# On the influence of coherent structures on flow hydrodynamics, transport and mixing at river confluences

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## Are fancy numerical simulations of any value for a river mechanics person?

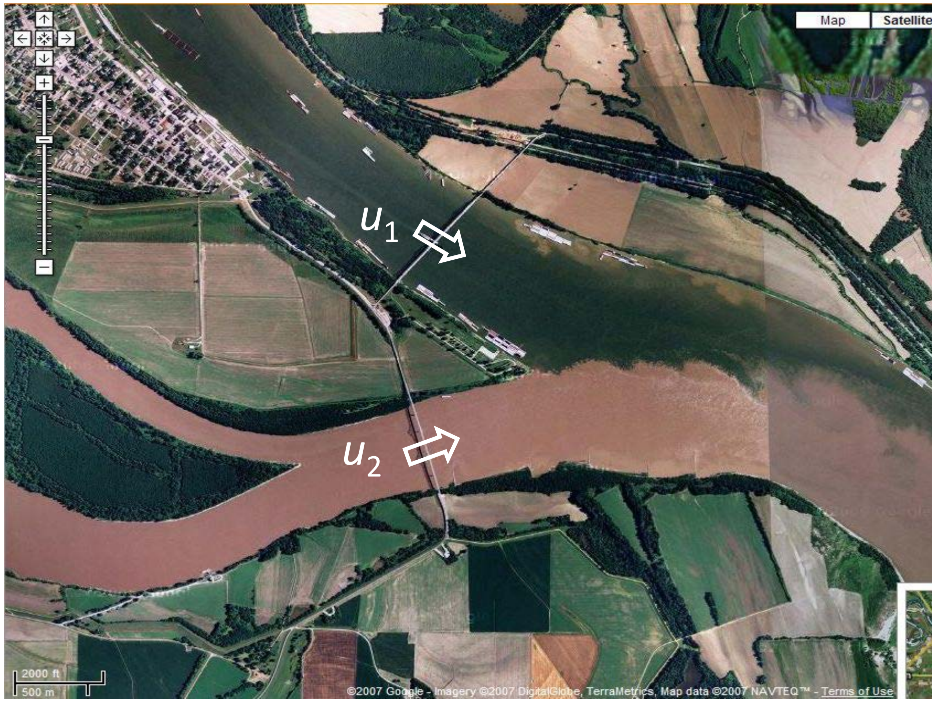
# INTRODUCTION

## River confluences

- fundamental elements of natural drainage networks

- play an important role in regulating the movement of sediment through braided river systems

- are habitats of high ecological value




- dynamics of mixing controls how tributary inputs of nutrients and food are dispersed within a main river

## General features:

- large-scale coherent structures form inside and around the MI

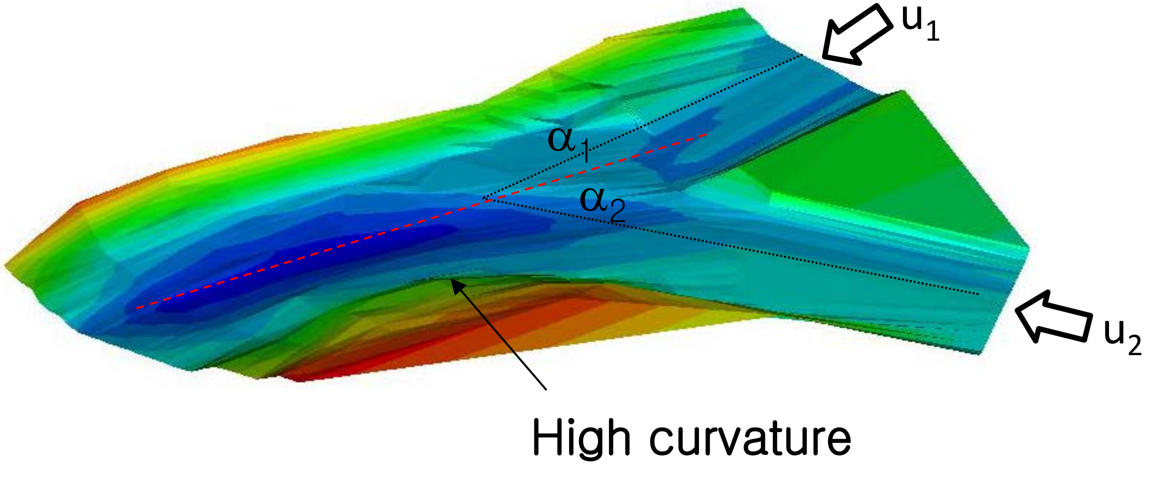
- flow conditions are fairly shallow

# MAIN PARAMETERS

- velocity ratio $VR=U_1/U_2$

- angles between the two incoming streams and downstream channel

- degree of concordance of the channel bed



# THE PLAN

-explore a system where large-scale coherent structures control mass exchange, mixing and transport processes

-try to validate/amend some hypotheses advanced based on limited amounts of field/laboratory data

-go from simple to complex:

-sometimes we can learn a lot from less complex cases (fewer variables, simpler to understand and parameterize)

-be aware these less complex cases are not relevant for all types of natural stream confluences

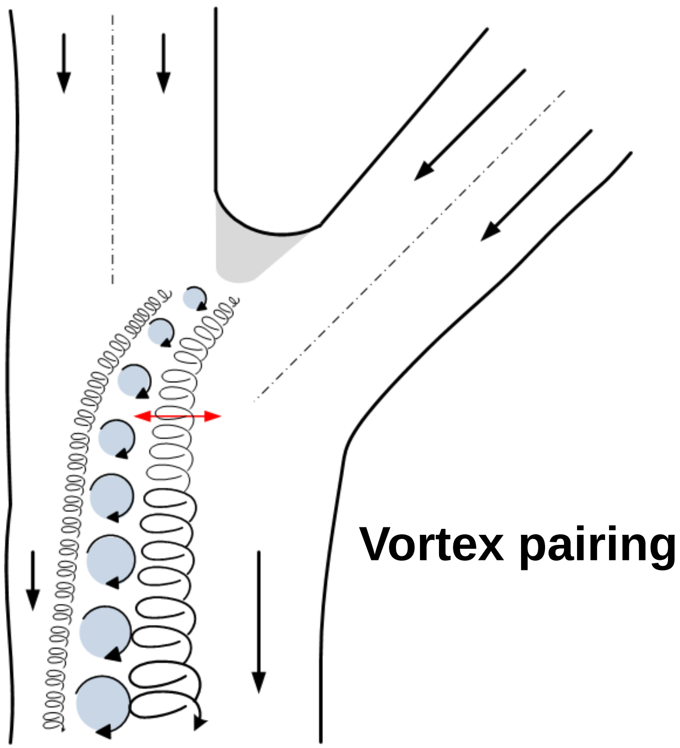
# MIXING INTERFACES AT RIVER CONFLUENCES

-Except maybe for confluences with a high degree of bed discordance, the region where the two streams come into contact can be described as a shallow MI containing quasi-2D eddies

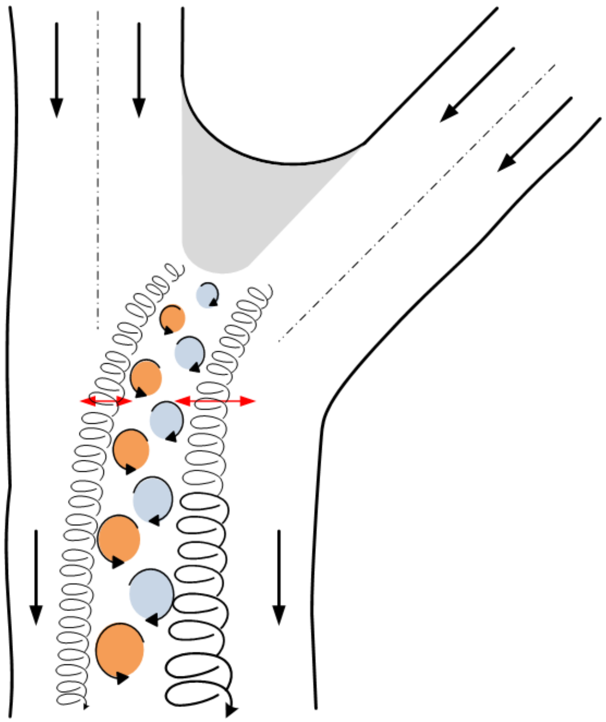
-At river confluences, development of MI is strongly affected by bed friction

# Classification of Mixing Interfaces
## (Constantinescu et al, WRR 2011, JGR 2012)

Kelvin-Helmholtz mode (VR>>1)




Wake mode (VR~1)



# MIXING INTERFACES

**-If the angle between the two streams is small and the velocity difference between the two streams is high, MI resembles a**

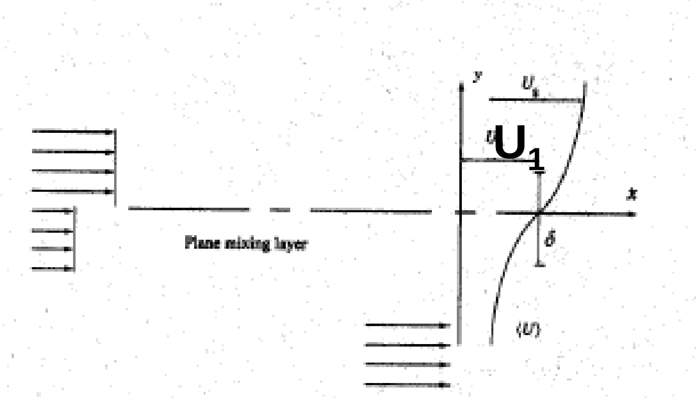
**SHALLOW MIXING LAYER developing between two parallel streams**

**-This is the simplest type of MI developing at a river confluence**

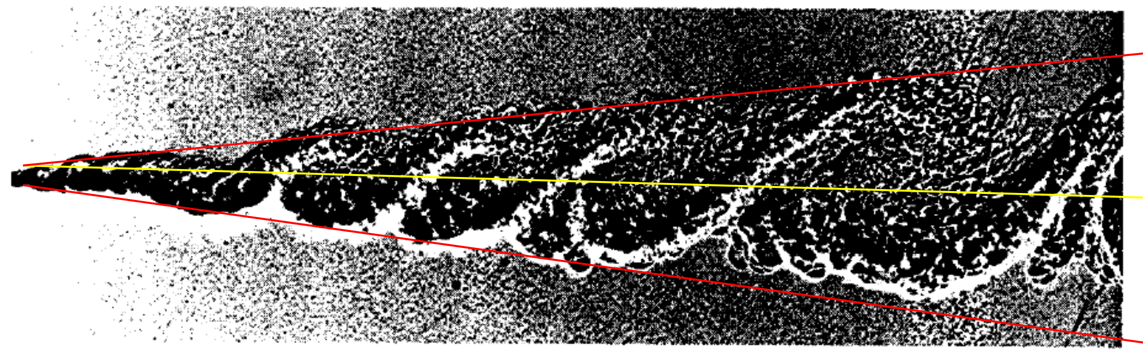
**-Some fundamental results:**

# BACKGROUND

## Simplest case of ML: ‘Deep’ ML




U2



**Visualization of structure of turbulent ML (Brown and Roshko, JFM 1974)**

**-Mixing layer is self-similar**

**Spreading Rate** $$\frac{d\delta(x)}{dx} = const = \frac{\Delta U}{U_c} S'$$ S’~0.09

**-A deep mixing layer grows linearly with no bound!**

**-Vortex pairing produces larger and larger KH billows**

# Confluences between parallel streams

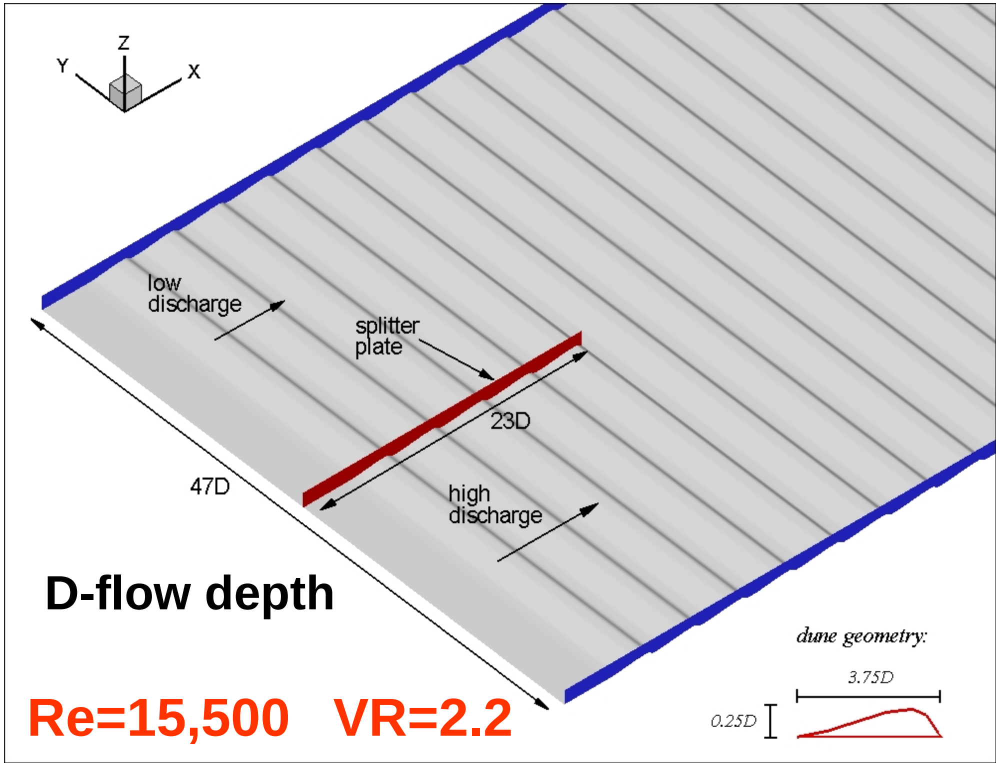
**Main parameter describing spatial development of a shallow ML:**

## S – bed friction number

$$S(x) = \frac{\bar{c}_f \delta(x)}{2D(x)} \frac{U_C(x)}{\Delta U(x)}$$

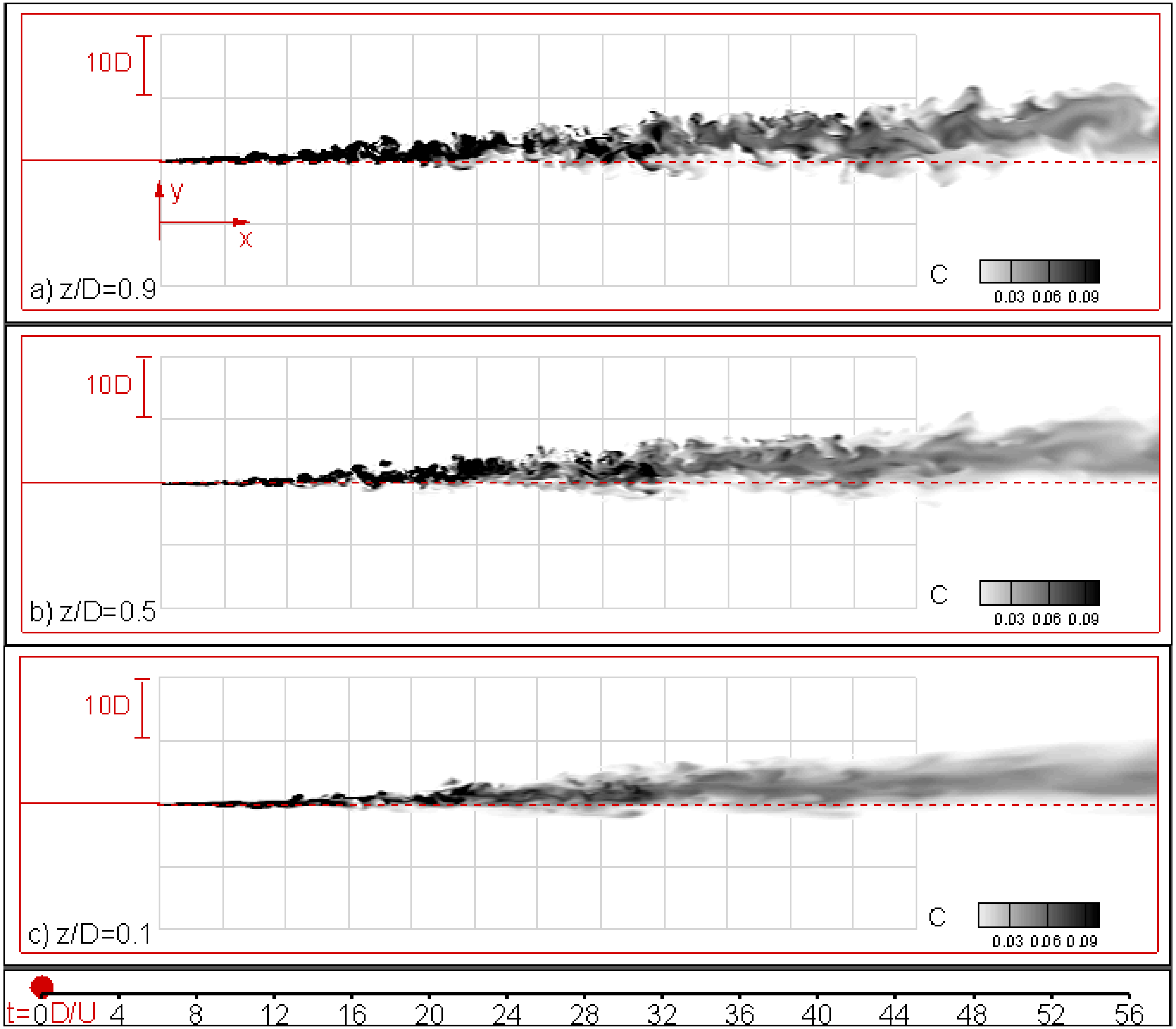
**-characterizes stabilizing influence of bottom friction on ML development**

**-S=Sc equilibrium**
**-Sc~0.1**
**-shift and width of ML do not vary with x**



# Confluences between parallel streams

## SMOOTH BED

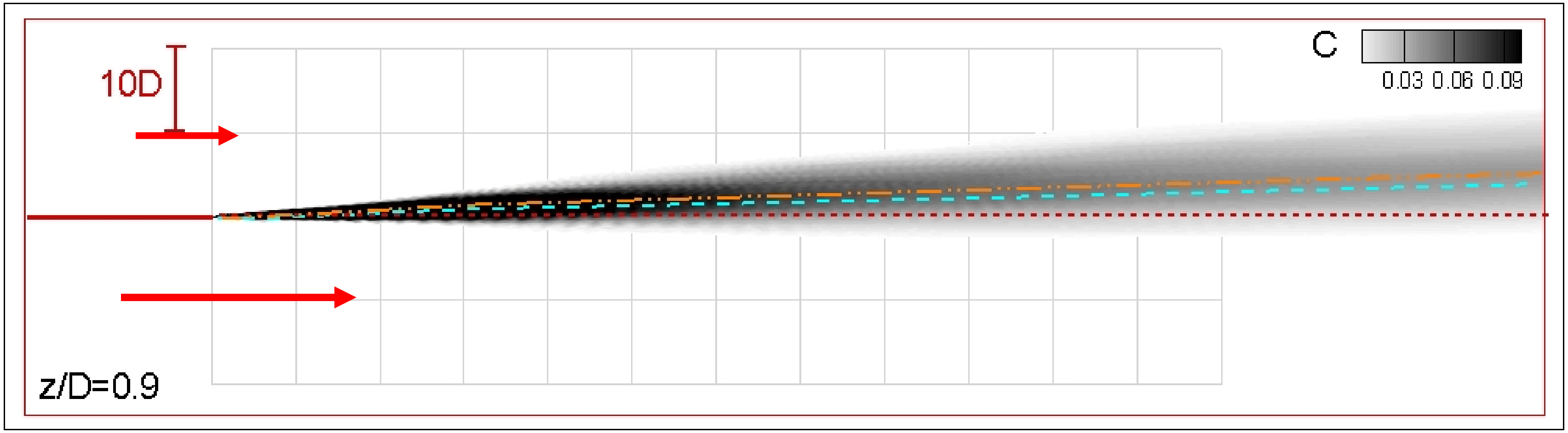



Kirkil and Constantinescu, 2009

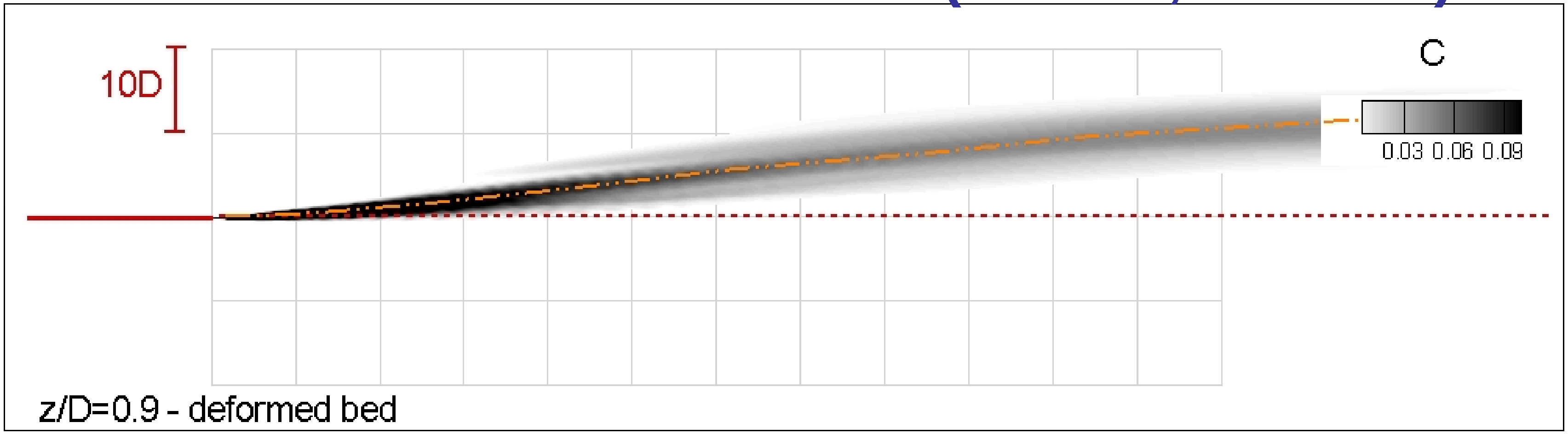
**Max size=10-15D**

# Confluences between parallel streams
# Effect of bed friction

## SMOOTH BED




## ROUGH BED (DUNES, H=0.25D)




Kirkil and Constantinescu, 2008

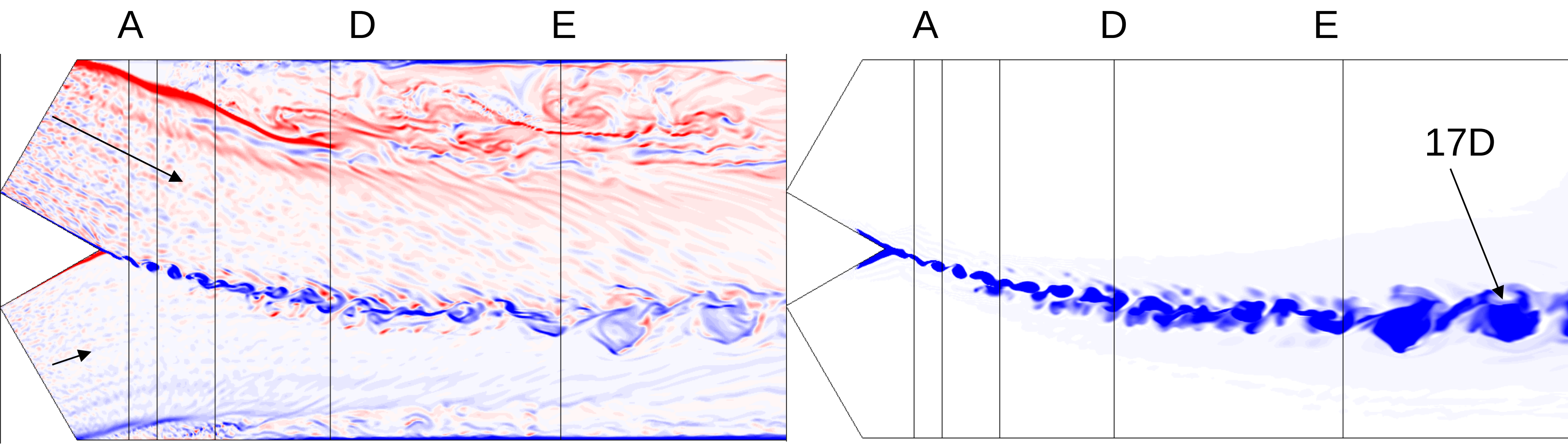
# MIXING INTERFACES

-If the angle between the two streams is large and the velocity difference between the two streams is high, we get a more complex type of MI:

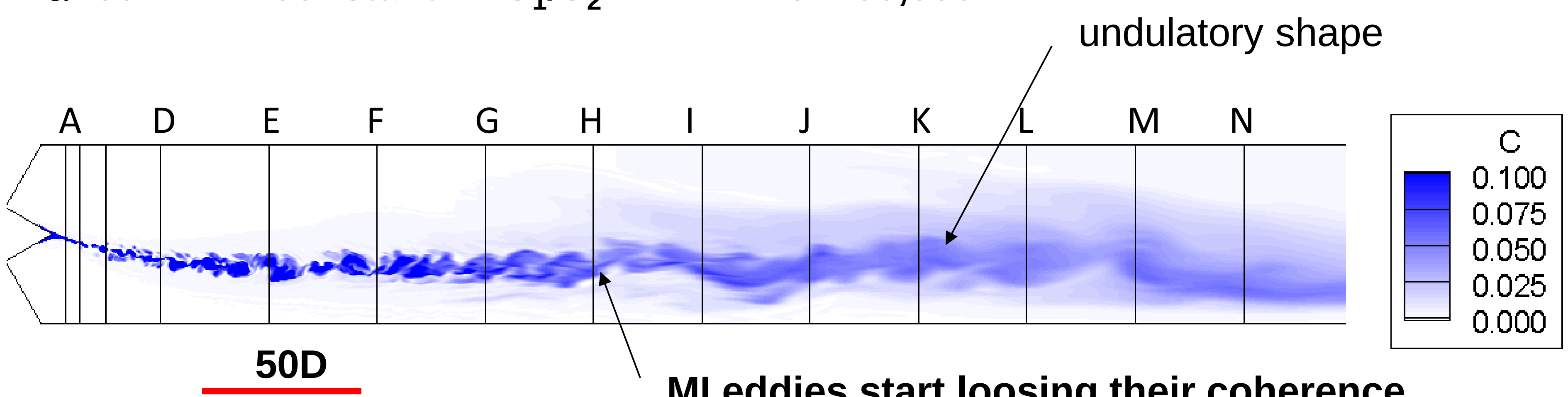
SHALLOW MIXING LAYER developing between two non-parallel streams

-Some interesting results obtained in an idealized geometry:

# MI at a confluence between two non-parallel streams




**$\alpha$=60$^0$  D=constant  $U_1/U_2$=2  Re=200,000**




**MI eddies start loosing their coherence after shift of the MI becomes constant (x~250D)**

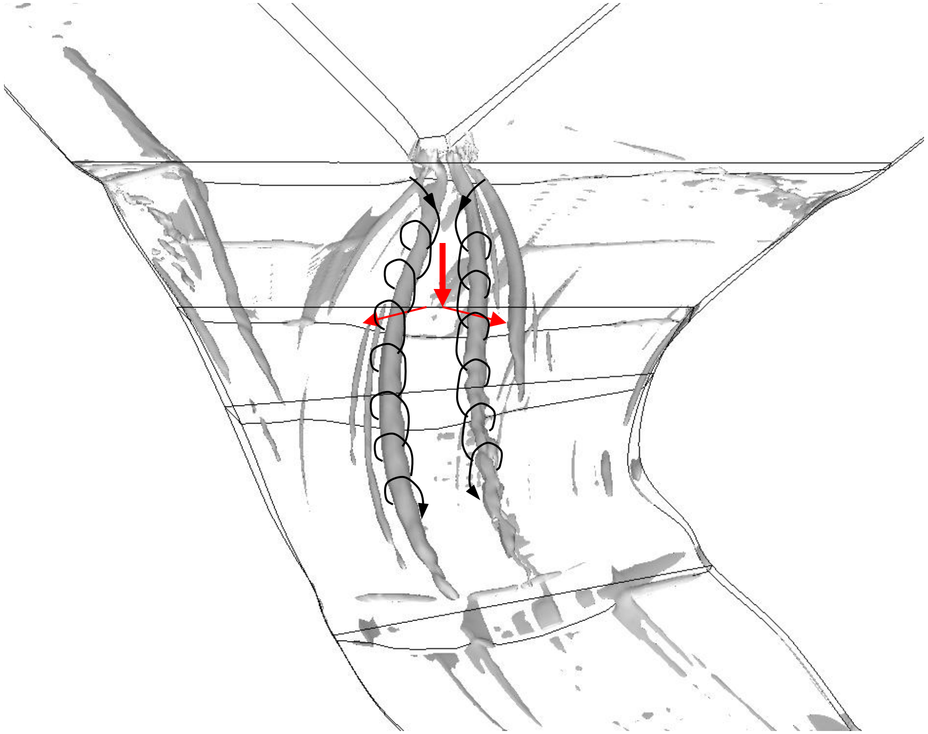
# QUESTION

## Besides MI eddies are there other types of large-scale coherent structures forming close to the MI?

-Generally, the answer is positive

-SOV cells can form in the vicinity of the MI, especially for confluences at which the degree of bed discordance is not very high

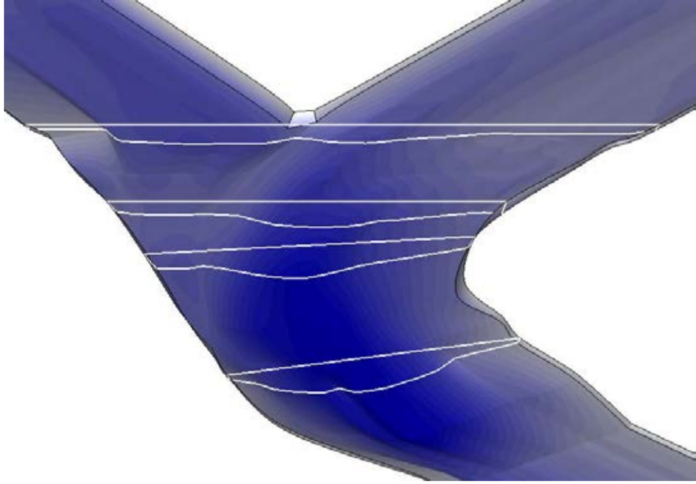
# Mechanism responsible for formation of SOV cells



-**Sediment entrained and transported by SOV cells** is the main cause for the large dimensions of confluence scour holes ($D_{scour}$~5D; Best & Ashworth, Nature 1997)

-**Mass exchange processes and thermal mixing** between the two streams are strongly affected by the SOV cells

# MIXING INTERFACES



**-Let us finally consider a natural stream confluence**

**-Small river confluence in Illinois**

**- Asymmetrical confluence with concordant bed**

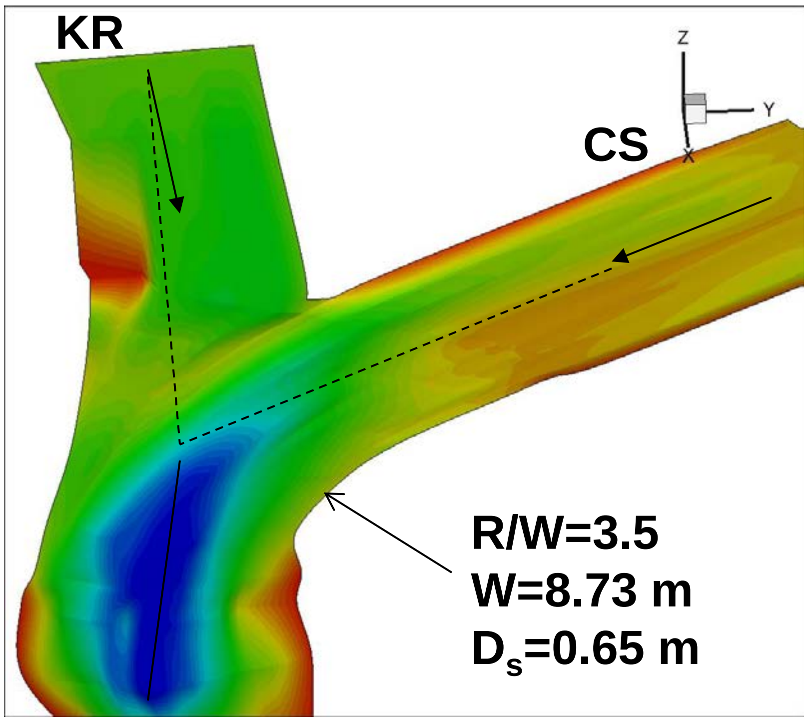
**-Angles: $0^0$, $60^0$**

**-Field data available for validation (Rhoads & Sukhodolov, 2001, 2004, 2008)**

# CONFLUENCE BATHYMETRY

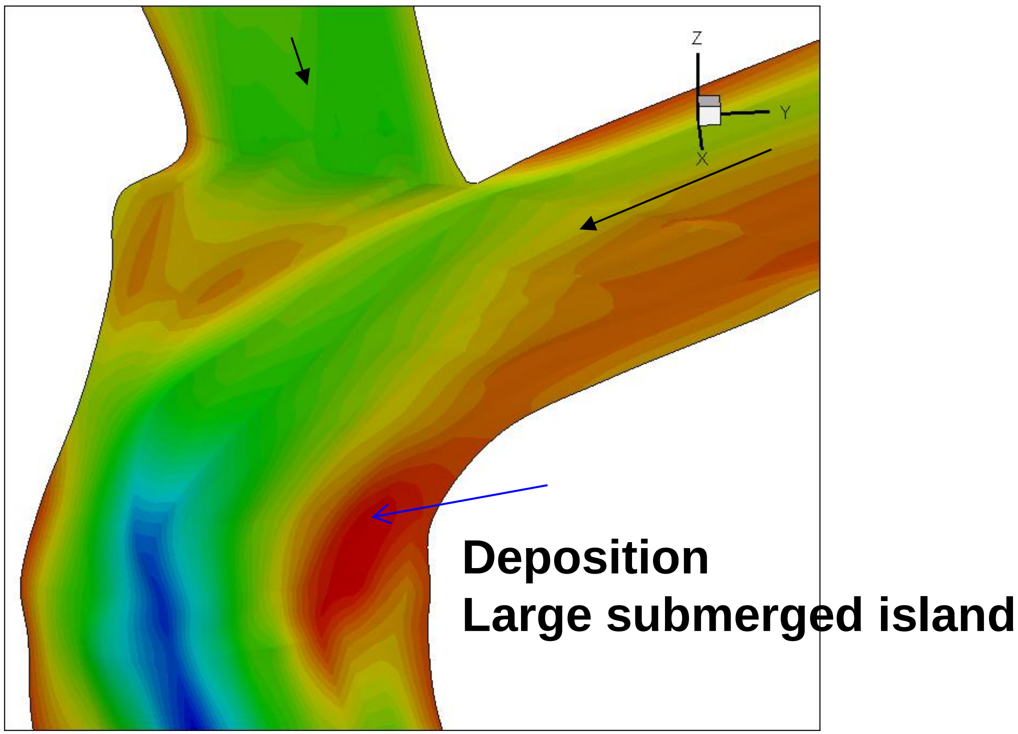
## CASE 1 (Vr~1)

Re~166,000 (D=0.36m U=0.45 m/s)




## CASE 2 (Vr=5.5) - 1 year later

Re~77,000 (D=0.23m U=0.34 m/s)

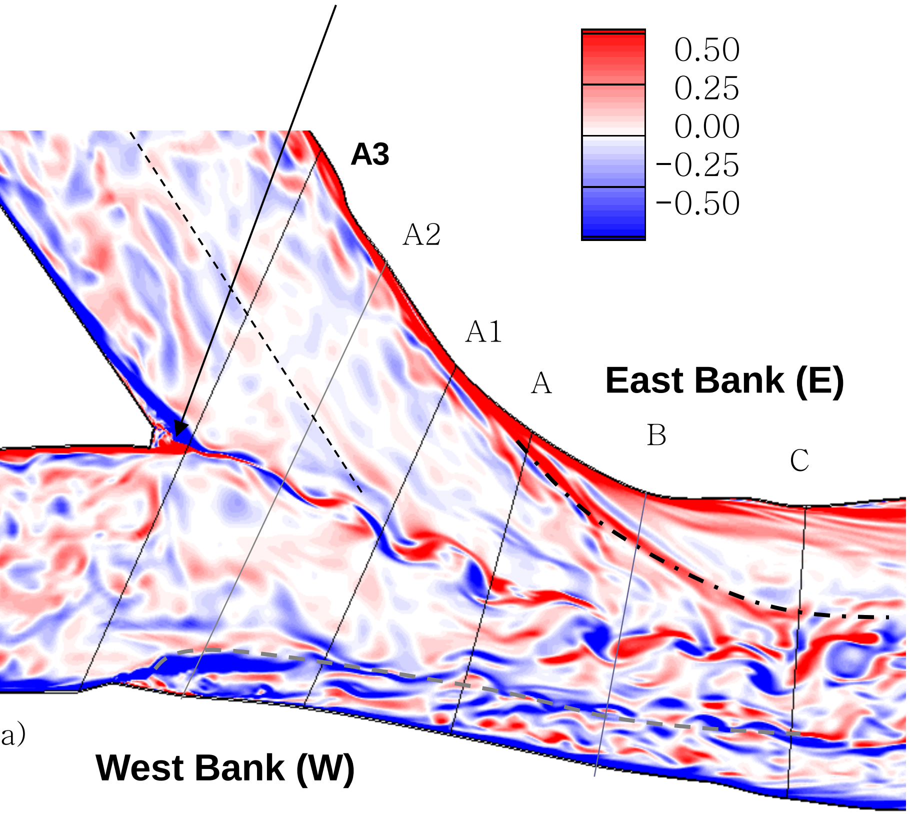


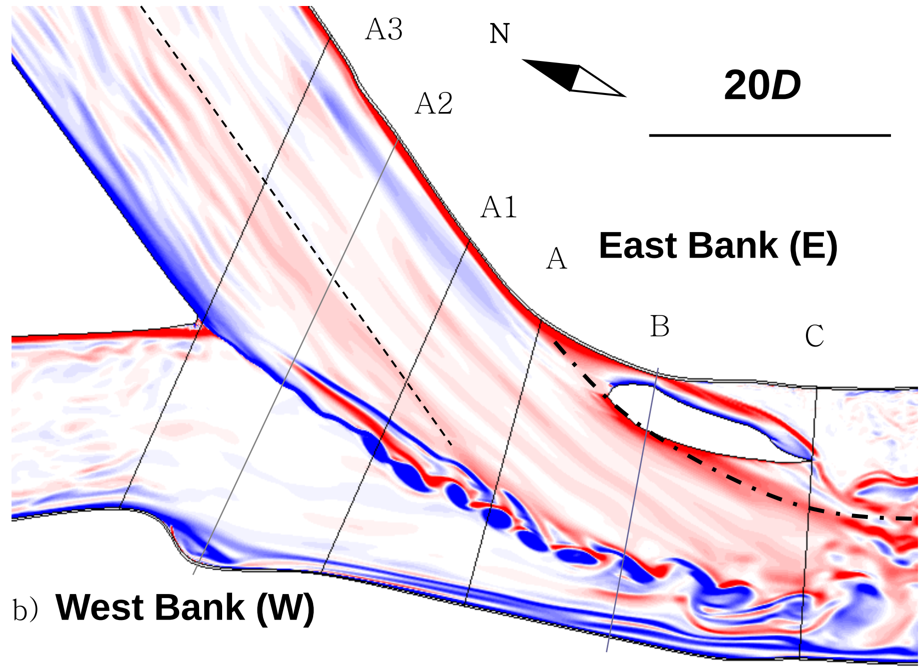
# Vortical structure close to free surface

**VR~1**

**VR=5.5**

**Wake region**



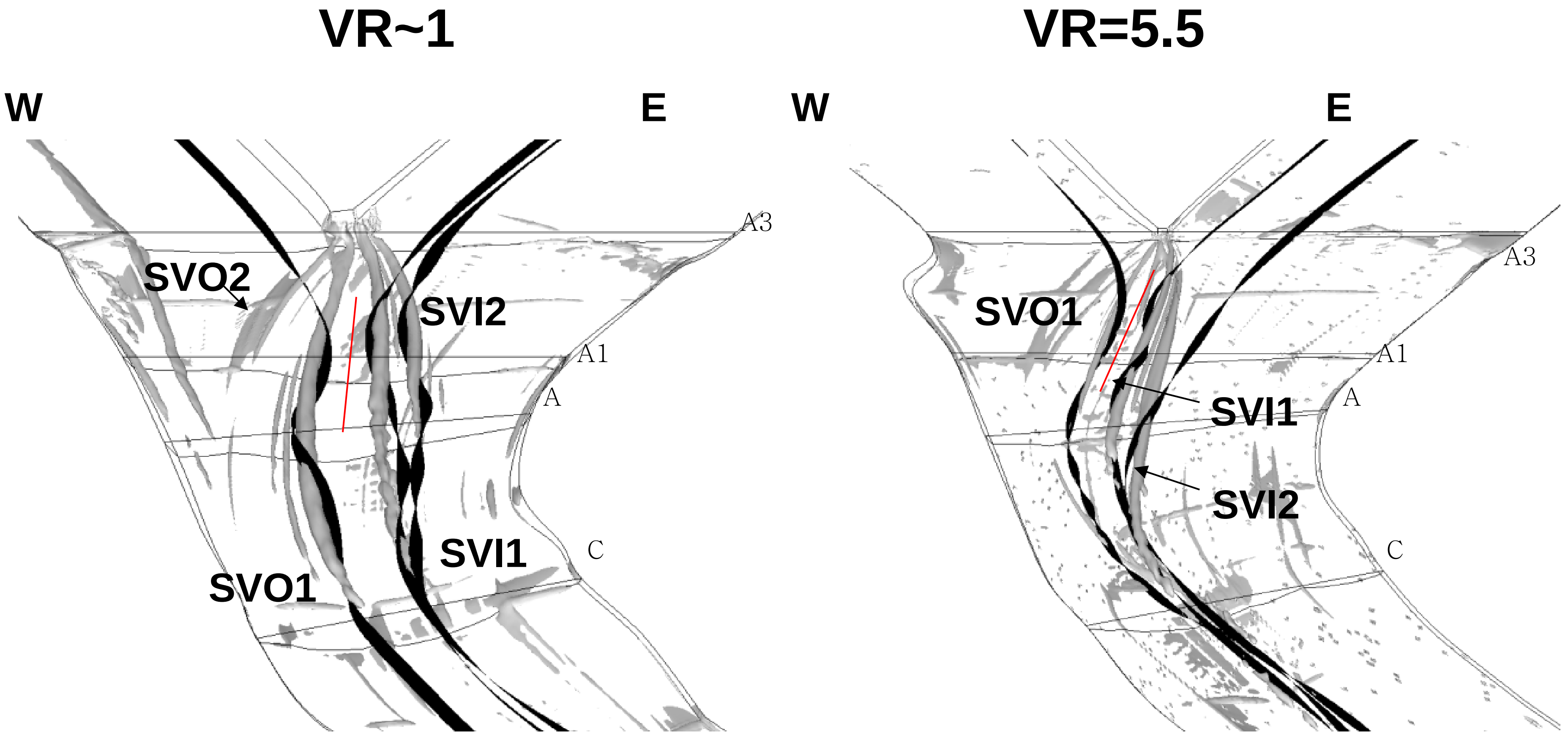

**Case 1: MI is in wake mode (von Karman vortex street)**

**Case 2: MI is in KH mode**

**-MI contains eddies with opposite sense of rotation shed from wake region**

**-MI contains co-rotating eddies**

# Large-scale eddies below the free surface
# MEAN FLOW

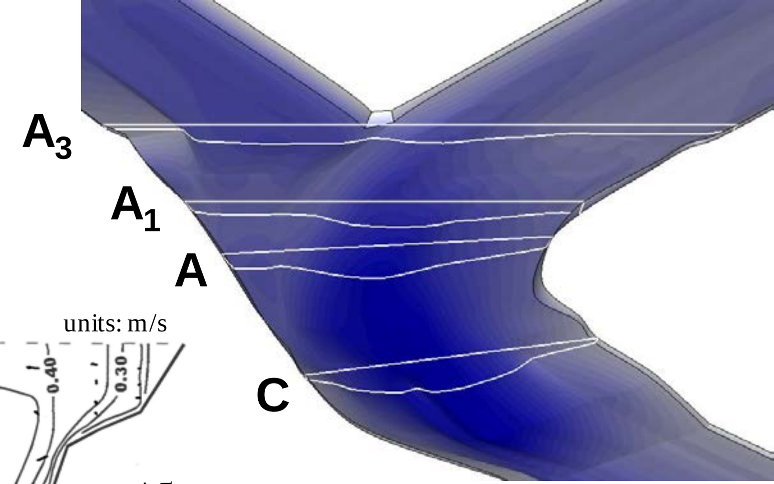



**-Primary SOV cells are counter-rotating**

**-VR=5.5: SOV cells are much more coherent on the high momentum side**

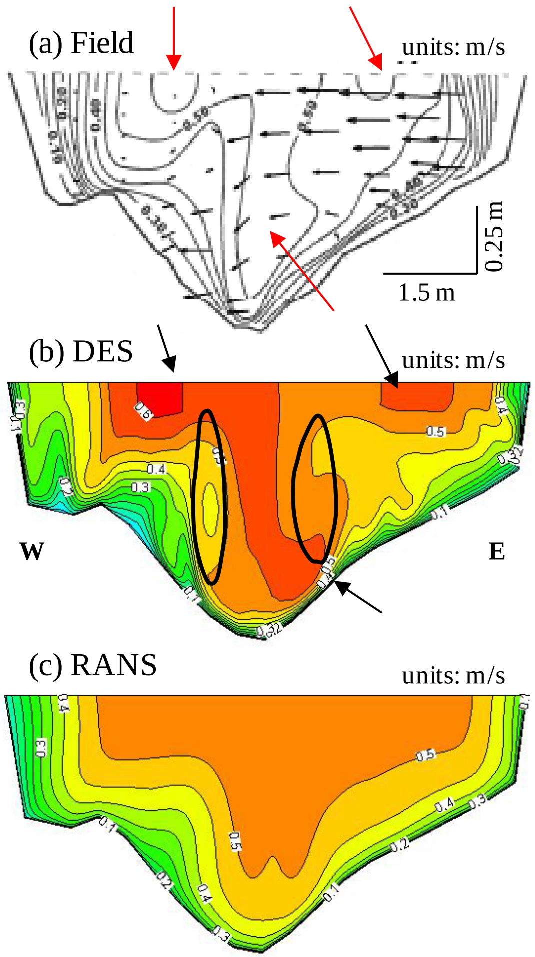
# VALIDATION (VR~1)

# Streamwise velocity

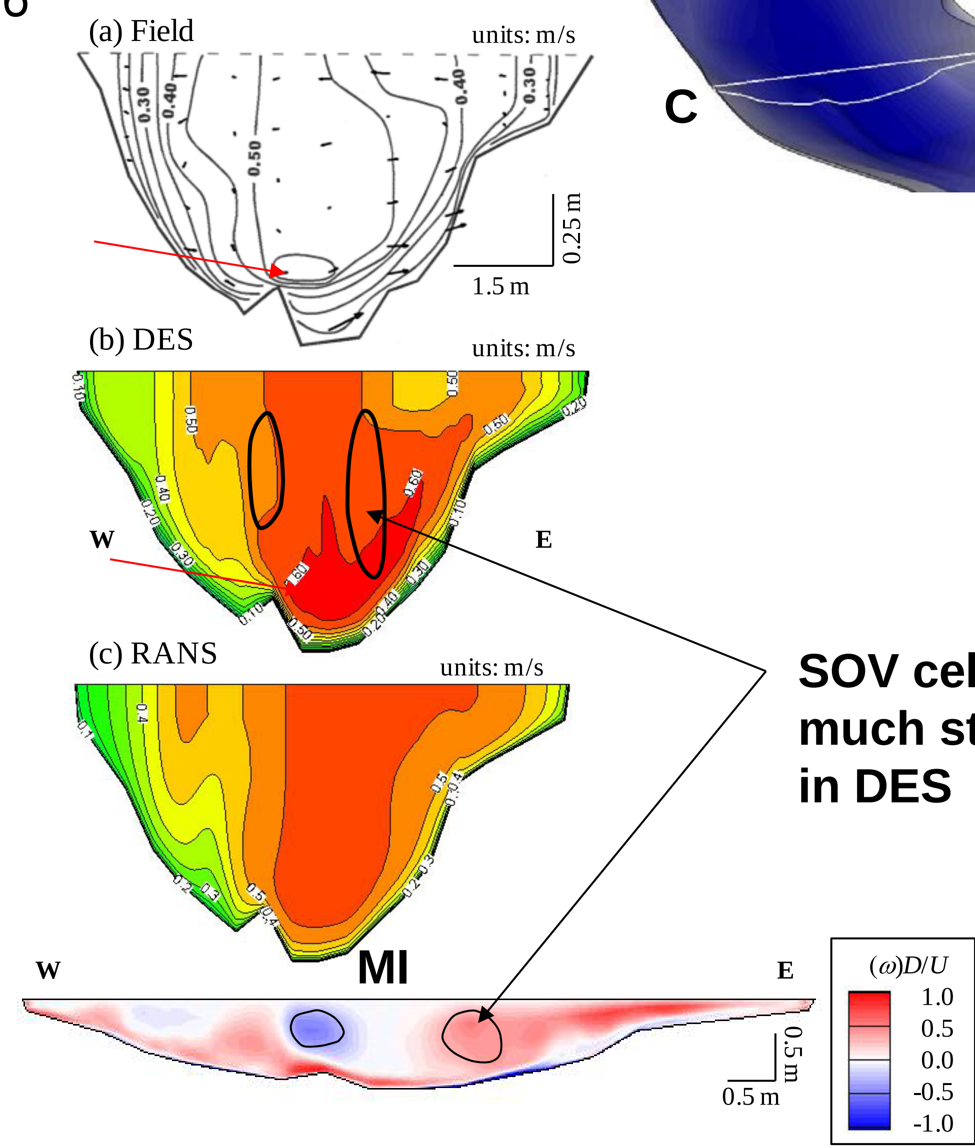



## Section A

Scale 1:6



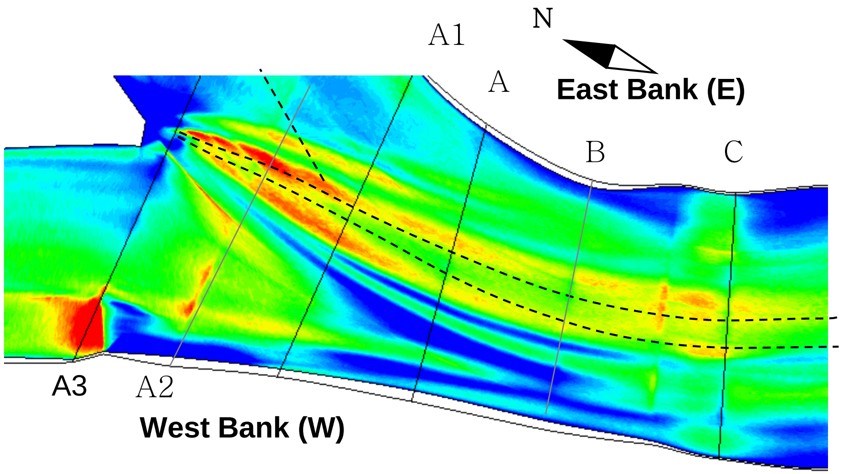

## Section C



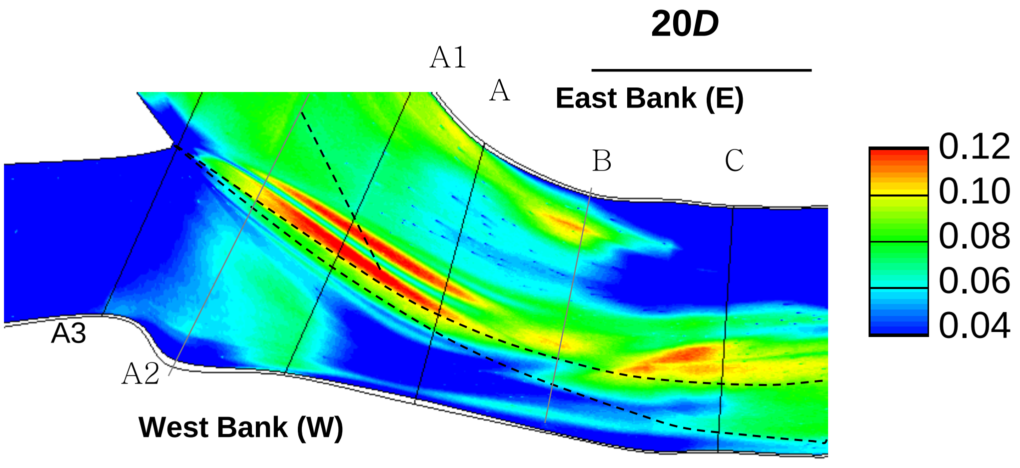

**SOV cells are much stronger in DES**

**Out-of-plane vorticity Section C –scale 1:1**

# Bed friction velocity: Mean flow

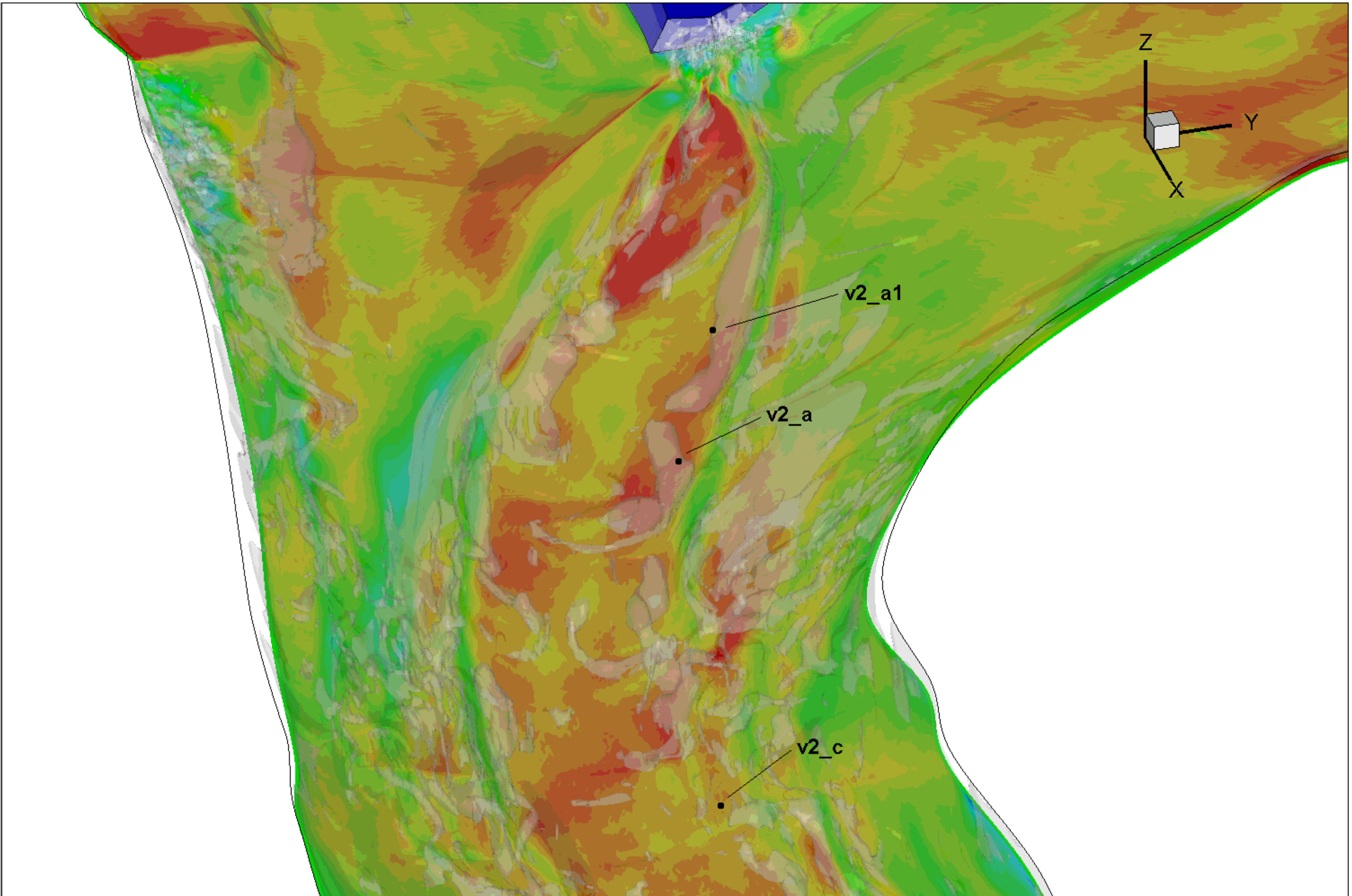



VR~1




VR=5.5

# Bed friction velocity: Instantaneous flow




**VR~1**

# Why do some of the SOV cells induce large bed friction velocities in the region where the two streams collide?

**-Incoming flow has to loose rapidly a large amount of transverse momentum as it approaches the MI**

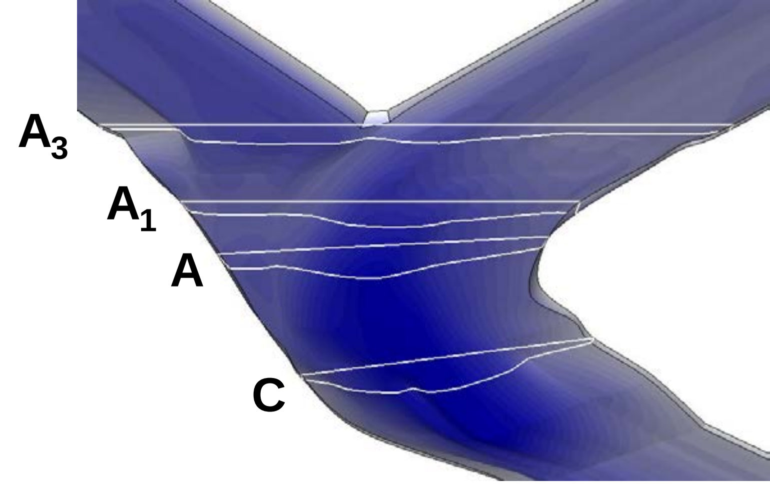
**-Strong adverse pressure gradients are created as the cores of high streamise velocities in the two streams approach the sides of the MI**

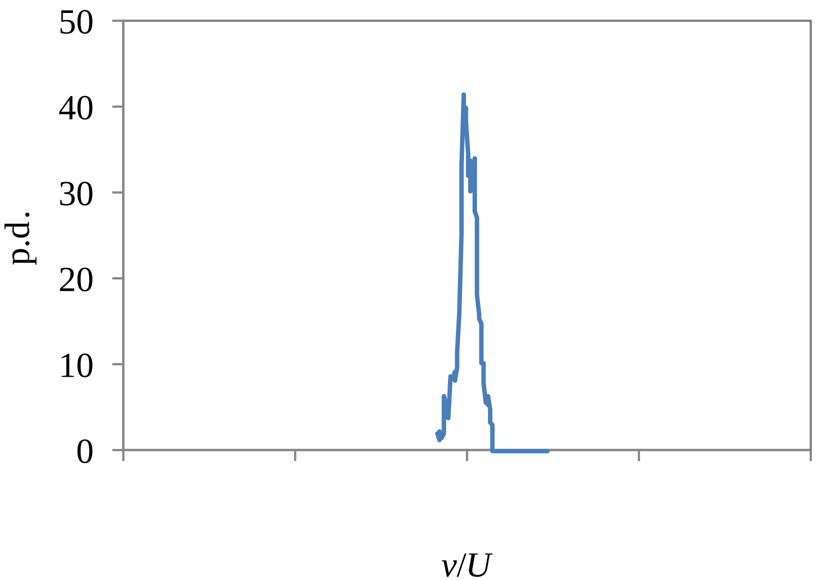
**-This situation is similar to junction flows in which the necklace vortices form in a region of strong flow deceleration**

**-The necklace vortices have a large capacity to entrain sediment because they are subject to large-scale bimodal oscillations**

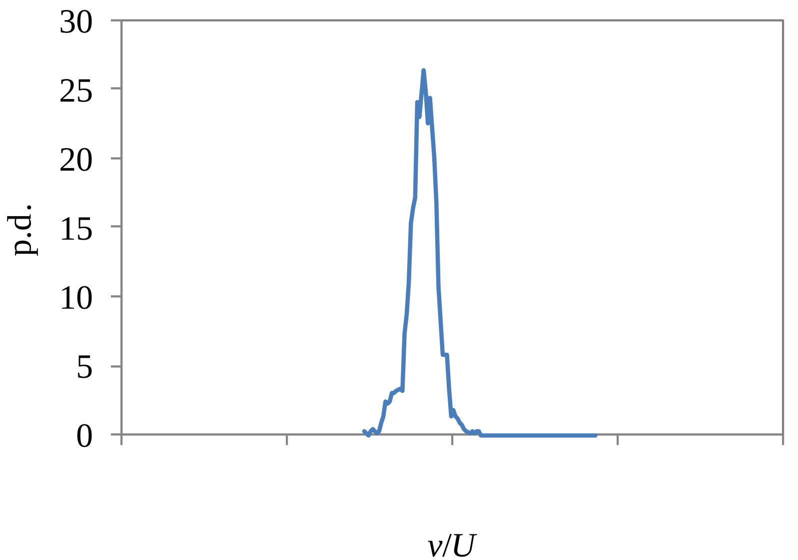
# Velocity histograms outside the main SOV cells:

## CASE 1 (VR~1)




**Incoming stream (CS)**



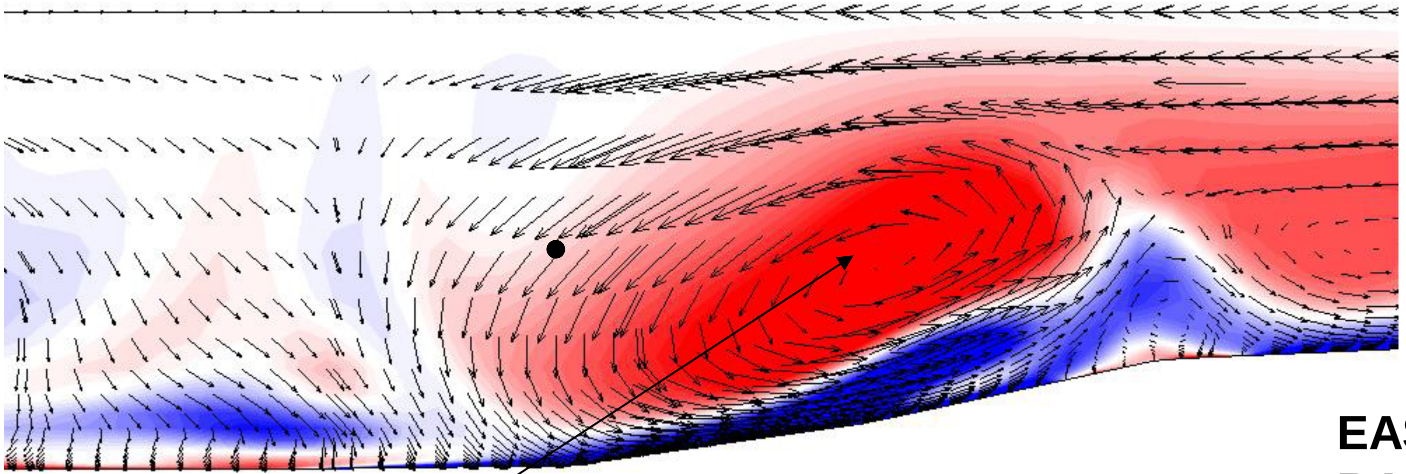

**Mixing Interface**

Velocity histograms contain only one peak

# Velocity histograms inside SVI1: VR~1

**Section $A_1$**

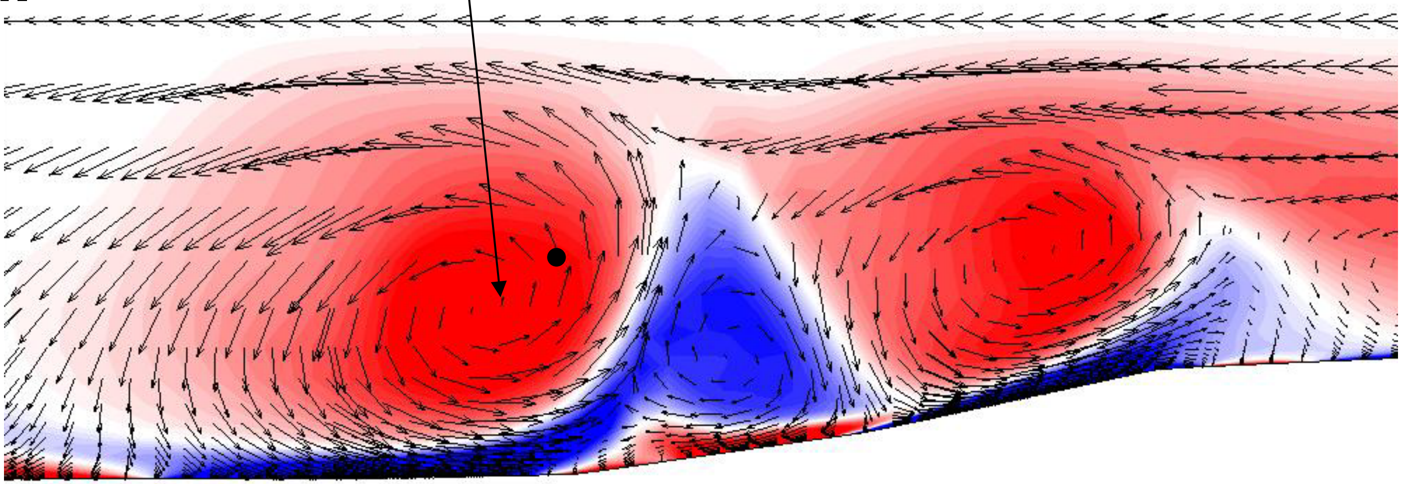
**Bank mode**



**MI**

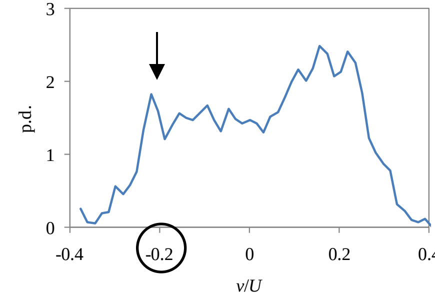
**SVI1**

**Interface mode**



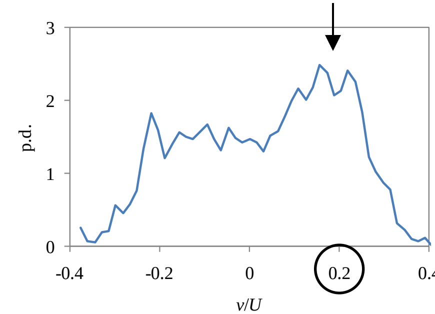
**Histograms of v**

BM




**EAST BANK**

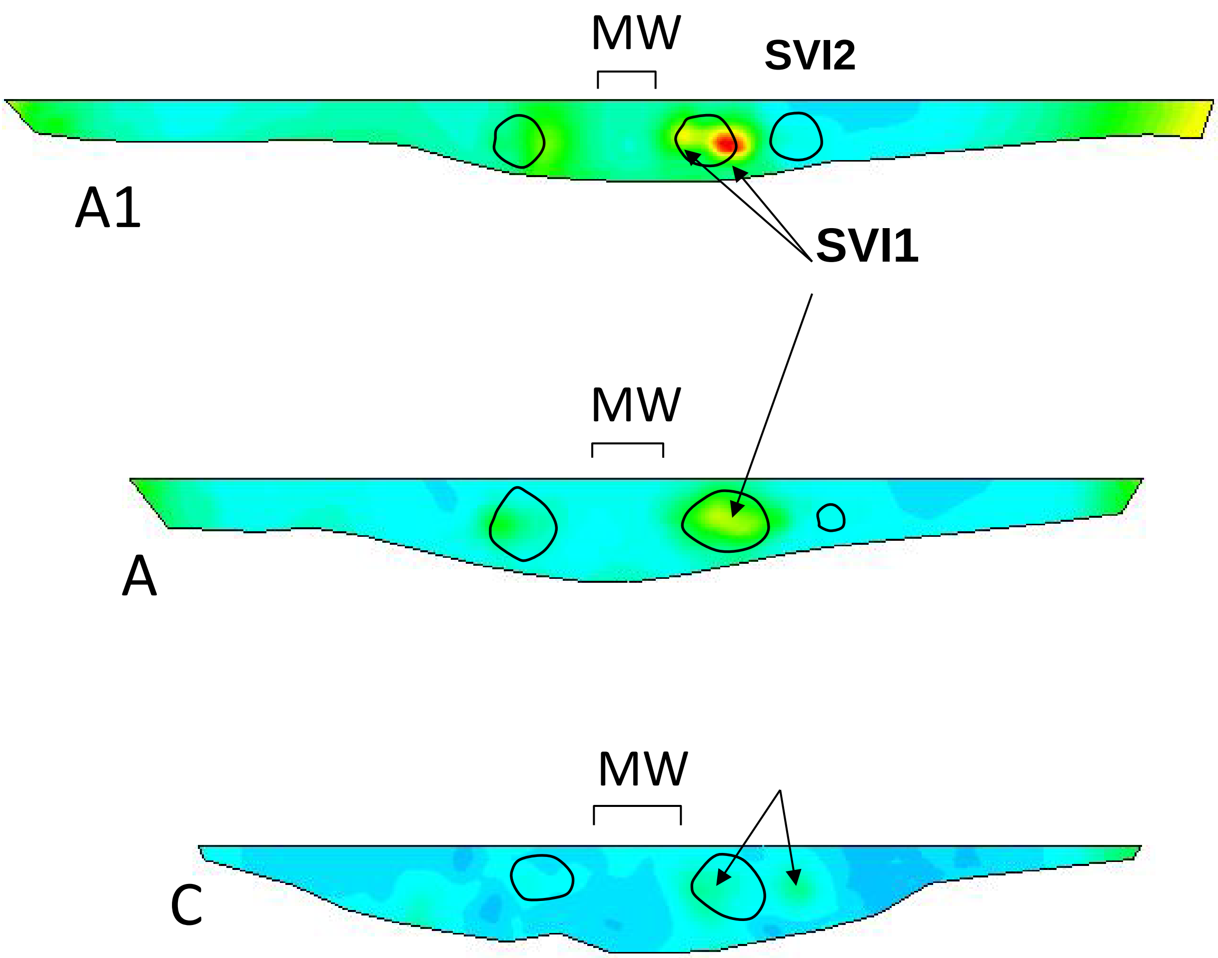
IM

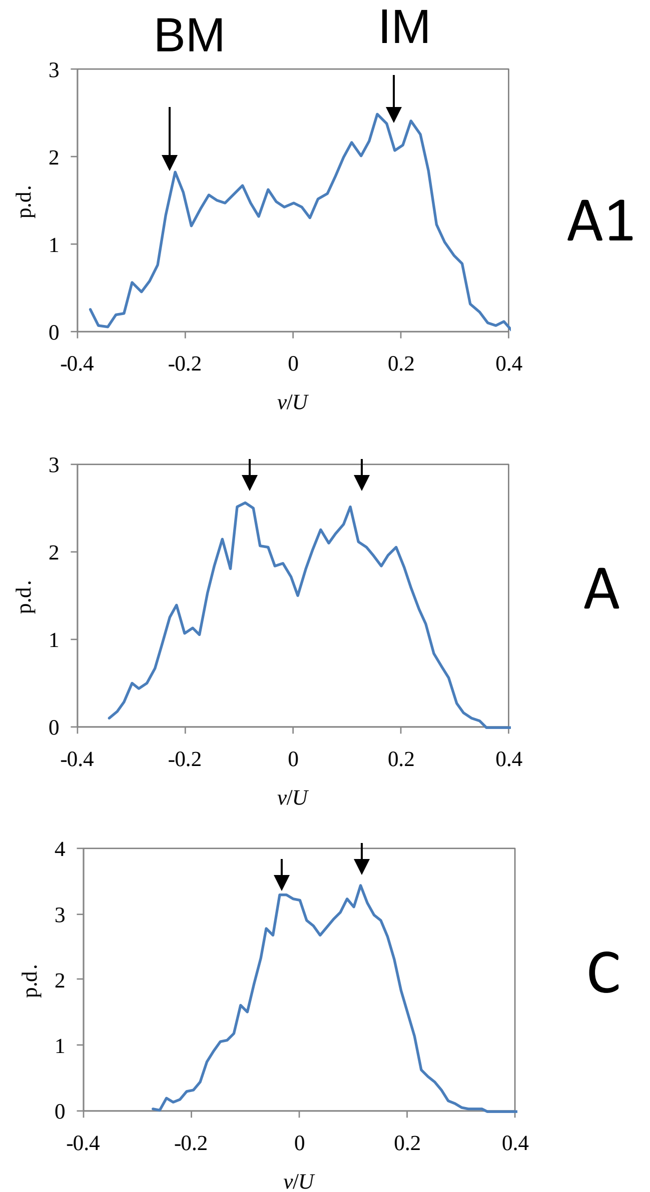



SVI1 is subject to bimodal oscillations

# Streamwise variation of intensity of bimodal oscillations:

**Pressure rms fluctuations**



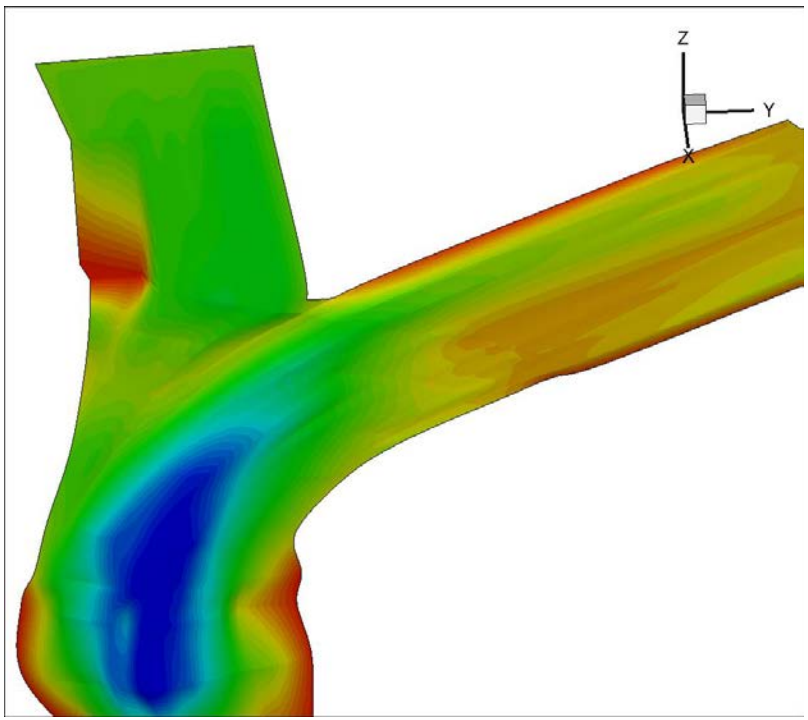




**Eventually, transition to 1-peak shape will occur in the downstream channel**

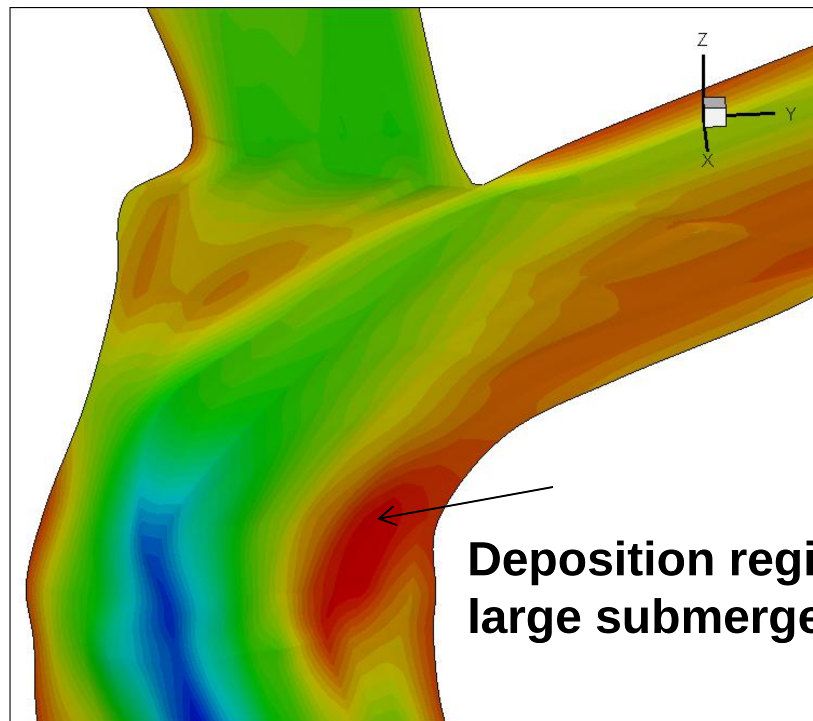
# Do SOV cells play a role in formation of a large deposition bar at the inner bank?

## BATHYMETRY

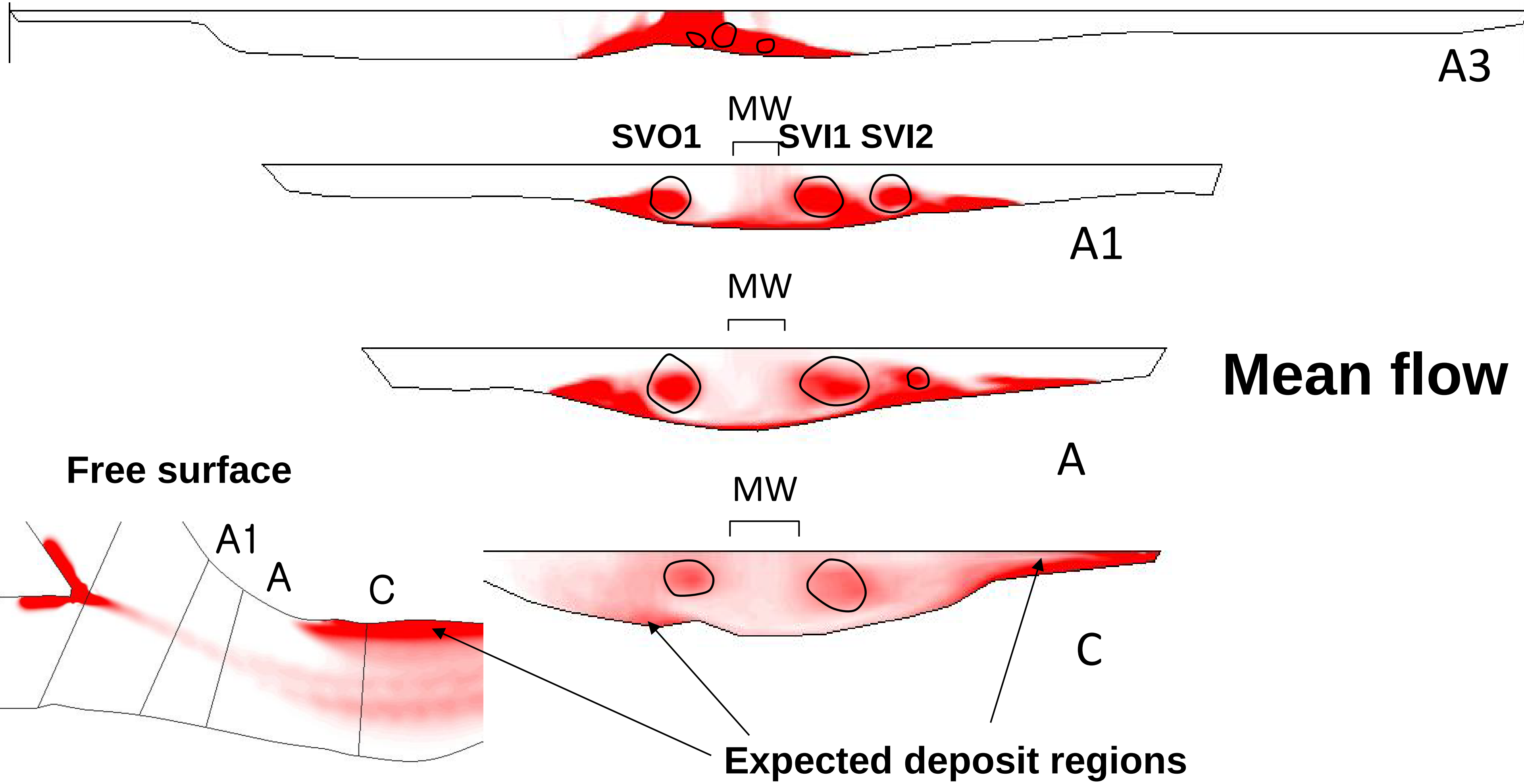
**CASE 1**




**CASE 2 (1 year later)**



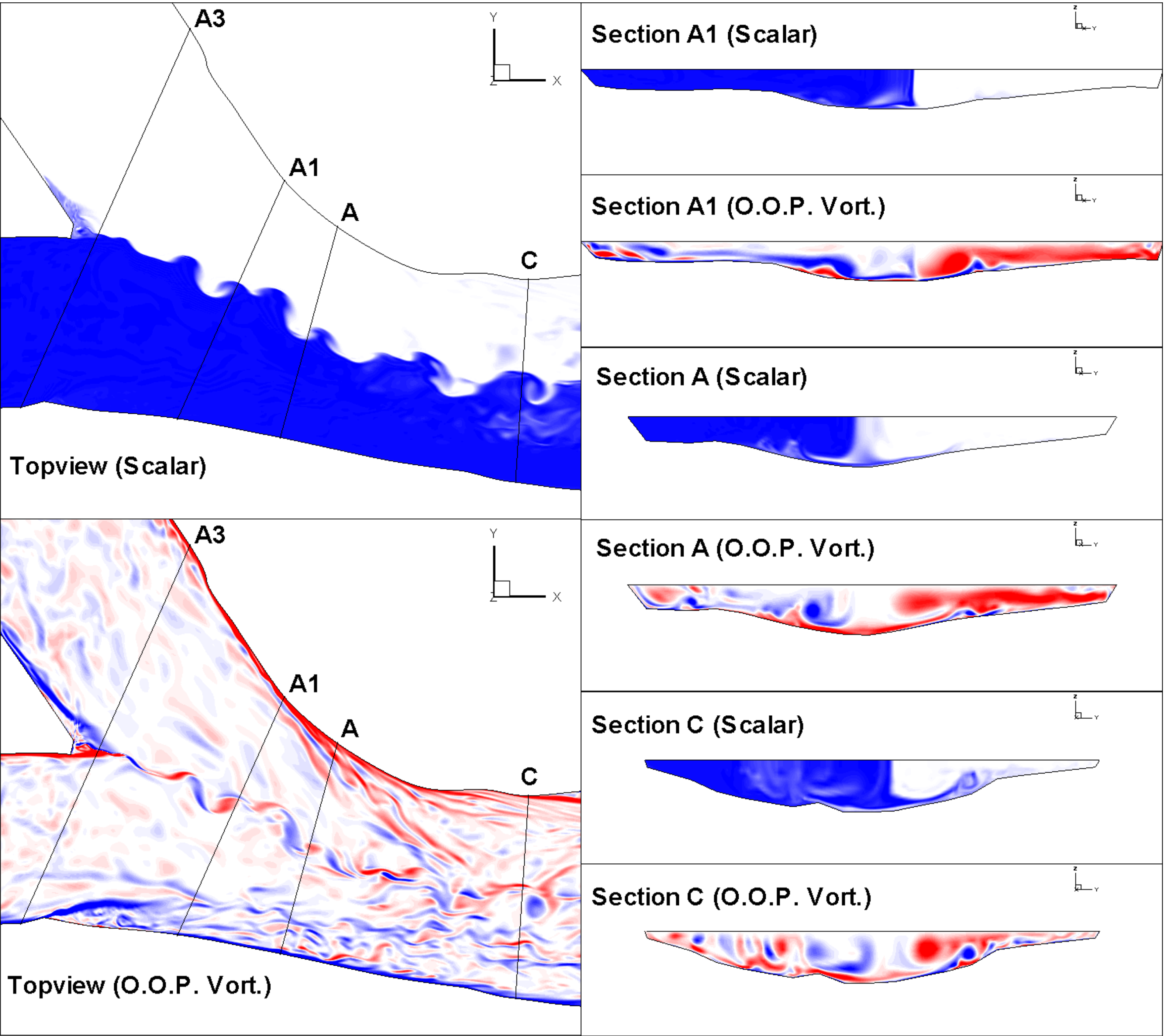
# TRACKING OF PASSIVE SCALAR INTRODUCED AT THE UPSTREAM JUNCTION CORNER: VR~1




SOV cells act as a pump of momentum and mass which besides entraining sediment from beneath, extract fluid and suspended sediment from the MI and advect them downstream of the CHZ

# Can SOV cells affect mixing within the confluence?

# THERMAL MIXING: VR~1



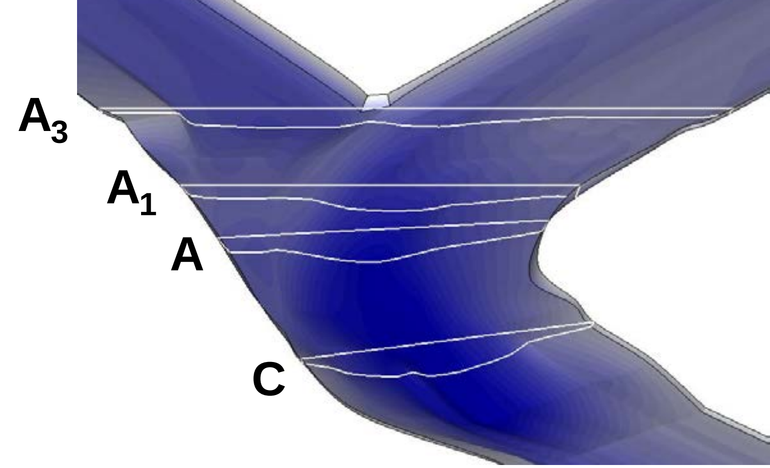

**Large-scale engulfing by the ML eddies**

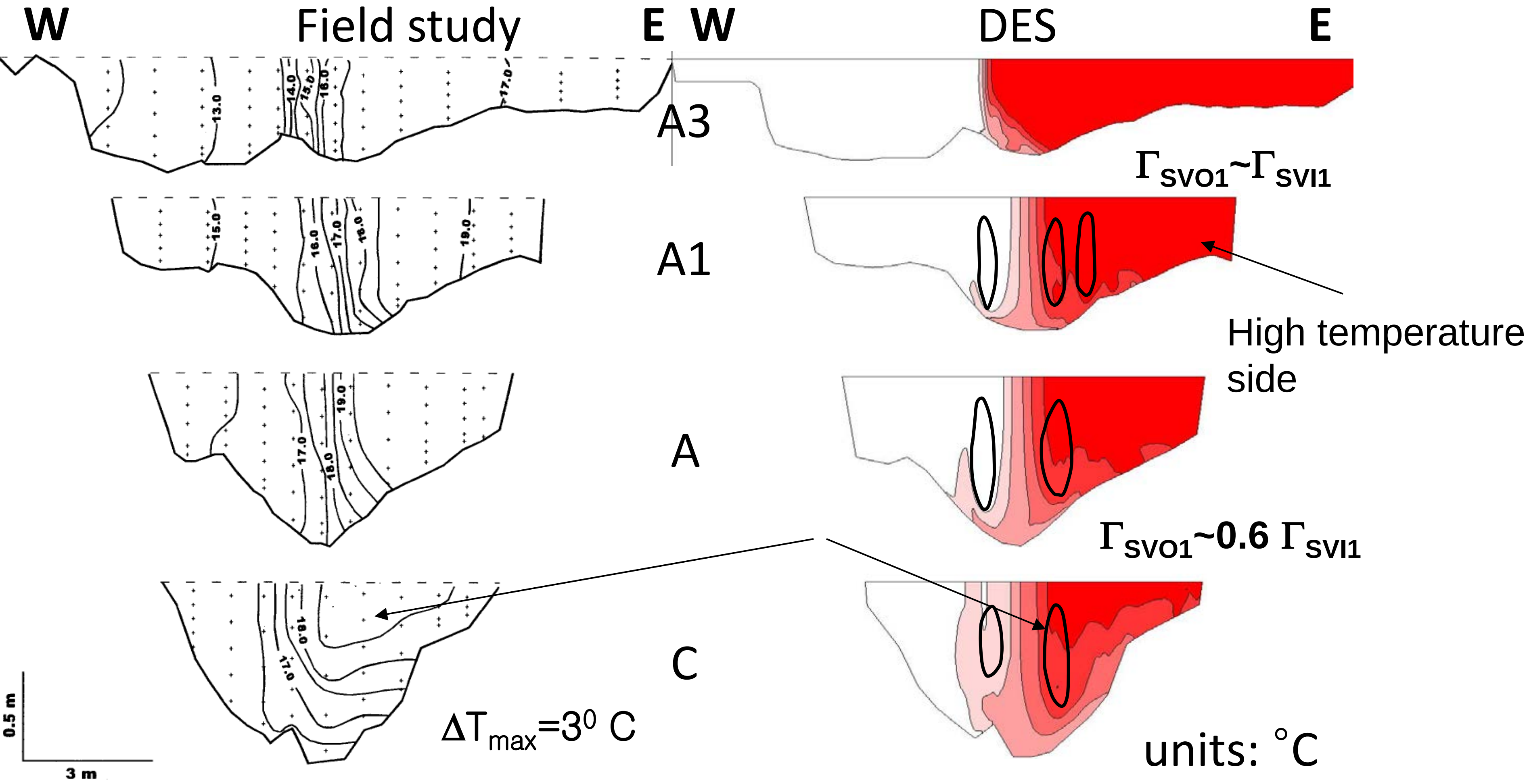
**Strong near-bed intrusions of low temperature fluid on East side driven by bimodal oscillations of SVI1**

**BLUE: low temp West side**

# VALIDATION: VR~1

# TEMPERATURE FIELD



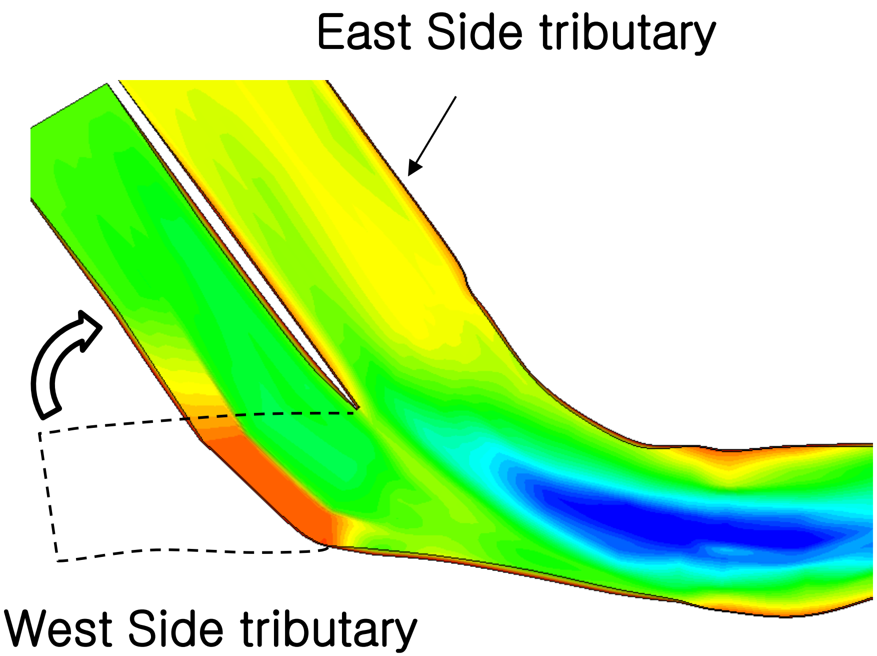



# Conditions needed for SOV cells to form

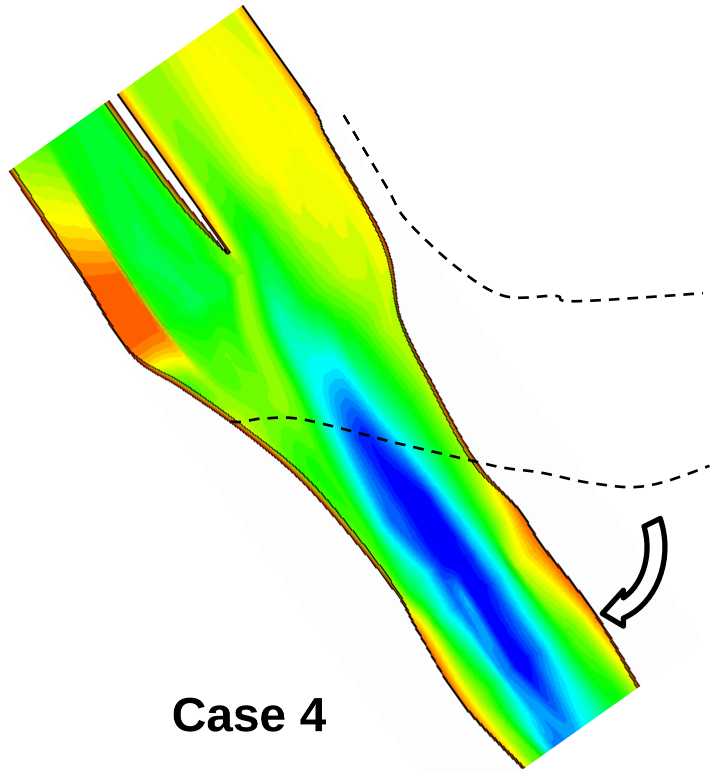
**-large angle between the two streams?**

**-large angle between at least one of the incoming streams and the downstream channel?**

## We will conduct a numerical experiment



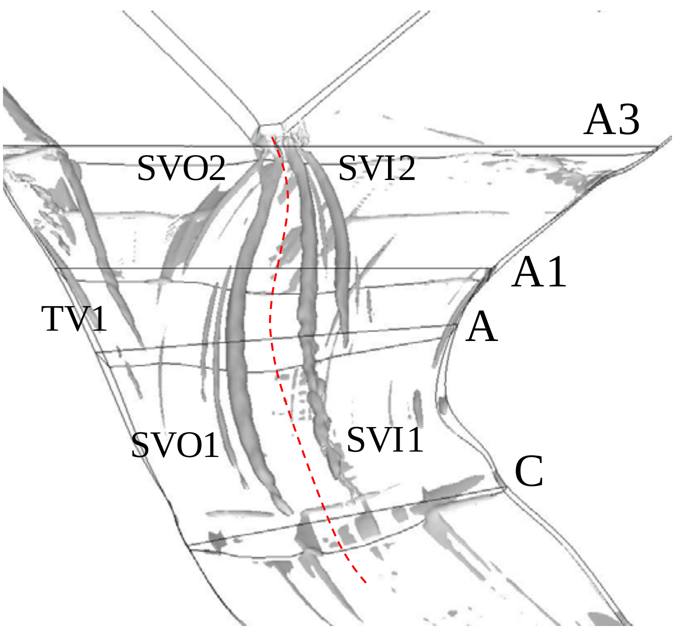

**Case 3**



**Case 4**

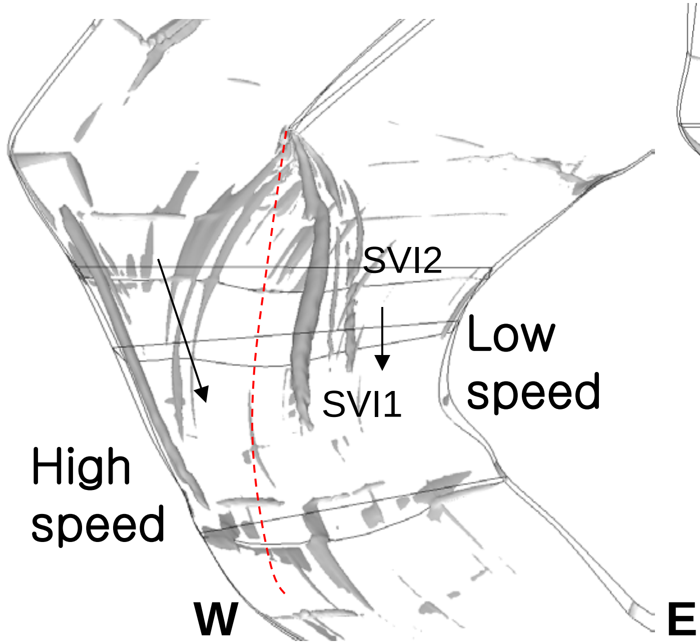
# Streamwise Oriented Vortical Cells

## Case 1




**MI: wake mode**

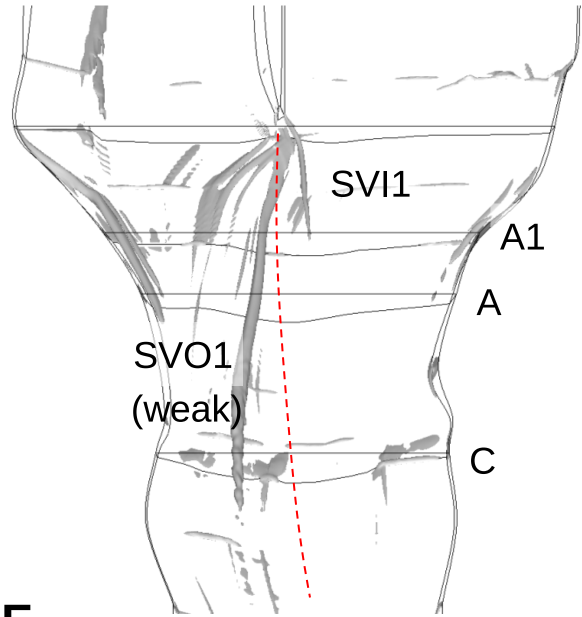
## Case 3




**MI: KL mode in ds part**

**-left tributary pushes into MI (SVI1)**
**-right tributary pushes into bank**

## Case 4




**MI: wake mode**

**-weak MI eddies**
**-weak SOV present**

## Why sometimes the two streams do not appear to mix for large distances from the confluence apex?

# A famous example (Amazon): Confluence of Solimoes and Negro Rivers

-Solimoes River contains sediment eroded from the Andes Mountains

-Negro River contains low sediment but high organic matters from the forest (black tea color)

-the two streams are also characterized by significant differences in temperature ($4^0$C), nutrient and oxygen content

-the two rivers run side by side for 6 Km before they start mixing!

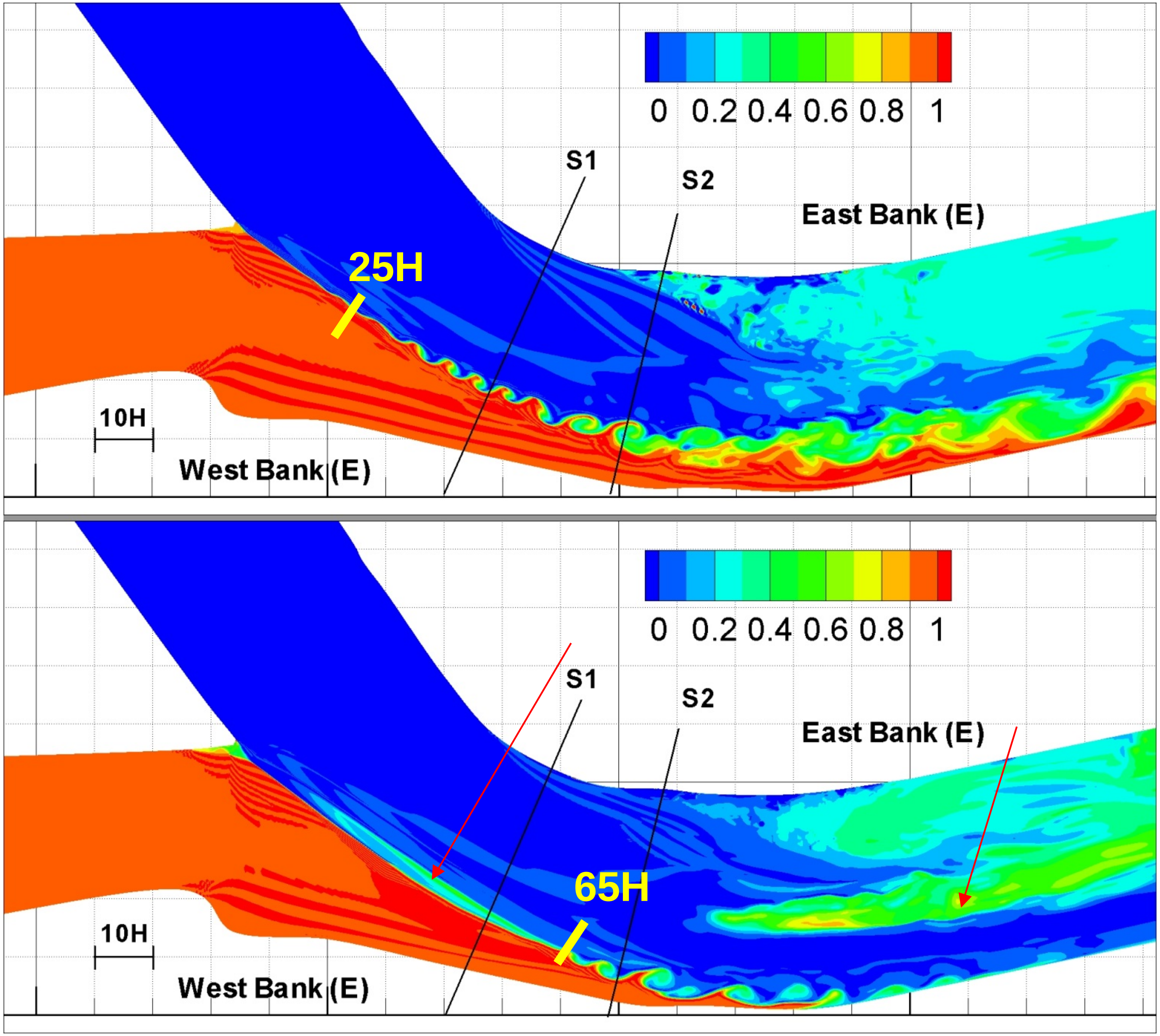
# Confluence of Solimoes and Negro Rivers


**-Differences in temperature and suspended sediment concentration means that stratification effects may be important !**

**-Can stratification delay formation of large-scale eddies within MI?**

**-Back to our small confluence in Illinois**

# STRATIFICATION EFFECTS (Case 2, Vr=5.5)




Ri=0.0

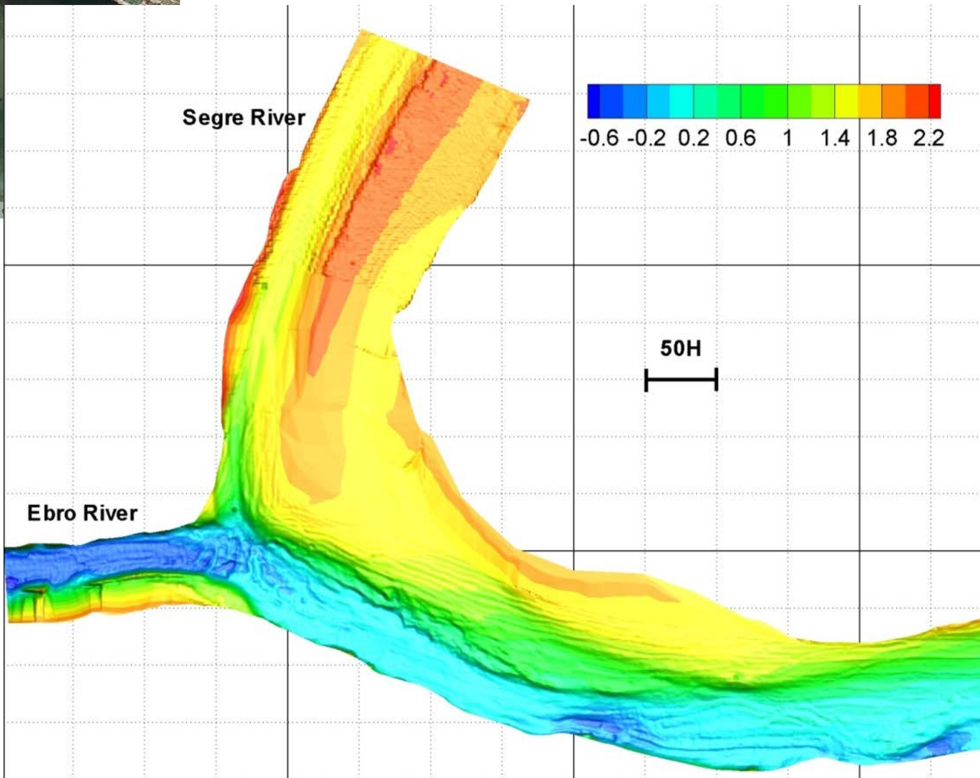
Ri=0.1

## Confluences with a strong discordance in bed levels and complex bathymetry features

-Are we still talking about a MI that is just a more complex case of a shallow mixing layer?

-Do SOV cells still form?

# Confluence of Ebro and Segre Rivers

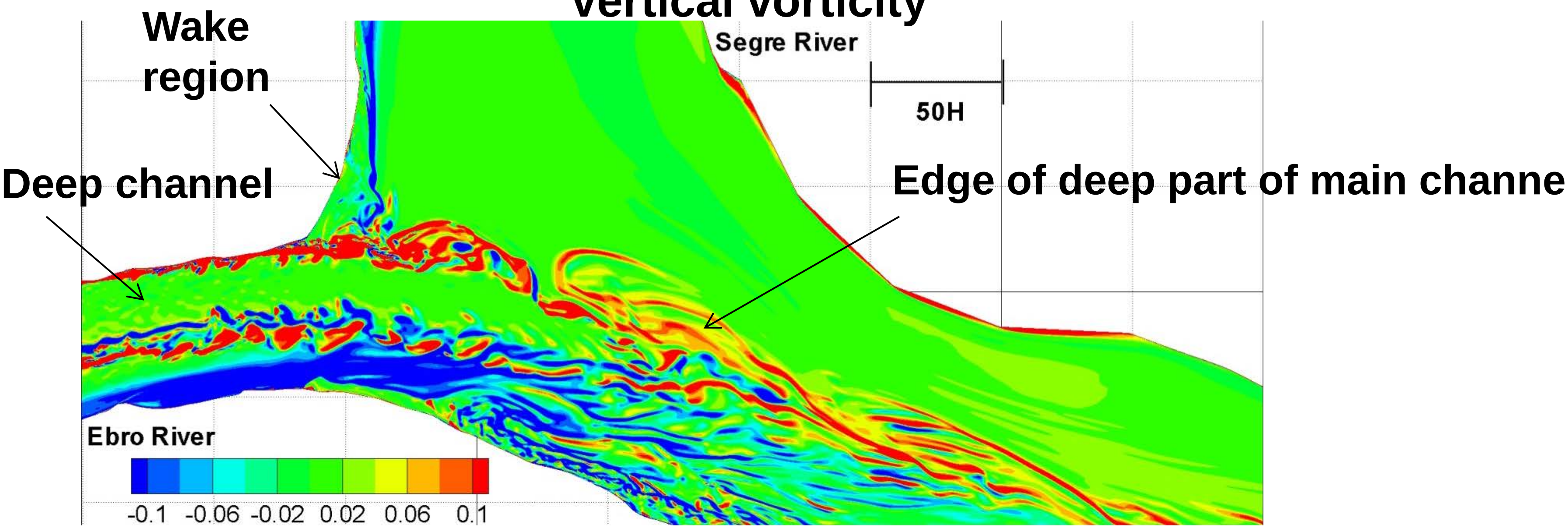

$Q_{EBRO}$~400-500 $m^3/s$
$Q_{SEGRE}$~15-90 $m^3/s$

**QR=2.5 to 13 !!!**

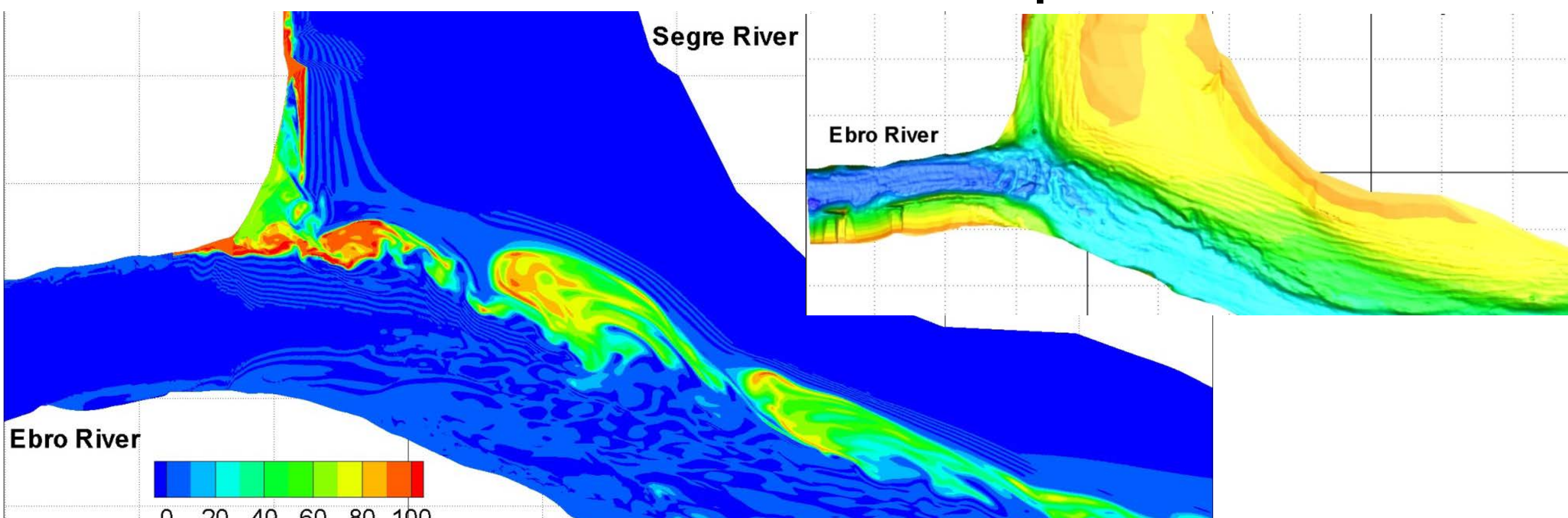
**Bathymetry data courtesy of J. Dolz and J. Prats-Rodriquez**

# Confluence of Ebro and Segre Rivers QR=2.5

## Vertical vorticity




## Passive scalar introduced at confluence apex



# FINAL REMARKS

**-Eddy resolving techniques can be used to better understand flow physics and to test hypotheses related to mixing and transport in natural streams**

## Challenges:

**-Simulate larger-scale systems**

**-Bed-morphology changes**

**-Integrate ecological modeling**