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Water Science and Engineering since 1967 at the University of Illinois at Urbana-Champaign

BLUE WATERS
SUSTAINED PETASCALE COMPUTING

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

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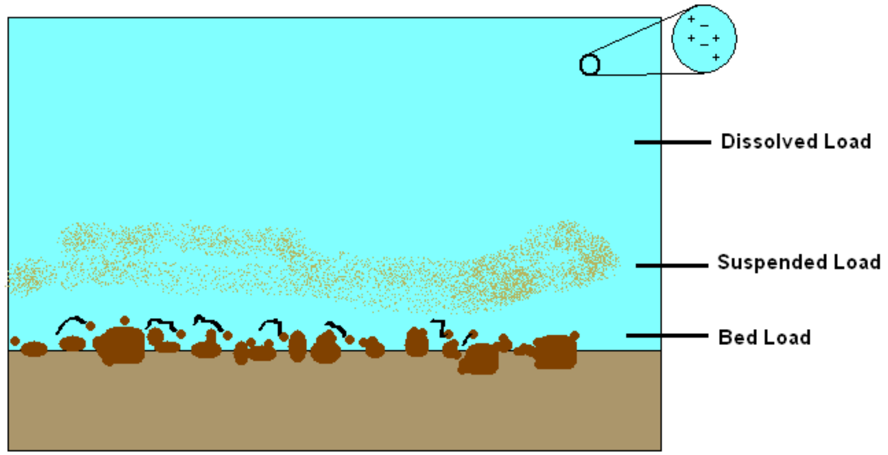
Bulle-Effect: the non-linear distribution of bed-load sediment between the lateral and the main channel of a steam/river diversion.

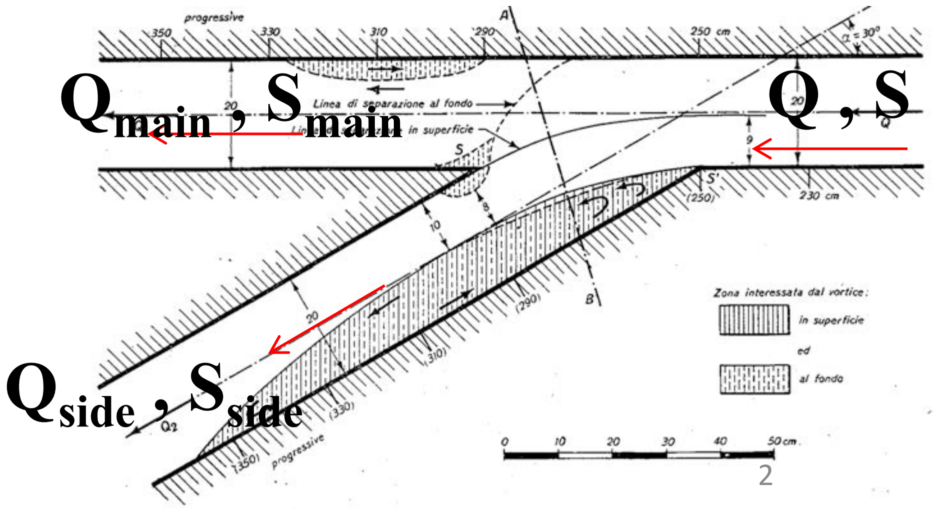
Bifurcation: when a river/stream splits into two. e.g. the Pannerdensche Kop bifurcation on Rhine River, Netherlands.

(image courtsey :http://www.citg.tudelft.nl/uploads/RTEmagicC_Rivers_Rijn_by_Gelderlander.jpg.jpg)



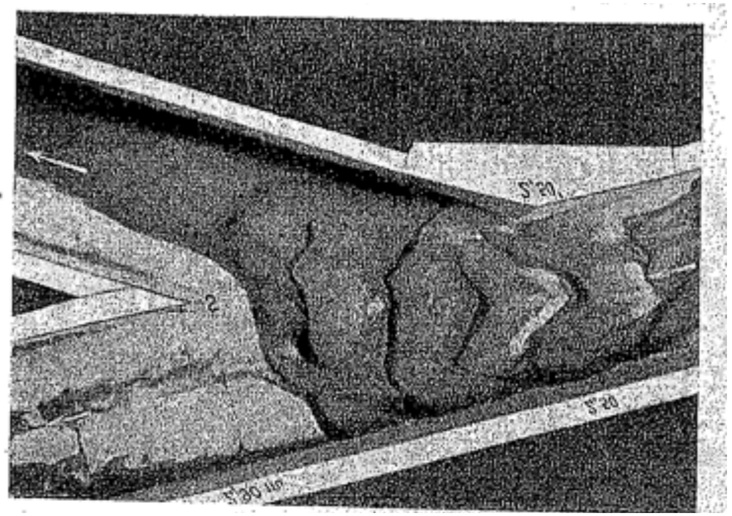
Diversion: A special type of bifurcation where the main-channel continues along the original path. e.g. Mississippi River, West Bay diversion.

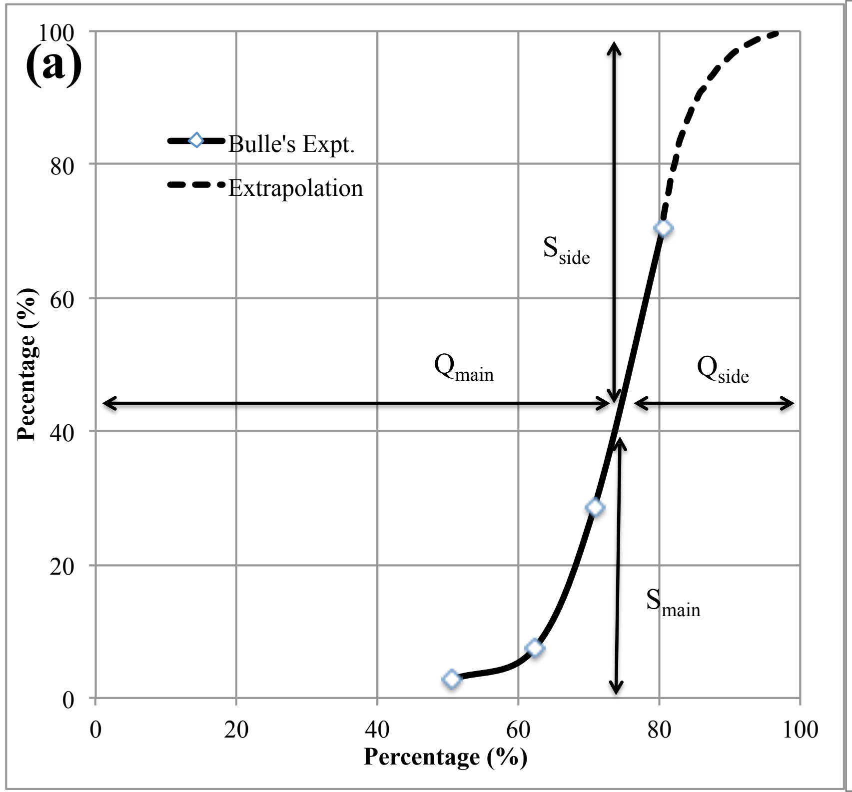
(image courtsey http://media.nola.com/hurricane_impact/photo/9034828-large.jpg)

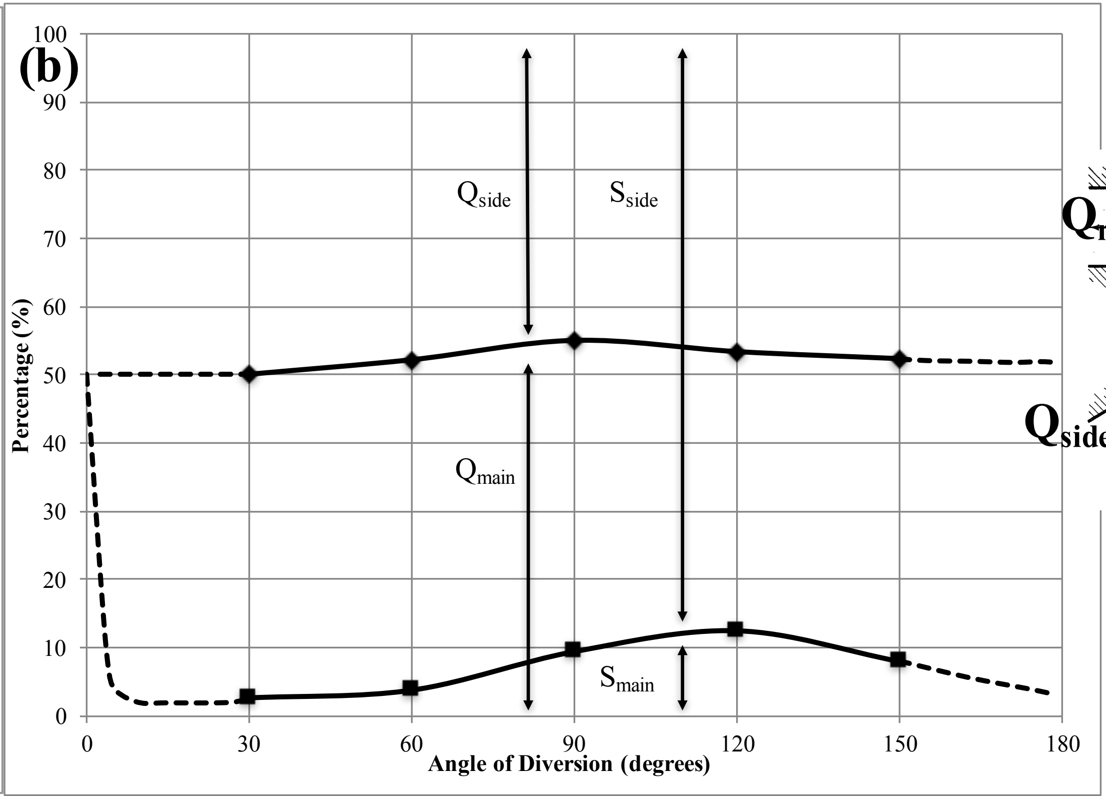


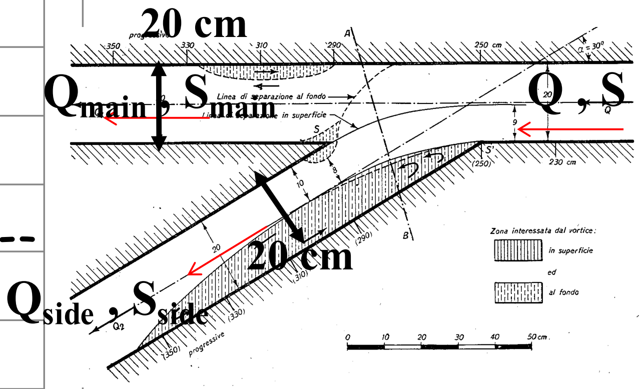
Bulle-Effect: first extensive set of experiments in 1926

- Data reproduced from Bulle's experiments from 1926.
- All the cases had a constant water discharge of Q = 5 l/sec = 0.005 m^3s^{-1}
- Experiments were done for five different diversion angles (30, 60, 90, 120 and 150 degree). Sediment of D_{50} < 1.2 mm.
- Sediment traveled as bedload.
- Experiments were also done for different water discharge ratios.





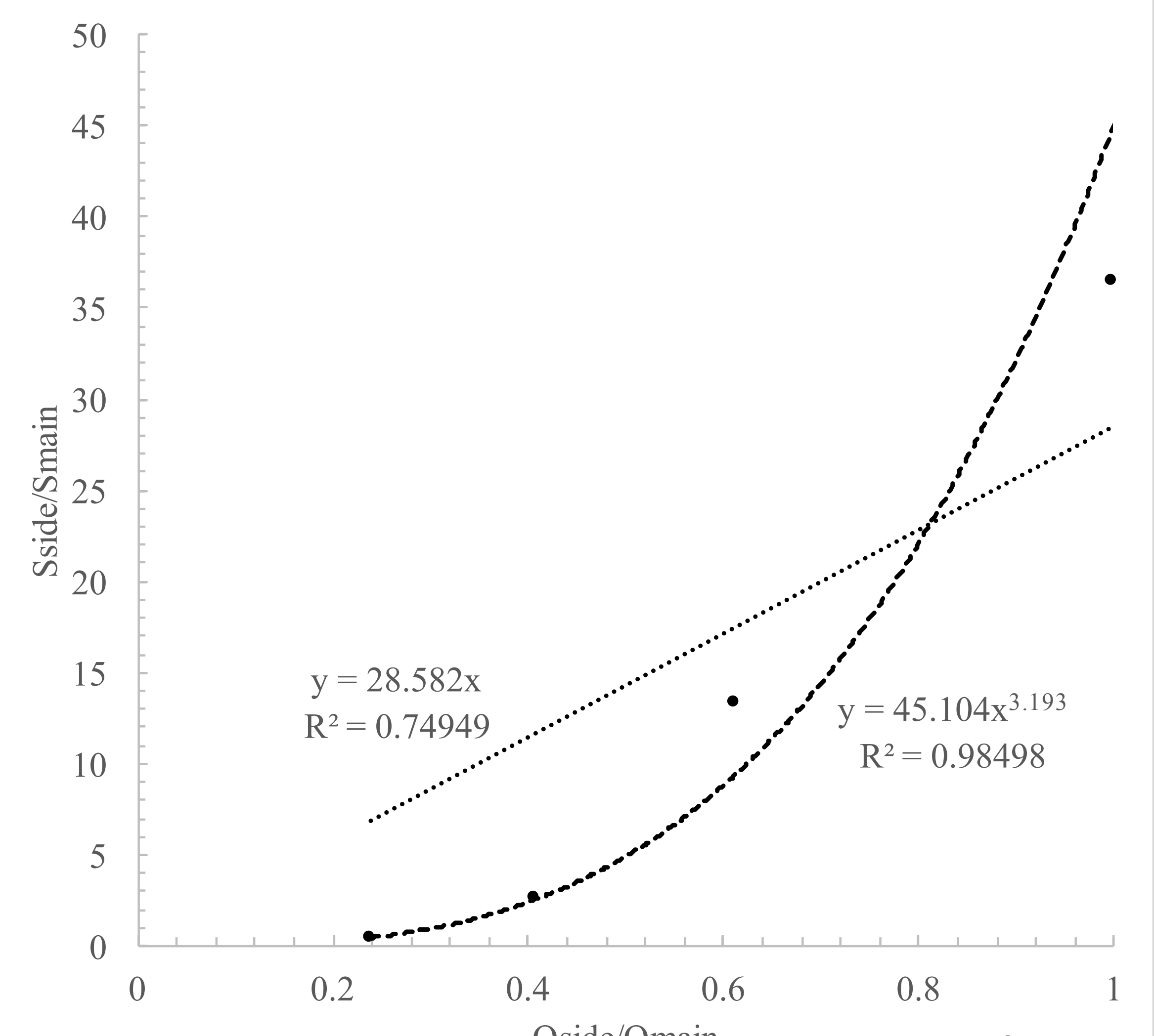




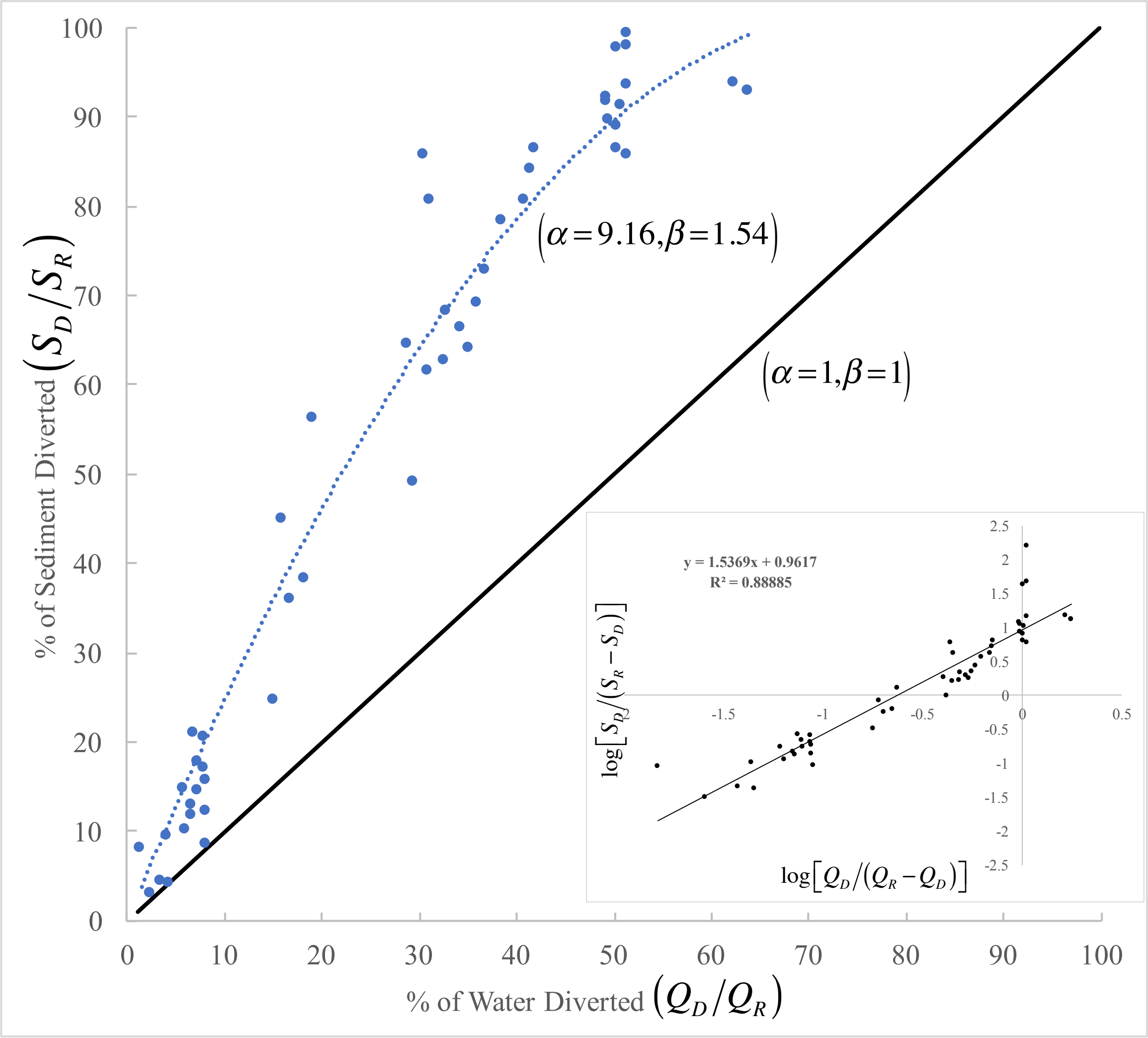
Bulle-Effect: the **non-linear** distribution of near bed sediment between the lateral and the main channel of a steam/river diversion.

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

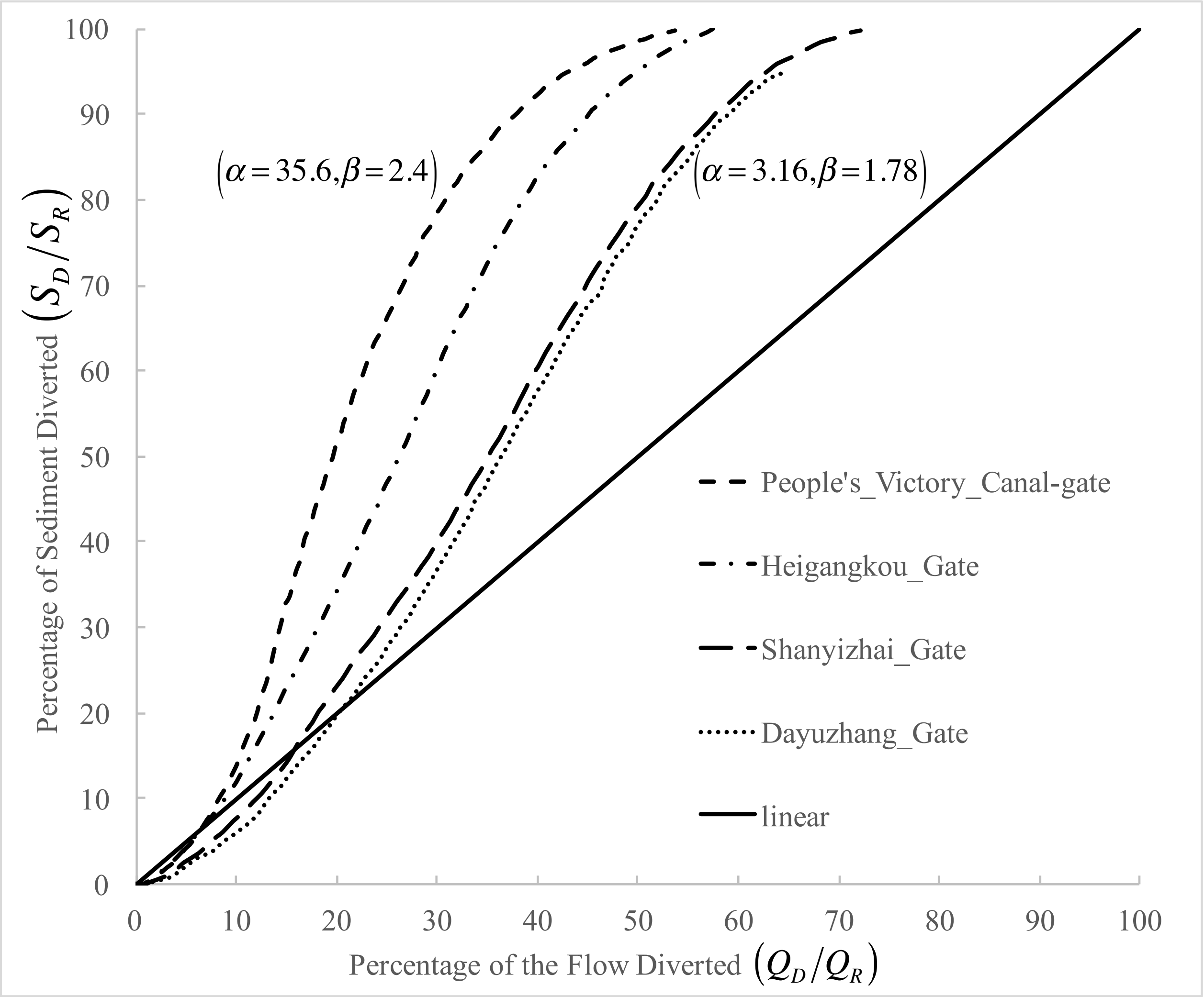
a, b > 1



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



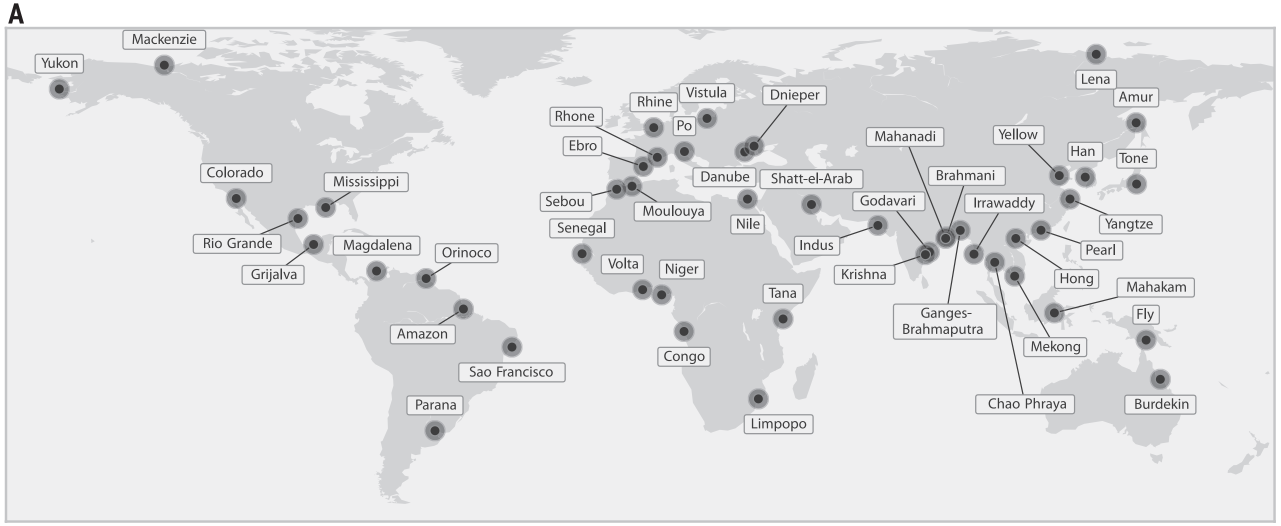
Bulle-Effect was observed in other experiments too. Above compilation of data reproduced from Ordonez (2013)



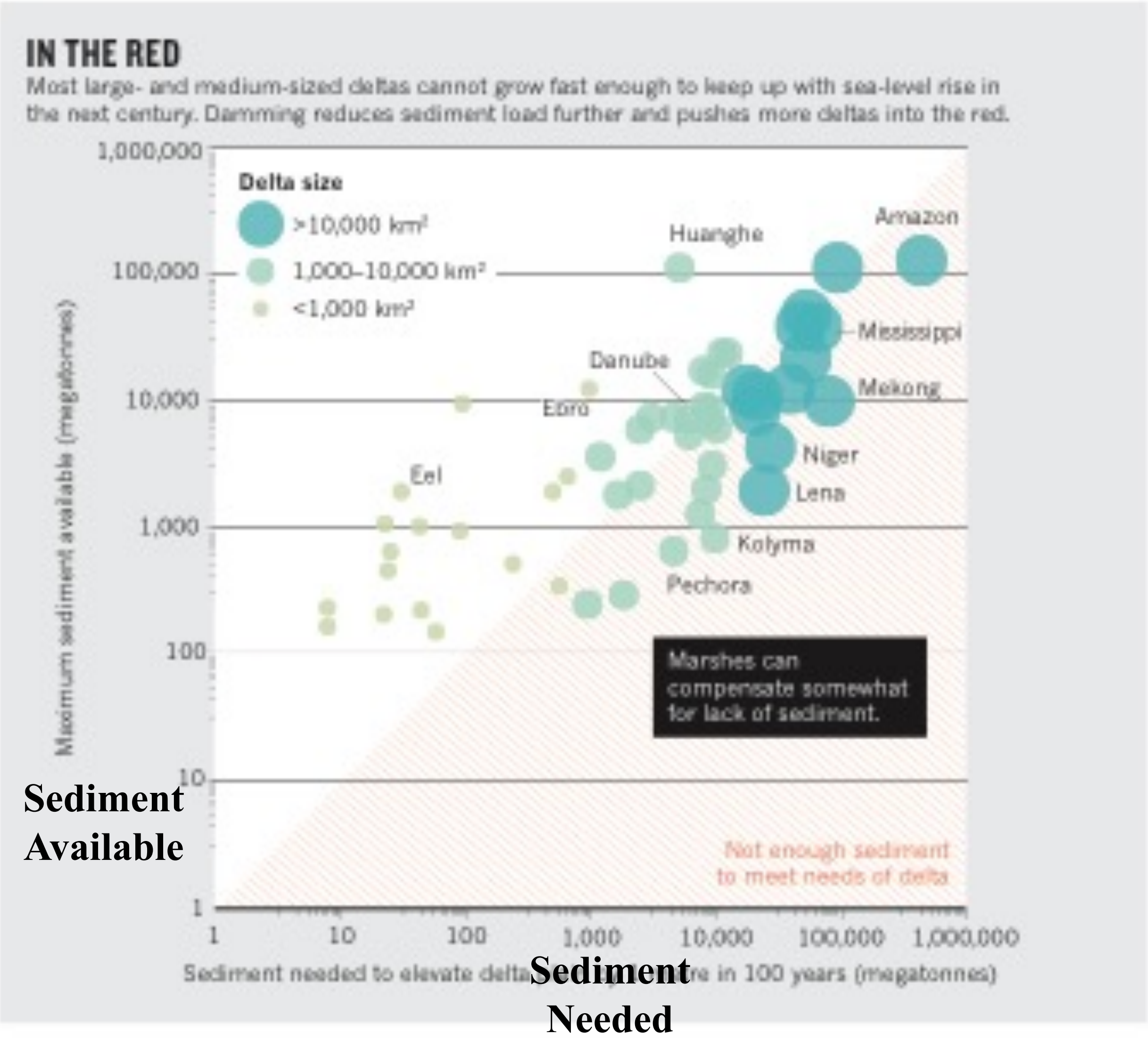
Similar pattern can also be observed in field data. Above data is from Lower Yellow River, reproduced from Erxun (1989)

Why is Bulle-Effect important ?

The knowledge gained from understanding the phenomenon will help **Save the Deltas** around the world from sea-level rise due to global warming.

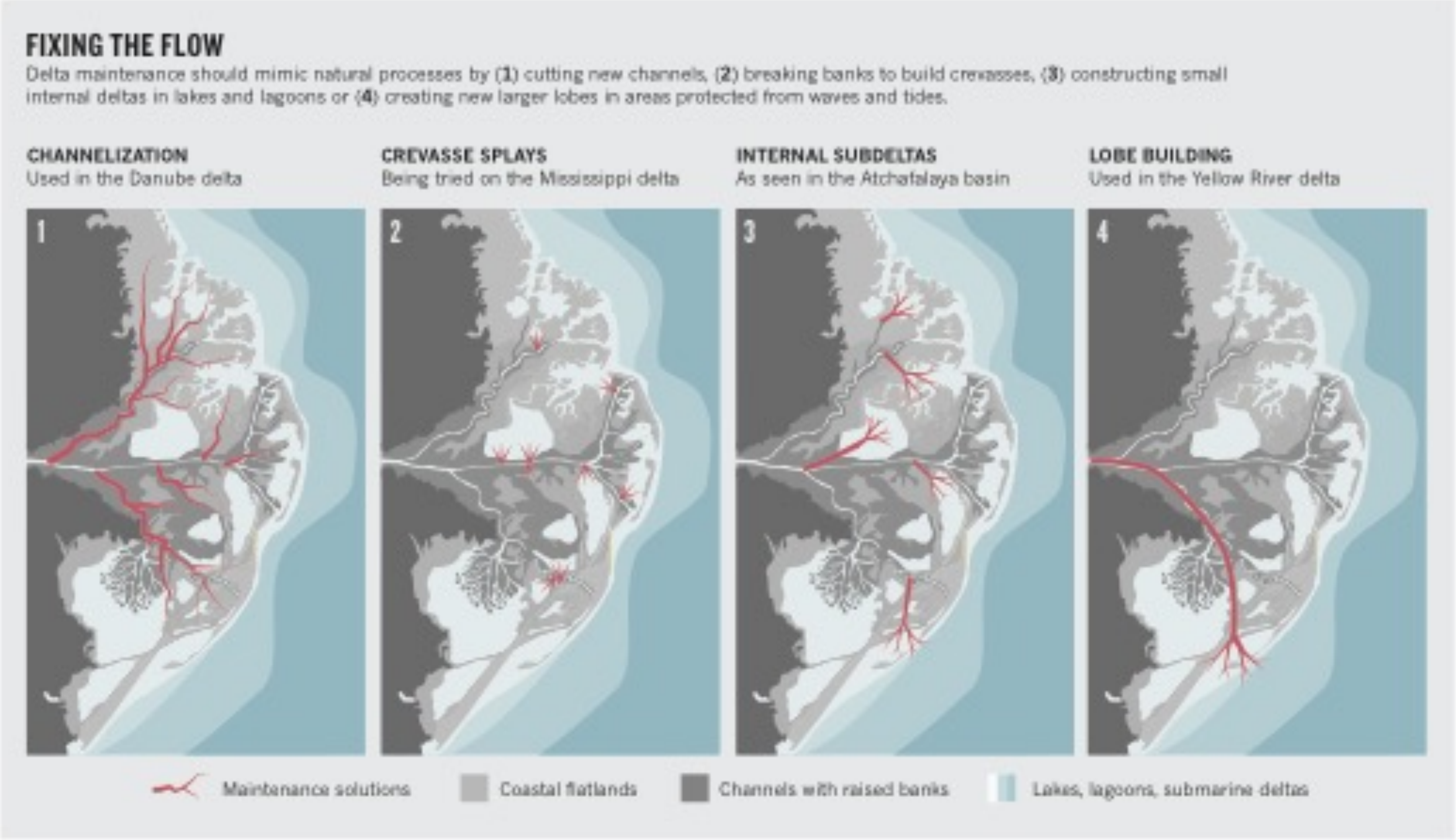


Profiling risk and sustainability in coastal deltas of the world
Z. D. Tessler *et al.*
Science **349**, 638 (2015);
DOI: 10.1126/science.aab3574



From Giosan et al. Nature, December 2014

Why is Bulle-Effect important ?



From Giosan et al. Nature, December 2014

- Only way the vulnerable deltas can be saved is through creating **diversions that divert sediment (and water),** for building land.
- Success of a diversion would depend on how efficiently sediment and water can be diverted into the engineered channels.
- Thus understanding of Bulle-Effect would be very helpful.

Understanding Bulle-Effect will also help predict morphological evolution of man-made and natural River systems

Canal del Dique on the Magdalena River, which has historically had a problem of silting up, ever since it opened in 1582.

Bifurcation of the Steamboat channel (top) and Centre Angling (right) following the avulsion of the river from the former to the latter, Cumberland Marshes, Saskatchewan.
Klienhans et al. (2013)

High-Resolution Numerical Simulations

- 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 $\mathbf{Q_{side}:Q_{main}}$ **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 = 300, 7000, 25000.

- For Re = 25000, simulations were also conducted for diversion angles of 30, 60, 120 and 150 degrees.

The Flow Model

$$\nabla \cdot \mathbf{u} = 0,$$

$$\frac{\partial \mathbf{u}}{\partial t} + (\mathbf{u} \cdot \nabla)\mathbf{u} = -\nabla p + \frac{1}{Re_b}\nabla^2 \mathbf{u}.$$

$Re = Re_b = UH/v$

U = *Mean Streamwise Velocity*
H = *Depth of the Channel*
v = *Viscosity of Fluid*

The high-resolution simulations were conducted with the above equation, which has been non-dimensionalized using the following parameters:

u using the average streamwise velocity from Bulle's experiments = Q/(WH)
Length using H
t using H/U

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

Nek5000: the highly scalable incompressible Navier-Stokes solver

- 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 Lagrangian interpolants based on Gauss-Lobatto-Legendre quadrature points, as the basis functions.

- 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 energy-dissipation scales are not fully 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).

The Lagrangian point-particle model for sediment transport

$$\left(\frac{\rho_s}{\rho}+C_m\right)\frac{dv_i}{dt} = \underbrace{\frac{3}{4}\frac{C_D}{d}|v_{ri}|v_{ri}}_{\text{Viscous Drag}} + \underbrace{\left(\frac{\rho_s}{\rho}-1\right)g_i}_{\text{Gravity}} + \underbrace{C_L\left(\epsilon_{ijk}v_{rj}\omega_k\right)}_{\text{Lift}} + \underbrace{C_m\frac{Du_i}{Dt}}_{\text{Added Mass}} + \underbrace{\left(-\frac{1}{\rho}\frac{\partial p}{\partial x_i}+\nu\frac{\partial^2 u_i}{\partial x_j x_j}\right)}_{\text{Fluid Stress on the particle}}$$

Non-dimensionalized momentum balance equation of the particles:

$$\frac{d\tilde{v}_i}{d\tilde{t}} = \frac{1}{C_m^R}\left[\frac{1}{St}\tilde{v}_{ri} - \frac{\delta_{i3}}{Fr^2} + C_L\left(\epsilon_{ijk}\tilde{v}_{rj}\tilde{\omega}_k\right) + (C_m+1)\frac{D\tilde{u}_i}{D\tilde{t}}\right]$$

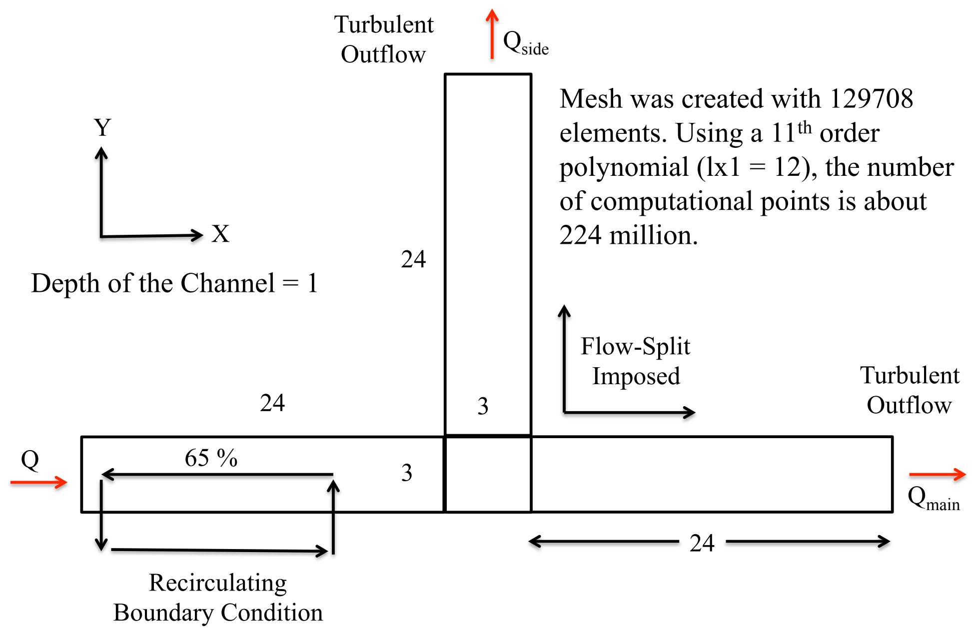
$$Fr^2 = \frac{U_m^2}{RgH} \qquad St = \frac{4}{3C_D}\frac{\tilde{d}}{|\tilde{v}_{ri}|} \qquad C_m^R = 1 + R + C_m$$

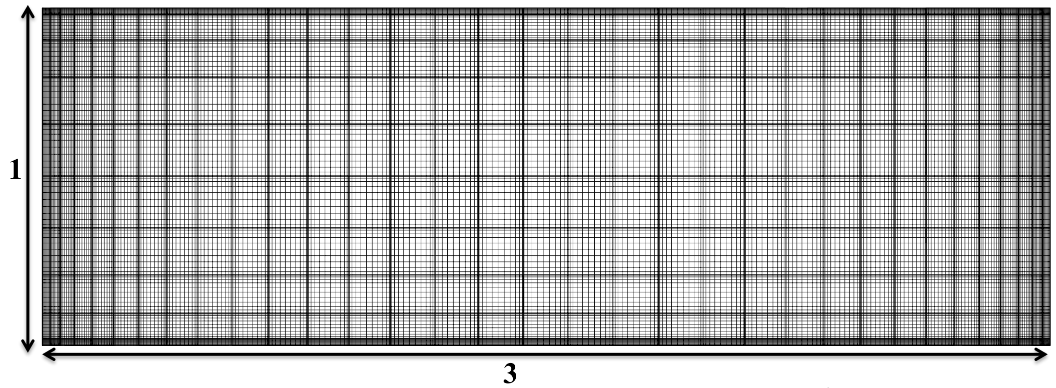
- **A novel semi-implicit time-stepping algorithm was developed to integrate the above equation. This algorithm was implemented in Nek5000**

- **In this new method, the time-step size for time-integration of the above equation is not constrained by the size (Stokes number) of the particle, unlike an explicit time-stepper.**

General Configuration of the Simulations

- Dimensions of the simulations are similar to 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 recycling the flow, to have a fully-developed turbulent flow at the diversion.
- The flow-split at the bifurcation was imposed using a fast implicit enforcement of the flow division. This helped in accurate yet faster convergence of the simulation.
- The computational requirements of the simulations were very high, thus the simulations were conducted on the petascale supercomputer Blue Waters, NCSA, UIUC.





For the points closest to the walls, $z^+ = 0.058$ and $y^+ = 0.65$, at $Re_{bulk} = 20{,}000$

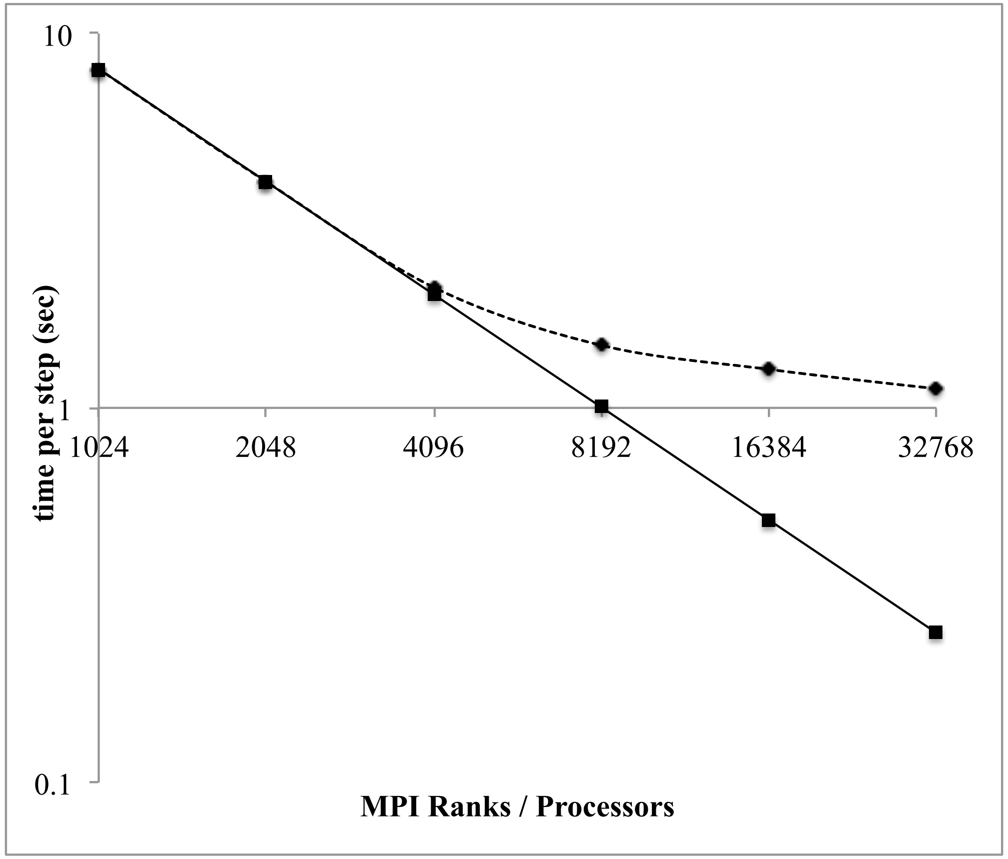
The need to use Blue Waters to conduct the simulations

- 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 this scale.

- The number of **computational points is in the range of 224 million to 242.74 million**, along with 200,000 sediment 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**.



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 %).

What is causing Bulle-Effect ?

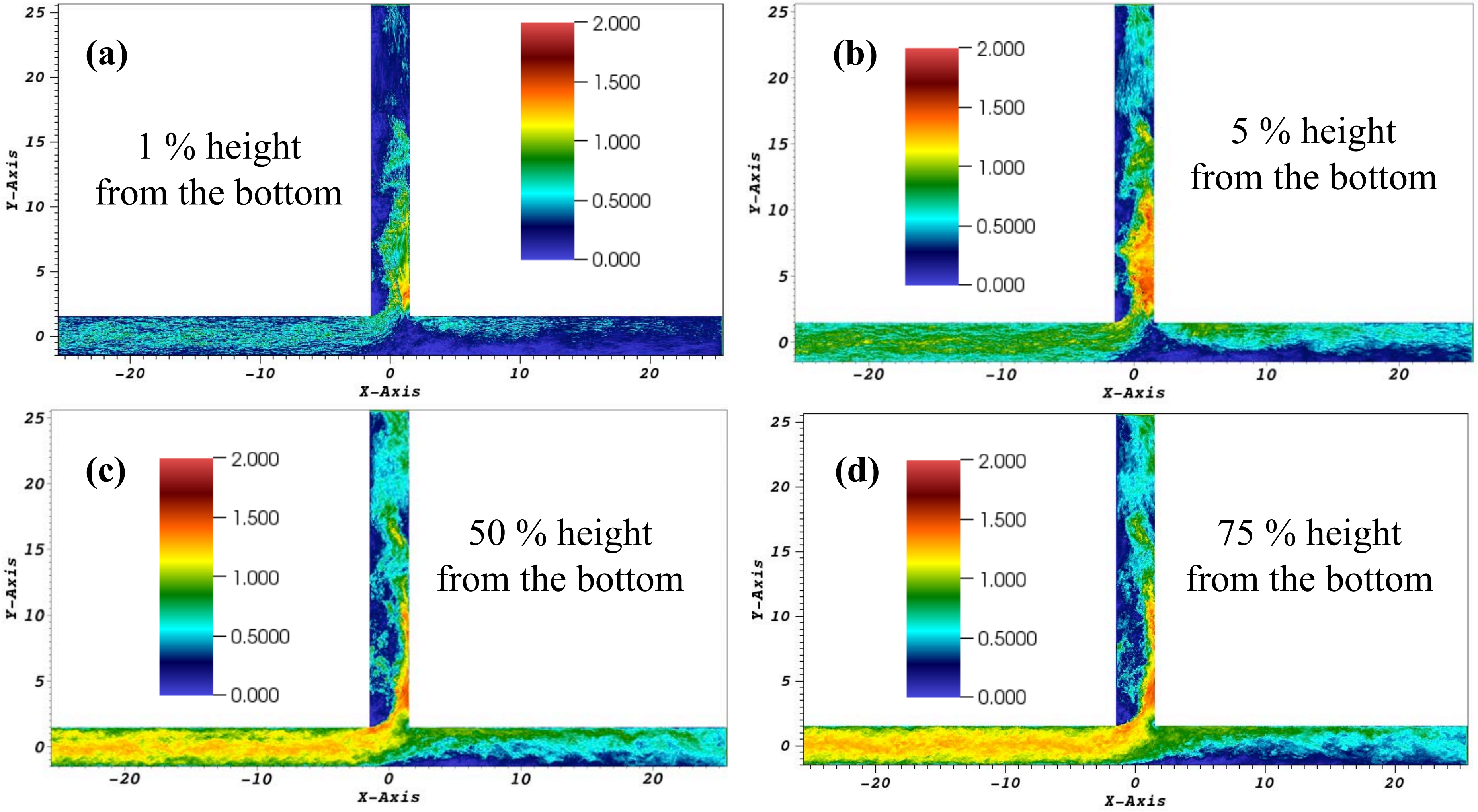
Velocity Magnitude for, Re=20000, 50:50 flow division

Re = HU/v

H – channel height

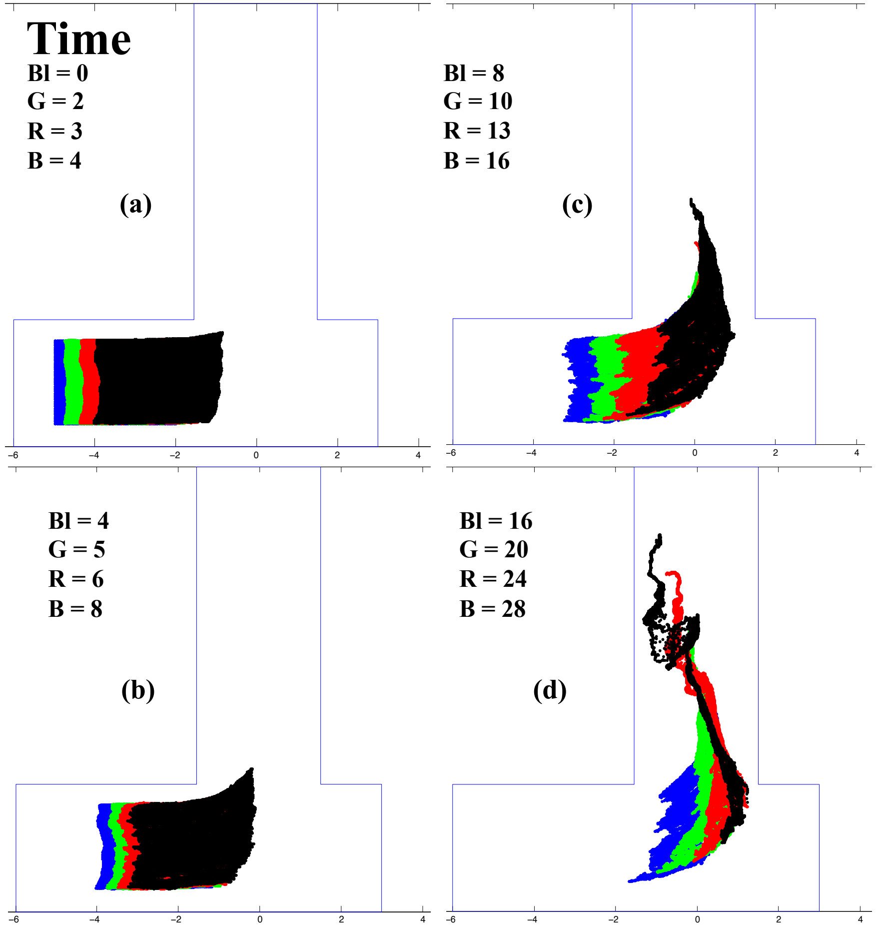
U – Mean velocity

v - viscosity

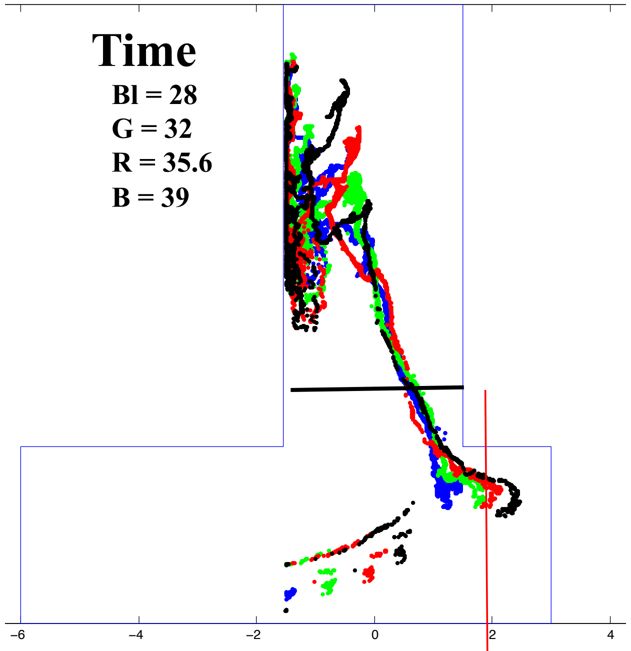


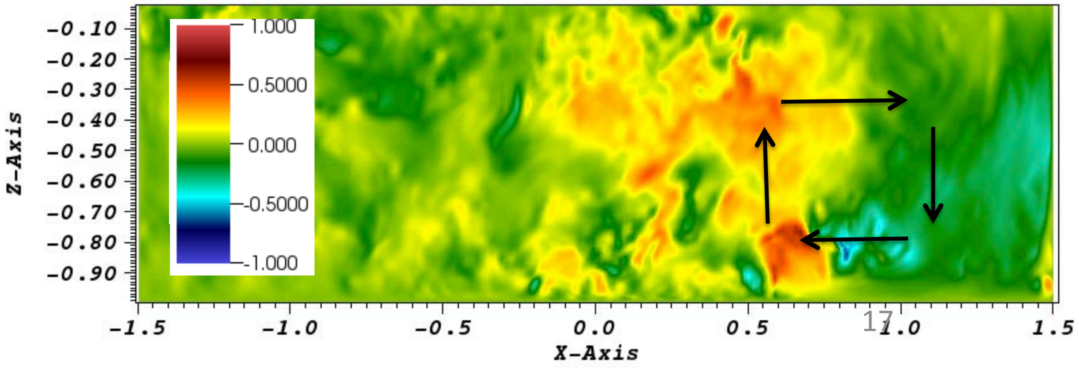
Instantaneous Velocity Magnitude at different levels

Evolution of the position of sediment particles moving as bedload: Re=20000, 50:50 flow division

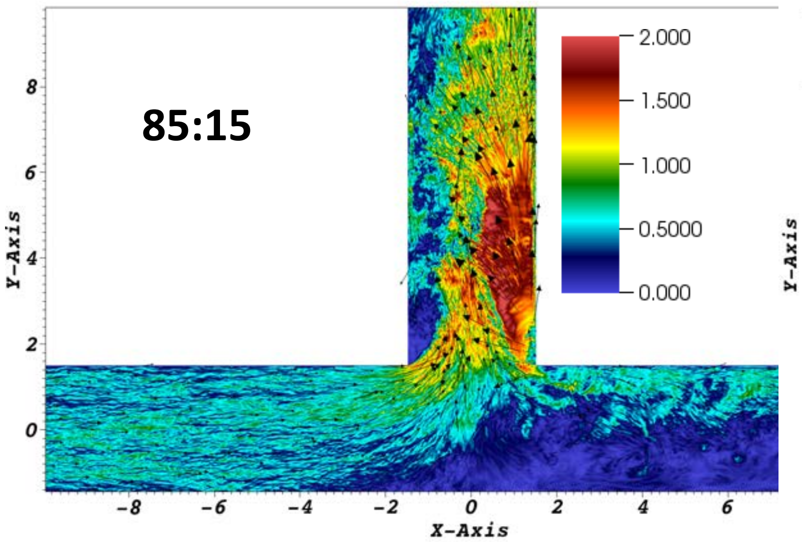


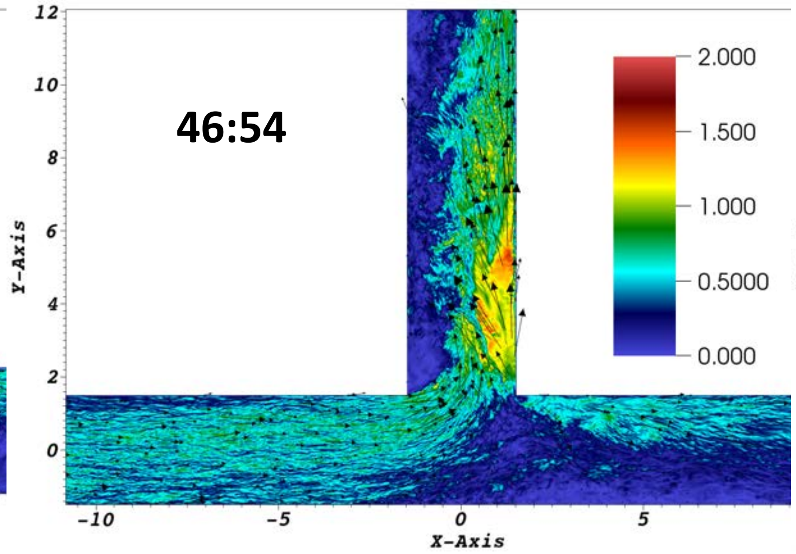
- 20000 sediment particles, of size 0.015 (actual size 1.05 mm, density 2.65 kgm^{-3}).
- Released together, upstream of the bifurcation.
- In agreement with the experiments, a very small quantity of the total sediment (4.29 %) entered the main-channel after the bifurcation.

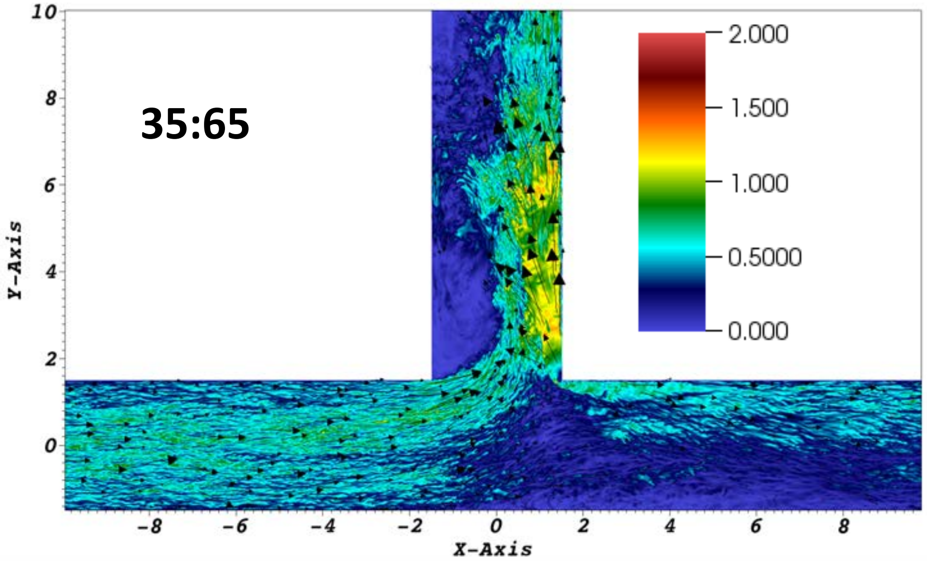


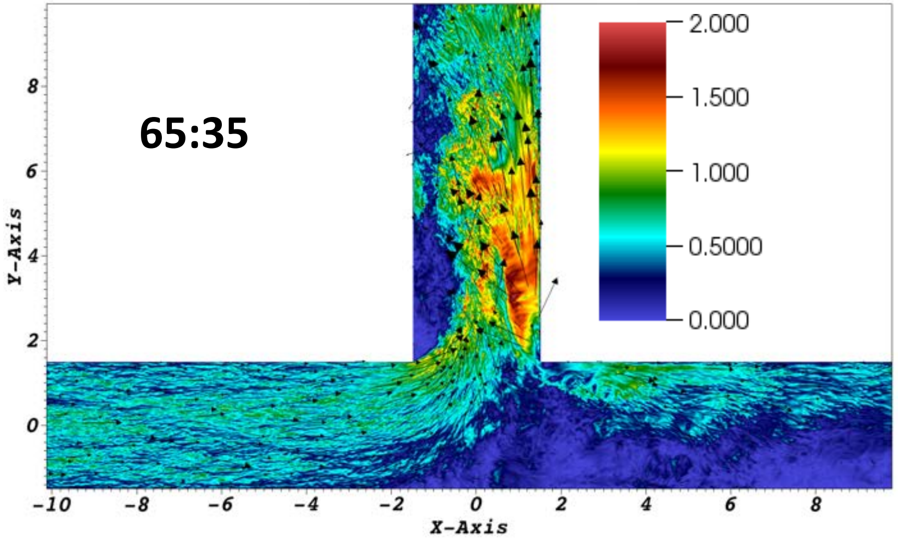


Re=25000 and Different Flow divisions. Instantaneous Velocity Magnitude at 5 % of the depth (from the bottom).

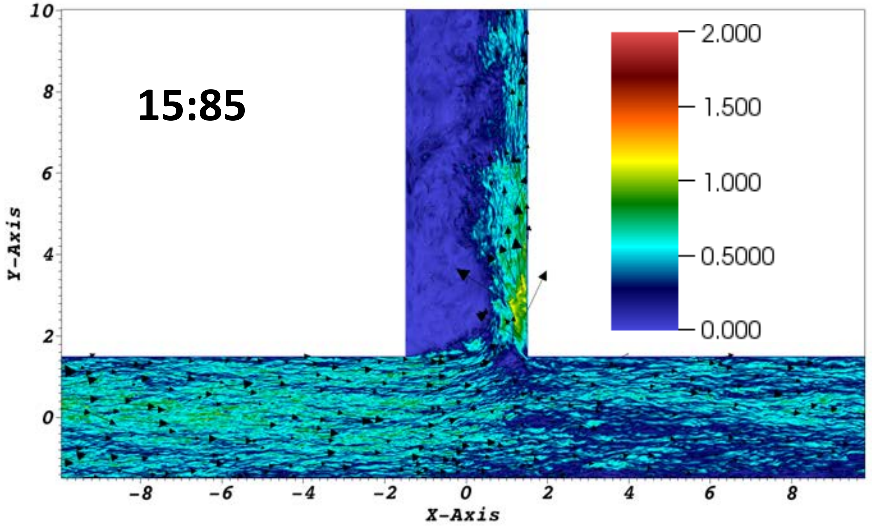




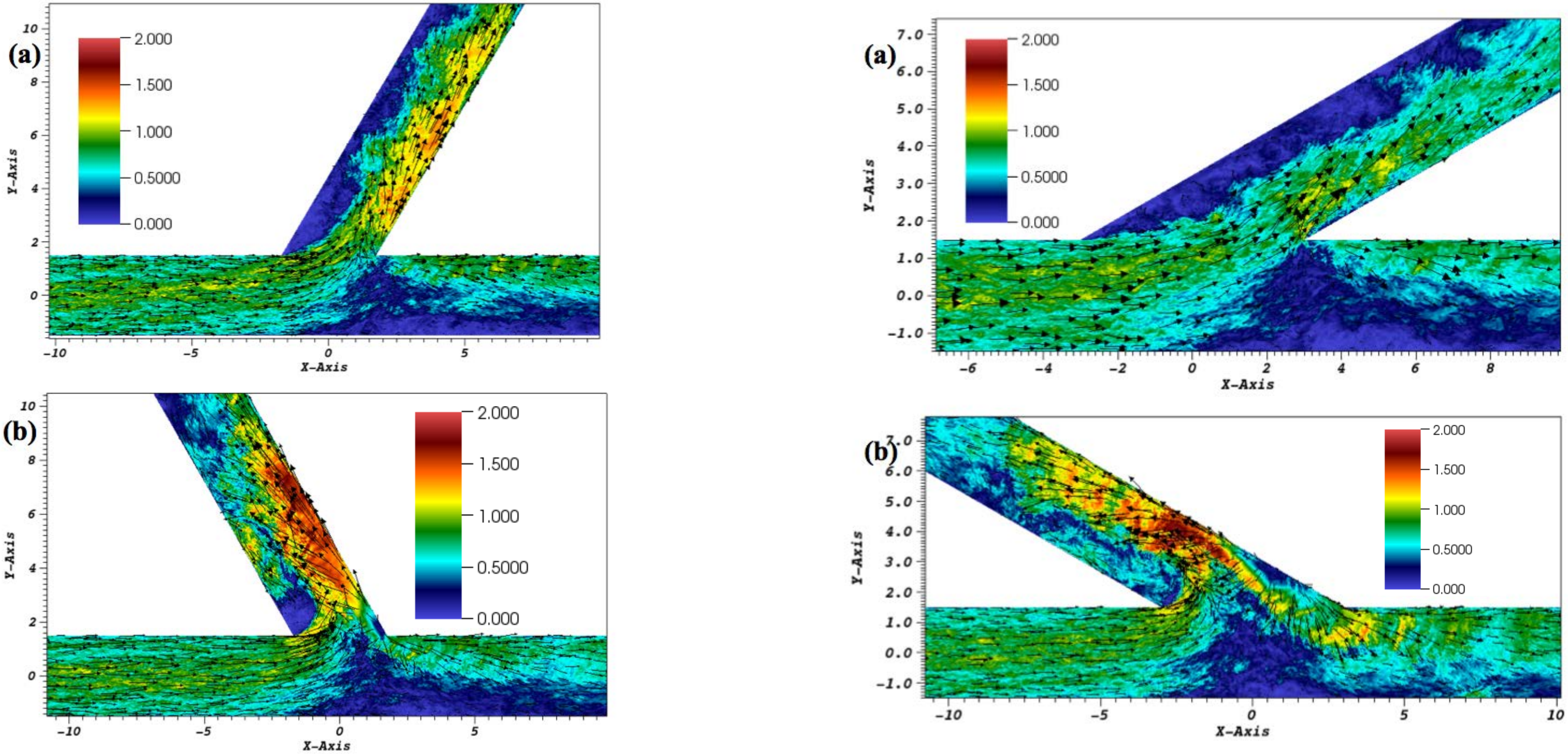




- Even for the case where only **35 percent** of the **total flow enters the lateral channel, most of the flow near the bottom** goes **into the lateral channel.**



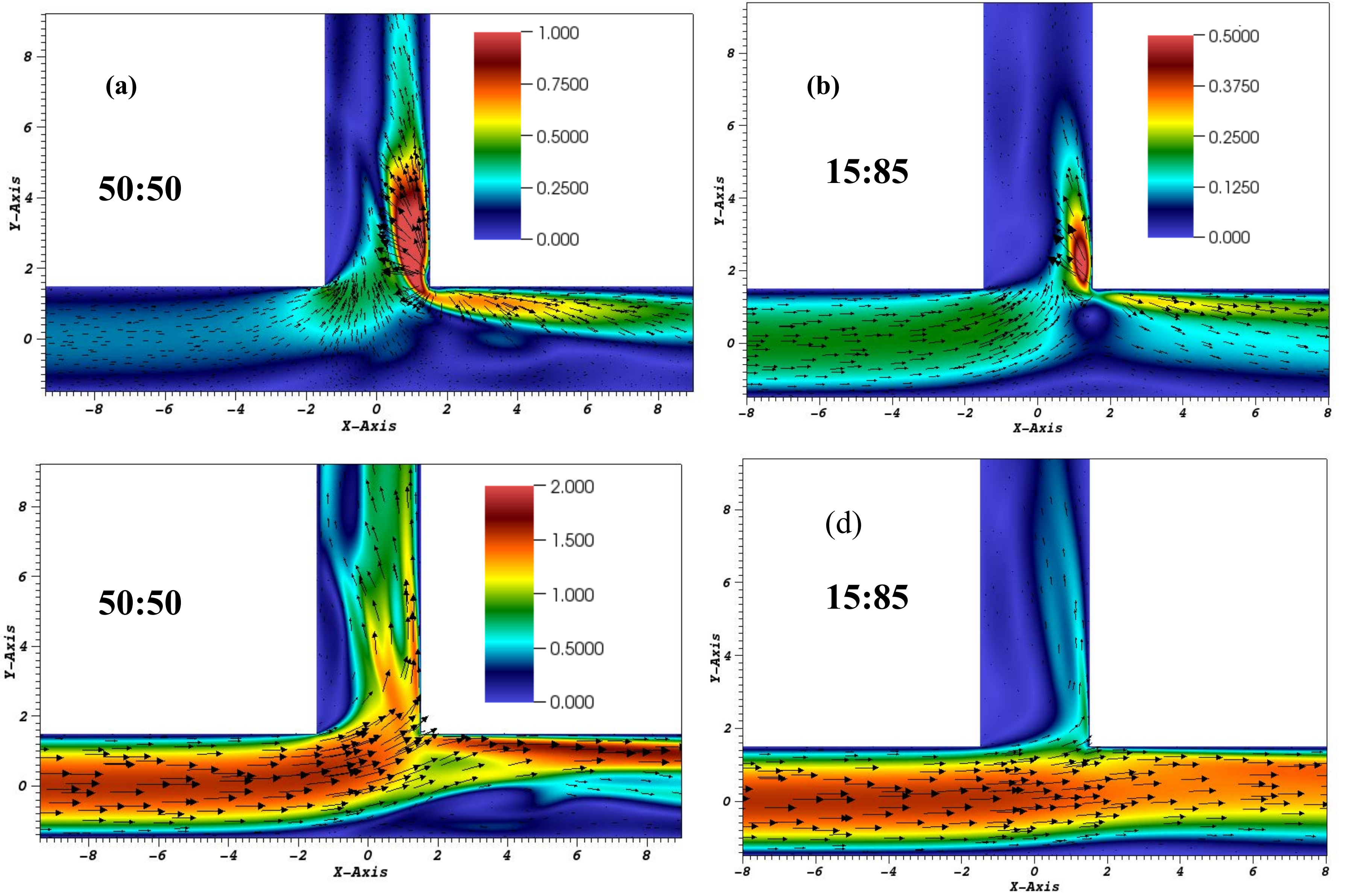
Re=25000 and Different Diversion Angles. Instantaneous Velocity Magnitude at 5 % of the depth. flow division ~ 48:52



Re=300 and Different flow-divisions. Instantaneous Velocity Magnitude at 5 % and 50 % of the depth (from the bottom).

5 % from the bottom

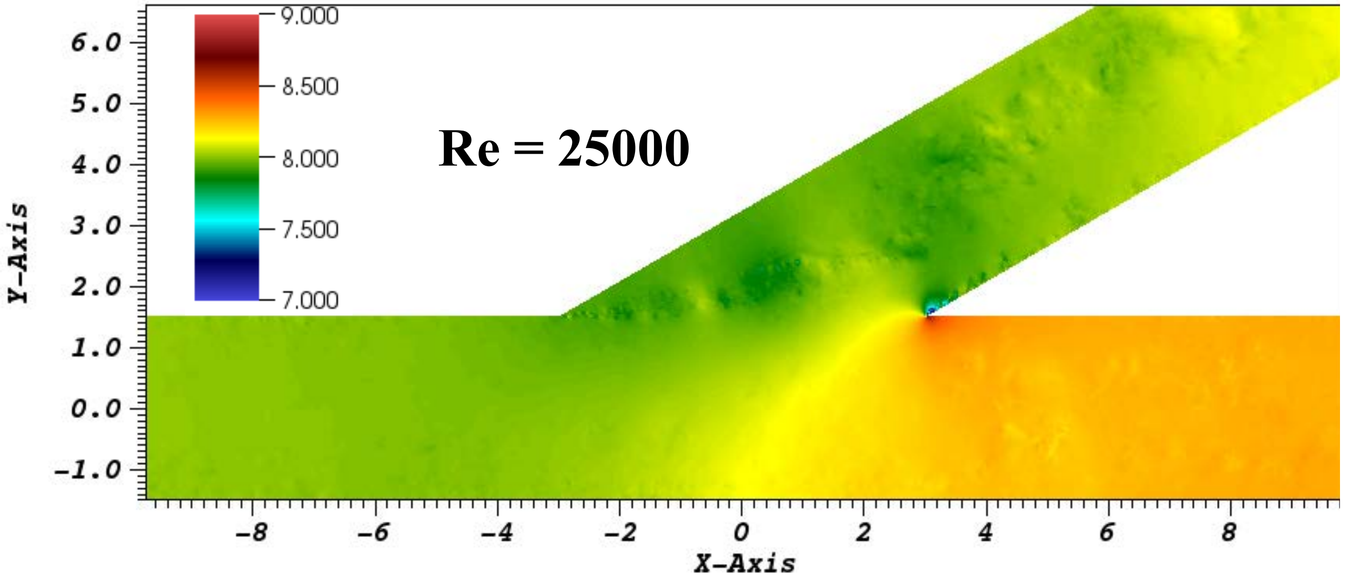
50 % from the bottom

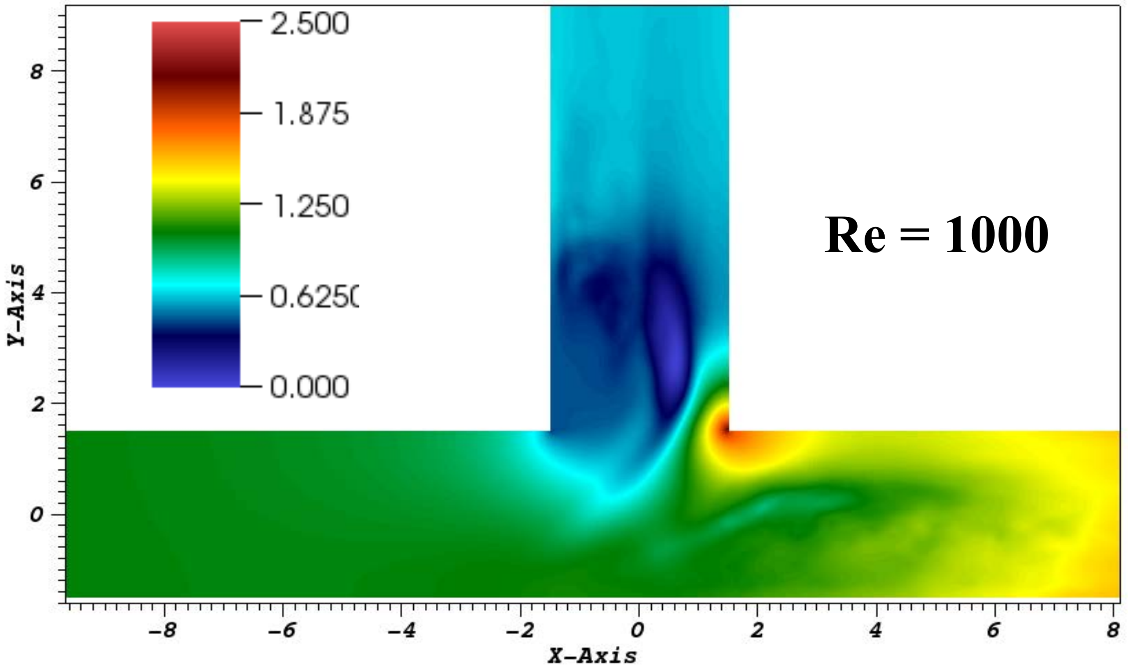


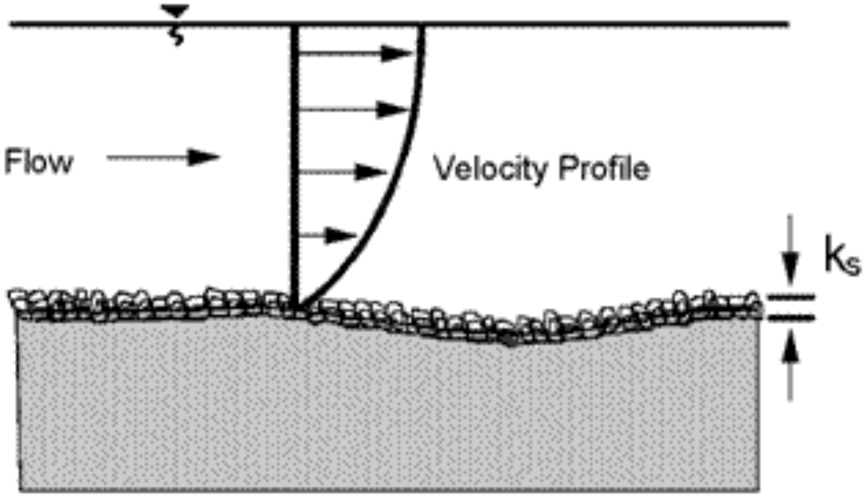
What is causing Flow near the bottom to enter the side-channel ?

Can we quantify how much flow is entering the side-channel from each depth ?

For different Reynolds numbers. Hydrodynamic Pressure at 50 % height from the bottom.



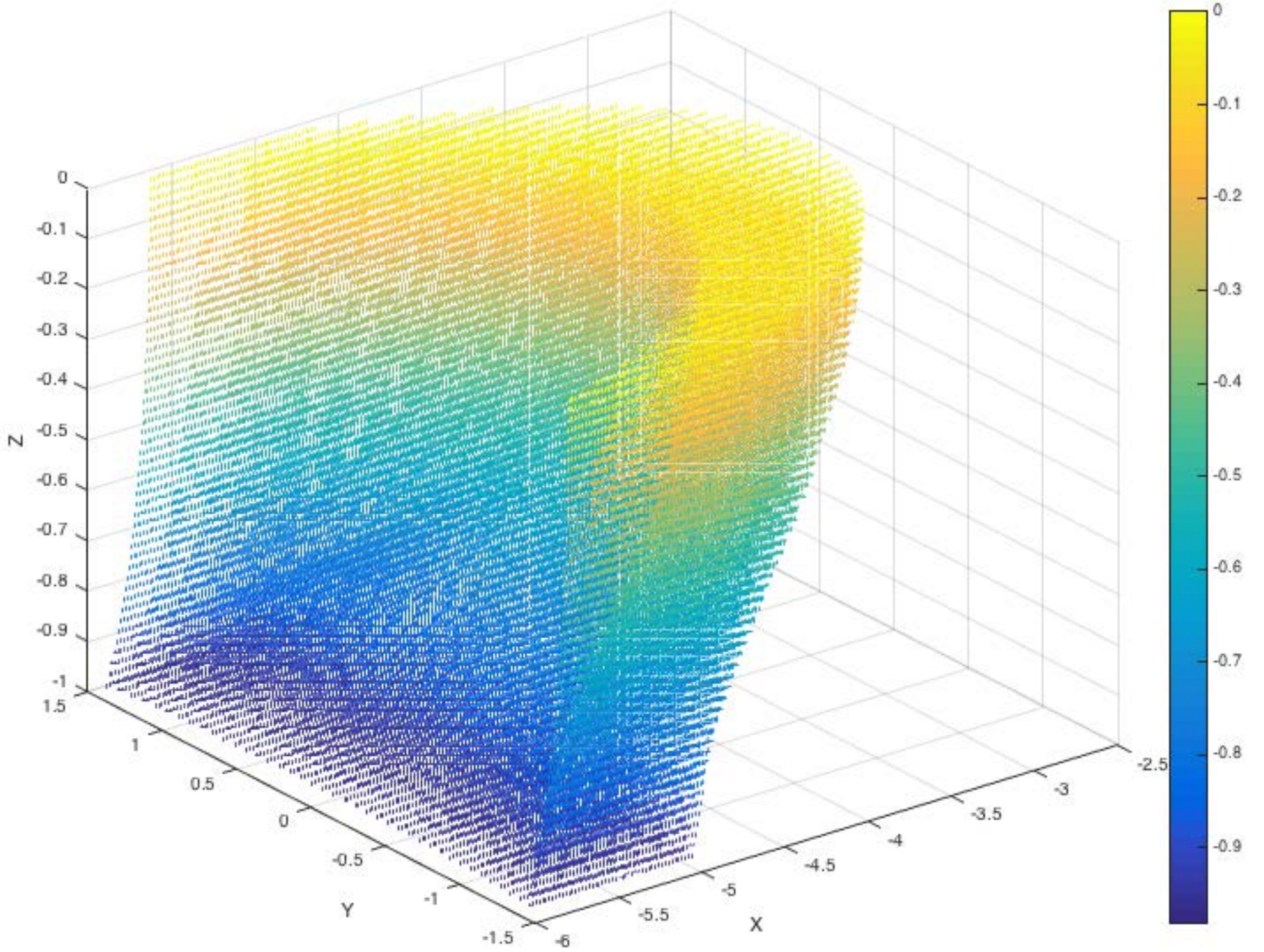




- An adverse pressure gradient is created in the main-channel, and a favorable one in the lateral.

- Thus part of the flow that has less Inertia (velocity) is more easily moved into the lateral-channel.

Dynamics of weight-less and very fine Lagrangian particles in Re = 300, 90-degree, and 50-50 flow division



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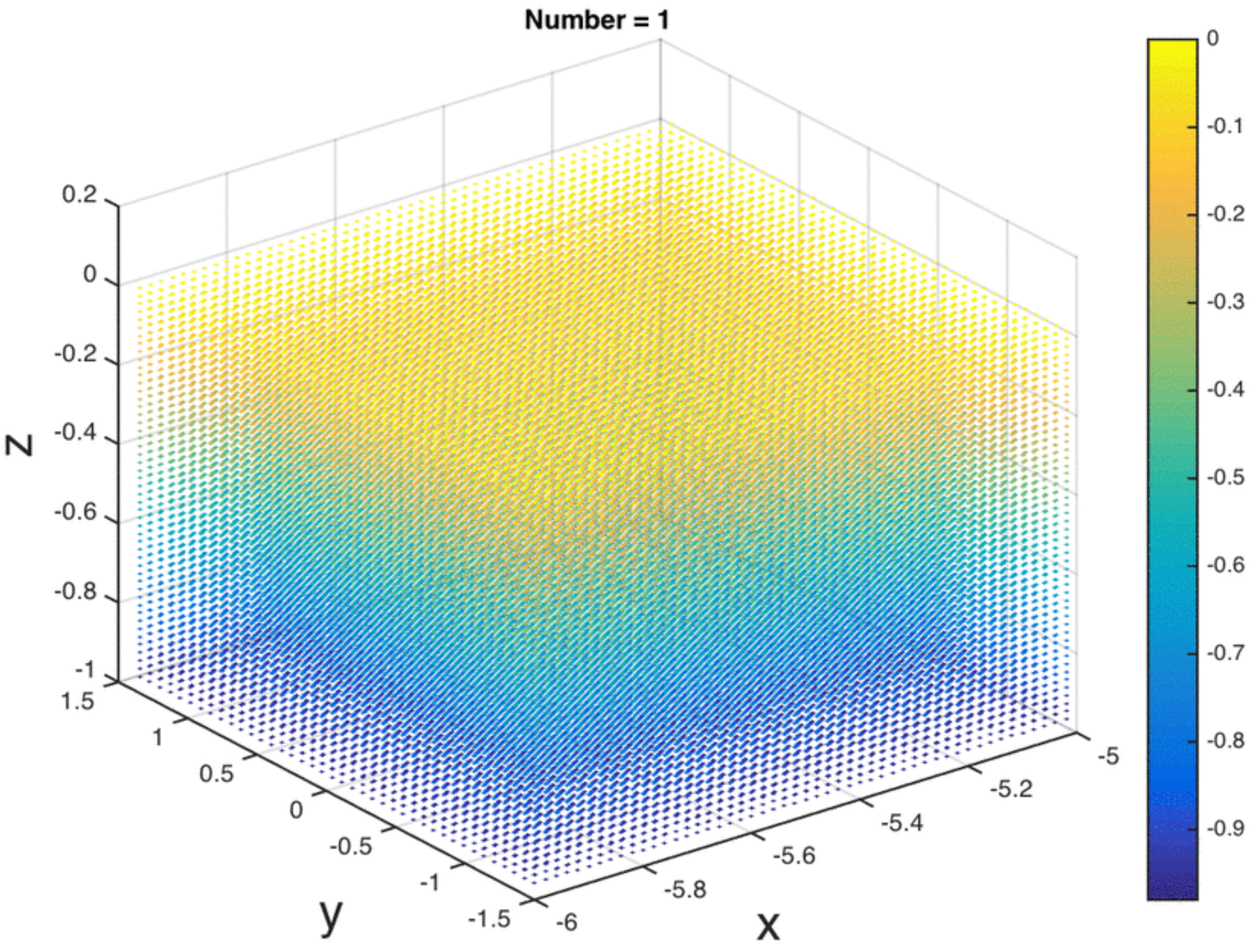
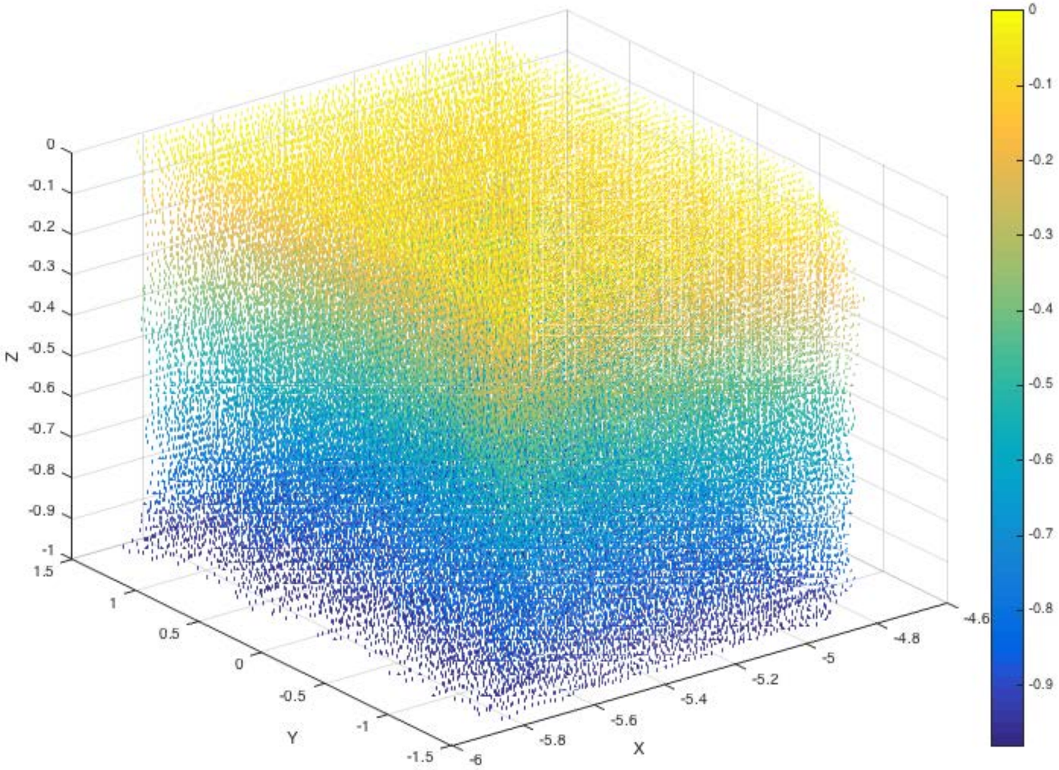
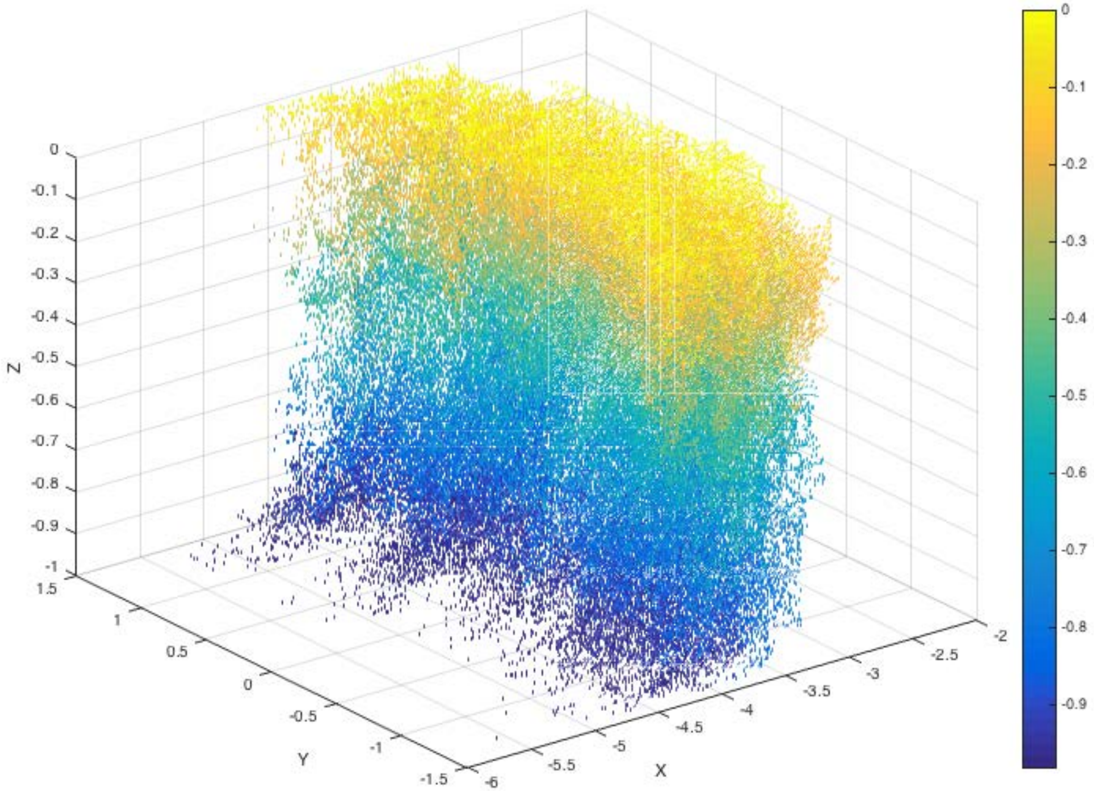
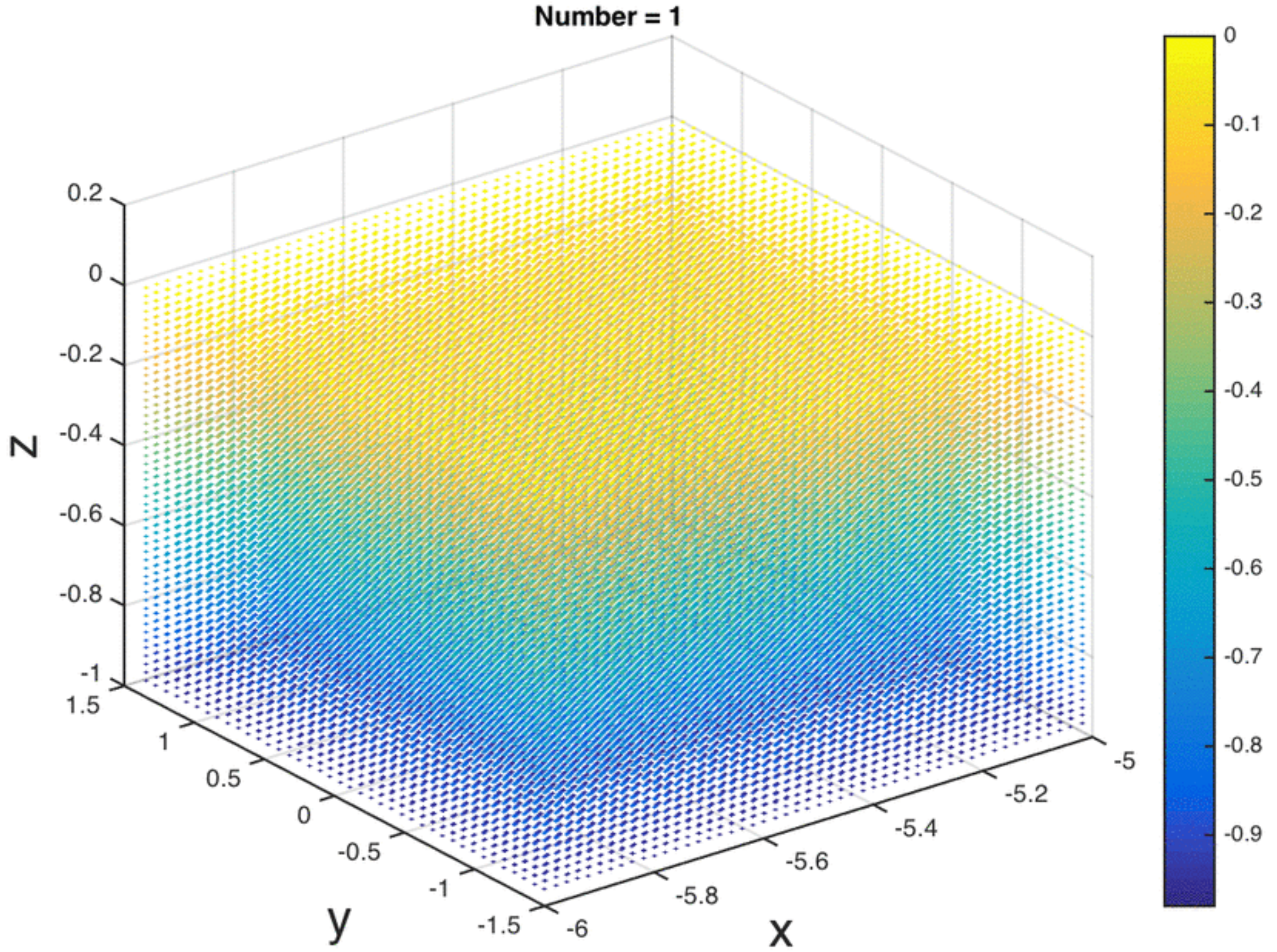


Dynamics of weight-less Lagrangian particles in Re = 25000, 90-degree, and 50-50 flow division

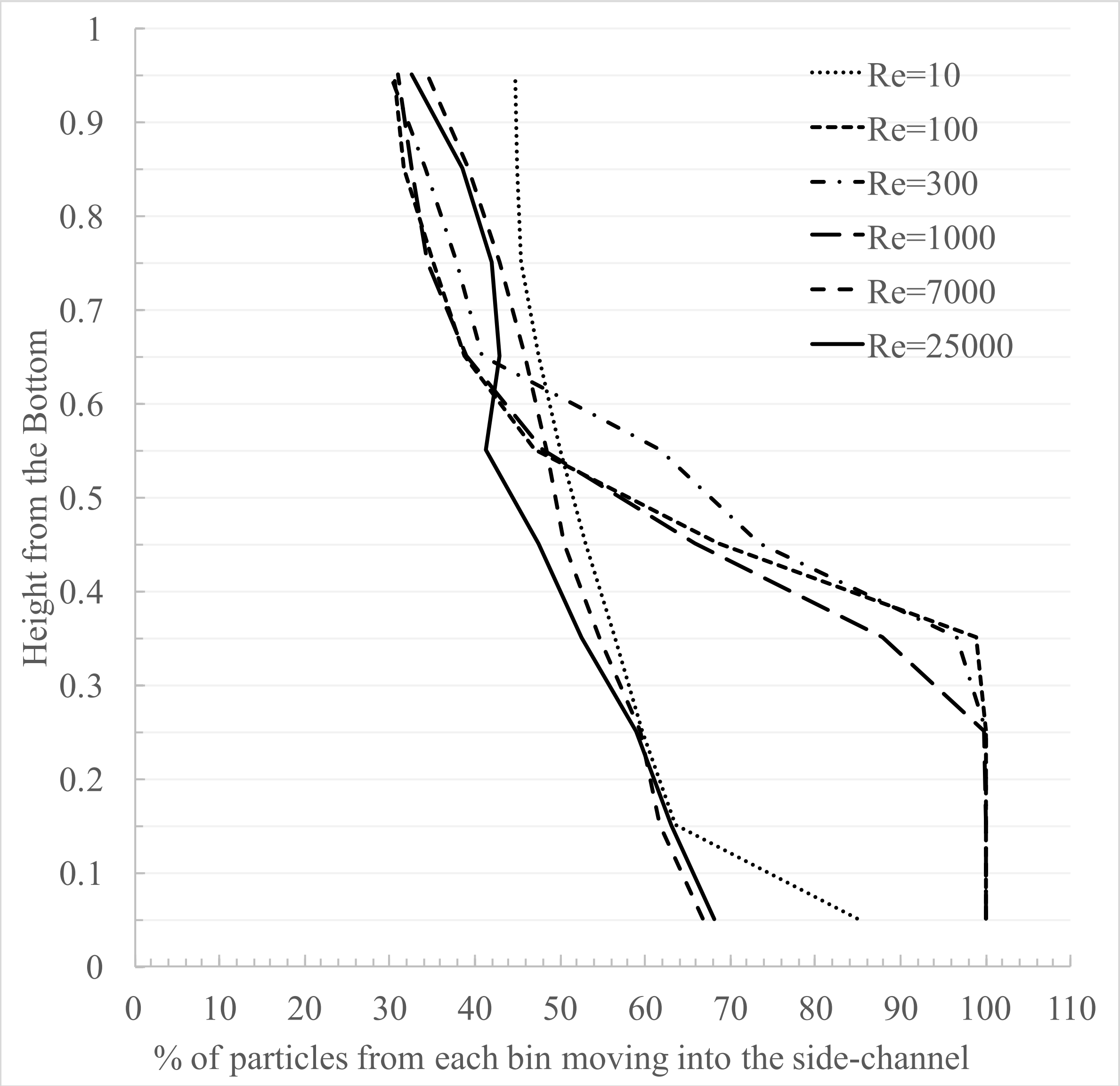




Dynamics of weight-less Lagrangian particles in Re = 25000, 90-degree, and 50-50 flow division

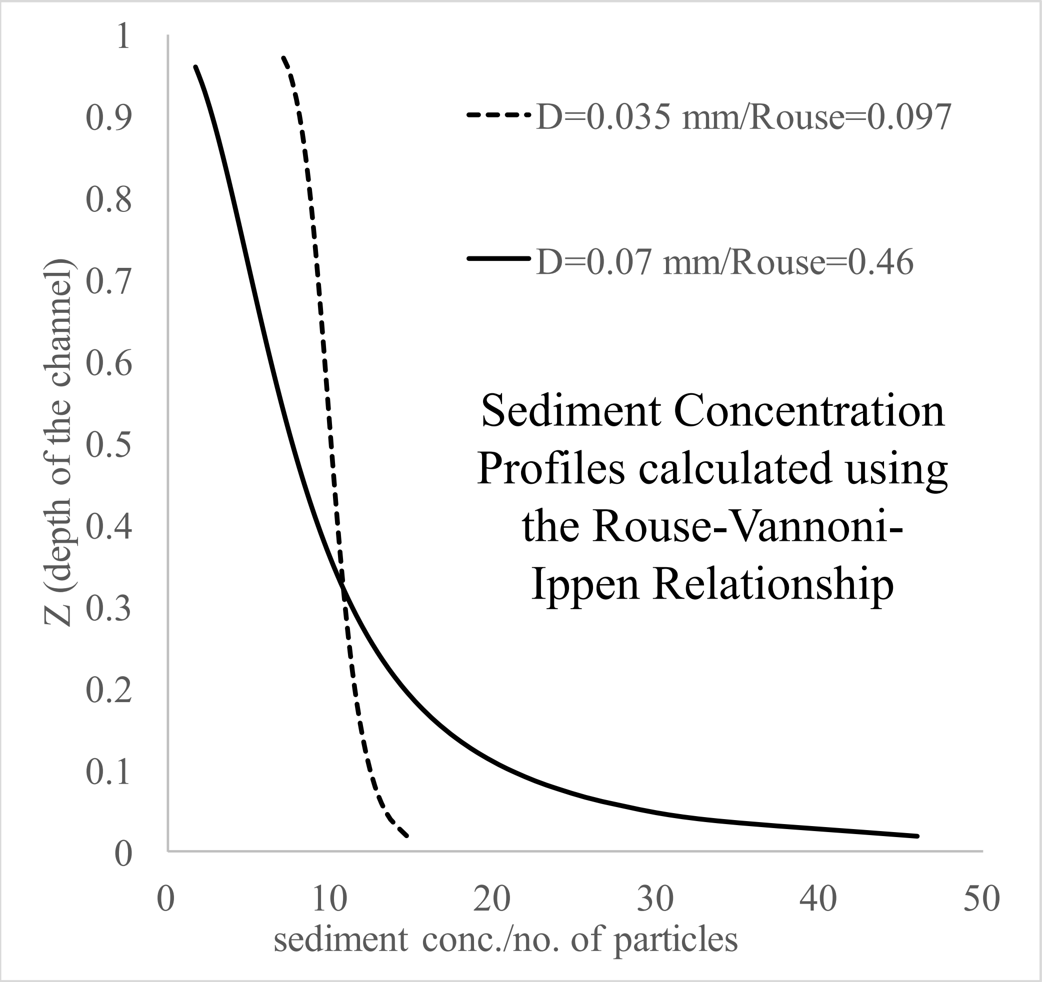


Percentage of weight-less particles from each segment entering the side-channel, for different Reynolds number, 90-degree, and 50-50 flow division

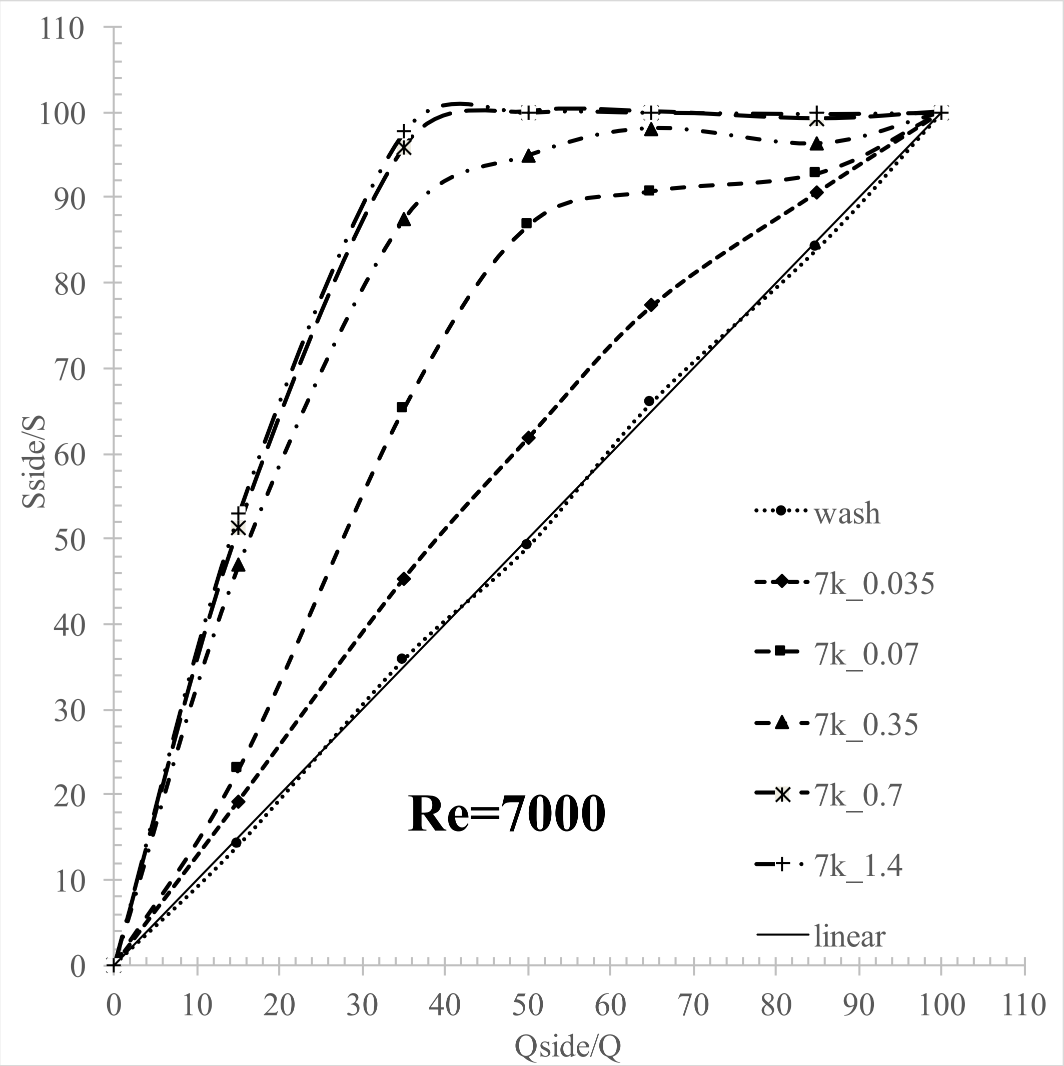


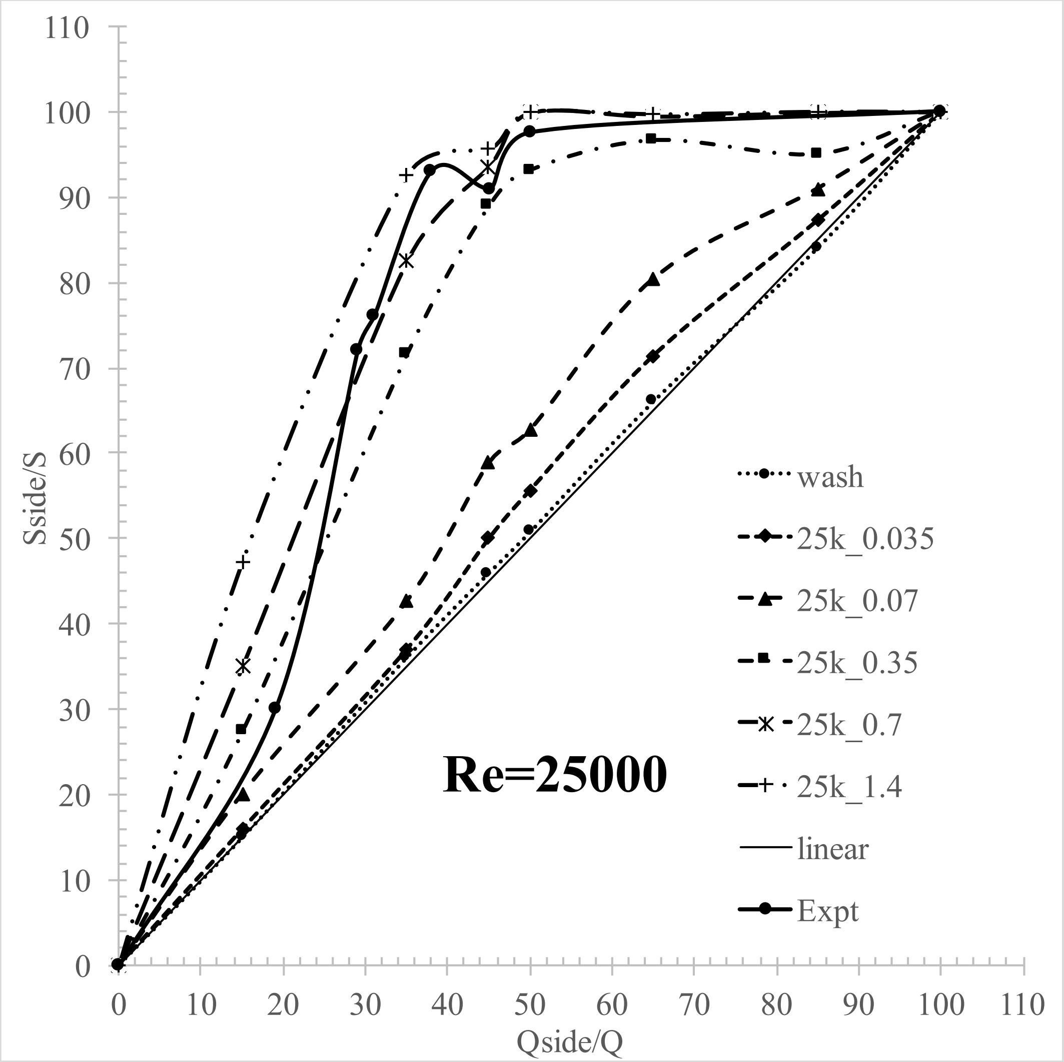
What does this mean for actual sediment particles ?

It means the phenomenon of Bulle-Effect not only transfers large percentage of bed-load to the side-channel, it will also transfer near bed suspended sediment

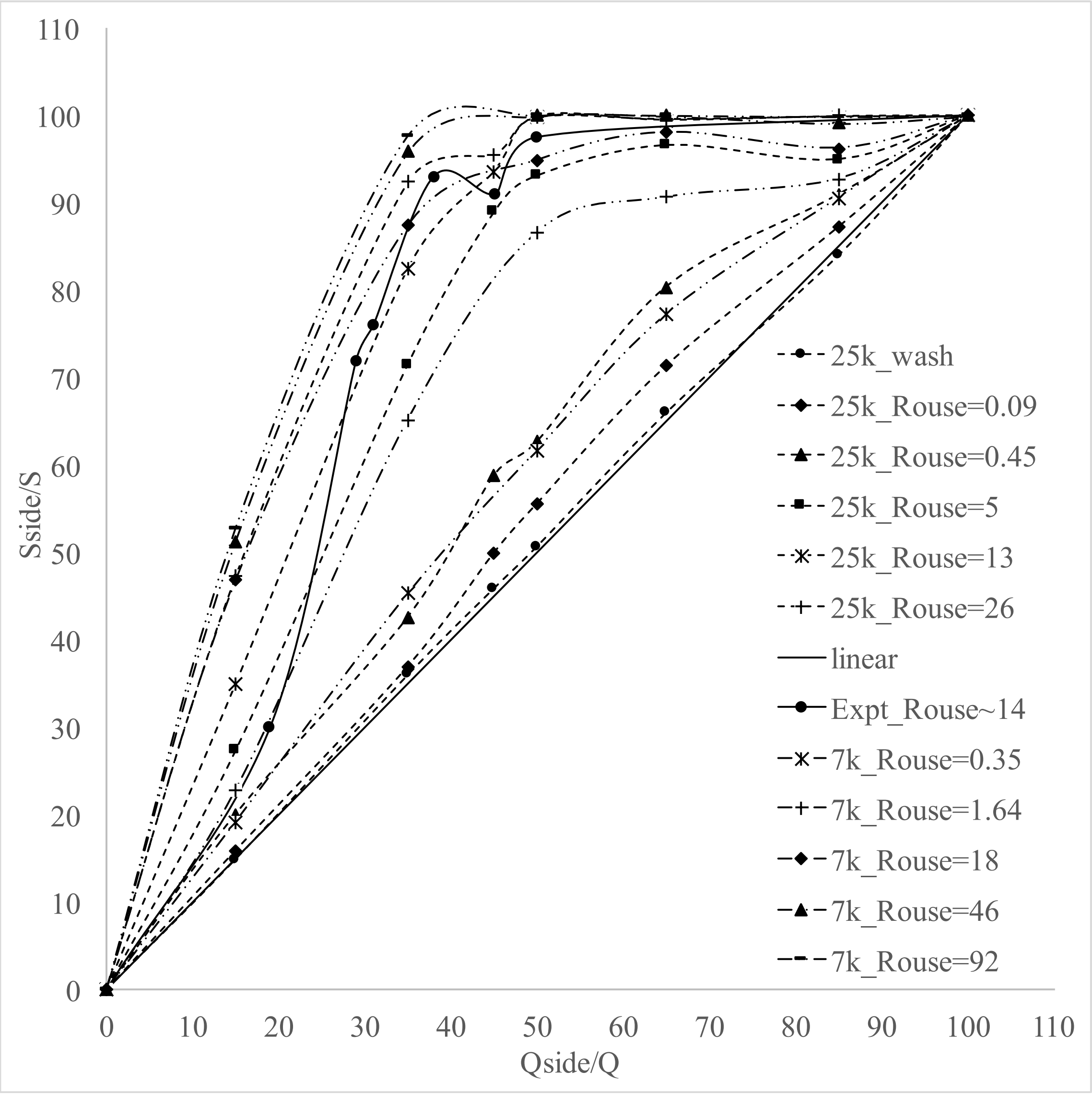


Percentage of sediment of different sizes entering the side-channel, for Re = 7000 and 25000, 90-degree, and different flow divisions





Percentage of sediment of different sizes entering the side-channel, for Re = 7000 and 25000, 90-degree, and different flow divisions

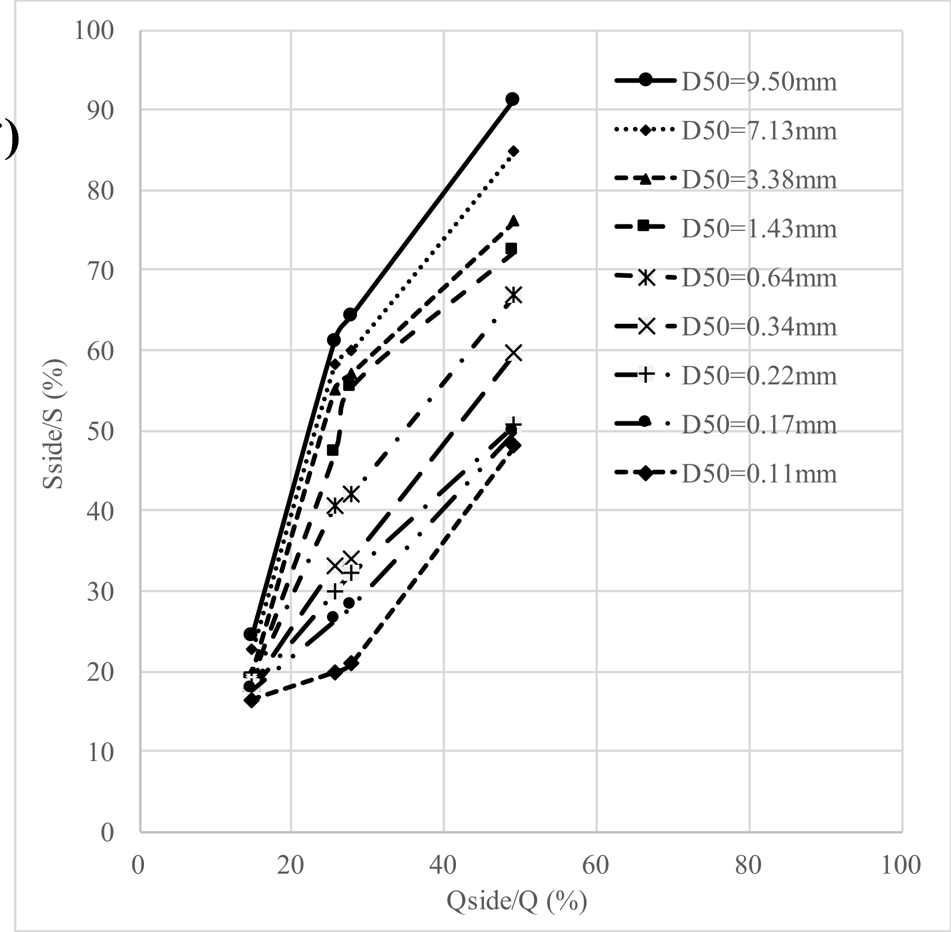


Rouse No. = Vs/(k u*)

Vs – particle settling velocity

u* - fluid shear velocity

k – Von Karman constant



Albert Dancy (1946) found the dependence of the phenomenon on size of sediment. Used a mixture of sediment of different sizes, Q = 0.59 l/sec, Angle = 30-degree

Key Findings

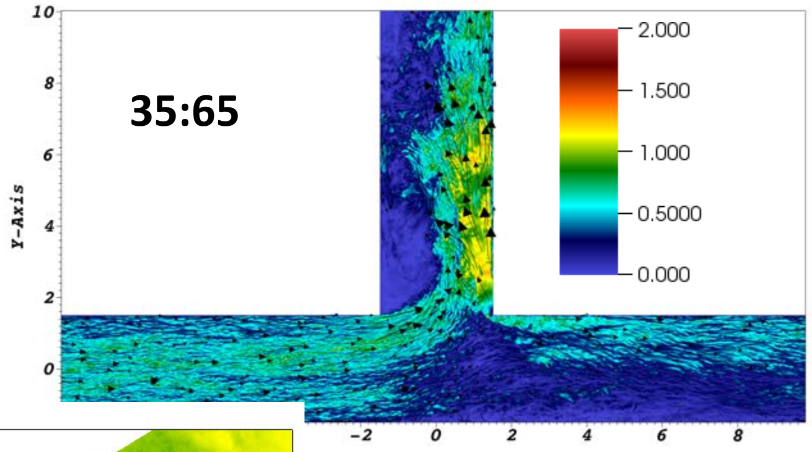
- Bulle-Effect is caused due to flow near the bottom preferentially entering the side-channel, even when only 35 percent of the total flow enters the lateral-channel.

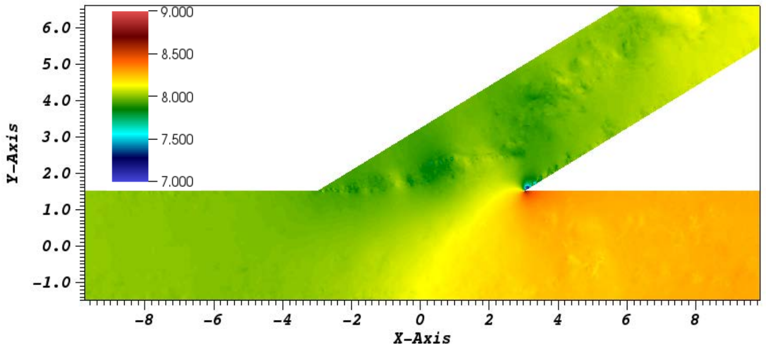
- This happens because Velocity of the flow near bottom is relatively low (compared to the top); thus when part of the flow in the main-channel changes direction to move into the lateral-channel, most of it comes from the bottom part of the flow.

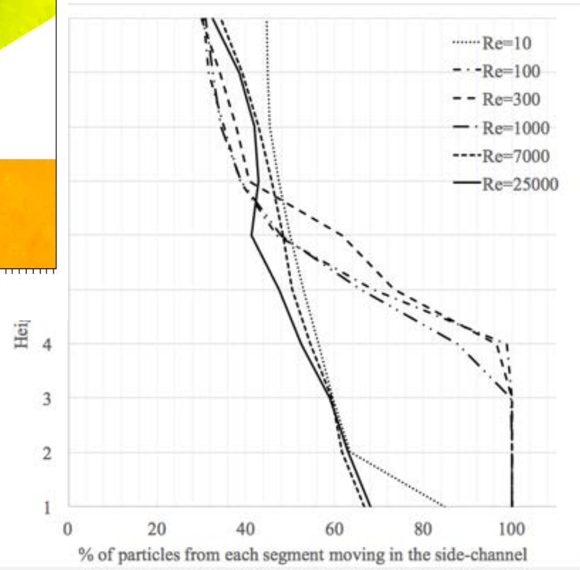
- For laminar cases almost 100 percent of the flow in the bottom 30-40 percent of the channel enters the lateral-channel, and for turbulent flows 60-70 percent in the bottom 25-35 percent of the flow. [when flow division 50:50]

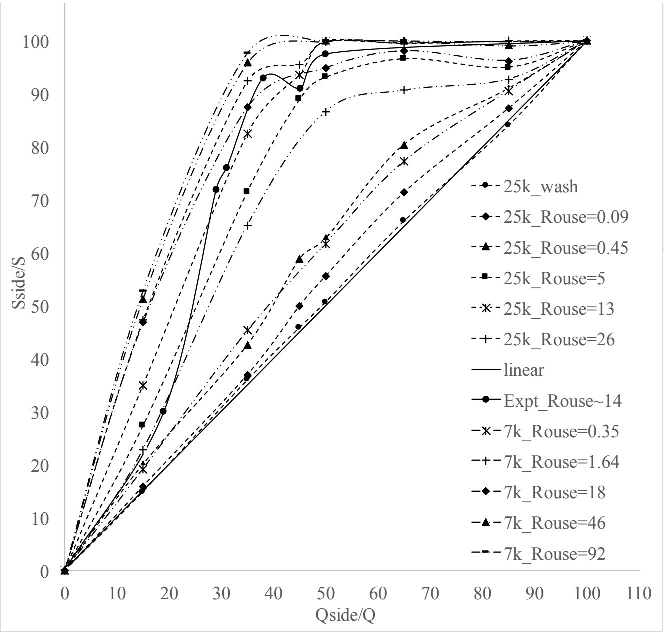
- Bulle-Effect not only causes non-linear distribution of bedload, it can also cause non-linear distribution of suspended sediment.

- The proclivity of sediment to enter lateral-channel increases with increase in sediment-size. Though a better parameter is Rouse number.





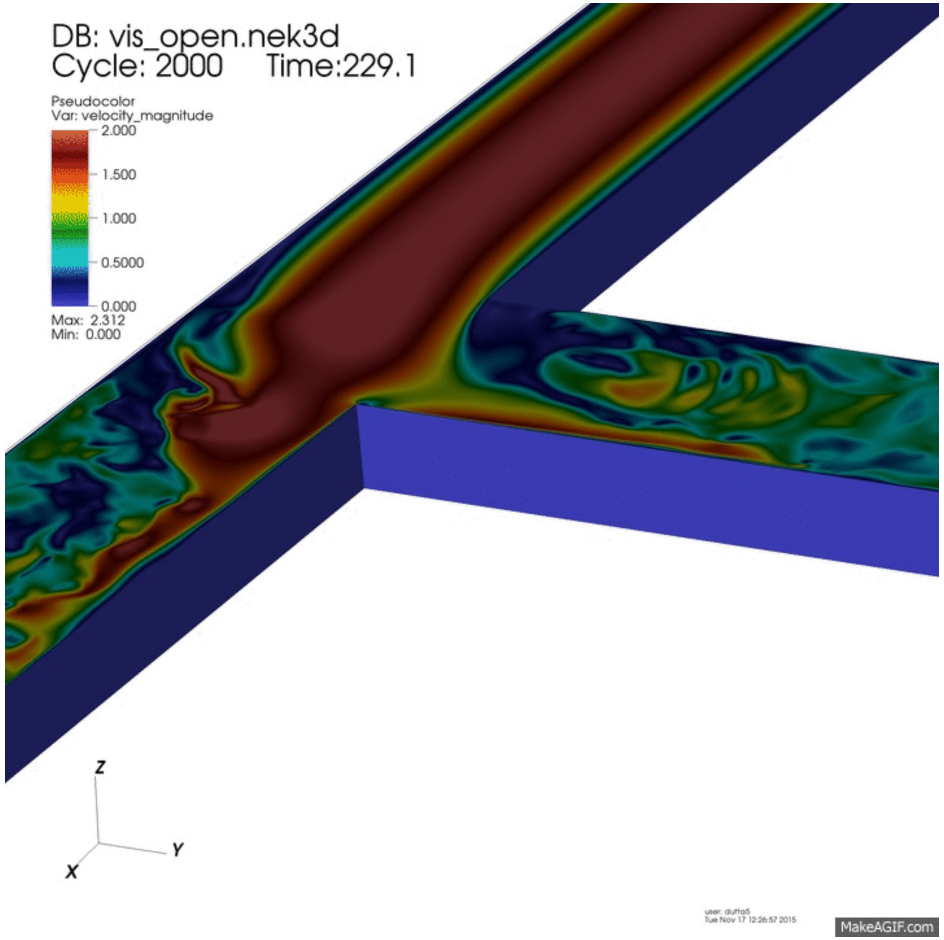




Acknowledgements and Collaboration with Blue Waters team

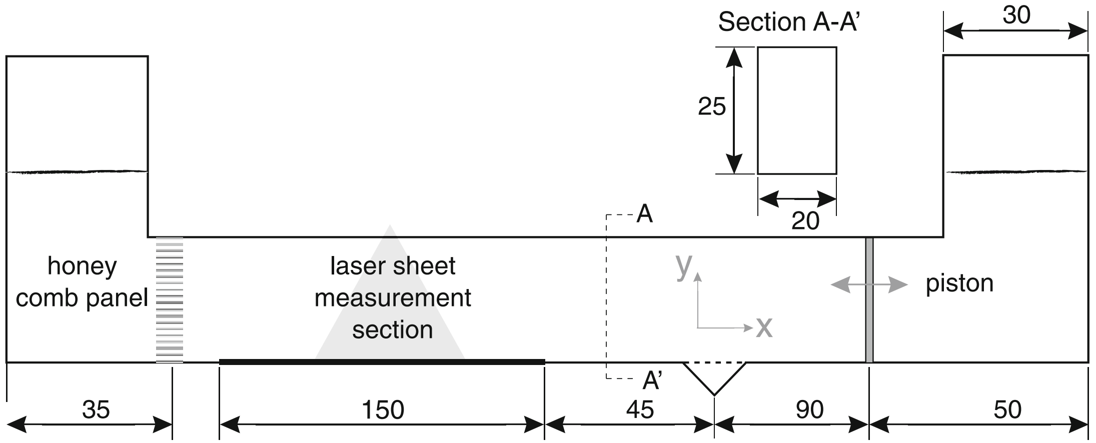
- We are also in communication with Rob Sisneros and Mark Van Moer to create animations for some of the simulation cases.

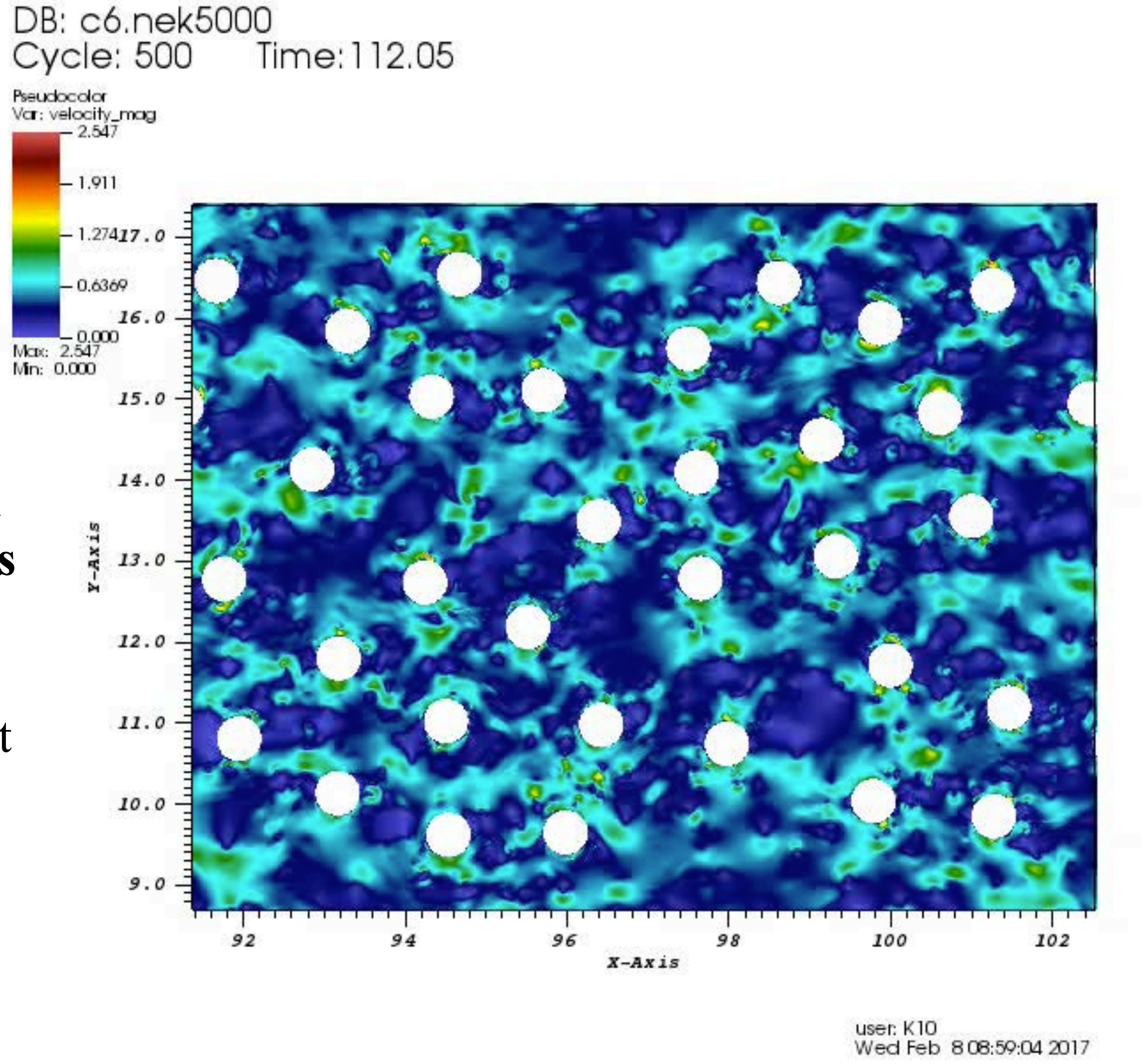
- Dr. Greg Bauer, for responding regularly on questions about proposals and optimizing Nek5000 on Blue-Waters.

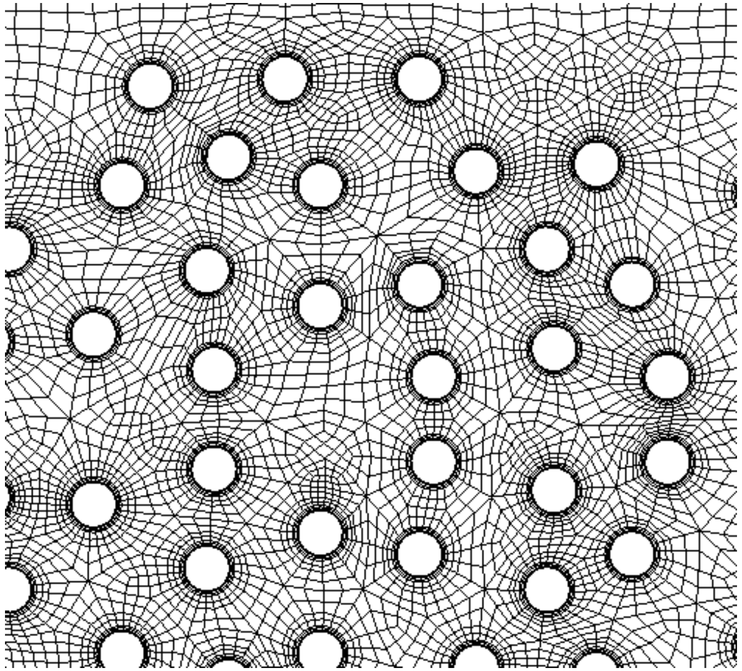


Other Phenomena currently being studied

Oscillatory Flow and Sediment transport through an array of aquatic vegetation







In collaboration with **Prof. Rafael Tinoco's group at UIUC**

The size of the largest simulations is of the order ~ 500 million computational points

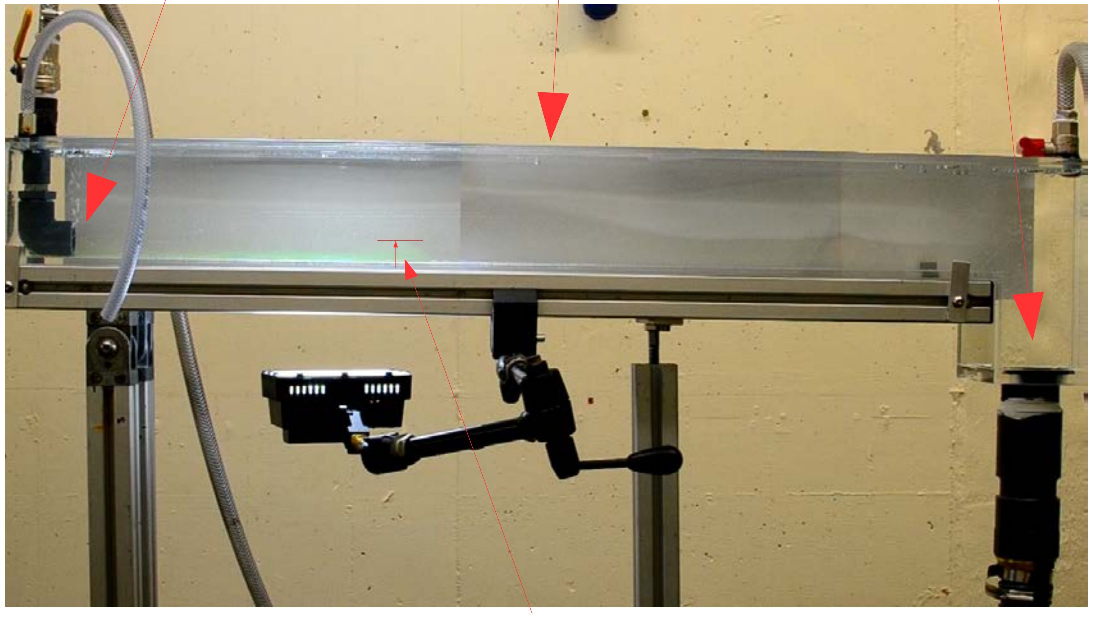
Other Phenomena currently being studied

Dynamics of continuously flowing gravity current

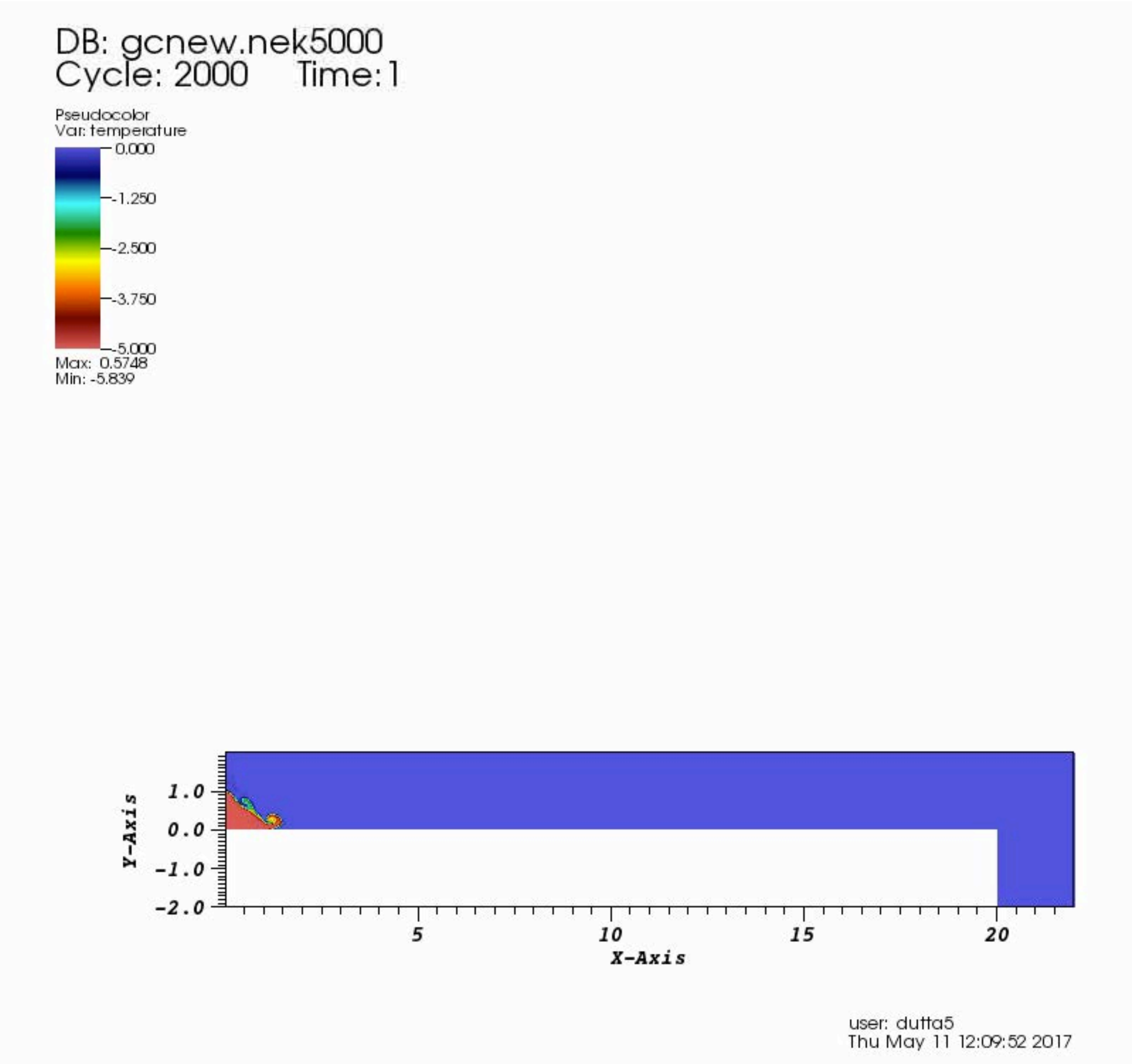
Dense fluid inlet

Duct, to prevent surface waves

Outlet



Approximate current height



In collaboration with Caroline Shields and Dr. Rob Dorell from U. Leeds, England