Hydraulic Engineering in the Era of Big Data and Extreme Computing: Can Computers Simulate River Turbulence?

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Introduction

As I was preparing to deliver the 2017 Hunter Rouse Hydraulic Engineering Lecture, I came to realize that, although I had the good fortune to interact and work with many outstanding colleagues throughout the years, four specific individuals have played a particularly pivotal role in my professional evolution. These individuals inspired, motivated, and mentored me in different ways at different stages of my career. It struck me that they all shared a common attribute, namely, that at some point in their careers they won the Hunter Rouse Hydraulic Engineering award. In the remainder of this section, I will briefly present how I encountered these four individuals and explain how each of them influenced my career. I will also explain the origin of the question in the title of this paper and highlight major milestones in my journey from my undergraduate studies in Mechanical Engineering at the National Technical University of Athens in Greece to the 2017 Hunter Rouse Hydraulic Engineering Lecture.

I arrived in the United States in August 1987 from Greece to pursue my graduate studies in Aerospace Engineering, initially at Penn State University and subsequently at the University of Cincinnati. Serendipity led me to work for my Ph.D. on incompressible flows and, specifically, the numerical solution of three-dimensional (3D) incompressible Reynolds-averaged Navier-Stokes (RANS) equations past ship hull geometries. Because this was the time when numerical methods for tackling complex 3D flows were in the early stages, I thought that working on a real ship-hull geometry presented a challenge worthy of a Ph.D. degree. I ended up presenting the results of my doctoral research at the 1990 SSPA-CTH-IIHR Workshop on Ship Viscous Flow in Gothenburg, Sweden (Larsson et al. 1991). During the workshop, I met Professor V. C. Patel from Iowa Institute for Hydraulic Research (IIHR) who introduced me to Professor Wolfgang Rodi from the Institute for Hydromechanics at the University of Karlsruhe. Professor Rodi—*the 1997 Hunter Rouse Award Winner*—offered me my first job when he asked me to join his group in Karlsruhe to work on simulating turbulent flows in rivers. At the time, I knew little about river flows because I had never been formally trained as a civil engineer; therefore, I was very much intrigued by the challenge and of course quite flattered by the offer to join such a prestigious research group and work with the pioneer in turbulence modeling and computational hydraulics. Although in the end I decided against leaving the United States at that time, Wolfgang Rodi remained a friend, a mentor, and a true inspiration for my research throughout the years.

A few weeks after the workshop, V. C. Patel called and invited me to visit IIHR to interview for a postdoctoral position under his mentorship on the topic of the numerical simulation of river turbulence in the vicinity of hydropower plants. This topic was just emerging at that time given that methods for performing 3D simulations of turbulent flows in real-life waterways were essentially nonexistent. In January 1991, I visited IIHR to interview for the position. During my interview, I met the IIHR director at the time, Professor John F. Kennedy, *the 1981 Hunter Rouse award winner*. As the interview was ending, Professor Kennedy asked me the question in the title of this paper: *Will computers ever be able to simulate river turbulence*? He made it quite clear that he meant whether computers would be able to simulate the complexity and richness of turbulent flows in real waterways as one observes them in the field: large-scale energetic eddies shed from river banks, natural and artificial obstacles, and migrating bedforms that vary in time and are highly dependent on very complex geometric features. The year was 1991, and I was a fresh Ph.D. graduate with many dreams and the audacity of my youth. Although I gave an overly optimistic answer, apparently, I did not make a complete fool of myself and ended up getting the job. Little did I know at the time that Professor Kennedy's question would persist in my mind through the years to motivate and guide my research efforts for decades to come. Sadly, this was my only interaction with Professor Kennedy; when I finally joined IIHR a few months later, he had already fallen gravely ill and passed away soon thereafter.

Fast forward several years later to January 2006, when I moved from the School of Civil and Environmental Engineering at Georgia Tech, where I had started my academic career in 1995, to the University of Minnesota to become the director of the St. Anthony Falls Laboratory (SAFL). During my second interview at SAFL, I met then acting director Professor Gary Parker, *the 2016 Hunter Rouse award winner*. Of course, I knew of Professor Parker and his groundbreaking work in river morphodynamics but meeting him in person for the first time suddenly made me appreciate the importance and significance of the job I was about to accept. At that time, although I had made some progress in my group simulating river flows, the simulation of migrating bedforms and their interactions with hydraulic structures and channel streambeds was still very much the holy grail of our field. Professor Parker's passion for sediment motion in rivers piqued my interest in this area and motivated much of the work that I did with my students and collaborators during my 10 years at SAFL.

During my first year as SAFL director, the faculty and I agreed that it was time to develop a new strategic plan for the laboratory—a plan that would position the laboratory to continue to thrive beyond the sunset of the National Science Foundation (NSF)-funded National Center for Earth Surface Dynamics (NCED). The SAFL strategic plan was completed in mid-2007 and outlined new strategic directions in renewable energy, biological fluid mechanics, and simulation-based engineering science for environmental applications. I assembled an external academic review board consisting of world-leading scholars in research areas relevant to SAFL and invited them to visit the laboratory in October 2007 to provide their input and advice on the strategic plan for the future of SAFL. Professor Robert Street from Stanford University, *the 2005 Hunter Rouse award winner*, was appointed to chair this committee and lead the visit. I have always admired Professor Street's work in large-eddy simulation (LES) of turbulent flows. His accomplishments in computational fluid dynamics and passion for developing high-fidelity computational tools and using them to uncover and explain complex 3D flow phenomena have always motivated and inspired much of the problems that I chose to tackle in my career. Professor Street has remained a mentor and friend during my tenure as SAFL director and beyond.

John F. Kennedy's question always stayed in my mind throughout my career, and the contributions of the other three leaders in our field provided context and inspiration for all that I have tried to accomplish. In the remainder of this paper, I will highlight the major milestones in my quest to contribute to the simulation of river turbulence and my thoughts for the role that numerical simulations can play in our field in the years to come.

IIHR Years (1991–1995): 3D Steady RANS Models

As I was getting started with my postdoctoral work at IIHR in the early 1990s, many hydropower installations around the country were coming up for relicensing. A major concern for securing a new license was for powerplant operators to demonstrate that the operation of their plant did not adversely impact water quality and aquatic ecosystem health. Depending on the geographic region in which the plant was located, problems ranged from low dissolved oxygen (DO) or the supersaturation of nitrogen in tailrace waters, which affects the salmon population migrating up and down river systems in the Pacific Northwest. Understanding turbulence upstream, through, and downstream of powerplants was the critical prerequisite for beginning to tackle such problems. The work of Sinha et al. (1998) provides a clear example of what 3D computational models of river turbulence could accomplish at that time.

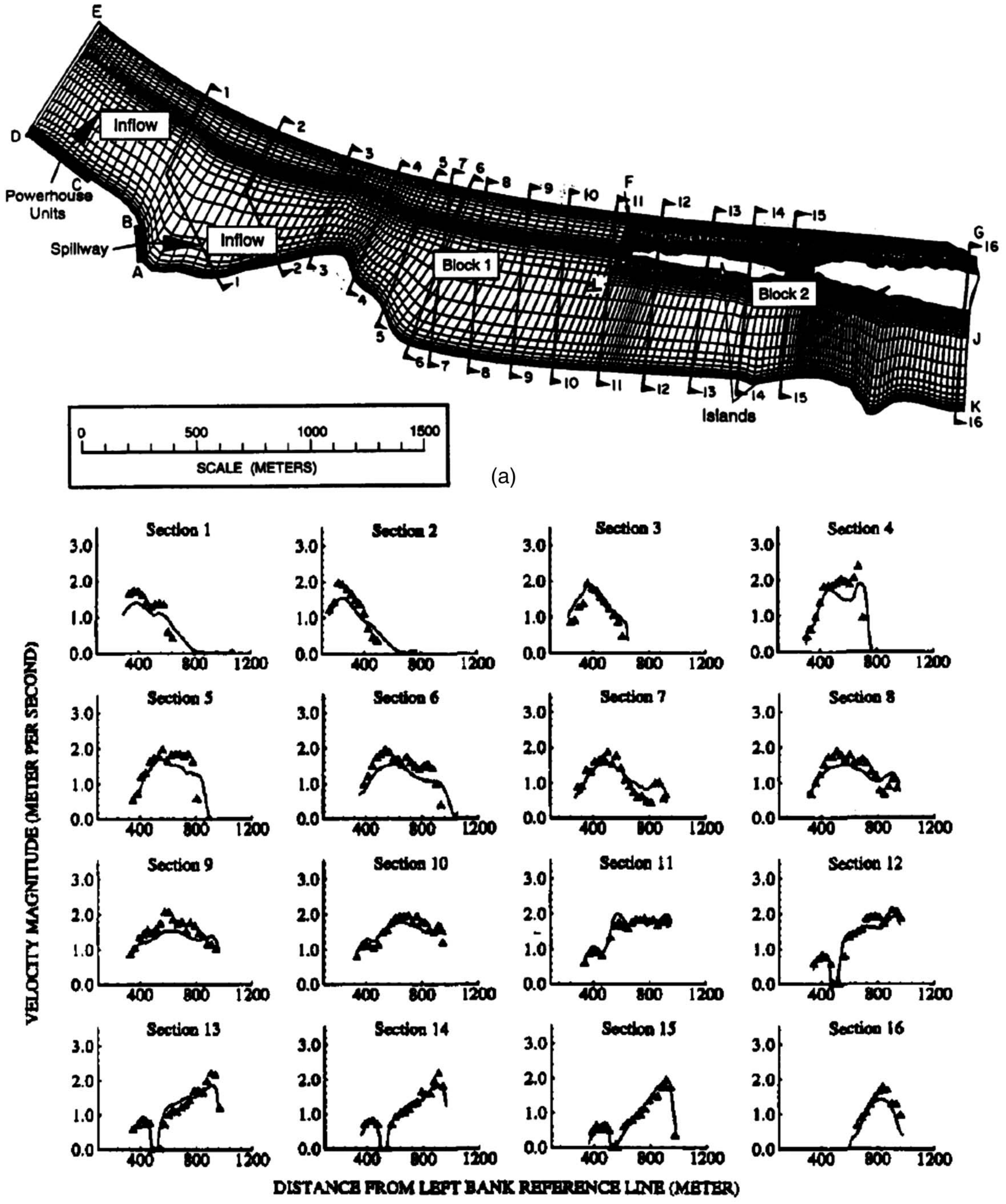
Sinha et al. (1998) undertook the numerical simulation of the flow through a 4-km reach of the Columbia River in the tailrace of the Wanapum Dam. This attempt was one of the first to simulate using high-fidelity (for the time) flow through a natural river reach. Field surveys were used to construct an accurate digital bathymetry model of the Wanapum Dam tailrace, which was quite complex because, in addition to the natural bathymetric complexity of the reach, included were two islands near the left bank that set up a very challenging computational problem (Fig. 1). Another complexity stemmed from the heterogeneously distributed roughness within the river reach, with several distinct patches of varying roughness throughout the reach. Sinha et al. (1998) developed a numerical method for solving the steady incompressible RANS equations closed with the standard k-ε model with wall functions based on the method I had developed earlier for my Ph.D. thesis (Sotiropoulos and Abdallah 1992). A structured curvilinear grid with a multiblock approach was developed to simulate the complex multiconnected flow domain with the islands. Implicit solvers with approximate factorization strategies were used to efficiently solve the RANS equations in high aspect ratio domains typical of natural river simulations. The computational model was tightly integrated and driven by measurements from the field and a 1:100 scale laboratory model set up at IIHR. Measurements at one discharge were used to calibrate the roughness distribution in the reach, which was subsequently held fixed to predict the flow at other discharges. Extensive comparisons with field and laboratory data indicated that the method was able to reproduce the measured mean flow field and turbulence kinetic energy with reasonable accuracy (see Fig. 1). This work clearly illustrated the power of interlacing computational models with field and laboratory experiments to advance our understanding of river turbulence, at least in a statistically averaged sense, and to use numerical simulation as a tool for hydraulic design.

Approximately 330,000 grid nodes were used to discretize the Wanapun Dam tailrace in the work of Sinha et al. (1998), and 130 h of central processing unit (CPU) time were required on an IBM-380 machine to obtain converged steady-state solutions. Of course, typical grid sizes today have grown by more than three orders of magnitude, and the steady RANS models have been replaced by unsteady, eddy-resolving models. This journey has been an exciting one of simulation-driven discovery in environmental hydraulics, riding the wave of exponentially growing computing power, which I will detail in the rest of this paper.

Georgia Tech Years (1995–2005): Unsteady RANS and Hybrid RANS/LES Models

My work at Georgia Tech shifted toward 3D unsteady simulations and coherent-structure-resolving turbulence models. During the 10 years I spent there on the faculty, the notion that steady RANS models closed with standard two-equation models calibrated for canonical equilibrium flows are unlikely to work for flows in which most of the turbulence energy is produced by geometry-induced, slowly varying coherent structures, such as those encountered in most hydraulic engineering applications of practical interest, was gaining acceptance in the research community [see Rodi (2017) for an excellent review of the turbulence modeling state of the art for hydraulic engineering flows]. Although promising RANS results had been obtained using more sophisticated and computationally more intensive full and/or algebraic Reynolds stress models (e.g., Sotiropoulos and Patel 1995), the computational stiffness of such models and the difficulties in obtaining converged solutions in complex flows made them cumbersome and impractical to pursue in real-life applications. A critical prerequisite for tackling complex hydraulic engineering flows with coherent structure resolving turbulence models, however, was the development of efficient algorithms for solving the unsteady 3D Navier-Stokes equations in complex multiconnected domains.

A major advance in this regard was the development of a domain decomposition method with overset grids by Tang et al. (2003), which was able to accurately and efficiently simulate unsteady flows in complex multiconnected domains such as those encountered in open channels and natural rivers with hydraulic structures. Ge and Sotiropoulos (2005) extended this method to solve the unsteady RANS (URANS) equations closed with the standard k-ε model and demonstrated its potential by applying it to simulate the flow past the piers of a bridge over the Chattahoochee River in Georgia placed on the actual bathymetry of the river reach. Fig. 2 shows a snapshot of the simulated unsteady structures shed by the bridge foundation. The total number of grid nodes used in this simulation was approximately 1.5 million, and integration of the governing equations for 3,000 physical time steps required three days of CPU time. These simulations were the first to demonstrate that URANS equations can resolve the very large-scale unsteady coherent structures shed by bridge foundations and yield results in reasonable agreement with the measurements for such a complex flow.



(a)

(b)

Fig. 1. Wanapum Dam tailrace simulation by Sinha et al. (1998). (a) Computational grid at the water surface indicating the location of powerhouse units, spillway, and multiblock grid structure for simulating the two islands; and (b) sample comparisons between calculated (lines) mean velocity profiles with measurements (symbols). Profile locations are identified in (a). (Reprinted from Sinha et al. 1998, © ASCE.)

More advanced coherent structure-resolving models are based on hybrid URANS/LES formulations, such as the so-called detached-eddy simulation (DES) proposed by Spalart (2009). To the best of my knowledge, the first application of DES to tackle hydraulic engineering flows was reported by Paik and Sotiropoulos (2005), who used the method of Tang et al. (2003) to simulate the flow past a bridge abutment mounted on a rectangular open channel—see also Paik et al. (2010). Abutment flows are especially challenging to simulate numerically because they are characterized by multiple regions of rich dynamics with coherent structures that evolve over disparate time scales (see Fig. 3). For example, upstream of the abutment at its intersection of the channel side wall is a separated flow region that has been shown by experiments (Chrisohoides and Sotiropoulos 2003) to be characterized by multiple highly-dynamic, albeit slowly evolving, eddies. Typical eddy coherence time scales in this region were found to be on the order of 4.0 s (Chrisohoides and Sotiropoulos 2003). In contrast, shedding of Kelvin-Helmholtz (KH) vortices from the energetic shear layer emanating from the sharp upstream tip of the abutment occurs at scales of one order of magnitude smaller, ~0.5 s. Yet, another region of complex dynamics is the separated region downstream of the abutment, which the abutment shear layer

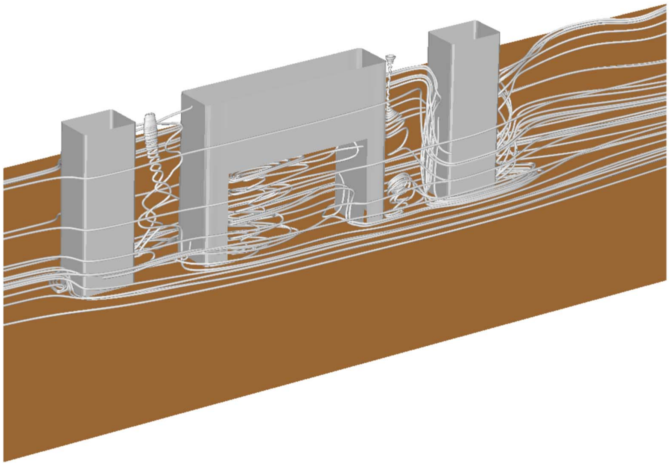


Fig. 2. Instantaneous streamlines of the flow past the Chattahoochee River bridge piers simulated with unsteady RANS by Ge and Sotiropoulos (2005). A similar figure appeared on the cover of the ASCE Journal of Hydraulic Engineering for several years.

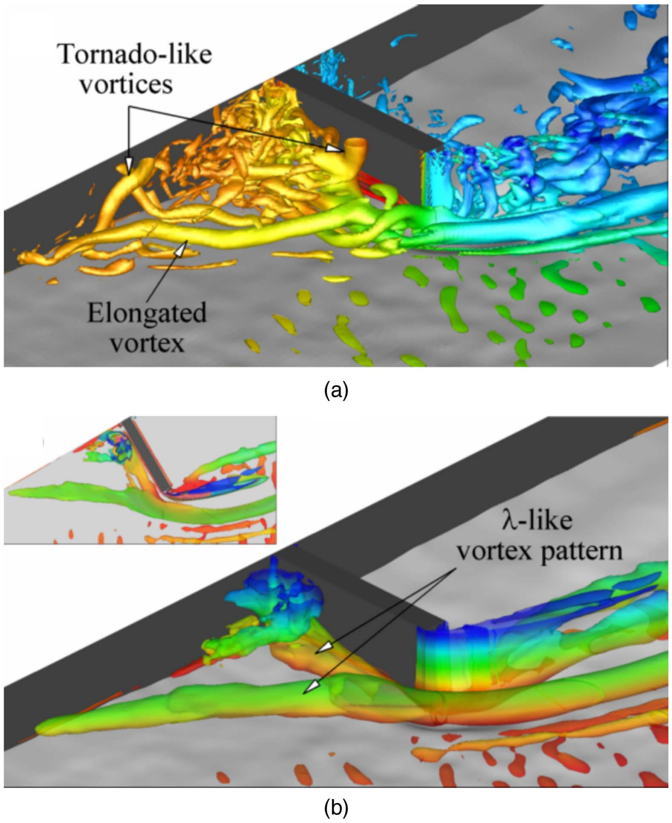


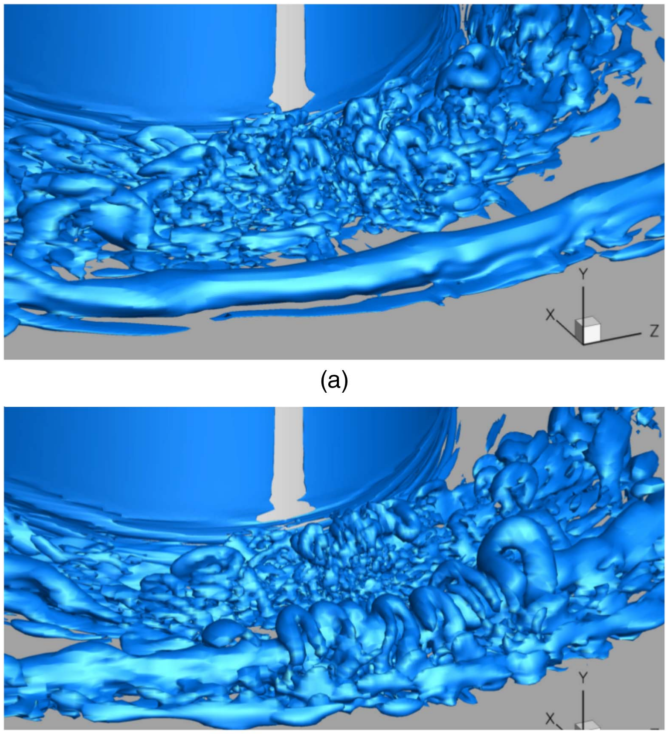
Fig. 3. Coherent structures visualized with the q-criterion obtained by carrying out DES for the flow past a rectangular bridge abutment: (a) instantaneous coherent structures; and (b) time-averaged coherent structures. (Reprinted from Paik et al. 2010, © ASCE.)

delineates from the outer flow. This region is also characterized by slow albeit very complex coherent eddies and their interaction with the KH eddies and the channel sidewall (see Fig. 3). The DES of Paik and Sotiropoulos (2005) was able to capture all of these complex phenomena and yielded results in very good agreement with the flow visualization experiments of Chrisohoides and Sotiropoulos (2003). The simulations elucidated the structure of 3D separation from the channel side walls and the abutment surfaces. They further showed that the phase-space dynamics of the flow in the upstream recirculating region, which is dominated by multiple eddies energized by the outer fast-moving flow and interacting with each other and the surrounding walls, is quasi-periodic as it occurs on a torus.

These simulations provided an exciting glimpse into the potential of coherent-structure resolving models in complex hydraulic engineering flows and showed that such models have true predictive power and can be used to dramatically augment experiments by uncovering new physical phenomena. This early success paved the way for the work that I pursued in the next decade of my career at SAFL.

SAFL Years (2006–2015): LES of River Turbulence and Morphodynamics

My early work at SAFL focused on continuing the exploration of the predictive power of DES for flows past complex hydraulic structures. A grand challenging problem in this regard, which is a critical prerequisite for developing predictive methods of bridge foundations scour, was the interaction of a turbulent boundary layer with a bridge-pier-like structure. A remarkable experimental study of this flow was carried out in the early 1990s by Devenport and Simpson (1990), who investigated the coherent dynamics of the turbulent horseshoe vortex (THSV) that develops at the junction of a wing-shaped bridge pier with the channel bed. The experiment revealed that the THSV is characterized by low-frequency energetic oscillations with velocity fluctuations that exhibit bimodal PDFs: the so-called backflow mode, when the return THSV flow, that is, the flow that is directed from the pier's leading edge toward the upstream direction along the channel bed, is able to penetrate far upstream to form a strong wall jet; and the zero-flow mode, when the return flow is unable to penetrate upstream and is ejected vertically upward away from the wall. These oscillations produced most of the turbulence kinetic energy (TKE) in the junction region, which exhibited a distinct C-shaped structure with two peaks: one peak near the wall and another peak above it. The Davenport and Simpson flow long served as a test case in many studies using steady RANS models with isotropic and nonlinear eddy viscosity models and Reynolds-stress models (see Paik et al. 2007 and references therein). Although these simulations, and especially those using nonisotropic statistical models, captured some features of the flow, they were inherently incapable of resolving the unsteady bimodal dynamics and explaining their physical origin, as well as capturing the double peak C-shaped structure of the high TKE region. The work of Paik et al. (2007) was the first to capture the dynamics of the THSV as observed by Devenport and Simpson (1990) and explain the mechanisms that give rise to the bimodal oscillations (see Fig. 4). These simulations further underscored the predictive power of coherent-structure resolving models and their potential to be used as a tool of scientific discovery that further augments insights derived from experiments (Paik et al. 2007, 2010). An example of using such simulations as a tool of scientific discovery was presented by Escauriaza and Sotiropoulos (2011a, b), who coupled DES of the TSHV past a cylindrical pier with new Lagrangian (Escauriaza and Sotiropoulos 2011b) and Eulerian (Escauriaza and Sotiropoulos 2011a) models of bedload transport to provide striking new insights into the mechanisms and dynamics of sediment grain transport and bedform formation by coherent vortices during initiation of scour.



(a)

(b)

Fig. 4. Instantaneous isosurfaces of the q-criterion for the flow past a wind-shaped pier indicating the two modes of the turbulent horseshoe vortex (TSV): (a) the back-flow mode characterized by an organized neckless-like vortex; and (b) the zero-flow mode for which hairpin vortices emerge between the primary vortex and the wall, and wrap around and disorganize it. (Reprinted from Paik et al. 2010, © ASCE.)

My work in river hydrodynamics during my 10 years at SAFL was greatly energized and inspired by my association with the NSF-funded Science and Technology Center National Center for Earth Surface Dynamics (NCED), which was in full gear when I arrived at the laboratory. NCED focused on predicting the evolution of the coupled geomorphic-ecological systems of the Earth's surface with the goal to develop science-based solutions for addressing the adverse impacts of nonsustainable anthropogenic practices on water resources and ecosystems and restoring rivers and streams. The way that I could contribute to this exciting scientific endeavor became immediately apparent because developing a predictive understanding of turbulent flow and transport processes in waterways across a range of scales was a critical prerequisite for any science-based approach to restoring rivers and streams. However, this effort was not going to reflect computational fluid dynamics as usual. Making a real impact required being able to carry out data-informed, site-specific simulations of flows in real-life natural rivers at resolutions sufficiently fine to capture unsteady energetic eddies across a range of scales: from hydraulic structures to woody debris to boulders and even fish or denitrification hot spots. We needed to be able to simulate scalar and sediment transport, including migrating bedforms and scour, and do this at unprecedented spatial and temporal resolutions and for the real flows of interest. In essence, we needed to be able to use computational models to create realistic virtual testbeds of streams and rivers on which we could test scientific hypotheses and design, evaluate, and optimize a range of solutions. Moreover, all of our computational methods at the time, advanced and powerful as they were, were not ready to tackle such complexities. Additionally, even if we had the computational methods, we would still need access to experiments at the field scale to be able to assess the predictive power of the simulations. Field-scale experimental facilities that enable controlled experiments under realistic conditions did not exist and were not at our disposal.

To address the need for controlled experiments at the field scale, we developed at SAFL the Outdoor StreamLab (OSL): a one of a kind experimental facility located right next to the SAFL building that draws water from the Mississippi River (Fig. 5) (see Kang et al. 2011). This research facility is a 40- by 20-m basin that has been configured into a sand-bed meandering stream channel that was approximately 50-m long, 2-m wide, and 0.1-m deep at base flow. Entrance conditions for the OSL allow accurate flow rate control and measurement of water and sediment discharge rates, and the facility is outfitted with a sedimentation basin at its downstream end where sediment is collected and stockpiled for recirculation. The OSL was equipped with instrumentation, such Acoustic Doppler Velocimetry (ADV) sensors, mounted to a channel-spanning portable traverse. This instrumentation was designed by SAFL engineers, enabling accurate lateral and vertical positioning and mean velocity and turbulence statistics measurements throughout the channel. Laser sensors were also developed to enable measurements of bed and water surface topography on a 1-cm horizontal grid at submillimeter vertical accuracy using instruments mounted to a separate channel-spanning portable carriage, the position of which was registered using the total station. The ability to control flow and sediment fluxes through the OSL, coupled with the wide array of flow, topography, and water surface elevation sensors, made this facility ideally suited for developing and validating our computational tools in an artificial albeit natural-like stream.

At the same time as the development of the OSL facility, my group started working on developing what we initially referred to as the Virtual StreamLab (VSL)—the code that later evolved into the Virtual Flow Simulator (VFS-Geophysics). Our goal was to be able to simulate the topographic complexity of natural waterways across a range of hydraulic, ecological, and biological scales of interest when resolving morphodynamic phenomena, such as migrating bedforms and scour, and water surface effects. The arbitrary geometric complexity of waterways, along with the fact that we were dealing with problems for which both the bottom (streambed) and the top (water surface) boundaries were dynamically evolving in a coupled manner with the flow, necessitated a range of algorithmic innovations. The key idea was to adapt to numerical techniques for stream and river flows that we had already developed in my group to simulate cardiovascular flows and flows past swimming fish (Gilmanov and Sotiropoulos 2005; Ge and Sotiropoulos 2007; Borazjani et al. 2008). The so-called Curvilinear Immersed Boundary (CURVIB) method (Ge and Sotiropoulos 2007) eliminated the need to generate boundary-fitted computational grids and significantly facilitated the simulation of flows with continuously evolving boundaries. The flow boundaries, say the river bed with all embedded structural elements of interest (hydraulic structures, rocks, boulders, and others), are discretized with an unstructured triangular mesh and immersed into a background Cartesian or curvilinear mesh outlining the geometry of interest (Fig. 5). The effect of the boundary conditions on the flow is accounted for using boundary conditions reconstruction techniques based on wall normal interpolation. For flows for which the background grid is sufficiently fine to resolve the near-wall laminar sublayer linear interpolation works well for reconstructing boundary conditions. However, for the high-Reynolds number flows encountered in real-life stream and river flows, generating such fine computational grids is not

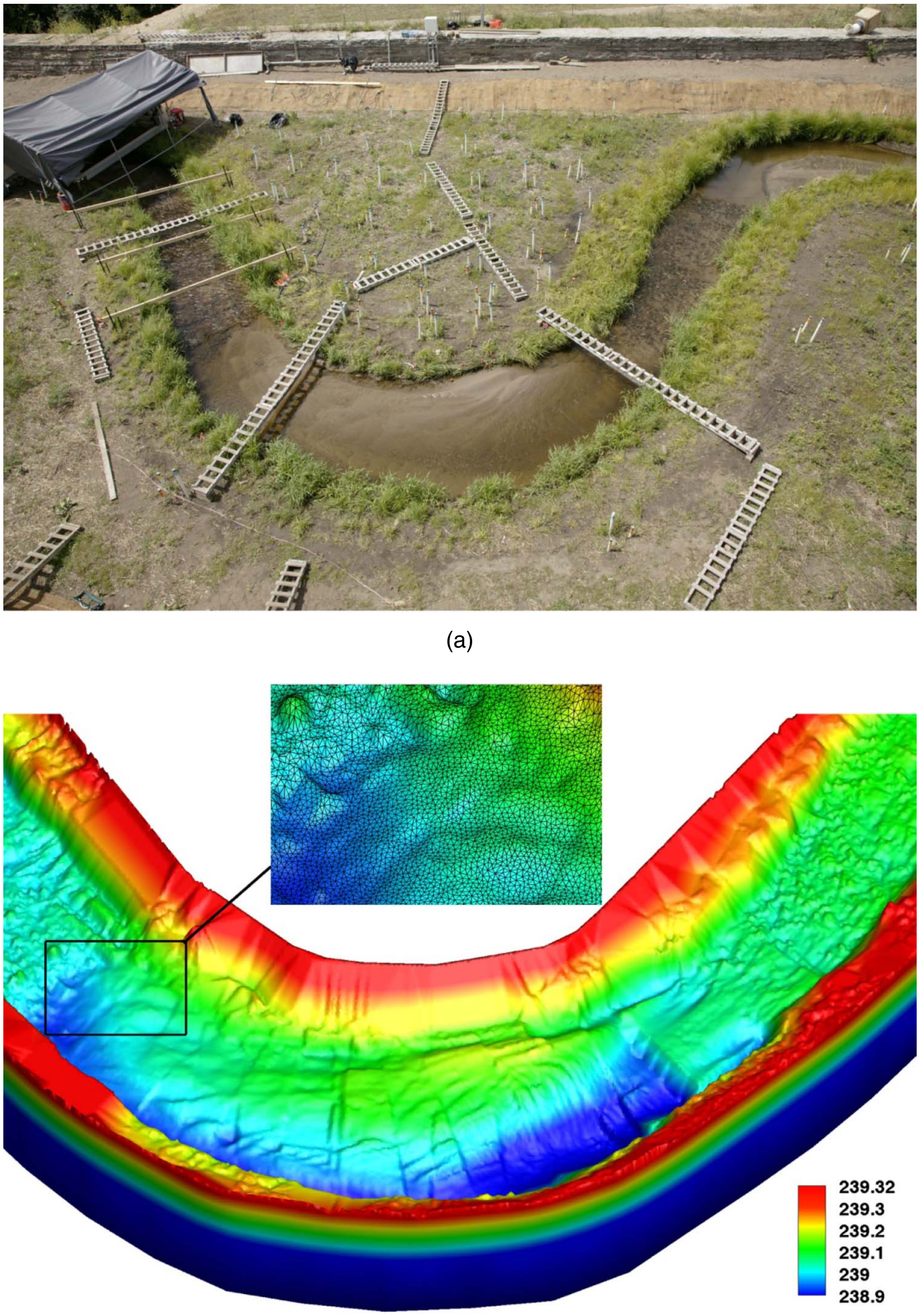


Fig. 5. SAFL Outdoor StreamLab (OSL). (a) the OSL facility located right next to the St. Anthony Falls Laboratory in Minneapolis; and (b) the OSL bathymetry obtained from high-resolution measurements. The streambed is discretized with an unstructured mesh and treated as an immersed boundary in a background curvilinear grid as required by the CURVIB method developed by Kang et al. (2011) for carrying out LES of stream and river flows. The contour levels denote bed elevations.

practical. For that, reconstruction of boundary conditions is carried out using wall models. Therefore, our goal was to carry out LES with wall models for real-life waterways that accounted for and directly resolved a range of topographic features of interest. Therefore, even though the near-wall flow would not be resolved down to the laminar sublayer, the total number of grid nodes required to discretize the computational domain would be in the tens or even hundreds of millions of nodes to resolve the topographic complexity of the waterways. Solving the unsteady, 3D, incompressible LES-filtered Navier-Stokes equations on such fine grids for flows with nonhomogeneous directions and in domains of very high aspect ratios, typical for long and shallow stream and river reaches in nature, is far from trivial because the discrete continuity equation needs to be efficiently satisfied to machine zero at every physical time step. For that, we had to develop fast iterative solvers with efficient preconditioners specifically designed to enable fast convergence of the pressure Poisson equation in long, wide, and very shallow domains, and parallelize the computer code to take advantage of massively parallel computer systems. The computational infrastructure developed to enable such simulations was first presented by Kang et al. (2011), who also presented our first attempt to carry out LES with wall modeling of flow in the OSL, including comparisons with experimental data. The potential of this method in simulations of turbulent flows in waterways with embedded structures was demonstrated by, among others, Kang and Sotiropoulos (2011, 2012a, 2015a), and Kang et al. (2016). To simulate nonlinear free surface effects in waterways with natural and artificial structures, we incorporated the CURVIB method with the level set approach (Kang and Sotiropoulos 2012b). We carried out experiments of flow past a rock structure mounted on the bed of one of SAFL's indoor flumes to obtain mean water surface elevations and RMS of water surface elevation fluctuations to compare with the measurements, and we obtained results in excellent agreement with the measurements (Kang and Sotiropoulos 2015b).

Extending our computational approach to simulate sediment transport, migrating bedforms and scour was far from a trivial undertaking and required major computational advances. The key idea was that the channel streambed immersed in the background grid—the sediment-water interface—was neither fixed nor known a priori but had to evolve as a result of bedload transport, sediment erosion, and suspension processes. New flow/structure interaction (FSI) computational tools had to be developed to allow for such physics to be incorporated in the context of the CURVIB framework, which were presented in a series of papers by Khosronejad and Sotiropoulos (2014) and Khosronejad et al. (2011, 2012, 2013). The details of these developments are far too elaborate and involved to be summarized in this brief paper, and I refer the reader to Khosronejad and Sotiropoulos (2014) for a detailed description.

Our vision for a computational framework that could simulate and accurately predict flow and transport phenomena in real-life waterways was now complete. We dubbed the resulting code the VFS-Geophysics- and undertook a series of computational studies informed by experiments to demonstrate how such a code could be used as a tool for scientific discovery. In Kang and Sotiropoulos (2012a), we showed how isotropic RANS models fail to predict essential features of secondary flows in meandering streams and demonstrated that this was the result of the inherent anisotropy of the flow, which could give rise to two—rather than one—counter-rotating streamwise cells. These two cells, which could only be resolved by LES, collide at the water surface flow along a line of convergence located near the outer bank of the meander (Kang and Sotiropoulos 2011). Slow lateral flow fluctuations along this line of convergence led to the production of very high levels of TKE (see Fig. 6). This region of TKE would be difficult to identify and resolve using standard experimental resolution without a priori knowledge from simulations, but the simulations suggested a very simple experiment in the OSL that readily uncovered the footprint of such complex 3D flow physics on the water surface. Namely, releasing small paper pieces on the surface upstream of the OSL meander captured the line of convergence in remarkable agreement with the simulations (see Fig. 6). This phenomenon demonstrated an exciting simulation-driven insight as the line of convergence coincides with the region of highest TKE on the water surface, marks the point of lateral collision of the two secondary flow cells, and identifies the exactly location of downward flow toward the bed, which coincides with the channel thalweg (Kang and Sotiropoulos 2011, 2012a).

The potential of VFS-Geophysics as a tool for predicting hydrodynamics-mediated bio-geo-chemical processes in streams and rivers was reported in Morris et al. (2015). The code was informed with high-resolution, site-specific bathymetric data and integrated with field measurements to develop a framework for predicting Glossosoma biomass spatial distribution in Valley Creek, Minnesota. Morris et al. (2015) indicated that the computational results explained 79% of the variation in observed dimensionless Glossosoma spatial density. This study demonstrated, for the first time, that computational fluid mechanics and high-resolution bed topography could be instrumental in predicting benthic macroinvertebrate spatial distribution in streams and rivers.

Another compelling application of our data-driven, high-fidelity simulation approach was recently reported by Khosronejad et al. (2016a), who applied the code to simulate turbulent flow and scalar transport through a 300-m reach of Eagle Creek in Minnesota. Field surveys were used to construct a high-resolution digital terrain model of the stream, incorporating directly features such as boulders and woody debris. Tracer release experiments were also carried out to obtain data for the rate of transport of nonreacting scalar in the stream. The simulations yielded results in striking agreement with the field measurements in terms of mean flow quantities, turbulence statistics, and tracer concentration time series (Fig. 7). This study clearly demonstrated the predictive power of VFS-Geophysics in data-driven simulations of real waterways.

The predictive capabilities of VFS-Geophysics for hydromorphodynamic simulations have been demonstrated in a series of studies by Khosronejad and Sotiropoulos (2014, 2017) and Khosronejad et al. (2011, 2012, 2013) for scour and bedforms of varying topology and across a range of spatial scales: from small ripples in laboratory flumes to mega-dunes in large rivers. Khosronejad and Sotiropoulos (2014) carried out coupled hydromorphodynamic LES for a laboratory flume experiment and captured the entire process of dune emergence, growth, and evolution: from the initial destabilization of the flat sand bed by near-bed sweeps in the turbulent boundary layer to the emergence of a quasi-equilibrium field of transverse dunes as large as one-third of the flow depth. The simulations not only captured the measure in the laboratory dynamic evolution of the topology and the kinematics of the bedforms (in terms of celerity, wave length, and amplitude) but further provided new insights into the mechanisms of bed destabilization and subsequent self-organization into large-scale transverse dunes. In a more recent study, Khosronejad and Sotiropoulos (2017) demonstrated the ability of VFS-Geophysics to simulate the emergence of quasi-equilibrium barchan dunes in the same channel used in Khosronejad and Sotiropoulos (2014) but with a finite supply of sand on the channel bed. That is, rather than circulating the sand exciting the domain as was done in Khosronejad and Sotiropoulos (2014), Khosronejad and Sotiropoulos (2017) started with a finite thickness sand layer on the bed and allowed the material to exit the computational domain. The simulations (see Fig. 8) produced the entire generation, evolution, and formation process of quasi-equilibrium barchan fields in striking agreement with laboratory studies and field observations. A major insight gained from this study is the precise explanation of the previously documented form satellite imagery process of calving, which has been proposed as the critical mechanism for sustaining quasi-equilibrium barchan fields in nature—see Khosronejad and Sotiropoulos (2017) for details.

The aforementioned studies focused on laboratory-scale dunes and served to demonstrate the potential of high-fidelity simulations to be used as a tool for scientific discovery, dramatically augmenting the insights gained by experiments alone. VFS-Geophysics incorporates several algorithmic features enabling computationally efficient simulations of field-scale dunes in rivers

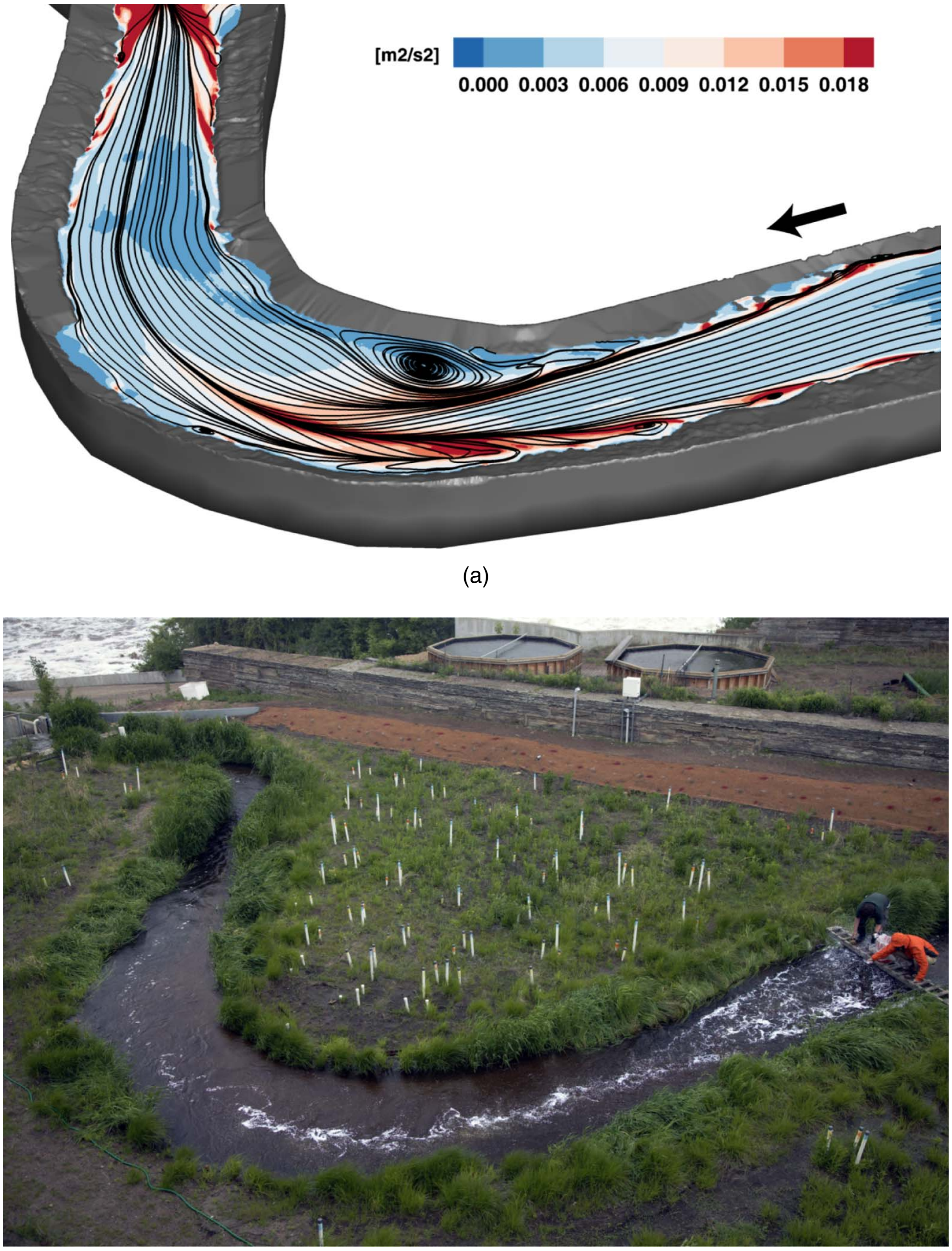


Fig. 6. (a) Time-averaged streamlines and turbulence kinetic energy contours at the water surface of the SAFL OSL from the LES of Kang and Sotiropoulos (2011); and (b) flow visualization experiment in the OSL conducted by releasing small paper particles upstream of the riffle. Convergence of the surface flow into a single line of convergence near the outer bank, as revealed by the LES, is evident from this photograph.

and streams. These features are reported in Khosronejad et al. (2015) in which simulations and validation studies were also reported for dune migration ranging in scale from the SAFL OSL to large, meandering rivers in nature. These features of the code enable it to be used as a powerful hydraulic-engineering design tool, as demonstrated by Khosronejad et al. (2014), who used VFS-Geophysics coupled with OSL and field measurements to report the first simulation-based design study of rock structures for restoring streams and rivers. The simulations incorporated coupled hydromorphodynamics and yielded specific guidelines for designing, installing, and operating stream restoration structures, such as, among others, J-hooks, rock vanes, cross vanes, and W-weirs (Sotiropoulos and Diplas 2014).

Looking Ahead: Data-Driven Virtual Test-Beds for Grand Challenge Societal Problems

Recently, I wrote a paper presenting my vision for the future of our field of hydraulic engineering (Sotiropoulos 2015). The key

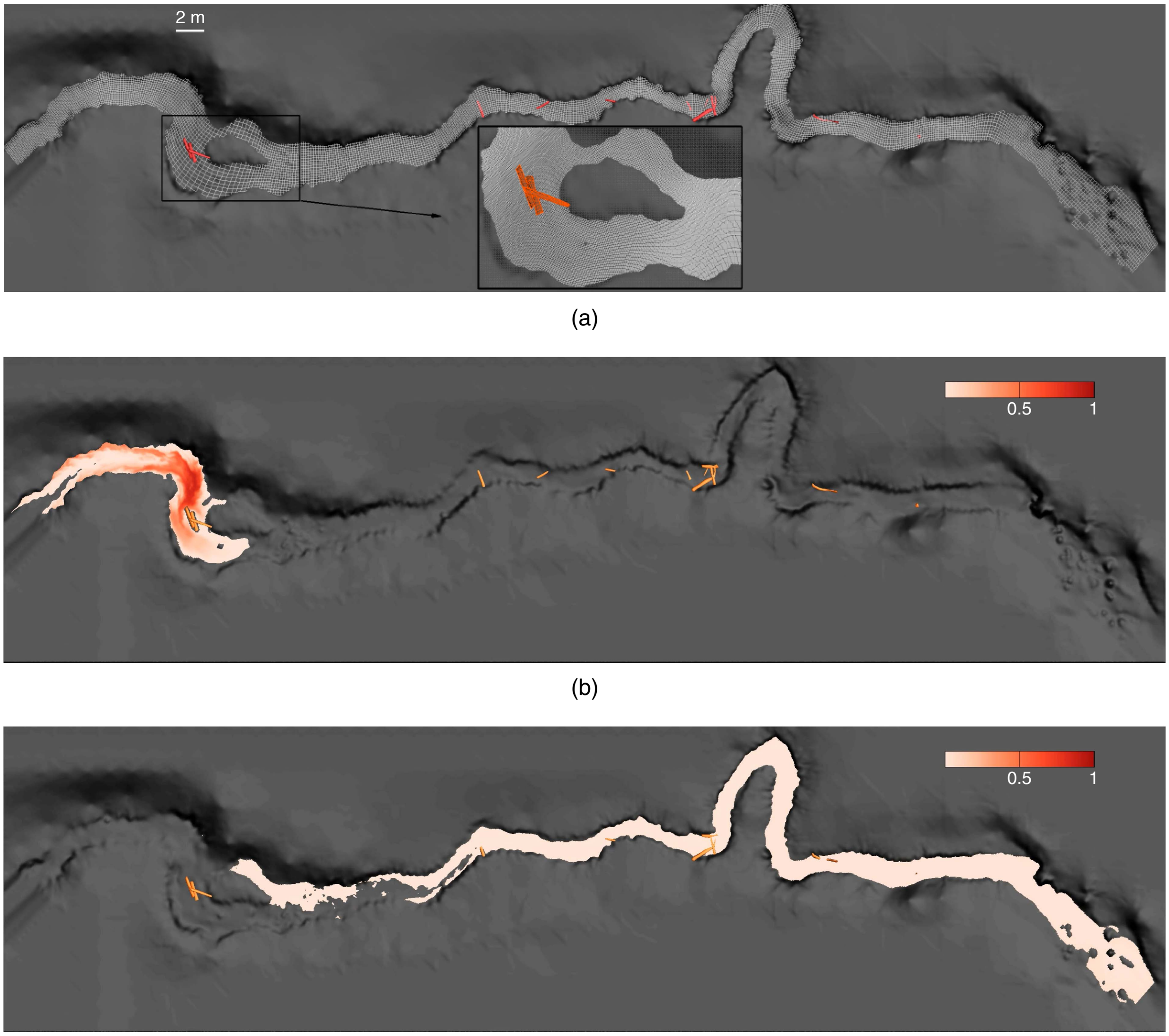


Fig. 7. LES of turbulent flow and conservative tracer transport (pulse release) in headwater stream in Minnesota (Eagle Creek) (Khosronejad et al. 2016a): (a) Eagle Creek bathymetry including woody debris and the CURVIB grid used to discretize the reach and all its features; and (b and c) simulated contours of instantaneous tracer concentration at mid-depth plane. Early release of the pulse is shown in (a), and late-stage transport of the tracer is shown in (c).

message that I tried to convey in this paper was that numerical simulations of complex real-life hydraulic engineering flows in natural waterways, which up until few years ago were considered intractable in the foreseeable future, are now well within reach. I argued that the advent of computational algorithms capable of data-informed, site-specific LES of flow and transport processes in real-life waterways, in conjunction with the exponential growth in computational power, pave the way for simulation-based engineering science to radically transform hydraulic engineering research in the years to come. Specifically, such simulations will enable our field to play an even more influential role in tackling some of the most challenging issues confronting humanity in its quest for a sustainable future.

For example, integrating predictive computational models, such as those previously reviewed, with data from satellites, LiDARs, and robotically deployed sensors in waterways will open up exciting opportunities for developing predictive, site-specific models of inland and coastal flooding of unprecedented realism and resolution. Such models will enable engineers, practitioners, and stakeholders to create in cyberspace virtual test beds of extreme flooding events, understand their potential impact on communities, infrastructure, and economic development, and develop effective flood protection and mitigation strategies to address the impacts of global environmental change. Khosronejad et al. (2016c) recently presented an exciting glimpse into such a future by carrying LES of turbulent flow and morphodynamics through a 3.2-km stretch of the Upper Mississippi River where it meets Interstate Highway I-694 under two flow conditions: base flow and a 100-year flood event. By fusing together LiDAR data with detailed bathymetric surveys of the river reach, we generated a high-resolution digital elevation model (DEM) of the river reach and surrounding floodplain and used it as a virtual test bed to study flow, sediment transport, and bridge foundation scour under baseline and extreme flooding conditions (Fig. 9). Simulations like this and at even larger scale and scope are bound to become routine in years to come and start impacting the decisions made by agencies,

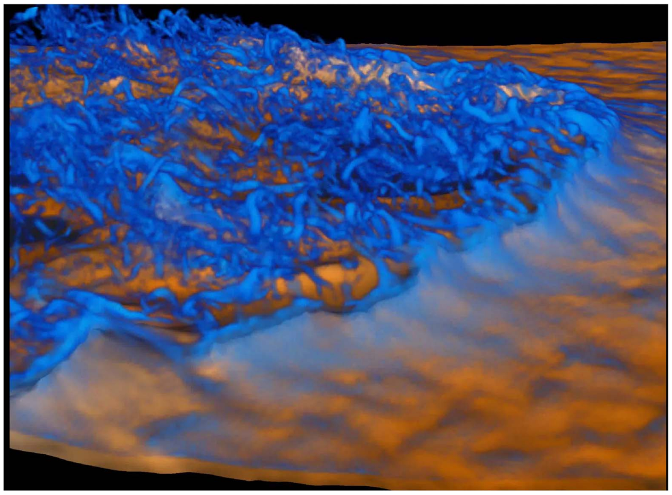


Fig. 8. Coupled hydromorphodynamic LES of turbulent flow in rectangular flume with finite sediment supply over bedrock indicating the evolution of barchan dunes (Khosronejad and Sotiropoulos 2017). Instantaneous isosurface of vorticity magnitude is superimposed to illustrate the complexity of the flow. Flow is from right to left.

stakeholders, and their consultants. Such simulations may not be used only to assess the impacts of extreme flooding events but also to develop science-based, site-specific strategies to restore streams and rivers, predict scalar and contaminant transport and their impact on ecosystems, understand biogeochemical processes and their connections to local hydraulic conditions, and manage nitrogen transport and processing in waterways.

Another major societal area in which high-fidelity, site-specific simulations will enable hydraulics to have a significant impact is the so-called nexus of water and energy. Marine and hydrokinetic (MHK) energy—including wave, tidal, and river technologies—is an emerging source of renewable energy that is aggressively being developed in many places around the globe. MHK in the United States has the potential to provide up to 10% of the nation's electricity. However, achieving this goal requires developing a predictive understanding of how energy-extracting devices (e.g., turbines, wave energy converters) will perform in multidevice arrays embedded in real-life waterways and coastlines with complex bathymetry, energetic coherent structures, free-surface and waves (for wave energy converters), and mobile sediment beds. A recently published experimental study explored for the first time the striking coupling between hydrokinetic power

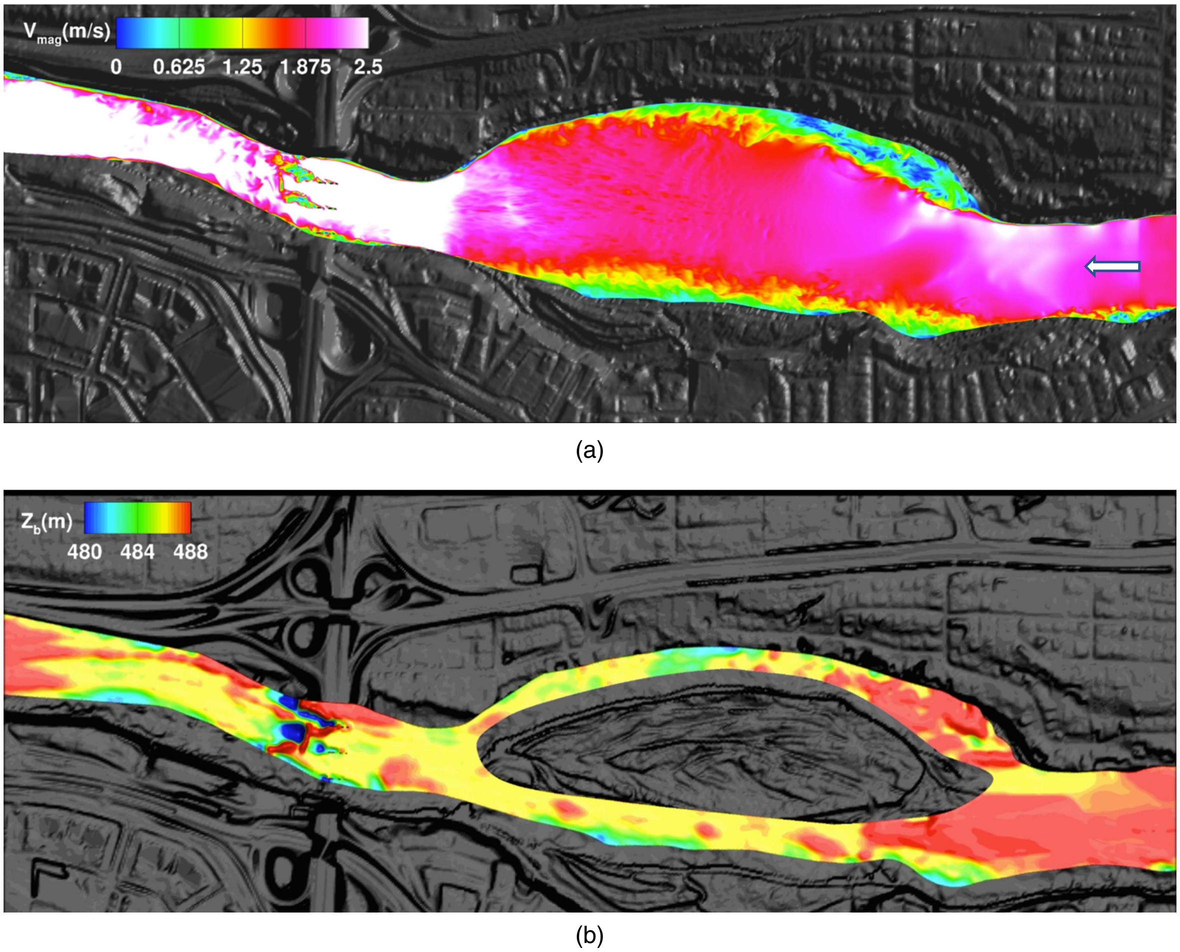


Fig. 9. Coupled hydromorphodynamic LES of turbulent flow through a 3.2-km reach of the Upper Mississippi River near Minneapolis to study the dynamics of scour near a geometrically complex bridge foundation (the I-694 bridge) under a 100-year flood event and live-bed conditions (Khosronejad et al. 2016c), indicating (a) instantaneous velocity magnitude contours at the water surface; and (b) bed elevation contours. Flow direction is from right to left.

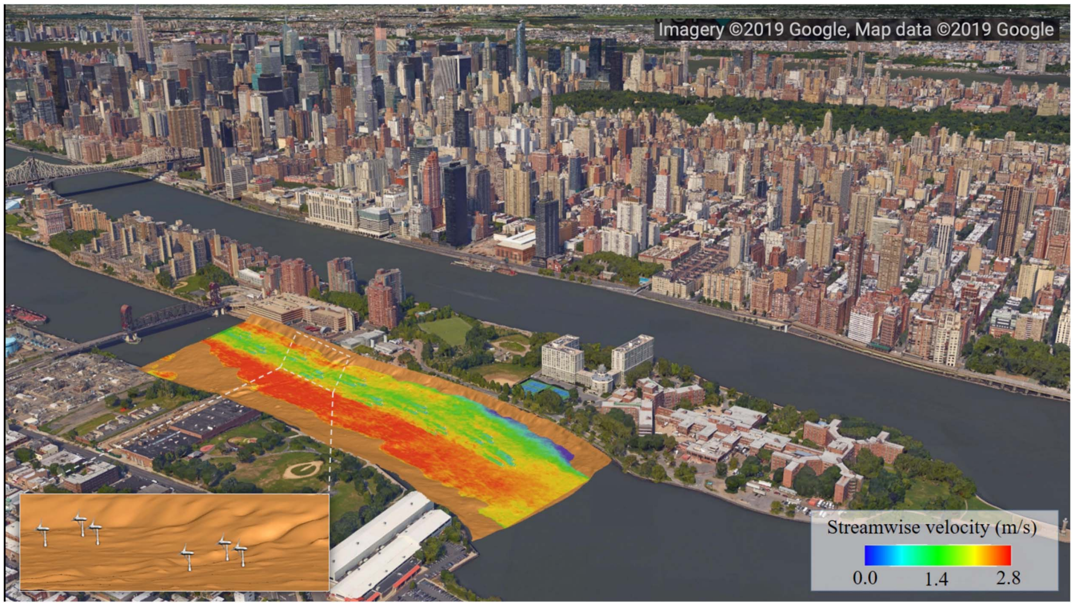


Fig. 10. LES of turbulent flow through the reach of the East River where the Verdant Power Roosevelt Island Tidal Energy (RITE) project will be installed in New York City (Chawdhary et al. 2018). Thirty hydrokinetic turbines are placed on the river bed in TriFrame arrangements. The city image is obtained from Google Maps and the flow domain, depicting instantaneous velocity contours at the water surface, has been superimposed. The lower left inset indicates a zoomed-in view of two TriFrames on the river bathymetry. Flow is from right to left. (Imagery © 2019 Google, Map data © 2019 Google.)

harvesting and channel hydromorphodynamics. Musa et al. (2018) reported a scaled demonstration of a hydrokinetic turbine power plant deployed in a quasi-field-scale channel with sediment transport and migrating bedforms. The experiments simultaneously measured sediment fluxes, spatiotemporally resolved bathymetry, and turbine model performance. With strategic turbine siting, extracting kinetic energy was shown to be done efficiently without compromising the geomorphic equilibrium of the river and the structural safety of the turbine foundation, even in the presence of large migrating dunes, thus paving the way for harnessing sustainable and renewable energy in rivers. This study further demonstrated the necessity for site-specific simulations coupling MHK power plant operations with waterway bathymetry and morphodynamics for power plant siting and optimization. Computational tools capable of such simulations have only recently begun to emerge. Kang et al. (2014) reported a high-fidelity LES of an axial flow MHK turbine mounted on a flat and immobile bed laboratory flume and uncovered new phenomena in the turbine wake that can dramatically augment the intensity of wake meandering. Chawdhary et al. (2017) reported high-fidelity LES of three hydrokinetic turbines mounted on a TriFrame (TriFrame is a trademark of Verdant Power) arrangement to study the dynamics of the superwake emerging as the wake of the three turbines merged. Yang et al. (2017) reported the first coupled hydro-morphodynamic LES of a hydrokinetic turbine mounted on a mobile sediment bed and systematically investigated the effects of turbine operating conditions and sediment particle sizes on bed-load sediment transport and turbine wake recovery. The potential of data-informed, site-specific simulations of MHK powerplants in real-life waterways was recently demonstrated by Chawdhary et al. (2018), who employed high-resolution bathymetry data to construct a virtual test bed of a segment of the East River in the vicinity of Roosevelt Island in New York City—the site of the proposed Verdant Power Roosevelt Island Tidal Energy (RITE) project. Thirty turbines arranged in TriFrames were placed on the river bathymetry, and multiresolution LES using locally refined grids (Angelidis et al. 2016) was carried out to study the array performance and wake dynamics (Fig. 10). Although these simulations did not consider river morphodynamics, because the East River is a fixed bed river with essentially no sediment, they clearly demonstrated the potential of such simulations for optimizing MHK powerplant siting, increasing resilience, and advancing science-based strategies for sustainable harvesting of hydrokinetic power from rivers.

Closing Remarks

As I also emphasized in Sotiropoulos (2015), because I am very optimistic and enthusiastic about the future role of simulation-based engineering science in hydraulics, I do not advocate that such computing capability will eliminate the role played by physical experiments. In contrast, the resolution and level of detail that will be required from experimentalists will even increase to catch up with the predictive capabilities of high-fidelity, multiphysics, and multiresolution simulations, help quantify their uncertainties, and develop confidence such that computational power can be used to design hydraulic engineering systems and make decisions. In fact, simulations and physical experiments must be closely intertwined to realize the full predictive power of computational modeling at such a scale. Validating the models with relevant experimental measurements for the phenomena of interest in a given application will allow advanced computational tools to drive scientific discovery, enabling engineers to conduct virtual experiments and realize hypothetical future scenarios that cannot possibly be realized in an experiment (e.g., the effect of a 100- or a 500-year flood on a specific bridge deck in a specific river).

In closing, although we still have a long way to go to affirmatively and conclusively answer the question posed to me by Professor John F. Kennedy some 27 years ago, I am optimistic that a simulations-driven hydraulic engineering future is just around the corner and will be realized within the next decade or even sooner, forever transforming our field.

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References

Angelidis, D., S. Chawdhary, and F. Sotiropoulos. 2016. “Unstructured Cartesian refinement with sharp interface immersed boundary method for 3D unsteady incompressible flows.” *J. Comput. Phys.* 325 (15): 272–300. https://doi.org/10.1016/j.jcp.2016.08.028.

Borazjani, I., L. Ge, and F. Sotiropoulos. 2008. “Curvilinear immersed boundary method for simulating fluid structure interaction with complex 3D rigid bodies.” *J. Comput. Phys.* 227 (16): 7587–7620. https://doi.org/10.1016/j.jcp.2008.04.028.

Chawdhary, S., D. Angelidis, J. Colby, D. Corren, L. Shen, and F. Sotiropoulos. 2018. “Multiresolution large-eddy simulation of an array of hydrokinetic turbines in a field-scale river: The Roosevelt Island tidal energy project in New York City.” *Water Resour. Res.* 54 (12): 10,188–10,204. https://doi.org/10.1029/2018WR023345.

Chawdhary, S., G. Hill, X. Yang, M. Guala, and F. Sotiropoulos. 2017. “Wake characteristics of a tri-frame of axial-flow hydrokinetic turbines.” *Renewable Energy* 109 (Aug): 332–345. https://doi.org/10.1016/j.renene.2017.03.029.

Chrisohoides, A., and F. Sotiropoulos. 2003. “Experimental visualization of lagrangian coherent structures in aperiodic flows.” *Phys. Fluids* 15 (3): L25–L28. https://doi.org/10.1063/1.1540111.

Devenport, W. J., and R. L. Simpson. 1990. “Time-dependent and time-averaged turbulence structure near the nose of a wing-body junction.” *J. Fluid Mech.* 210 (Jan): 23–55. https://doi.org/10.1017/S0022112090001215.

Escauriaza, C., and F. Sotiropoulos. 2011a. “Initial stages of erosion and bed-form development in turbulent flow past a bridge pier.” *J. Geophys. Res.* 116: F03007. https://doi.org/10.1029/2010JF001749.

Escauriaza, C., and F. Sotiropoulos. 2011b. “Lagrangian dynamics of bed-load transport in turbulent junction flows.” *J. Fluid Mech.* 666 (Jan): 36–76. https://doi.org/10.1017/S0022112010004192.

Ge, L., and F. Sotiropoulos. 2005. “3D unsteady RANS modeling of complex hydraulic engineering flows. I: Numerical model.” *J. Hydraul. Eng.* 131 (9): 800–808. https://doi.org/10.1061/(ASCE)0733-9429(2005)131:9(800).

Ge, L., and F. Sotiropoulos. 2007. “A numerical method for solving the 3D unsteady incompressible navier-stokes equations in curvilinear domains with complex immersed boundaries.” *J. Comp. Phys.* 225 (2): 1782–1809. https://doi.org/10.1016/j.jcp.2007.02.017.

Gilmanov, A., and F. Sotiropoulos. 2005. “A hybrid Cartesian/immersed boundary method for simulating flows with 3D geometrically complex moving bodies.” *J. Comput. Phys.* 207 (2): 457–492. https://doi.org/10.1016/j.jcp.2005.01.020.

Kang, S., C. Hill, and F. Sotiropoulos. 2016. “On the turbulent flow structure around an instream structure with realistic geometry.” *Water Resour. Res.* 52 (10): 7869–7891. https://doi.org/10.1002/2016WR018688.

Kang, S., A. Lightbody, C. Hill, and F. Sotiropoulos. 2011. “High-resolution numerical simulation of turbulence in natural waterways.” *Adv. Water Resour.* 34 (1): 98–113. https://doi.org/10.1016/j.advwatres.2010.09.018.

Kang, S., and F. Sotiropoulos. 2011. “Flow phenomena and mechanisms in a field-scale experimental meandering channel with a pool-riffle sequence: Insights gained via numerical simulation.” *J. Geophys. Res.* 116 (F3): 1–22. https://doi.org/10.1029/2010JF001814.

Kang, S., and F. Sotiropoulos. 2012a. “Assessing the predictive capabilities of isotropic, eddy-viscosity Reynolds-averaged turbulence models in a natural-like meandering channel.” *Water Resour. Res.* 48 (6): W06505. https://doi.org/10.1029/2011WR011375.

Kang, S., and F. Sotiropoulos. 2012b. “Numerical modeling of 3D turbulent free surface flow in natural waterways.” *Adv. Water Resour.* 40 (May): 23–36. https://doi.org/10.1016/j.advwatres.2012.01.012.

Kang, S., and F. Sotiropoulos. 2015b. “Large-eddy simulation of 3D turbulent free surface flow past a complex stream restoration structure.” *J. Hydraul. Eng.* 141 (10): 04015022. https://doi.org/10.1061/(ASCE)HY.1943-7900.0001034.

Kang, S., and F. Sotiropoulos. 2015a. “Numerical study of flow dynamics around a stream restoration structure in a meandering channel.” *J. Hydraul. Res.* 53 (2): 178–185. https://doi.org/10.1080/00221686.2015.1023855.

Kang, S., X. Yang, and F. Sotiropoulos. 2014. “On the onset of wake meandering for an axial flow turbine in a turbulent open channel flow.” *J. Fluid Mech.* 744 (Apr): 376–403. https://doi.org/10.1017/jfm.2014.82.

Khosronejad, A., A. T. Hansen, J. L. Kozarek, K. Guentzel, M. Hondzo, M. Guala, P. Wilcock, J. C. Finlay, and F. Sotiropoulos. 2016a. “Large-eddy simulation of turbulence and solute transport in a forested headwater stream.” *J. Geophys. Res. Earth Surf.* 121 (1): 146–167. https://doi.org/10.1002/2014JF003423.

Khosronejad, A., C. Hill, S. Kang, and F. Sotiropoulos. 2013. “Computational and experimental investigation of scour past laboratory models of stream restoration rock structures.” *Adv. Water Resour.* 54 (Apr): 191–207. https://doi.org/10.1016/j.advwatres.2013.01.008.

Khosronejad, A., S. Kang, I. Borazjani, and F. Sotiropoulos. 2011. “Curvilinear immersed boundary method for simulating coupled flow and bed morphodynamic interactions due to sediment transport phenomena.” *Adv. Water Resour.* 34 (7): 829–843. https://doi.org/10.1016/j.advwatres.2011.02.017.

Khosronejad, A., S. Kang, and F. Sotiropoulos. 2012. “Experimental and computational investigation of local scour around bridge piers.” *Adv. Water Resour.* 37 (Mar): 73–85. https://doi.org/10.1016/j.advwatres.2011.09.013.

Khosronejad, A., J. L. Kozarek, P. Diplas, and F. Sotiropoulos. 2014. “Simulation-based approach for stream restoration structure design: Model development and validation.” *J. Hydraul. Res.* 140 (9): 04014042. https://doi.org/10.1061/(ASCE)HY.1943-7900.0000904.

Khosronejad, A., J. L. Kozarek, M. L. Palmsten, and F. Sotiropoulos. 2015. “Numerical simulation of large dunes in meandering streams and rivers with in-stream rock structures.” *Adv. Water Resour.* 81 (July): 45–61. https://doi.org/10.1016/j.advwatres.2014.09.007.

Khosronejad, A., T. Le, P. DeWall, N. Bartelt, S. Woldeamlak, X. Yang, and F. Sotiropoulos. 2016c. “High fidelity numerical modeling of Upper Mississippi River under extreme flood condition.” *Adv. Water Resour.* 98 (Dec): 97–113. https://doi.org/10.1016/j.advwatres.2016.10.018.

Khosronejad, A., and F. Sotiropoulos. 2014. “Numerical simulation of sand waves in a turbulent open channel flow.” *J. Fluid Mech.* 753 (Aug): 150–216. https://doi.org/10.1017/jfm.2014.335.

Khosronejad, A., and F. Sotiropoulos. 2017. “On the genesis and evolution of barchan dunes: Morphodynamics.” *J. Fluid Mech.* 815 (Mar): 117–148. https://doi.org/10.1017/jfm.2016.880.

Larsson, L., V. C. Patel, and G. Dyne. 1991. *Proceedings of the 1990 SSPA-CTH-IIHR workshop on ship viscous flow.* Research Rep. No 2. Gothenburg, Sweden: FLOWTECH International AB.

Morris, M., M. H. Mohammadi, S. Day, M. Hondzo, and F. Sotiropoulos. 2015. “Prediction of Glossosoma biomass spatial distribution in Valley

Creek by field measurements and a three-dimensional turbulent open-channel flow model." *Water Resour. Res.* 51 (3): 1457–1471. https://doi.org/10.1002/2014WR015887.

Musa, M., G. Hill, F. Sotiropoulos, and M. Guala. 2018. "Performance and resilience of hydrokinetic turbine arrays under large migrating fluvial bedforms." *Nat. Energy* 3 (10): 839–846. https://doi.org/10.1038/s41560-018-0218-9.

Paik, J., C. Escauriaza, and F. Sotiropoulos. 2007. "On the bi-modal dynamics of the turbulent horseshoe vortex system in a wing-body junction." *Phys. Fluids* 19 (4): 045107. https://doi.org/10.1063/1.2716813.

Paik, J., C. Escauriaza, and F. Sotiropoulos. 2010. "Coherent structure dynamics in turbulent flows past in-stream structures: Some insights gained via numerical simulation." *J. Hydraul. Eng.* 136 (2): 981–993. https://doi.org/10.1061/(ASCE)HY.1943-7900.0000089.

Paik, J., and F. Sotiropoulos. 2005. "Coherent structure dynamics upstream of a long rectangular block at the side of a large aspect ratio channel." *Phys. Fluids* 17 (11): 115104. https://doi.org/10.1063/1.2130743.

Rodi, W. 2017. "Turbulence modeling and simulation in hydraulics: A historical review." *J. Hydraul. Eng.* 143 (5): 03117001. https://doi.org/10.1061/(ASCE)HY.1943-7900.0001288.

Sinha, S. K., F. Sotiropoulos, and A. J. Odgaard. 1998. "Three-dimensional numerical model for flow through natural rivers." *J. Hydraul. Eng.* 124 (1): 13–24. https://doi.org/10.1061/(ASCE)0733-9429(1998)124:1(13).

Sotiropoulos, F. 2015. "Hydraulics in the era of exponentially growing computing power." *IAHR J. Hydraul. Res.* 53 (5): 547–560. https://doi.org/10.1080/00221686.2015.1119210.

Sotiropoulos, F., and S. Abdallah. 1992. "A primitive variable method for the solution of external, 3-D, incompressible, viscous flows." *J. Comput. Phys.* 103 (2): 336–349. https://doi.org/10.1016/0021-9991(92)90405-N.

Sotiropoulos, F., and P. Diplas. 2014. *Design methods for in-stream flow control structures*. NCHRP Technical Rep. No. (Project 24-33). Washington, DC: Transportation Research Board, National Academies of Science.

Sotiropoulos, F., and V. C. Patel. 1995. "On the role of turbulence anisotropy and near-wall modeling in predicting complex, 3D, Shear Flows." *AIAA J.* 33 (3): 504–514. https://doi.org/10.2514/3.12605.

Spalart, P. 2009. "Detached-eddy simulation." *Annu. Rev. Fluid Mech.* 41 (1): 181–202. https://doi.org/10.1146/annurev.fluid.010908.165130.

Tang, H., S. C. Jones, and F. Sotiropoulos. 2003. "An overset grid method for 3D, unsteady, incompressible flows." *J. Comput. Phys.* 191 (2): 567–600. https://doi.org/10.1016/S0021-9991(03)00331-0.

Yang, X., A. Khosronejad, and F. Sotiropoulos. 2017. "Large-eddy simulation of a hydrokinetic turbine mounted on an erodible bed." *Renewable Energy* 113 (Dec): 1419–1433. https://doi.org/10.1016/j.renene.2017.07.007.