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Large Eddy Simulation of periodic flow characteristics at river channel confluences

Simulation des grandes échelles de turbulence des caractéristiques périodiques d’écoulement aux confluents des cours d’eaux

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ABSTRACT
This paper describes an application of Large Eddy Simulation methods to the flow in a laboratory-style confluence of parallel channels of unequal depths (Reynolds No. = 13,500), and a natural river channel confluence that also exhibits pronounced bed discordance (Reynolds No. = 100,000). The aim is to investigate the formation of periodic flow features inherent in the flow dynamics in river confluences. The laboratory-style confluence predictions are compared with experimental data, and suggest that the simulation was capable of capturing some of the key flow periodicities. The model provides detailed flow and mixing data which help inform understanding of the production and evolution of large scale turbulence features in confluences.

RÉSUMÉ
L’article présente une simulation en laboratoire des grandes échelles de turbulence au confluent de deux cours d’eaux parallèles (nombre de Reynolds = 13500), et au confluent de deux cours d’eaux naturels aux lits discordants (nombre de Reynolds = 100000). L’étude a pour objet la formation de caractéristiques d’écoulement périodiques aux confluents des cours d’eaux. Les résultats de la simulation en laboratoire sont comparés avec des données expérimentales. La comparaison suggère que le modèle numérique arrive à simuler quelques périodicités importants. Le modèle fournit des informations détaillées sur les champs de vitesses et le mélange des cours d’eaux, ce qui aide à la compréhension de la formation et de l’évolution des grandes échelles de turbulence aux confluents des cours d’eaux.

1 Introduction
There has been much interest in the flow dynamics of river channel confluences in recent years. However, due to empirical constraints, measurements in both the laboratory (e.g. McLelland et al.; Biron et al.) and the field (e.g. Rhoads and Kenworthy; De Serres et al.) have primarily concentrated upon estimation of mean flow patterns, with turbulence represented by statistics such as turbulent kinetic energy. However, observations have highlighted several unsteady components in the flow behaviour at confluences, such as Kelvin-Helmholtz instabilities in the mixing layer (Best and Roy, 1991; Biron et al., 1993), longer-term mixing layer migration (Biron et al., 1993), and periodic upwelling of fluid from one tributary within the fluid from the other (Biron et al., 1993; Biron et al., 1996). Field or laboratory monitoring of such features requires a dense array of simultaneous velocity measurements, which is as yet beyond most practical applications. Recent research has shown the potential of numerical modelling for detailed investigation of three-dimensional flow structures at river channel confluences (e.g. Bradbrook et al., 1998; Lane et al., 1999), but these have also only simulated steady state flow conditions, accounting for the effect of turbulence on the mean flow by the use of modified k-ε turbulence models. In this paper, Large Eddy Simulation (LES) is used, allowing unsteady solutions that resolve turbulent eddies at the scale of the computational grid used.

LES has received most attention in atmospheric and oceanographic geophysical applications (e.g. Deardorff, 1970; Denbo and Skyllingstad, 1996), and in simple engineering situations (e.g. Rodi et al., 1997; Sagaut, 1996). It is a well-established technique (Rogallo and Moin, 1984), although explicit application to open channel flow has been limited. Exceptions to this include Thomas and Williams (1995a,b) who present results for an asymmetric ($R_e = 42,000$) and a symmetric ($R_e = 430,000$) compound channel respectively. This study showed that LES was capable of producing predictions of mean velocities, turbulence intensities and distributions of boundary shear stress that compared well with experimental data. The present study takes a different approach, in that the potential of LES to investigate the production and evolution of large-scale vortices is explored.

To our knowledge, such an investigation has not been undertaken for the confluence of two flows at fully-turbulent Reynolds numbers. The model is first applied to a laboratory-style confluence of parallel channels with unequal depths and a Reynolds Number of about 13,500. Previous experimental work (Best and Roy, 1991) has shown that this simple geometry is nevertheless associated with complex periodic flow behaviour. Bradbrook et al. (1998) have shown that the modified k-ε form of the model used in this paper is able to predict the steady state flow characteristics in such a confluence to a high degree of
accuracy (e.g. correlation coefficient of 0.99 between measured and predicted resultant mean velocity based upon 43 points, and regression line not statistically different from the line of equality). However, Large Eddy Simulation allows the periodic aspects of the flow to be investigated. Visualisation of the dynamic results allows comparison with the observations of Best and Roy, and aids interpretation of a quantitative comparison of these results with high-frequency velocity data from laboratory experiments. The application of Large Eddy Simulation to confluences is then extended to a complex natural river confluence (Reynolds Number about 100,000) which field observations have indicated exhibits periodic flow features on a number of scales (Biron et al., 1993).

2 The numerical model

Large Eddy Simulation lies between the extremes of Direct Numerical Solution (DNS), in which the basic form of the Navier-Stokes equations is used and no turbulence model is required, and the classical approach that applies Reynolds’ averaging to the Navier-Stokes equations and which only models mean flow. This approach requires a turbulence model to deal with the effects of Reynolds averaging upon the structure of the Navier-Stokes equations. Large Eddy Simulation attempts to compute the large-scale motion, which is thought to contain most of the variation and motion. These stresses (τ) are given by:

\[ \tau_{ij} = -2\rho v_i S_{ij} \quad (1) \]

where \( \rho \) is the fluid density, \( v_i \) is the eddy viscosity and \( S_{ij} \) is the local mean strain rate:

\[ S_{ij} = 0.5\left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) \quad (2) \]

where \( u_i \) is the component of velocity in the direction \( x_i \). The eddy viscosity is determined using a mixing-length relationship:

\[ v_i = \left( 2S_{ij} \frac{\partial u_i}{\partial x_j} \right)^{1/3} \quad (3) \]

The mixing length, \( l \), is the characteristic length of unresolved eddies, defined as:

\[ l = \min(C_s h, \kappa \cdot d_{wall}) \quad (4) \]

where \( C_s \) is the Smagorinsky constant (= 0.17). (The value of \( C_s \) falls at the lower end of a small range of values (0.17–0.21) calculated theoretically from Kolmogorov’s spectrum (Lilly, 1966) and empirically defined (0.19–0.24) for isotropic turbulence (see Rogallo and Moin, 1984). This is appropriate since experiments (Deardorff, 1970) and direct numerical simulation (McMillan et al., 1980) of strained homogeneous turbulence suggest the value of \( C_s \) decreases with increasing mean strain rate., \( \kappa \) is the von Karman constant (= 0.4), \( d_{wall} \) is the normal distance to the nearest wall, and \( h \) is the representative mesh interval:

\[ h = \sqrt{\frac{d_x^2 + d_y^2 + d_z^2}{3}} \quad (5) \]

where \( dx, dy, dz \) are the local mesh dimensions in the three coordinate directions. Obviously with this formulation, anisotropic meshes will cause ambiguity in the definition of SGS length scales. Grid resolution should be sufficient that the scales of interest are adequately resolved, and as these scales are separated further from the modelled scales by grid refinement, the less the accuracy of the SGS model matters (Rogallo and Moin, 1984). Indeed, comparison of predicted SGS stresses with the ‘exact’ stresses calculated by Direct Numerical Simulation are poor. The notable success of calculations using the Smagorinsky model seems to...show that low-order statistics of the large scales are rather insensitive, in the flows considered, to details of the SGS motions’ (Rogallo and Moin, 1984, p.110).

The eddy viscosity model is also relatively simple: it is isotropic and implicitly assumes the SGS turbulence is in equilibrium with the large eddies and adjusts itself instantaneously to changes of the large-scale velocity gradients. More complex formulations have been proposed, analogous to the development of turbulence models based on Reynolds-averaging. For example, these may relate the eddy viscosity to the kinetic energy of the SGS eddies (Schumann, 1975), or derive transport equations for the individual SGS stresses (Deardorff, 1973). However, if, with an appropriate mesh, a simple SGS model can provide adequate information about the scales of interest then this is consistent with the LES philosophy: ‘the model is not required to supply detailed information about the subgrid scales’ (Rogallo and Moin, 1984, p.107).

2.2 The Numerical Method

A finite-volume method is used to discretise the equations, and in this case allows curvilinear co-ordinates in order to fit a grid to complex natural river boundaries. The interpolation scheme used is hybrid-upwind where upwind-differences are used in high convection areas (Peclet number > 2) and central-differences where diffusion dominates (Peclet number < 2). Although this scheme can suffer from numerical diffusion, it is very stable. Since the aim is to investigate periodic aspects of the flow,
this is important in order to avoid the introduction of spurious oscillations in the solution which can occur with some higher-order numerical schemes. Coupling of the pressure and momentum equations is achieved using SIMPLEST, a variation on the SIMPLE algorithm of Pantankar and Spalding (1972). A steady-state solution was obtained using a modified two-equation \( \tilde{k}-\varepsilon \) turbulence model (Bradbrook et al., 1998), and this formed the initial condition for an unsteady simulation with the LES model, and a fully implicit temporal solution.

2.3 Boundary Conditions

At the bed and banks the standard 'law-of-the-wall' is used:

\[
\frac{u}{u_*} = \frac{1}{\kappa} \ln \left( \frac{y}{y_*} \right)
\]

where \( u_* \) is the shear velocity = \( \sqrt{\nu K y} \), \( \kappa \) is the Von Karman constant (= 0.4) and \( y_* \) is the height of zero velocity, which depends on the bed roughness:

\[
y_* = \frac{v}{9u_*} \quad \text{for smooth boundaries in the laboratory experiment and}
\]

\[
y_* = \frac{1}{30} D_{50} \quad \text{for rough boundaries in the natural confluence}
\]

At the upstream cross-section, a fully developed flow profile, calculated by a separate model, is used for the velocity component parallel to the banks at this cross-section. No fluctuations were superimposed on the incoming velocities, as the aim was to investigate any inherent instability in the flow dynamics at the confluence, rather than either to investigate how the confluence filters incoming instabilities, or to represent natural conditions faithfully.

3 Periodic Flow in a Parallel Confluence

3.1 Numerical Simulation

The geometry of the parallel confluence is shown in Figure 1 and is based upon Best and Roy (1991). The two tributaries are parallel and join at the end of the splitter plate. One tributary is half the depth of the other, and the post-confluence channel is the same depth as the deepest tributary (0.1m) with a width equal to the combined width of the two tributaries and the splitter plate. A grid of \( 70 \times 44 \times 25 \) cells was used (following the grid dependence studies reported in Bradbrook et al., 1998); all walls were smooth (equation 9); and a porosity-based free-surface model was employed as described in Bradbrook et al. (1998). The average upstream velocity was 0.3ms\(^{-1}\) in each tributary, which gives an average Reynolds number in the post-confluence channel of 13,500, comparable to that in the experiment of Best and Roy (1991). A time step of 0.1s was selected, which gives an average Courant number of 1.6 (acceptable for a fully implicit solution scheme). A LES was also conducted with a time-step of 0.04s for a short period of time (20s). However, there was no statistical difference between the predictions with a time-step of 0.1s and a time-step of 0.04s over this period. Simulation with a time-step of 0.1s was therefore accepted as the most computationally efficient. To investigate mixing patterns between water from the two tributaries, solution was also undertaken for a numerical tracer subject to advection and turbulent diffusion by model predictions. The tracer concentration was set to 0.0 at the entrance of the shallow channel and 1.0 in the deep channel.

![Sampling point for Figure 2](image)

Fig. 1. Geometry for simulation of a parallel confluence. The channel was 0.30m wide, the step was 0.05m high and the water depth in the main channel was 0.10m. Location of sample point for Figure 2 and cross-sections for Figures 4 and 6 are indicated.

3.2 Nature of periodic flow

Figure 2 shows a time-series of relative concentration of the numerical tracer at a point close to the side of the shallower channel, 5.8 step heights downstream and 1.2 step heights from the bed. This shows the model is predicting upwelling of fluid from the deeper channel along the wall of the shallower channel, and that this is periodic. Fourier analysis indicates dominant time periods of 26s and 5s. Visual rendition of contours of relative concentration near the bed (Figure 3) suggests the shorter periodicity is related to instabilities that develop at the base of the shear layer between the two flows.

![Time series of relative concentration at a point 5.8 step heights downstream and 1.2 step heights from the bed in Figure 1.](image)

Fig. 2. Time series of relative concentration at a point 5.8 step heights downstream and 1.2 step heights from the bed in Figure 1. Mean concentration = 0.059, Standard deviation = 0.004, Maximum concentration = 0.314.
A recirculation zone exists below the step, and a strong lateral pressure gradient towards this zone (Bradbrook et al., 1998) entrains water from the deeper channel and causes the shear layer to bulge towards the wall of the shallower channel (1s; Figure 3.1). Further entrainment causes this ‘bulge’ to extend downstream by a small amount at the next time-step (2s; Figure 3.2). The ‘bulge’ becomes unstable (3s; Figure 3.3), and divides, with one ‘bulge’ convected downstream and another remaining attached to the recirculation zone (4s; Figure 3.4), which is now shorter. At the next time-step (5s; Figure 3.5), the process begins again, with a secondary ‘bulge’ shed at 10s (Figure 3.10).

The upwelling events shown in Figure 2 are linked with shear layer instabilities via streamwise eddies (Figure 4). At 2s, the ‘bulge’ in the shear layer has reached cross-section \( x/h = 8 \) (Figure 3.2). This is associated with strong near-bed cross-stream velocities towards the wall of the shallower channel at \( x/h = 8 \) in Figure 4a. Upon reaching the wall, the water is forced to rise, leading to strong upward velocities at the wall as part of a streamwise eddy. The mixing layer instability is convected downstream, and at 3s into this cycle the strongest cross-stream flows occur at \( x/h = 10 \) (Figure 4b). An eddy is beginning to form in front of this at \( x/h = 12 \). At \( x/h = 8 \), the eddy is pushed closer to the bed, with downward velocities occurring near the wall. After 4s (Figure 4c), the eddy at \( x/h = 8 \) has been destroyed by strong downwards flow, which brings tributary water to the bed and creates a ‘trough’ of low concentration between the two ‘bulges’ (Figure 3.4). The near-bed concentrations are now highest (Figure 3.4), and the eddy strongest (Figure 4c), at cross-section \( x/h = 12 \). After 5s, the ‘bulge’ and eddy are passing \( x/h = 14 \). Further upstream, a coherent eddy is no longer apparent, although the beginnings of the next eddy can be seen at \( x/h = 8 \) (Figure 4d).

This simulation shows that instability is inherent in the flow dynamics of this simple confluence even without turbulent fluctuations in the upstream velocity field. The style of mixing-layer instability and upwelling events interpreted from these numerical simulations agrees well with observations from laboratory experiments for similar confluences (Best and Roy, 1991; Biron et al., 1996). Laboratory visualisation shows the formation of small Kelvin-Helmholtz vortices in the shear layer between the two flows, but while some of these are convected quickly downstream, coalescence of a number of slower vortices leads to a larger feature, seen as a ‘bulge’ of dye. Vortices within this feature are distorted more readily towards the low pressure zone in the lee of the step and lead to upwelling of dye further downstream near the wall of the shallower channel. It appears that the pattern of fluid movement, and the periodicity associated with these larger features, is predicted by the numerical simulation. The generation of Kelvin-Helmholtz vortices at smaller scales, by shear between the two flows, is not simulated with the grid dimensions reported in this study.

3.3 Comparison of model output and empirical data

The reliability of the interpretation of the nature of periodic flow described above will depend on the confidence we can place in the Large Eddy Simulation model. Therefore comparison of the predictions with empirical data is required, both in terms of the mean flow predictions derived from time-series generated by the Large Eddy Simulation, and the periodic nature of these time-series. Measured values for comparison with model predictions were obtained for a confluence with similar geometry to that shown in Figure 1, but with a depth of 0.15m. An Acoustic Doppler Velocimeter (ADV) (Kraus et al., 1994) was used to obtain time-series of three-dimensional velocities at a number of points. Details of the experimental design are as in Bradbrook et al. (1998).

3.4 Mean parameters

Figure 5 shows a comparison of the mean flow predictions with the LES simulation (averaged over a period of 50s) for points at a cross-section 3 step heights downstream (just downstream of
the separation zone), with predictions obtained using a $k$-$\varepsilon$ RNG turbulence model (Bradbrook et al., 1998), and with those obtained using ADV measurements (averaged over 30s). For the downstream velocity (Figure 5a), the correlation with the measured velocity is high (0.98), but the magnitude of the lowest velocities, which occur near the bed and the wall, is underpredicted by the LES simulation compared to both the measured velocities and the $k$-$\varepsilon$ RNG predictions. This may be a result of the use of the standard law-of-the-wall, which is less appropriate near reattachment points than the non-equilibrium version used in conjunction with the $k$-$\varepsilon$ RNG turbulence model (Bradbrook et al., 1998). The predictions of mean cross-stream and vertical velocities are very similar to those of the $k$-$\varepsilon$ RNG turbulence model, although these tend to underestimate the strength of these secondary velocities compared to those measured using the ADV (Figure 5b,c). The values of turbulent kinetic energy (Figure 5d) calculated from the velocity time-series generated by the Large Eddy Simulation compare better with those generated from the ADV time-series (correlation of 0.86) than those predicted by the $k$-$\varepsilon$ RNG model (correlation of 0.54), although the magnitude is generally lower than that measured.

Figure 6 shows vectors of mean secondary velocities calculated from the LES time series at the cross-section 3 step heights downstream from the confluence. A small secondary circulation cell can be identified with upwelling flow at the wall and secondary vectors in the rest of the flow orientated towards this corner. This pattern is similar to the steady-state predictions with the $k$-$\varepsilon$ RNG model, but here it is an artefact of the averaging process. This cell is actually an intermittent feature similar to that illustrated in Figure 4.

3.5 Periodicities

For comparison of periodicities predicted by the LES model, 5 minute velocity time-series at 25Hz were obtained using the ADV in the laboratory confluence at the 10 points shown in Figure 7. Time-series of 1024 points at 10Hz (102.4s) were extracted for equivalent points from the LES results. To determine the dominant frequencies present in these two sets of time-series, power spectra were calculated using Fast Fourier Transforms. The power spectra for downstream velocity at Point 7 are shown in Figure 8. Exact co-incidence of the spectra would not be expected, particularly given the higher frequency of the ADV time-series. The steeper ‘roll-off’ of the LES spectrum indicates that most of the predicted variance is concentrated at lower frequencies, whereas the ADV signal contains much more variance at higher frequencies. However the highest peaks in the ADV spectrum do occur at the lower frequencies and the following analysis attempts to identify correspondence between such dominant frequencies in the two series.

For each spectrum the 3 largest distinct peaks were identified (as in Figure 8), and correspondence between these dominant frequencies in predicted and measured time-series were noted. These are given as periodicities to the nearest second in Table 1. At the lowest frequencies, the resolution of the power spectra is low and matching adjacent frequency bands were noted and are given in Table 1 as a broader range of periodicities. Where a direct match did not occur, but a dominant peak in one time-
series was matched by a peak at twice that frequency in the other time series, these are also noted as matches in the 1st harmonic, since this may be an artefact of the different time-series frequencies. For example, at point 1, the vertical velocity fluctuations showed a peak at 2s in the ADV series and a harmonic at 4s in the LES series. Out of the 30 time-series, there were 18 with direct matches of dominant frequencies, and apart from 4, the rest showed matches in the 1st harmonic (Table 1). This suggests that LES is able to recreate some of the periodicities associated with the physical processes observed in confluences of this kind. Periodicity of around 5 seconds is common, and relates to the eddy shedding from the shear layer described above. Longer period frequencies were identified at points 7 and 8 which lie near the end of the splitter plate where the shear layer is almost vertical, and could relate to lateral motion of the shear layer at this point. Where harmonics are recorded, it is usually the case that the periodicity in the ADV time-series is shorter than that in the LES time-series and, in general, a peak of 2-2.5 seconds in the ADV time-series was common. This probably reflects other turbulent structures which the Large Eddy Simulation is unable to reproduce.

Thus, it appears that the LES model is able to reproduce some, but not all of the periodic flow features in this simple confluence geometry. Features similar to those described above have been observed at natural confluences where contrasts in suspended sediment concentrations between two tributaries vis-

ally delineate the mixing layer, for example at the confluence of the Rio Negro and the Rio Solimoes in the Amazon basin (Sternberg, 1975), and at the confluence of the Bayonne and Berthier Rivers (Biron et al., 1993). The application of the LES model to the Bayonne-Berthier confluence will now be discussed in order to assess the potential of this technique to explore the controls on and nature of these periodic flow features in a natural confluence.

4 Periodic flow in a natural river confluence

4.1 Introduction and method

As in the simple confluence above, the confluence of the Bayonne and Berthier rivers, Québec, Canada, exhibits bed discordance between the two tributaries (Figure 9; Biron et al. 1993). Velocity measurements by Biron et al. (1993) indicated the presence of three distinct time-scales of turbulent motion: (i) longer term (> 80secs) shifts in the position of the entire shear layer within the junction; (ii) the passage of discrete large-scale (Kelvin-Helmholtz) eddies (3-15secs); and (iii) shorter term, higher magnitude fluctuations associated with coherent motion within these large-scale eddies (0.5–1sec).

The hydraulic conditions for numerical simulation of this confluence are shown in Table 2. A grid of 82 x 56 x 12 grid cells, covering typical dimensions of 30m x 20m x 0.75m was chosen on the basis of grid dependence tests for a steady-state simulation using the k-ε RNG turbulence model. Results from this simulation compared favourably with field measurements of the mean downstream and cross-stream mean velocity components (correlation coefficients of 0.71 and 0.83 respectively). These results were then used as initial conditions for the Large Eddy Simulation with a time-step of 1 second. This gives an average Courant number of around 1. A shorter simulation (2 seconds) was also conducted using a time-step of 0.1 seconds to check that no higher frequency changes were predicted with a shorter time-step. As for the laboratory confluence, the water at the entrance to each tributary was labelled with a numerical tracer.
of concentration 1.0 in the true-left tributary (Bayonne) and 0.0 in the true-right tributary (Berthier).

Table 2 Hydraulic conditions for Bayonne-Berthier confluence, 2nd October.

<table>
<thead>
<tr>
<th></th>
<th>Average Width (m)</th>
<th>Average Depth (m)</th>
<th>Average Velocity (m/s)</th>
<th>Discharge (m^3/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bayonne</td>
<td>6.0</td>
<td>0.87</td>
<td>0.14</td>
<td>0.73</td>
</tr>
<tr>
<td>Berthier</td>
<td>7.75</td>
<td>0.45</td>
<td>0.26</td>
<td>1.01</td>
</tr>
<tr>
<td>Ratio (Berthier/Bayonne)</td>
<td>1.29</td>
<td>0.32</td>
<td>1.86</td>
<td>1.38</td>
</tr>
</tbody>
</table>

4.2 Results

Contours of relative concentration of the numerical tracer were obtained for 5 cross-sections at 20 second intervals (Figure 10).

Very little fluctuation occurs at the first cross-section at the apex. At the second cross-section, however, a clear bulge has formed with the lower half of the mixing layer distorted strongly towards the tributary side. Over the next 60 seconds the bulge at this cross-section declines as it is convected downstream, being evident at \( x = 15m \) at \( T = 20s \), \( x = 7m \) at \( T = 40s \) and \( x = 0m \) at \( T = 60s \). The passage of this zone of enhanced mixing layer distortion through the confluence is illustrated in ploranform in Figure 11, which shows the contour of relative concentration = 0.5 at the bed and at the surface. At \( T = 0s \), the maximum distortion is at \( x = 15m \). As this zone moves downstream, it becomes wider as water at the bed moves towards the true-right and the mixing layer at the surface moves towards the true-left bank.

Fig. 10. Concentration at 20 second intervals for 5 cross-sections at the Bayonne-Berthier (a) \( x = 26.5m \), (b) \( x = 20m \), (c) \( x = 26.5m \), (d) \( x = 15m \), and (e) \( x = 0m \). (See Figures 9 and 11 for location of cross-sections). View is upstream with vertical exaggeration \( \times 5 \). Greyscale is from dark (concentration = 0.0) to light (concentration of 1.0).

Fig. 11. Relative concentration contour of 0.5 at bed and surface of the Bayonne-Berthier confluence for 4 time periods.

The associated secondary flow vector patterns at the five cross-sections are shown in Figure 12. The differences in these patterns are more subtle than those in Figure 4. At \( x = 26.5m \) (Figure 12a), the zone of downwelling over the avalanche face at the first time-step \( (T = 0s) \) is slightly larger than at subsequent times. This creates some flow towards the true-left at the base of this avalanche face, and a weak clockwise (viewed downstream) circulation cell can be identified in the deeper channel. At \( T = 20s \), such a cell is not clear as there is no lateral component to the upwelling at the base of the main channel. The patterns are very similar to this at \( T = 40s \) and \( T = 60s \).

At \( x = 20m \) (Figure 12b), there is a zone of upwelling (marked ‘A’) towards the true-right in the centre of the channel near the bed at \( T = 0s \) which leads to water from the deeper channel penetrating underneath tributary water (Figure 10b). Above this zone, downwelling occurs at approximately the position of the vertical portion of the mixing layer (Figure 10b, \( T = 0s \)). At \( T = 20s \), the upwelling near the bed towards the true-right has weakened, explaining the reduction in the size of the ‘bulge’ in Figure 10b (at \( T = 20s \)). The central downwelling is stronger and includes a lateral component towards the true-left as part of a clockwise (looking downstream) rotation cell in the true-left half of the channel. This suppresses the mixing layer distortion at the bed, and the associated surface flow towards the centre of the channel repositions the surface mixing layer. The strength of central downwelling is reduced at \( T = 40s \) and is associated more with the flow of water from the tributary, and by \( T = 60s \) no coherent rotation is visible on the true-left.

At \( x = 15m \) (Figure 12c), the flow on the true-right side exhibits a strong anti-clockwise (looking downstream) rotation at all time-periods. At \( T = 0s \), the downwelling in the centre of the channel has a lateral component towards the true-right throughout the flow depth at \( T = 0s \), with an angle similar to that of the mixing layer (Figure 10c). The flow in the true-left half of the channel is predominantly towards the centre of the channel. At \( T = 20s \) in Figure 11c, the downwelling is stronger but it is more vertical in the upper half of the flow, reflecting the shape of the mixing layer in Figure 10c (\( T = 20s \)). The strength of flow in the true-left half of the channel towards the centre has increased at the surface, but decreased near the bed. These trends continue to \( T = 40s \) and \( T = 60s \), and are reflected in the degree of mixing layer distortion (Figures 11 and 12).

At \( x = 7m \) (Figure 12d), flow is predominantly towards the true-right at all time periods, and changes in the lateral component
are difficult to detect. At $T = 0\text{s}$, vertical velocities are generally small, except for some upwelling near the bed in the centre of the channel and near the true-left bank. At $T = 20\text{s}$, the central zone of upwelling has expanded to about mid-depth and downwelling has been initiated at mid-depth over the deepest part of the channel. These flow patterns will confine advection of water from the deeper channel towards the true-right to an area close to the bed, thus distorting the mixing layer as shown in Figure 10d. By $T = 40\text{s}$, the central zone of upwelling extends almost to the surface and the downwelling has increased in strength, and extends throughout most of the flow depth (Figure 12d, $T = 40\text{s}$). This accentuates the mixing layer distortion (Figure 10d). The pattern at $T = 60\text{s}$ is very similar to this. Changes at the furthest downstream cross-section (Figure 12e) are difficult to detect. This may suggest that the increasing mixing layer distortion shown in Figure 10e is related to advection from upstream rather than active distortion at this cross-section.

These LES results show how the degree of penetration of a wedge of water from the deeper main channel underneath water from the shallower relates to changes in the velocity patterns in the vicinity of the mixing layer. The passage of the ‘bulge’ of main channel water downstream is matched by enhanced lateral flow towards the true-right, particularly near the bed (e.g. $x = 15\text{m}$ at $T = 0\text{s}$, and $x = 7\text{m}$ at $T = 20\text{s}$). This is followed by an increase in the strength of downwelling in the centre of the channel, which suppresses mixing layer distortion over most of the flow depth (e.g. $x = 26.5\text{m}$ at $T = 0\text{s}$, $x = 20\text{m}$ at $T = 20\text{s}$, $x = 15\text{m}$ at $T = 40\text{s}$, and $x = 7\text{m}$ at $T = 60\text{s}$).

The fluctuation described above is related to a period of enhanced mixing layer distortion, resulting in migration of the mixing layer at the bed and at the surface in opposite directions (Figure 11). The time period of one of these events is greater than 1 minute in this simulation of the Bayonne-Berthier confluence and may therefore relate to the longer-term mixing layer migration observed by Biron et al. (1993). The form of this event is not dissimilar to that predicted in the laboratory confluence. Both are characterised by enhanced lateral velocities near the bed which promote mixing layer distortion and greater advection of water from the deeper channel below water from the shallower channel to form a ‘bulge’ in the mixing layer. This is followed by strong downwelling that suppresses the mixing layer distortion and lateral velocities. Although the degree of distortion, and the time-scale of this process are very different, the similarity of form suggests that the generating mechanisms in the model may also be similar in these two situations and are related to the strong lateral pressure gradient generated by the bed discordance (Bradbrook et al., 1998).

5 Conclusions

This paper has shown the potential of Large Eddy Simulation to investigate periodic aspects of flow at river channel confluences. Without any turbulent fluctuations in the incoming flow, periodic instabilities developed in simulations of both a laboratory-style confluence and a natural confluence, each of which showed pronounced bed discordance. The time scale of the simulated periodicity generally matches with the longer period frequency scales present in measured velocity series. The instabilities simulated are related to changes in the local pressure gradient. The smaller scale Kelvin-Helmholtz eddies which develop in the mixing interface due to shear between the two flows are not reproduced. Since the scale of eddy simulated by LES is dependent on the grid size used, simulation of such features may require a much smaller grid at the shear interface, which may prove impractical for simulation of natural confluences. The initiation of these features might also require imposition of incoming flow instabilities. Further work is in progress to establish which of these factors is most critical for the successful simulation of Kelvin-Helmholtz instabilities.

The scale of the larger simulated eddies is similar to the mean secondary circulation and such circulation is shown as a time-averaged map in Figure 6. This cautions against the continued emphasis in the interpretation of field and laboratory measurements on mean parameters, and explanations based on mean controls. This emphasis has been a necessary reflection of instrumentation limitations: instantaneous three-dimensional measurements at a three-dimensional array of points in the flow is as yet impracticable. Numerical modelling therefore provides an important methodology with which to begin to address this issue and reveals that the appearance of a persistent secondary circulation may be an artefact of averaging intermittent flow structures.

Numerical modelling also has the potential to address the implications of such features for the transport of solutes. Empirical evidence from a natural confluence has illustrated that the passage of large scale coherent structures through the mixing layer can result in high magnitude temporal variation of tracer concentration (Gaudet, 1995). A model based on Reynolds averaging which is used to predict mean concentrations of a pollutant, or mean temperatures, at a point downstream of a junction may, for example, suggest that levels are less than some critical threshold, but this threshold could still be breached by intermittent processes leading to higher-than-average concentrations. The results shown in Figure 2 suggest that Large Eddy Simulation could be used to indicate the range of concentration that might occur at different points in the flow. A convoluted mixing layer also provides a greater surface area for solute diffusion (Gaudet and Roy, 1995).

The variation in flow direction and strength in a dynamic shear layer has implications for shear stress on the bed, and therefore on bed load transport, sediment reworking (Mosley and Schumm, 1977), and related patterns of erosion and deposition at confluences. The mixing layer instabilities described here are of particular importance wherever a shear layer or recirculation exists, such as at embayments (Kimura and Hosoda, 1997), meanders (Page and Nanson, 1982), groynes (Tingsanchali and Maheswara, 1990) and other engineering structures, and side discharges into the river (Rodi et al., 1981). The results in this paper show that, although these shear layers will have a time-averaged position, consideration of the periodic nature of the
associated processes is both possible, and critical for understanding these time-dependent phenomena.

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