Application of detached-eddy simulation to free surface flow over dunes

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(Received 3 June 2013; final version received 19 July 2015)

Detached-eddy simulation (DES) is proposed for simulating shallow water flow in the present paper. Compared to the traditional numerical model used in river flow simulation that is based on hydrostatic assumption, the non-hydrostatic pressure terms are introduced into the momentum equations to improve the accuracy of simulating flow over a distinct, uneven bottom. The numerical scheme is a finite volume method based on an unstructured grid in the horizontal plane, and the \( \sigma \) coordinate in the vertical direction to fix the free surface and the uneven bottom. The in-house codes are parallelized by OpenMP. While most of the domain (including the near bottom zone and the upstream and downstream boundary zones) is designed as a Reynolds-Averaged Navier Stokes (RANS) zone, only a local computational zone is simulated by large-eddy simulation (LES), which is implemented by means of properly designing the grid scales. A case study of flow over a series of five dunes was used to validate the model, focusing on the influence of the inflow condition on the small-scale vortical structures. As an improved method to inspire much more sufficient velocity fluctuation, a zonal detached-eddy simulation (ZDES) technique was introduced into the present model. The same case study was also carried out in a RANS model for comparison with the hybrid RANS and DES or ZDES results. The proposed model is shown to be equally effective in the prediction of small-scale vortical structures in shallow water flow with free surface, and to have potential for simulating large-scale flows, such as natural river flows.

Keywords: dune; detached-eddy simulation; separation flow; free surface

1. Introduction

The coupling of the Reynolds-Averaged Navier Stokes (RANS) equation model with large-eddy simulation (LES) is arguably the main strategy to simulate a wide range of complex flows with higher Reynolds numbers (Re) to reduce computational cost. Spalart, Jou, Strelets, and Allmaras (1997) proposed the detached-eddy simulation (DES\textsuperscript{97}) – one of the interfacing RANS and LES models – by means of modifying the turbulence length in the primary transport equation for the eddy viscosity devised by Spalart and Allmaras (1994). To date, there are three progressive models in the DES family: DES\textsuperscript{97}, Delayed Detached-Eddy Simulation (DDES) and Improved Delayed Detached-Eddy Simulation (IDDES) (Shur, Spalart, Strelets, & Travin, 2008; Spalart, 2009). Spalart (2009) has given a comprehensive overview of the developments, applications and some issues of DES. The DES method has been successfully applied in the case of aerodynamic simulation. Recently, some researchers (Constantinescu, Koken, & Zeng, 2011; Keylock, Constantinescu, & Hardy, 2012) developed a numerical model with DES and tried to simulate natural flows. The domain scale is limited to experimental scale or small rivers, and the rigid water surface is used to take place of the simulation of the free water surface. For environmental hydrodynamics, commonly referring to river, estuarine or ocean flow, RANS is still the preferential numerical tool because DES is still unaffordable for such a large computational domain with a strict requirement of grid resolution in the LES zone.

For environmental hydrodynamic simulation, the hydrostatic assumption is widely used, based on a coarse grid. The coarse grid cannot depict small-scale geometry or the sharp evolution of the bottom, and as a result, the river bed is actually smoothed numerically. However, the grid must be fine enough for DES so that even a small pool can be discretized by the mesh. It is well known that the hydrostatic assumption is invalid when the vertical acceleration induced by flow over a sharp bed is no longer much less than the gravity; instead, the model must be extended to a fully hydrodynamic mode. To improve the predictions of shallow flows, fully hydrodynamic models are often implemented by decomposing the pressure into hydrostatic and non-hydrostatic components via means of a predictor-corrector method (Casulli, 1999; Casulli & Zanolli, 2002; Chen, 2003; Fringer, Gerritsen, & Street, 2006; Jankowski, 1999; Kocyigit, Falconer, & Lin, 2002;...
Zhang, Liu, & Xue, 2006). In the present work, the fully hydrodynamic model with free surface has been switched from RANS to DES.

The main idea of DES is that RANS is used in the near wall zone, and then it is switched to LES far away from the wall. The goal of the present work is to seek a feasible way for large-scale flow with free surface, whereby only a small local domain is simulated by LES while the rest of the domain is covered by RANS. The rationale behind this method is to restrict the computationally intensive LES to a smaller portion of the domain, therefore making the overall simulation more efficient. Meanwhile, because no velocity fluctuation is needed for inflow, the inflow condition can be simplified, which is vital for LES application. For traditional LES application, the velocity fluctuation at inlet can be obtained by different numerical methods, such as periodic boundary condition, adding stochastic forces, using precursor simulations, and so on. For natural river flow simulation, however, it is a bit difficult to implement these methods because of the complex boundaries and irregular geometry. In this regard, all of the mentioned methods can be considered as numerical generators for velocity fluctuation. Provided that the LES zone is properly extended to upstream from the focused region, 'LES-content' should be gradually obtained approaching the focused zone. To validate the idea, a series of five dunes is used to quantitatively investigate the influence of the upstream velocity fluctuation on the prediction of small-scale vortical structures. In this flow configuration, the frontal dune provides the velocity fluctuation for the latter one, and as a result, the LES-content is more and more sufficient. The strategy of imparting stochastic forcing at the interface between RANS and LES. The same zonal technique is also adopted to overcome the MSD problem in the present model.

2. Methodology

2.1. Mathematical model

The governing equations for DES of an incompressible flow are the filtered equations of the conservation of mass and momentum. In the present DES model, the governing equations used in RANS and LES zones are written in the same expression. The fully hydrodynamic model is extended from the shallow water equation based on hydrostatic assumption by means of introducing the non-hydrostatic terms into the momentum equations. To fit the free surface and the uneven bottom, an σ coordinate transformation is adopted (Phillips, 1957), which is widely used in river, estuary and ocean flow simulations. The governing equations are as follows:

\[ \begin{align*}
\frac{\partial \eta}{\partial t} & + \frac{\partial q_x}{\partial x} + \frac{\partial q_y}{\partial y} + \frac{\partial q_z}{\partial \sigma} = 0 \\
\frac{\partial q_x}{\partial t} + \frac{\partial q_x u}{\partial x} + \frac{\partial q_x v}{\partial y} + \frac{\partial q_x \tilde{\omega}}{\partial \sigma} + gD \frac{\partial \eta}{\partial x} - \frac{D}{\rho_0} \frac{\partial p_n}{\partial x} \\
& + \frac{1}{D} \frac{\partial}{\partial \sigma} \left( \frac{(v + \nu_1) \frac{\partial q_x}{\partial y}}{D} \right) \tag{1}
\end{align*} \]

\[ \begin{align*}
\frac{\partial q_y}{\partial t} + \frac{\partial q_y u}{\partial x} + \frac{\partial q_y v}{\partial y} + \frac{\partial q_y \tilde{\omega}}{\partial \sigma} & = -gD \frac{\partial \eta}{\partial y} - \frac{D}{\rho_0} \frac{\partial p_n}{\partial y} \\
& + \frac{1}{D} \frac{\partial}{\partial \sigma} \left( \frac{(v + \nu_1) \frac{\partial q_y}{\partial y}}{D} \right) \tag{2}
\end{align*} \]

\[ \begin{align*}
\frac{\partial q_z}{\partial t} + \frac{\partial q_z u}{\partial x} + \frac{\partial q_z v}{\partial y} & + \frac{\partial q_z \tilde{\omega}}{\partial \sigma} = -\frac{1}{\rho_0} \frac{\partial p_n}{\partial \sigma} - \frac{1}{D} \frac{\partial}{\partial \sigma} \left( \frac{(v + \nu_1) \frac{\partial q_z}{\partial y}}{D} \right) \\
& + \frac{1}{D} \frac{\partial}{\partial \sigma} \left( \frac{(v + \nu_1) \frac{\partial q_z}{\partial y}}{D} \right) \tag{3}
\end{align*} \]

where \( u, v \) and \( w \) are the velocities, \( q_x = Du, q_y = Dw, q_z = D\tilde{\omega}, \tilde{\omega} \) is the vertical velocity in the \( \sigma \) coordinate framework, \( D \) is the total water depth, \( \eta \) is...
the free surface elevation, \( p_a \) is the non-hydrostatic pressure and \( g \) is the gravity acceleration. The molecule viscous coefficient is \( \nu \) and the eddy viscosity is \( \nu_t \). In the \( \sigma \) coordinate, the vertical velocity \( q_x \) is calculated based on the coordinate transformation

\[
q_x = \frac{q_z}{D} - \frac{q_z}{D} \left( \sigma \frac{\partial D}{\partial x} + \frac{\partial q_z}{\partial x} \right) - \frac{q_x}{D} \left( \sigma \frac{\partial D}{\partial y} + \frac{\partial q_x}{\partial y} \right) \]

When the hydrodynamic pressure is neglected, the above equations are reduced to the shallow water equations based on the hydrostatic assumption. The necessity of introducing the non-hydrostatic pressure into the model has been validated for flows over sharp bottom, nonlinear wave propagation and other cases where the vertical acceleration cannot be neglected compared to the gravity (Zhang, Sukhodolov, & Liu, 2014).

The eddy viscosity \( \nu_t \) is obtained by solving the one-equation Spalart-Allmaras (S-A) turbulence model, in which an advection and diffusion equation for an auxiliary variable \( \tilde{v} \) is given by

\[
\frac{D\tilde{v}}{Dt} = c_{b1} S \tilde{u} - c_w f_w \left( \frac{\tilde{v}}{\tilde{d}} \right)^2 + \frac{1}{\tilde{d}} \left[ \nabla \cdot \left( \nu + \tilde{v} \nabla \tilde{v} \right) \right] + c_{b2} (\nabla \tilde{v})^2
\]

where \( \chi \equiv (\tilde{v}/\nu), f_w = g(1 + c_{b3}/\sqrt{g} + c_{b4})^{1/6}, g = r + c_{w2}(\sqrt{r} - r), r \equiv (\tilde{v}/\sqrt{\tilde{S} x^2 \tilde{d}^2}), \tilde{S} = |S| + (\tilde{v}/\sqrt{\tilde{S} x^2 \tilde{d}^2}) f_{c2}, f_{c1} = (\chi^3/\chi^2 + c_{k1}), \) and \( f_{c2} = 1 - (\chi/1 + c_{k1}). \) Here \( |S| = (2S_{u,v})^{1/2} \) is the magnitude of the strain rate tensor \( S_{ij} = (\partial u_i/\partial x_j + \partial u_j/\partial x_i)/2 \).

The standard constants are \( c_{b1} = 0.1355, \tilde{c} = (2/3), c_{b2} = 0.622, \kappa = 0.41, c_{w1} = c_{b1}/\sqrt{\kappa} + (1 + c_{b2}/\tilde{c}) c_{w2} = 0.3, c_{w3} = 2.0, \) and \( c_{v1} = 7.1. \) The eddy viscosity \( \nu_t \) is calculated from \( \tilde{v} \):

\[
\nu_t = \tilde{c} f_{c1}
\]

In a DES model, the length-scale in the destruction term, \( \tilde{d} \), is determined by the minimum of RANS and LES length-scales:

\[
\tilde{d} = \min (d, C_{\text{DES}} \Delta)
\]

where \( \Delta = \max(\sqrt{A}/\pi, \Delta_x), A \) is the area of the horizontal grid for unstructured grids, \( \sqrt{A}/\pi \) is the characteristic length for the horizontal grid, \( \Delta_x \) is the vertical grid size, \( C_{\text{DES}} = 0.65 \) is constant, and \( \Delta \) is the distance far away from the bottom.

### 2.2 Numerical method

A predictor-corrector scheme is used in the numerical method. In summary, the flow driven by hydrostatic pressure is calculated as the predictor step, and then the flow driven by non-hydrostatic pressure is further resolved in the corrector step. The grid system is composed of unstructured horizontal grids and multi-layers in the vertical direction. The governing equations are discretized based on Finite Volume Method (FVM). The second-order total variation diminishing (TVD) scheme, sometimes referred to as the modified-flux approach, was originally developed by Harten (1984). In the present numerical model, 11 kinds of second-order TVD schemes have been successfully implemented, and the OSHER scheme is adopted in the case study. The semi-implicit scheme (Casulli, 1990) with \( \theta = 0.5 \) is adopted to improve the numerical stability when simulating the fast speed gravity waves. In the corrector step, the Poisson-type equation for the non-hydrostatic pressure is numerically obtained by the pre-conditioned Bi-CGSTAB approach.

### 2.3 Channel and dune geometry and the hydrodynamic conditions

The single dune geometry is the same as that in the experiments of Balachandar et al. (2002), in which measurements were made on the 17th dune of a train of 22 dunes mounted in a hydraulic flume. Figure 1 shows the dune geometry at the central vertical plane. Yue, Lin, and Patel (2005, 2006) summarized the numerical simulations of the single dune flow and developed a LES model to investigate the statistical mean flow and instantaneous vortical structures. In the paper, the same single dune is considered and extended to a five-dune series with a one-meter-long upstream and downstream extending zone to validate and illustrate the primary target of the model implementation.

The horizontal grids with a finest resolution of 5 mm × 5 mm are designed in the dune zone, and then are gradually stretched to 20 cm × 20 cm when reaching the upstream and downstream open boundaries. The design of the computational grids ensures that the LES in activity for flow over the dunes and the RANS is switched beyond the dunes (see Figure 2).

![Figure 1. The dune geometry (in the central vertical plane).](image1)

![Figure 2. Schematic of computation domain division.](image2)
Based on the water depth $L$ and the free-surface velocity $U_0$ at the inlet of the solution domain, the Reynolds number is about $5.7 \times 10^4$, and the Froude number is about 0.44. In the vertical direction, the first grid point to the bottom is maintained at about $1.0 \ z^+$, and a stretching ratio of about 1.15 between grid cells in the log layer. The 5 mm-length scale grid is selected by means of a few tests to ensure that the mode is switched from RANS to LES at about decades of $z^+$, which is important for DES application (Keating & Piomelli, 2006). When the mode is switched to LES at the very lower level near the bottom, the gray-layer problem is significant and the Reynolds stress is depressed significantly (Spalart et al., 2006) – but if the interface is too far away from the wall (about several hundreds of $z^+$), the stochastic turbulent flow cannot be well predicted because the most vigorous turbulent activity occurs in the viscous wall region ($z^+ < 50$).

In order to improve the computational efficiency, the simulation was firstly run in RANS mode with hydrostatic pressure until convergence, and then the non-hydrostatic mode was turned on. Based on the convergent simulation obtained by RANS, the mode was therefore switched from RANS to DES, and lasted about 15 large-eddy turnover times ($L/\delta_t$) to obtain enough data for the statistics of turbulent flows.

### 2.4. Overcoming the model-stress depletion (MSD) via zonal detached-eddy simulation (ZDES)

The MSD is a severe issue for the RANS/LES hybrid model, which is pronounced for DES when switching from RANS to LES in the boundary layer, so Spalart et al. (2006) proposed a new version of DES, i.e., DDES, to delay the switch from RANS to LES. Although the MSD issue is partially overcome in that version, the LES-content is not sufficient in the boundary layer because of the simulation in RANS mode. Shur et al. (2008) extended a new model, named IDDES, for simulation with an ambiguous grid scale, which can overcome the MSD problem by modifying the turbulent length scale, initial condition and inflow condition. In fact, as the MSD issue comes from the non-sufficient velocity fluctuation when simulation is switched from RANS to LES, generation of fluctuation by numerical method is one feasible way to inspire much more LES-content at the interface between RANS and LES. Keating and Piomelli (2006) presented a dynamic stochastic forcing method which significantly speeds up the transition and results in more accurate predictions of the velocity fluctuation. Compared to numerical generation of fluctuation, Deck (2005a, 2005b) and Deck et al. (2011) proposed a ZDES approach to avoid the MSD in a different spirit, which is more efficient by means of modifying several parameters in the S-A turbulence model instead of calculating stochastic velocity based on the resolved flows. Breuer, Jovičić, and Mazaev (2003) obtained a much better agreement with the reference LES solution via ZDES when simulating a massively separated flow around a flat plate. In the present model, ZDES is adopted to overcome the MSD. Different from the standard DES, the sub-grid length scale within the LES is given by the cube root of the cell $\Delta = (4 \Delta z)^{1/3}$, where $\Delta$ is the horizontal area of mesh, and the functions, $f_1, f_2$, and $f_w$ are set in accordance to the following equations:

$$f_1 = 1, f_2 = 0, f_w = 1$$

As a validation of the model, the DES and ZDES were both carried out in the present case study.

### 3. Results and discussion

#### 3.1. Time-averaged mean flow

The results simulated by RANS are ultimately steady in the present case study. However, the flow simulated by DES is unsteady because of the velocity fluctuation being successfully simulated, and the flow signals during 15 large-eddy turnover times ($L/\delta_t$) were averaged to obtain the mean flow. In the experiments, six vertical lines were laid to measure the velocity. Comparing the RANS results with the measured data, there is little discrepancy for the five dunes, and therefore only the results extracted from the third dune computational zone were used to compare with the experimental data. Figure 3 shows the profiles of streamwise mean velocity at six selected streamwise locations, i.e., $x/h = 2, 4, 5, 6, 12, 18$. Except for $x/h = 12$, where the predicted velocities are lower than the experimental data, the data agreement is good for the upper half water, i.e., $z/L > 0.5$. A more pronounced overshoot is observed around $z/L = 0.2$ for $x/h = 2, 4, 6$. For $x/h = 5$, the predicted velocities coincide well with the experimental data, except those for $z/L < -0.1$. At $x/h = 2$ there is no measured data for $z/L < -0.1$, but the simulation reveals a pronounced negative velocity. Downstream of the location $x/h = 5$, there is no negative current observed in the experiments, but the negative velocity is still observed in the simulation, which means that the predicted reattachment point is put downstream compared to the experiments.

Three groups of streamwise mean velocities were extracted from the first, third and fifth dune zones, respectively, with the same relative distance to the crest of the dune coinciding with the experiments, i.e., $x/h = 2, 4, 5, 6, 12, 18$. Figure 4 shows the comparison of the results simulated by DES with the experimental data, and in each panel, the three lines are respectively for locations at the first, third and fifth dunes. The predicted velocities at six locations are more accurate than those predicted by RANS, particularly for the fifth dune. Because no velocity fluctuation is input at the inlet, insufficient LES-content is obvious in the first dune, but the velocity fluctuation inspired locally can be transported into the downstream dune zone, which acts like a velocity fluctuation generator.
As a technique to speed up the transition from RANS to LES, ZDES was used to generate much more LES-content at the interface. The streamwise mean velocities simulated by ZDES were validated by experimental data (see Figure 5). Compared to DES, ZDES predicts the velocities more accurately, especially for the third and fifth dunes. While the numerical simulation exhibits a pronounced overshoot around $z/L \approx 0$ at $x/h = 2$ and 12 for the fifth dune than the measurements, the data agreement for the third dune is good.

The prediction of the reattachment point is one of the commonly-used criteria for numerical model validation. The time-averaged streamlines were used to explicitly reveal the flow recirculation in each dune zone. Figure 6 shows the streamlines predicted by RANS and the time-averaged streamlines in the vertical plane at $y = 0$ (central plane) predicted by DES and ZDES, respectively, in which only the data for the first, third and fifth dunes are given. The reattachment points in the three dunes predicted by RANS are almost kept constant ($\sim 0.3 \lambda$), where $\lambda$ is the streamwise wavelength of the dunes. On contrary, the results from DES and ZDES reveal that the reattachment point is gradually shifted upstream from the first dune to the fifth dune. The recirculation length in the first dune is more pronounced than the experimental data, which typically varies between 0.2 $\lambda$ and 0.25 $\lambda$. A comparison with the experimental data shows that ZDES is the most accurate in predicting the reattachment point. The decreasing trend of the reattachment length from the first dune to the fifth dune predicted by DES/ZDES implies that the LES-content can be gradually inspired by the upstream dune, which is discussed in the following section.

### 3.2. Instantaneous flow

It is expected that small-scale vortical structures are well predicted by the DES model. A positive isovalue of criterion $Q$ shows the turbulent structures, which
are defined as the vortex tubes in the regions where the second invariant of the velocity gradient tensor is positive:

\[ Q = \frac{1}{2} (\Omega_{ij} \Omega_{ij} - S_{ij} S_{ij}) = -\frac{1}{2} \frac{\partial u_i}{\partial x_j} \frac{\partial u_j}{\partial x_i} > 0 \]  \hspace{1cm} (10)

where \( S_{ij} \) and \( \Omega_{ij} \) are the symmetric and antisymmetric components of \( \nabla \mathbf{u} \), respectively. Figure 7 shows a snapshot of the instantaneous isosurface of \( Q = 10 \) simulated by DES. It clearly shows the evolution of vortical structures from the first dune to the fifth dune. There are few vortex tubes in the first dune zone, which is attributed to the insufficient velocity fluctuation transported from upstream or generated in the interface of RANS and LES. For the dunes further downstream, on the other hand, the frontal dune flow provides much more LES-content (i.e., plenty of vortical structures). As depicted in Figure 7, the vortical structures are better predicted by ZDES than by DES because the transition from RANS to LES can be speeded up in the ZDES mode. There is still insufficient LES-content observed in the first dune for ZDES, but it has been remarkably improved compared to DES, which again verifies the importance of the velocity fluctuation transported from the upstream.

The instantaneous velocity vectors in the cross-sectional planes of \( 0.2\lambda \) for the five dunes simulated by DES and ZDES are shown in Figure 8. Two aspects are highlighted: one is the upstream fluctuation affecting the simulation of vortical structures in the following dune zone, and the other is the validity of ZDES to speed up the transition from RANS to LES at the interface.

Figure 9 shows the instantaneous velocity fluctuation \( (u', w') \) in the vertical central plane \( (y = 0) \) simulated by DES and ZDES, respectively. ZDES predicts more abundant turbulent coherent structures in the fifth dune zone compared to the first one.
Figure 7. Comparison of isosurface with $Q = 10$ between DES and ZDES.

Figure 8. Comparison of the instantaneous velocity at different cross-sections between DES and ZDES.

Figure 9. Comparison of the instantaneous velocity vectors $(u', w')$ in the central $x$-$z$ plane between DES and ZDES.

The most accurate results by DES and ZDES in the fifth dune domain verify the importance of the influence of the upstream fluctuation when simulating large-eddy structures. Drawing an analogy between the velocity fluctuation generated by the numerical method and by the frontal four dunes, the fluctuation injected into the fifth dune can be considered as a result of a physical method other than a numerical method. Fortunately, in natural rivers, there are sufficient disturbing forces induced by uneven bottom and curvilinear river bank, which can generate velocity fluctuation for a focused zone with the most fine grid resolution. Therefore, the strategy of the simulation in the
present work is feasible for large-scale river flow simulations to obtain LES-content only in a local focused zone by the aid of the practical computer power.

3.3. Statistic property

The mean Reynolds shear stress, $-u'w'$, is obtained by time-averaging the signal of instantaneous Reynolds shear stress $-u'w'$ calculated from the resolved scale by DES. Figure 10 shows the profiles of $-u'w'$ along different vertical lines for the first, third and fifth dunes, together with the measured data for comparison. The peak occurring at $z/L \approx 0$ is clearly predicted. The location of the predicted peak is in good agreement with the experimental data, although the magnitudes are considerably smaller, especially for the first dune. The improvement of the agreement between measurements and simulations from the first dune to the fifth dune verifies that the velocity fluctuation from upstream affects the turbulence simulation passing the downstream dunes.

The improvement of ZDES lies in the much greater amount of LES-content inspired at the interface between RANS and LES, indicating that much more turbulent fluctuation can be resolved by the model. This merit of ZDES is again verified by the predicted mean Reynolds stress (see Figure 11). Compared to the experimental data, the calculated Reynolds stress for the third dune is the most accurate among the three selected dunes. For the fifth dune, however, there is a noticeable overshoot at location $x/h = 2$. This is not in line with the ideal deduction that the accuracy would gradually improve from the first dune to the fifth dune. One fact should be highlighted that the unsteady turbulent flow has not converged to a steady statistic status until the fifth dune in the present case study, so it cannot be concluded that the accuracy will decrease with extending dunes.

Figure 10. Comparisons of predicted mean Reynolds stress by DES with experimental data at selected streamwise stations.

Figure 11. Comparisons of predicted mean Reynolds stress by ZDES with experimental data at selected streamwise stations.
The turbulent energy spectra contains an inertial subrange with a slope of $-5/3$, which can be simulated by LES, as well as by DES or ZDES. In the present case study, only the results by ZDES are used to validate the model for the simulation of the turbulence in the inertial subrange. Time signals of the streamwise velocity in the first, third and fifth dunes at the same relative position $(x, z) = (0.1 \lambda, 0)$ in the central vertical plane are recorded and used to calculate the streamwise turbulent kinetic energy $k = u'^2$. The energy spectra ($E_{11}$), determined by using a Fourier transform with a Hamming window, are shown in Figure 12 for the first, third and fifth dune, respectively. A slope with $-5/3$ is observed for the third and fifth dune, whereas it is not very evident for the first dune. As analyzed above, the insufficient LES-content in the first dune is the main reason for the unsuccessful turbulence simulation.

Sediment transportation is one important issue in environmental hydraulics, which is attributed to the evolution of the river bank and topography, and even the behavior of some benthic fauna. The pronounced merit of DES over RANS is its ability to simulate the instantaneous small-scale vortical structures and velocity fluctuation. The velocity fluctuation leads to the instantaneous forces on bed sediment, which is different from the effects of time-averaged mean velocity. For example, the reattachment point is steady as predicted by RANS, so one can deduce that there is no sediment movement at this point; however, the sand may move upstream or downstream instantaneously with the velocity fluctuation. Although it is possible to obtain a nearly zero mean value because of the summation of positive and negative instantaneous velocities, the power of the flow forcing on the bed must be positive, which is the energy to drive the sediment. The basic idea for Bagnold’s formula of bed load prediction (Qian & Wan, 1983) is balancing the energy extracted from the flow and the weight of the sediment picked up from the river bed. The power is calculated by the following formula:

$$W = \tau_b U_b$$

where $\tau_b$ is the mean bed shear stress in RANS (in the first formula), or the instantaneous bed shear stress in DES/ZDES (in the second formula). The comparison of the mean power predicted by RANS and ZDES is shown in Figure 13 along the central line ($y = 0$) for the third dune. The difference is visible especially at about $0.1 \lambda$, while there is little power predicted by RANS, but there is a peak value calculated by ZDES. The local power characteristics imply a different status of sediment transportation. Time-averaging is carried out in the Eulerian framework, whereas the motion of a single sand particle is described in the Lagrangian framework. It is clear that a zero mean velocity cannot move a particle, but the instantaneous velocity fluctuation possibly moves the particle away, and then the particle deposits downstream without returning back. So the instantaneous velocity fluctuation may be much more important as a driving force than the long time-averaged velocity.

4. Conclusions

A hybrid RANS/LES model, DES, was introduced to the simulation of hydrodynamics with a free surface. The proper design of the grid in the present case study, i.e., the division of RANS and LES zones, ensured that the inflow condition in RANS could be used in the DES model, which is efficient for the natural river flow because of the difficulty of generation of fluctuation for inflow in a domain with complex geometry. For DES, the velocity fluctuation, i.e., the LES-content, contained in the inflow affects the simulated small-scale vortical structures, which is confirmed by the case study. However, the inflow problem can be improved by physical disturbing, as the frontal four dunes in the case study. The flow passing one dune injects...
velocity fluctuation locally inspired into the downstream dunes, which can be considered as a physical fluctuation generator instead of a numerical generator. As a velocity fluctuation generator at the interface, ZDES speeds up the transition from RANS to LES, and much more LES-content can be obtained. As a consequence, ZDES improves the prediction of turbulent flow, particularly in terms of small-scale vortical structures.

It is not economical to carry out simulation of five dunes instead of one dune, but the numerical strategy may be feasible for natural river flow. Limited by the present computer power, LES cannot be implemented, but the computational cost can be sharply decreased because only a local zone is simulated by LES. As mentioned in the case study, the insufficient fluctuation from the upstream is a severe problem, but the fluctuation can be gradually inspired by means of extending the upstream zone with a series of dunes. Fortunately, the irregular bank and uneven bottom can act as physical generator for turbulent fluctuation in natural river flow.

Another point in the present work is the comparison between RANS and DES/ZDES. DES/ZDES displays a better agreement with the experimental data than RANS, in terms of time-averaged streamwise velocity, circulation flow and the reattachment point. Similarly, the superiority of DES/ZDES over RANS is in predicting small-scale vortical structures rather than mean flow properties. As with the analysis of flow power, the different numerical model leads to a different bed load calculation, and DES/ZDES is expected to work better because of its superiority on turbulence simulation.

Acknowledgements

The first author is most grateful for inspiring discussions with Dr Alexander Sukhodolov, Leibniz-Institute of Freshwater Ecology and Inland Fisheries, Germany.

Disclosure statement

No potential conflict of interest was reported by the authors.

Funding

This work was supported by the National Basic Research Program of China [973 Program, No. 2014CB046200]; and the Non-profit Industry Financial Program of MWR [201401027].

References

Balachandar, R., Polatel, C., Hyun, B.-S., Yu, K., Lin, C.-L., Yue, W., & Patel, V. C. (2002). LDV, PIV and LES investigation of flow over a fixed dune. In Proceeding of the Symposium Held in Monte Verità: Sedimentation and Sediment Transport (pp. 171–178). Dordrecht: Kluwer Academic.

Breuer, M., Jovičić, N., & Mazaev, K. (2003). Comparison of DES, RANS and LES for the separated flow around a flat plate at high incidence. International Journal for Numerical Method in Fluids, 41, 357–388.

Casulli, V. (1990). Semi-implicit finite difference methods for the two-dimensional shallow water equations. Journal of Computational Physics, 86, 56–74.

Casulli, V. (1999). A semi-implicit finite difference method for non-hydrostatic, free-surface flows. International Journal for Numerical Methods in Fluids, 30, 425–440.

Casulli, V., & Zanolli, P. (2002). Semi-implicit numerical modeling of nonhydrostatic free-surface flows for environmental problems. Mathematical and Computer Modelling, 36, 1131–1149.

Chen, X. J. (2003). A fully hydrodynamic model for three-dimensional, free-surface flows. International Journal for Numerical Methods in Fluids, 42, 929–952.

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 Resources Research, 47, 1–62. W05515. doi:10.1029/2010WR010114

Deck, S. (2005a). Numerical simulation of transonic buffet over a supercritical airfoil. AIAA Journal, 43(7), 1556–1566.

Deck, S. (2005b). Zonal-detached eddy simulation of the flow around a high-lift configuration. AIAA Journal, 43(11), 2372–2384.

Deck, S., Weiss, P., Pamięs, M., & Garnier, E. (2011). Zonal detached eddy simulation of a spatially developing flat plate turbulent boundary layer. Computers & Fluids, 48, 1–15.

Fringer, O. B., Gerrissen, M., & Street, R. L. (2006). An unstructured-grid, finite-volume, nonhydrostatic, parallel coastal ocean simulator. Ocean Modelling, 14, 139–173.

Harten, A. (1984). On a cals of high-resolution total variation stable finite difference schemes. SIAM Journal on Numerical Analysis, 21, 1–23.

Jankowski, J. A. (1999). A non-hydrostatic model for free surface flows. Ph.D. Dissertation, University of Hannover, Germany.

Keating, A., & Piomelli, U. (2006). A dynamic stochastic forcing method as a wall-layer model for large-eddy simulation. Journal of Turbulence, 7(12), 1–24.

Keylock, C. J., Constantinescu, G., & Hardy, R. J. (2012). The application of computational fluid dynamics to natural river channels: Eddy resolving versus mean flow approaches. Geomorphology, 179, 1–20. doi:10.1016/j.geomorph.2012.09.006

Kocyigit, M. B., Falconer, R. A., & Lin, B. (2002). Three-dimensional numerical modeling of free surface flows with non-hydrostatic pressure. International Journal for Numerical Methods in Fluids, 40, 1145–1162.

Phillips, N. A. (1957). A coordinate system having some special advantages for numerical forecasting. Journal of Meteorology, 14, 184–185.

Piomelli, U., Balaras, E., Pasinato, H., Squires, K. D., & Spalart, P. R. (2003). The inner-outlet layer interface in large-eddy simulations with wall-modelers. International Journal of Heat and Fluid Flow, 24, 538–550.

Qian, N., & Wan, Z. H. (1983). Sediment dynamics. Bei Jing: Science Publishing Company. (in Chinese).

Shur, K. L., Spalart, P. R., Strelets, M. K., & Travin, A. K. (2008). A hybrid RANS-LES approach with delayed-DES and wall-modelled LES capabilities. International Journal of Heat and Fluid Flow, 29, 1638–1649.

Spalart, P. R. (2009). Detached-eddy simulation. Annual Review of Fluid Mechanics, 41, 181–202.

Spalart, P. R., & Allmaras, S. R. (1994). A one-equation turbulence model for aerodynamic flows. La Recherche Aéospaciale, 1, 5–21.

Spalart, P. R., Deck, S., Shur, M. L., Squires, K. D., Strelets, M. K., & Travin, A. (2006). A new version of Engineering Applications of Computational Fluid Mechanics 565
detached-eddy simulation, resistant to ambiguous grid densities. *Theoretical and Computational Fluid Dynamics*, 20, 181–195.

Spalart, P. R., Jou, W.-H., Strelets, M., & Allmaras, S. R. (1997). Comments on the feasibility of LES for wings, and on a hybrid RANS/LES approach. In C. Liu & Z. Liu (Eds.), *Advances in DNS/LES* (pp. 137–47). Columbus, OH: Greyden Press.

Yue, W., Lin, C. L., & Patel, V. C. (2005). Large eddy simulation of turbulent open-channel flow with free surface simulated by level set method. *Physics of Fluids*, 17, 1–12.

Yue, W., Lin, C. L., & Patel, V. C. (2006). Large-eddy simulation of turbulent flow over a fixed two-dimensional dune. *Journal of Hydraulic Engineering*, 132(7), 643–651.

Zhang, J. X., Liu, H., & Xue, L. P. (2006). A vertical 2-D mathematical model for hydrodynamic flows with free surface in $\sigma$ coordinate. *Journal of Hydrodynamics Ser. B*, 18(1), 82–90.

Zhang, J. X., Sukhodolov, A. N., & Liu, H. (2014). Fully hydrodynamic versus hydrostatic modeling for shallow environmental flows. *Journal of Hydrodynamics*, 26(4), 840–847.