Large Eddy Simulation of Sediment Transport and Hydrodynamics at River Bifurcations using a Highly Scalable Spectral Element based CFD Solver

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Bulle-Effect: the non-linear distribution of near bed sediment between the lateral and the main channel of a steam/river diversion.

Bifurcation: when a river/stream splits into two. e.g. the Pannerdensche Kop bifurcation on Rhine River, Netherlands. (image courtesy :http://www.citg.tudelft.nl/uploads/RTEmagicC_Rivers_Rijn_by_Gelderlander.jpg)

Diversion: A special type of bifurcation where the main-channel continues along the original path. e.g. Mississippi River, West Bay diversion. (image courtesy http://media.nola.com/hurricane_impact/photo/9034828-large.jpg)

\[
\frac{S_{\text{side}}}{S_{\text{main}}} = a \left( \frac{Q_{\text{side}}}{Q_{\text{main}}} \right)^b
\]

where \(a\) and \(b\) are constants. If the distribution of bedload sediment between the two channels was linear, then \(b = 1\), thus making the sediment distribution non-linear.

Figure 2, plotted using data from Bulle's experiments, shows the division of water and bedload sediment at diversions of different angles for experiments conducted with \(Q = 0.005 \text{ m}^3 \text{s}^{-1}\) (where \(Q = Q_{\text{main}} + Q_{\text{side}}\)). It is evident from the plot that sediment discharge \(S_{\text{side}}\) entering the diverted channel is disproportionately higher than that remaining in the main channel \(S_{\text{main}}\), even for cases where \(Q_{\text{main}} > Q_{\text{side}}\). It can also be observed that the amount of bedload entering the lateral-channel varies with increase in diversion-angle, with the maximum amount of sediment continuing in the main channel for diversion angle of 120 degrees. Bulle has also conducted experiments for different flow partitioning and channel layouts, which are further discussed and compared with simulations results in the following sections. Eventhough the exact mechanism behind the Bulle-Effect is not fully understood, Bulle himself and some studies after his have hinted towards presence of strong secondary currents that sweep the near-bed sediment into the diversion channel [11, 9].
Bulle-Effect: what does the experiments say?

- Data reproduced from Bulle’s experiments from 1926.
- All the cases had a constant water discharge of $Q = 5 \text{ l/sec} = 0.005 \text{ m}^3\text{s}^{-1}$
- Experiments were done for five different diversion angles (30, 60, 90, 120 and 150 degree).
- Experiments were also done for different water discharge ratios.

\[
\frac{S_{\text{side}}}{S_{\text{main}}} = a \left( \frac{Q_{\text{side}}}{Q_{\text{main}}} \right)^b
\]

Bulle found that the amount of bedload sediment entering the diversion channel ($S_{\text{side}}$) was disproportionately higher with respect to the water discharge. This highly non-linear distribution of bedload sediment discharge, between the main and diverted channel at a diversion is often referred to as the Bulle-Effect \[10]. The relationship between the ratio of bedload discharge moving into the two channels $S_{\text{side}}/S_{\text{main}}$, and the ratio of the corresponding water discharge $Q_{\text{side}}/Q_{\text{main}}$ can be defined using the equation:

\[
\frac{S_{\text{side}}}{S_{\text{main}}} = a \left( \frac{Q_{\text{side}}}{Q_{\text{main}}} \right)^b
\]

where $a$ and $b$ are constants. If the distribution of bedload sediment between the two channels was linear, then $b = 1$, thus making the sediment distribution non-linear.

Figure 2, plotted using data from Bulle’s experiments, shows the division of water and bedload sediment at diversions of different angles for experiments conducted with $Q = 0.005 \text{ m}^3\text{s}^{-1}$ (where $Q = Q_{\text{main}} + Q_{\text{side}}$). It is evident from the plot that sediment discharge ($S_{\text{side}}$) entering the diverted channel is disproportionately higher than that remaining in the main channel ($S_{\text{main}}$), even for cases where $Q_{\text{main}} > Q_{\text{side}}$. It can also be observed that the amount of bedload entering the lateral-channel varies with increase in diversion-angle, with the maximum amount of sediment continuing in the main channel for diversion angle of 120 degrees. Bulle has also conducted experiments for different flow partitioning and channel layouts, which are further discussed and compared with simulations results in the following sections. Eventhough the exact mechanism behind the Bulle-Effect is not fully understood, Bulle himself and some studies after his have hinted towards presence of strong secondary currents that sweep the near-bed sediment into the diversion channel \[11, 9\].

In his experiments, Bulle also observed recirculation zones (see fig. 1); one
Bulle-Effect: what does the experiments say?

- 20 years later Mario Cristani extended Bulle’s experiments, and found that the data matched the trend predicted by Bulle.
- Albert Dancy (1946) found the dependence of the phenomenon on size of sediment (particle fall velocity).
- Experiments over the years, have further confirmed the phenomena, but a clear idea about the mechanism is still elusive.
Why is Bulle-Effect important?

The knowledge gained from understanding the phenomena will help **Save the Deltas** around the world.

- Only way the vulnerable deltas can be saved is through creating **diversions** to build land.
- Also the structure of the river in a delta is highly dendritic and full of bifurcations/natural diversions.

Profiling risk and sustainability in coastal deltas of the world
Z. D. Teessler et al.
Science 349, 638 (2015);
DOI: 10.1126/science.aab3574

Building land with a rising sea
Stijn Temmerman and Matthew L. Kirwan
Science 349, 588 (2015);
DOI: 10.1126/science.aac8312

Image source: http://www.mississippiriverdelta.org/
An example where delta rebuilding is already on the drawing board

The Mississippi River Delta

The knowledge gained from understanding the mechanism behind *Bulle-Effect* will help design these diversions for efficiently.

Source: http://www.mississippiriverdelta.org/

(Meselhe et al. 2012)
Objectives of the study

- Conduct high quality **Large Eddy Simulations** of the flow and sediment transport at the scale of Bulle’s experiments. The simulations will resolve all the important features of the flow, thus simulate the hydrodynamics accurately. And the Lagrangian particle model will help capture the response of the sediment to the complex flow field accurately.

- In order to understand the effect of Reynolds number of the flow on Bulle-Effect, simulations were conducted for a range of bulk Reynolds numbers (Re), from 10 to 25,000, for diversion angle of 90 degrees.

- For Reynolds numbers in the range 10-7000, the resolution of the mesh is good-enough for Direct Numerical Simulation (DNS).

- Most of the simulations were conducted for the discharge ratio $Q_{\text{side}}:Q_{\text{main}}$ of 50:50, though in order to study the effect of different discharge ratios on Bulle-Effect, simulations with five different discharge ratios (15:85, 35:65, 50:50, 65:35, 85:15) were conducted for $Re = 7000, 25000$.

- For $Re = 25000$, simulations were also conducted for diversion angles of 30, 60, 120 and 150 degrees.
Nek5000: the highly scalable incompressible Navier-Stokes solver

- Simulations were conducted using Nek5000, which is an open-source spectral element based incompressible Navier-Stokes solver. (Fischer et al., https://nek5000.mcs.anl.gov/)

- The spectral element method (SEM) combines the accuracy of spectral methods with the flexibility of local approaches, like Finite Element Methods.

- Nek5000 uses high-order Legendre polynomials as the basis function, along with a Gauss-Lobatto-Legendre grid.

- Using high-order polynomial eliminates dispersion errors, which is very important for large-scale and long-term turbulence calculations. (Kreiss & Oliger 72, Gottlieb et al. 2007)

- Time-stepping is done using the combination of 3rd order Backward Differencing (BDF) and Extrapolation (for the non-linear terms).

- In case the dissipative scales are not resolved at higher Reynolds number (LES), a local element based explicit cutoff filter (a spectral filter) in the wave number space is used to remove energy from the highest wavenumbers (Fischer and Mullen, 2001).
Parallel scalability of Nek5000

- Nek5000 used MPI for parallelization.

- Nek5000 has a history of scaling efficiently on different HPC platforms throughout the world.

- Recently it has shown strong scaling up to a million MPI ranks on MIRA (at ALCF), with parallel efficiency of 60 percent. The tested problem had about 2 billion computational points, showing strong scaling for granularity of ~ 2000 points/processors.

- Nek’s very efficient parallel scalability is due to, a scalable ‘gather-scatter’ kernel, that helps reduce the communication cost during the simulation, especially for the global communication needed in the pressure (Poisson) solver.

- Scalability will depend on the architecture and hard-ware of the machine.
Configuraiton of Current Problem

- Dimensions of the simulations are same as Bulle’s experiments.
- The 90-degree mesh has around 130,000 elements, and combined with the 12 collocation points for each direction at each element, in total about 224 million computational points. The mesh for the 30-degree case has around 242.74 million grid points.
- Part of the inlet channel is used for recirculating the flow, in order to have a fully-formed turbulent flow.
- The flow-split at the bifurcation was imposed using a using a fast implicit enforcement of the flow division. This helped in accurate yet faster convergence of the simulation.
- Sediment particles were modeled using a semi-implicit Lagrangian particle tracking algorithm developed for the current study. (the algorithm has been presented during the poster session here.)

For the points closest to the walls, $z^+ = 0.058$ and $y^+ = 0.65$
Why Blue Waters?

- Scale of the simulations are same as Bulle’s experiments, which makes them one of the few simulations in the field of River Mechanics that has conducted high-quality LES at the scale of experiments.

- The number of **computational points is in the range of 224 million to 242.74 million**, along with 120,000 particles.

- Each simulations were run long enough to reach a statistical steady state, which can range from 90 to 150 convective time units depending on the flow-split. And then sediment particles were added to the domain, which took around 40-50 time units to move out from the main channel. So **130 -200 convective time-units**.

- The Re = 25000 cases takes approximately 256 node hours for 1 convective time units, **which means it can take up to 51200 node hours for a complete simulation** … this would not have been possible without a petascale system which can provide sustained performance = Blue Waters.
Performance of Nek5000 on Blue Waters

- Parallel scalability on Blue Waters, was tested for the target problem using a case with 224.136 million grid points
- We always use XE nodes, with 32 processors on each node.
- Nek5000 was found to scale strongly up to 32768 mpi ranks, with linear speedup up to 4096 mpi ranks and relatively efficient scaling up to 16384 mpi ranks (40%).
- Thus on Blue Waters, Nek5000 achieved strong scaling till n/P ~ 6840, though at n/P ~ 27360 the parallel efficiency has already reduced to 68.3 %. (n is number of grid points, and P is number of processors)
- Thus Nek5000, for the target problems scales efficiently, but not to the level achieved on MIRA.
- But Why ?
Performance of Nek5000 on Blue Waters compared to Mira (BGQ/ANL)

Nonoverlapping: \[ T(n, P) = \frac{T_a}{P} + T_c(n, P) + c_0 \]

Overlapping: \[ T(n, P) = \max[T_a/P, T_c(n, P)] + c_0 \]

For parallel efficiency of 100 %
\[ T_a/P \gg T_c(n, P) + c_0, \]

For reasonable parallel efficiency, that is 50 to 70 %
\[ T_a/P \geq T_c(n, P) + c_0. \]

So, we will try to come up with the theoretical values of n/P to which we can expect our problem to scale on Blue Waters.

Analysis inspired by Fischer et al., 2015, AIAA
Performance of Nek5000 on Blue Waters compared to Mira (BGQ/ANL)

Inter-processor communication costs

\[ t_c(m) = (\alpha + \beta m) \ t_a \]

- \( t_a \) estimated through matrix-matrix product performance for sets of noncached matrices of order 10. (typical for Nek5000).

- Internode latency and inverse bandwidth are parameters that tells us about the inter-node communication. These are estimated using Ping-Pong tests.
Performance of Nek5000 on Blue Waters compared to Mira (BGQ/ANL)

Ping-Pong test results, on Cray XK7 Titan, BGQ (ANL)

<table>
<thead>
<tr>
<th>Year</th>
<th>(t_a) (µs)</th>
<th>(\alpha t_a) (µs)</th>
<th>(\beta t_a) (µs/word)</th>
<th>(\alpha)</th>
<th>(\beta)</th>
<th>(m_2)</th>
<th>machine</th>
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<td>50</td>
<td>5960</td>
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<td>1.28</td>
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<tr>
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<td>Cray XK7</td>
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For Blue Waters: we found \(t_a = 0.00045\), averaged alpha = 4800, averaged betta = 4.91

For Blue Waters: we found \(t_a = 0.00045\), max alpha = 5530, max betta = 7.47
Performance of Nek5000 on Blue Waters compared to Mira (BGQ/ANL)

If the work the computer is doing primarily involves Jacobi Iterations:

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\[ \frac{T_{cJ}}{T_{aJ}} = \frac{6(\alpha + \beta(n/P)^{\frac{3}{2}})}{14n/P} \leq 1. \]

\[ \frac{T_{cCG}}{T_{aCG}} = \frac{6(\alpha + \beta(n/P)^{\frac{3}{2}}) + 4\alpha \log_2 P}{27n/P} \leq 1. \]

MIRA > n/P ~ 1700 , Blue Waters (avg) > n/P ~ 2500 , Blue Waters (max) > n/P ~ 3000

MIRA > n/P ~ 1700 , Blue Waters (avg) > n/P ~ 2500 , Blue Waters (max) > n/P ~ 3000

If the work the computer is doing primarily involves Jacobi preconditioned Conjugate-Gradient iterations (e.g. Pressure-Poisson):

MIRA > P = 10^9 n/P ~ 12000 , P = 10^9 n/P ~ 17000

MIRA > P = 10^9 n/P ~ 12000 , P = 10^9 n/P ~ 17000

MIRA + hardware support for MPI all reduce > P = 10^9 n/P ~ 2200

So, the difference maker was

“hardware supported MPI all reduce”

Blue Waters (avg) > n/P ~ P = 32768 n/P ~ 12500

Blue Waters (avg) > n/P ~ P = 32768 n/P ~ 12500

Blue Waters (max) > n/P ~ P = 32768 n/P ~ 14000

Blue Waters (max) > n/P ~ P = 32768 n/P ~ 14000
Results: 90-degree, Re=20000, 50:50 flow split

\[ \text{Re} = \frac{HU}{v} \]

H – channel height

U – Mean velocity

v - viscosity

Instantaneous Velocity Magnitude at different levels

(a) 1% height from the bottom

(b) 5% height from the bottom

(c) 50% height from the bottom

(d) 75% height from the bottom

In order to get a holistic picture of the flow, the time averaging was done for the profile at a height 1 percent from the bottom (a), 5 percent height (b), 50 percent height (c) and 75 percent height from the bottom (d).

We can also observe in Figure 4 that instantaneous streaks at the bottom of the main channel, especially near the bottom, the flow almost covers the whole width. In general, the flow continues in the main channel, with a more complete preferential flow path formed in the lateral channel. A relative wider flow at heights 50 percent and above, and the flow near the bottom moves into the lateral channel. This perfectly matches observations made by Bulle (1926).

The turbulent bursts from bottom and the sidewalls and this perfectly matches observations made by Bulle (1926). We can also observe that the turbulent bursts from bottom and the sidewalls and the rotating arrows show the clockwise rotation. Direction of the flow is into the plane, and after the bifurcation, the high velocity core has shifted towards the diversion. A vortex is formed in the lateral channel.

In Figure 5 for (a), the flow is coming out of the plane, for (c), the flow is going into the plane. Also, for (d) the flow is going into the plane. Also, (a) and (b) are in the main channel just after the bifurcation, and (c) and (d) are in the main channel. A more complete preferential flow path is formed in the lateral channel.

For (a), (b) and (c), the flow is coming out of the plane, for (c), and vice versa for (d). The time averaging was done for the profile at a height 1 percent from the bottom, 5 percent height, 50 percent height and 75 percent height from the bottom. The turbulent bursts from bottom and the sidewalls and the rotating arrows show the clockwise rotation. Direction of the flow is into the plane, and after the bifurcation, the high velocity core has shifted towards the diversion. A vortex is formed in the lateral channel. This perfectly matches observations made by Bulle (1926).
Results: 90-degree, Re=20000, 50:50 flow split

Time averaged Velocity Magnitude at different levels

(a) 1% height from the bottom
(b) 5% height from the bottom
(c) 50% height from the bottom
(d) 75% height from the bottom
Results: 90-degree, Re=20000, 50:50 flow split

- In the panels (a), (b), and (c), the general direction of the flow is out of the plane.
- For cross-section (d), it is into the plane.
Results: 90-degree, Re=20000, 50:50 flow split

Vorticity at different cross-sections.
(a) main-channel before bifurcation. (b, c) are from the two channel after the bifurcation.

Time-averaged velocity in the z-direction, in the two channels after the bifurcation. Top panel is for the main-channel.
Results: 90-degree, Re=20000, 50:50 flow split

- 11250 sediment particles of size 0.015 (actual size 1.05 mm, density 2.65 kgm$^{-3}$) were released at the same time, upstream of the bifurcation.
- In agreement with the experiments, a very small quantity of the total sediment (4.29%) entered the main-channel after the bifurcation.

- For that case, Bulle observed that for the experiment was run, 2.67 to 4.47 percent of bed sediment would be trapped in the recirculation zone near the left and (d) have been plotted using different scales.

The time averaging was done over 4 convective time unit for the profile at a height 1 percent height (d) 75 percent height from the bottom.
85% of the original flow is in the main channel.

Simulation with Bulk Reynolds number 300 (and 50:50 split)

The flow is laminar and steady.
Wall normal velocity at different cross-sections of the two branches
Regimes of the flow, changing with bulk Reynolds of the flow (Re)

The slice is taken at 70% depth of the flow
Conclusions and next-steps

- Flow and sediment transport was successfully modeled at an idealized 90-degree diversion for Re = 20000, and were able to capture the phenomena of Bulle-Effect.

- The driving mechanism for this highly non-linear phenomena has been identified, that is most of the flow near the bottom of the channel enters the lateral channel, taking along with it the near bed sediment.

- The flow patterns at other Re numbers were found to be similar, so it is expected that the phenomena will show up irrespective of Re.

- Currently simulations are being done to complete the sediment transport portion of the model for the range of cases mentioned before.

- Nek5000 was found to strongly scale up to 32768 mpi ranks on Blue Waters, though the efficiency reduces below 68.5 % after 8192 mpi ranks.

- Even though Nek5000’s parallel scalability performance on Blue Waters is relatively good, it seems compared to MIRA the issue is the lack of “a hardware supported MPI all reduce”. We need to find a way around ….
Acknowledgements and Collaboration with Blue Waters team

• Currently we use the PGI compiler, as we had been unable to compile with CRAY, so we are in communication with Dr. Tom Cortese to look in to the matter.

• We are also in communication with Dr. Rob Sineros to create an animation for one of the cases.