Politecnico di Bari

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The role of physical models and field monitoring in Environmental and Maritime Hydraulics

Michele Mossa

POLITECNICO DI BARI
DICATECh - Dpt. of Civil, Environmental, Building Engineering and Chemistry
Professor of Hydraulics
Chief Scientist of the LIC (Coastal Engineering Laboratory)
michele.mossa@poliba.it
www.michelemossa.it
www.iahrmedialibrary.net

Typical environmental problems where knowledge of the land, monitoring and physical modeling are of great help

- Coastal erosion and sand transport

- Diffusion of pollution

- Oil spilling

- Support to administrations for the design, construction and maintenance of hydraulic engineering works

- Many others…

Typical scientific approach to the problem

- Field Measurement and Monitoring
- Physical models
- Numerical models
- Hybrid models

LIC – Coastal Engineering Laboratory of the DICATECh - Dpt. of Civil, Environmental, Land, Building Engineering and Chemistry of the Polytechnic University of Bari (Italy)

Coastal Engineering Laboratory funded by Programma Operativo Plurifondo Puglia

D.R. 29/10/90 n. 6155, cofinanced with structural funds CEE-REG.

CEE n. 20522/68 e 4253/88, Sottoprogramma 6, Misura 6.3

3D WAVE BASIN

Width=50 m; length=100m; depth=1.2 m.

3D wavemaker:

- Number of modules = 6
- Number of paddles = 8
- Paddle width = 60 cm
- Max wave front length = 28.8 m
- Hmax=30 cm

OFF-SHORE PHYSICAL MODEL BASIN

Width=50 m; length=30 m; depth=3 m

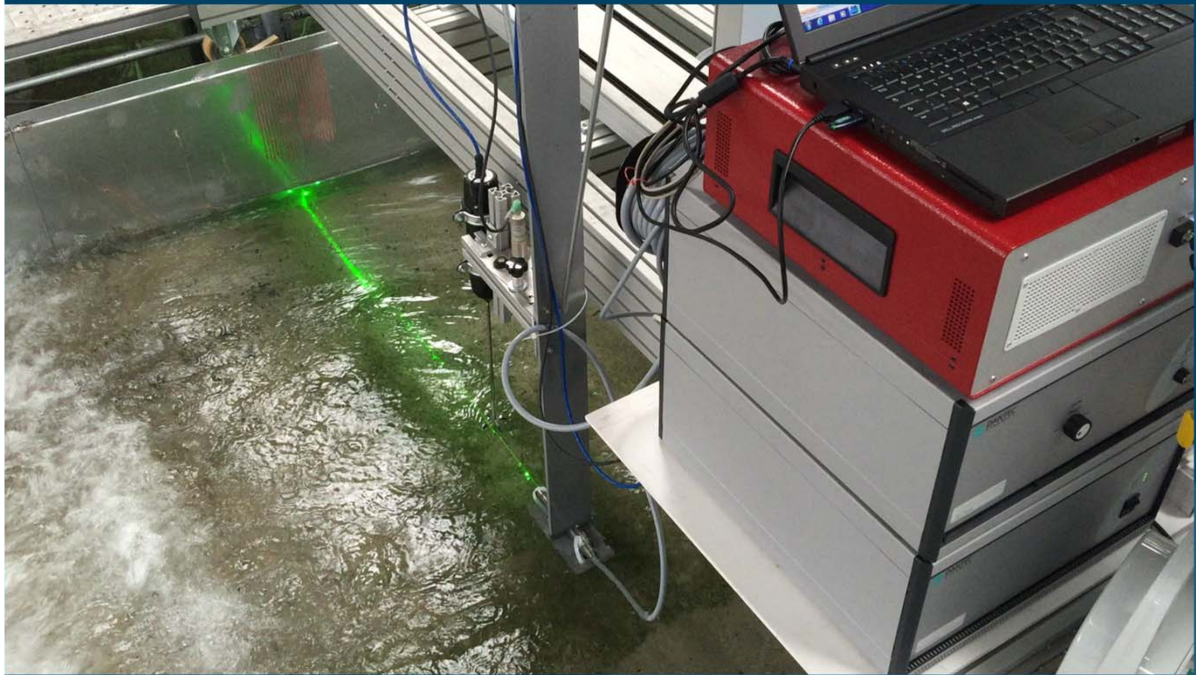
National Interest Research Program approved with D.M. N. 174/2004.
TSUNAMI WAVES GENERATED BY LANDSLIDES IN WATER: MECHANICS OF WAVE GENERATION AND PROPAGATION, DEVELOPMENT OF FORECASTING TOOLS AND REAL-TIME WARNING SYSTEMS BASED ON TIDAL MEASUREMENTS. The photo shows a tsunami scenario generated by landslide at Sciarra del Fuoco (Stromboli island). The physical model was constructed at the LIC of the Technical University of Bari.

TWO WAVE CHANNELS

Experimental research of different regular and irregular waves breaking and the coherent structures due to the wave breaking using LDA and PIV, in cooperation with the Polytechnic University of Marche and the network Hydralab+.

The investigation refers particularly to the surf zone, with the aim to develop two themes: **the study of velocity and Reynolds and wave shear stresses** distributions greatly influence many coastal processes, such as **undertow currents, sediment transport and action on maritime structures.**

Awarded with a fellowship **Gii Placement** in Water Engineering. Call of 23rd October 2015



Some references:
De Serio F, Mossa M (2016). Assessment of classical and approximated models estimating regular waves kinematics. OCEAN ENGINEERING, vol. 126, p. 176-186, ISSN: 0029-8018
De Padova D, Dalymple R A, Mossa M (2014). Analysis of the artificial viscosity in the smoothed particle hydrodynamics modelling of regular waves. JOURNAL OF HYDRAULIC RESEARCH, ISSN: 0022-1686
De Serio F, Mossa M (2013). A laboratory study of irregular shoaling waves. EXPERIMENTS IN FLUIDS, ISSN: 0723-4864, doi: 10.1007/s00348-013-1536-0
De Serio F, Mossa M (2006). Experimental study on the hydrodynamics of regular breaking waves. COASTAL ENGINEERING, vol. 53, p. 99-113, ISSN: 0378-3839.

Other images of the LIC

VERY LARGE FLUME

Channel with a very large aspect ratio (width 4 m) used for the study of the jet diffusion, in cooperation with prof. Peter Davies (University of Dundee, UK).

A part of the very large channel of the LIC is the buoyant jet thermal-hydraulic system. The discharged heated water generating the turbulent buoyant jet is pumped into the channel through a round steel tube mounted at the bottom of the channel in the central longitudinal section.

WHY IS MONITORING IMPORTANT?

1. **Systematic collection of data of interest** (hydrodynamic and physical parameters) to be made **available to stakeholders** with database analysis, processing and storage

Support local government in its coastal planning and management activities

check currents and waves role in coastline erosion and their impact on recreational activities

Allow intervention in an emergency (i.e., accidental oil spilling)

diffusion and dispersions of polluting tracers is strictly connected to currents and waves propagation

2. **Establish a reliable set of 'good' measurements** to be used for calibration and validation of numeric models.

MONITORING
Measurement stations installed and operated in the Gulf of Taranto by the Research Group of the LIC

The area in question is in southern Italy and is composed by two basins, an inner one named **Mar Piccolo and an external one named Mar Grande**

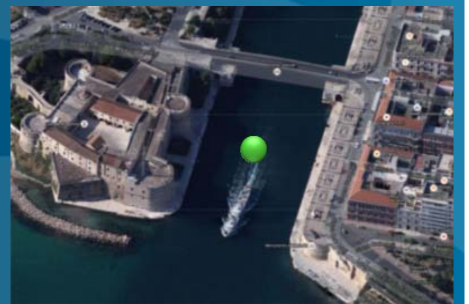
This study area is highly vulnerable, because exposed to a strong anthropic pressure, to urban and industrial discharges as well as to an intense naval traffic. For all these reasons, at present, it is enclosed in the so-called SIN (site of national interest) list and is under the control of the Special Commissioner appointed by the Italian Government to evaluate and dispose urgent measures of **remediation and environmental requalification of Taranto city**.

Automatic Monitoring of the Sea - Mar Grande - Taranto (Italy)

System in the Mar Grande Taranto (Italy) for the monitoring of sea currents (ADCP) and waves. Also a meteo station, a CTD, a combined fluorometers, turbidity meters and a C3 Submersible Fluorometer for CDOM, Crude Oil and Refined Fuels have been installed.

The real time data area available from this web site:
http://www.michelemossa.it/stazionemeteo.php

Automatic Monitoring of the Sea - Mar Piccolo - Taranto (Italy)

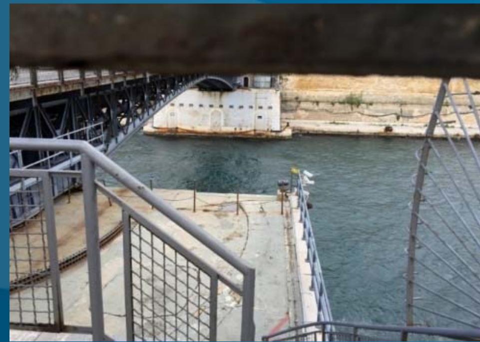


ADCP installed in the Navigable Channel

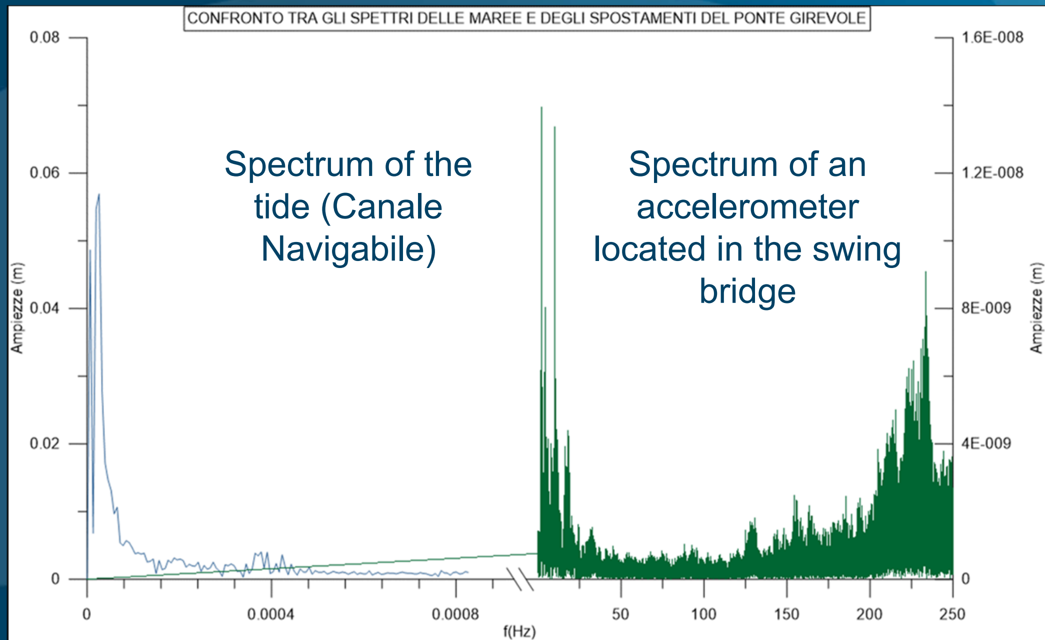
RITMARE is the Italian leading national marine research project for the period 2012-2016 (overall project budget amounts to 250 million euros, co-funded by public and private resources). In this frame, we installed a system in the Navigable Channel of the Mar Piccolo of Taranto (Italy) for the monitoring of sea currents and waves.

The real time data are available from this web site:
http://www.michelemossa.it/stazionemeteo2.php

Ultrasonic tide gauge in Navigable Channel of Mar Piccolo (Taranto)



- Installed on August 2015
- Acquisition frequency: 5Hz



Spectral analysys of the sea currents and the tide in the Navigable Channel

Some references:

De Serio Francesca, Mossa Michele (2016). Assessment of hydrodynamics, biochemical parameters and eddy diffusivity in a semi-enclosed Ionian basin. DEEP-SEA RESEARCH. PART 2. TOPICAL STUDIES IN OCEANOGRAPHY, ISSN: 0967-0645.

De Serio Francesca, Mossa Michele (2016). Environmental monitoring in the Mar Grande basin (Ionian Sea, Southern Italy). ENVIRONMENTAL SCIENCE AND POLLUTION RESEARCH INTERNATIONAL, ISSN: 0944-1344.

Mossa M (2006). Field measurements and monitoring of wastewater discharge in sea water. ESTUARINE, COASTAL AND SHELF SCIENCE, vol. 68, p. 509-514.

FIELD MEASUREMENTS OF THE SEA CURRENT WITH A VM-ADCP (VESSEL-MOUNTED ACOUSTIC DOPPLER PROFILER)
for the comparison between the field mesurements and the numerical codes

Sea current measurements: **VM-ADCP** with GPS receiver (the accuracy of the GPS velocity should be 0.05 m/s or better (DGPS)
Gyro: with serial output and accuracy better than 1°. It is also possible to use combined gyro and GPS system
Computer: The survey computer needs at least 3 serial ports and it is advisable to use an intelligent multi-port card.

Simultaneous measurements of water temperature and salinity with a CTD

THE ENVIRONMENT TODAY AND THE POTENTIAL HELP OF HYDRAULICS

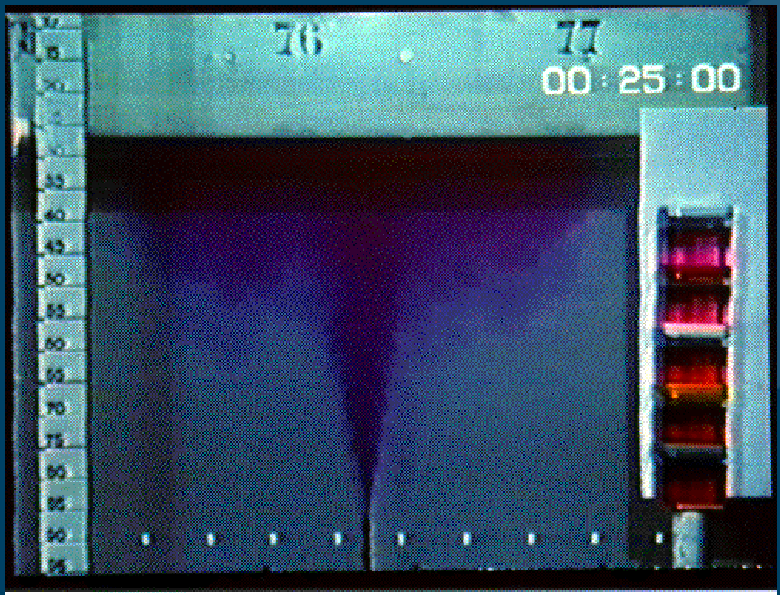
Two case studies:

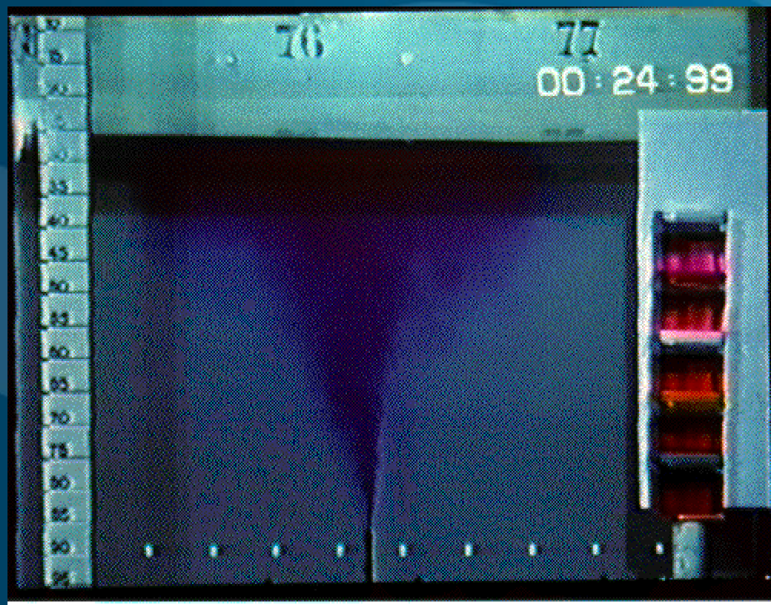
1) **Jets with waves**

2) **Jets in vegetated flows**

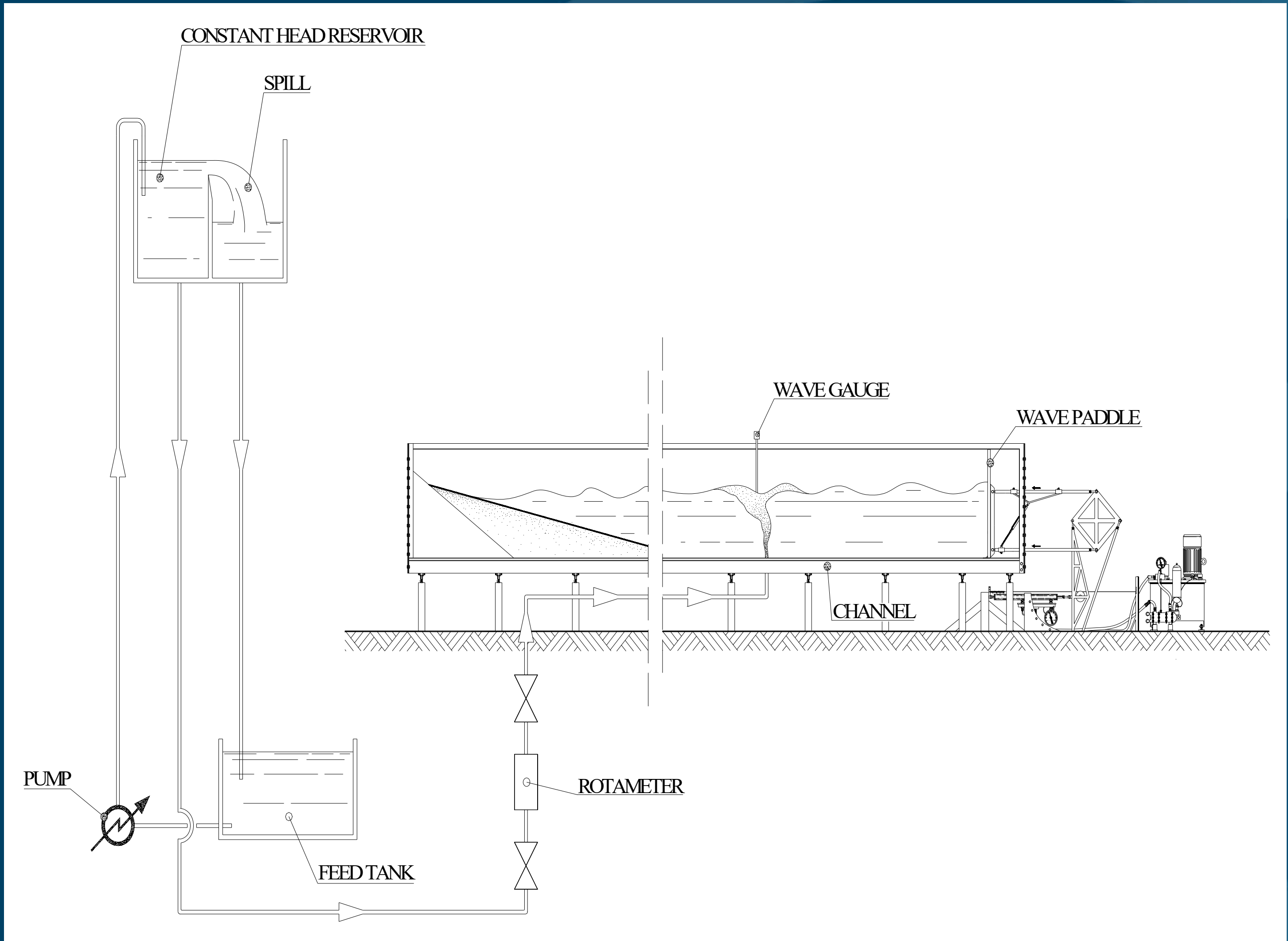
CASE STUDY 1
JETS IN WAVE ENVIRONMENT

- The sea has always been the final destination for water-borne waste products coming from the land.
- While there are several studies in literature on jets and their interaction with currents, few deal with jet-wave interaction.





EXPERIMENTAL SET-UP



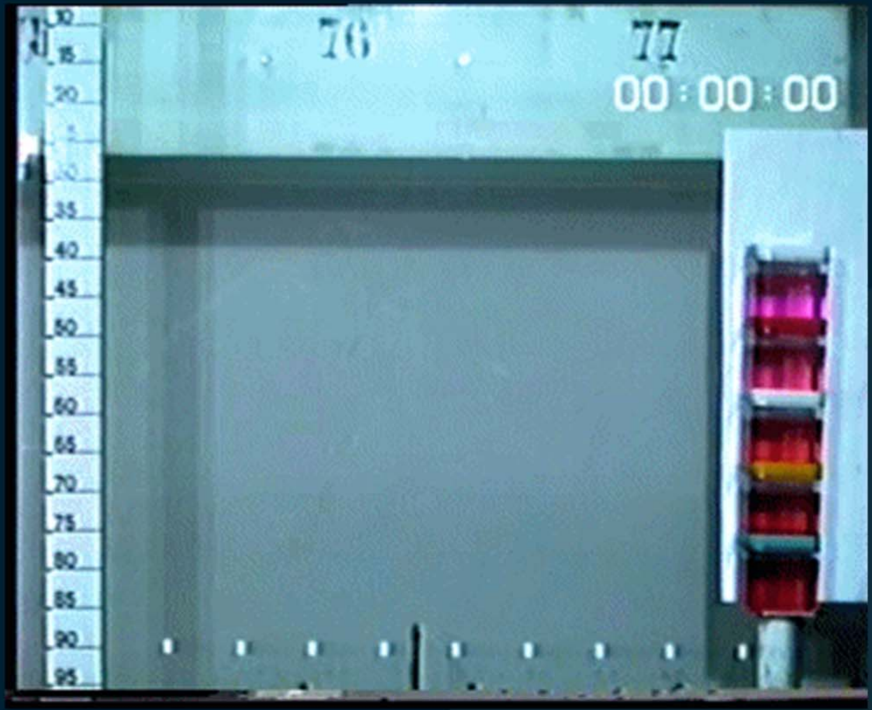
Experiments were carried out in a wave channel at the hydraulics laboratory of the Polytechnic University of Bari.
The channel is about 45 m long and 1 m wide, with a depth of 1.2 m

We used resistance probes for wave profile measurements.

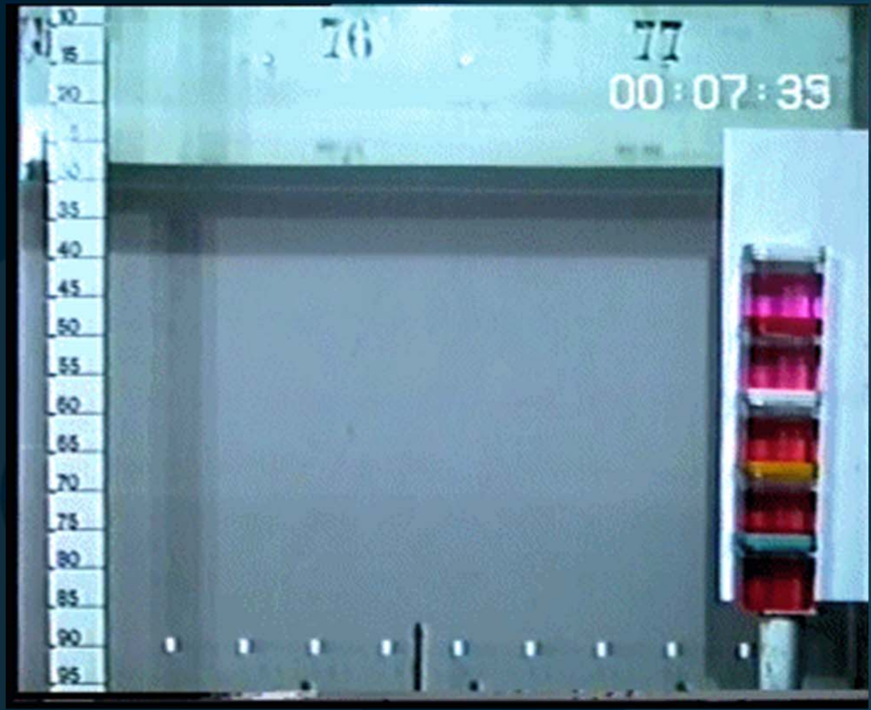
The velocities were measured with a LDA system.

COMPARISON BETWEEN JETS IN STAGNANT WATER AND WITH WAVES

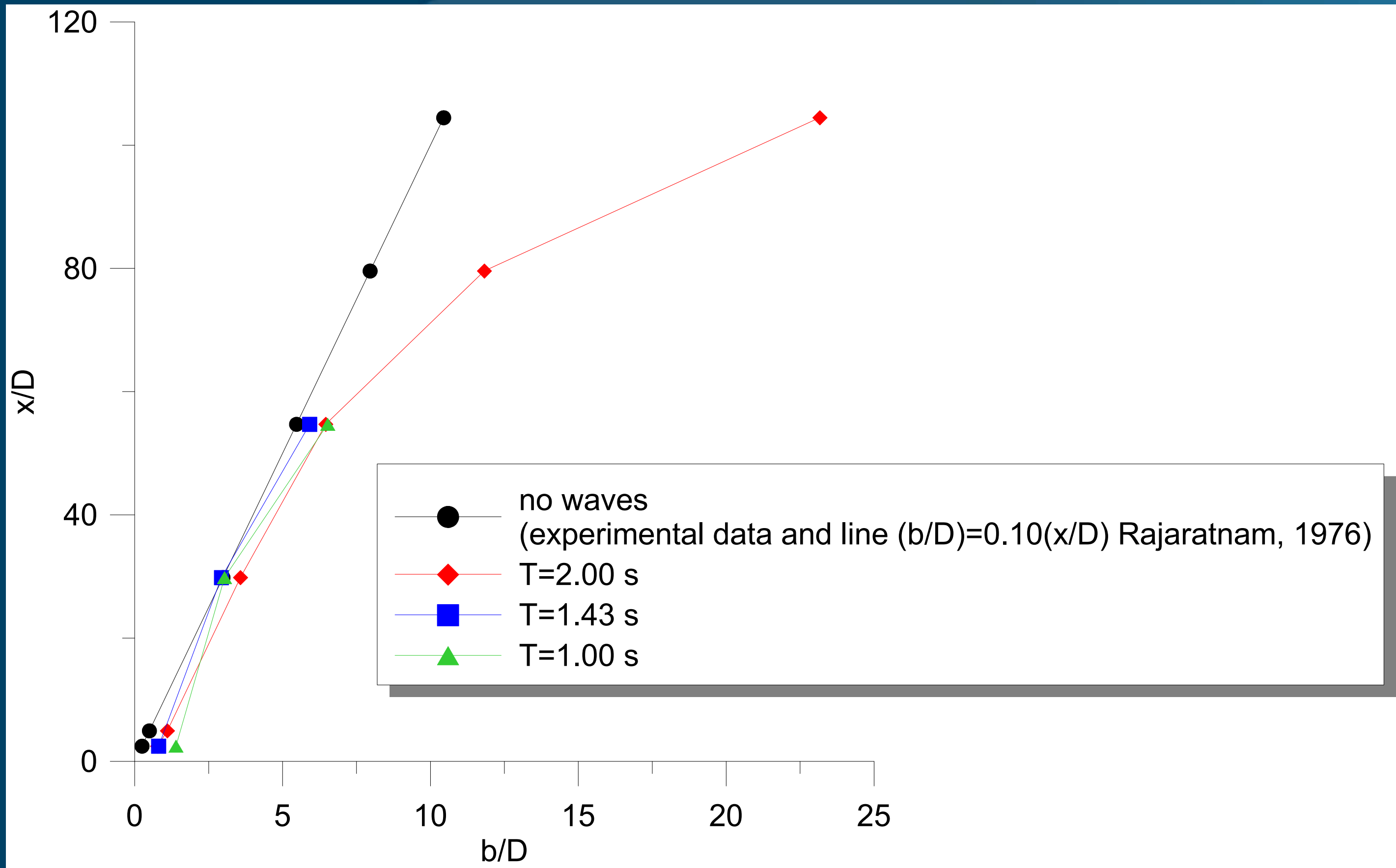
Jet without waves



Jet with waves



Variation of the cross length scale *b* (jet enlargement) as a function of the distance from the jet nozzle



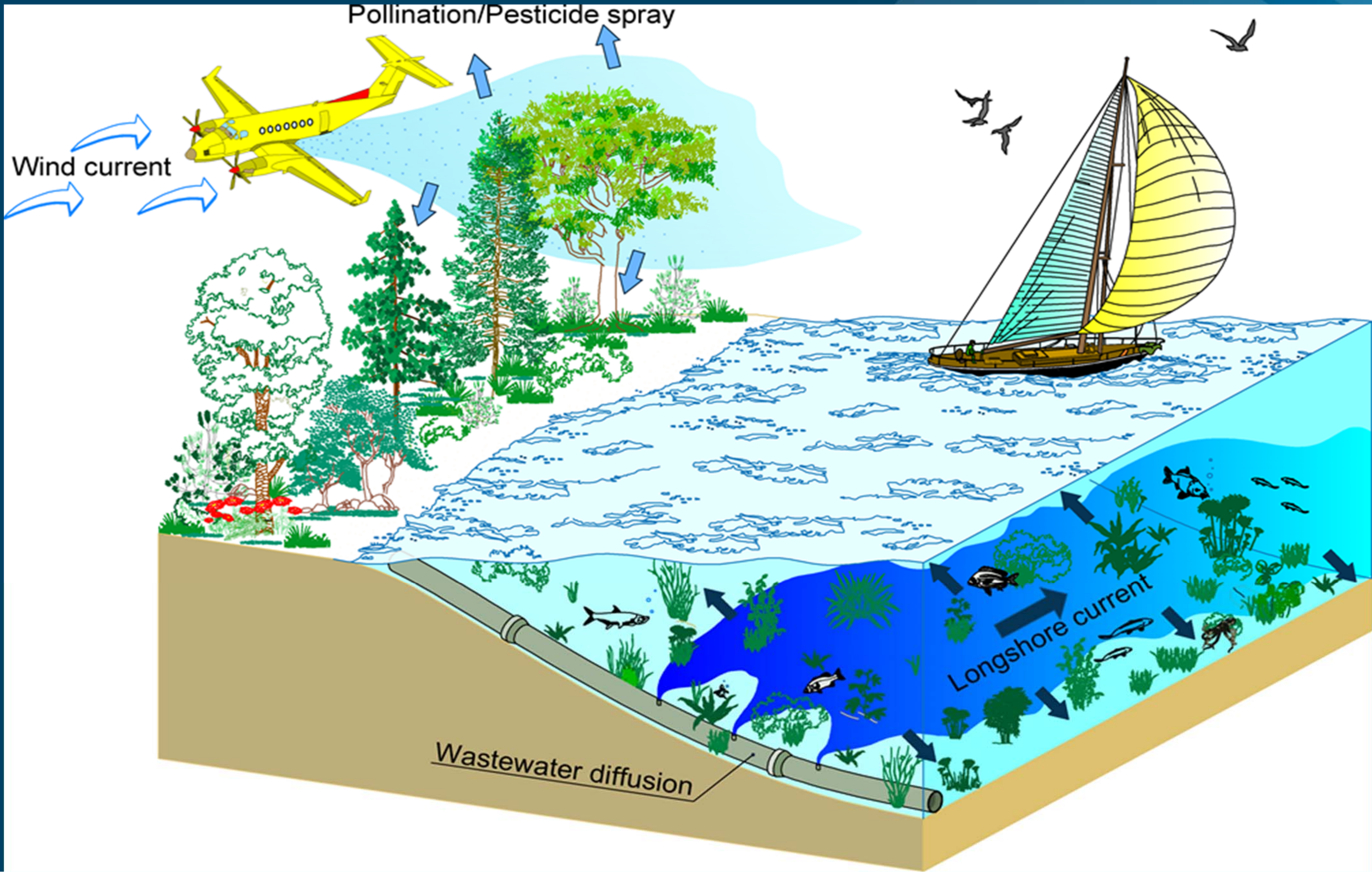
For further details see:

Mossa M. Experimental study on the interaction of non-buoyant jets and waves, Journal of Hydraulic Research, IAHR, 42(1), 13-28, 2004.

Mossa M. Behavior of Non-Buoyant Jets in a Wave Environment, Journal of Hydraulic Engineering, ASCE, 130(7), 2004.

CASE STUDY 2
JETS IN VEGETATED FLOWS

Vegetation is not just a static element of marine and fluvial ecosystems, unchanging with changing conditions, but it interacts with different processes at different scales, e.g. blade scale, patch scale or canopy scale.

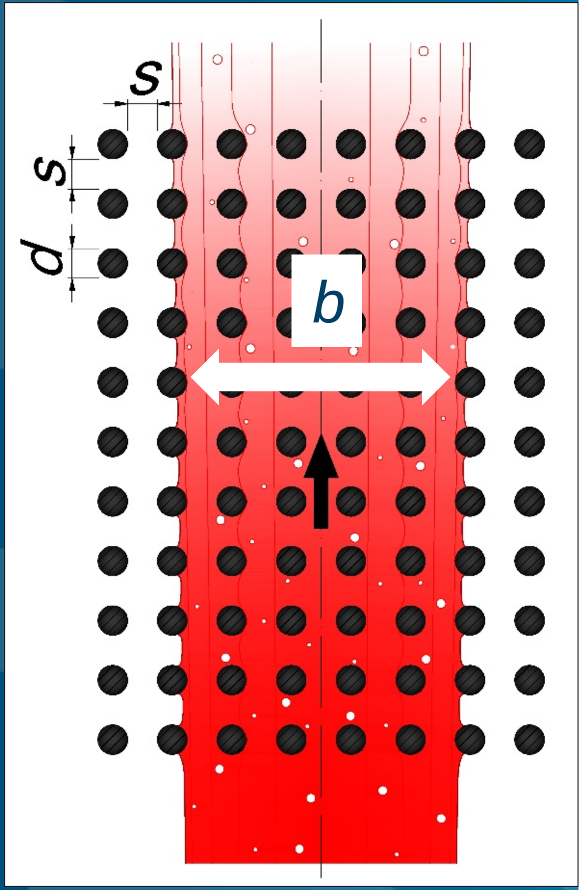


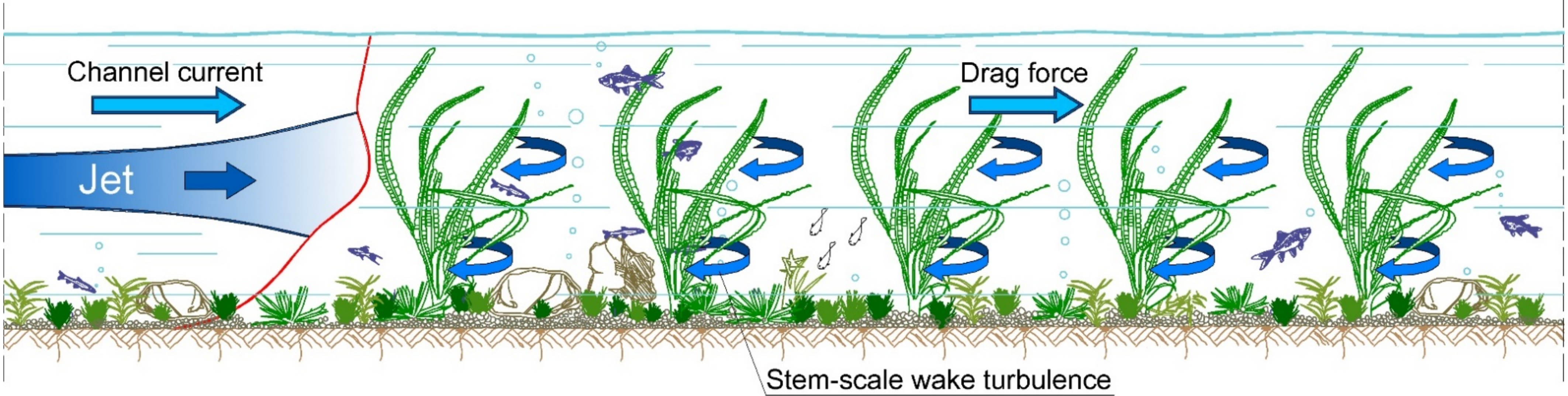
JETS IN VEGETATED FLOWS

Vegetation is not just a static element of marine and fluvial ecosystems, unchanging with changing conditions, but it interacts with different processes at different scales, e.g. blade scale, patch scale or canopy scale.

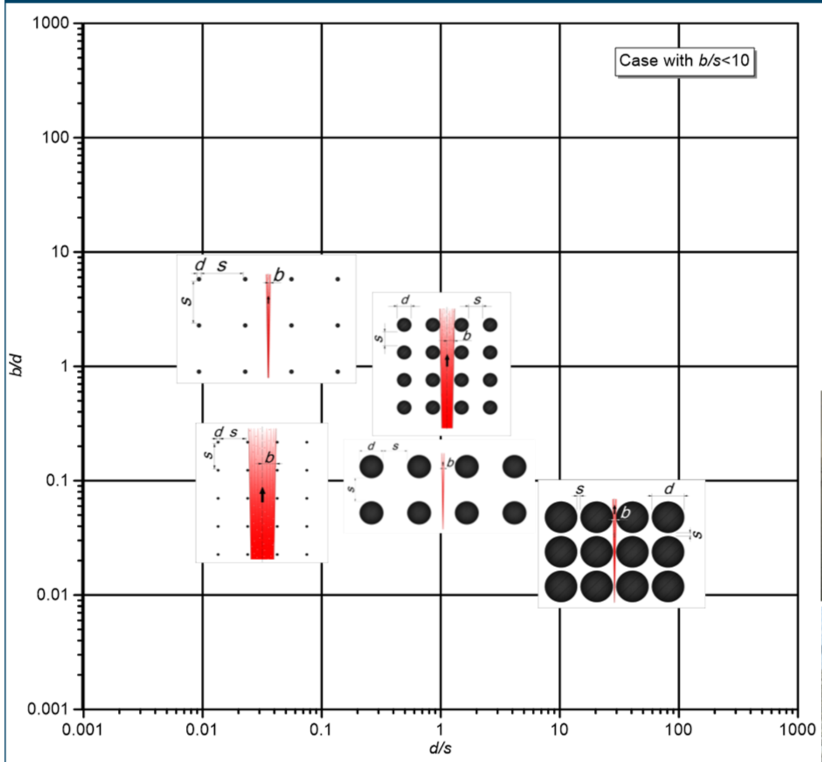
Important parameters:

1) Stem diameter *d*
2) Jet cross section length *b*
3) Distance between two neighboring stems *s*





Examples of jets with vegetation as a function of *d/s* and *b/d* and *b/s*

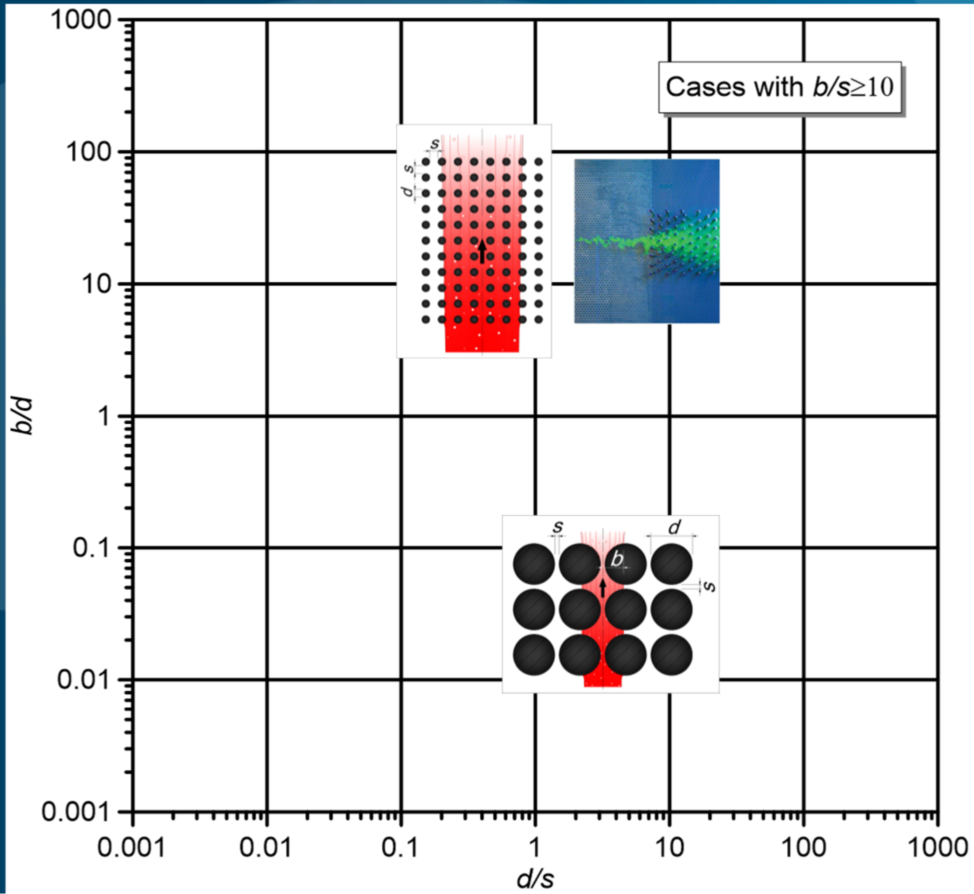


Case with *b/s*<10

Case *d/s*=O(1), *b/d*=O(1), *b/s*=O(1): effects mainly on the ambient current and local effects on the jet boundary at the same scale of *b*. Example of flows: peculiar situation of the cases described below.
Case of *d/s*= O(10^{-2}-10^{-1}), *b/d*=O(1-10), *b/s*=O(10^{-2}-10^{-1}): Effects almost absent on the jet and locally present on the ambient current. Example of flows: release of water of boats between oyster farms.
Case *d/s*=O(10^{-2}-10^{-1}), *b/d*=O(10-10^{2}), *b/s*=O(1): Local effects on the jet boundary at a scale with an order of magnitude less than *b*. Effects locally present on the ambient current. Example of flows: peculiar situation of the previous case; river in a flood plain with an array of trees.
Case *d/s*=O(10-10^{2}), *b/d*=O(10^{-2}-10^{-1}), *b/s*=O(1): Very strong effects on the ambient current and locally at the jet boundary. Example of flows: narrow jets in groundwater; release of a dye trace in groundwater.
Case di *d/s*=O(1), *b/d*=O(10^{-1}), *b/s*=O(10^{-1}): Very strong effects on the ambient current and locally at the jet boundary. Example of flows: narrow jets in groundwater; release of a dye trace in groundwater.

Case with *b/s*≥10

Case *d/s*=O(≤10^{-1}-1), *b/d*=O(10-10^{2}), *b/s*=O(10-10^{2}): Widespread effects on both the ambient current and the jet. Example of flows: jets in rivers and sea with vegetated bottom current.
Case *d/s*=O(1-10), *b/d*=O(10^{-2}-10^{-1}), *b/s*=O(10^{2}-10): Big effects on both the jet and the ambient current. Example of flows: High-flow-blockage canopy; diffusion of contaminants in porous groundwater; injections of jets in groundwater; interior flows associated with porous obstruction. In this case, the jet will tend to diverge significantly in the canopy.



Transport of tracers and turbulent kinetic energy

$$\frac{\partial \bar{c}}{\partial t} + \frac{\partial \overline{u_i c}}{\partial x_i} = K_{ii} \frac{\partial^2 \bar{c}}{\partial x_i^2} \quad \Longleftrightarrow \quad \frac{\partial k}{\partial t} + \frac{\partial \overline{u_i k}}{\partial x_i} = D_k \frac{\partial^2 k}{\partial x_i^2}$$

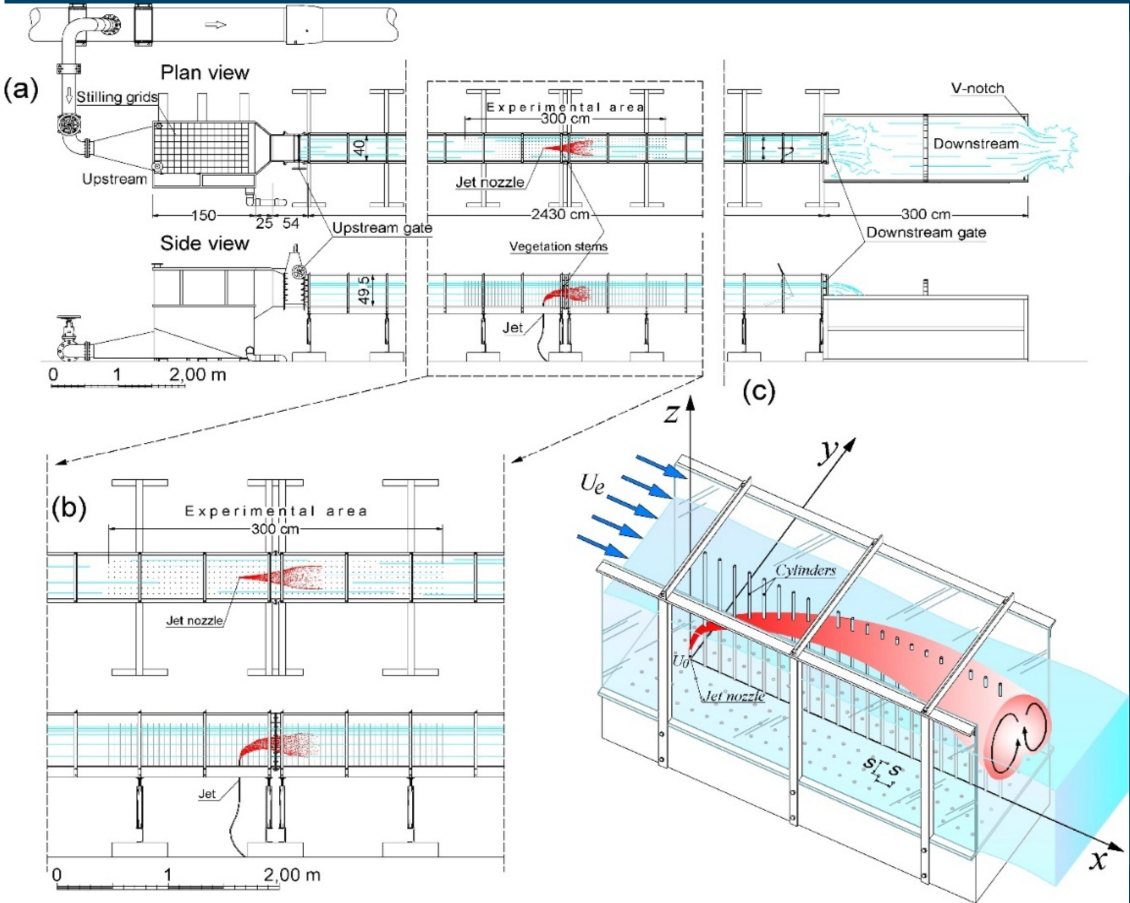
where *c*= tracer concentration and $k = \frac{1}{2}\overline{u_i' u_i'}$ is the time-averaged turbulent kinetic energy.

The analogy between the two equations enables us to conclude that the dispersion coefficients is

$$K_{ii} = \alpha \sqrt{k} l_i$$

The scale factor α could be different for horizontal and vertical diffusion, even if generally it is of O(1).

In the present study, the integral length scale l_i is evaluated by multiplying the integral time scale T_u by the local time-averaged velocity, where T_u is estimated by the autocorrelation function of the turbulent velocity fluctuations.



Experimental apparatus

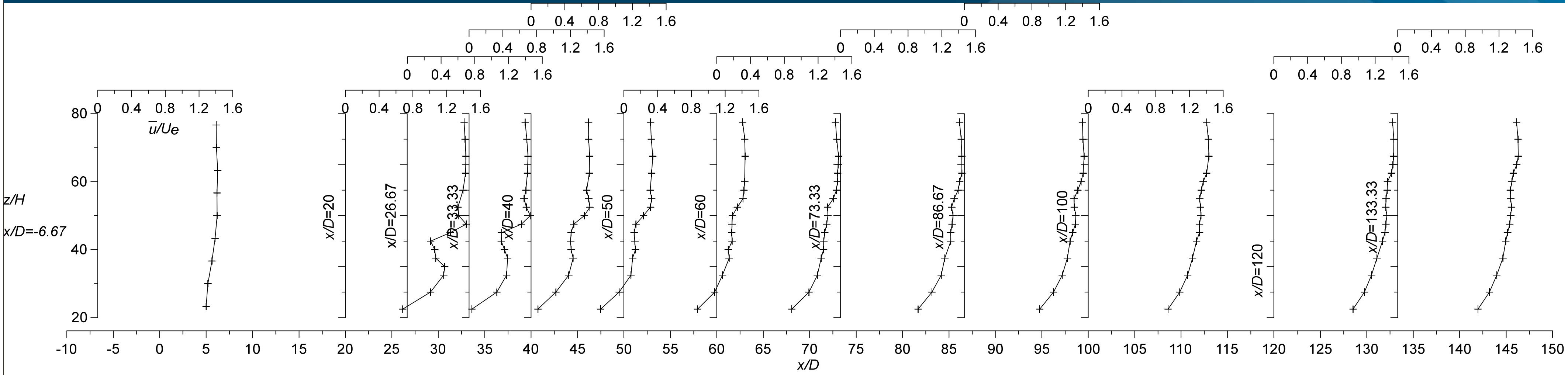
A square array of rigid circular steel cylinders was used to simulate vegetation stems. The stem diameter, *d*, was equal to 0.003 m.

Stems were spaced longitudinally and transversally with the same distance *s* 0.05 m, so that the stem density, *n*, was 400 stems/m^2, and the projected plant area per unit volume, was $a=nd=dH/s^2H=d/s^2$=1.2 m^{-1}

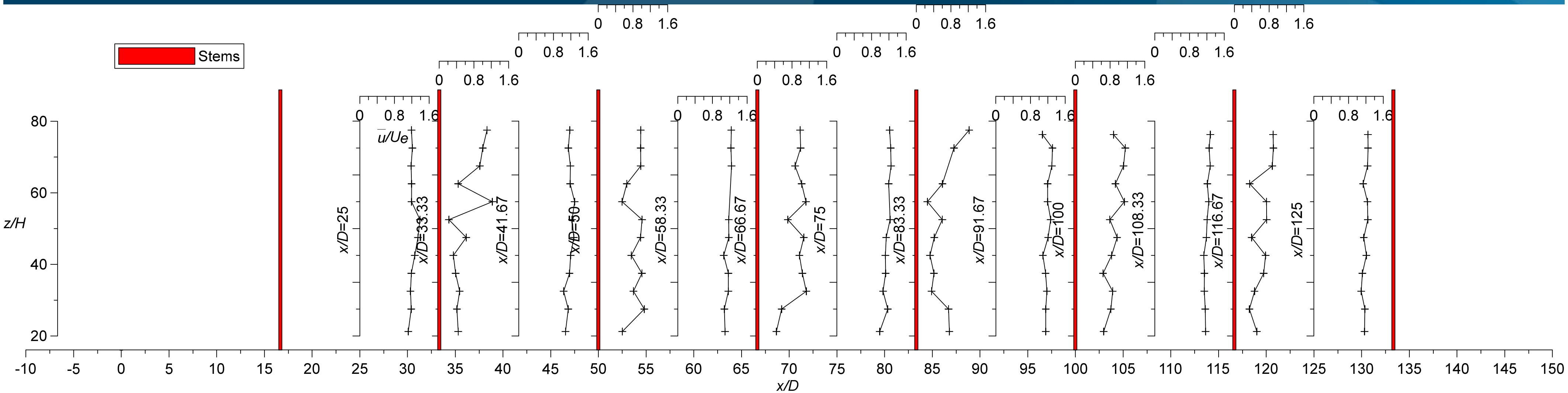
Main parameters of the analyzed runs

Flow type	Runs	H [cm]	U_e [ms^{-1}]	U_0 [ms^{-1}]	R [-]	Re [-]	Re$_0$ [-]
Jet in an unobstructed flow	U1	37	0.16	5.90	37.36	16036	13845
	U2	30	0.19	5.90	30.29	20383	15437
	U3	37	0.16	3.93	24.91	18802	10822
	U4	30	0.19	3.93	20.20	20733	10468
Jet in an obstructed flow	O1	37	0.16	5.90	37.36	23054	19904
	O2	30	0.19	5.90	30.29	26282	19904
	O3	37	0.16	3.93	24.91	24591	14154
	O4	30	0.19	3.93	20.20	26282	13270

Longitudinal profiles of the dimensionless time-averaged streamwise *u* velocity components without and with vegetation

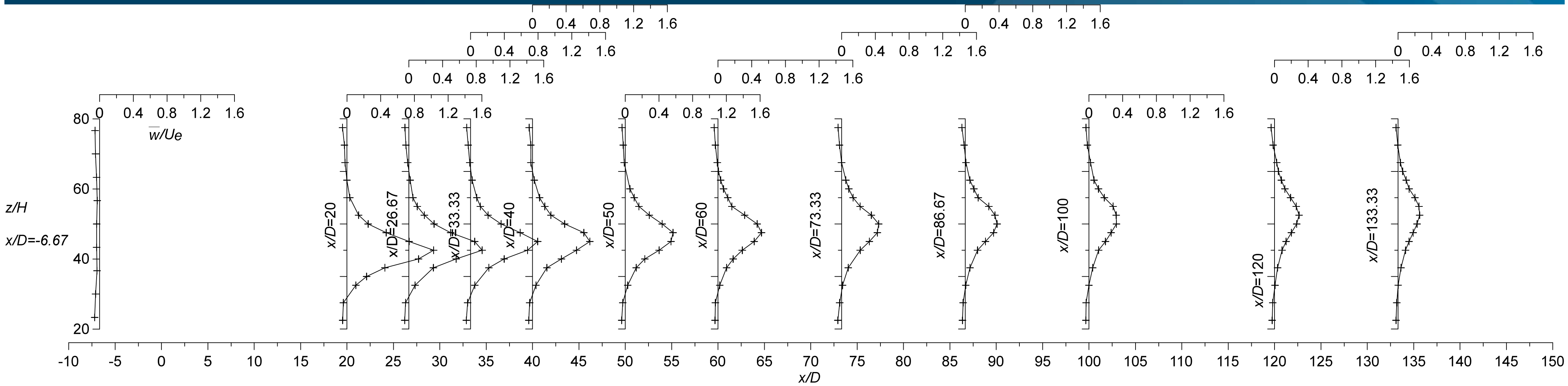


a) $\overline{u}$/Ue of run U4

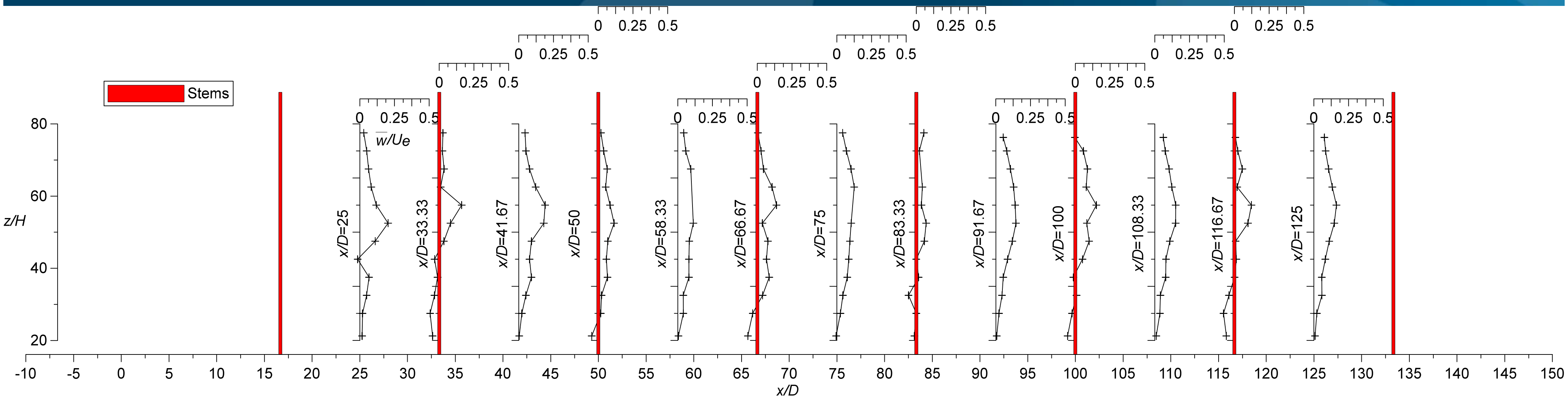


b) $\overline{u}$/Ue of run O4

Longitudinal profiles of the dimensionless time-averaged vertical *w* velocity components without and with vegetation

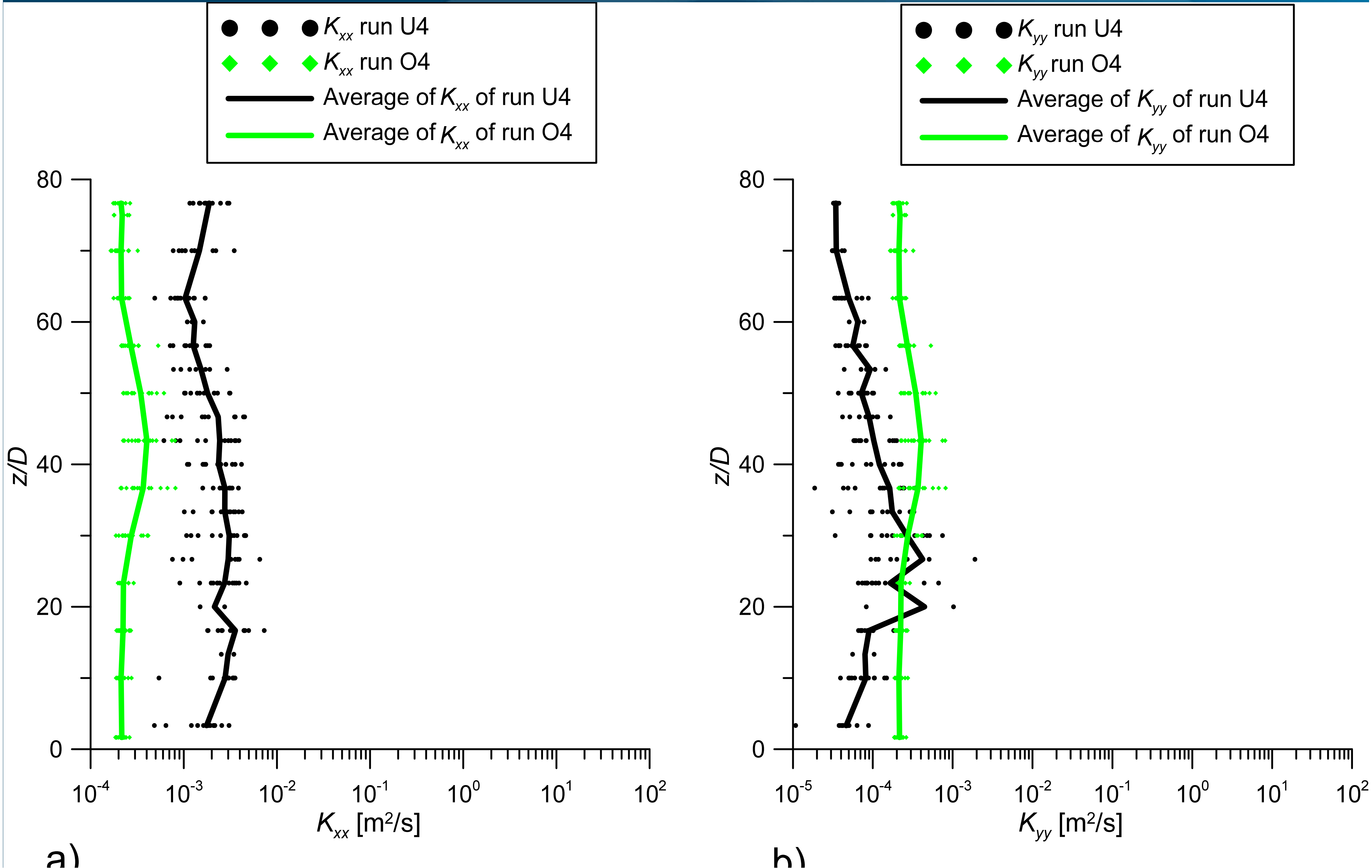


c) $\overline{w}/Ue$ of run U4



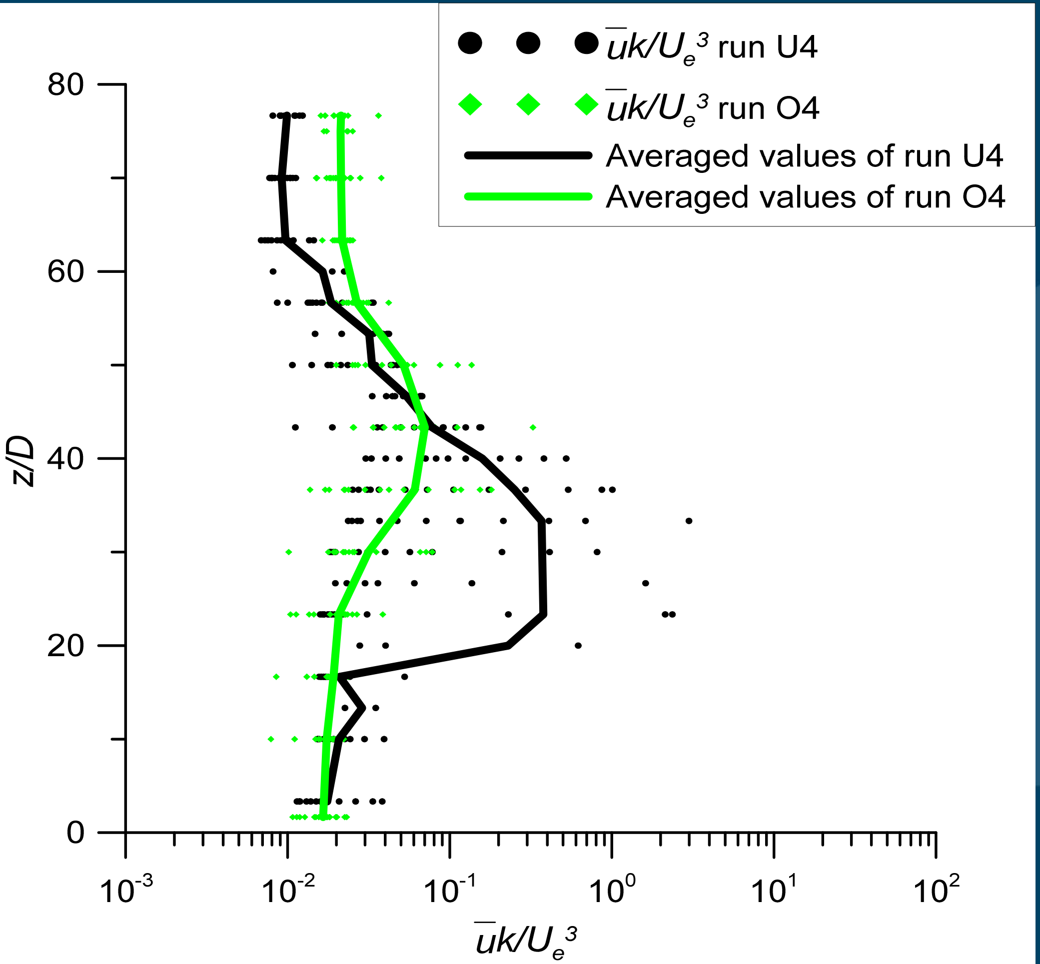
d) $\overline{w}/Ue$ of run O4

Effects of vegetation on the diffusion
Values of K_{xx} (longitudinal diffusion) e K_{yy} (transversal diffusion) of tests U4 (without vegetation) and O4 (with vegetation) with the line of the averaged-values

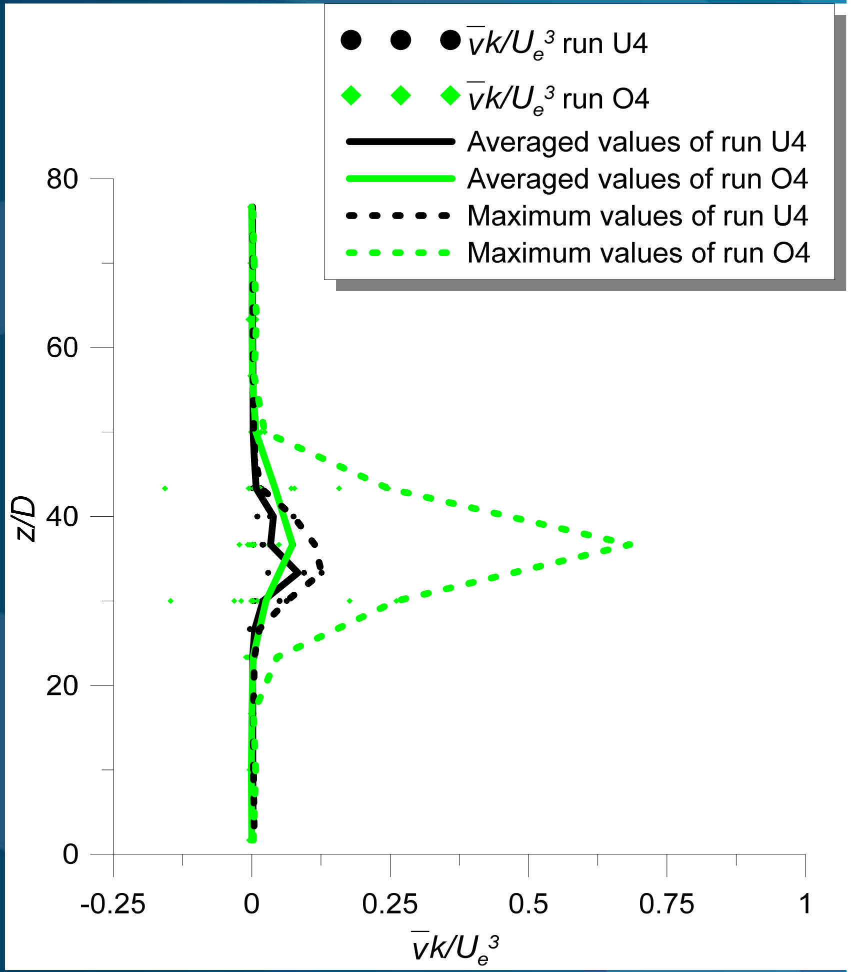


Effects of vegetation on the advection

Values of *Uk* (longitudinal advection) of tests U4 (without vegetation) and O4 (with vegetation) of the longitudinal sections with the time-averaged values



Values of *Vk* (transversal advection) of tests (without vegetation) and O4 (with vegetation) of the transversal section at *x/D*=26.67 with the time-averaged values



MAIN CONCLUSIONS FOR THE CASE STUDY 2

Turbulent jets flowing in currents have been widely examined because of their relevance to many environmental conditions. This study examines a pure turbulent jet issued into an obstructed flow (i.e. vegetated flow), simulated with a regular array of cylinders. The main conclusions can be summarized as follows:

1) Differently from the case of jets in unobstructed flows, in the presence of a cylinder array, **the streamwise turbulent diffusion is reduced**, while the transverse diffusion is enhanced. Importantly, in the obstructed condition, the streamwise and transverse turbulent diffusion coefficients are of the same order of magnitude.

2) The presence of the **vegetation reduces both the diffusion and advection processes of the jet in the longitudinal direction**. In contrast, the **lateral dispersion does not experience the same reduction**, because of the transversal deviation of the streamwise flow around individual cylinders.

For further details, see:

Mossa, M. and De Serio, F. Rethinking the process of detrainment: jets in obstructed natural flows. Sci. Rep. 6, 39103; doi: 10.1038/srep39103 (2016)
https://www.nature.com/articles/srep39103
and M. Mossa, M. Ben Meftah, F. De Serio, H.M. Nepf, How vegetation in flows modifies the Turbulent mixing And spreading of jets. Sci. Rep. 7, 6587 (2017)
https://www.nature.com/articles/s41598-017-05881-1

Other channels of the LIC for the same study

Some references :
Ben Meftah, M. & Mossa, M. Prediction of channel flow characteristics through square arrays of emergent cylinders. Phys. Fluids, 25 (4), 45111-45121, 045102, 2013.
Ben Meftah, M., De Serio, F. & Mossa, M. Hydrodynamic behavior in the outer shear layer of partly obstructed open channels. Physics of Fluids, 26, 65102. doi:10.1063/1.4881425, 2014.
Ben Meftah, M., De Serio, F., Malcangio, D., Mossa, M. & Petrillo A.F. Experimental study of a vertical jet in a vegetated crossflow. Journal of Environmental Management, 164, 19-31, 2015.
Ben Meftah, M. & Mossa, M. A modified log-law of flow velocity distribution in partly obstructed open channels. Environmental Fluid Mechanics, 16, issue 2, 453-479, 2016.
Ben Meftah, M., Malcangio, D., De Serio, F. & Mossa, M. Vertical dense jet in flowing current. Environmental Fluid Mechanics, doi:10.1007/s10652-017-9515-2, 2017.
Malcangio, D. & Mossa, M. A laboratory investigation into the influence of a rigid vegetation on the evolution of a round turbulent jet discharged within a cross flow. Journal of Environmental Management, 173, 105–120. doi:10.1016/j.jenvman.2016.02.044, 2016.
Mossa M. Field measurements and monitoring of wastewater discharge in sea water, Estuarine, Coastal and Shelf Science, 68, 509-514, 2006.
De Serio F. & Mossa M. Streamwise velocity profiles in coastal currents. Environmental Fluid Mechanics, 14, 895-918, 2014.
De Serio F. & Mossa M. Analysis of mean velocity and turbulence measurements with ADCPs. Advances in Water Resources, 81, 172-185, 2015.
De Serio F. & Mossa M. Assessment of hydrodynamics, biochemical parameters and eddy diffusivity in a semi-enclosed Ionian basin. Deep-Sea Research Part II: Topical Studies in Oceanography, 133, 176-185, 2016.
De Serio F. & Mossa M. Environmental monitoring in the Mar Grande basin (Ionian Sea, Southern Italy). Environmental Science and Pollution Research, 23(13), 12662-12674, 2016.
Mali M., De Serio F., Dell'Anna M.M., Mastrorilli P., Damiani L. & Mossa M. Enhancing the performance of hazard indexes in assessing hot spots of harbour areas by considering hydrodynamic parameters. Ecological Indicators, 73, 38-45, 2017.
Mossa, M. & De Serio, F. Rethinking the process of detrainment: jets in obstructed natural flows, Scientific Reports, 6, Article number: 39103, doi:10.1038/srep39103, 2016.
Mossa, M. Experimental study on the interaction of non-buoyant jets and waves. J. Hydraul. Res., 42 (1), 13-28, 2004.
Mossa, M. Behavior of non-buoyant jets in a wave environment. J. Hydraul. Eng., ASCE, 130(7), 704-717, 2004.
Cuthbertson, A.J.S., Malcangio, D., Davies, P.A. & Mossa, M. The influence of a localised region of turbulence on the structural development of a turbulent, round, buoyant jet. Fluid Dynamics Research, 38, 683-698, 2006.

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- Water & wastewater treatment
- Urban water management
- Water footprint assessment
- Water-food
- Water-energy
- Water-human development
- Water-ecosystems

water MDPI

Article

SPH Modelling of Hydraulic Jump Oscillations at an Abrupt Drop

Diana De Padova [1,*], Michele Mossa [1] and Stefano Sibilla [2]

1 Department of Civil, Environmental, Land, Building Engineering and Chemistry (DICATECh), Polytechnic University of Bari, Via E. Orabona 4, 70125 Bari, Italy; michele.mossa@poliba.it
2 Department of Civil Engineering and Architecture, University of Pavia, via Ferrata 3, 27100 Pavia, Italy; stefano.sibilla@unipv.it
* Correspondence: diana.depadova@poliba.it

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Abstract: This paper shows the results of the numerical modelling of the transition from supercritical to subcritical flow at an abrupt drop, which can be characterised by the occurrence of oscillatory flow conditions between two different jump types. Weakly-Compressible Smoothed Particle (WCSPH) model was employed and both an algebraic mixing-length model and a two-equation model were used to represent turbulent stresses. The purpose of this paper is to obtain through the SPH model a deeper understanding of the physical features of a flow, which is, in general, difficult to be reproduced numerically, owing to its unstable character. In particular, the experience already gained in SPH simulations of vorticity-dominated flows allows one to assess the fluctuations of hydrodynamic characteristics of the flow field, (e.g., free surface profile downstream of the jump, velocity, pressure and vorticity). Numerical results showed satisfactory agreement with measurements and most of the peculiar features of the flow were qualitatively and quantitatively reproduced.

Keywords: hydraulic jumps; smoothed particle hydrodynamics models; oscillating characteristics

Thank you for your attention

Prof. Michele Mossa, PhD
Professor of Hydraulics – TECHNICAL UNIVERSITY OF BARI
Chief Scientist of the LIC (Coastal Engineering Laboratory)

www.michelemossa.it
e-mail: michele.mossa@poliba.it
skype name: michele.mossa

DICATECh - Dpt. of Civil, Environmental, Building Engineering and Chemistry
Via E. Orabona, 4 - 70125 Bari - Italy
ph.: +39 080 596 3289
fax: +39 080 2209969
www.dicatech.poliba.it

LIC – Coastal Engineering Laboratory
Area Universitaria di Valenzano
Strada Provinciale Valenzano - Casamassima, Km 3, 70010 Valenzano, BA - Italy
ph.: +39 080 4605 204
fax: +39 080 4605 243
www.poliba.it/lic

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CONCLUSIONS

- This presentation has the main aim of exposing the importance of Hydraulic research (with physical and numerical models and with monitoring) in the branch of the environment.

- The importance of physical models and monitoring systems have been highlighted.

- A deeper knowledge of complex environmental flows should be pursued both for research and technical interests.

- Two case studies have been analyzed, i.e. jets in wave environment and jets in vegetated flows.

- The results highlight that the diffusion and advection processes of the same jet issued in a wave environment or in a vegetated flows are different from those of the same jet issued in still water.

- On this point, the recommendation to explore this research field is very strong, considering that now connections to physics, geology, geomorphology, erosion science, ecology, biology, plant physiology, etc. are to be considered obvious.

- We should instead work with the sole fascinating purpose of protecting this small spacecraft which is our planet Earth.

THEORETICAL BACKGROUND

The u_i (i=1,2,3) velocity components can be expressed as follows

$$u_i(x_i,t) = \langle u_i \rangle (x_i,t) + u_i'(x_i,t) = U_i(x_i) + \tilde{u}_i(x_i,t) + u_i'(x_i,t)$$

The ensemble average of the motion equations for turbulent non-buoyant jet flow under wave action are

$$\frac{\partial \langle u_i \rangle}{\partial t} + \frac{\partial \langle u_i \rangle \langle u_j \rangle}{\partial x_j} = \frac{1}{\rho} \frac{\partial}{\partial x_j} \left(-\langle p \rangle \delta_{ij} + \mu \left(\frac{\partial \langle u_i \rangle}{\partial x_j} + \frac{\partial \langle u_j \rangle}{\partial x_i} \right) - \rho \langle u'_i u'_j \rangle \right)$$

The motion of the incompressible fluid is periodic, so the average over the period T

$$\frac{\partial}{\partial x_j} \left(U_i U_j + \overline{\tilde{u}_i \tilde{u}_j} + \overline{u'_i u'_j} \right) = \frac{1}{\rho} \left(-\frac{\partial P}{\partial x_j} \delta_{ij} + \mu \frac{\partial^2 U_i}{\partial x_j \partial x_j} \right)$$

MAIN QUANTITIES OF THE RUNS

Quantities	Configuration 1	Configuration 2	Configuration 3
H [cm]	4.20	4.40	4.13
L [m]	5.10	3.05	1.56
T [s]	2.00	1.43	1.00
H/L	0.0082	0.014	0.027
h/L	0.157	0.262	0.513
M [m^4/s^2]	1.43E-4	1.43E-4	1.43E-4
L_Q [mm]	1.9	1.9	1.9
$\tilde{v}_{max}$ [m/s]	0.0530	0.0375	0.0103
X_M [m]	0.23	0.32	1.16
X_M/L_Q	1.21E+02	1.68E+02	6.11E+02

H = wave height
L = wave length
T = period
M = momentum flux
L_Q = discharge geometric scale
$\tilde{v}_{max}$ = maximum horizontal wave-induced velocity at the tank bottom
$X_M = M^{1/2}/\tilde{v}_{max}$ is the length scale of jet penetration before jet is strongly affected by the wave

Transport of tracers and turbulent kinetic energy

The time-averaged, turbulent transport of a solute concentration is described by the following equation

$$\frac{\partial \bar{c}}{\partial t} + \frac{\partial \overline{u_i \bar{c}}}{\partial x_i} = K_{ii} \frac{\partial^2 \bar{c}}{\partial x_i^2}$$

where the overbar indicates the time-average operator and the prime symbol denotes the turbulent fluctuations, $c(x)$ is the solute concentration, $v(x)=(u,v,w)=(v_1,v_2,v_3)$ is the fluid velocity, $x=(x,y,z)=(x_1,x_2,x_3)$, with $x=x_1$, $y=x_2$ and $z=x_3$ the longitudinal, transversal and vertical axes, respectively, and K_{ii} are the coefficients for dispersion. For further details see *Tanino, Y. & Nepf, H.M. Lateral dispersion in random cylinder arrays at high Reynolds number. Journal of Fluid Mechanics, 600, 339-371, 2008*.

In the analysis of the flow-dispersion interaction, the turbulent kinetic energy is important in determining the turbulent dispersion coefficient and thus the mass transport. For high Reynolds numbers, assuming that the production term is of order of the dissipation term, the equation of the turbulent kinetic energy is

$$\frac{\partial k}{\partial t} + \frac{\partial \overline{u_i} k}{\partial x_i} = D_k \frac{\partial^2 k}{\partial x_i^2}$$

where $k = \frac{1}{2}\overline{u_i' u_i'}$ is the time-averaged turbulent kinetic energy and D_k is the turbulent diffusion coefficient, which can be expressed as the product of a length scale and a velocity scale. A physical meaningful velocity scale

$$D_k = l\sqrt{k}$$

Velocity and vorticity (positive with dashed line and negative with continuous lines) in some transversal section of the jet