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Non-uniform flows in a compound open-channel: assessment of a hybrid RANS-LES approach

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Key Points:

- The streamwise developments of mean flow, secondary currents, and turbulence statistics are well predicted
- The large coherent structure length-scales are confirmed to be controlled by the dimensionless velocity shear, irrespective of flow depth
- The secondary current patterns depend on the direction and magnitude of transverse currents, and on the development of coherent structures.

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Abstract

Overbank flows in rivers, also termed compound open-channel flows, are rarely uniform in the streamwise direction. Flow non-uniformity involves transverse currents directed from the river main channel (MC) to adjacent floodplains (FPs) or *vice versa*. Depending on their direction and magnitude, the transverse currents can laterally displace the planform shear layer that forms at the interface between MC and FP. They can also modify the cross-sectional distribution of the helical secondary currents (SCs). This paper reports a numerical study that focuses on assessing the ability of a hybrid RANS (Reynolds averaged Navier-Stokes) - LES (Large Eddy Simulation) approach, namely, the Scale Adaptive Simulation (SAS), to capture the evolving structure of both depth-uniform and non-uniform flows in a straight compound open-channel. The simulated flows have recently been studied in an 18 m long and 3 m wide laboratory flume by Proust and Nikora (2020). The originality of the study lies in the modeling of flows over the entire flume length, and in the estimate of the length-scales of the large Kelvin-Helmholtz-type coherent structures (KHCSs). The SAS approach can accurately predict the longitudinal evolution of: (i) the streamwise time-averaged flow, including the planform shear layer width; (ii) the SC patterns; (iii) the turbulence statistics. The emergence and development of the KHCSs are qualitatively retrieved, and are confirmed to be controlled by dimensionless velocity shear irrespective of flow depth. The simulations also show that SC patterns depend on the magnitude and direction of the transverse currents, and also on the development of KHCSs.

1 Introduction

Overflowing rivers often give rise to flows in a compound open-channel, which consists in the river main channel (MC) and one or two adjacent floodplains (FPs). While streamwise uniform flow conditions are quite common for inbank flows in MC, the hypothesis of longitudinal flow uniformity is more hazardous when considering overbank flows in compound open-channels. Flow non-uniformity can be promoted by longitudinal changes in the topography and/or width of FPs (Jasem, 1990; Sellin, 1995; Bousmar, 2002; Bousmar et al., 2004; Proust, 2005; Bousmar et al., 2006; Proust et al., 2006; Peltier et al., 2013; Das et al., 2019) or in the FP land use (Jahra et al., 2011; Dupuis et al., 2017), by a MC meandering within a compound channel of constant width (Shiono & Muto, 1998), by an unbalanced discharge partition between MC and FPs at an upstream cross-section of a river reach (Bousmar et al., 2005; Proust et al., 2013, 2017), or by backwater surface effects (Sturm & Sadiq, 1996; Bousmar, 2002).

The non-uniform flows involve streamwise changes in flow depth and transverse currents directed from MC to FPs or vice-versa. The latter represent a transverse mass exchange that is quantified by the time- and depth-averaged transverse velocity. The transverse currents were found to alter the flow structure that is usually observed under uniform flow conditions. First, they can laterally displace the planform shear layer (based on the transverse distribution of streamwise time-averaged velocity) over FPs or in MC depending on their direction and magnitude. This was observed in laboratory flumes, e.g., in a skewed two-stage flood channel (Elliot & Sellin, 1990), in a straight compound channel with a transverse embankment set over the FP (Peltier et al., 2013), in a compound open-channel with narrowing FPs (Bousmar et al., 2004) and diverging FPs (Proust, 2005; Bousmar et al., 2006), and for non-uniform flows in straight compound channels (Proust et al., 2013; Proust & Nikora, 2020). Second, the transverse currents can also displace the turbulence statistics over FPs or in MC, as observed by Peltier et al. (2013) and Proust et al. (2013). For instance, with increasing transverse currents towards MC, the region of high Reynolds shear stress is increasingly shifted into the MC, going downwards along the MC side-slope bank in the case of a trapezoidal MC (Proust et al., 2013). Third, the helical secondary currents (SCs) with a longitudinal axis that are observed in uniform flows (Tominaga & Nezu, 1991; Knight & Shiono, 1990), and which are in-

duced by the compound channel topography and flow heterogeneity, can be altered by transverse currents between MC and FP (called herein the sub-sections). This was observed in compound meandering channels (Shiono & Muto, 1998), in the presence of converging FPs (Bousmar et al., 2004; Proust et al., 2006), and also for non-uniform flows in a straight compound channel (Proust & Nikora, 2020). Lastly, the latter authors have observed that transverse currents had less impact on the horizontal Kelvin-Helmholtz-type coherent structures (KHCSs) that may populate the planform shear layer than on the shear layer itself. This results in a mismatch between the widths of the shear layer in MC and FP on the one hand, and the transverse length scales of the KHCSs on the other hand.

From a practical point of view, this interplay between the key mechanisms of mass and momentum transfer (transverse currents, SCs and planform shear layer turbulence) affects the river flow conveyance and the lateral transfer of sediments, pollutants and nutrients between sub-sections. As this interplay between key mechanisms is dependent on (i) the streamwise development of the flow structure, (ii) the existence or absence of KHCSs, and (iii) the magnitude and direction of transverse currents, any three-dimensional (3-D) numerical modeling should be performed over a whole river reach in the field, or over the entire flume length in the lab. The motivation of the present study was therefore to determine what type of three-dimensional (3-D) numerical approach would be: (i) able to account for the streamwise evolution of this interplay between key mechanisms, irrespective of the degree of flow non-uniformity; (ii) able to accurately predict the longitudinal evolution of the main flow features, including the KHCSs and their length-scales, in both depth-uniform and non-uniform flows; and (iii) applicable for operational engineering at the river reach scale with a reasonable computational cost. As an initial step, the numerical modeling of flows in a large laboratory flume was considered.

The first tool available is the 3-D Reynolds Averaged Navier-Stokes (RANS) simulation, which is widely used to investigate uniform flows in straight compound open-channels (Naot et al., 1993; Fischer-Antze et al., 2001; Rameshwaran & Naden, 2003; Kang & Choi, 2005; Conway et al., 2013; Brito et al., 2016). The relatively low computational cost of RANS models make them a major tool for hydraulic engineering, and the increasing computational capacities enable large scale simulations for field applications like e.g., flood wave propagation along an 18 km long reach of the Iowa River (Munoz & Constantinescu, 2018).

The second tool available is the Large Eddy Simulation (LES), which is used to investigate and describe the turbulent structure of uniform flows in straight compound open-channels (Thomas & Williams, 1995; Cater & Williams, 2008; Kara et al., 2012; Xie et al., 2013). LES is also used to investigate flows in non-prismatic compound channel geometries, like a compound channel with converging FPs (Mohanta et al., 2015), meandering main channels (Moncho-Estève et al., 2018) and bridge abutments over FPs (Vui Chua et al., 2019). However, due to a relatively high computational cost related to spatial resolution requirements, most LES studies use periodic boundary conditions, or focus on specific channel areas with precursor simulations to define the inlet flow (Vui Chua et al., 2019). Note that the LES of non-uniform flows in long and wide laboratory flumes or along river reaches remain computationally highly expensive.

A third tool available for the simulation of non-uniform flows in compound channels is the hybrid RANS-LES approach. The latter aims at limiting the computational cost using LES only in relevant areas, and solving stationary flow regions with a RANS model. Some authors use zonal RANS-LES models to perform accurate LES computations in complex geometries like channel junctions (Zeng & Li, 2010) or vegetated areas (Li & Yu, 2010). This method is particularly efficient when unstable flow regions (i.e., regions featuring transient instabilities) are induced by geometric singularities. However, a zonal RANS-LES model is not adapted to streamwise evolving depth-uniform and non-uniform flows in compound open-channels. Indeed, although we know that the emergence of KHCSs occurs in the interfacial region between MC and FP, we do not know *a priori* at which streamwise position KHCSs can emerge depending on flow conditions. An

Figure 1. Compound open-channel flume ($18 \text{ m} \times 3 \text{ m}$) in the HHLab at INRAE, Lyon-Villeurbanne, France: (a) view looking upstream; (b) sketched cross-section (view looking upstream), in which D_m and D_f are the flow depths in the main channel (MC) and each floodplain (FP), and B_m and B_f are the widths of the MC and each FP, respectively; ε is the height of the synthetic grass blades over the FPs; and H_{bf} is the bank full stage in the MC.

implicit RANS–LES model was therefore used to simulate the emergence and development of KHCSs along the entire channel.

The Scale Adaptive Simulation (SAS) approach developed by Egorov and Menter (2008) appeared to be a suitable candidate. As explained by these authors, SAS models are a class of unsteady RANS models (URANS) that provide a RANS solution in stable (or stationary) flow regions and are able to capture large unsteady structures in unstable flow regions. The SAS approach has been applied to several underlying RANS models (Egorov et al., 2010). The $k-\omega$ SST (Shear Stress Transport) SAS model, which has already been tested for various complex flows (Egorov et al., 2010; Yu et al., 2013), was chosen for this study. This model was used to simulate the depth-uniform and non-uniform flows studied by Proust and Nikora (2020) in an 18 m long and 3 m wide straight compound open-channel flume, consisting of a central rectangular glass bed MC and two adjacent FPs covered by dense artificial grass (Figure 1a).

The originality of the present study lies in: (i) the 3–D modeling of compound channel flows over the entire flume length, for both depth-uniform and non-uniform flows; (ii) the analysis of the emergence and development of KHCSs, based on an estimate of the streamwise and spanwise length-scales of the KHCSs; and (iii) the analysis of the interplay mechanisms between transverse currents and helical SCs, in conjunction with the development of the KHCSs.

Section 2 below outlines the previous experiments (flume, flow conditions, and measuring techniques) and section 3 presents the numerical model (turbulence model, computational domain, hypotheses and numerical settings). The ability of the hybrid RANS–LES approach to predict the time-averaged flow (streamwise velocities, shear layer width, and SCs) is assessed in section 4. Its ability to predict planform shear-layer turbulence (KHCSs and turbulence statistics) is studied in section 5. The main conclusions are eventually drawn in section 6.

2 Experimental Data

The experiments that have been simulated in the present study were conducted by Proust and Nikora (2020). We briefly recall hereafter some details about the experimental facility, the studied flow cases and the flow depth and velocity measurements.

Figure 2. Experimental water depth over the right-hand FP, D_f (average value between $y^* = 0.3$ and 0.7), with respect to streamwise coordinate, x^* , and interpolation of $D_f(x^*)$ by a third-order polynomial function (dotted lines) that is used for the numerical simulations.

2.1 Experimental Facility

The experiments were conducted in an 18 m long and 3 m wide compound open-channel flume (Figure 1a) in the Hydraulics and Hydro-morphology Laboratory (HH-Lab) at INRAE, Lyon-Villeurbanne, France. The longitudinal bed slope, S_0 , was 1.10×10^{-3} . As sketched in Figure 1b, the symmetrical cross-section was composed of a 1 m wide rectangular glass bed MC and of two 1 m wide flat rough-surface FPs, which were covered with dense synthetic ‘grass’ (rigid blades of height $\varepsilon = 5$ mm, with a density of 256 blades per square centimeter). The vertical distance from the MC glass bed to the blades tips, H_{bf} , was 0.117 m, which defined the bank-full stage in the MC. A Cartesian right-handed coordinate system was set up. The x -, y -, and z -axes represented the longitudinal (parallel to flume bottom), crosswise and vertical (normal to flume bottom) directions, respectively. The origin was defined as: $x = 0$ located at the trailing edge of the vertical splitter plates between MC and FPs (each plate is 75 cm long and starts at the outlet of the inlet tanks); $y = 0$ located at the right-hand sidewall of the compound channel; and $z = 0$ located at the MC bottom. In the following, the longitudinal, lateral, and vertical distances are normalized by the FP width B_f ($x^* = x/B_f$, $y^* = y/B_f$, and $z^* = z/B_f$, see Figure 1b).

As recommended by Bousmar et al. (2005), the three sub-sections (MC, right-hand and left-hand FPs) are supplied with water by three independent inlet tanks to accelerate flow development. Each inlet tank is filled with water through a tower with a constant water level reservoir. Each sub-section flow rate, i.e., Q_m in the MC and Q_f in each of the two FPs, is controlled by an electromagnetic valve and monitored with an electromagnetic flow-meter. At the downstream end of the flume, three variable tail weirs (one per sub-section) are used to control the water surface profiles.

2.2 Flow Conditions

The flow conditions are presented in Table 1. The experiments have started with a scenario corresponding to streamwise uniform flow conditions, defined here by constant flow depths along the x^* -axis in each sub-section. These conditions were achieved by injecting at $x^* = 0$ inflow discharges $Q_m = 98 \text{ L.s}^{-1}$ and $Q_f = 8 \text{ L.s}^{-1}$ (see Proust and Nikora (2020) for more details), resulting in FP flow depth D_f^u (upper script u refers to

Table 1. Flow conditions of the experimental test cases: Q_f and Q_m are inflows in each of the two FPs and in the MC respectively; ranges of the FP flow depth D_f between $x^* = 0.45$ and 16.55; streamwise velocities averaged across a FP, $U_{x,f}$, and across the MC, $U_{x,m}$, at $x^* = 0.45$.

Case	Q_f (L s ⁻¹)	Q_m (L s ⁻¹)	D_f (mm)	$U_{x,f}$ (m s ⁻¹)	$U_{x,m}$ (m s ⁻¹)
Qf0	0	114	17.6 - 31.3	0.00	0.84
Qf4	4	106	24.2 - 31.1	0.17	0.75
Qf8	8	98	30.6 - 30.5	0.26	0.66
Qf12	12	90	34.3 - 30.9	0.35	0.60
Qf16	16	82	37.7 - 31.2	0.42	0.53
Qf20	20	74	40.5 - 31.7	0.49	0.47

Figure 3. Detection of Kelvin-Helmholtz-type coherent structures (KHCSs) using a dye tracer injected at $x^* = 5.65$ for cases Qf4 (left) and Qf20 (right). Arrows indicate the direction of the transverse currents.

flow uniformity) in the range 30.6 mm to 30.5 mm between $x^* = 0.45$ and 16.55 (see case Qf8 in Table 1 and Figure 2). In the following, each flow case will be identified by its Q_f -value, e.g., the depth-uniform flow scenario is denoted as Qf8.

The experiments continued with flow scenarios that were non-uniform in terms of flow depth along the longitudinal direction. They were generated by imposing an imbalance in the discharge distribution between sub-sections at the flume entrance, keeping the total flow rate Q the same as for the depth-uniform flow scenario, i.e., $Q = 114$ L.s⁻¹. Five non-uniform flow cases have been studied, with $Q_f = 0, 4, 12, 16$ and 20 L.s⁻¹ at each FP. These cases feature significant longitudinal changes in the FP flow depth D_f as shown in Figure 2 and Table 1. In particular, the relative discrepancy between D_f and D_f^u varies from -40% to $+30\%$ at $x^* = 0.45$. The non-uniform flows also involve noticeable transverse currents directed from FP to MC (Qf12, Qf16, and Qf20) or *vice versa* (Qf0 and Qf4). These currents, whose spatial extent reaches the flume length (Proust & Nikora, 2020, Figure 5a), are quantified by the time- and depth-averaged transverse velocity.

Lastly, all test cases are sub-critical in terms of the sub-section Froude number and turbulent in terms of the sub-section Reynolds number except for case Qf0 that is laminar near the flume entrance over the FPs (Proust & Nikora, 2020, Table 1). These numbers in the sub-sections are based on the flow depths D_f and D_m , and on the two velocities that are located outside the planform shear layers (to be considered in section 4.2) on the MC side, $\overline{u_{x2}}$, and FP side, $\overline{u_{x1}}$.

2.3 Measuring Techniques

Water surface elevation was measured using an ultrasonic sensor (BAUMER UNDK 20I6903/S35A) at a rate of 50 Hz for 200 s with a standard measurement error around 0.1 mm. Measurements were taken at transverse positions $y^* = 0.3$ and 0.7 on the right-hand FP. Velocity was measured using one-point or two-point acoustic Doppler velocime-

try. Two 3-D Nortek Vectrino+ Acoustic Doppler Velocimeters (ADV) with side looking probes were used. The three instantaneous velocity components (u_x , u_y , u_z) were recorded at 100 Hz for 300 s. The standard sampling errors on velocity data were estimated at around: 1%, 9%, and 16%, for the time-averaged velocities $\overline{u_x}$, $\overline{u_y}$, and $\overline{u_z}$, respectively; 3%, 2%, and 3% for the velocity fluctuations $\sqrt{u_x'^2}$, $\sqrt{u_y'^2}$, and $\sqrt{u_z'^2}$; and 10% for the transverse Reynolds shear stress $-\rho\overline{u_x' u_y'}$ (Proust & Nikora, 2020).

For the one-point velocity measurements, transverse velocity profiles at a fixed elevation z^* (i.e., 21 mm from the FP bed for case 8 L s^{-1} , and 17 mm for the other cases) and various x^* -positions were measured, and full half cross-sections at three x^* -positions were also covered (measurements at intervals of 4 to 10 mm in the vertical direction at 17 z^* -elevations in the MC including 5 above the bank full stage, and at 3 to 5 z^* -elevations over the FP depending on flow conditions; and measurements at intervals of 10 to 100 mm in the lateral direction at 40 y^* -positions in a half cross-section). For the two-point velocity measurements, two ADV probes are simultaneously used at a fixed z^* -elevation (21 mm from the FP bed for case 8 L s^{-1} , and 17 mm for the other cases). In a first step, ADV probes were placed along the y^* -axis at a given x^* -position. A fixed probe was measuring at the interface between MC and right-hand FP ($y^* = 1$) while the second probe was moving, point-by-point, along y^* -axis, across the MC or across the right-hand FP. In a second step, the ADV probes were positioned along the flow at the MC/right-hand FP interface. The upstream probe was fixed (measuring at a given x^* -position) and the second probe was moving point-by-point downstream.

Lastly, the KHCSs that can populate the planform shear layer were detected using a dye tracer (potassium permanganate), which was injected near the interface on the FP side at $x^* = 5.65$ as shown in Figure 3 for $Q_f = 4$ and 20 L s^{-1} .

3 Numerical Model

The transient simulations of the flows presented in section 2 have been performed with the open-source CFD code OpenFOAM. As mentioned in section 1, the $k-\omega$ SST-SAS turbulence model developed by Egorov and Menter (2008) has been used. This section presents the turbulence model, the computational domain and numerical settings.

3.1 Turbulence Modeling

In the $k-\omega$ SST-SAS turbulence model, the continuity and momentum equations for an incompressible flow are solved in an unsteady RANS (URANS) framework as follows:

$$\frac{\partial \tilde{u}_i}{\partial x_i} = 0, \quad (1)$$

$$\frac{\partial \tilde{u}_i}{\partial t} + \tilde{u}_j \frac{\partial \tilde{u}_i}{\partial x_j} = -\frac{1}{\rho} \frac{\partial \tilde{p}}{\partial x_i} + \frac{\partial}{\partial x_j} \left[\nu \frac{\partial \tilde{u}_i}{\partial x_j} + \frac{R_{ij}}{\rho} \right], \quad (2)$$

where $\tilde{u}_i$, $\tilde{p}$, ρ and ν stand for the resolved instantaneous velocity component in the i^{th} direction, the resolved instantaneous pressure, water density and kinematic viscosity, respectively. The modeled Reynolds stresses, R_{ij} , are defined as follows:

$$R_{ij} = \mu_t \left(\frac{\partial \tilde{u}_i}{\partial x_j} + \frac{\partial \tilde{u}_j}{\partial x_i} \right) - \frac{2}{3} \rho k \delta_{ij}, \quad (3)$$

where μ_t and k are the turbulent dynamic viscosity and turbulent kinetic energy, respectively, and δ_{ij} is the Kronecker symbol.

The transport equations for the turbulent kinetic energy k and specific dissipation rate ω (Eqs. 4 and 5) are based on the well known k - ω SST model developed by Menter (1994).

$$\frac{\partial \rho k}{\partial t} + \frac{\partial}{\partial x_i}(\tilde{u}_i \rho k) = P_k - \rho c_\mu k \omega + \frac{\partial}{\partial x_i} \left[\left(\mu + \frac{\mu_t}{\sigma_k} \right) \frac{\partial k}{\partial x_i} \right], \quad (4)$$

$$\begin{aligned} \frac{\partial \rho \omega}{\partial t} + \frac{\partial}{\partial x_i}(\tilde{u}_i \rho \omega) = & \alpha \frac{\omega}{k} P_k - \rho \beta \omega^2 + \frac{\partial}{\partial x_i} \left[\left(\mu + \frac{\mu_t}{\sigma_\omega} \right) \frac{\partial \omega}{\partial x_i} \right] \\ & + (1 - F_1) \frac{2\rho}{\sigma_{\omega 2}} \frac{1}{\omega} \frac{\partial k}{\partial x_i} \frac{\partial \omega}{\partial x_i} + Q_{SAS}. \end{aligned} \quad (5)$$

Readers can refer to Menter (1994) for the description of the k - ω SST model and to Egorov and Menter (2008) for the application of the SAS approach. According to Egorov and Menter (2008), the additional term Q_{SAS} in Eq. 5 enables the turbulence length scale to be adjusted to the local flow inhomogeneity, which is not the case in the RANS k - ω SST model. The default values of coefficients are used in Q_{SAS} term in the simulations. The SAS model is then designed to provide a RANS solution for stationary flows and to allow the break-up of large unsteady structures, in an LES-like behavior, for flows featuring transient instabilities.

3.2 Computational Domain and Numerical Settings

The computational domain encompasses the total width of the flume (3 m) and the full flume working length (17.25 m) in order to investigate the flow development from the flume entrance to the tail weirs for both depth-uniform and non-uniform flows. At the trailing edge of the splitter plates ($x^* = 0$), the time-averaged streamwise velocity $\overline{u_x}$ was assumed to be uniform across each sub-section, and the upstream discharge partition between sub-sections is equal to the measured experimental partition. Classical wall functions were used to define the near-wall flow for all channel walls. The bottom and sidewalls of the MC and the sidewalls of the FPs were treated as smooth walls, while the bottoms of the FPs were considered as rough walls. The rough wall function used in the longitudinal direction over the FP bed is defined as:

$$\overline{u_x^+} = \frac{1}{\kappa} \ln \left(\frac{E z^+}{1 + C_s k_s^+} \right), \quad (6)$$

where $\overline{u_x^+} = \overline{u_x} / (\sqrt{\tau_x / \rho})$, $z^+ = z(\sqrt{\tau_x / \rho}) / \nu$ and $k_s^+ = k_s(\sqrt{\tau_x / \rho}) / \nu$ are respectively the normalized time-averaged streamwise velocity, normalized vertical distance to the wall and normalized equivalent sand grain diameter (τ_x being the wall shear stress in the longitudinal direction); the von Karman constant κ equals to 0.41; the empirical constant E equals to 9.8; and C_s is a calibrating parameter related to the roughness type that equals to 0.3 in the present study.

The equivalent sand grain diameter k_s was set to the real height of the grass blades (i.e. 5 mm) in all simulations. Dupuis et al. (2016) estimated k_s -values of the same order of magnitude for fully developed uniform flows over the same rough-surface bed in the same flume, but with a 1 m wide single rectangular cross-section.

At free surface, a rigid lid assumption was adopted and a free slip condition was imposed. Note that the rigid lid is not parallel to the flume bottom for the non-uniform flows since noticeable changes in flow depth were observed along the flume for cases Qf0, Qf4, Qf12, Qf16, and Qf20 (Figure 2). The rigid lid corresponds to the measured water surface, which was approximated by a polynomial function of degree three. For comparison purposes, case Qf20 was simulated by considering an horizontal water surface

Figure 4. Cross-sectional view of the computational grid for case Qf8 (only one half of the domain is displayed).

and a total flow rate equals to the measured one. This assumption led to an overestimate of the inlet velocity by 10 % in MC and 32 % in FPs. This also resulted in mean flow and shear layer turbulence features in poor agreement with the experimental data, confirming the need to account for water level variations in the model. The method used in the present study is open to criticism as it requires a complete knowledge of the water surface profiles, while the use of a free surface tracking method like the volume of fluids (V.O.F) method would have permitted the solving of the water depth variations. The latter was actually out of the scope of the present work with respect to our main scientific motivations (see section 1).

Regular meshes were used, with cell lengths $l_x = 2.5$ cm, $l_y = 1$ cm and $l_z = 0.5$ cm in the x -, y - and z - directions, respectively. The meshes comprises about 3.24 million cells. The choice of the vertical length l_z was dictated by the use of rough wall functions over FPs. The first cell adjacent to the bed had to be high enough to encompass the whole roughness elements and to ensure the validity of the log-law for the near-wall flow. A grid convergence study was performed by varying the lengths l_x and l_y . This study confirmed that the spatial resolution was sufficient to achieve convergence of mean velocity and turbulence statistics, especially within the planform shear layer. The grid convergence study also highlighted that KHCS development and space-time correlations was dependent on the cell aspect ratio in the horizontal plane l_x/l_y , a ratio close to unity leading to the best results. The retained grid has provided more physically sound results and a better agreement with the experimental data. Figure 4 shows a cross-sectional view of the computational grid for case Qf8.

Lastly, second order schemes were used for spatial discretization and a second order Crank-Nicholson scheme was used for the discretization of time derivatives. A time step of 10 ms (5 ms for Qf0) was used to ensure that: (1) the maximum Courant number remained lower than 1; and (2) temporal discretization was sufficient to capture the main flow features. This second point was confirmed by the fact that the Kelvin-Helmholtz instability period was experimentally estimated to approximately 5 s (Proust & Nikora, 2020). The simulations started with a warm up phase to dissipate initial transients prior to the computation of time-averaged flow and turbulence statistics. Defining the flow-through time $t_f = l/U_Q^u \approx 33$ s, where l is flume length and U_Q^u is the bulk velocity for the depth-uniform case (Qf8), it was observed that a warm up over $3 t_f$ was sufficient. The simulations were then continued over $15 t_f$ for the convergence of time-averaged flow and turbulence statistics. The whole transient simulations then covered about 118 Kelvin-Helmholtz instability periods. Note that the simulations were run in parallel on 6 computational nodes, each node featuring 64 GB of RAM and 24 processor cores. The computational time for one simulation was about 32 hours.

4 Time-averaged flow

4.1 Transverse profiles of streamwise velocity

Transverse profiles of the local time-averaged streamwise velocity, $\overline{u_x}$, for all flow cases are shown in Figure 5. For $Q_f = 4, 8, 12, 16$, and 20 L s^{-1} , a very good agreement between numerical simulations and experimental data is found irrespective of the x^* -position.

Under uniform flow conditions (Qf8, Figure 5c), the longitudinal development of the planform shear layer between MC and FP (based on the lateral distributions of $\overline{u_x}$) is perfectly reproduced. The effect of transverse currents directed towards MC on the shear layers is also well captured: with significant transverse currents (Qf16 and Qf20), the shear layer is mostly located in MC (i.e., $y^* \geq 1$).

For $Q_f = 0 \text{ L s}^{-1}$, numerical and experimental results collapse for $x^* \geq 7.64$ (Figure 5a). On the other hand, further upstream (see the data at $x^* = 1.64$ and 3.64), the discrepancies between data and simulations can be noticeable within the shear layer. This is actually due to the upstream boundary condition over the FPs that is imposed in the numerical model for case Qf0. We assumed that $\overline{u_x} = 0$ at $x^* = 0$ (longitudinal position of the splitter plate trailing edge) across each FP, while the visualization of the velocity field in this region by pouring saw dust at water surface showed that $\overline{u_x}$ can be negative at $x^* = 0$ across a part of each FP (note that ADV measurements could not be performed at $x^* = 0$, as this position was not reachable by the automatic movement system). The jet in the MC is indeed associated with a recirculating flow area over each FP, with a part of this flow directed towards the inlet tank and entering this tank. The actual (measured) shear layer development is accordingly slower than the simulated one at the two first measuring sections because of the observed negative values of $\overline{u_x}$ at $x^* = 0$.

4.2 Dimensionless velocity shear and shear layer width

In this section, we first focused on a parameter based on two velocities that are located outside the planform shear layer, namely the dimensionless velocity shear λ (Brown & Roshko, 1974):

$$\lambda = \frac{\overline{u_{x2}} - \overline{u_{x1}}}{\overline{u_{x2}} + \overline{u_{x1}}} \quad (7)$$

where $\overline{u_{x1}}$ is here the streamwise velocity averaged across the plateau region of $\overline{u_x}(y^*)$ over the right-hand FP, and $\overline{u_{x2}}$ is the peak streamwise velocity in the MC (Figure 5).

In the experiments, the width of the plateau region of $\overline{u_x}(y^*)$ that is considered for the calculation of $\overline{u_{x1}}$ is variable from one case to another, and with the x^* -position, in agreement with the observed streamwise development of flows. In the simulations, owing to smoother velocity profiles (compared to the measured ones), a plateau region of constant width extending from $y^* = 0.1$ to $y^* = 0.5$ was considered, as this region was outside the shear layer for all cases and x^* -positions.

Figure 6 shows the longitudinal profiles of λ for all flow cases. The simulations match fairly well the λ -measurements. The RANS-LES approach accurately predicts the changes in the characteristic velocities of the shear layer, $\overline{u_{x1}}$ and $\overline{u_{x2}}$, for the depth-uniform flow (Qf8), and also for the non-uniform flows with transverse currents towards MC (Qf12, Qf16, and Qf20) and towards FPs (Qf0 and Qf4).

It must be recalled that, based on the two-point velocity measurements and associated spatial correlations (to be considered in section 5.1), Proust and Nikora (2020) found that no KHCS could emerge if dimensionless velocity shear $\lambda < 0.3$. This result was consistent with earlier one-point measurements of Proust et al. (2017), who have observed this threshold value of 0.3 by studying 25 flow cases in two different flumes, with a relative flow depth D_r ranging from 0.1 to 0.4. Note that Proust et al. (2017) have additionally observed that $\lambda \geq 0.3$ was a necessary condition for the emergence of KHCSs, but not a sufficient one, as the presence of an inflection point in the mean velocity profile was required (Rayleigh's criterion). Dimensionless velocity shear can be interpreted e.g., as a measure of a ratio of the conventional vorticity scale to the shear scale, or as a ratio of the turbulence energy associated with KHCSs to the energy associated with bed-friction depth-scale turbulence (Proust & Nikora, 2020).

Figure 5. Transverse distributions of the time-averaged streamwise velocity, $\overline{u_x}$, at various streamwise positions, x^* , and at elevation $z^* = 0.135$ for $Q_f = 0, 4, 12, 16,$ and 20 L s^{-1} , and at $z^* = 0.139$ for $Q_f = 8 \text{ L s}^{-1}$. Numerical results (—) versus experimental data (×).

Figure 6. Dimensionless velocity shear λ according to Brown and Roshko (1974), see Eq. (7): numerical results (—) versus experimental data ($\times$). Measurements at elevation $z^* = 0.139$ for Qf8 and at $z^* = 0.135$ for the other cases.

Second, we investigated the longitudinal evolution of the shear layer half-width, $\delta_0/2$, at a given z^* -elevation. The transverse size δ_0 is quantified using the definition of van Prooijen et al. (2005):

$$\delta_0 = 2(y_{75\%} - y_{25\%}) \quad (8)$$

where $y_{25\%}$ corresponds to a location where $\overline{u_x}(y_{25\%}) = \overline{u_{x1}} + 0.25(\overline{u_{x2}} - \overline{u_{x1}})$ and $y_{75\%}$ is a location where $\overline{u_x}(y_{75\%}) = \overline{u_{x1}} + 0.75(\overline{u_{x2}} - \overline{u_{x1}})$.

The numerical and experimental results for $y_{25\%}$ and $y_{75\%}$ are plotted in Figure 7. Also displayed is the position $y_{50\%}$ of the mean streamwise velocity $\overline{u_x}(y_{50\%}) = \overline{u_{x1}} + 0.50(\overline{u_{x2}} - \overline{u_{x1}})$. The data for Qf0 at $x^* = 1.64$ and 3.64 must be considered as irrelevant due to the upstream boundary condition issue over the FPs (see section 4.1) for this flow case.

The development of the shear layer across the MC when moving downstream is well predicted for all flow cases (see the data of position $y_{75\%}$). The lateral displacement of the position $y_{50\%}$ is also fairly well modeled for both uniform and non-uniform flows. The crosswise displacement of $y_{50\%}$ clearly indicates that the planform shear layers are displaced in the direction of transverse currents, with the depth-uniform case Qf8 as the reference flow. It also highlights the asymmetry in the relaxation towards flow uniformity depending on the direction of transverse currents. Relaxation is slower with currents towards MC than with currents towards FPs. This is related to the two main contributions to transverse momentum exchange: shear layer turbulence and transverse currents in each sub-section (Proust & Nikora, 2020). With currents towards FPs, these two key mechanisms act in the same direction, e.g., they both accelerate the FP flow and decelerate the MC flow, while with currents towards MC, they act against each other. Last, it should be noted that the prediction of transverse position $y_{25\%}$ is less accurate than position $y_{75\%}$. This lower accuracy on the FP side can be ascribed to the difficulty to describe a shallow flow over a rough-surface bed using a wall function, which requires here a low vertical mesh resolution (see section 3.2).

Figure 7. Half-width of the shear layer, $\delta_0/2$ (normalized by B_f), bounded by the simulated transverse positions $y_{25\%}$ ($\cdots$) and $y_{75\%}$ ($--$) according to van Prooijen et al. (2005), see Eq. (8). The simulated position $y_{50\%}$ ($-$) is also plotted. The numerical results are compared to the measurements of $y_{25\%}$ ($\triangle$), $y_{75\%}$ (∇), and $y_{50\%}$ ($\times$). Measurements taken at $z^* = 0.139$ for Qf8 and at $z^* = 0.135$ for the other cases.

4.3 Velocities in the main channel

Figure 8 shows the cross-sectional distributions of the time-averaged streamwise velocity, $\overline{u_x}$, in the MC for $Q_f = 0, 8$, and 20 L s^{-1} , at longitudinal position $x^* = 7.45$. Velocity $\overline{u_x}$ is scaled by the peak velocity across the compound channel denoted as $\overline{u_{x,max}}$. Some discrepancies can be observed between numerical results and measurements for the three flow cases.

First, we can notice that, for $1.2 \leq y^* \leq 1.5$, i.e., mostly outside the planform shear layer (Figures 5 and 7), the vertical distributions of simulated velocity $\overline{u_x}$ significantly differ from the measured velocity distributions. In the simulation, the velocity gradient is essentially oriented along the vertical axis, which is not in agreement with the observations. These differences could be explained by the approximation of the wall function on a smooth bottom used in the code and/or by the RANS solving in this stable flow region that can lead to an overestimate of the turbulent viscosity.

On the other hand, in the shear layer region (for $1 \leq y^* \leq 1.2$), the simulated velocities $\overline{u_x}$ are closer to the measured ones, as illustrated by the vertical distributions of $\overline{u_x}$ at $y^* = 1.1$ in Figure 8, plots a3, b3, and c3. These results demonstrate that the LES solving in this region can account for the complex interplay between KHCSs, helical SCs (to be considered in the next section), and transverse currents. The effect of the latter on the streamwise mean flow is also well captured. For instance, for case Qf20 (Figure 8, plots c1, c2, and c3), a strong reduction in the velocity $\overline{u_x}$ can be observed in the upper part of the flow (for $z^* \geq 0.07$) due to the entrance of slow momentum fluid coming from the FP in the MC flow. This is explained in Proust and Nikora (2020) by the predominance of the transverse currents in the lateral exchange of streamwise momentum in the first half of the flume (compared to the contributions of KHCSs and SCs to this exchange).

Figure 8. Cross-sectional distributions of the time-averaged streamwise velocity, $\overline{u_x}$, normalized by the peak velocity $\overline{u_{x,max}}$, in the MC at $x^* = 7.45$, for cases Qf0, Qf8, and Qf20: experimental measurements (a1, b1, and c1) versus numerical results (a2, b2, and c2). Vertical distributions of $\overline{u_x}$ at $y^* = 1.1$: experimental data ($\times$) versus numerical results ($-$) for Qf0 (a3), Qf8 (b3), and Qf20 (c3).

Figure 9. Depth-uniform flow case (Qf8): (a) vertical distributions of the time-averaged transverse velocity, $\overline{u}_y$, across the right-hand half of MC at $x^* = 15.15$; (b) transverse distributions of $\overline{u}_y$ at elevation $z^* = 0.139$ at $x^* = 3.45$ (left) and 13.45 (right); (c) simulated in-plane streamlines across a half-channel at $x^* = 15.15$, the colorbar represents the in-plane velocity magnitude normalized by its maximum value.

4.4 Secondary currents

Under uniform flow conditions (case Qf8), the helical SCs with a longitudinal axis are caused by flow heterogeneity and turbulence anisotropy, which are induced by the compound channel geometry and the lateral change in bed roughness from MC to FP. Figure 9a shows vertical profiles of the computed and measured time-averaged transverse velocity, $\overline{u_y}$, in a half-MC at various y^* -coordinates at $x^* = 15.15$. Transverse profiles of the computed and measured velocity $\overline{u_y}$ at elevation $z^* = 0.139$ at $x^* = 3.45$ and 13.45 are also shown in Figure 9b. Last, computed streamlines and normalized velocity magnitude across the channel at $x^* = 15.15$ are displayed in Figure 9c. In keeping with the experimental measurements (Proust & Nikora, 2020), three SC cells are modeled across the half compound channel. The first one is located within the planform shear layer near the interface on the FP side (Figure 9c) and is associated with negative values of $\overline{u_y}$ near the water surface when the cell is fully developed (Figure 9b, right plot). The second one is also located in the shear layer but on the MC side. These two cells arise from the anisotropy of the planform shear layer turbulence driven by the KHCSs. The third and last one is located at the foot of the MC bank, mostly induced by the rectangular shape of the MC. The two cells near the interface in MC are associated with negative values of $\overline{u_y}$ between $0.2 \leq z^* \leq 0.8$ with a close agreement between numerical results and measurements near the interface (see the data in Figure 9a at $y^* = 1.02$ and 1.06). Lastly, Figure 9b shows that, in MC, the width of the large SC cell is underestimated by the numerical model at both x^* -positions, and in FP, there is a spatial lag in the longitudinal development of the FP vortex between numerical results and experimental data. At $x^* = 3.45$, the numerical values of $\overline{u_y}$ reflect an initial stage of development of the SC cell (with a local deficit in $\overline{u_y}$ but with positive $\overline{u_y}$ -values) while the measurements indicate that the cell is already well developed at this position with negative values of $\overline{u_y}$ very similar to the ones measured at $x^* = 13.45$.

Figure 10 shows the simulated in-plane streamlines and normalized velocity magnitude across the half-channel at $x^* = 9$ and 18 for all cases. This figure is complemented by Figure 11 that focuses on the streamlines and velocity magnitude over the FP near the interface at $x^* = 9$.

In the presence of significant transverse currents towards the MC (Qf16 and Qf20), Figures 10 and 11 indicate that the cross-sectional distribution of SCs at $x^* = 9$ radially differs from the one simulated for the uniform case Qf8. First, the small cell near the interface on the FP side has vanished (Figure 11d). Second, a unique large cell is observed in MC (Figures 10e and 10f), instead of two for case Qf8 (Figures 10c). This new SC pattern is in total agreement with the observations of Proust and Nikora (2020). As KHCSs are not developed at $x^* = 9$ for cases Qf16 and Qf20 in the simulations (to be considered in section 5, Figures 15e-f and 16e-f), this unique cell cannot be ascribed to the planform shear layer turbulence. As suggested by the in-plane streamlines in Figures 10e-f, the simulations confirm that the large cell in MC is generated by the horizontal shearing between the upper mean flow (above the bank full stage in the MC) coming from the FP and the mean flow region below the bank full stage, with a velocity magnitude across the channel that is the highest in the interfacial region.

In addition, the simulations interestingly clarify the interplay mechanisms between transverse currents towards MC and SC cells. First, the size of the unique cell in MC increases with the magnitude of transverse currents (Figures 10e-f, data at $x^* = 9$). Second, the development across the MC of the horizontal-shearing-induced cell leads to the disappearance of the cell at the foot of the bank in MC, which has been observed for case Qf8 (simulations and measurements). Third, a weak transverse current towards MC (Qf12, Figure 10d, data at $x^* = 9$) results in a small horizontal-shearing, which is not able to induce the formation of a large cell spanning vertically over the entire MC depth. Last, the disappearance of the FP cell in the simulations (in keeping with the experimental measurements) may be related to two combined effects: the lateral displacement of the shear layer into MC by the transverse currents (section 4.2 and Figure 7) prevents the development over the FP of any potential SC cell relating to this shear layer; the absence

Figure 10. Simulated in-plane streamlines colored by the in-plane velocity magnitude (normalized by the maximum value across the section), for a half-channel at $x^* = 9$ and 18.

Figure 11. Focus on the helical SC cell over the FP near the interface: simulated in-plane streamlines colored by the in-plane velocity magnitude (normalized by the maximum value across the section) at $x^* = 9$ four 4 cases

of KHCSs in the simulations at $x^* = 9$ (next Figures 16e-f) for cases Qf16 and Qf20 reduces the turbulence anisotropy in the interfacial region, which was responsible for the emergence of the two upper cells from either side of the interface for case Qf8 (Figure 9c).

In the presence of transverse currents towards the FPs (Qf0 and Qf4), Figures 10a-b and 11a-b show that the cross-sectional distribution of SCs is rather similar to the uniform flow distribution (Figures 10c and 11c). Owing to the high levels of planform shear layer turbulence (see section 5), two cells can be observed from either side of the interface, and the corner cell at the bank foot is conserved (Figures 10a and 10b), in agreement with the SC patterns measured by Proust and Nikora (2020). In addition, simulations give further information on the interplay between the transverse currents toward FPs and the SC cells near the interface on the FP side (which could not be investigated from the experimental ADV measurements with only 3 to 5 measuring points over the depth). Figures 11a-b indicate that: (i) the transverse currents, which contribute to the net mass flux towards the FP, are located above the FP helical cell; (ii) the size of the FP SC cell is increasingly reduced (compared to the uniform flow case, Figure 11c) with increasing transverse currents, reflecting that the near-surface transverse current prevents the helical cell from spanning vertically, and subsequently laterally.

Overall, the hybrid RANS–LES simulations well predict the variable effects of transverse currents on the helical SCs, depending on the direction and magnitude of these transverse currents: three SC cells are observed in uniform flow and non-uniform flow with transverse currents towards FPs; they are replaced by a unique cell in the presence of significant transverse currents towards MC in the upstream part of the flow. The simulations have also complemented the experiments by highlighting the links: (i) between the magnitude of transverse currents towards FPs and the size of the FP SC cell; and between the magnitude of transverse currents towards MC and the existence and the size of the unique SC cell in MC induced by horizontal shearing.

5 Planform Shear Layer Turbulence

5.1 Kelvin-Helmholtz-Type Coherent Structures

5.1.1 Space Correlation Functions

In the experiments of Proust and Nikora (2020), the emergence and development of KHCSs were investigated based on two-point velocity measurements (see section 2.3) and associated space correlation functions of the velocity fluctuations. Focusing on the spanwise velocity fluctuations, the two following space correlation functions were used in the streamwise and spanwise directions, respectively:

$$R_{yy}^x(x, y, \epsilon_x) = \frac{\overline{u_y'(x, y, t) u_y'(x + \epsilon_x, y, t)}}{\sqrt{\overline{u_y'^2(x, y)} \overline{u_y'^2(x + \epsilon_x, y)}}} \quad (9)$$

where x is the longitudinal position of the fixed upstream ADV probe and ϵ_x is spatial lag in the x -direction between the fixed probe and the second probe moving away point-by-point downstream, both probes measuring at the MC/FP interface, i.e. at $y^* = 1$; and

$$R_{yy}^y(x, y, \epsilon_y) = \frac{\overline{u_y'(x, y, t) u_y'(x, y + \epsilon_y, t)}}{\sqrt{\overline{u_y'^2(x, y)} \overline{u_y'^2(x, y + \epsilon_y)}}} \quad (10)$$

where x is the longitudinal position of the two ADV probes, the fixed probe measuring at the interface ($y^* = 1$), and the second probe moving point-by-point along y -axis across MC and FP, ϵ_y being spatial lag in the y -direction between the two probes.

Figure 12. Simulated spatial correlation functions of transverse velocity fluctuations, u'_y : (a) along the MC/right-hand FP interface; and (b) across the right-hand FP ($\epsilon_y \leq 0$) and MC ($\epsilon_y > 0$). Also displayed are the characteristic length scales of the KHCSs along the interface, δ^{CS}_{int} , and across MC, δ^{CS}_m . Simulations at $x^* = 9$ and at elevation $z^* = 0.131$ for case 8 L s^{-1} .

The same spatial correlation functions were used in the simulations. Figure 12a shows an example of simulated spatial correlation function of the transverse velocity fluctuation u'_y in the streamwise direction along the interface ($y^* = 1$), for the case of 8 L s^{-1} at $x^* = 9$ (position of the reference upstream probe) and elevation $z^* = 0.131$. Figure 12b shows an example of simulated spatial correlation function of u'_y in the spanwise direction across the MC ($\epsilon_y > 0$) and right-hand FP ($\epsilon_y \leq 0$).

5.1.2 Characteristic Length Scales

The two-point spatial correlation functions were used to estimate characteristic length scales of the planform shear layer turbulence. The first length scale used in the experiments and simulations is a longitudinal scale along the interface, δ^{CS}_{int} , which corresponds to the longitudinal distance between the upstream fixed probe and the downstream moving probe when R^x_{yy} crosses zero for the second time (Figure 12a). When function R^x_{yy} is approximated by a periodic function, δ^{CS}_{int} defines the 3/4 of the spacing between the dominant structures in the longitudinal direction. The second characteristic scale of KHCSs, δ^{CS}_m , corresponds to the lateral distance from the MC/FP interface to the y -value in MC where R^y_{yy} equals to 0.05 (Figure 12b). The third scale, δ^{CS}_f , is similar to δ^{CS}_m but over the FP. The correlation level at 0.05 is chosen as it gives an estimate approximately equal to three integral scales (if the correlation function is close to exponential) as shown in Proust and Nikora (2020).

Figure 13 shows the longitudinal evolution of δ^{CS}_{int} along the interface for all flow cases. Putting aside some non-physical peaks related to numerical issues for the detection of the second crossing of function R^x_{yy} to zero when R^x_{yy} is tangent to x -axis near the second crossing, the scale δ^{CS}_{int} and its longitudinal evolution are fairly well modeled for $Q_f = 0, 4, 8$, and 12 L s^{-1} , while δ^{CS}_{int} is noticeably underestimated for $Q_f = 16$ and 20 L s^{-1} . This underestimation seems to be related to a spatial lag in the emergence and development of KHCSs, when comparing with the other flow cases. It is important to recall at this stage that in the experiments of Proust and Nikora (2020) (and also of Proust et al. (2017) in two other flumes), it was shown that KHCSs can emerge once dimensionless velocity shear exceeds a critical value ($\lambda \geq 0.3$ is a necessary condition for the emergence of KHCSs) above which KHCSs length-scales increase with the velocity shear. The underestimation of δ^{CS}_{int} for Cases Qf16 and Qf20 by the numerical model cannot be ascribed to erroneous values of λ since numerical and experimental results perfectly col-

Figure 13. Longitudinal length scale of the KHCSs, δ_{int}^{CS} , for all flow cases. Comparison between numerical results (—) and experimental data (×).

lapse (section 4.2, Figure 6). As the numerical model also well reproduces the increase in δ_{int}^{CS} with λ for Qf0, Qf4, Qf8, and Qf12, there may be a physical process specific to Qf16 and Qf20 responsible for the spatial lag in the δ_{int}^{CS} -development.

The transverse scales δ_m^{CS} and δ_f^{CS} of the KHCSs are displayed in Figure 14a for $Q_f = 8 \text{ L s}^{-1}$. On the FP side, δ_f^{CS} could not be defined numerically for $x^* \geq 3$ as the correlation function R_{yy}^y remains always higher than 0.05 (as shown in Figure 12b). This behavior can be, once again, ascribed to the rough wall function and the low vertical mesh resolution, and to the simulated stable flow over the FPs outside the shear layer (RANS solution), which results in the absence of small resolved turbulent structures that would dissipate turbulent kinetic energy and limit the development of KHCSs. On the MC side, δ_m^{CS} was computed all along the MC/FP interface. However, the way this length scale is computed (see the detection procedure above) remains rather hazardous as long as KHCSs are not sufficiently developed. Once this condition is fulfilled ($x^* \geq 8$), some qualitative agreement is observed between numerical and experimental results.

In the presence of transverse currents towards FPs (case Qf4), a quantitative agreement can be observed for both δ_m^{CS} and δ_f^{CS} (Figure 14b). On the other hand, some noticeable differences between numerical results and experimental data are found in the presence of transverse currents towards MC (not shown here), especially over the FPs.

On the whole, we can conclude that the longitudinal scale is better predicted than the spanwise length scales, and that the spanwise length scale in MC is better predicted than the scale over the FPs. The latter result highlights the limits of this hybrid RANS–LES approach that uses wall laws in the presence of a FP bed roughness whose height is of the same order of magnitude as flow depth, which requires a low vertical mesh resolution over the FPs.

5.1.3 Vorticity and λ_2 -criterion

To numerically visualize the KHCSs, two different techniques were used. First, we relied on the local instantaneous vorticity in the horizontal plane, which is the vertical component of the rotational of the flow velocity vector, defined as $v_z = \frac{\partial u_y}{\partial x} - \frac{\partial u_x}{\partial y}$. Isocontours of v_z -values are displayed in Figure 15 for all cases (data at mid-depth of the upstream FP flow depth, i.e., in the plane $z^* = (H_{bf} + D_f(x^* = 0)/2)/B_f$). Second,

Figure 14. Transverse length scales of the KHCSs δ_m^{CS} (triangle markers) and δ_f^{CS} (circle markers) for cases Qf8 (a) and Qf4 (b). Comparison between numerical results (filled markers) and experimental data (open markers).

Figure 15. Contours of instantaneous vertical vorticity v_z for all cases.

Figure 16. Instantaneous contour of iso-value $\lambda_2 = -0.01 \text{ s}^{-2}$ for all cases.

we relied on the λ_2 -method or λ_2 -vortex-criterion, which is a vortex core line detection algorithm. The λ_2 -method consists of several steps, which are detailed in Jeong and Hussain (1995). In particular, the gradient velocity tensor $\mathbf{J}$ is decomposed into its symmetric ($\mathbf{S}$) and antisymmetric ($\mathbf{\Omega}$) parts. Then, the three eigenvalues of $\mathbf{S}^2 + \mathbf{\Omega}^2$ are calculated, and ordered in such a way that $\lambda_1 \geq \lambda_2 \geq \lambda_3$. A point in the velocity field is part of a vortex core only if at least two of its eigenvalues are negative i.e. if $\lambda_2 < 0$. The iso-contours of $\lambda_2 = -0.01 \text{ s}^{-2}$ for all cases are shown in Figure 16 (data in the plane $z^* = (H_{bf} + D_f(x^* = 0)/2)/B_f$).

Both methods are efficient ways to visualize the KHCSs and to qualitatively describe their development along the channel. The λ_2 -criterion provides a more accurate description of the KHCS length scales in longitudinal and transverse directions and of the spatial distribution of the structures. For case Qf0 (Figure 16a), large structures are simulated from the flume entrance, in accordance with the planform shear-layer development previously described. For the other flow cases, the growth of KHCSs along the whole flume is well modeled. Note that, for cases Qf16 and Qf20, the emergence and development of KHCSs is delayed in the numerical model (compared to the experimental observations), resulting in an underestimate of the size of KHCSs at the downstream end of the flume. Lastly, the simulations confirmed the strong link between dimensionless velocity shear (Figure 6) and the size of KHCSs. The latter increases with the velocity shear value in the upstream part of the flows (Figures 15 and 16), without any effect of the shallowness on the KHCSs as the largest structures are observed for Qf0, the shallowest flow case (Figure 2).

5.2 Turbulence Statistics

Transverse distributions of the transverse Reynolds shear stress $-\overline{u'_x u'_y}$ and transverse turbulence intensity $\overline{u'^2_y}$ at various x^* -positions and at elevation $z^* = 0.139$ for cases Qf0, Qf8, and Qf20, are shown in Figures 17 and 18, respectively.

For case Qf20, while the mean velocity profiles are very well predicted (Figure 5f), transverse turbulence intensity $\overline{u'^2_y}$ is overestimated across the FP, especially in the first half of the flume (note that streamwise turbulence intensity $\overline{u'^2_x}$ (not shown here) is underestimated). The same results were obtained for case Qf16 (not shown here). As turbulence is essentially induced by the FP bottom in this flow region (shear layer located in the MC, Figures 5f and 7f), the numerical model has some difficulties to reproduce bed-induced turbulence. Once again, this is likely due to the use of rough wall function over the FPs that implies a low vertical resolution of the mesh.

For case Qf0, putting aside the upstream boundary condition issue in $\overline{u_x}$ at the outlet of the FP inlet tanks, satisfactory results are obtained for both $\overline{u'^2_y}$ and $-\overline{u'_x u'_y}$ distributions, which is consistent with the good prediction of the KHCS development.

Lastly, for case Qf8, $\overline{u'^2_y}$ and $-\overline{u'_x u'_y}$ distributions are fairly well predicted all along the flume. The increase in the turbulence statistics along the streamwise direction (Figures 17b and 18b) is consistent with the growth of the planform structures (Figures 15c and 16c).

6 Conclusions

The focus of the study was on assessing the ability of a hybrid RANS-LES approach, namely the $k-\omega$ SST SAS turbulence model developed by Egorov and Menter (2008), to capture the evolving flow structure along depth-uniform and non-uniform flows in a straight compound open-channel with rough-surface FPs. The originality of the study lied in: (i) the modeling of compound channel flows over the entire flume length; (ii) the analysis of the emergence and development of KHCSs relying on an estimate of their streamwise and spanwise length-scales; and (iii) the analysis of the interplay mechanisms between transverse currents and helical SCs, in conjunction with the development of the KHCSs.

Figure 17. Transverse distributions of the Reynolds shear stress, $\overline{u'_x u'_y}$, at various streamwise positions x^* , and at elevation $z^* = 0.139$ for $Q_f = 0, 8$, and 20 L s^{-1} . Numerical results (—) against experimental data (×).

Figure 18. Transverse distributions of the transverse turbulence intensity, $\overline{u_y'^2}$, at various x^* -positions and at $z^* = 0.139$ for $Q_f = 0, 8$, and 20 L s^{-1} . Numerical results (—) against experimental data (×).

The experimental data of Proust and Nikora (2020) collected in a 18 m long and 3 m wide laboratory flume were used.

It was found that the Scale Adaptive Simulation approach was able to capture, for both depth-uniform and non-uniform flows, the streamwise development of: (i) the streamwise time-averaged flow; (ii) the cross-sectional distribution of helical SC cells depending on the magnitude and direction of the transverse currents; (iii) the planform shear layer width (based on time-averaged streamwise velocity); and (iv) the turbulence statistics. The emergence and development of the KHCSs were qualitatively retrieved. The estimate of their longitudinal length-scale is better than the estimate of the spanwise length-scales. The simulations have confirmed that the emergence of KHCSs was driven by the velocity shear and independent of the flow depth.

The simulations have also complemented the experiments by highlighting the links: (i) between the magnitude of transverse currents towards FPs and the size of the FP SC cell; and between the magnitude of transverse currents towards MC and the existence and size of the unique SC cell in MC induced by horizontal shearing.

The Scale Adaptive Simulation approach appears as a promising tool for the simulation of overbank flows in rivers, irrespective of the degree of flow non-uniformity in the streamwise direction. This model is able to capture complex physical phenomena in flow regions with transient instabilities like planform shear layers and give consistent and efficient RANS solutions in more stationary flow regions.

On the other hand, the use of a rough wall function over the FPs is likely the main limitation of the present study, as the height of the bed roughness elements was of the same order of magnitude as flow depth, leading to a low vertical resolution of the mesh. In particular, this led to errors in the estimate of the spanwise length scales of the KHCSs and also of the turbulence intensities over the FPs. Other methods could be investigated to improve the spatial resolution of the flow dynamics close to the bed roughness elements (e.g., porous media approach).

Lastly, as the water surface was considered here as a rigid lid (based on the measured flow depth profiles for both uniform and non-uniform flows), a perspective of this study is the implementation of a surface capture method (e.g. Volume of Fluid Method) in the Scale Adaptive Simulation approach.

Acronyms

ADV	Acoustic Doppler Velocimeter
FP	Flood Plain
HHLab	Hydraulics and Hydro-morphology Laboratory
KHCS	Kelvin-Helmholtz-type Coherent Structure
LES	Large Eddy Simulation
MC	Main Channel
RANS	Reynolds Averaged Navier-Stokes
SAS	Scale Adaptive Simulation
SC	Secondary Current
SST	Shear Stress Transport
URANS	Unsteady Reynolds Averaged Navier-Stokes

Notation

ε	height of the rigid blades of synthetic grass
ρ	water density
B_f	width of each floodplain
B_m	width of the main channel
D_f	flow depth in each of the two floodplains

679	D_m	flow depth in the main channel
680	D_m^u	flow depth in the main channel under depth-uniform flow conditions
681	H_{bf}	bank-full stage in the main channel
682	Q_f	inflow discharge in each of the two floodplains
683	Q_m	inflow discharge in the main channel
684	S_0	longitudinal bed slope
685	u_x, u_y, u_z	longitudinal, lateral and vertical instantaneous velocities
686	u'_x, u'_y, u'_z	longitudinal, lateral and vertical velocity fluctuations
687	$\overline{u_x}, \overline{u_y}, \overline{u_z}$	longitudinal, lateral and vertical time-averaged velocities
688	$\widetilde{u_x}, \widetilde{u_y}, \widetilde{u_z}$	longitudinal, lateral and vertical resolved instantaneous velocities
689	$\overline{u_{xd}}, \overline{u_{yd}}$	longitudinal and lateral time- and depth-averaged velocity
690	$U_{x,f}$	Streamwise velocity averaged across the FP
691	$U_{x,m}$	Streamwise velocity averaged across the MC
692	v_z	instantaneous vertical vorticity
693	x, y, z	longitudinal, lateral and vertical positions or directions
694	x^*, y^*, z^*	longitudinal, lateral and vertical normalized positions or directions

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