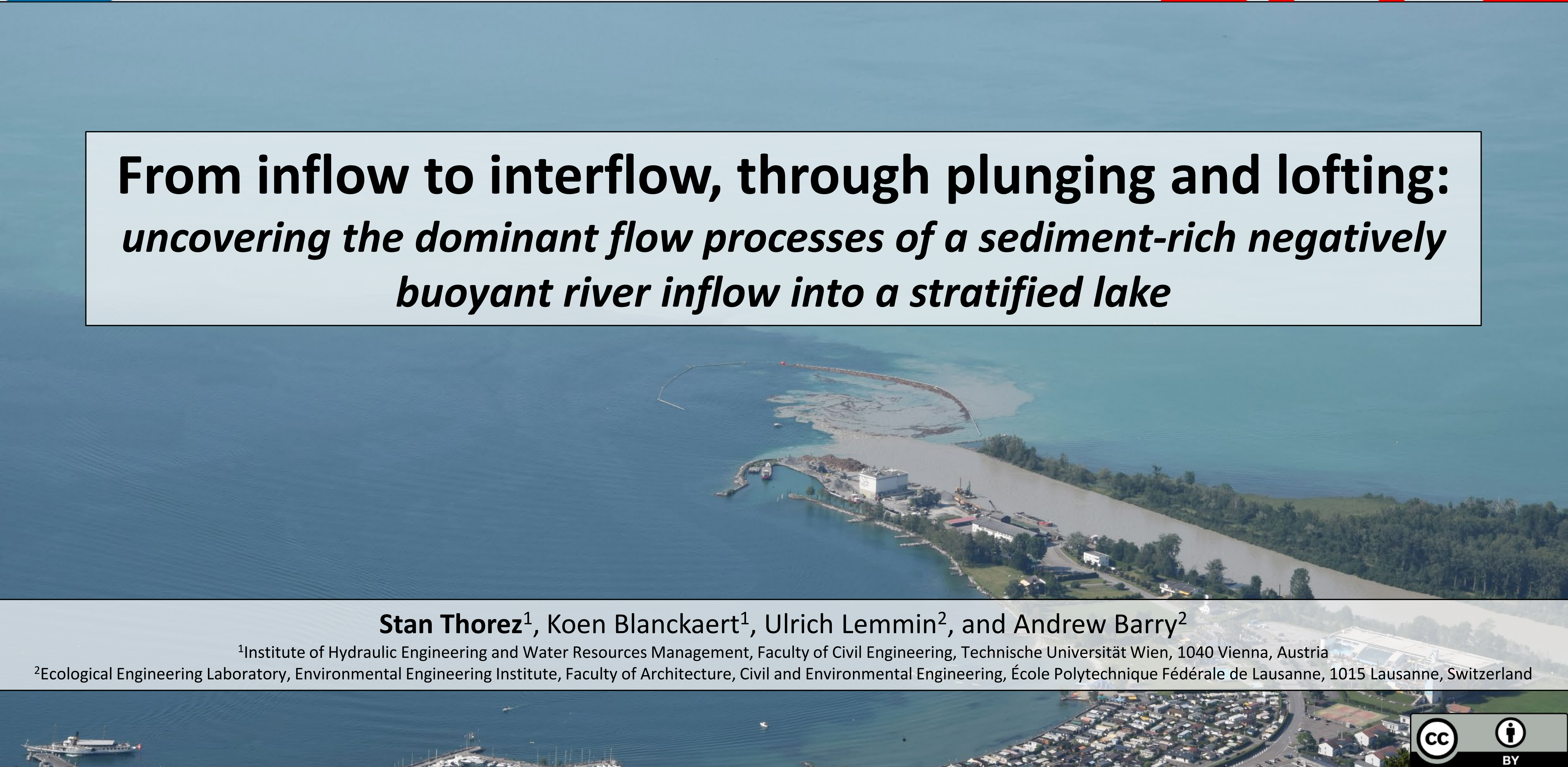

From inflow to interflow, through plunging and lofting:

uncovering the dominant flow processes of a sediment-rich negatively buoyant river inflow into a stratified lake

Stan Thorez[1], Koen Blanckaert[1], Ulrich Lemmin[2], and Andrew Barry[2]

[1]Institute of Hydraulic Engineering and Water Resources Management, Faculty of Civil Engineering, Technische Universität Wien, 1040 Vienna, Austria

[2]Ecological Engineering Laboratory, Environmental Engineering Institute, Faculty of Architecture, Civil and Environmental Engineering, École Polytechnique Fédérale de Lausanne, 1015 Lausanne, Switzerland

Motivation

River inflows…

…are an important input of sediment, oxygen, contaminants, nutrients, heat, and momentum for lakes and reservoirs

→influence on water quality, reservoir storage capacity & hazards

→hydrodynamic processes at the river-lake/reservoir interface control the fate of these components

Hydrobiologia **226**: 51–63, 1991.

Eutrophication processes regulated by a plunging river inflow

Warwick F. Vincent,[1,3] Max M. Gibbs[1] & Robert H. Spigel[2]
[1] *Taupo Research Laboratory, DSIR, P.O. Box 415, Taupo, New Zealand;* [2] *Department of Civil Engineering, University of Canterbury, Private Bag, Christchurch, New Zealand;* [3] *permanent address for correspondence: Département de biologie, Université Laval, Québec G1K 7P4, Canada*

Received 25 July 1990; in revised form 26 February 1991; accepted 1 March 1991

Hydrological Sciences–Journal–des Sciences Hydrologiques, **51**(1) February 2006

Loss of reservoir volume by sediment deposition and its impact on water availability in semiarid Brazil

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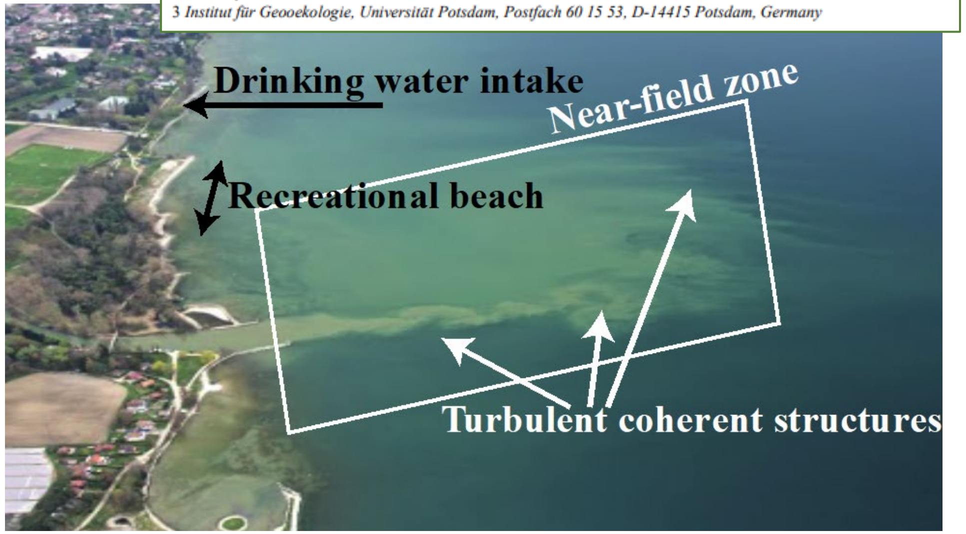
2 *GeoForschungsZentrum Potsdam (GFZ), Section 5.4: Engineering Hydrology, Telegrafenberg, D-14473 Potsdam, Germany*
3 *Institut für Geooekologie, Universität Potsdam, Postfach 60 15 53, D-14415 Potsdam, Germany*



Inflow of the River Venoge into Lake Geneva (Switzerland). An intake of drinking water for the highly urbanized Lausanne-Geneva region is situated at 1 km from the inflow, and recreational beach areas are situated at both sides of the inflow.→

Motivation

River inflows…

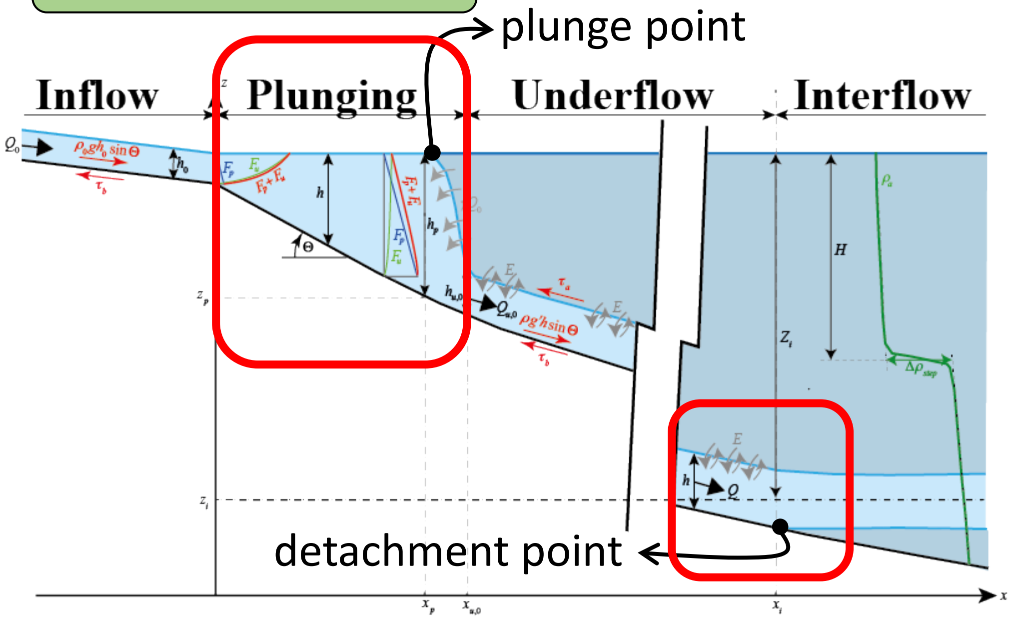
…will plunge and form a gravity-driven density current near the bed (underflow, UF) and/or intermediate current (interflow, IF) when they are negatively buoyant w.r.t. lake surface water

→plunging process provides upstream boundary conditions for density currents

→UF-IF transition has crucial influence on final destination of sediment, nutrients and contaminants

→important to identify and quantify the mixing processes involving entrainment of ambient water into the plunging flow as a function of the inflow properties (characterized by Fr_d)

Classic (2D) model:



! hydrodynamics of plunging process still poorly understood, especially in laterally unconfined configurations

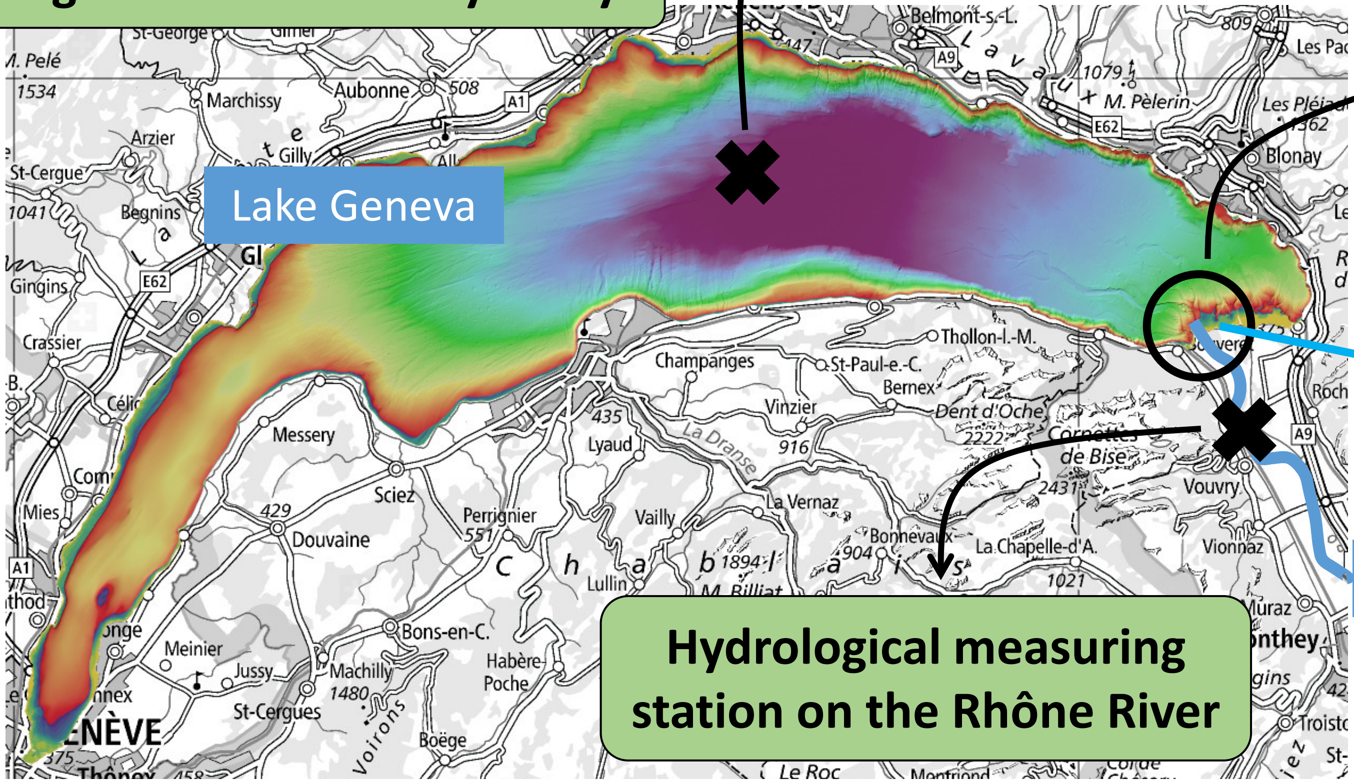
! hydrodynamics of UF-IF transition still poorly understood, especially in turbid flows (density excess due to sediment)

Study site: Rhône inflow into Lake Geneva

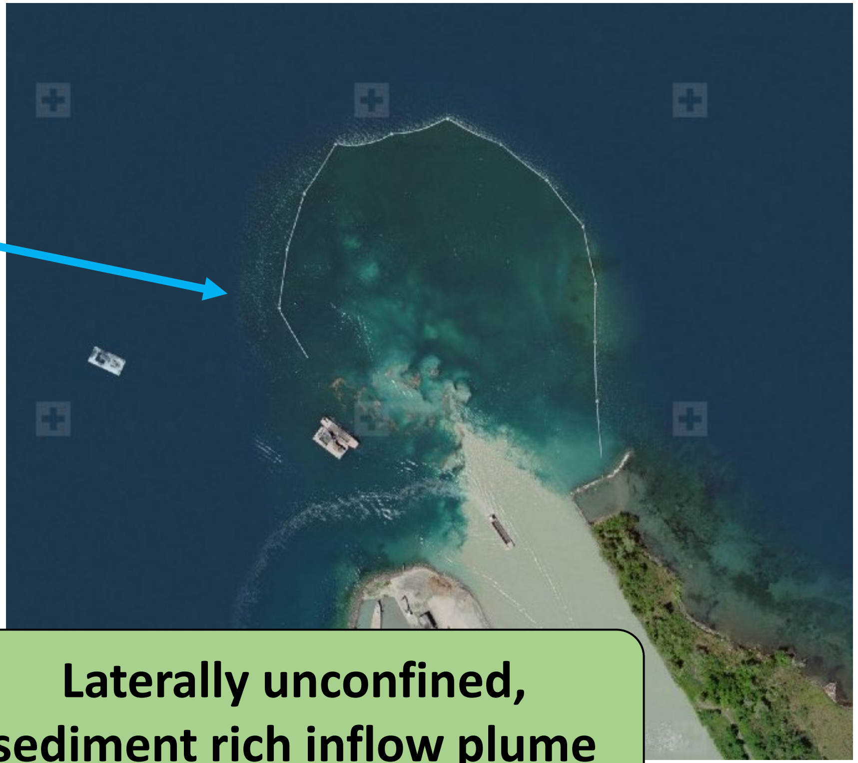
High-resolution bathymetry

Hydrological measuring station on Lake Geneva

Wide range of inflow conditions



Hydrological measuring station on the Rhône River



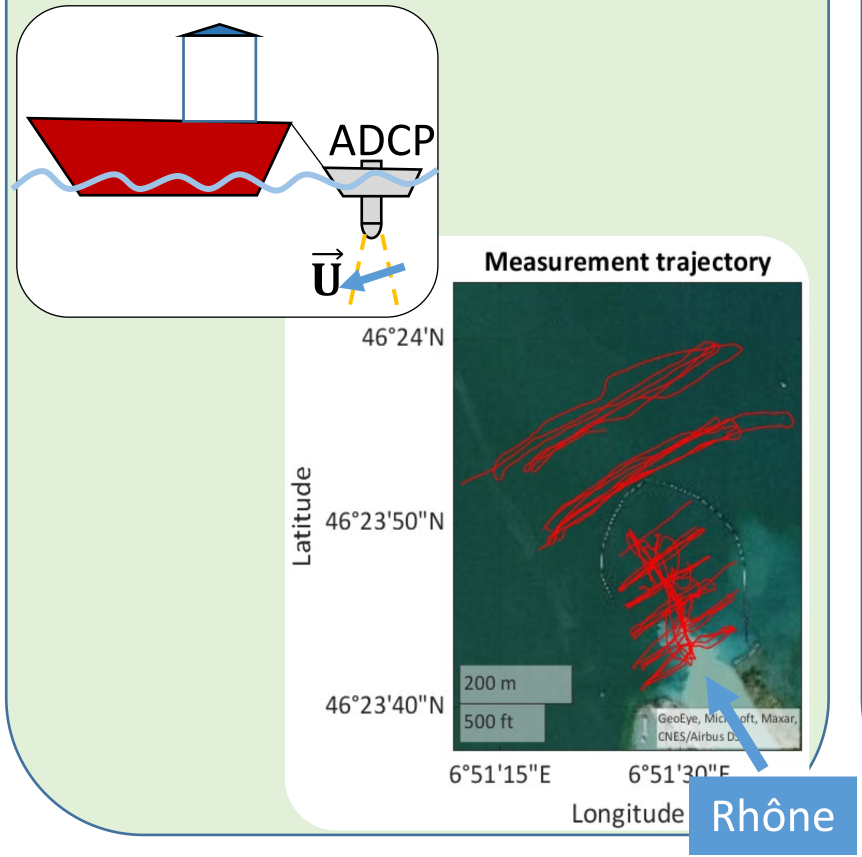
Laterally unconfined, sediment rich inflow plume

Virtually all boundary conditions are known!

Methods

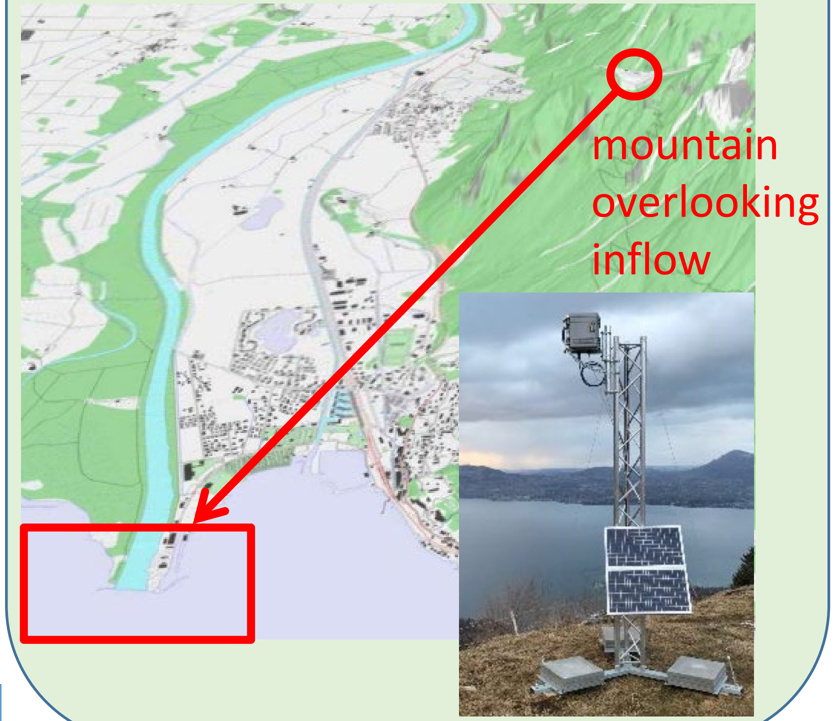
vessel-mounted ADCP

→three-dimensional velocity field along transversal and longitudinal transects
→multiple repetitions to catch low magnitude, secondary currents
→event-wise



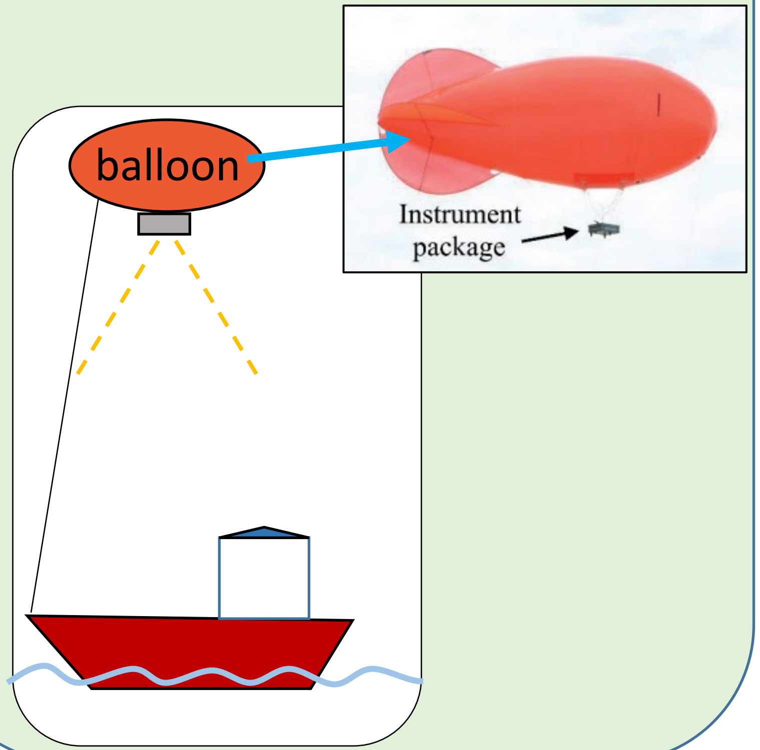
static remote-sensing camera system

→two-dimensional surface patterns
→large to intermediate scale processes
→1-10 minute resolution
→continuous: ongoing since June 2019



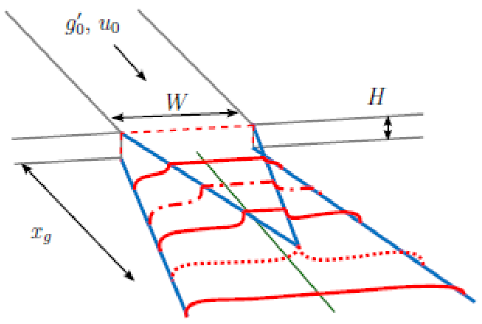
mobile balloon-mounted camera system

→two-dimensional surface patterns
→intermediate to small scale processes
→1 second resolution
→event-wise

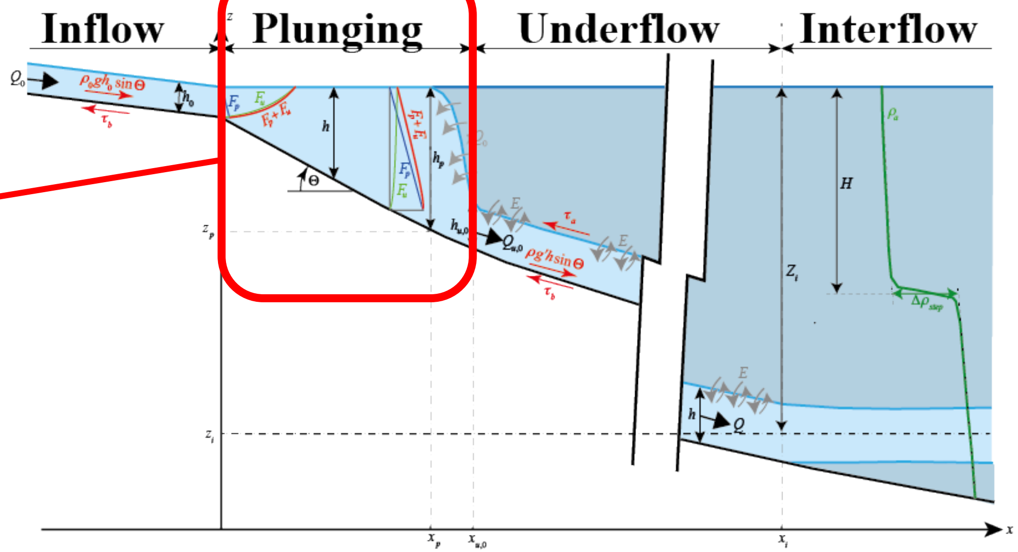


Results: overview

Literature:

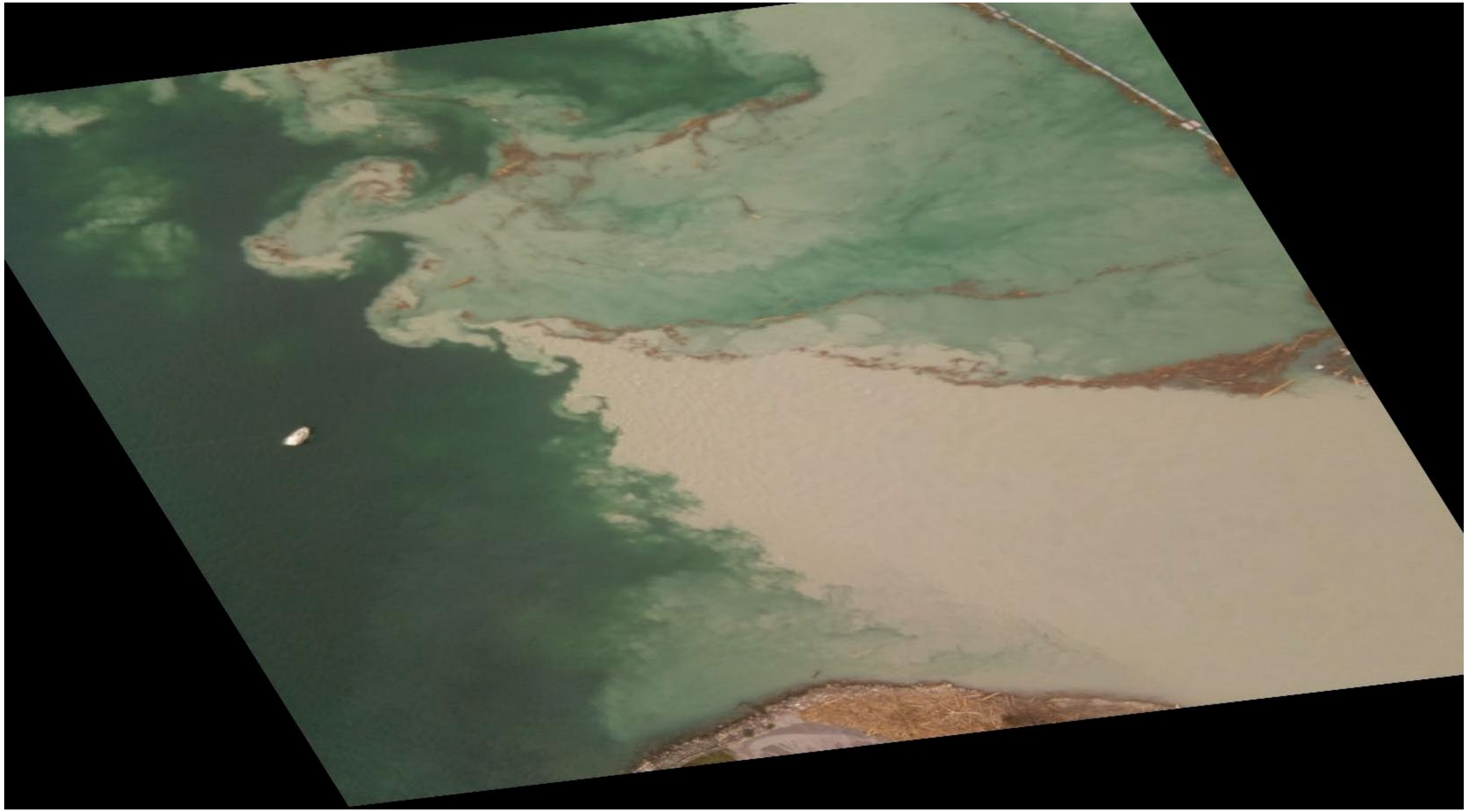


Fr_d driving parameter

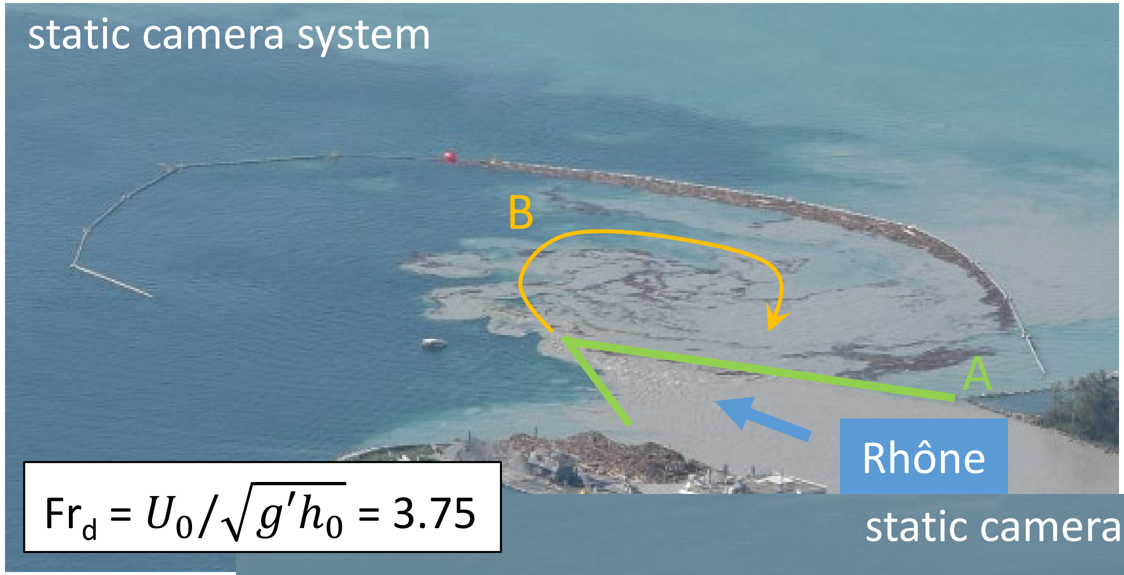


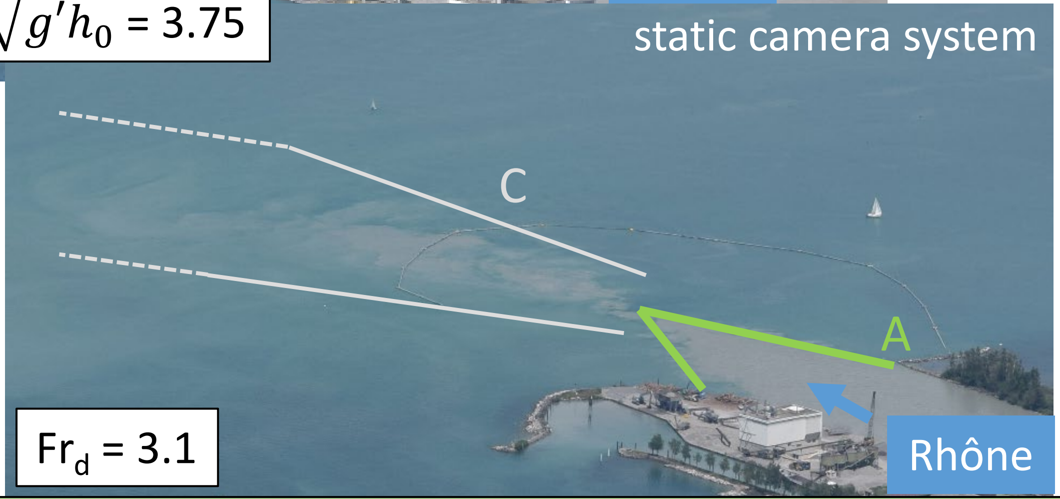
Results: plunging

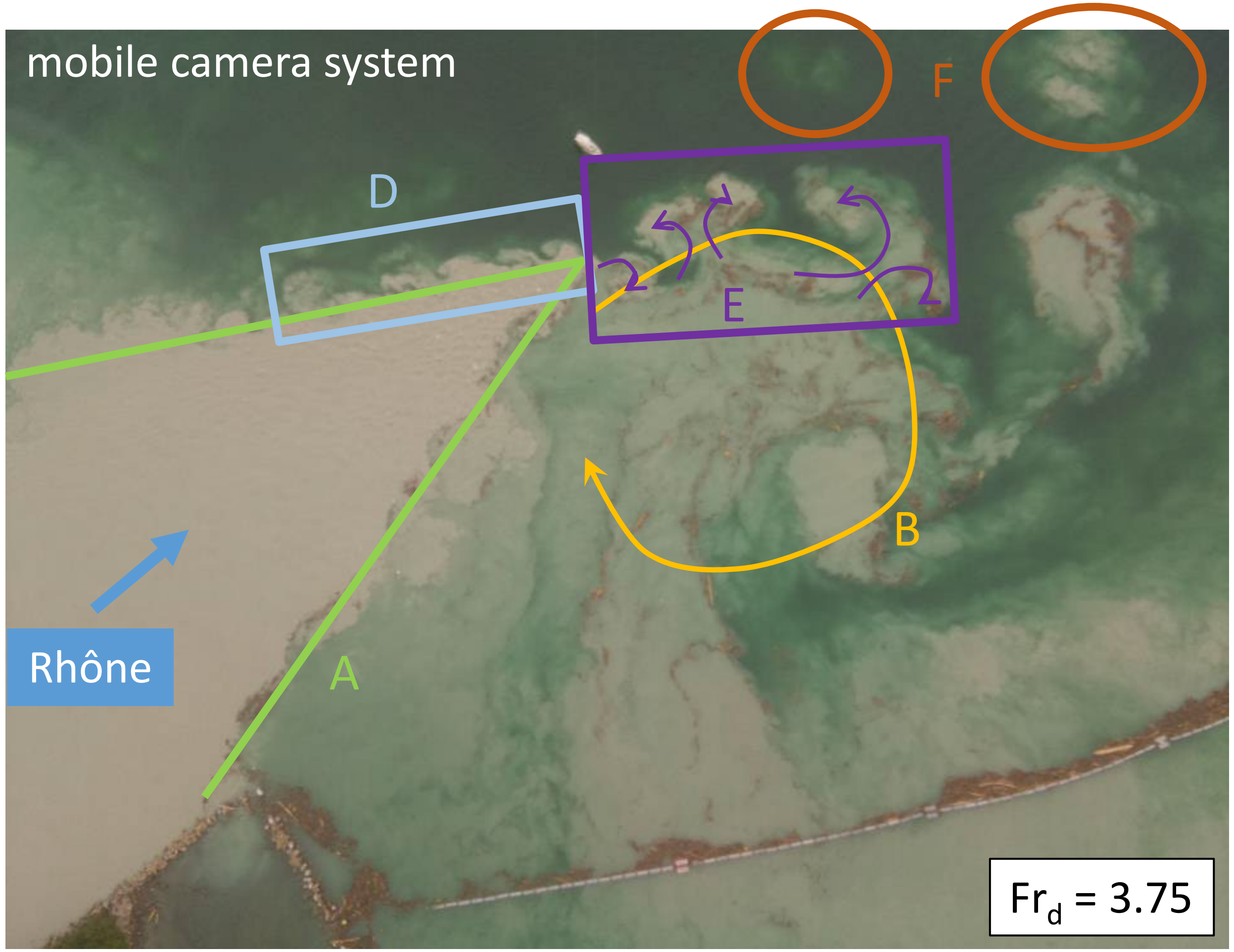
Video for 1 BLIMP run → here $\mathrm{Fr_d} = U_0/\sqrt{g'h_0} = 3.75$ at inflow



Results: plunging



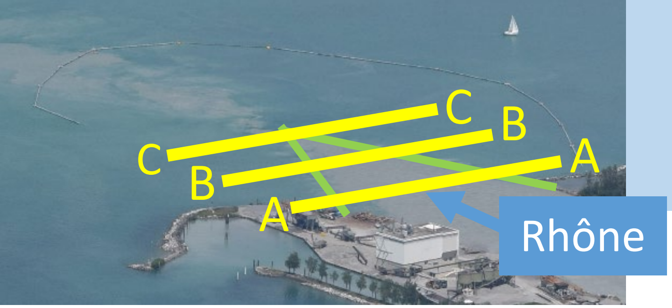




Process description:

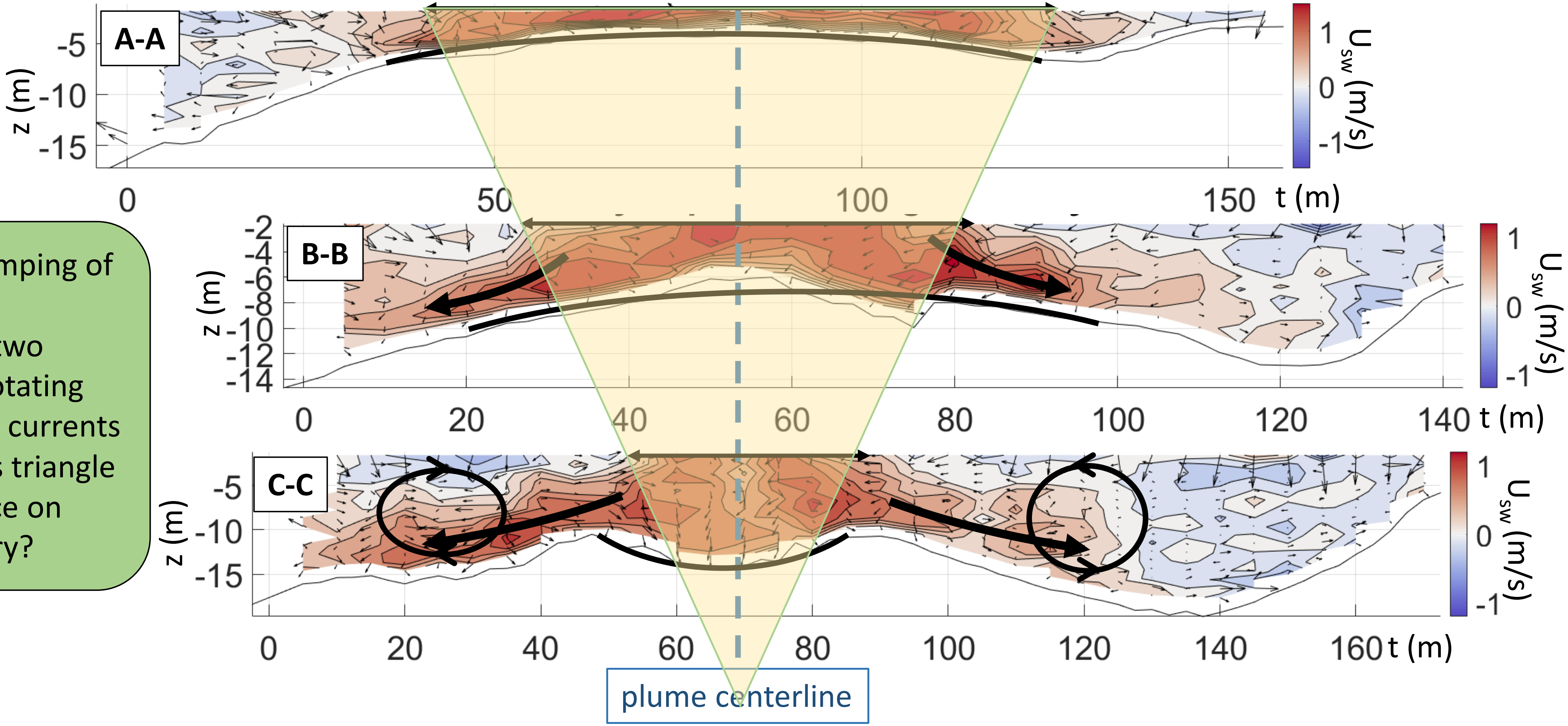
→ Question: what causes the plume to have a persistent triangular shape over all measured inflow conditions?

Results: plunging



Results for 1 ADCP campaign → here $\mathrm{Fr_d} = U_0/\sqrt{g'h_0} = 4$ at inflow

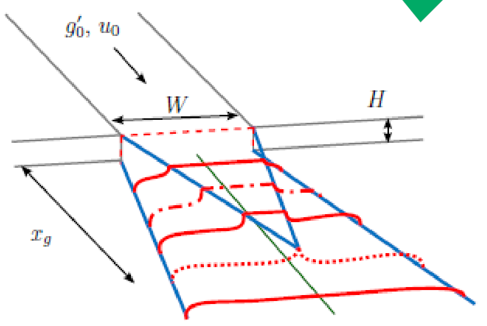
Velocities in "streamwise" (colors) and transverse (vectors) direction



lateral slumping of plume
→causes two counter-rotating secondary currents
→explains triangle
→influence on bathymetry?

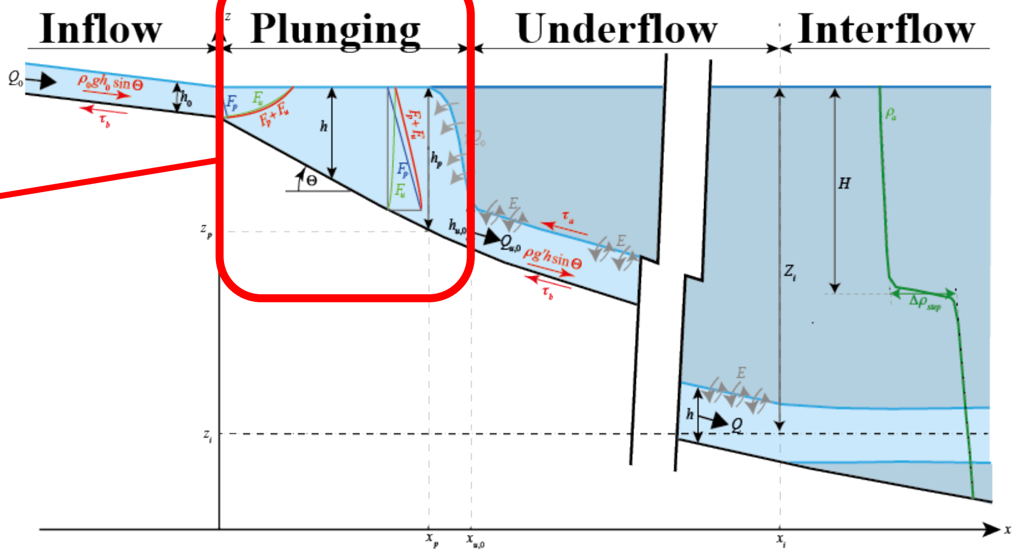
Results: overview

Literature:



Hogg (2014)

Fr_d driving parameter



Plunging additions:

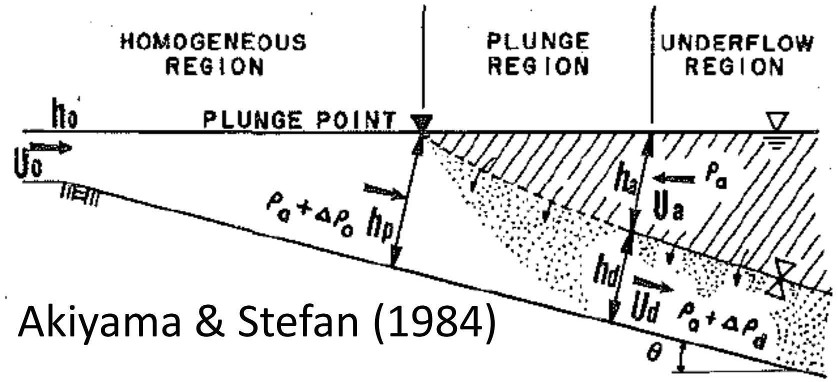
Qualitative:

1. First detailed direct measurements of main flow processes
2. More mixing processes described

Results: plunging

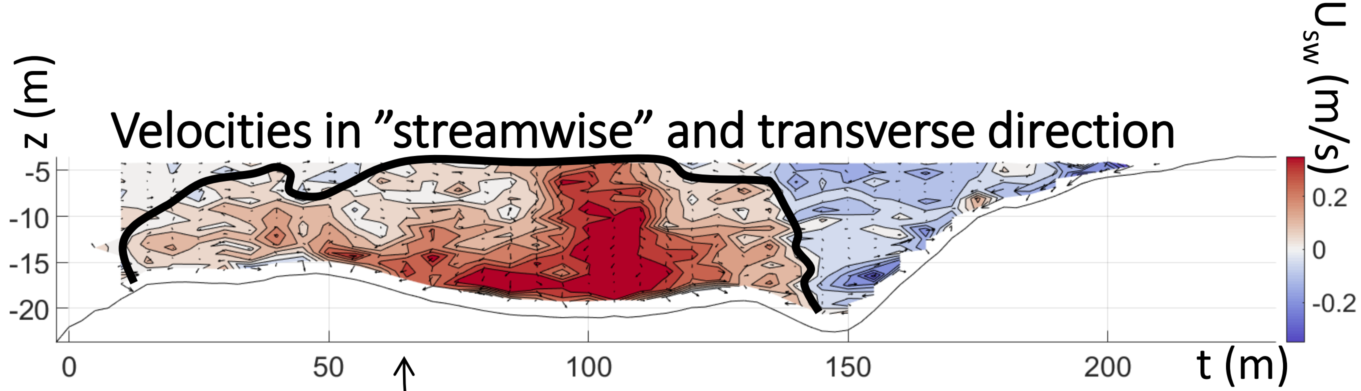
Quantifying mixing through the entrainment coefficient *E*:

- Akiyama & Stefan (1984) for 2D case: $u_d = \frac{(1+E)q_0}{h_d}$
- In 3D: $E = \frac{Q_d}{Q_0} - 1$ → integrate streamwise velocities over high velocity core to find Q_d in every transversal transect, Q_0 is (known) discharge at inflow



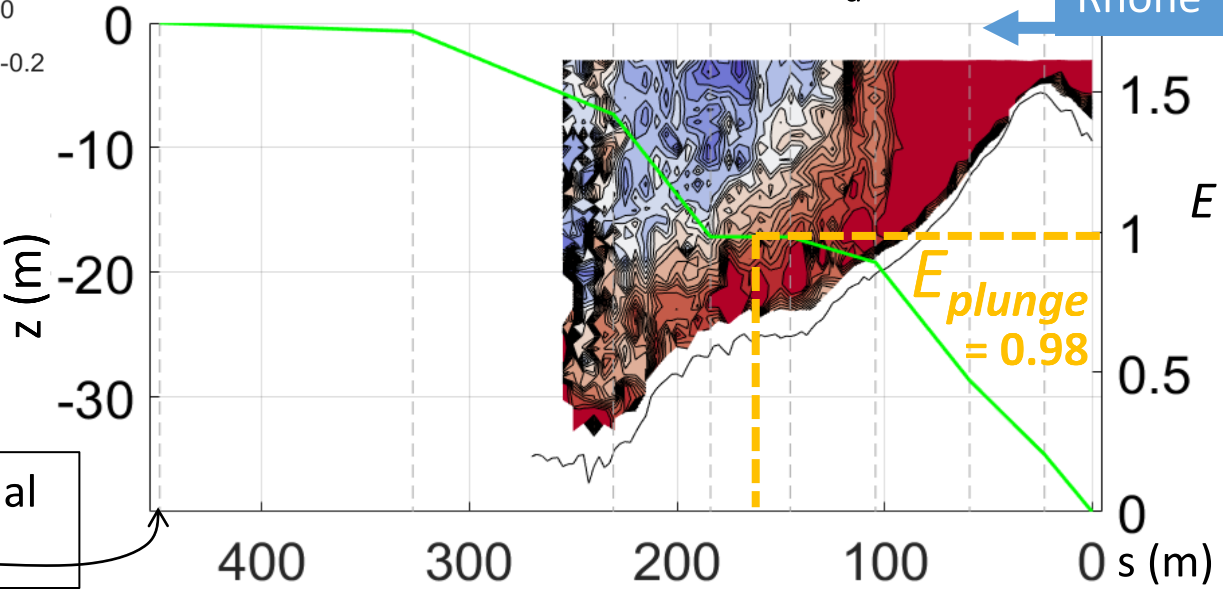
Akiyama & Stefan (1984)

Velocities in "streamwise" and transverse direction



Manually define underflow extent and integrate velocities

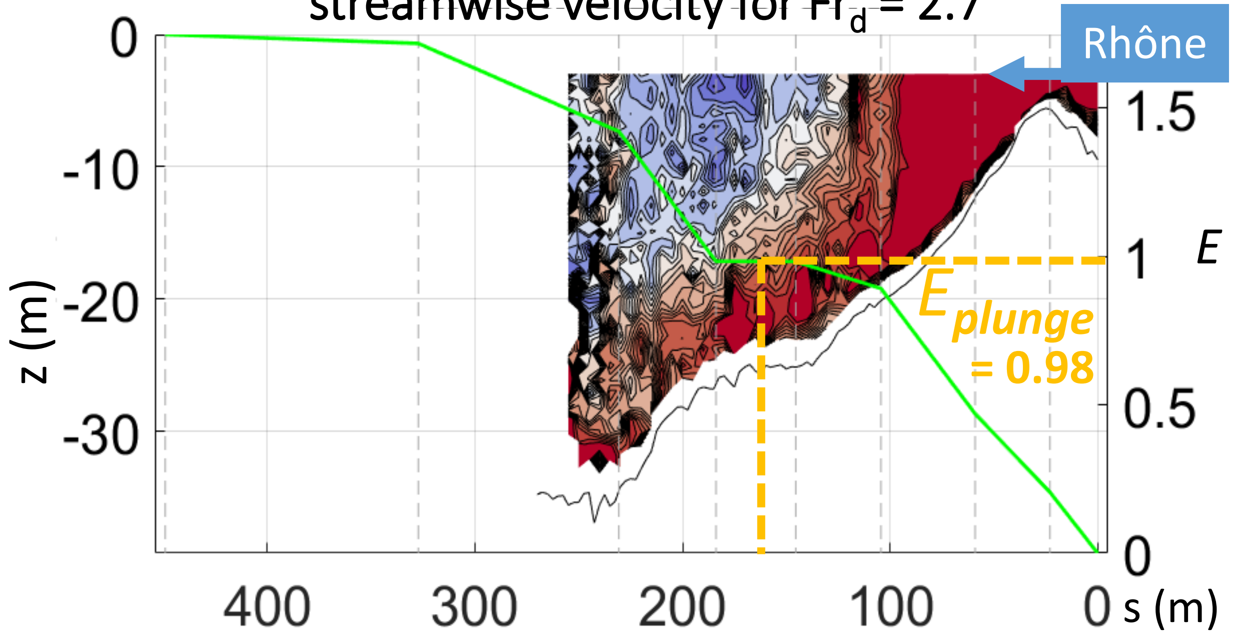
Entrainment coefficient superposed on streamwise velocity for Fr_d = 2.7



Gray, dotted lines indicate longitudinal positions of transversal transects

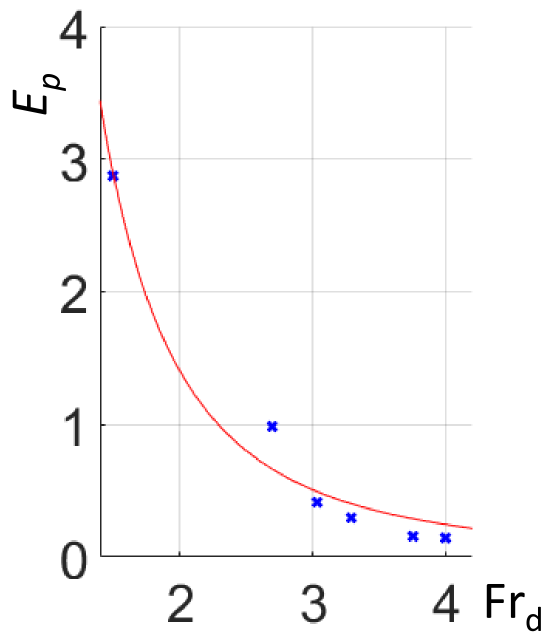
Results: plunging

Entrainment coefficient superposed on streamwise velocity for $Fr_d = 2.7$



Do this for multiple inflow conditions

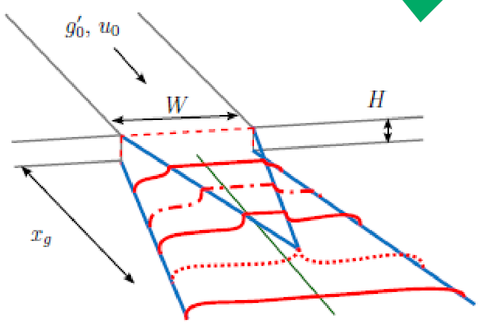
E_p as a function of Fr_d



$Fr_d \nearrow \Rightarrow E_p \searrow$

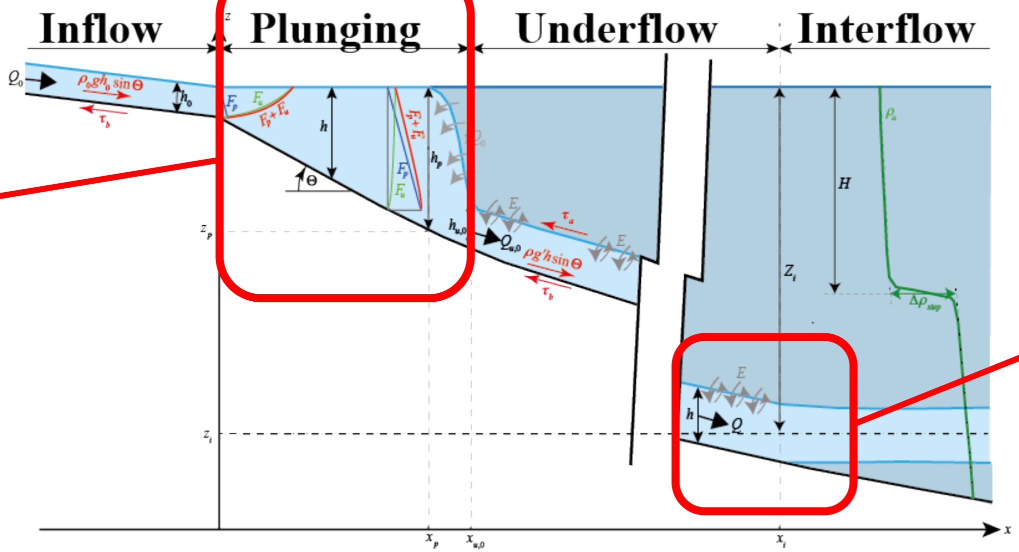
Results: overview

Literature:

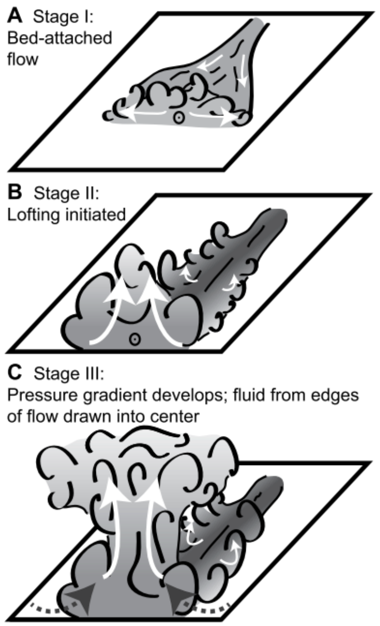


Hogg (2014)

Fr_d driving parameter



Literature:



Steel et al. (2017)

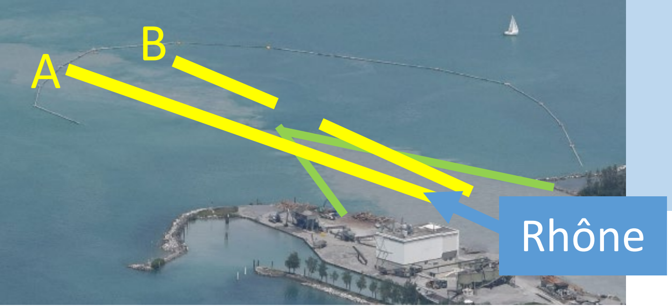
Plunging additions:

Qualitative:

1. First detailed direct measurements of main flow processes
2. More mixing processes described

Quantative:

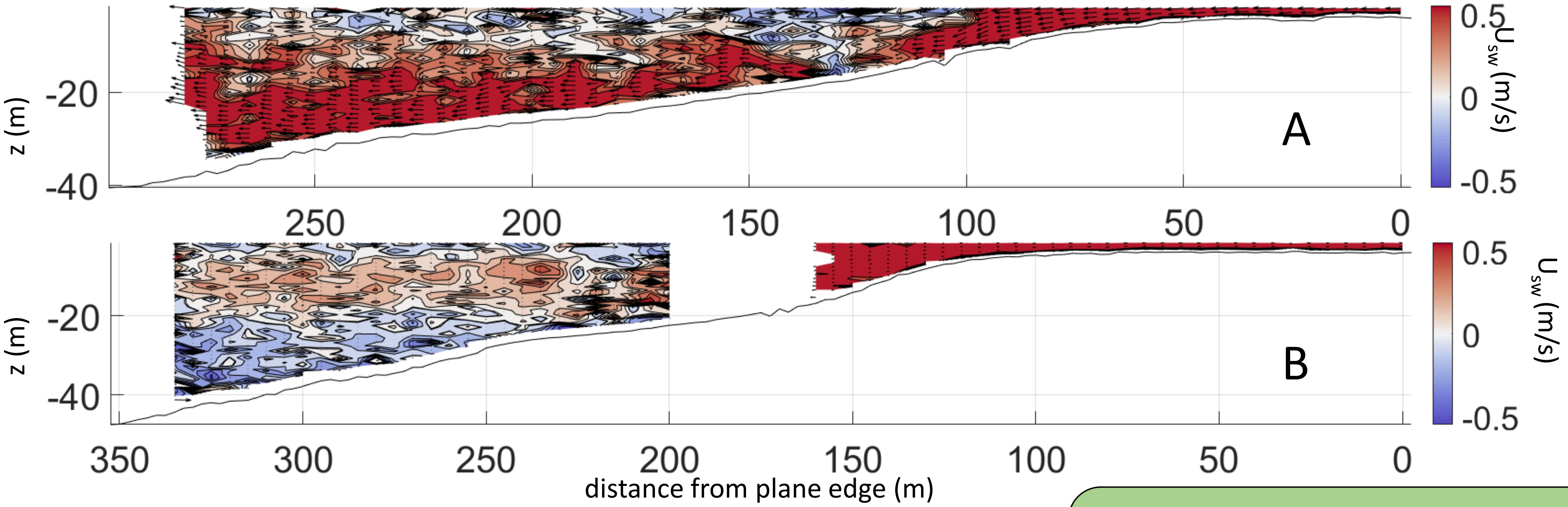
1. First direct quantification of mixing processes
2. Relation driving parameter-mixing processes



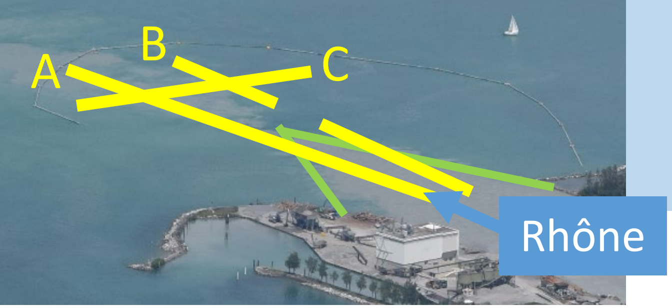
Results: UF-IF transition

Results for 1 ADCP campaign → here $Fr_d = U_0/\sqrt{g'h_0}$ = 3.3 at inflow

Velocities in "streamwise" direction



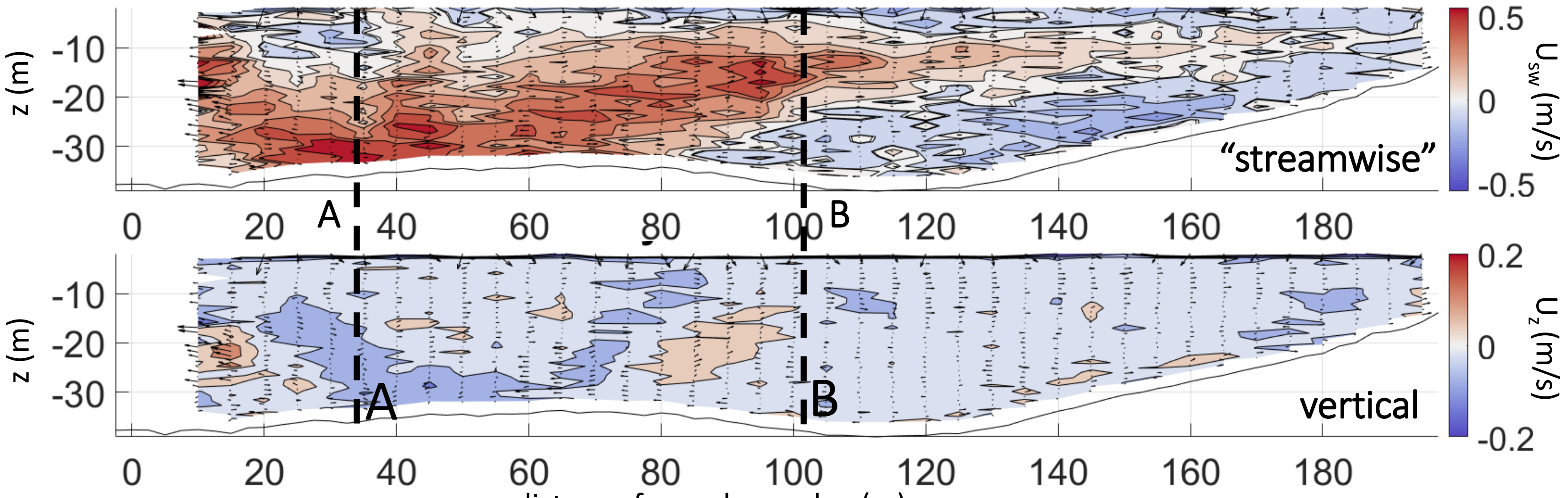
2 "streamwise" transects A and B
→A: plunge at d = 100 m and continuous UF
→B: plunge after d = 160 m and IF right after
→inconsistent results? **NO**



Results: UF-IF transition

Results for 1 ADCP campaign → here $Fr_d = U_0/\sqrt{g'h_0}$ = 3.3 at inflow

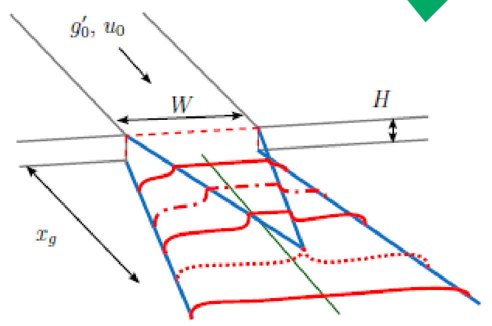
C. Velocities in … direction



- →transversal plane C shows 2 flow regions: core continues as UF, while sides form IF
- →planes A and B cut through C in different flow regions
- →certain parts of plume become positively buoyant and rise up, process known as lofting
- →higher rate of particle sedimentation on lower velocity plume edges, resulting in increased lowering of density?
- →followed by lofting of UF core in later stage of UF (not shown here)

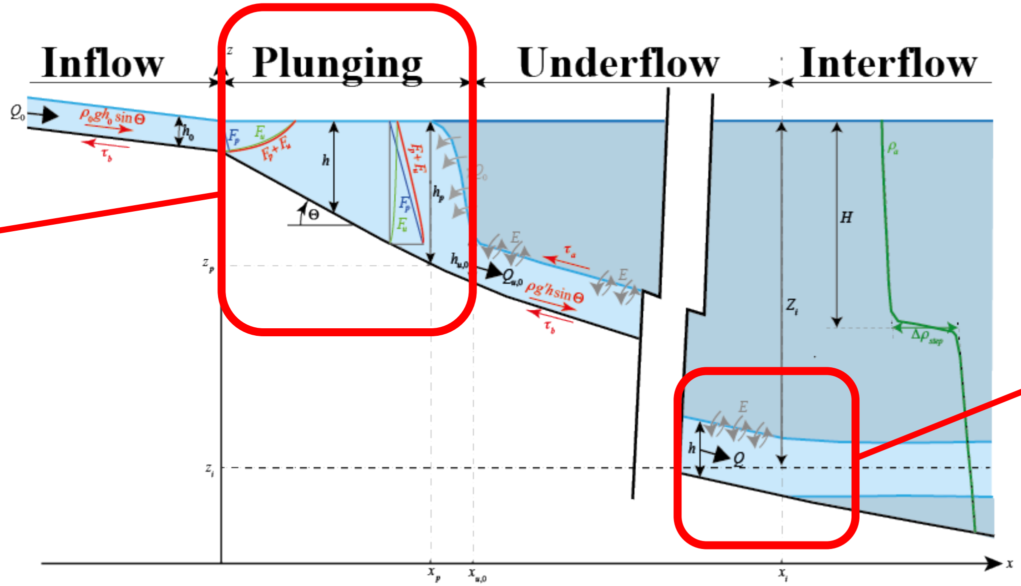
Results: overview

Literature:

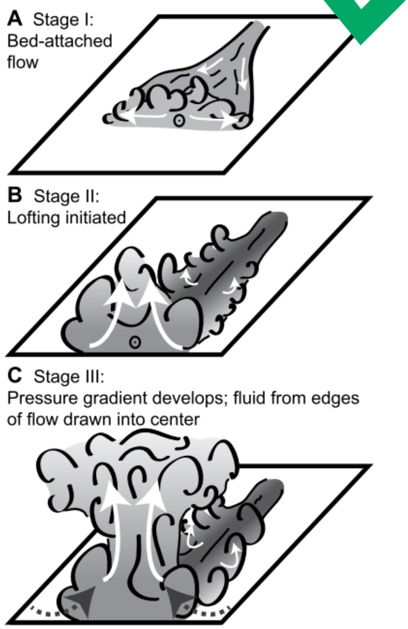


Hogg (2014)

Fr_d driving parameter



Literature:



Steel et al. (2017)

Plunging additions:

Qualitative:

1. First detailed direct measurements of main flow processes
2. More mixing processes described

Quantative:

1. First direct quantification of mixing processes
2. Relation driving parameter-mixing processes

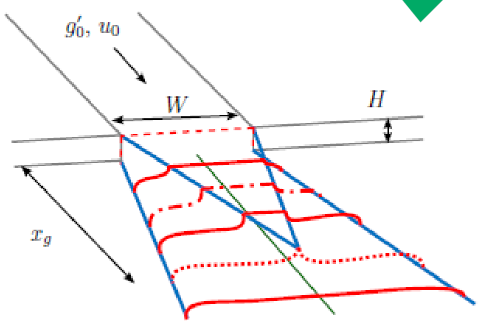
Lofting additions:

Qualitative:

1. First direct measurements of main flow process
2. Sideways lofting also present

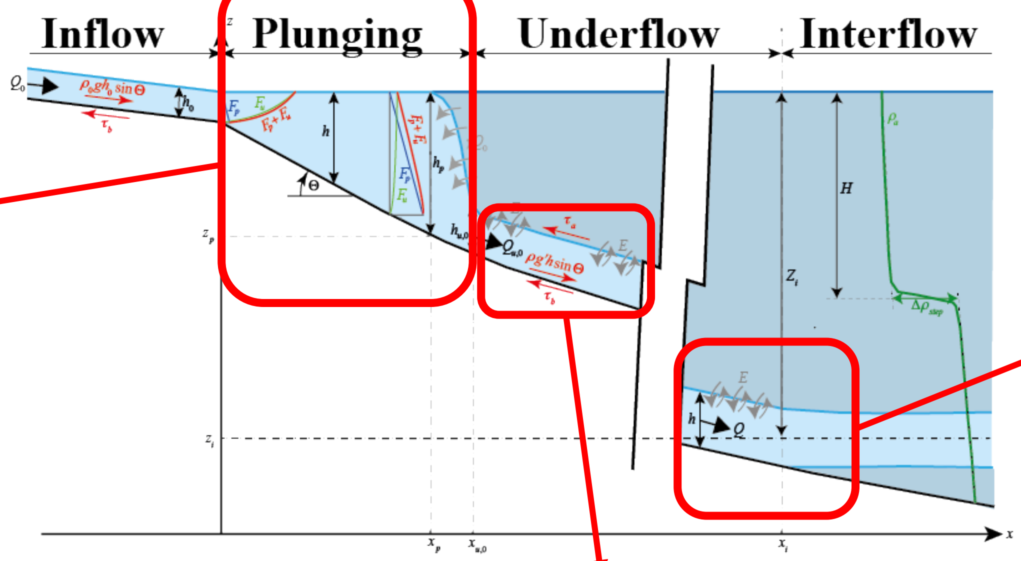
Ongoing work: overview

Literature:

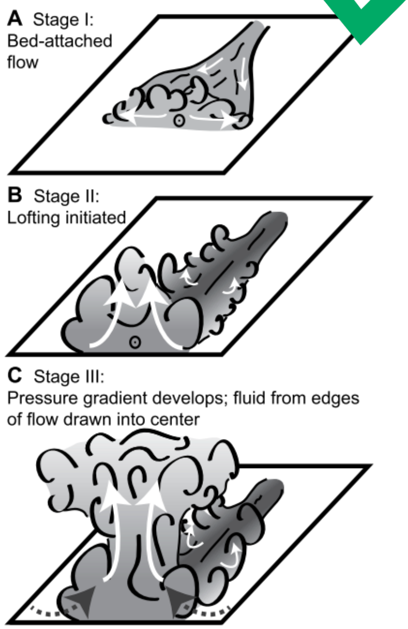


Hogg (2014)

Fr_d driving parameter



Literature:



Steel et al. (2017)

Plunging additions:

Qualitative:

1. First detailed direct measurements of main flow processes
2. More mixing processes described

Quantative:

1. First direct quantification of mixing processes
2. Relation driving parameter-mixing processes
3. *Fr_d driving parameter?*

Underflow additions:

Qualitative:

1. Interesting flow processes visible?

Quantative:

1. Quantify processes?
2. Link processes to plunging?

Sediment?

Lofting additions:

Qualitative:

1. First direct measurements of main flow process
2. Sideways lofting also present

Conclusions

Combination of static and mobile camera systems and boat-towed ADCP measurements enables the investigation of the full 3D velocity field of a plunging flow

- The dominant flow processes were **identified**
  → Inflow-underflow: plunging, with lateral settling and a wide range of other processes
  → Underflow-interflow: lofting, both longitudinal and lateral

- The dominant flow processes related to plunging were **quantified**
  → Relation inflow properties to amount of plunging mixing
  → Plunging entrainment decreases for higher inflow densimetric Froude numbers

- *Work to find with certainty the main **control parameter(s)** driving the flow processes is ongoing*