Uncertainty quantification of large-eddy simulation results of riverine flows: a field and numerical study

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Abstract
We present large-eddy simulations (LES) of riverine flow in a study reach in the Sacramento River, California. The riverbed bathymetry was surveyed in high-resolution using a multibeam echosounder to construct the computational model of the study area, while the topographies were defined using aerial photographs taken by an Unmanned Aircraft System (UAS). In a series of field campaigns, we measured the flow field of the river across multiple transects throughout the field site using an acoustic Doppler current profiler (ADCP) and estimated using large-scale particle velocimetry of the videos taken during the operation UAS. We used the measured data of the river flow field to evaluate the accuracy of the LES-computed hydrodynamics. The propagation of uncertainties in the LES results due to the variations in the riverbed’s effective roughness height and the river’s inflow discharge was studied and showed that both parameters redistributed the flow distribution laterally and vertically in the velocity profile. For the uncertainty quantification (UQ) analyses, the polynomial chaos expansion (PCE) method was used to develop a surrogate model, which was randomly sampled sufficiently by the Monte Carlo Sampling (MCS) method to generate confidence intervals for the LES-computed velocity field. Also, Sobol indices derived from the PCE coefficients were calculated to help understand the relative influence of different input parameters on the global uncertainty of the results. The UQ analysis showed that uncertainties of LES results in the shallow near bank regions of the river were mainly related to the roughness, while the variation of inflow discharge leads to uncertainty in the LES results throughout the river, indiscriminately.

Article highlights
● Changes in discharge and bed roughness altered the flow distribution laterally and vertically in the vertical profile.
● Polynomial chaos expansions provided a practical approach for characterizing uncertainty in LES results of a natural river.
● Uncertainty in simulation results near the bank is mainly due to parameter uncertainty in bed roughness characterization.
● Uncertainty related to the inflow discharge dominated the overall uncertainty in LES results of the river.
1 Introduction

Enabled by improvements in high-performance computing, advanced computational fluid dynamic (CFD) models can provide meaningful insights into the three-dimensional (3D) flow structures naturally occurring in riverine environments. Examples include the dynamics of the secondary flow at meander bends and vortex shedding processes from man-made obstructions such as bridge foundations and spur dikes [1–5]. The early use of CFD models for the study of rivers was limited to relatively coarse computational meshes and employed time-averaged Reynolds Averaged Navier-Stokes (RANS) turbulence closure models [6–10]. Recently, more sophisticated, high-fidelity models using detached eddy simulation (DES) and large eddy simulation (LES) have provided the capability to capture even greater spatial and temporal details of the flow [2, 11–13]. For instance, LES models for full-scale rivers like the Mississippi River in Minnesota and the Feather River in California have recently been modeled using LES [3, 14]. Despite these massive improvements in the resolution of the hydrodynamic in rivers, little attention has been paid to quantifying the results’ relative uncertainty potentially imposed by uncertainty in the model leading to an excessive level of confidence being placed in model and may pose misleading or, even worse, incorrect interpretation of the results.

Uncertainty in numerical modeling arises from many factors, which can be broadly divided into four primary types: (1) modeling uncertainty, (2) discretization and truncation errors, (3) convergence errors, and (4) computer round-off errors [15]. Some of these sources of error can be estimated or minimized through increased computational effort, such as using higher-order numerical schemes, smaller temporal and spatial steps, and specifying reduced tolerance for reaching convergence [16]. However, the uncertainty associated with model simplifications, limited knowledge of model parameters, boundary conditions, or accurate calibration data cannot be eliminated or easily reduced. These sources make it necessary to quantify these errors to enable a more comprehensive understanding of the model results. In particular, hydrodynamic modeling of natural waterways has many sources of uncertainty. This is due to the spatial nature of the domain, which is typically large, highly complex, and frequently changing boundaries. In a typical river, heterogeneity of the channel bed materials, variations in density and vegetation types, and complex shapes on the bed, including bedforms and pools, make it impossible to capture this degree of variation fully and requires many modeling simplifications [17–20].

In addition to topography, the inflow boundary conditions could be complicated by uncertainty in the inflow rate associated with the hydrology parameters or data sources and the error associated with the flow field measurements. For instance, Acoustic Doppler Current Profilers (ADCPs) are commonly used for estimating discharges in natural streams because of their relative speed and accuracy. However, ADCPs are known to have many potential sources of error, including operator error, programming errors, instrument errors, and extrapolation errors near the bed, water surface, and channel banks which have been studied by many researchers. [21–27] Despax et al. [28] investigated the statistical uncertainty in cross-section and systematic errors in ADCP field measurements using analysis of variance (ANOVA) showing the value of using multiple transects for discharge estimation. Additionally, when used for model calibration, ADCP data can also suffer from the practical difficulty of obtaining enough passes over the same transect line to provide a reliable time-averaged velocity from the instantaneous data it measures. Uncertainty in high-fidelity
modeling associated with ADCP measurements used for inflow flow rates was explored in this study.

Another field measurement for riverine models, which can be subject to several sources of error, is inaccurate or incomplete mapping of the bathymetry of the channel [29, 30]. In a case study, Pasternack et al. (2006) estimated that 21% of the predicted depth error in a two-dimensional (2D) model could be attributed to the errors in topographic resolution [31]. Moreover, in 3D modeling, accurate bathymetry data is critical for determining the mean flow characteristics such as depth and mean velocity values and turbulent structures and secondary velocity components [32, 33]. Improved accuracy in the bathymetric surface is possible with more precise equipment such as (1) augmenting GPS with an inertial navigation unit (INU) for improved spatial accuracy and (2) using a multibeam echosounder (MBES) when possible, instead of a single-beam echosounder. A comparison of LES results from MBES and single-beam sonar data showed improved bathymetric resolution reduced near-bed velocities and turbulent kinetic energy (TKE), but increased the number of turbulent structures in areas with highly irregular topography [20].

Resistance in a channel can be due to many sources, including instream obstacles such as vegetation and bridge piers, bank irregularities, meander bends, bedforms, and roughness due to individual grain particles [34, 35]. While the more prominent features may be captured in bathymetric/topographic survey data and resolved directly in the discretization of a high-fidelity model, the surface roughness of the individual grains cannot be practically resolved when modeling a natural river. Instead, wall models are employed to account for this type of resistance. Wall models capture different grain sizes by assigning an equivalent roughness height value, \( k_s \), which is proportional to a characteristic grain size. Unfortunately, there is no general consensus among researchers for the constant of proportionality or which specific grain size among the distribution of grain sizes should be used [36]. Chanson [37] has provided a summary of equivalent roughness heights of several past researchers regarding flow resistance, which ranged between \( 1.5d_{50} \) by Sumer [38] in cases of sheet flow to \( 3d_{90} \) by van Rijn [39] in bedload transport of experimental and field data. This general lack of consensus creates uncertainty in what value of \( k_s \) is appropriate for use in wall models and was a major topic of exploration in this study.

Hence, the objectives of this study are to (1) collect bathymetric and flow measurement data for a case study in a reach of the Sacramento River in California, (2) conduct high-fidelity large-eddy simulations (LESs) of the river flow, and (3) quantify the uncertainty in the hydrodynamic results of the river flow for two input modeling parameters: discharge and the equivalent roughness height. Specifically, the inflow rate will be varied based on the measurement uncertainty identified from the ADCP measurements at multiple transects in the river reach. Also, a range of equivalent roughness height parameters will be used in the wall model to determine how changing the characteristic grain size will alter the flow velocities of this natural river. To quantify the combined uncertainty of the LES results, polynomial chaos expansion (PCE) and Monte Carlo (MC) simulations will be used to provide approximate velocities at select transects over a continuous range of input parameters to generate 95% confidence levels for the computed velocity fields. Sobol indices, also known as “variance-based sensitivity analysis,” used as a form of global sensitivity analysis, were determined to estimate the relative impact of these two parameters on the hydrodynamics simulation results. Finally, the computed depth-averaged velocity magnitudes along ADCP
transect lines and velocity profiles at select locations were compared against the measured flow field data.

This paper is organized as follows. First, we introduce the governing equations and the wall model used in the numerical model. Next, the case study and the field data collection for the river bathymetry and flow field measurement are discussed. Subsequently, the computational details, boundary conditions, and the range of input parameters for the LES are described. Afterward, the uncertainty quantification procedures are described, followed by presenting and discussing the LES results and UQ analysis of the computed flow field. Finally, conclusions concerning the importance of assessing uncertainty in numerical modeling of natural rivers are presented.

2 Numerical Framework

To simulate instantaneous, 3D, incompressible, turbulent flow for our case study, we use our in-house, open-source CFD code, the so-called Virtual Flow Simulator (VFS-Geophysics) model. The successful use of VFS-Geophysics for simulating flow in natural waterways has been well documented [3, 12, 14, 40, 41]. For implementing LES in VFS-Geophysics model, the curvilinear immersed boundary (CURVIB) method described by Ge and Sotiropoulos [42] is used to resolve the arbitrarily complex geometric shapes associated with a natural river bathymetry such as channel bedforms, vegetation, bridge piers, and irregularly shaped banks. In the context of the Immersed Boundary Method (IBM), a structured background mesh is used for the flow domain. The solid boundaries of objects such as the channel banks and channel bed are treated as unstructured triangular meshes, which are superimposed inside the flow domain (Fig. 1). The IBM classifies each node inside the flow domain as either a solid, fluid, or immersed boundary (IB) node. Solid nodes are removed from the computations; fluid nodes which reside outside of the solid boundary are where the governing equations for the flow computations are applied; the IB nodes are adjacent to the boundary and where the velocities are reconstructed using a wall model.

In the VFS-Geophysics model, the methodology for solving the Navier-Stokes equations for incompressible flow for the flow domain is described in detail by Khosronejad and Sotiropoulos (2014) [43]. The implementation of LES using the Smagorinsky sub-grid scale (SGS) model [44] is fully described by Kang et al. [45]. A wall model is used to solve indirectly for the velocity at the first grid point off the solid boundaries for cases when the viscous sublayer itself cannot be resolved directly, such as in a large flow domain like a natural river and where the individual grains are too small to be resolved. The wall modeling approach assumes that the first grid points off the wall reside within the log layer and reads as follows [46]:

\[
\frac{u}{u^*} = \begin{cases} 
\frac{y^+ y^+}{k} & y^+ \leq 11.53 \\
\frac{1}{\ln (E y^+)} & y^+ > 11.53
\end{cases}
\]

(5)

where \(u\) is the local velocity magnitude at the node located a distance, \(y\), from the wall, \(u^* = \sqrt{\frac{\tau}{\rho}}\) is the shear velocity [47], \(k\) is von Karaman’s constant (\(\approx 0.41\)), and \(y^+\) is the
distance of the first node off the wall in wall unit \(= \frac{y^+}{\nu} \), and \( E \) is the roughness parameter, defined as follows:

\[
E = \exp \left[ \kappa (B - \Delta B) \right]
\]  

(6)

where

\[
\Delta B = \begin{cases} 
0 & k_s^+ < 2.25 \\
B - 8.5 + \frac{1}{\kappa} \ln (k_s^+) \sin [0.4258 (\ln (k_s^+) - 0.811)] & 2.25 < k_s^+ < 90 \\
B - 8.5 + \frac{1}{\kappa} \ln (k_s^+) & k_s^+ \geq 90
\end{cases}
\]  

(7)

where \( B \) is a constant \((-5.2) \) and \( k_s^+ \) is the roughness Reynolds number \( \frac{k_s \nu}{\nu} \), where \( k_s \) is the equivalent roughness height. The three cases for \( \Delta B \) in Eq. 7 represent different effects on the flow caused by how far above the channel boundary the roughness elements extend, relative to the viscous sublayer, \( \delta_v \), where viscous forces dominate. When \( k_s^+ < 2.25 \), the roughness elements are entirely within \( \delta_v \), where the turbulence generated by roughness elements themselves are fully dampened out by the viscous forces and do not contribute to the overall channel resistance, which is referred to as hydraulically smooth flow. However, in natural rivers, this condition typically does not exist since roughness elements generally extend beyond \( \sim 5 \delta_v \) \([34]\). For this study, \( k_s \) will be varied to observe how changes in the equivalent roughness height in the wall model influence the hydrodynamics of the river.

Fig. 1 Schematic of the flow domain. The slice outlined in (a) is shown enlarged in (b) with the white lines representing the structured grid system of the flow domain, and the black triangles on the bed are the unstructured mesh of the IB.
3 Case Study: Sacramento River at Knights Landing

3.1 Site description

The Sacramento River is a major river in Northern California with headwaters in the Klamath Mountains, which flows over 700 km into the San Francisco Bay Delta. Approximately 50 km upstream from the City of Sacramento, the Sacramento River makes a sharp bend as it passes through the town of Knights Landing, CA, which is the site for this case study (Fig. 2). The reach of interest for our simulations is approximately 610 m long, with a two-lane highway bridge on Route 113 crossing the river just downstream from the meander bend. The river in this location is confined by levees on each bank and has an average channel top width of about 70 m during our field data collection stage. During our field investigation, the mean flow depth in the channel was about 3.3 m, with a deep section approximately 8.5 m deep along the outer bank located at the channel bend. A side tributary, called Sycamore Slough, enters the Sacramento River along the right bank near the middle of the study area; however, this inflow is considered an insignificant addition to the main channel flow in the Sacramento River.

3.2 Field measurements

In December 2020, we collected three types of field data: (1) Aerial photogrammetry and video imagery, (2) ADCP flow field, and (3) bathymetric survey. Nearly 700 4 K photos were taken from an altitude of about 60 m using a DJI Phantom 4 unmanned aircraft system (UAS) to generate over 37 million topographic data points from the Structure from Motion (SfM) [48] methodology using the open-source software of OpenDroneMap [49] version 1.4.2 with an estimated vertical accuracy of 5 cm. The elevation data above the water surface (Fig. 2b) was tied into the 30 ground control points surveyed using a 1 cm accurate Trimble GeoExplorer 7x GPS unit augmenting the bathymetric survey data to generate a complete digital map of the river within the study reach.

On December 15, 2020, ADCP streamflow measurements were collected using a Teledyne RD Workhorse Rio Grande® 1200 kHz ADCP and their WinRiver® II data acquisition software version 2.20. Spatial data for the survey was obtained using the Advanced Navigation Spatial Dual® Inertial Navigation Unit (INU). In total, 17 ADCP transects were made for the Sacramento River at 5 locations, with three locations being upstream from the highway bridge and two locations downstream. Flow rates from each transect are shown in Table 1, with an average flow rate of 130.5 m$^3$/s, a standard deviation of 4.7 m$^3$/s and a coefficient of variation (COV) of 3.6%. Variability in the measurements could be primarily attributed to operator error and a minor inflow from the Sycamore Slough stream that was equal to 5.3 m$^3$/s. Each of the five transect locations was post-processed using the Velocity Mapping Toolbox (VMT) software version 4.09 available from the USGS [50]. Using VMT, multiple transects at each location were combined to provide a single set of velocity values along a spatially averaged cross-section to provide a more time-averaged depiction of the flow than the instantaneous velocities measured during each transect. The velocity values were also depth-averaged and used for comparison with the LES simulations.

On the same date as the ADCP measurements, a bathymetric survey of the channel bed was made using a Picotech PICOMB-120 MBES, which operated at 25 pings per second.
The PICOMB-120 has a 120-degree swath angle projecting 256 beams equally spaced at 0.47 degrees. Overlapping passes of the operating boat were used to measure the detailed bed bathymetry of the river. The boat movements and locations were measured using the Advanced Navigation Spatial Dual INU and post-processed for improved coordinates using Advanced Navigation’s Kinematica™ version 2.0 algorithms. The heading for the INU was provided using 2 Trimble Zephyr antennas. Over 26 million bathymetric data points were collected with a typical vertical accuracy within 5 cm and, subsequently, post-processed using the BeamworX™ Hydrographic Suite of software version 2020.3 (Fig. 3). As clearly seen, the survey data captured large bedforms that are 1 to 1.5 m high and present throughout the reach. Also, scour regions that are approximately 4 m deep can be seen along the outer bank of the meander bend, while about 2 m deep scour regions were detected near the bridge crossing. As shown in the deeper parts of the river (in blue), the thalweg of the river switches sides by crossing over from the right bank at the bridge crossing to the left bank near the downstream end of the study reach. This shift in thalweg is typical of a meandering river and influences the bathymetry and hydrodynamics, as will be seen in the LES results presented in Section Results.

Fig. 2 (a) Site map of the study area in the Sacramento River in Knights Landing, California. Flow is from the East to the South. (Earth data © 2020 Google.) (b) Textured model showing the measured above water topographic data for Sacramento River at Knights Landing.

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Table 1  Summary of ADCP Measurements

| Location | Transect | \( Q \) (m\(^3\)/s) |
|----------|----------|----------------|
| 1        | 1        | 131.9          |
| 2        | 5        | 124.5          |
| 3        | 8        | 133.9          |
| 4        | 11       | 132.8          |
| 5        | 15       | 130.6          |
| Mean     |          | 130.5          |
| Std Dev. |          | 4.7            |
| COV      |          | 3.6%           |

Fig. 3  Bathymetric survey data for the Sacramento River at Knights Landing. Color maps show the relative bed elevation of the river in meters

4  Computational details

4.1  Simulation Parameters

The LESs of the river flow in the study area were carried out for a mean-flow depth of 3.3 m and mean-flow velocity of 0.565 m/s, which result in the Reynolds and Froude numbers of \(1.86 \times 10^6\) and 0.11, respectively. Based on the field observations of the water surface
elevation during the bathymetric survey, there was minimal variation in the water surface throughout the reach. The water slope of the river was highly mild (0.005%). For this reason, we employed a flat rigid-lid assumption at the free surface to facilitate the computations of the LESs using the location of the free surface obtained from the measured water surface elevation. The no-slip boundary condition was prescribed at the wall boundaries and bridge piers. As discussed in Section Results, a range of flow rates for the Sacramento River was assigned at the inlet. Before conducting the LESs of the study reach, a short and straight reach with uniform channel geometry was derived from the inlet cross-section of the study reach. This short channel was used to develop turbulent inlet boundary conditions at the inflow boundary of the study reach. Separate precursor runs were completed for each discharge used in this study. For each flow rate, when the precursor simulation reached a fully developed, turbulent flow state, the instantaneous velocity field at the outlet was stored for later use in the LESs of the study reach. No additional flow was assumed to enter the flow domain at the confluence with Sycamore Slough.

4.2 Grid Sensitivity

Four structured grids with uniform grid resolutions were used to evaluate the grid sensitivity of the first-order results having uniform grid spacing of 0.6 m, 0.4 m, 0.3 m, and 0.2 m, corresponding to 5.1 M, 8.4 M, 39.5 M, and 65.0 M grid nodes, respectively. Additional details of the computational grids are provided in Table 2, including the number of grid nodes, grid spacing, and wall distances. Since the wall distances were over 1000 for each resolution, the use of a wall function at the bridge pier and channel bed solid boundaries was required. Figure 4 presents the time-averaged non-dimensional velocity magnitudes for each grid resolution at the water surface. While higher grid resolution is expected to capture more of the fine-scale turbulent structures, compared to the computed flow fields of the four grid systems, the overall dominant, large-scale flow patterns and velocity magnitudes are very similar for each case. Only near the banks where the flow depth is shallow, it is apparent that the higher resolution grid schemes show improved resolution of the hydrodynamics; however, throughout the vast majority of the flow, each grid resolution shows considerable agreement. Figure 5 presents transects taken at 4 locations in the spanwise direction to quantitatively compare the grid resolution sensitivity for both the time-averaged surface velocity magnitude and the time- and depth-averaged velocity magnitudes where the depth-averaged velocities were obtained by averaging the velocity components throughout the flow depth at each location in the river. For each transect, the velocity magnitude at the water surface (Fig. 5 (b), (d), (f), and (h)) are within about 10% for each grid resolution, except near the banks where the higher resolution grids have higher velocities. The depth-averaged velocities (Fig. 5 (c), (e), (g) and (i)) also demonstrate that flow velocity magnitude in the majority of the channel is within 15% for each grid resolution. Moreover, the grid resolution does not significantly influence the overall mean flow velocities throughout the deep portions of the channel. Since this study involves numerous simulations for the UQ analysis and the general flow structure was captured for all grid resolutions, the coarsest grid resolution (0.6 m) will be used for all cases for computational efficiency.
4.3 Discretization

The flow domain was discretized using a uniform grid node spacing in all directions equivalent to ~0.3 m resulting in a flow domain with approximately 39.5 M million computational grid nodes. About half of these nodes were classified as solid nodes and banked out of the computations (Table 2). Typical values for $y^+$ were greater than 1000. Given the Reynolds number of the river flow in this study, the employed grid resolution is understandably too coarse to capture the viscous sublayer of the turbulent flow. However, since in such large-scale riverine flows, large bathymetry features and other wall-mounted structures are responsible for producing slowly evolving but very energetic coherent structures, which are responsible for producing most of the turbulence, we have been able to successfully resolve such flows using wall models [3, 20, 46, 52–56]. That is without needing to resolve the details of the near-wall flow, provided that one uses grids fine enough to capture key geometrical features and resolve the slowly coherent flow structures they induce. This has been the basic premise for the success of LES linked with the immersed boundary method developed for and introduced in simulations of river hydrodynamics and morphodynamics [3, 4, 14, 54].

5 Uncertainty in model parameters

The hydrodynamic results of our LESs are presumed to be highly dependent on two crucial input parameters: (1) the inflow discharge and (2) the equivalent roughness height. As shown in Table 1, in the study reach, several different flow rates were measured using the ADCP. Using the mean value of 130.5 m$^3$/s would be a logical choice for inflow discharge. However, one needs to determine how much uncertainty this mean discharge value will introduce in the LES results. To quantify this uncertainty, a range of nine different flow rates representing flow rates ranging from 10% less than the mean discharge to 10% greater than the mean value was simulated. In addition, the equivalent roughness height, $k_s$, used in the wall model (Eq. 7) could impact the computed velocity profiles within the river and possibly redistribute the velocities laterally, as well. As stated earlier, there is a lack of consensus among researchers for how to define $k_s$. For this study, values for the equivalent roughness height ranging between $1.5d_{50} < k_s < 3d_{90}$ were utilized based on the disparity of values.
and relationships related to $k_s$ in literature [36–39, 57, 58]. Furthermore, it was assumed that the uncertainty associated with $k_s$ is uniformly distributed and that a single value of $k_s$ could adequately characterize the grain roughness of the entire reach. This later assumption was necessary due to both the lack of spatially varied sediment data and limitations with the numerical code. The USGS sampled bed material from the river on November 1, 1977, at the USGS Gage No. 11,391,000 [59]. Based on three representative sediment samples, $d_{50} = 7.0\text{mm}$ and $d_{90} = 21.6\text{mm}$ making the equivalent roughness height to range between 10 and 65 mm. Therefore, for this study, values of $k_s$ equal to 10, 14, 20, 40 and 60 mm were used in the LESs. Due to the computational cost for running each LES, only 11 cases combining different discharges and equivalent roughness heights were run (see Table 3). To augment the “gaps” for other combinations of these two parameters, a PCE was used to estimate the flow field results of all possible combinations of parameter values for the inflow

Fig. 4 (a) – (d) show contours of the time-averaged velocity magnitude ($V$) at the water surface for the 0.6 m, 0.4 m, 0.3 m, and 0.2 m grid spacing, respectively. $V$ is normalized with the mean-flow velocity ($U_{bulk} = 0.565 \text{m/s}$). Flow is from left to right.
Fig. 5 The locations for four transects taken spanwise across the river are plotted with the contours of the time-averaged velocity magnitude ($V$) at the water surface for the 0.6 m grid spacing in (a). At each transect, a comparison of the normalized velocity magnitude ($U_{bulk} = 0.565$ m/s), for the 0.2 m, 0.3 m, 0.4 and 0.6 m grid resolution are presented. For each location, the time-averaged surface velocity magnitudes ((b), (d), (f) and (h)) and time- and depth-averaged velocity magnitudes ((c), (e), (g) and (i)) are compared.
rate and equivalent roughness height. Although discharge and bed roughness were varied for each of the 11 cases, the rigid lid elevation was not modified since the objective of the UQ was to study the role that uncertainty in discharge and roughness play in developing the water surface measured during the time of the investigation; rather, than predicting how the water surface would change due to the inflow or roughness parameters as is commonly done in engineering studies.

The PCE is a general methodology that can be used in uncertainty quantification evaluations, representing the functional relationship between input parameters and the resulting output rather than only the statistical correlation between the parameter inputs and hydrodynamic outputs [60]. Herein, non-intrusive PCE simulations are used as black boxes, and the calculation of the PCE coefficients for flow velocities is based on the set of LES cases [61]. Once the correct polynomial coefficients are determined, the PCE can approximate finite-dimensional series expansions of the flow velocities for any input variables. The chaos expansion for the Response, \( R \), can be approximated as [61]:

\[
R \approx \sum_{j=0}^{P} \alpha_j \psi_j (\xi)
\]  

(8)

where \( \alpha_j \) is a deterministic coefficient, \( \psi_j \) is the jth multidimensional orthogonal polynomial, and \( \xi \) is a vector of standardized random variables. Herein, the Askey family of orthogonal polynomials are employed for the PCE evaluation. More specifically, since the probability distributions for the inflow and \( k_s \) are assumed to be uniformly distributed, the Legendre orthogonal polynomials are used for the PCE [62].

To assess the relative sensitivity caused by different variables in the uncertainty of the hydrodynamics results, the coefficients in PCEs can be analyzed using variance-based decomposition to extract values known as “Sobol” indices [63]. This analysis identifies the fraction that either individual variables or a specific combination of variables contribute to the total uncertainty in the response, \( Y \). This effect is known as the main effect sensitivity index, and for a single variable, \( x_i \), is represented by the Sobol Index value, \( S_i \), which is defined as [64]:

| Case Number | \( k_s \) (mm) | \( k_s^+ \) | Mean \( Q \) (m\(^3\)/s) | Per.-cent of Mean \( Q \) |
|-------------|---------------|-------------|----------------|---------------------|
| 1           | 10            | 150         | 130.5          | 100                 |
| 2           | 14            | 210         | 130.5          | 100                 |
| 3           | 20            | 300         | 130.5          | 100                 |
| 4           | 20            | 300         | 140.3          | 107.5               |
| 5           | 40            | 600         | 130.5          | 100                 |
| 6           | 60            | 900         | 130.5          | 100                 |
| 7           | 60            | 900         | 120.7          | 92.5                |
| 8           | 40            | 600         | 137.0          | 105                 |
| 9           | 40            | 600         | 124.0          | 95                  |
| 10          | 20            | 300         | 120.7          | 92.5                |
| 11          | 60            | 900         | 140.3          | 107.5               |
where $\text{Var}_{x_i}[E(Y|x_i)]$ represents the variance of the conditional expectation of $Y$ for a given $x_i$ and $\text{Var}(Y)$ is the total variance.

Once the PCE is evaluated, the full range of inflow rates and equivalent roughness heights can be explored using the surrogate model by MC sampling. The MC sampling repeatedly selects random values of the two parameters and evaluates the corresponding velocities from the PCE to define the confidence intervals from the statistical variance in the PCE responses. This process is repeated for each location in the study reach where confidence intervals are desired. Herein, we evaluated the depth-averaged velocities along four ADCP locations and four vertical profiles, where ADCP measurements were taken. For the sake of brevity, we present and discuss the results of only two cross-sections and vertical profiles. The Design Analysis Kit for Optimization and Terascale Applications (Dakota version 6.13.0) software developed by Sandia National Laboratory was used to conduct the UQ analysis. Based on the 11 LES cases, Dakota first determined the PCE coefficients and Sobol indices for the points of interest in the study reach and then randomly sampled 10,000 combinations of parameter inputs using MC sampling to define 95% confidence intervals.

6 Results and discussions

Each of the 11 LES Cases listed in Table 2 ran until flow was well established through the reach, as determined by monitoring the kinetic energy in the flow. Figure 6(a) represents this state and shows a large flow separation region occurring along the outer bend of the river near the confluence with Sycamore Slough. A smaller separation zone is also noted at the inner bend. Upstream of the bend, flow is relatively uniform, showing only velocity fluctuations corresponding to the bedforms on the left side of the channel. Due to the meander bend, however, the flow becomes noticeably less streamlined and exhibits continuous large-scale turbulence. After the kinetic energy of the flow stabilized, time-averaged results were computed until the mean statistics converged. Like the instantaneous flow, the small fluctuations in the time-averaged velocity magnitudes on the water surface reflect the presence of the channel bedforms throughout the channel and the flow separation along the right bank as depicted by the time-averaged streamlines for the flow (Fig. 6(b)). As seen in Fig. 6(c), the sharp meander bend leads to large-scale redistribution of the velocity core in the water column. The strong secondary flow at the bend produces non-typical velocity profiles in vertical, which can be clearly seen in cross-Sect. 3 of Fig. 6(d). The velocity magnitude at the water surface elevation is significantly lower than that of mid-depth near the outer bank. Trying to measure the discharge in this area will likely create inaccurate readings. For instance, if an ADCP is used, the flow near the water surface cannot be measured directly and is estimated using a power law approximation for using a logarithmic profile assumption which is not valid at this location.

Due to the uncertainty in the inflow discharge, several LESs were conducted using identical equivalent roughness heights while varying only the flow discharge to assess the effect of flow discharge alone on the computed hydrodynamics. For instance, both Cases 4 and 10 simulated the flow field using $k_s = 20$ mm but varied the inflow discharge from 140.3 m$^3$/s
Fig. 6 (a) Contours of the instantaneous velocity magnitude ($V$) at the water surface. $V$ is normalized with the mean-flow velocity ($U_{bulk} = 0.565$ m/s). The mean-flow depth is 3.3 m and is conveyed from left to right. The streamlines colored by $V$ are shown in (b), with flow moving from the lower left to the top. Slices are taken through the water column throughout the study reach and are presented in (c), with the white dashed area enlarged in (d).
to 120.7 m$^3$/s that are 107.5% and 92.5% of the mean flow, respectively. The time-averaged surface velocity magnitudes for these two cases showed noticeably higher velocity magnitudes at the water surface. However, when comparing the difference in velocity magnitudes in Fig. 7(a), the increase in velocity magnitude at the water surface scales nonuniformly concerning the 15% difference in discharges. Upstream of the bend along the inner bend of the river in the shallower parts of the river, flow velocity magnitudes increase by roughly 30%, whereas, along the outer bend, the velocity magnitudes increase by less than 10%. Even more surprisingly, the velocity field throughout the flow depth scales nonuniformly with the increased flow rate but shows highly variable increases throughout the study reach (Fig. 7(b)). We argue that this could be attributed to the complex secondary flows and nonuniformity of bed bathymetry. The former is known to cause the lateral movement of the high-velocity core [40, 45], while the latter is known to produce heterogeneous turbulent flow structures in the water column [65, 66].

Like the variability in velocity field throughout the river caused by changing the discharge, LES cases were also computed using different equivalent roughness heights while maintaining the same flow rate at the inlet. For Case 1 and Case 6, which used $k_s$ values of 10 and 60 mm, respectively, the velocity magnitudes at the water surface appear to be quite similar; however, considering the difference in the two surface velocity magnitudes, one can see that increasing the bed roughness results in a decrease in the velocity magnitude ranging from 5 to 15% along the left bank (see Fig. 7(c)). Conversely, downstream from the bend along the right bank, increasing the bed roughness leads to an increase in surface velocities by 5 to 15%. Within the bend itself, these effects are even more evident, causing the same velocity changes to be even more significant. As seen in Fig. 7(d) at the three cross-sections in different parts of the bend, the degree and location of the velocity magnitude changes

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**Fig. 7** Comparison is shown for how different flow rates and bed roughness affect the velocity in the river. Time-averaged velocity magnitudes normalized by the mean flow velocity ($U_{bulk}$) at the water surface are shown. Contours of the difference in surface velocity magnitudes for the two flow rates of 92.5% and 107.5% of the mean are shown in (a). The three cross-sections drawn with white lines in (a) are presented enlarged in (d). In (c), contours of the difference in surface velocity magnitudes with two different $k_s$ values of 10 and 60 mm are shown. The three cross-sections drawn with white lines in (c) are enlarged in (d). Flow is from left to right.
are nuanced, with varying changes being induced by the roughness seen in other velocity structures in the cross-sections.

Typically, the vertical velocity profile of a river flow follows a logarithmic or parabolic profile \([34]\). Accordingly, the depth-averaged velocity magnitude is often approximated to be about 85% of the surface velocity magnitude \([67]\); however, this ratio also depends on the site specific channel characteristics such as the ratio of the roughness height to flow depth and local flow nonuniformity \([68,69]\). The surface velocity magnitude and depth-averaged velocity magnitudes are compared for Case 3 to investigate the 85% approximation using our simulation results in the study reach of the Sacramento River. This case corresponds to the inflow rate of 130.5 m\(^3\)/s and the equivalent roughness height of \(k_s = 20\) mm. As seen in Fig. 8(a) and (b), as expected, the velocity magnitude is generally lower for the depth-averaged values. Closer examination of the percentage of the depth-averaged velocity magnitude relative to the surface velocity magnitude in Fig. 8(c), however, reveals that the percentage varies appreciably from the 85% estimate with blue regions being a higher percentage typically occurring along the inside of the bend and red regions being a lower percentage located principally along the outside of the bend. Based on the four cross-sections plotted in Fig. 8(d), the range for the ratio varies considerably in the bend, i.e., from 70 to 95%. However, in cross-section B, extreme values that range from 50% to as much as 160% are found near the outside of the bend. Cross-section D is located near the outlet of the flow domain and shows the closest agreement with the 85% approximation while only deviating by about 5% higher and lower across most of the study reach, except near the banks where there is less agreement.

Thus far, we have demonstrated the strong yet somewhat unpredictable effect that both the inflow discharge and equivalent roughness height can have on the velocity field of the river flow in the study reach. Of principal interest in this study is the potential combined effect of these two uncertain parameters on the LES results, as expressed by confidence.
intervals. In other words, we seek to determine, with 95% confidence, the velocity magnitude of the river in the study reach, considering the uncertainty associated with the flow discharge and equivalent bed roughness. The computed velocities along selected cross-sections and the vertical velocity profile points were sampled using the 11 LES cases to determine the joint effect. Specifically, four locations were selected corresponding to the ADCP transect measurements, and 16 equally spaced depth-averaged velocities were determined and used for the Uncertainty Quantification analysis. Similarly, four point locations were selected for samples of the vertical velocity profiles, but for brevity, we only focused on two of those point locations. Depending on flow depth, between 21 and 28 velocity magnitude values were extracted from the LES results at each point location and labeled as VP1 and VP2. These values were then used in the software program, Dakota, to determine the PCE coefficients and Sobol indices. Subsequently, the PCE results were utilized to determine the confidence intervals by randomly sampling 10,000 combinations of discharge and equivalent roughness heights combinations using MC simulations. The range of variables used in the MC simulations was as follows. Inflow discharge ranged uniformly within 10% of the mean discharge, and $k_s$ was varied uniformly between 10 and 65 mm. Selected results of these evaluations are presented in Fig. 9, which also contains plots of the channel bed cross-sections for reference using the NGVD 88 datum in (d) and (e).

Location 3 is immediately downstream from the river bend and the confluence with Sycamore Slough (Fig. 9(a)). Despite the strong secondary flow caused by the bend and the additional (although minor) flow entering at the confluence, the computed LES results are still in close agreement with the ADCP measured velocity field (Fig. 9(b)). The 95% confidence interval varied from over 20% of the mean value for the velocity near the banks to less than 10% from the mean value near the center of the channel with an average deviation of about 11%. Near each bank, the measured depth-averaged velocities are slightly outside of the 95% confidence bands. From the Sobol indices in Fig. 9(d), the uncertainty in the depth-averaged results is almost entirely due to the uncertainty in the discharge near the center of the channel; however, near the banks, a stronger influence of the bed roughness can be seen – particularly along the left bank where the uncertainty due to the equivalent roughness height is more pronounced.

At Locations 4, the cross-section is relatively uniform in shape (Fig. 9(a)) since it is located at a cross-over point of the river thalweg. At this location, the depth-averaged velocity measurements generally fall within the uncertainty of the LES results except near the side banks (Fig. 9(c)). Similar to Location 3, the average difference in velocity magnitude for the 95% confidence intervals was about 11% from the mean value. The Sobol indices at this cross-section show that near the center of the river, the uncertainty in the computed results is strongly influenced by the uncertainty in the flow rate with values typically exceeding 90%. However, the uncertainty is strongly influenced by the equivalent roughness height near the side banks and ranges from 30 to 50%. It is worth noting that the confidence intervals near the side banks show less uncertainty than in the center of the river. Therefore, the increased Sobol index values (Fig. 9(e)) do not necessarily indicate an absolute increase in the uncertainty caused by the bed roughness but may only be a more significant percentage of the total uncertainty in these regions.

The vertical velocity profiles in the water column were also analyzed using the same UQ methodology to define the confidence bands and Sobol indices of the LES results at 4 locations within the study reach. Locations VP1 and VP2 fall along the cross-section at Location
5, with VP1 and VP2 being located near the left and right banks, respectively (Fig. 10(b)). At these two locations, the ADCP measurement data agree well with the LES results, considering the instantaneous nature of the ADCP measurements. For each case, the Sobol indices for \( k_s \) increases appreciably from less than 5% near mid-depth to between 15 and 40% near the bed (Fig. 10(c) and (d)). This increased the influence of equivalent roughness height on the uncertainty near the bed seems reasonable since the value for \( k_s \) is directly applied to the wall model to reconstruct the velocity field of the computational nodes near the bed.
However, it is also noted that the confidence limits near the riverbed are minimal for each of the four vertical profiles indicating the uncertainty associated with $Q$ and $k_s$ are primarily experienced away from the bed. In this light, the influence of $k_s$ on the uncertainty should be recognized as higher relative to $Q$ and not as causing more significant uncertainty in an absolute sense.

Fig. 10 The vertical profile of velocity magnitude normalized by $U_{bulk}$. (a) and (b) illustrate the locations of the VP1 and VP2 over the riverbed. In (c) and (d), the solid line shows the time-averaged LES results, dashed black lines mark the 95% confidence bands, and circles represent the instantaneous ADCP data for locations VP1 and VP2, respectively. The time-averaged ADCP readings across the channel are shown in the inserts, with the white box representing the area of the velocity profile. (e) and (f) depict the Sobol indices for $Q$, $k_s$, and combined effect of $Q$ and $k_s$, at VP1 and VP2, respectively, showing each parameter’s relative influence on the overall uncertainty.
7 Conclusions

We evaluated the propagation of uncertainties, due to the variations in the inflow discharge and roughness parameters, through LES computed hydrodynamics of the Sacramento River. Both parameters redistributed the flow laterally in the river and modified the vertical velocity profiles in nonuniform ways when considered independently. The overall uncertainty introduced by these two parameters averaged about 11% to the modelled results at the two transects studied in this investigation. The presence of the meander bend in the study area and associated secondary flows created nonintuitive changes in the flow structure, making the relationship between depth-averaged velocity magnitudes and the surface velocities highly variable. However, farther downstream from the bend, the depth-averaged flow from the LES results seemed to be typically between 80 and 90% of the velocity magnitude at the free surface. This conclusion demonstrates the value of collecting field velocity data at locations in the river away from meander bends to obtain more predictable flow data.

The UQ analysis of the joint effect of equivalent roughness height and inflow discharge uncertainty provided 95% confidence bands of the depth-averaged velocities at selected locations which were generally validated by the ADCP measurements. The Sobol indices analysis showed that uncertainty in the flow discharge at the inlet contributed to most (over 90%) of the uncertainty of the computed depth-averaged velocities. However, the equivalent roughness height at regions near the side banks contributed more influence ranging from 10 to 80%. This variability was associated with the location with higher uncertainty attributed to the bed roughness, i.e., near the meander bend. Moreover, the uncertainty of the vertical velocity profiles near the bed was low and mostly was dominated by the equivalent roughness height. Away from the riverbed, the Sobol indices indicate that inflow discharge contributed almost exclusively to the uncertainty in the vertical velocity profile.

While the results of this study apply to the specific flow conditions and river reach on the Sacramento River, they also illustrate the importance of quantifying the uncertainty in both the model parameters and the resulting hydrodynamics results when conducting numerical modeling of natural river flows. A proper UQ assessment of the model can provide helpful confidence levels for the computed results and, thus, can add valuable context for interpreting and applying the model to real-world applications.

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Data Availability Some or all data, models, or code that support the findings of this study are available from the corresponding author upon reasonable request. The code in this paper includes the Virtual Flow Simulator (VFS-Geophysics) model. The data include the bathymetric and topographic data of the Sacramento River and the high-fidelity simulation results of the river.
References

1. Kang S, Khosronejad A, Hill C, Sotiropoulos F. Mean flow and turbulence characteristics around single-arm instream structures. J Hydraul Res 2020:1–17. https://doi.org/10.1080/00221686.2020.1780494
2. Kara S, Kara MC, Stoesser T, Sturm TW (2015) Free-Surface versus Rigid-Lid LES Computations for Bridge-Abutment Flow. J Hydraul Eng 141:04015019. https://doi.org/10.1061/(ASCE)HY.1943-7900.0001028
3. Khosronejad A, Flora K, Kang S. Effect of inlet turbulent boundary conditions on scour predictions of coupled LES and morphodynamics in a field-scale river: bankfull flow conditions. J Hydraul Eng 2020;146. https://doi.org/10.1080/00221686.2019.1673372
4. Khosronejad A, Flora K, Zhang Z, Kang S (2020) Large-eddy simulation of flash flood propagation and sediment transport in a dry-bed desert stream. Int J Sediment Res 35:576–586. https://doi.org/10.1016/j.ijscr.2020.02.002
5. McCoy A, Constantinescu G, Weber LJ (2008) Numerical Investigation of Flow Hydrodynamics in a Channel with a Series of Groynes, vol 134. J Hydraul Eng, New York, NY, pp 157–172
6. Fischer-Antze T, Olsen NRB, Gutknecht D (2008) Three-dimensional CFD modeling of morphological bed changes in the Danube River. Water Resour Res 44. https://doi.org/10.1029/2007WR006402
7. Wilson C, Stoesser T, Olsen NRB, Bates P (2003) Application and validation of numerical codes in the prediction of compound channel flows. Proc Inst Civ Eng - Water Marit Eng 156:117–128. https://doi.org/10.1680/wame.2003.156.2.117
8. Rüther N, Jacobsen J, Olsen NRB, Vatne G (2010) Prediction of the three-dimensional flow field and bed shear stresses in a regulated river in mid-Norway. Hydrol Res 41:145–152. https://doi.org/10.2166/nh.2010.064
9. Liu X, Garcia MH (2008) Three-Dimensional Numerical Model with Free Water Surface and Mesh Deformation for Local Sediment Scour. J Waterw Port Coastal Ocean Eng 134:203–217. https://doi.org/10.1061/(asce)0733-950x(2008)134:4(203)
10. Ge L, Fotis S (2005) 3D Unsteady RANS Modeling of Complex Hydraulic Engineering Flows. I: Numerical Model. J Hydraul Eng 131:800–8. https://doi.org/10.1061/(ASCE)0733-9429(2005)131:9(800)
11. Constantinescu G, Koken M, Zeng J (2011) The structure of turbulent flow in an open channel bend of strong curvature with deformed bed: Insight provided by detached eddy simulation. Water Resour Res 47. https://doi.org/10.1029/2010WR010114
12. Khosronejad A, Kang S, Flora K (2019) Fully coupled free-surface flow and sediment transport modeling of flash floods in a desert stream in the Mojave Desert, California. Hydrol Process 33:2772–2791. https://doi.org/10.1002/hyp.13527
13. Khosronejad A, Kozarek JL, Diplas P, Sotiropoulos F (2015) Simulation-based optimization of in-stream structures design: J-hook vanes. J Hydraul Res 53:588–608. https://doi.org/10.1080/00221686.2015.1093037
14. Khosronejad A, Le T, DeWall P, Bartelt N, Woldeamlak S, Yang X et al (2016) High-fidelity numerical modeling of the Upper Mississippi River under extreme flood condition. Adv Water Resour 98:97–113. https://doi.org/10.1016/j.advwatres.2016.10.018
15. Sadreghahighi I, Computational, Error, Uncertainty Quantification Within CFD V & V Validation (2020) & https://doi.org/10.13140/RG.2.2.33074.43200/1
16. Celik IB, Ghia U, Roache PJ, Freitas CJ, Coleman H, Raad PE (2008) Procedure for estimation and reporting of uncertainty due to discretization in CFD applications. J Fluids Eng Trans ASME 130:0780011–0780014. https://doi.org/10.1115/1.2960953
17. Lawless M, Robert A (2001) Scales of boundary resistance in coarse-grained channels: Turbulent velocity profiles and implications. Geomorphology 39:221–238. https://doi.org/10.1016/S0169-555X(01)00029-0
18. Casas A, Lane SN, Hardy RJ, Benito G, Whiting PJ (2010) Reconstruction of subgrid-scale topographic variability and its effect upon the spatial structure of three-dimensional river flow. Water Resour Res 46:1–17. https://doi.org/10.1029/2009WR007756
19. Warmink JI, van der Klis H, Booij MJ, Hulscher S (2011) Identification and Quantification of Uncertainties in a Hydrodynamic River Model Using Expert Opinions. Water Resour Manag 25:601–622. https://doi.org/10.1007/s11269-010-9716-7
20. Flora K, Khosronejad A. On the impact of bed-bathymetry resolution and bank vegetation on the flood flow field of the American River, California: Insights gained using data-driven large-eddy simulation. J Irrig Drain Eng 2021;Forthcomin. https://doi.org/10.1061/(ASCE)IR.1943-4774.0001593
21. Matahel AG-CJ, Orlin A (2002) Hydraul Meas Exp Methods 2021:1–10. https://doi.org/10.1061/40655(2002)15. K. Comparison of Discharge Estimates from ADCP Transect Data with Estimates from Fixed ADCP Mean Velocity Data
22. Moore SA, Jamieson EC, Rainville F-M, De, Rennie CD, Mueller DS (2017) Monte Carlo Approach for Uncertainty Analysis of Acoustic Doppler Current Profiler Discharge Measurement by Moving Boat. J Hydraul Eng 143:4016088
23. Mueller DS (2016):50
24. Mueller DS, Wagner CR(2009) Measuring discharge with acoustic Doppler current profilers from a moving boat.
25. Muste M, Yu K, Spasojevic M (2004) Practical aspects of ADCP data use for quantification of mean river flow characteristics; Part I: Moving-vessel measurements. Flow Meas Instrum 15:1–16. https://doi.org/10.1016/j.flowmeasinst.2003.09.001
26. Muste M, Kim D, González-Castro JA (2010) Near-Transducer Errors in ADCP Measurements: Experimental Findings. J Hydraul Eng 136:275–289. https://doi.org/10.1061/(asce)hy.1943-7900.0000173
27. Schmalz S, Hörmann B, Fohrer G (2012) Accuracy, reproducibility and sensitivity of acoustic Doppler technology for velocity and discharge measurements in medium-sized rivers. Hydrol Sci Journal-Journal Des Sci Hydrol 57:1626–1641. https://doi.org/10.1080/02626667.2012.727999
28. Despax A, Le Coz J, Hauet A, Mueller DS, Engel FL, Blanquart B et al (2019) Decomposition of Uncertainty Sources in Acoustic Doppler Current Profiler Streamflow Measurements Using Repeated Measures Experiments. Water Resour Res 55:7520–7540. https://doi.org/10.1029/2019WR025296
29. Legleiter CJ, Kyriakidis PC, McDonald RR, Nelson JM (2011) Effects of uncertain topographic input data on two-dimensional flow modeling in a gravel-bed river. Water Resour Res 47:1–24. https://doi.org/10.1029/2010WR009618
30. Casas A, Benito G, Thorndycraft VR, Rico M (2006) The topographic data source of digital terrain models as a key element in the accuracy of hydraulic flood modelling. Earth Surf Process Landforms 31:444–456. https://doi.org/10.1002/esp.1278
31. Pasternack GB, Gilbert AT, Wheaton JM, Buckland EM (2006) Error propagation for velocity and shear stress prediction using 2D models for environmental management. J Hydrol 328:227–241. https://doi.org/10.1016/j.jhydrol.2005.12.003
32. Lane SN, Bradbrook KF, Richards KS, Biron PA, Roy AG (1999) The application of computational fluid dynamics to natural river channels; Three-dimensional versus two-dimensional approaches. Geomorphology 29:1–20. https://doi.org/10.1016/S0169-555X(99)00003-3
33. Keylock CJ, Constantinescu G, Hardy RJ (2012) The application of computational fluid dynamics to natural river channels: Eddy resolving versus mean flow approaches. Geomorphology 179:1–20. https://doi.org/10.1016/j.geomorph.2012.09.006
34. Robert A (2003) RIVER PROCESSES: An introduction to fluvial dynamics – 1st Edition - A, 1st edn. Arnold Publishers
35. Recking A, Frey P, Paquier A, Belleudy P, Champagne JY (2008) Feedback between bed load transport and flow resistance in gravel and cobble bed rivers. Water Resour Res 44:1–21. https://doi.org/10.1029/2007WR006219
36. Camenen B, Bayram A, Larson M (2006) ;132:1146–58. https://doi.org/10.1061/(ASCE)0733-9429(2006)132:11(1146)
37. Chanson H (2004) Sediment transport capacity and total sediment transport. Hydraul. Open Channel Flow, Elsevier; p. 218–38. https://doi.org/10.1016/b978-075065978-9/50018-0
38. Sumer BM, Kozakiewicz A, Fredsøe J, Deigaard R (1996) Velocity and Concentration Profiles in Sheet-Flow Layer of Movable Bed, vol 122. J Hydraul Eng, New York, NY), pp 549–558
39. van Rijn L (1984) Sediment transport; Part I, Bed load transport. J Hydraul Eng 110:1431–1456
40. Kang S, Sotiropoulos F (2012) Numerical modeling of 3D turbulent free surface flow in natural waters. Adv Water Res 40:23–36. https://doi.org/10.1016/j.advwatres.2012.01.012
41. Giang LS, Hong TTM (2019) 3D numerical modeling of flow and sediment transport in rivers and open channels. Sci Technol Dev J - Sci Earth Environ 3:23–36. https://doi.org/10.32508/stdjsec.v3i1.508
42. Ge L, Sotiropoulos F (2007) A numerical method for solving the 3D unsteady incompressible Navier-Stokes equations in curvilinear domains with complex immersed boundaries. J Comput Phys 225:1782–1809. https://doi.org/10.1016/j.jcp.2007.02.017
43. Khosronejad A, Sotiropoulos F (2014) Numerical simulation of sand waves in a turbulent open channel flow. J Fluid Mech 753:150–216. https://doi.org/10.1017/jfm.2014.335
44. Smagorinsky J (1963) General circulation experiments with the primitive equations I. The basic experiment.Mon Weather Rev:91
45. Kang S, Lighthbody A, Hill C, Sotiropoulos F (2011) High-resolution numerical simulation of turbulence in natural waterways. Adv Water Resour 34:98–113. https://doi.org/10.1016/j.advwatres.2010.09.018
46. Khosronejad A, Kang S, Borazjani I, Sotiropoulos F (2011) Curvilinear immersed boundary method for simulating coupled flow and bed morphodynamic interactions due to sediment transport phenomena. Adv Water Resour 34:829–843. https://doi.org/10.1016/j.advwatres.2011.02.017
47. Wilcox DC (1993) Turbulence modeling for CFD.
48. Fonstad MA, Dietrich JT, Courville BC, Jensen JL, Carbonneau PE (2013) Topographic structure from motion: A new development in photogrammetric measurement. Earth Surf Process Landforms 38:421–430. https://doi.org/10.1002/esp.3366
49. Drone Mapping Software (2021) - OpenDroneMap n.d. https://www.opendronemap.org/
50. Parsons DR, Jackson PR, Czuba JA, Engel FL, Rhoads BL, Oberg KA et al (2013) Velocity Mapping Toolbox (VMT): A processing and visualization suite for moving-vessel ADCP measurements. Earth Surf Process Landforms 38:1244–1260. https://doi.org/10.1002/esp.3367
51. Khosronejad A, Ghazian Arabi M, Angelidis D, Bagherizadeh E, Flora K, Farhadzadeh A. Comparative hydrodynamic study of rigid-lid and level-set methods for LES of open-channel flow. J Hydraul Eng 2019;145. https://doi.org/10.1061/(asce)hy.1943-7900.0001546
52. Flora K, Santoni C, Khosronejad A (2021) Effect of bank vegetation on the hydrodynamics of the American River under flood conditions: a numerical study. J Hydraul Eng Forthcomin:1–14. https://doi.org/10.1061/(ASCE)HY.1943-7900.0001912
53. Khosronejad A, Kang S, Sotiropoulos F (2012) Experimental and computational investigation of local scour around bridge piers. Adv Water Resour 37:73–85. https://doi.org/10.1016/j.advwatres.2011.09.013
54. Khosronejad A, Hill C, Kang S, Sotiropoulos F (2013) Computational and experimental investigation of scour past laboratory models of stream restoration rock structures. Adv Water Resour 54:191–207. https://doi.org/10.1016/j.advwatres.2013.01.008
55. Khosronejad A, Diplas P, Angelidis D, Zhang Z, Heydari N, Sotiropoulos F (2020) Scour depth prediction at the base of longitudinal walls: a combined experimental, numerical, and field study. Environ Fluid Mech 20:459–478. https://doi.org/10.1007/s10652-019-09704-x
56. Khosronejad A, Kozarek JL, Palmsten ML, Sotiropoulos F (2015) Numerical simulation of large dunes in meandering streams and rivers with in-stream rock structures. Adv Water Resour 81:45–61. https://doi.org/10.1016/j.advwatres.2014.09.007
57. Hey RD (1979) Flow Resistance in Gravel-Bed Rivers. ASCE J Hydraul Div 105:365–379. https://doi.org/10.1061/jyceaj.0005178
58. Ferguson R (2007) Flow resistance equations for gravel- and boulder-bed streams. Water Resour Res 43. https://doi.org/10.1029/2006WR005422
59. Adams B, Bohnhoff W, Dalbey K, Ebeida M, Eddy J, Eldred M et al (2020) Dakota, A Multilevel Parallel Object-Oriented Framework for Design Optimization, Parameter Estimation, Uncertainty Quantification, and Sensitivity Analysis: Version 6.12 User's Manual.
60. Eldred MS. Recent advances in non-intrusive polynomial chaos and stochastic collocation methods for uncertainty analysis and design. Collect Tech Pap - AIAA/ASME/ASCE/AHS/ASC Struct Struct Dyn Mater Conf 2009. https://doi.org/10.2514/6.2009-2274
61. Narayan A, Xiu D (2012) Stochastic Collocation Methods on Unstructured Grids in High Dimensions via Interpolation. SIAM J Sci Comput 34:A1729–A1752. https://doi.org/10.1137/110854059
62. Sudret B (2008) Global sensitivity analysis using polynomial chaos expansions. Reliab Eng Syst Saf 93:964–979. https://doi.org/10.1016/j.ress.2007.04.002
63. Eldred MS, Bohnhoff W, Hart W, DAKOTA(1999) A Multilevel Parallel Object-Oriented Framework for Design Optimization, Parameter Estimation, Sensitivity Analysis, and Uncertainty Quantification Acknowledgment.
64. Khosronejad A, Hansen AT, Kozarek JL, Guentzel K, Hondzo M, Guala M et al (2016) Large eddy simulation of turbulence and solute transport in a forested headwater stream. J Geophys Res F Earth Surf 121:146–167. https://doi.org/10.1002/2014JF003423
65. Le TB, Khosronejad A, Sotiropoulos F, Bartelt N, Woldeamlak S, Dewall P (2019) Large-eddy simulation of the Mississippi River under base-flow condition: hydrodynamics of a natural diffuence-confluence region. J Hydraul Res 57:836–851. https://doi.org/10.1080/00221686.2018.1534282
66. Buchanan TJ, Somers WP, Survey USG(1976) Discharge measurements at gaging stations. Le Coz J, Hauet A, Pierrefeu G, Dramais G, Camenen B (2010) Performance of image-based velocimetry (LSPIV) applied to flash-flood discharge measurements in Mediterranean rivers. J Hydrol 394:42–52. https://doi.org/10.1016/j.jhydrol.2010.05.049
67. Welber M, Le Coz J, Laronne JB, Zolezzi G, Zamlar D, Dramais G et al (2016) Field assessment of non-contact stream gauging using portable surface velocity radars (SVR). Water Resour Res 52:1108–1126. https://doi.org/10.1002/2015WR017906
68. Welber M, Le Coz J, Laronne JB, Zolezzi G, Zamlar D, Dramais G et al. Field assessment of non-contact stream gauging using portable surface velocity radars (SVR). Water Resour Res 2016;52:1108–26. https://doi.org/https://doi.org/10.1002/2015WR017906.
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