbine performance
- Array hydrodynamics
- Impact of turbine arrays on stream-bed erosion and channel stability
- Impacts on fish biota



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- SAFL engineers:

  Leonardo Chamorro, Jessica Kozarek, Jeff Marr, Craig Hill, Chris Ellis

- Collaborators:

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