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ALTERATION OF HYDROLOGICAL CONDITIONS AND SPREADING PROCESSES IN VEGETATED NATURAL FLOWS

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EXTENDED ABSTRACT

La vegetazione acquatica interagisce con differenti ecosistemi. Come è ben noto, l'assorbimento di sostanze nutritive e la produzione di ossigeno migliorano considerevolmente la qualità dell'acqua. Allo stesso tempo la presenza diffusa di vegetazione nei corsi d'acqua può contribuire fortemente alla rimozione di azoto e fosforo. Inoltre, promuove la biodiversità, favorendo la formazione di habitat diversi, anche a seguito delle variazioni di velocità della corrente indotte dalla presenza della stessa vegetazione. Le alghe sono alla base di molte catene alimentari. Le paludi e le mangrovie riducono l'erosione costiera, attenuando e smorzando l'effetto del moto ondoso. Inoltre, la vegetazione posta a protezione degli argini fluviali ne incrementa la stabilità.

Ancor più in periodi caratterizzati da forti cambiamenti climatici, che potrebbero alterare le condizioni idrologiche, il monitoraggio dello sviluppo della vegetazione è un'attività fondamentale nella gestione dei fiumi e delle coste, sia al fine di garantire una protezione dei vari ecosistemi, sia per controllare i rischi di inondazione o erosione. Quanto detto dipende strettamente dal campo di moto che si instaura all'interno e intorno alla regione vegetata. Allo stesso tempo, la vegetazione influenza la struttura stessa del flusso e il suo comportamento turbolento, determinando modifiche nel trasporto di traccianti o sedimenti o nell'intrappolamento di particelle. Pertanto, la vegetazione non è solo un elemento statico degli ecosistemi marini e fluviali, immutabile al variare delle condizioni al contorno. Piuttosto, essa interagisce con molteplici processi a diverse scale. In letteratura sono presenti numerosi studi sperimentali e teorici incentrati su diversi aspetti relativi all'interazione tra flussi in canale e vegetazione, ma ulteriori approfondimenti sono ancora necessari.

In particolare, un altro punto chiave, ancora scarsamente investigato e che merita uno studio più dettagliato, è l'effetto indotto dalla vegetazione, o, più in generale, da ostruzioni simili a questa, su un getto turbolento immesso in un corpo idrico recettore, tipico di efflussi in mare o fiumi.

Il presente lavoro analizza i tipici getti sversati in un ambiente vegetato, dimostrando teoricamente e sperimentalmente come i processi di diffusione e avvezione possano essere drasticamente modificati dalla presenza di vegetazione. Tutto ciò può comportare un drastico cambiamento nella morfologia di un corso d'acqua o di una regione costiera marina e nel processo stesso di trasporto di nutrienti o contaminanti.

In questo contesto diventa fondamentale l'azione di controllo durante le fasi di pianificazione e gestione delle attività e degli interventi costieri e fluviali, in modo che si possano valutare le interazioni della vegetazione con i flussi idrodinamici. Infatti, i risultati presentati in questo lavoro evidenziano l'importanza degli effetti indotti dalla vegetazione, i quali, dunque, non possono essere trascurati.

In particolare, dopo avere introdotto la bibliografia di riferimento, viene presentato il metodo analitico, basato sull'equazione del moto e di continuità dei getti con l'aggiunta di una legge di resistenza per la presenza della vegetazione. Gli sviluppi portano alle leggi sulla variazione della portata in ogni sezione trasversale del getto, alla legge della scala della dimensione di ogni sezione trasversale del getto, alla scala della velocità longitudinale di ogni sezione trasversale del getto, del coefficiente di entrainment e della quantità di moto in funzione della distanza longitudinale dall'ugello. I risultati evidenziano una variazione delle suddette leggi per i getti in presenza di vegetazione rispetto al caso dei medesimi getti in assenza di vegetazione.

Successivamente, attraverso l'analogia tra l'equazione della concentrazione di un soluto trasportato da una corrente, mediata nel tempo, e l'equazione dell'energia cinetica turbolenta, si perviene ad una valutazione dei coefficienti di dispersione longitudinale e trasversale del getto nei casi di assenza o presenza di vegetazione. Viene descritto l'apparato sperimentale utilizzato e i relativi risultati ottenuti applicando le leggi dei coefficienti di dispersione, precedentemente ricavate analiticamente. Il confronto dei risultati sperimentali consente di evidenziare che tali coefficienti si riducono nella direzione longitudinale e aumentano nella direzione trasversale nel caso dei getti in presenza di vegetazione. Tali risultati confermano l'influenza della vegetazione sul comportamento dei getti e sui processi di dispersione.

ABSTRACT

Aquatic vegetation provides a wide range of ecosystem services. The uptake of nutrients and production of oxygen improve water quality. The widespread planting in waterways could strongly contribute to the removal of nitrogen and phosphorous. Seagrasses form the foundation of many food webs and vegetation promotes biodiversity by creating different habitats with spatial heterogeneity in the stream velocity. Marshes and mangroves reduce coastal erosion by damping waves and storm surge, as well riparian vegetation enhances bank stability. Even more in times of a changing climate, which could alter hydrological conditions, the monitoring of vegetation development is a fundamental activity in coastal and river management, to both protect ecological services and control flood or erosion risks. A further key point remains poorly investigated and still deserves a thorough study, that is the effect induced by vegetation or similar obstructions on a discharged effluent assumed as a turbulent jet. The present paper shows how vegetation greatly affects the jet entrainment, reversing it into a detrainment process, the diffusion and advection of the jet solute and particles and the jet momentum, demonstrating that it is one of the main cause of the river morphology alteration.

Keywords: *jets, vegetated jets, turbulence, diffusion, advection, obstructed flows*

INTRODUCTION

Aquatic vegetation provides a wide range of ecosystem services (Nikora, 2010; Nepf, 2012; Aberle & Järvelä, 2013). The uptake of nutrients and production of oxygen improve water quality (Wilcock *et alii*, 1999). The widespread planting in waterways could strongly contribute to the removal of nitrogen and phosphorous (Mars *et alii*, 1999). Seagrasses form the foundation of many food webs and vegetation promotes biodiversity by creating different habitats with spatial heterogeneity in the stream velocity (Kemp *et alii*, 2000). Marshes and mangroves reduce coastal erosion by damping waves and storm surge (Marois & Mitsch, 2015) as well riparian vegetation enhances bank stability (Pollen & Simon, 2005). These services are all influenced in some way by the flow field existing within and around the vegetated region. At the same time, vegetation also affects the flow structure and turbulence along with the transport of tracers or sediments and particle trapping. Therefore, vegetation is not only 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 (Nepf, 1999; Tanino & Nepf, 2008a; Ben Meftah & Mossa, 2013; Ben Meftah & Mossa, 2015; Ben Meftah *et alii*, 2015; De Serio *et alii*, 2017). Nepf (1999) observed that the presence of vegetation modifies the velocity field across several scales, relevant to different processes.

For example, the uptake of nutrients by an individual blade depends on the boundary layer on that blade, i.e. on the blade-scale flow. Similarly, the capture of pollen is mediated by the flow structure generated around individual stigma. On the contrary, the retention or release of organic matter, sediments, seeds and pollen from a meadow or patch depends on the flow structure at the meadow or patch scale. Furthermore, spatial heterogeneity in the canopy-scale parameters and architecturally varying components may originate complex flow patterns, which is difficult to interpret, even if using data collected from real channels with live vegetation

Even more in times of a changing climate, which could alter hydrological conditions, the synergistic use of physical models, numerical models and field data, also with the satellite use, and the monitoring of vegetation development is a fundamental activity in coastal and river management, to both protect ecological services and control flood or erosion risks (Mossa, 2006; De Serio & Mossa, 2013; De Carolis *et alii*, 2013; De Serio & Mossa, 2015; De Serio & Mossa, 2016; Armenio *et alii*, 2016; Armenio *et alii*, 2017; De Padova *et alii*, 2017a; De Padova *et alii*, 2017b). In fact, fluvial as well as coastal and estuarine environments are sensitive and vulnerable to climate change, especially to more and more recurrent extreme events.

Average global temperatures have been rising in recent time and climate change is expected to measurably affect stream hydrology. Climate change affects many stream variables, including channel morphology. For example, a decrease in precipitation can cause channels to infill with sediment and change from an incised channel to a broader, shallower channel. On the contrary, an increase in precipitation and, therefore, flow discharge can cause channels to infill if sediments stored on alluvial fans and valley bottoms are remobilized and transported into the stream. In this case, channel aggradation raises base level, with an increase of flooding on terraces and floodplains. The described phenomena have undoubtedly many consequences also on the river vegetation, which in turn has big effects on the river.

In fact, vegetation has a primary control on river planform, for example determining whether a river will present a braided or single-thread pattern. Studies have shown that overall behavior of the system correlates with vegetation type or density, shifting between a single-thread channel and a multi-thread system as vegetation changes (Murray & Paola, 1994; Ward & Tockner, 2000).

In natural systems the stabilization of the bank can derive either from fine-grained sediment (silt, clay) or from vegetation. Vegetation increases bank stability through root binding of the sediment and increases the threshold shear stress needed to erode the sediment. In addition, vegetation offers local resistance to flow by increasing drag and reducing velocity, thus decreasing the shear stress available for erosion and transport. The physical details of vegetation effects on river channels are complex. In fact, increased vegetation density is typically linked to a decrease in bank erosion and lateral migration rates. Roots function like the bars in reinforced concrete or the fibers in a carbon-fiber composite material. Thus, vegetation colonizes large areas of the bed and plays an active role in determining the channel morphology. The case is similar for periods of drought.

Even if the effects of vegetation on the changes in river planform have been extensively studied, few papers analyze the effect of vegetation on the diffusion and advection processes of jets issued in a river or also in other type of water bodies, such as lakes, seas, oceans. The described phenomena show that the variations of some characteristics of a water body can be assumed as the effects of a specific cause, which, in turn, becomes causes of other effects; all the process resulting in a vicious circle, where we lose track of what is cause and effect (resembling a sort of chicken-egg process).

Since acknowledged the importance of flows through regions with vegetation, many experimental and theoretical studies have been carried out focusing on many aspects of the interaction of channel flows and vegetation (Nepf *et alii*, 1997; Poggi *et alii*, 2009; Defina & Peruzzo, 2010; Albayrak *et alii*, 2011; Nepf, 2012; Nikora *et alii*, 2013; De Serio *et alii*, 2017). Nevertheless, a further key point remains poorly investigated and still deserves a thorough study, that is the effect induced by a vegetated current on a turbulent jet, i.e. a discharged effluent. In fact, the jet mixing processes have been extensively studied in the simpler case of unobstructed flows (Fischer *et alii*, 1979; Mossa, 2004a; Mossa, 2004b; Smith & Mungal, 1998; Cuthbertson *et alii*, 2006), revealing that they are greatly affected by the initial jet characteristics (e.g. nozzle shape, dimensions, flow rate), the boundary conditions (e.g. topography, bathymetry) and the hydrodynamic features of the ambient current.

As shown by Mossa & De Serio (2016) and Mossa *et alii* (2017), the interaction of aquatic vegetation and, more generally, of porous obstructions in natural environments with a stream flow remains insufficiently explored and represents a challenge for scientists. In fact, multiple ecological, morphological and physical aspects characterizing plant canopies, such as shoot density, leaf length, plant stiffness, standing biomass, as well as plant submergence ratio, size and location, influence the flow hydrodynamics (Aberle & Järvelä, 2013; Nikora, 2010). On the other hand, hydrodynamics affects the structure of the underwater vegetation fields by dispersing spores, by mediating the availability of nutrients (Nikora, 2010; Nepf, 2012) and by exerting drag forces and associated turbulence (Wilcock *et alii*, 1999; Mars *et alii*; 1999), which could be responsible for vegetation development and survival (Kemp *et alii*, 2000).

There is a continuous and mutual interaction between the canopy and its surrounding flow. It is well known that seagrasses can significantly influence the hydrodynamic environment by reducing current velocity, dissipating wave energy and increasing deposition or retention of finer sediments, to which benthic invertebrates are sensitive (Marois & Mitsch, 2015; Pollen & Simon, 2005; Tanino & Nepf, 2008b; Nepf, 1999). They have important ecological consequences, reducing turbidity and increasing light penetration, thus enhancing primary production and photosynthesis, which in turn guarantee their growth and reproduction.

Therefore, as also pointed out by Nepf (1999), aquatic vegetation is of tremendous significance to many ecosystem functions: i) promoting biodiversity and creating different habitats with spatial heterogeneity in the stream velocity; ii) improving water quality due to the uptake of nutrients and production of oxygen; iii) reducing coastal erosion and enhancing bank stability, as in the case of marshes mangroves and riparian vegetation. For all the above-mentioned reasons, vegetation hydrodynamics should not be strictly studied from a hydraulic perspective.

METHODS

Possible cases of jets issued in vegetated flows

Figure 1 shows an example of release of jets interacting with the vegetation, i.e. jet-like flows in sea currents between mussel farms.

In obstructed flows the motion depends strongly on the stem diameter, the jet cross section scale and the distance between the stems. Particularly, in the present analysis, referring to figure 2 the scale of the jet is the dimension of its cross-section b, generally assumed as the distance between the jet axis, where the longitudinal mean velocity is $\bar{u}_m$ and the point where the mean longitudinal velocity is $\bar{u}$ with $\bar{u}/u_m = 1/e$.

The other scales are the stem diameter d and the distance between the cylinders s. The vegetation density per meter, i.e. the projected plant area per unit volume, is $a = nd$, where n is the stem density, i.e. the number of stems per unit planar area.

Fig. 1 - Typical release of jets interacting with the vegetation: jet-like flows in sea currents between mussel farms

Jet discharge and entrainment metrics

In the case of a plane turbulent jet issued in an ambient fluid at rest with the presence of a cylinder array (Fig. 2), we used the Reynolds equations of motions and the quadratic form of the resistance laws for flow in the presence of vegetation

$$D_x = \frac{1}{2}\rho C_D a \left|\overline{u}\right| \overline{u} \qquad (1)$$

where $\bar{u}$ is the time-averaged longitudinal velocity of the flow, ρ is the fluid density and C_D is the bulk drag coefficient (Nepf, 1999). For further details, see Mossa & De Serio (2016).

Considering the entrainment coefficient of the jet α_e, we derive that

$$\frac{dQ}{dx} = 2\overline{v_e} = 2\overline{u_m}\alpha_e \qquad (2)$$

where Q is the jet flow rate in each cross section and $\bar{v}_e$ is the time-averaged transversal velocity at the nominal outer boundary of the jet, which is oriented towards the jet centerline in the case of a positive entrainment coefficient and vice versa in the case of a negative entrainment coefficient, i.e. when a detrainment flow is present (for further details, see Rajaratnam, 1976 and Mossa & De Serio, 2016). The jet discharge Q as function of x was calculated as

$$Q \propto 2b \cdot \overline{u_m} \Rightarrow$$

$$Q = 2C_Q C_b C_{um} \frac{x}{x_0} \cdot \left(\frac{x}{x_0}\right)^{-\frac{1}{2}-\frac{1}{4}C_D a x} = 2C_Q C_b C_{um} \left(\frac{x}{x_0}\right)^{\frac{1}{2}-\frac{1}{4}C_D a x} \qquad (3)$$

where x_0 is the distance from the nozzle where the jet flow starts to be fully developed, C_b and C_{um} are the values of b and $\bar{u}_m$,

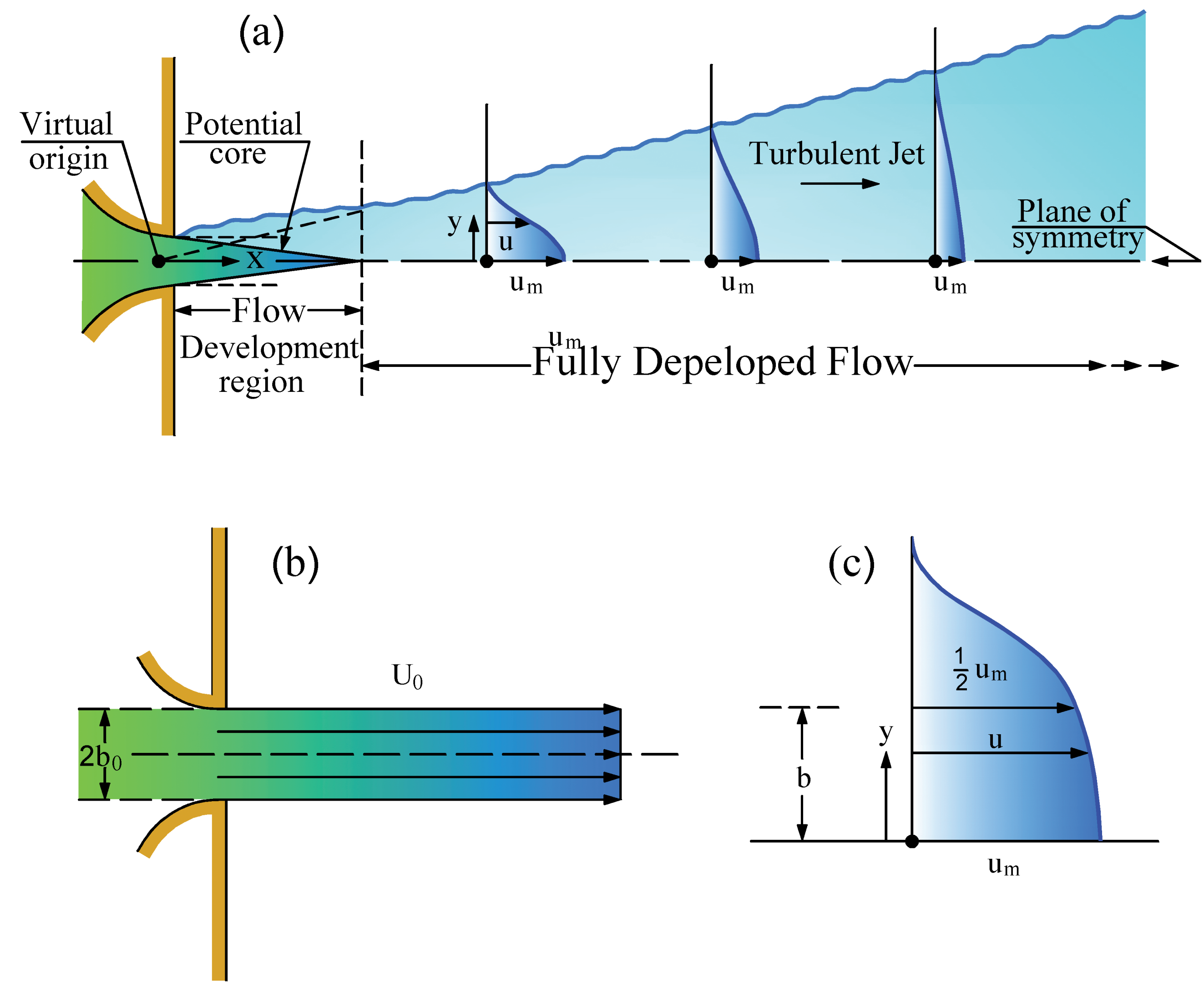

Fig. 2 - Sketch of plane jet: a) lateral view; b) jet exit from the nozzle; c) typical longitudinal velocity profile in a cross-section

respectively, for x equal to x_0. In eq. (3) C_Q is a dimensionless coefficient which considers both the geometry of each cross section of the jet and the ratio between the average longitudinal velocity and the maximum longitudinal velocity of each analyzed cross section. Furthermore, b was calculated as

$$b = C_b \left(\frac{x}{x_0} \right)^{-\frac{1}{2} - \frac{1}{4} C_D a x} \tag{4}$$

and $\overline{u_m}$ was calculated as

$$\overline{u_m} = C_{um} \left(\frac{x}{x_0} \right) \tag{5}$$

For further details see Mossa & De Serio (2016). The entrainment coefficient of eq. (2) was calculated as

$$\alpha_e = \frac{C_Q C_b}{4 x_0} \cdot \left(2 - C_D a x - C_D a x \ln \left(\frac{x}{x_0} \right) \right) \tag{6}$$

The derivative of the jet momentum in each cross section with respect to the longitudinal distance from the nozzle x is equal to

$$\frac{dM(x)}{dx} = \frac{d}{dx} \int_0^\infty \rho \overline{u}^2 dy = -\frac{1}{2} C_D a \int_0^\infty \rho \overline{u}^2 dy \tag{7}$$

where y is the transversal distance from the jet axis (Fig. 2). The solution is

$$M(x) = M_0 \exp\left(-\frac{1}{2} C_D a x \right) \tag{8}$$

Equation (8) shows an interesting result, since a pure plane jet in an obstructed flow does not preserve the momentum as in the analogous case of unobstructed flow.

Metrics of the tracer transport of jets in vegetated ambient

Neglecting the molecular diffusion, being small in a turbulent flow, the time-averaged transport of a solute concentration is described by

$$\frac{\partial \overline{c}}{\partial t} + \frac{\partial \overline{u_j c}}{\partial x_j} = -\frac{\partial \overline{u_j' c'}}{\partial x_j} \tag{9}$$

with the overbar denoting the time average and the prime symbol denoting the turbulent fluctuations and where t is time, $c(\mathbf{x},t)$ is the solute concentration, $\mathbf{v}(\mathbf{x},t)=(u,v,w)=(v_1,v_2,v_3)$ is the fluid velocity, and $\mathbf{x}=(x,y,z)=(x_1,x_2,x_3)$, with $x=x_1$, $y=x_2$ and $z=x_3$ the longitudinal, transversal and vertical axes, respectively. Equation (9) shows that the concentration mass flux is due to the convection by the time averaged flow, uc, vc and wc , and the transport by turbulent velocity fluctuations, $\overline{u'c'}$, $\overline{v'c'}$ and $\overline{w'c'}$.

It can be rewritten as follows

$$\frac{\partial \overline{c}}{\partial t} + \frac{\partial \overline{u_j c}}{\partial x_j} = K_{jj} \frac{\partial^2 \overline{c}}{\partial x_j^2} \tag{10}$$

where K_{jj} are the coefficients for net dispersion, which parameterizes $\overline{u_j'c'}$, i.e. the turbulent diffusion.

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 (Finnigan, 1985). For high Reynolds numbers, assuming that the production term is of order of the dissipation term, the equation of the turbulent kinetic energy is

$$\frac{\partial k}{\partial t} + \frac{\partial \overline{u_j} k}{\partial x_j} = D_k \frac{\partial k}{\partial x_j} \tag{11}$$

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

$$D_k = l\sqrt{k} \tag{12}$$

Furthermore, analogously to eq. (12), it is possible to assume that the net dispersion coefficients of eq. (10) could be set equal to

$$K_{jj} = \alpha \sqrt{k} l_j \tag{13}$$

where the scale factor α could differ for horizontal and vertical diffusion, even if generally it is of O(1). In the present study, the integral length scale l is evaluated by multiplying the integral time scale T_u by the local time-averaged velocity $\overline{u_i(x)}$, where T_u is estimated by the autocorrelation function of the turbulent velocity fluctuations.

This integral length scale of turbulence l strongly depends on the presence of vegetation (De Serio *et alii*, 2017). In the unobstructed flow, l increases with the scale of the diffusion patch until the largest length scale is reached, that is the length scale defined by the flow domain.

In the case of jet issued in an unobstructed flow it is reasonable to assume that the maximum value of the longitudinal mixing length scale l_x is O(H), where H is the channel flow height, since the jet interacts with the channel current. On the contrary, the transversal mixing length scale is expected to be of O(b), where b is the length scale of the jet transverse cross section, since in this direction the ambient channel flow velocity (secondary currents) is small compared to the longitudinal one.

Emergent canopies impose a specific structure on both the mean and turbulent flow over the entire water column. In flows with emergent vegetation, the canopy dissipates eddies with scales greater than the stem scale of s and d, while contributing additional turbulent energy at these stem scales. Thus, the dominant turbulent length scale within a canopy is shifted downward from analogous condition without vegetation. Particularly, in a channel with a regular array of cylinders, the integral length scale of the turbulence is set by the smaller of the stem diameter, d, or the distance between the stems s, regardless of the water depth. In other words, for $d \leq s$, turbulence is generated within stem wakes (if the Reynolds number is sufficient) so that $l=d$; on the contrary, for $d>s$, turbulence is generated within the pore channels so that $l=s$.These two depicted regimes in presence of cylinders are not exhaustive, since for low solid volume fractions (ad less than 0.01) the integral length scale of the turbulence should have a value intermediate between those previously mentioned, i.e. $l=O(\min(d,s)\div H)$.

Experimental procedure

The experimental runs were carried out in a smooth horizontal rectangular channel, extensively described in Meftah *et alii* (2015). The channel was 25.0 m long, 0.40 m wide and 0.50 m deep. The lateral walls and the bottom surface of the channel were constructed of Plexiglas.

To simulate vegetation stems, a square array of rigid circular steel cylinders was used. The stem diameter, d, was equal to 0.003 m. The stems were inserted into a plywood board 3.0 m long, 0.398 m wide and 0.02 m thick, which in turn was fixed along the channel bottom, forming the experimental area. In order to reduce the effect of plywood board thickness on the experimental area, two other 3.0 m x 0.398 m x 0.02 m plywood boards, without vegetation stems, were attached to the channel bottom at both the upstream and the downstream side of this area. Stems were spaced longitudinally and transversally, with the same distance s of 0.05 m, so that the stem density, n, was 400 stems/m^2 and the vegetation density per meter, i.e. the projected plant area per unit volume, was $a=nd=dH/s^2H=d/s^2=1.2$ m^{-1}.

The main characteristics of the analyzed runs are shown in Tab. 1, where U_0 is the initial jet velocity, U_e the ambient current, Re is the channel Reynolds number and Re_0 is the initial jet Reynolds number.

Therefore, both channel and jet flows were turbulent. The geometry of the obstructions remained unchanged for all runs (for further details, see Mossa & De Serio, 2016). For each run we analyzed both the case with an unobstructed flow and obstructed flow. Therefore, in the text, to refer to one of the two configurations, we placed the letter U or O before the run number of Table 1. As shown by Nepf (2012), the bulk drag coefficient C_D is a function of the array density and, in the case of the present experiments, it was assumed equal to 1.2.

RESULTS

How entrainment and momentum of a jet change with the presence of obstructions

Entrainment is an important phenomenon of the mixing process. Considering as an example the case of figure 3, illustrating the mixing process in a stationary salt water wedge, entrainment can be defined as the incorporation of non-turbulent, usually irrotational fluid into the turbulent region of the entraining fluid or the diffusion of the turbulent entraining fluid into non-turbulent ambient fluid.

In the case of environmental flows, we are quite often faced with flow situations where an interface separates two flow regions of different levels of energy, as for example in estuaries (such as fjords, salt water wedges), dense bottom currents in the sea, seiching in a stratified lake, smoke from a chimney in a wind field, etc.

In the case of the example of figure 3, denoting the upward and downward volume fluxes q_u and q_d, respectively, the flux by entrainment is the difference q_u-q_d.

Entrainment is closely related to turbulence and consequently it is one of the most outstanding and complicated problems in environmental flows. Brown & Roshko (1971) visually observed the existence of the most beautiful, well-defined large structure rollers or vortices as those in Figure 4. The phenomenon is followed by a successive vortex coalescence process, where a pair of vortices are ingested by a single large vortex, which together with its neighbor, is ingested by a single larger vortex (see Winant & Browand, 1974). In this case the entrainment process is concerned with very high Froude number flows.

Jet dynamics are generally associated with the entrainment process, i.e. the one-way transport process from the ambient fluid to the flowing turbulent fluid. The entrainment process can be intended as the net transport of fluid from a less to a more turbulent fluid, considering that turbulence intensity can be conceived as a measurement of turbulence (Fig. 4).

Nevertheless, in some specific configurations, jets experience detrainment, which is the process by which fluid is expelled from a turbulent flow. Detrainment is an important mechanism in some fluid flows in nature, often observed in cloud dynamics, when cloudy air is transferred outside of the cloud volumes, with consequent influence on the vertical heat and moisture fluxes in the atmosphere. Also in the ocean, detrainment is an important process, which explains the sediment transport from large density currents on the continental slope as well as the fate of hydrothermal plumes from submarine volcanic rift zones in the middle of the ocean.

Runs	***H [cm]***	***U_e [ms^{-1}]***	***U_0 [ms^{-1}]***	***U_0/U_e [-]***	***Re [-]***	***Re_0 [-]***
1	37	0.16	5.90	0.027	23054	19904
2	30	0.19	5.90	0.032	26282	19904
3	37	0.16	3.93	0.041	24591	14154
4	30	0.19	3.93	0.050	26282	13270

Tab. 1 - Main parameters of the experimental runs

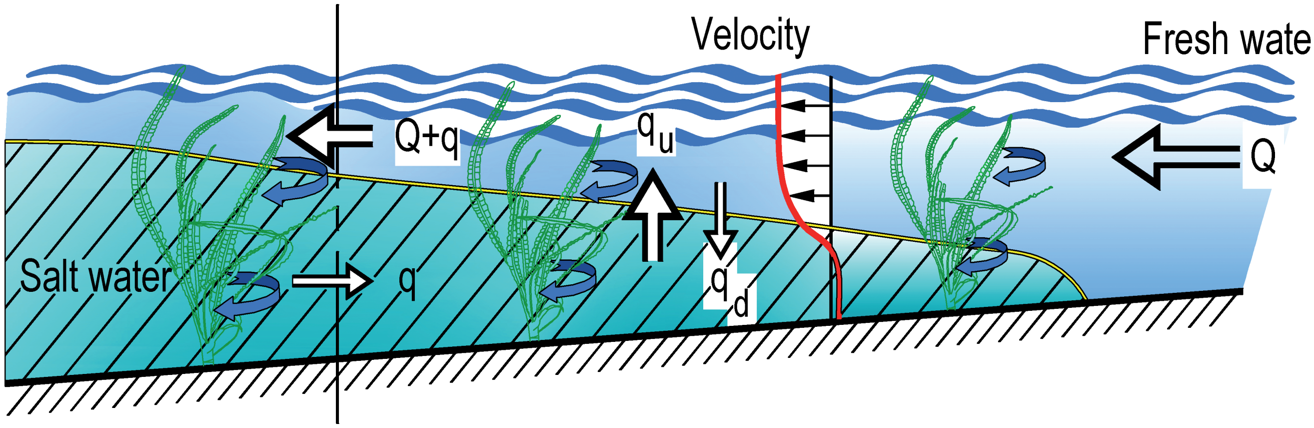

Fig. 3 - A typical mixing process and entrainment in a stationary salt water wedge

In any case, to the authors knowledge, previous studies point out that detrainment can occur when a jet or a plume impinges on a stratified interface without investigating into the necessary conditions for detrainment (Mossa & De Serio, 2016). Previous research studies analyzed plumes and thermals in a uniform environment, observing that a type of detrainment could be produced by buoyancy reversal, affecting the trajectory of the flow. It should be remarked that transport across a stratified interface is an essential aspect of many geophysical processes, such as pollution transport and dispersion by winds in urban areas or dispersion of effluents from sewage in coastal waters. For this reason, to quantify the physical processes occurring at the interface, a profound understanding of turbulent mixing, entrainment and vortex dynamics at the interface has always been pursued, also considering that the more accurate these deductions are, the more transport models can be developed accurately.

In any case, all these previous research studies principally focused on the entrainment rate or the behavior of turbulence at the interface, rather than on the conditions for detrainment. This brief review shows that the physics of jet detrainment is still not fully understood, and even its occurrence in different flows is an unresolved question. While detrainment in nature is usually associated with buoyancy-driven flows, like plumes or density currents flowing in a stratified environment, the present study demonstrates that detrainment occurs also when a momentum-driven jet is issued in a not-stratified obstructed current, such as a vegetated flow.

As an example, referring to the case of a plane jet issued in a vegetated ambient sketched in figure 2 and using eq. (3), Figure 5 shows the variation of the flow rate at different conditions of vegetation, described by the bulk drag coefficient C_D of the stems and the frontal area per unit volume of the canopy $a=nd=d/s^2$.

Using eq. (6), Figure 6 shows the trend of the entrainment

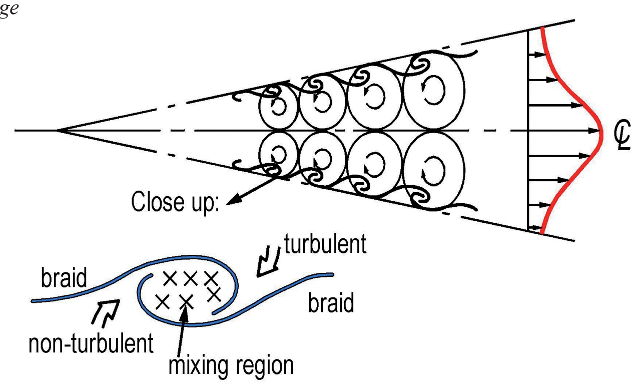

Fig. 4 - A typical vorticity structure in free jet, with close-up of the entrainment process, whose direction is inverted in the case of detrainment

coefficients for the same jets, highlighting the main conclusion that the entrainment process is prevented and, on the contrary, a detrainment process is present.

The analysis of figures 5 and 6 shows how the process of entrainment is dramatically changed, reversing in a detrainment process, when the jets are issued in obstructed flows.

Furthermore, a pure plane jet in an obstructed flow does not preserve the momentum in each cross section along the longitudinal direction x as in the analogous case of unobstructed flow. This result is particularly interesting since it gives the reason of the phenomena of the decrease in bank erosion and variation of the river morphology in the case of obstructed flows. In fact, the reduction of the jet momentum could be responsible of a dramatic increase of the deposit of the sediments naturally transported with, consequently, a variation of the river morphology. Using eq. (8), Figure 7 shows the ratio between the jet momentum M in each cross section and its initial value M_0, as a function of the distance x of the cross section from the nozzle, for some values of the bulk drag coefficient C_D and the frontal area per unit volume of the canopy a.

How diffusion and advections change with the presence of obstructions

The estimation of the streamwise K_{xx} and transversal K_{yy} turbulent diffusion coefficients of a jet in a vegetated flow is based on the theoretical analysis briefly described afterwards. Figure 8 shows the streamwise and transversal turbulent diffusion coefficients of jet experimentally analyzed with and without vegetation in the cross sections with the average lines. The transversal diffusion is also influenced by the entrainment process, with which, as previously described, the surrounding fluid enters the jet with a direction transversal to its center axis, then deviating in the longitudinal direction. The observed trends are totally different when the jet flows within the vegetation. In this case, the turbulent diffusion coefficient K_{xx} shows a remarkable reduction in comparison of the corresponding streamwise values K_{xx} of the case of the same jet without vegetation, revealing a reduction in the diffusion process in the case of obstructed flows. In contrast, the transversal turbulent diffusion coefficient K_{yy} is enhanced by the array obstruction of vegetation, in comparison with the jet without obstruction (Fig. 8), confirming the theoretical results on the jet detrainment process deeply analyzed and demonstrated by Mossa & De Serio (2016). Because of this shift in magnitudes, within the array the lateral diffusion becomes as important as the longitudinal one.

Figure 9 shows the longitudinal profiles of $\overline{u}k$ of the runs with unobstructed and obstructed flows, respectively. The experimental results demonstrate that the streamwise advection of the jet in the unobstructed flow is greater than that of the jet in the obstructed flow.

In contrast, the transversal advection, shown as an example in Figure 10 is increased within the array, due to the deflection of the longitudinal flow towards the transversal direction. These results are better shown by the lines of the averaged values, which enable us to quantify the difference between the cases with and without the stem array of vegetation.

From the experimental results presented above, it is possible to conclude that the presence of vegetation reduces both the diffusion and advection processes 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.

CONCLUSIONS

As detailed written in the introduction, aquatic vegetation provides a wide range of ecosystem services. The variations of some characteristics of a water body, also due the climate change, can be assumed as the effects of a specific cause, which, in turn, becomes causes of other effects; all the process resulting in a vicious circle, which could dramatically alter hydrological conditions. Therefore, the monitoring of vegetation development is a fundamental activity in coastal and river management, to both protect ecological services and control flood or erosion risks.

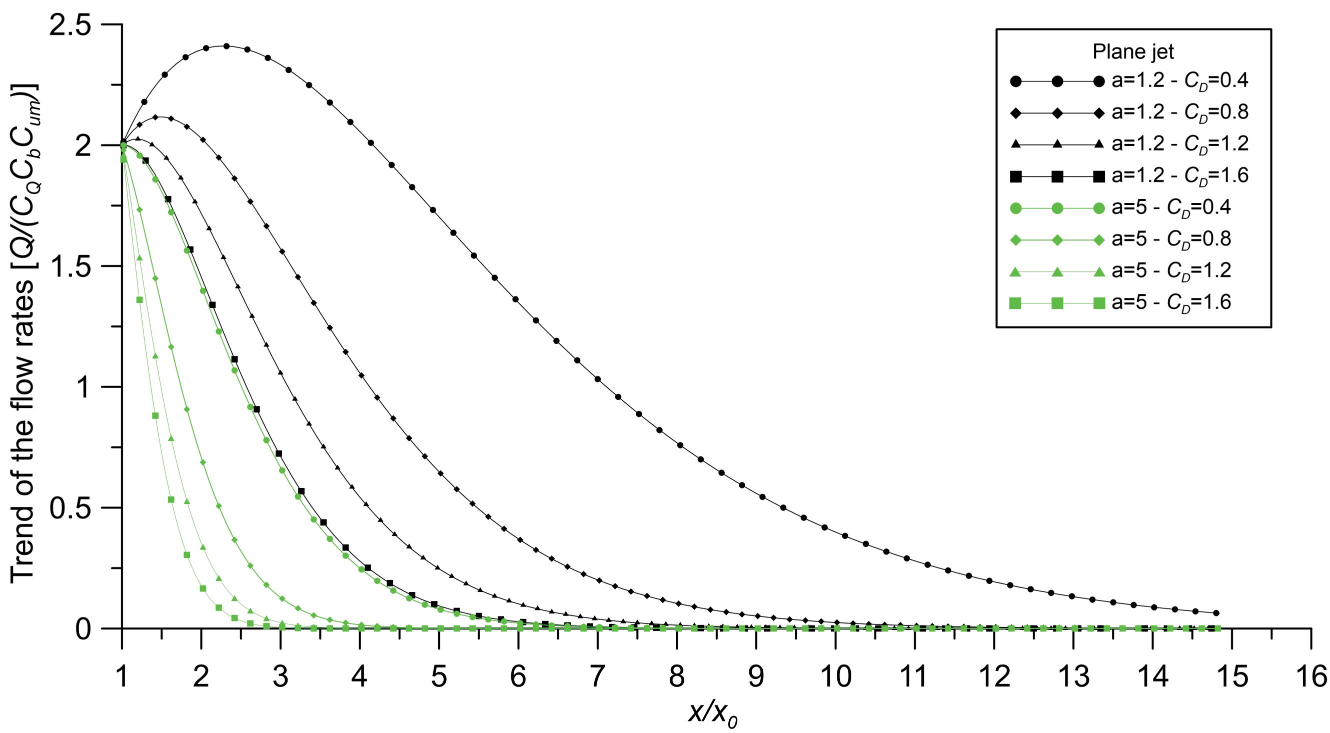

Fig. 5 - Trend of the flow rates of plane jets issued in vegetated still fluid

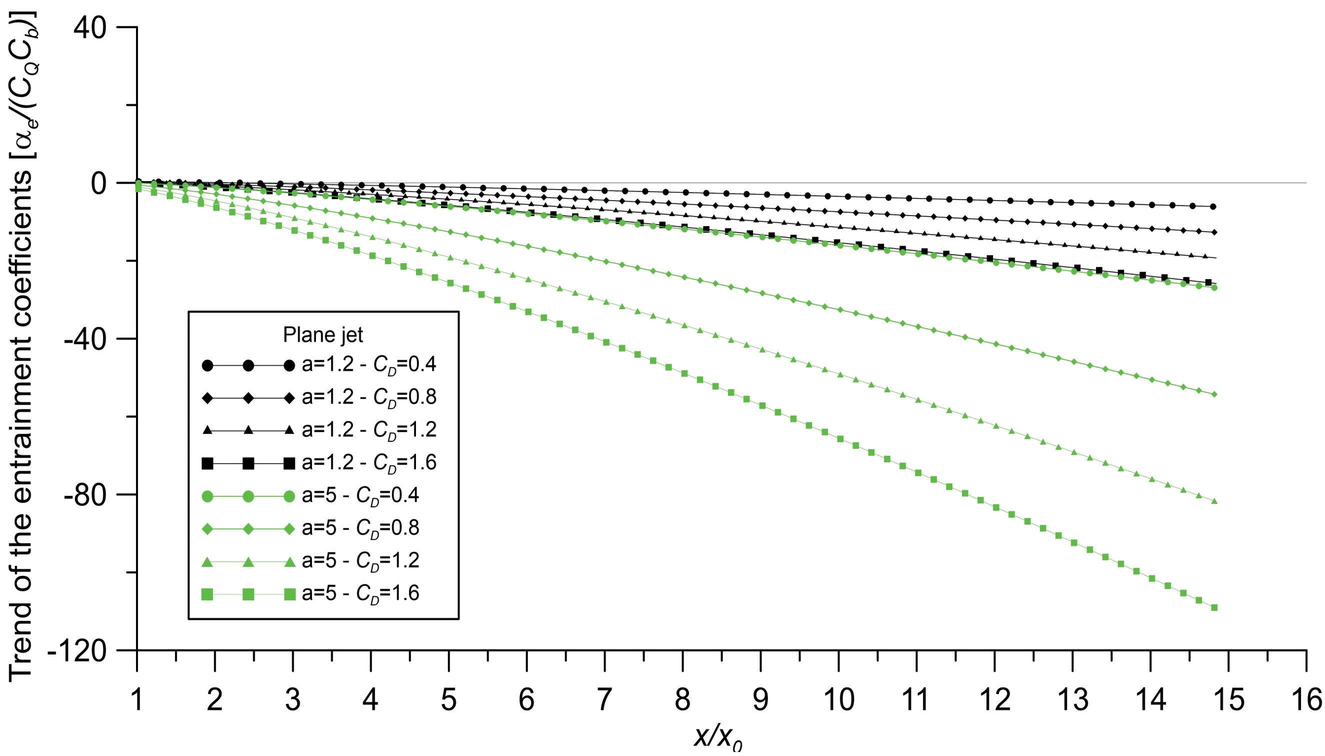

Fig. 6 - Trend of the entrainment coefficients of plane jets issued in vegetated still fluid

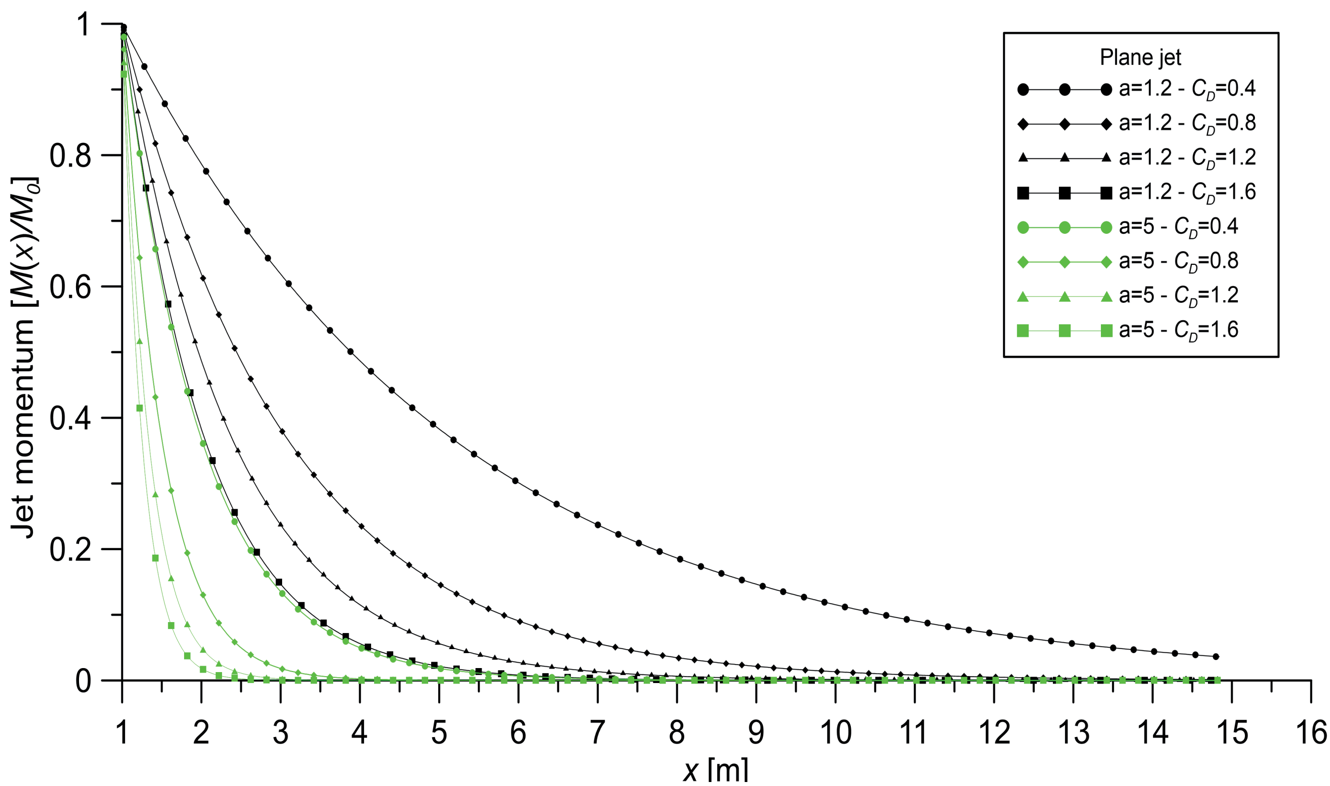

Fig. 7 - Ratio between the jet momentum and its initial value

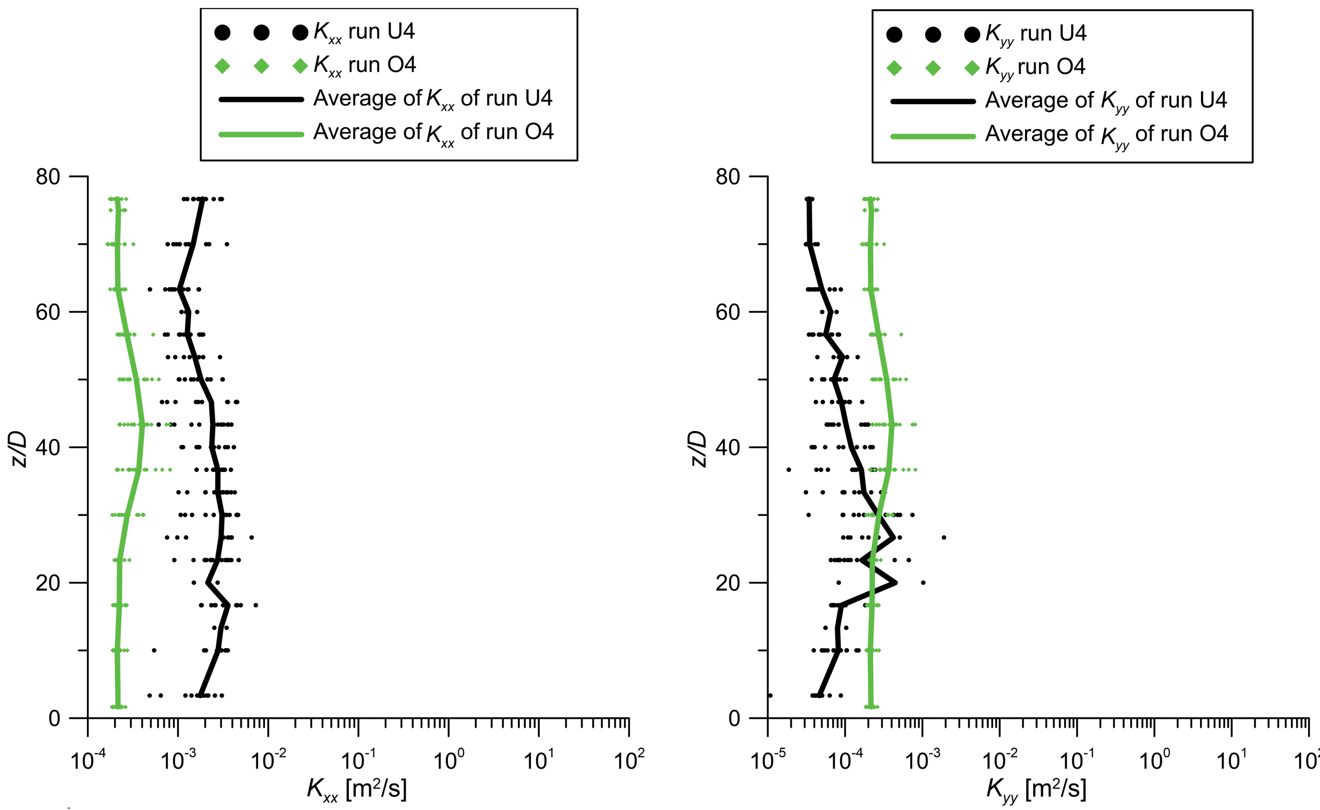

Fig. 8 - Values of K_{xx} and K_{yy} of runs with unobstructed flow (U4) and obstructed flow (O4) with the line of the averaged-values. The values are dimensionlessed by the ambient velocity U_e

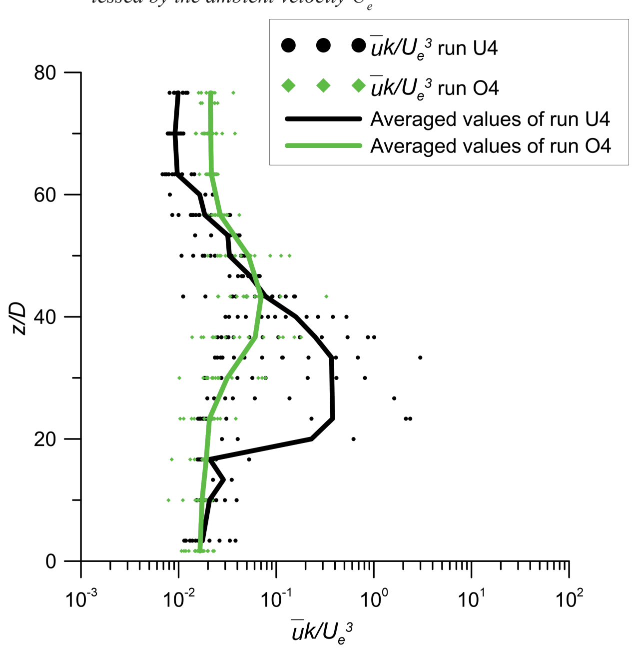

Fig. 9 - Values of uk of runs with unobstructed flow (U4) and obstructed flow (O4) of the longitudinal section with the line of the averaged values. The values are dimensionlessed by the ambient velocity U_e

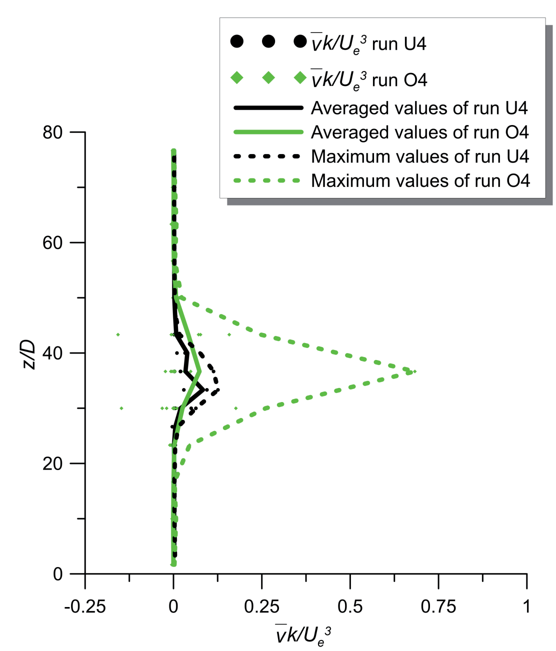

Fig. 10 - Values of vk of runs with unobstructed flow (U4) and obstructed flow (O4) of the transversal section at x/D=26.67 with the lines of the averaged-values and the maximum-values. The values are dimensionlessed by the ambient velocity U_e

The present paper shows the typical jets issued in vegetated ambient, demonstrating theoretically and experimentally how the processes of entrainment, diffusion and advection of the jets can be dramatically changed by the presence of vegetation.

Particularly, we demonstrated that in the case of jets issued in an obstructed flow:

1) the jet entrainment is reversed in a detrainment process;
2) the jet momentum decreases along its longitudinal direction;
3) the diffusion and advection along the longitudinal direction decreases while increases in the transversal direction.

The consequences of the above-mentioned conclusion are the cause of a dramatic change in the river and sea morphology and in the process of diffusion and advection of nutrients or contaminants transported by jet-type flows.

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