Colloque TSMR – CFBR Transport sédimentaire: rivières et barrages réservoirs

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Interactions between vegetation, turbulence and fluvial processes: lessons learned from the experiments

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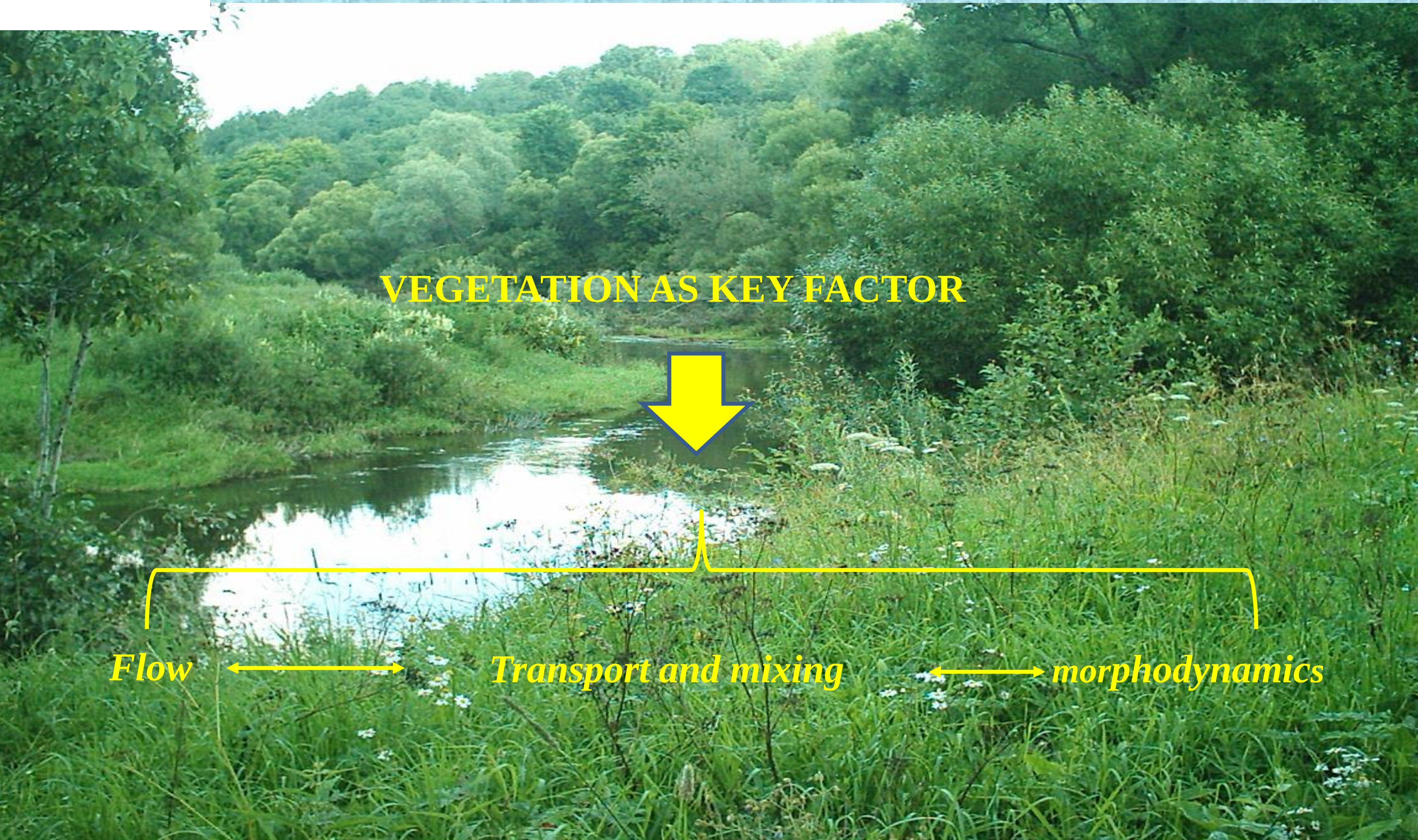
INTRODUCTION



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INTRODUCTION

ROLE IN AQUATIC ECOSYSTEMS

- Flow resistance → velocity reduction
- Sediment deposition increase
- Turbulent structure → transfer and diffusion mechanisms

⇓

- biota
- Trapping sediments
- Retention or diffusion of nutrients/tracers/substances….

Important role in **maintaining suitable habitat and ecological equilibrium**.

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INTRODUCTION

OBJECTIVES

- Variability with the flow depth:

✓ effect on velocity profile

✓ complex mechanism of exchange between the free stream and the vegetated region

✓ turbulent flow structure and its implication in diffusion processes.

⇩

laboratory experiments
(Hydraulic laboratory - University of Palermo)

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I: MAIN ASPECTS

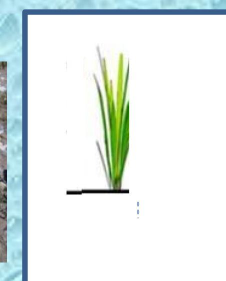
AT WHICH SCALE?

Small scales (single blade; stem scale, canopy scale,..)

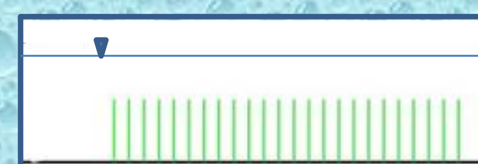
- ✓ Vegetation hydraulic behavior (mechanical resistance, stiffness,…)
- ✓ Diffusion of solute
- ✓ Sediments transfer and budget

Stem dimension

stem scale: community of individual plants



patch scale: community of individual plants of finite geometry



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MAIN ASPECTS AND PROCEDURES

AT WHICH SCALE?

Larger scale

Reach scale
(group of plants sparse and dense)

- ✓ Flow resistance
- ✓ Morphodynamics
- ✓ Regulating ecological services protecting from flood risks

Blockage factor: fraction of the space blocked by vegetation

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I: MAIN ASPECTS

VEGETATION BEHAVIOR

- shape, size → Stiffness and mechanical properties EI
- concentration (density) → Distributions, heterogeneity
- submergence

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I: MAIN ASPECTS

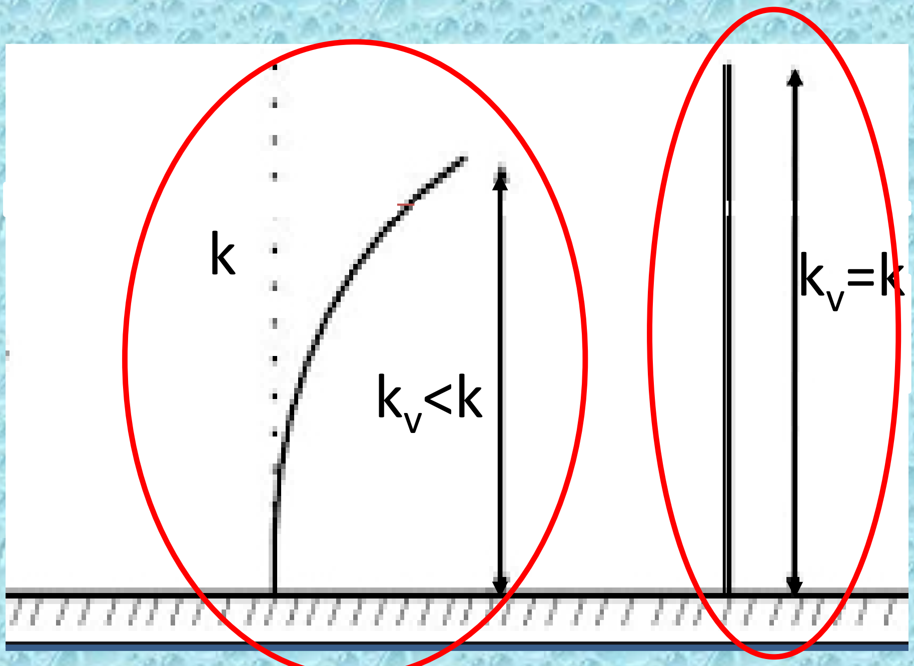
CLASSIFICATION
Based on mechanical proprierties

Stem scale

RIGID VEGETATION
(trees, rigid bushes,…)

FLEXIBLE VEGETATION
(herbaceous types,…)

- the hydrodynamic action of the flow
- the bending stiffness EI



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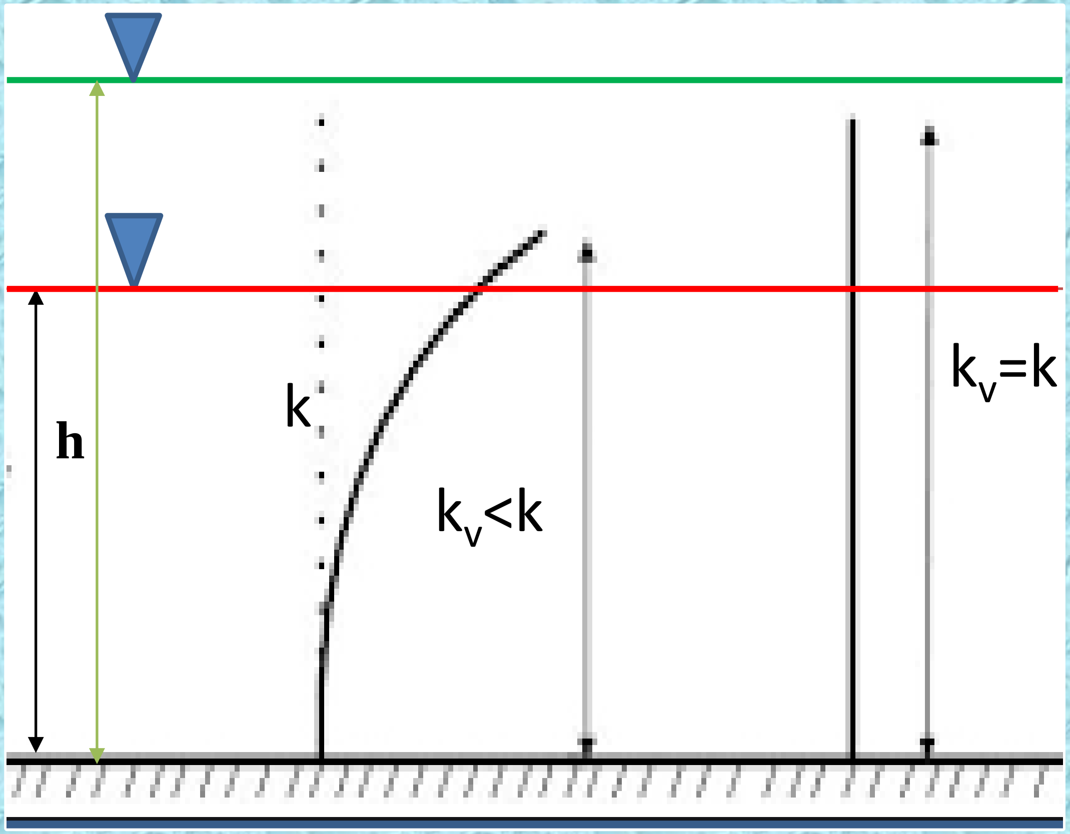
MAIN ASPECTS AND PROCEDURES

CLASSIFICATION

Based on the submergence

Stem scale



Emerged

h<k

$h<k_v$

k_v =bent vegetation height

Submerged

h>k

$h>k_v$

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I: MAIN ASPECTS

SUBMERGED FLEXIBLE VEGETATION

patch scale

The response of vegetation to the flow can change in time.

erect (as rigid)

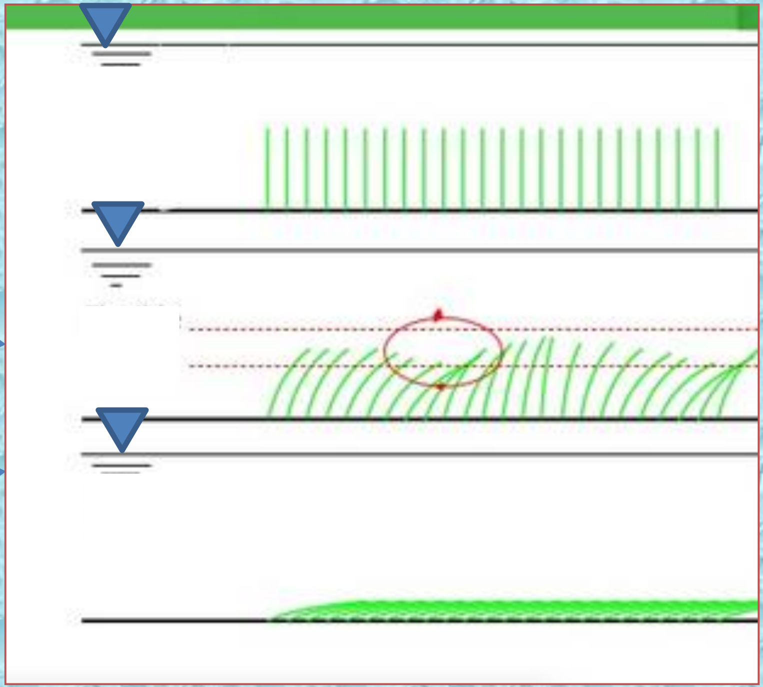
low flows: without bending

Subjected to waving motion

intermediate flows: inflection

prone position

high flows: vegetated stems forced to a prone position.



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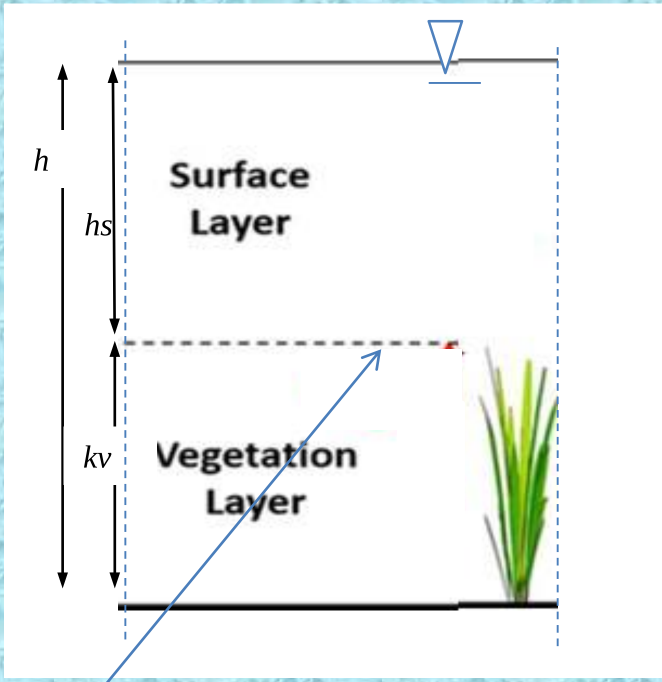
I: FLOW VELOCITY PROFILE

The velocity profile could be examined:

- the upper layer

- the vegetation layer



boundary conditions at the interface (reference distance from the bed).

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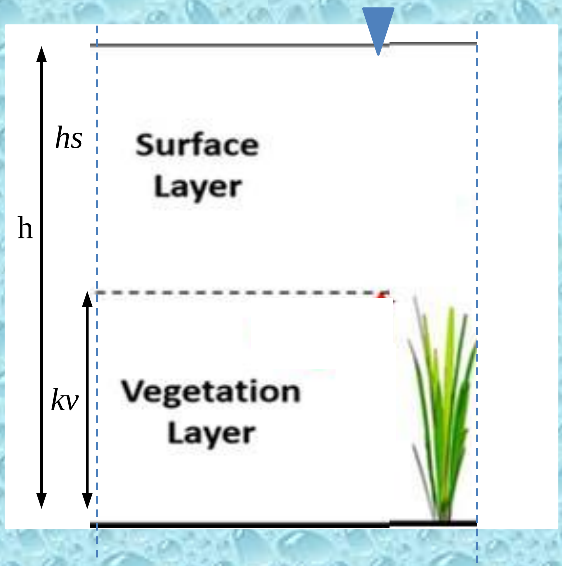
I: FLOW VELOCITY PROFILE

BOUNDARY-LAYER SCHEME



The velocity distribution over vegetation could be represented by the logarithm law:

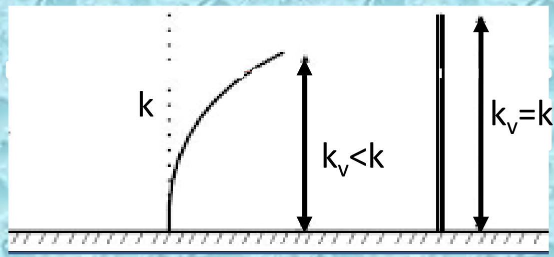
$$\frac{u}{u_*} = \frac{u_{k_v}}{u_*} + \frac{1}{k} ln\left(\frac{y}{k_v}\right)$$

k **= von Karman's constant,**
y **= distance from the channel bed**
u_{kv} **= velocity at distance** k_v
u_* **= shear velocity**
u **= velocity at level** ***y***

The logarithmic velocity profile is applicable above a reference distance which can vary depending on:

-hydrodynamics (erect, waving, prone)

-vegetation characteristics



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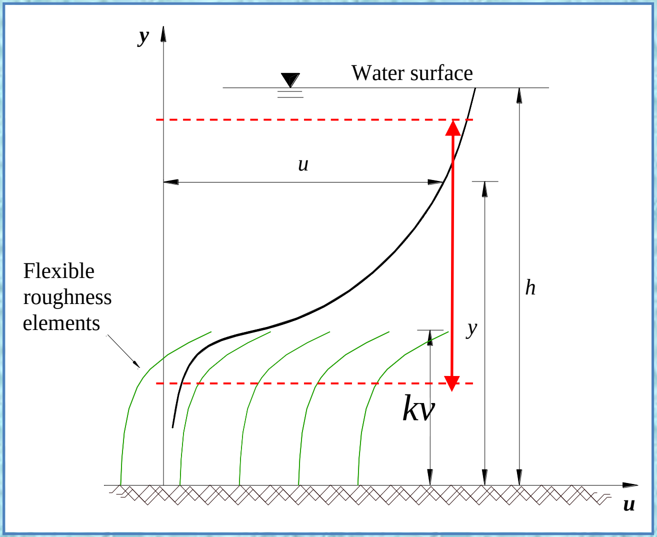
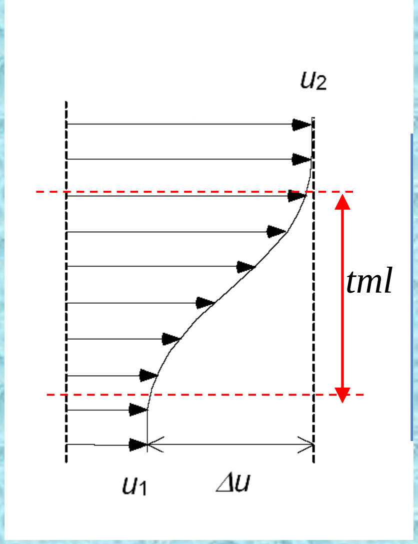
I: FLOW VELOCITY PROFILE

MIXING-LAYER SCHEME





Hyperbolic tangent function:

$$u = \bar{u} + \frac{\Delta u}{2} \tanh\left(\frac{y - \bar{y}}{2\theta}\right)$$

$$\theta = \int_{-\infty}^{+\infty}\left[\frac{1}{4} - \left(\frac{u - \bar{u}}{\Delta u}\right)^2\right] dy$$

$\bar{u} = (u_1 + u_2)/2$

$\Delta u = u_2 - u_1$

$\bar{y}$ =distance from the bed where $u = \bar{u}$

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I: FLOW VELOCITY PROFILE

TRANSITION

- **BOUNDARY-LAYER SCHEME**
- **MIXING-LAYER SCHEME**

✓ relative submergence: h/k_v

✓ vegetation concentration: δ

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Experimental data

Photo: View from the top of vegetation

82 runs
h/kv=1.83÷6.04
δ=280÷440 stems/dm^2

laboratory experiments
(Hydraulic laboratory - University of Palermo)

Carollo et al. 2002 JHE – ASCE
Carollo et al. 2005 JHE – ASCE;

Termini 2012 – Int. J. River Manag.

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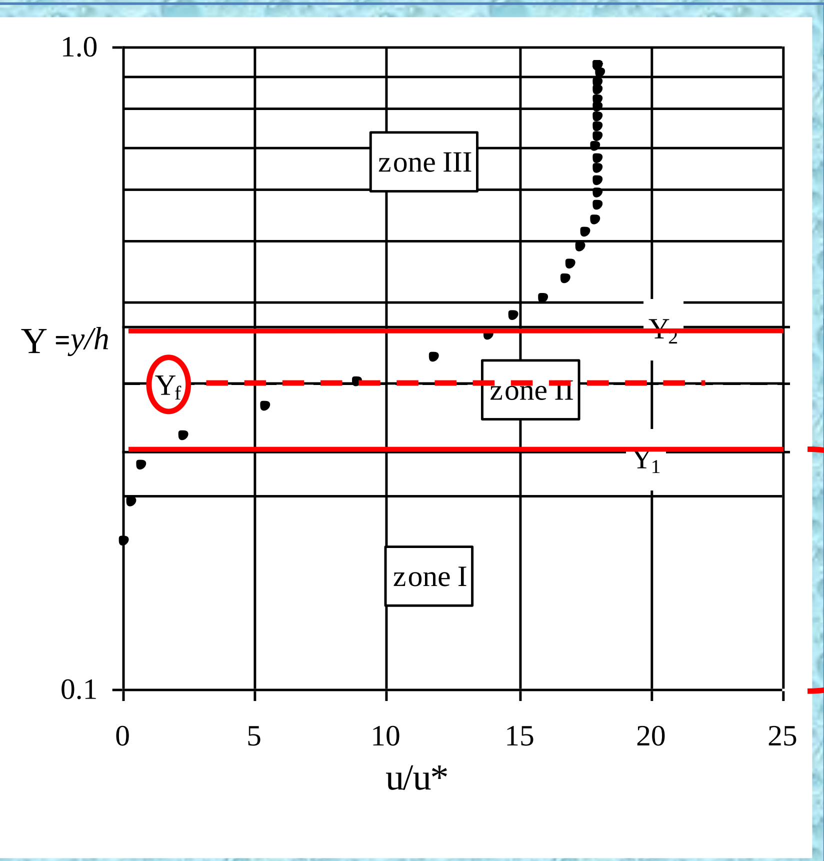
I: FLOW VELOCITY PROFILE



zone III: for $Y>Y_2$.

decreasing vertical velocity gradients, which is null near the free surface.
Concavity towards the free surface

zone II: for $Y_1 \leq Y \leq Y_2$.

the logarithm velocity profile can be fitted
This zone includes the flex point at Yf

zone I: for relative depth values $Y<Y_1<k_v/h$

velocities are very small.
An increasing vertical velocity gradient.
Concavity towards the bed

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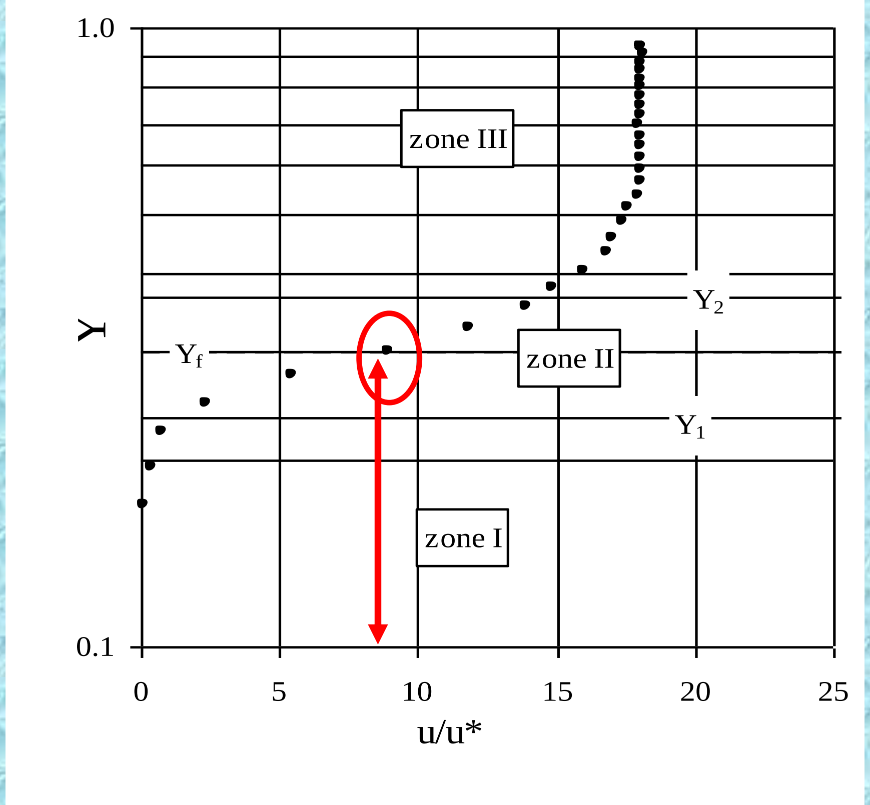
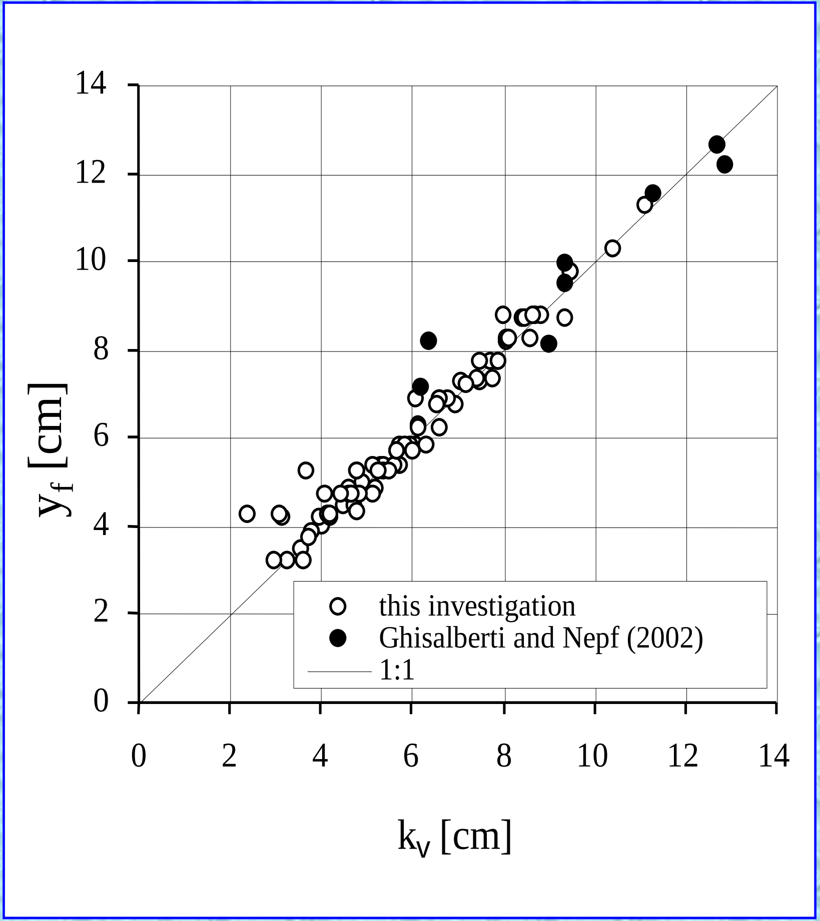
I: FLOW VELOCITY PROFILE

INFLECTION POINT AND BENT VEGETATION HEIGTH

the inflection point can be located at a distance from the bed close to the bent vegetation heigth k_v,





$$k_v \simeq y_f$$

Carollo et al. 2002 JHE – ASCE
Carollo et al. 2005 JHE – ASCE

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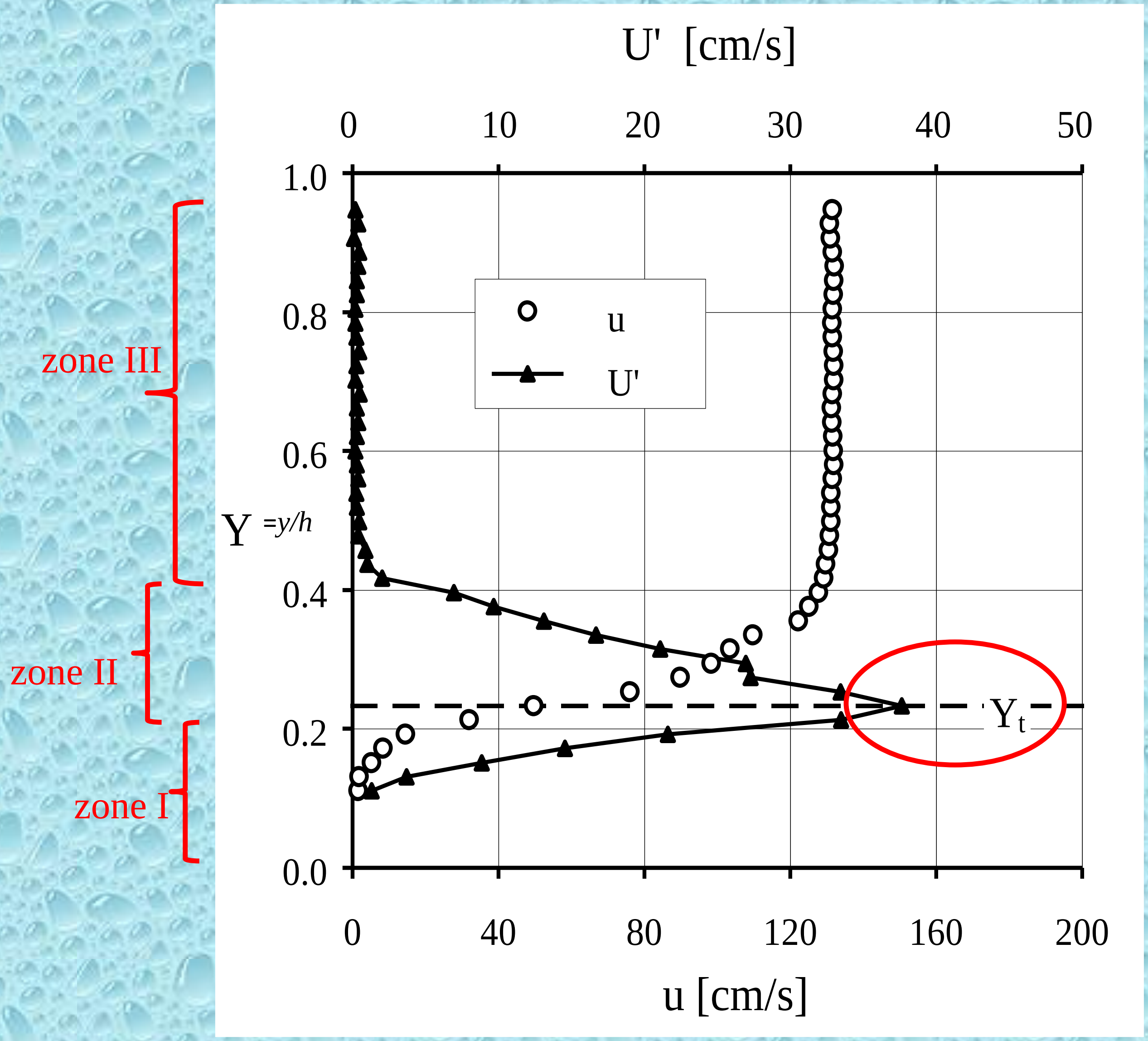
TURBULENCE INTENSITY

The turbulence intensity *U'*:

$$U' = \sqrt{\frac{\sum_{i=1}^{m}(u_i - u)^2}{m}}$$



Carollo et al. 2002 JHE – ASCE
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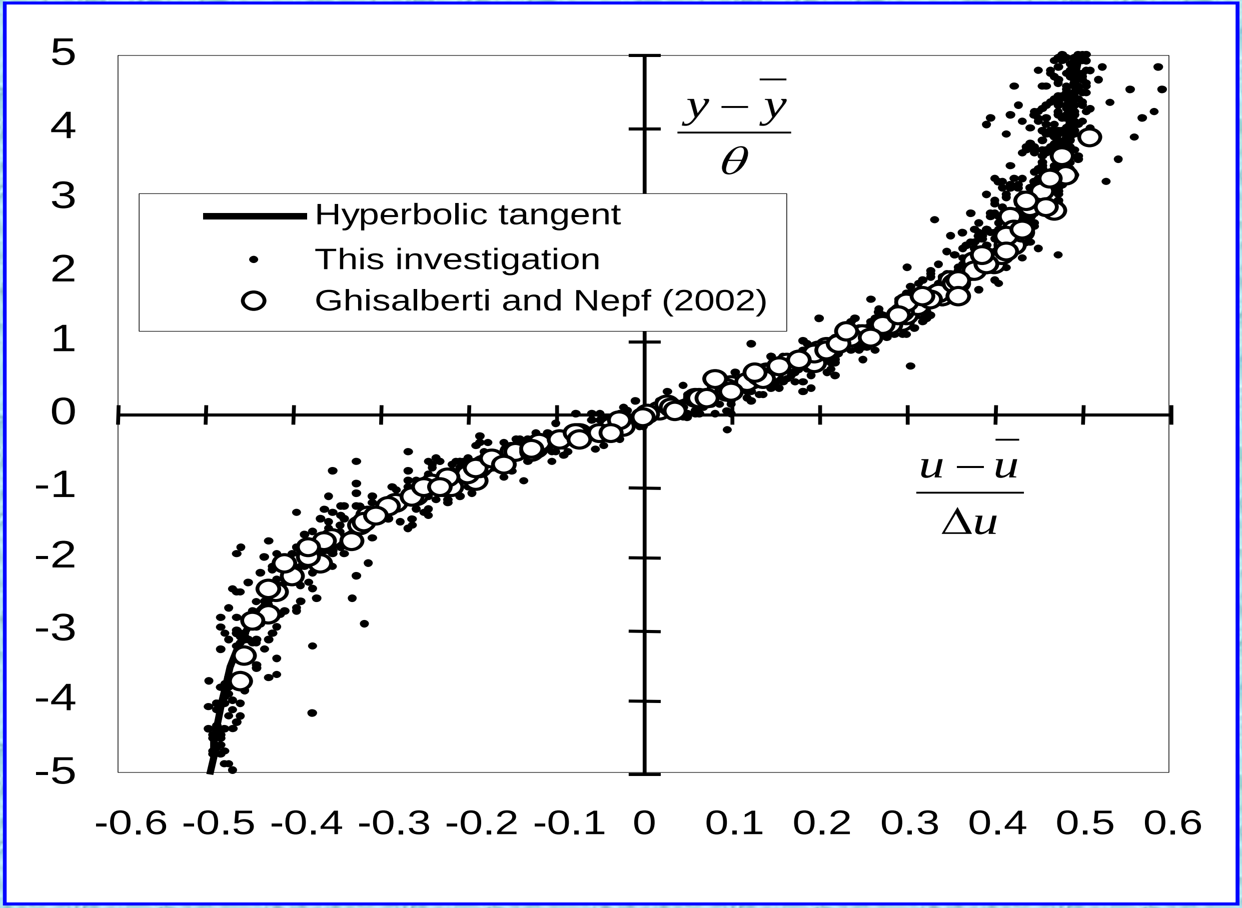
I: FLOW VELOCITY PROFILE

MIXING LAYER SCHEME

$Y_t \cong Y_f$ =local estimate of the bent vegetation heigth *kv*



Carollo et al. 2002 JHE – ASCE
Carollo et al. 2005 JHE – ASCE;

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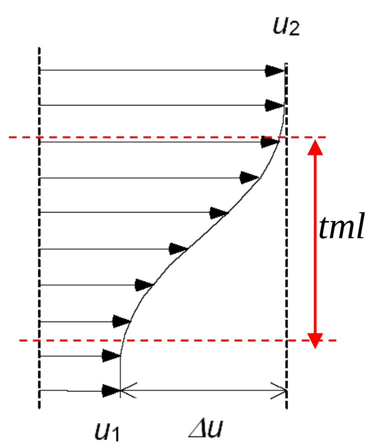
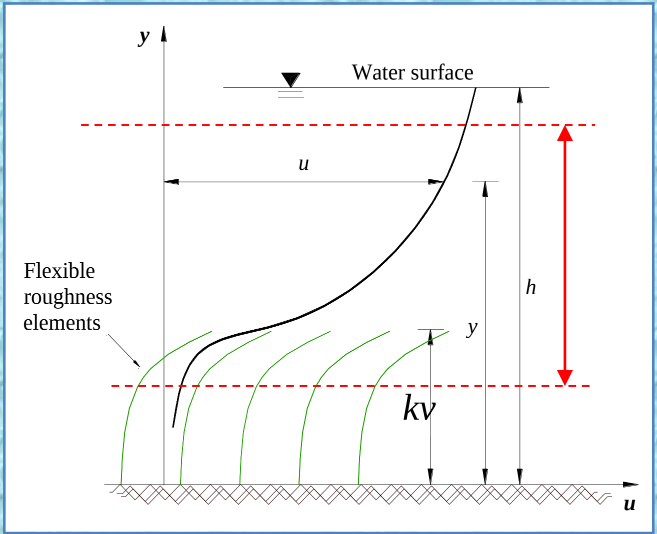
I: EXCHANGE MECHANISM

MIXING LAYER THICKNESS AND MOMENTUM THICKNESS





$$\theta = \int_{-\infty}^{+\infty} \left[\frac{1}{4} - \left(\frac{u - \bar{u}}{\Delta u} \right)^2 \right] dy$$

t_{ml} difference between the two distances from the bed where the profile become vertical.

Within the vegetated stems:
Turbulent ddies scale with the dimention of vegetated stems

In the mixing layer:
Large-scale vortices – significant vertical turbulent exchange

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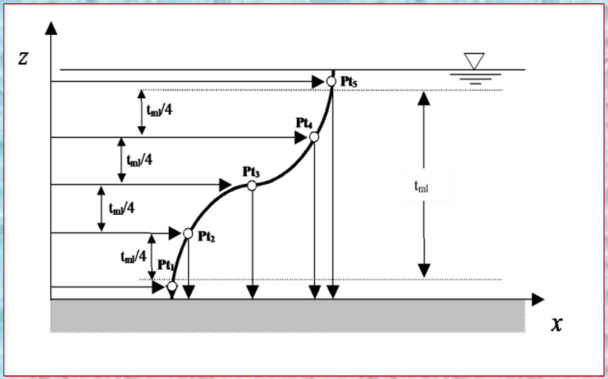
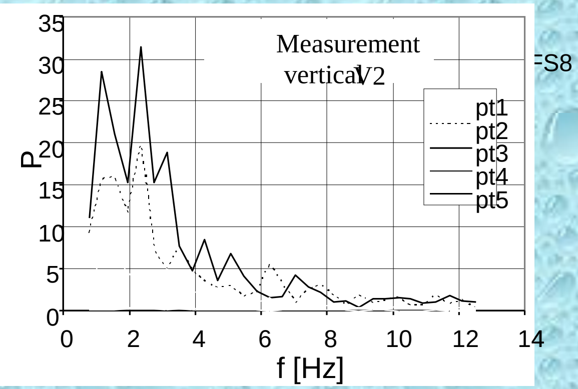
I: EXCHANGE MECHANISM

Velocity spectra analysis

Peak frequency, *fc* , of velocity spectra (observed frequency)





Frequency, f_{KH}, determined as function of the mixing layer thickness.

$$f_{KH} = 0.032\left(\frac{\overline{U}}{\theta}\right)$$

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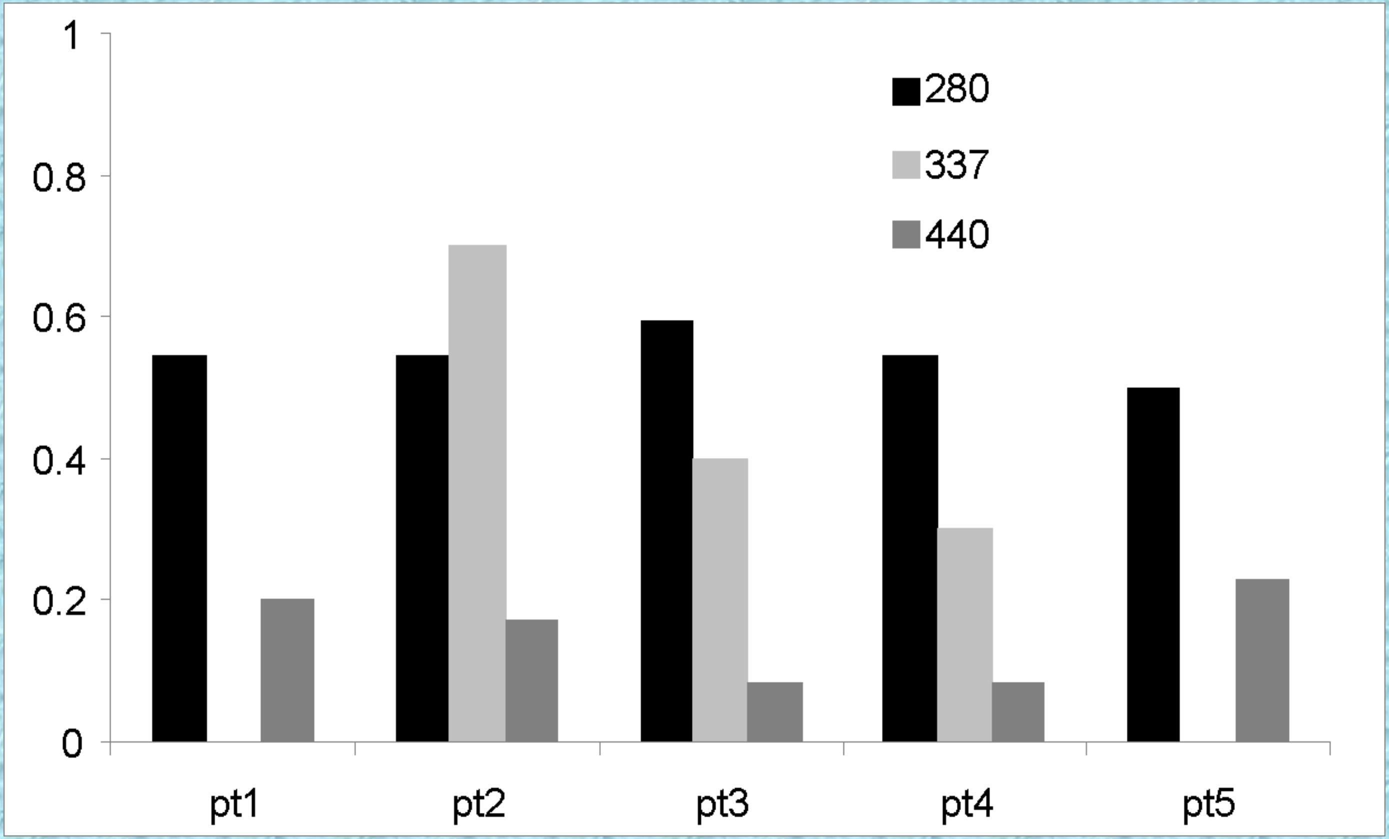
I: EXCHANGE MECHANISM

Velocity spectra analysis



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EXCHANGE MECHANISM

MIXING LAYER THICKNESS

?

CHANGES

- ✓ concentration

⇓

δ (stems/dm^2);

- ✓ Relative submergence

⇓

h/k_v

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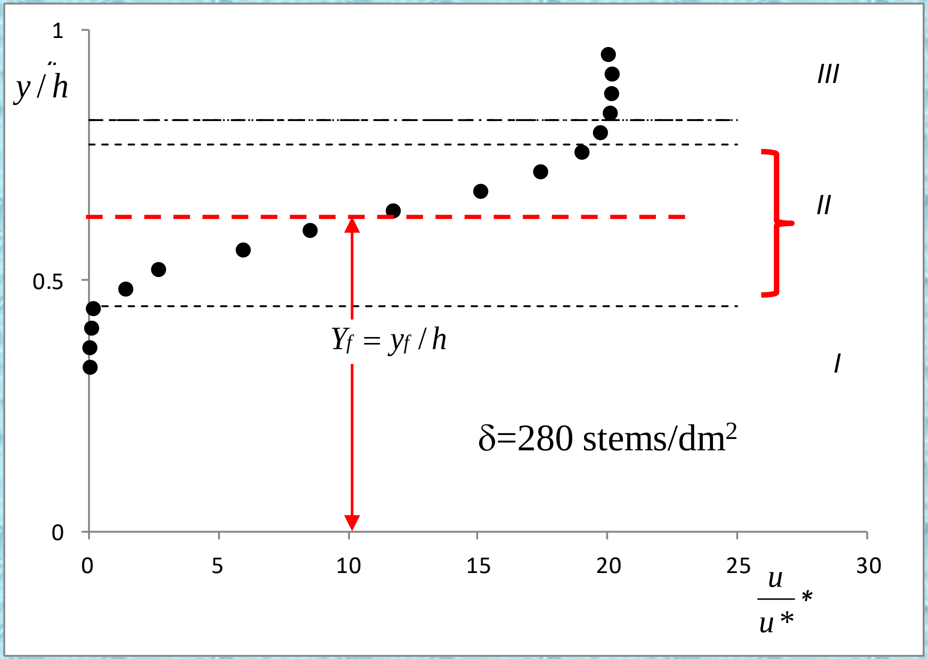
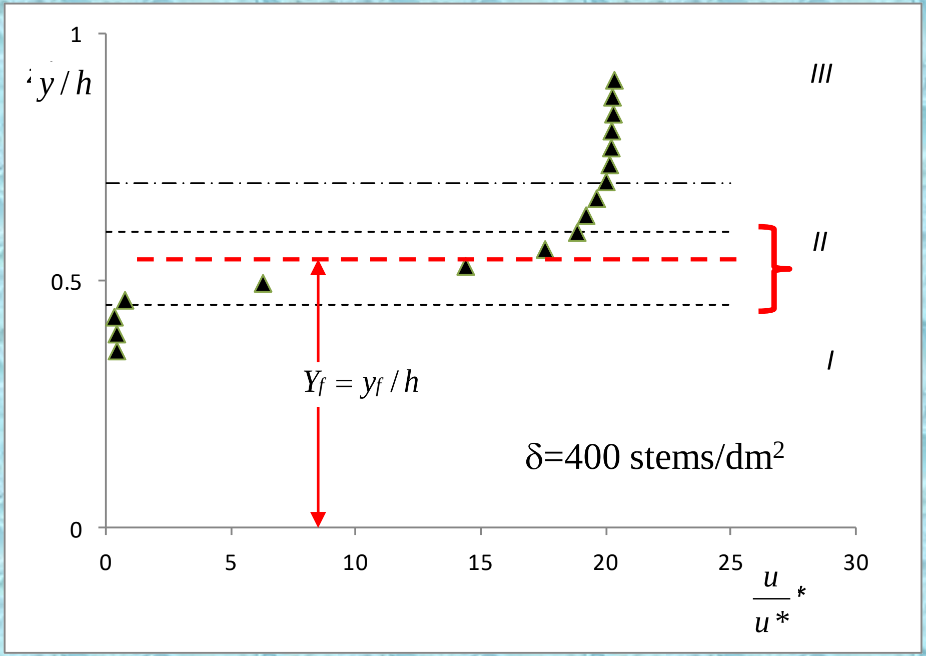
I: EXCHANGE MECHANISM

EFFECT OF CONCENTRATION

(h/kv=1.83)





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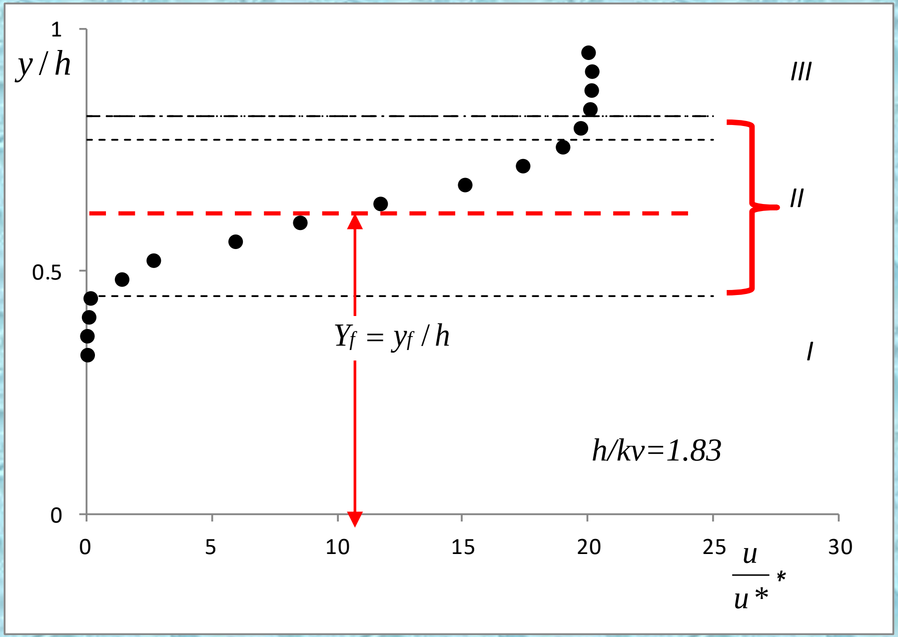
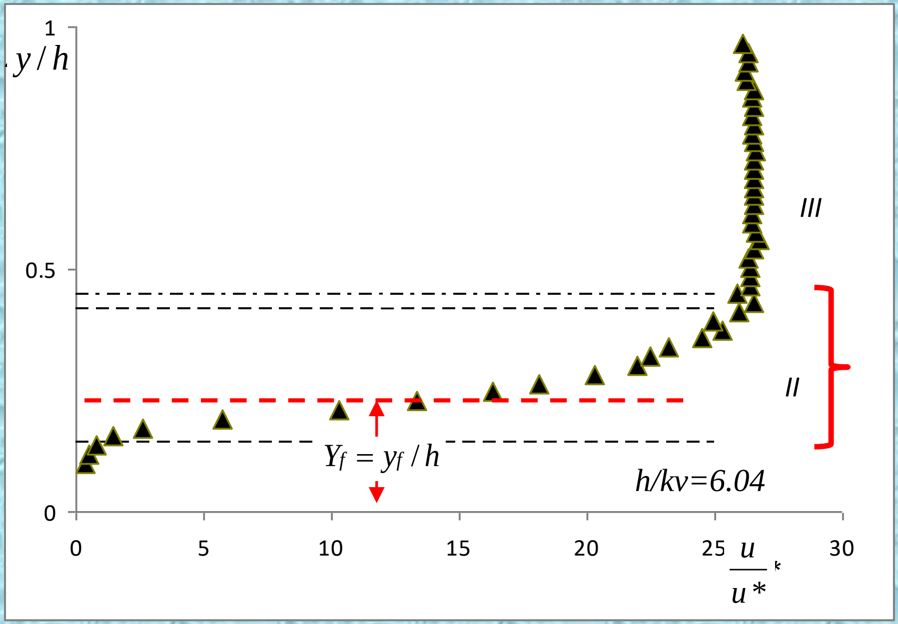
I: EXCHANGE MECHANISM

EFFECT OF FLOW SUBMERGENCE *h/kv*

(δ=280 stems/dm^2)





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INDICATIONS –I

The **logarithm law** should be applied with caution *for low stems concentration and flow submergence*

Otherwise: **mixing layer** scheme: velocity profile schematized by a composition of two parts of constant velocity separated by a confined intermediate region (mixing layer) containing the inflection point.

The *thickness of the mixing layer*: reduces as the stems concentration increases

For high concentration: the flow can be schematized by two layers separated at the top of vegetation.

The *location along the depth of mixing layer* varies with the **relative submergence**, determining a different behavior especially for values of $h/k_v>2$.

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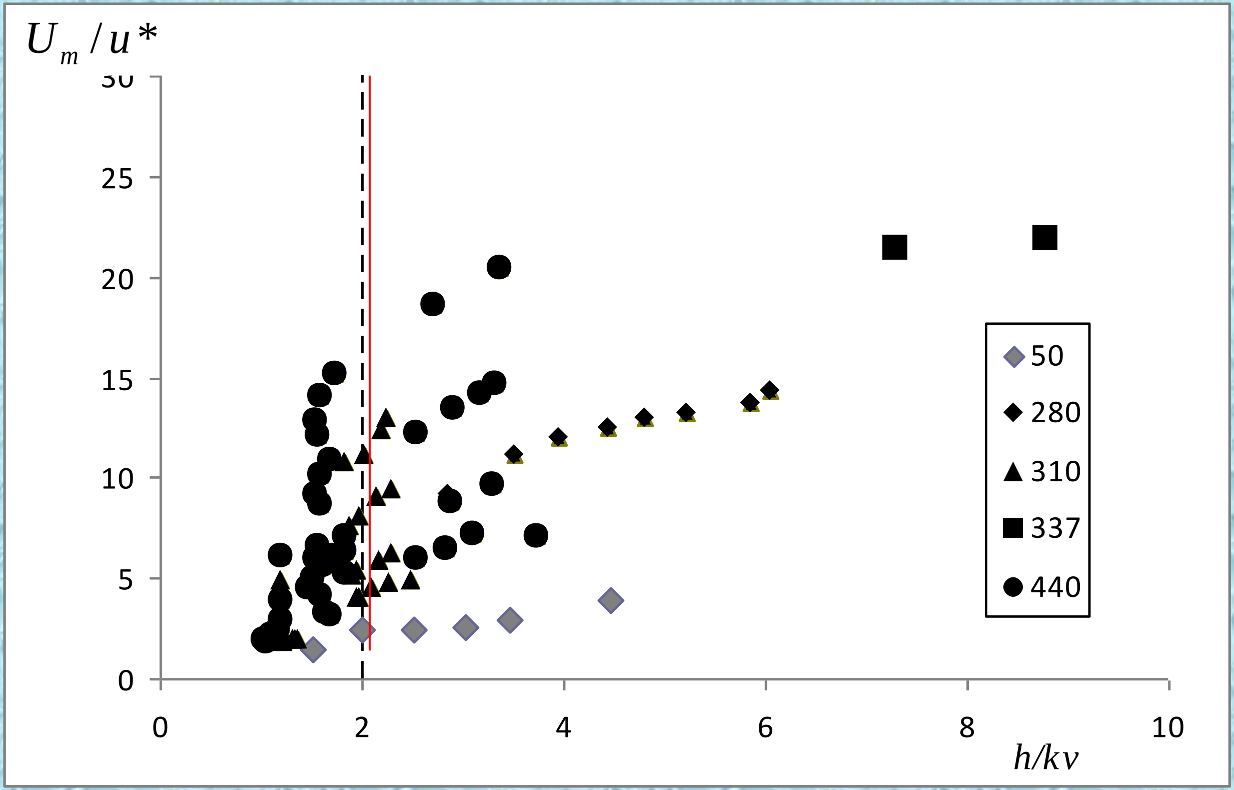
II: EFFECT ON FLOW CONVEYANCE

Friction factor $U_m / u*$



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II: EFFECT ON TRANSPORT AND DIFFUSION

How material is exchanged between vegetation and the overflow: *h/kv*

Deeply submerged: *vertical turbulent transport of momentum*

Emergent (*h/kv*=1): *longitudinal transport*

in the transition condition, both the vertical turbulent exchange and the longitudinal transport are important

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II: EFFECT ON TRANSPORT AND DIFFUSION

Theorethical considerations

The transport equation of a tracer *c* (concentration of substances), after having applied the temporal and spacing average method, can be written as:

$$\frac{\partial\langle\bar{c}\rangle}{\partial t}+\langle\overline{\mathrm{v}}_{\mathrm{j}}\rangle\frac{\partial\langle\bar{c}\rangle}{\partial x_j}=K_{jj}\frac{\partial^2\langle\bar{c}\rangle}{\partial x_j^2}$$

where K_{jj} is the coefficient for net dispersion along the *j-th* direction

proportional to the product of the velocity scale and the average turbulent length associated with mixing due to turbulent eddies

According to literature on vegetated flows (among others Nepf, 1999; Nepf and Vivoni, 2000; Tanino and Nepf, 2008):

velocity scale → $\sqrt{k'}$

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

Where:

α =scale factor (which could generally differ for horizontal and vertical diffusion)

lj = the integral length scale of turbulence in the *j-th* direction

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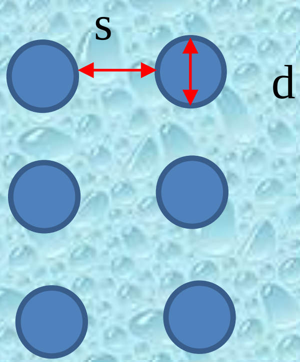
II: EFFECT ON TRANSPORT AND DIFFUSION

Theorethical considerations

$$K_{jj} = \alpha\sqrt{k}\,l_j$$

lj = the integral length scale of turbulence in the *j-th* direction



The integral length scale of the turbulence, *l*:

-for $d \leq s$, turbulence is generated within stem wakes
so that $l=d$

-for $d>s$, turbulence is generated within the pore channels
so that $l=s$

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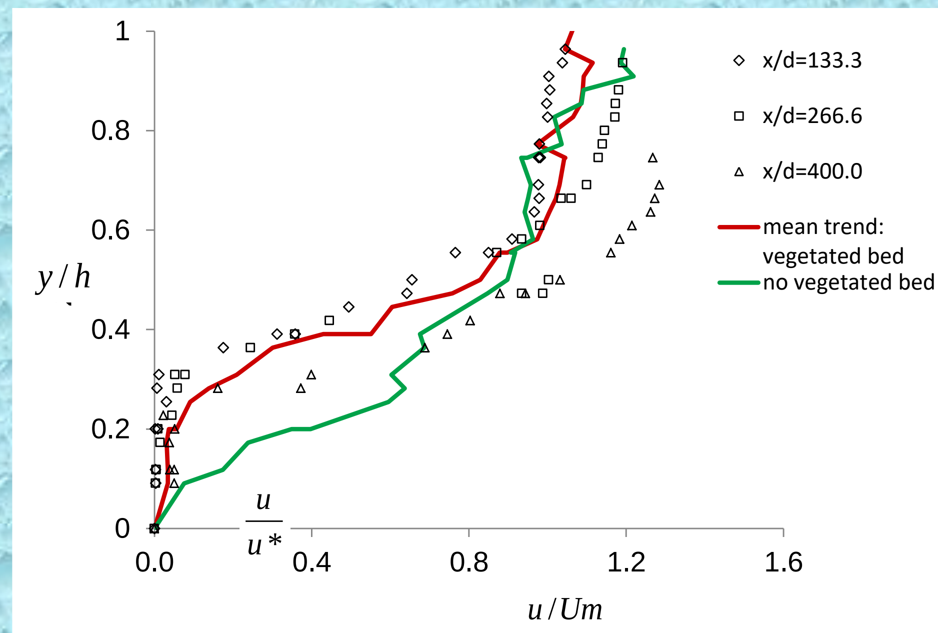
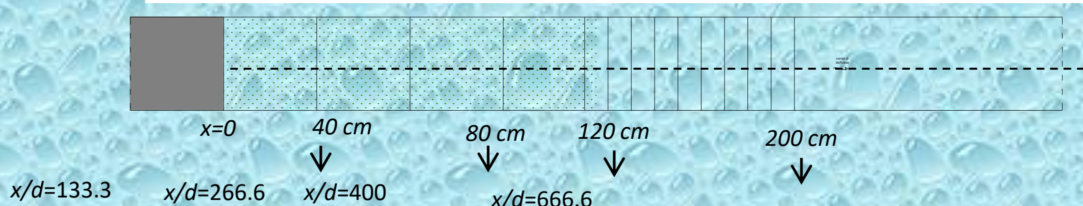
EFFECT ON TRANSPORT AND DIFFUSION

Time-averaged longitudinal velocity *u* normalized by *Um* (=Q/B)





Line in red: space-averaged profile for different *x/d* distances from the initial section in vegetated reach
Line in green: profile without vegetation (at position x/d=666.6)

De Serio et al. 2018. AWR

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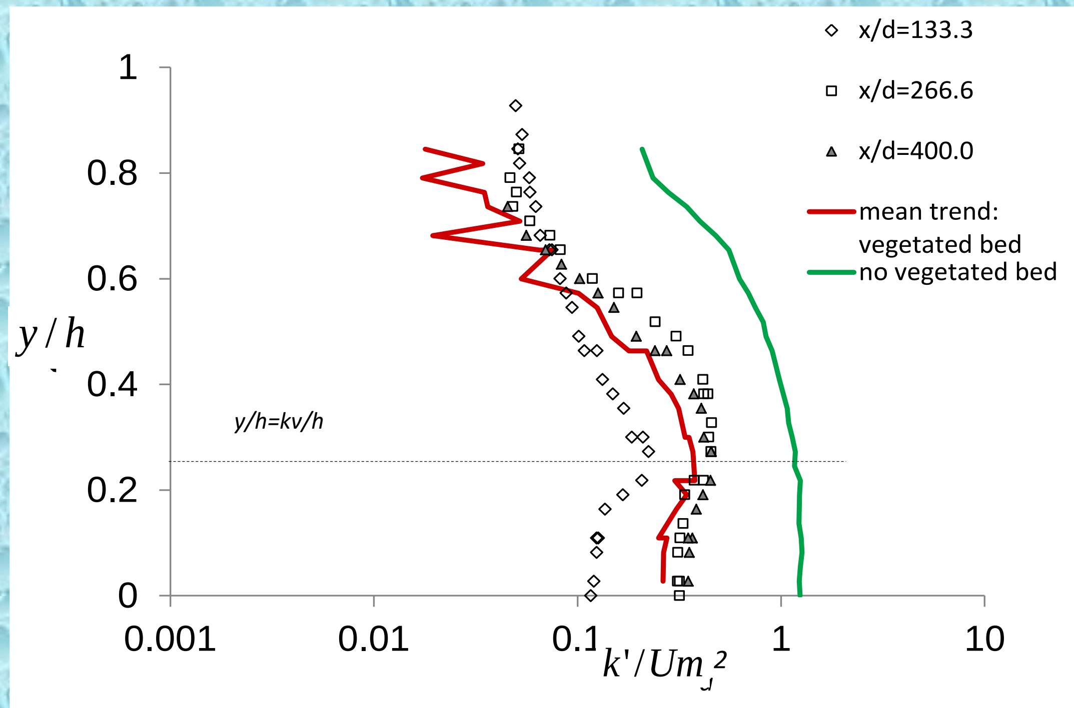
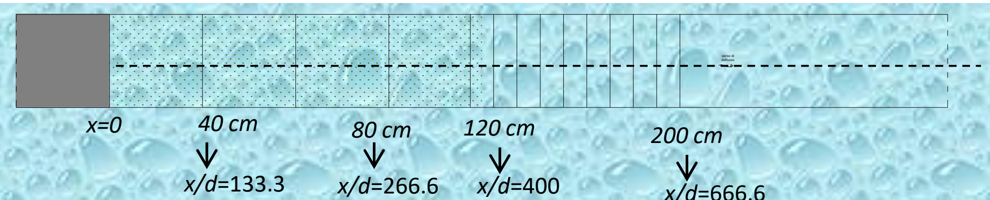
II; EFFECT ON TRANSPORT AND DIFFUSION

NORMALIZED TURBULENT KINETIC ENERGY





Line in red: space-averaged profile in vegetated reach for different *x/d* distances from the initial section
Line in green: profile without vegetation (at position x/d=666.6)

De Serio et al. 2018. AWR

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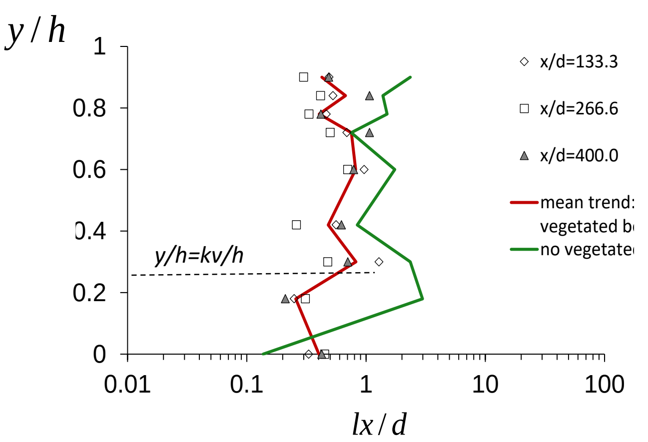
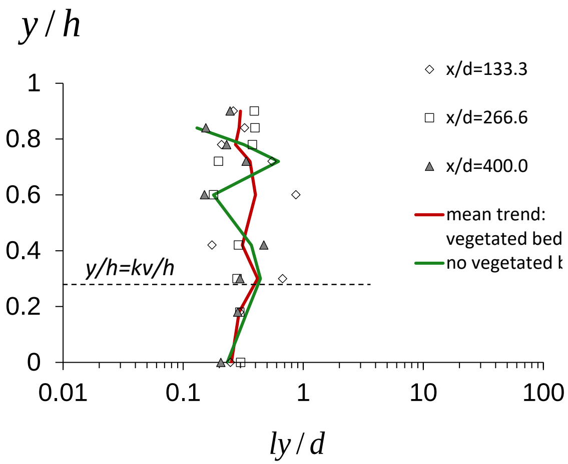
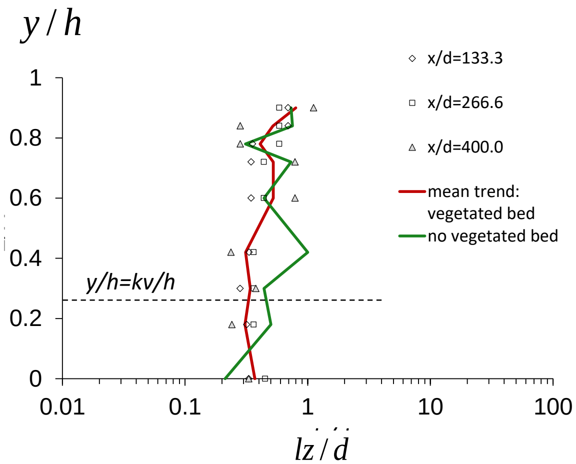
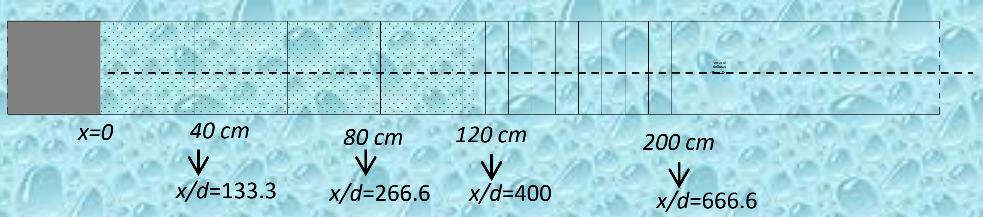
II: EFFECT ON TRANSPORT AND DIFFUSION

INTEGRAL TURBULENT LENGTHS









Line in red: space-averaged profile in vegetated reach for different *x/d* distances from the initial section

Line in green: profile without vegetation (at position x/d=666.6)

De Serio et al. 2018. AWR

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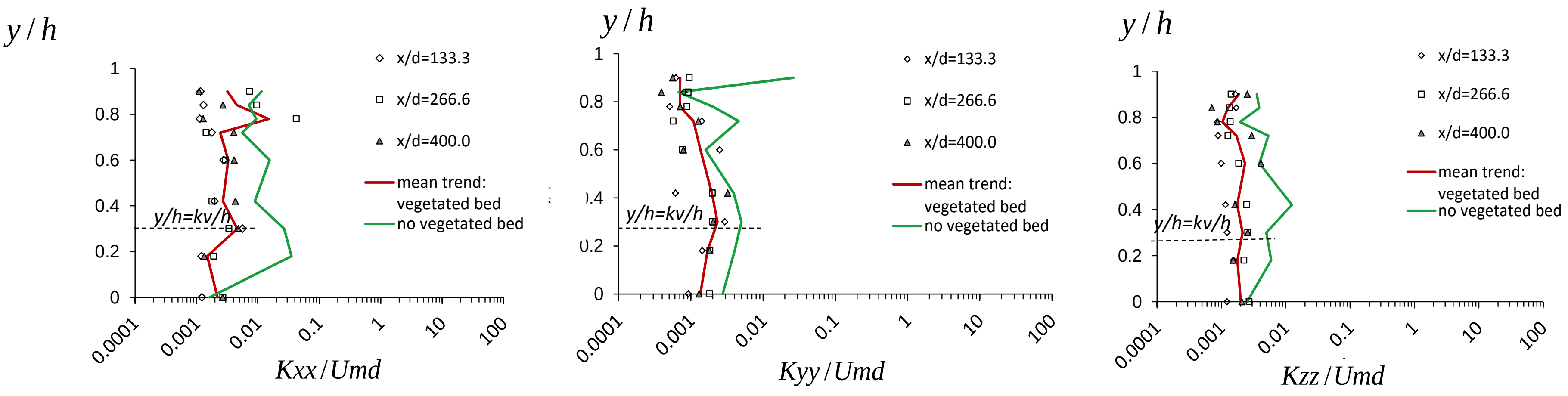
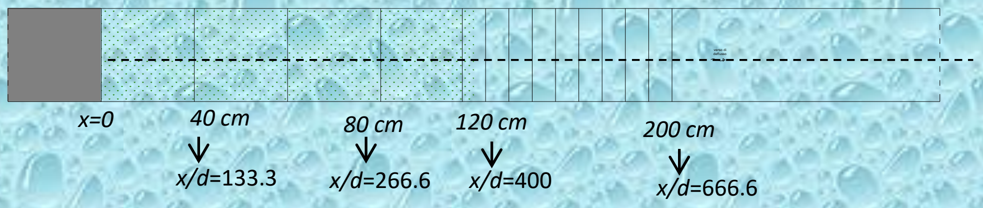
II: EFFECT ON TRANSPORT AND DIFFUSION

DISPERSION COEFFICIENTS K_{jj}





Line in red: space-averaged profile in vegetated reach for different *x/d* distances from the initial section

Line in green: profile without vegetation (at position x/d=666.6)

De Serio et al. 2018. AWR

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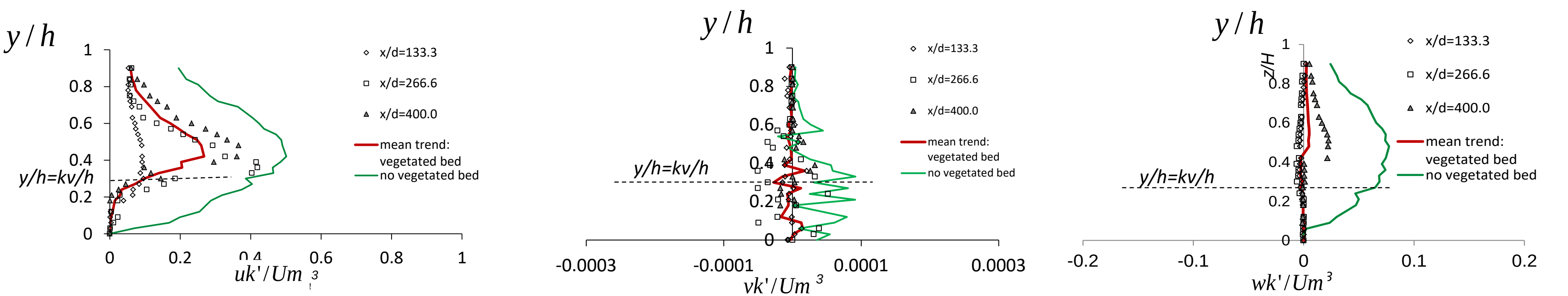
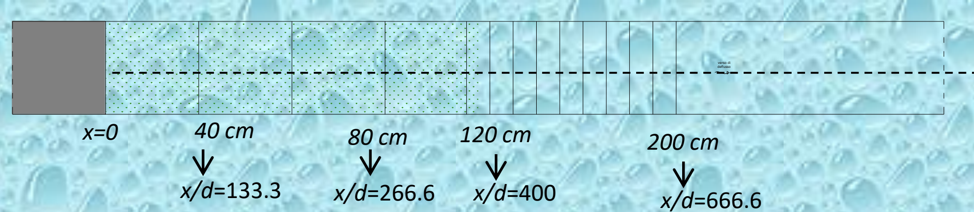
II: EFFECT ON TRANSPORT AND DIFFUSION

ADVECTIVE TRANSPORT OF TURBULENT KINETIC ENERGY





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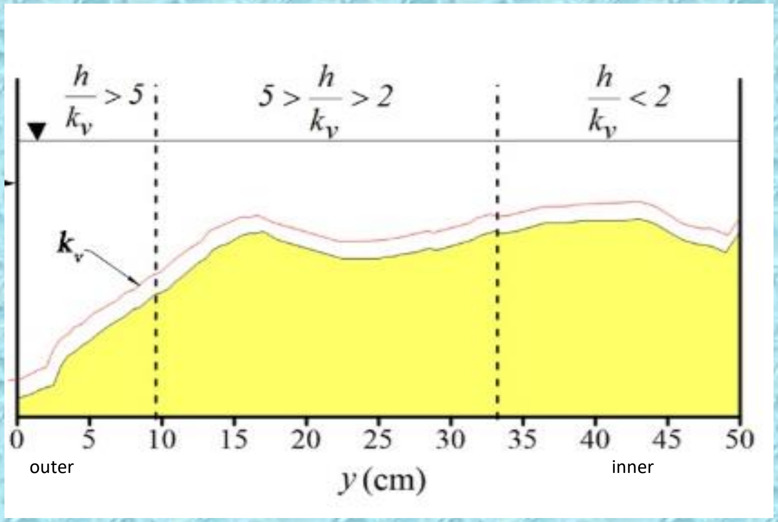
II: EFFECT ON TRANSPORT AND DIFFUSION

EFFECT OF CHANNEL CURVATURE

$$\frac{K_{yy}}{Umd} \approx \left\langle \frac{\sqrt{k'}d}{Umd} \right\rangle = \left\langle \frac{\sqrt{k'}}{Um} \right\rangle$$



Termini and Di Leonardo. 2018. AWR

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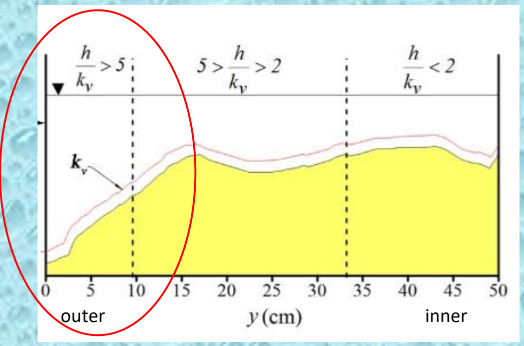

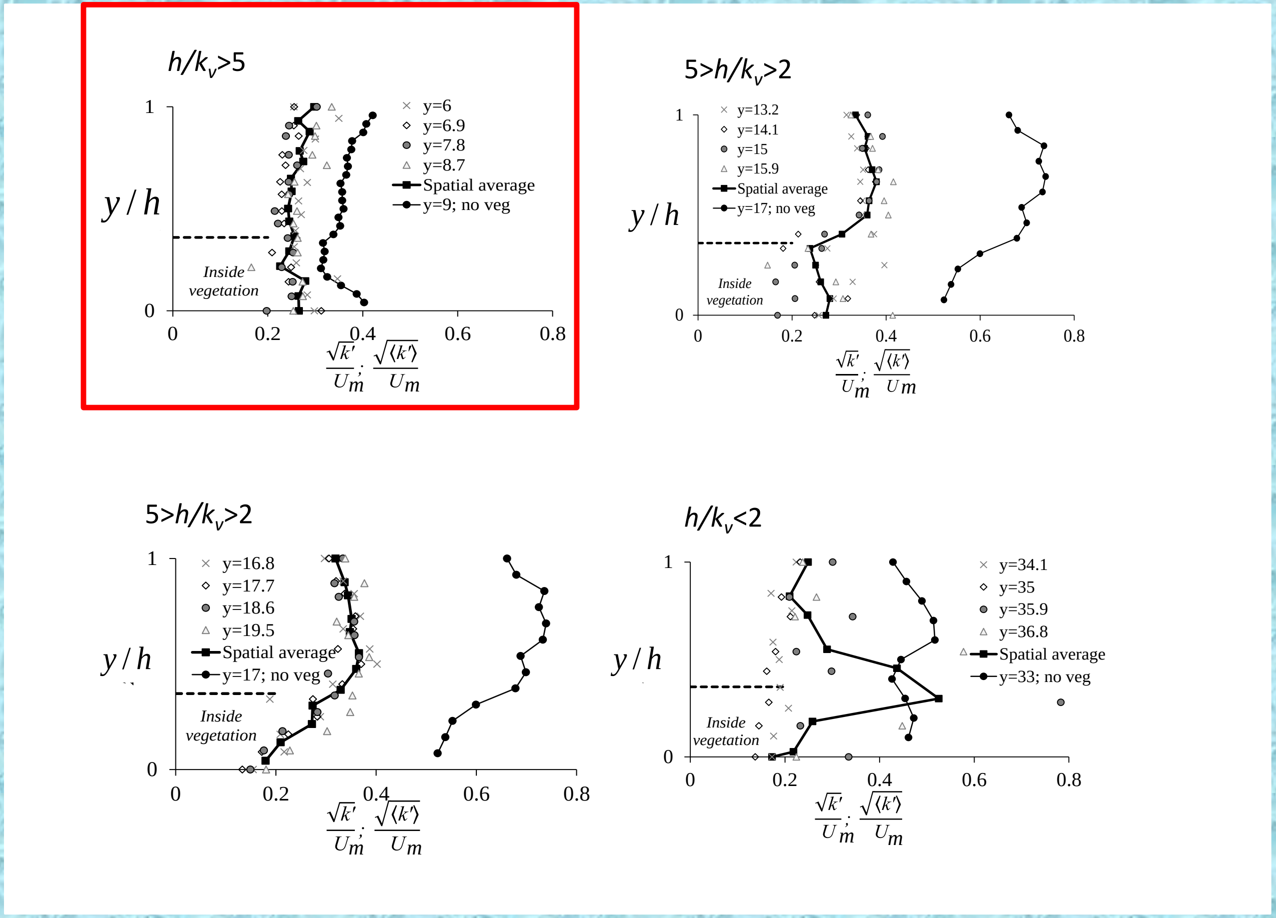

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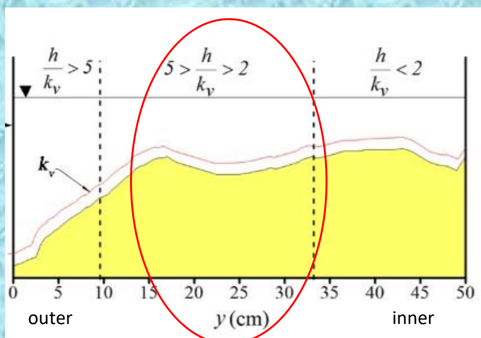

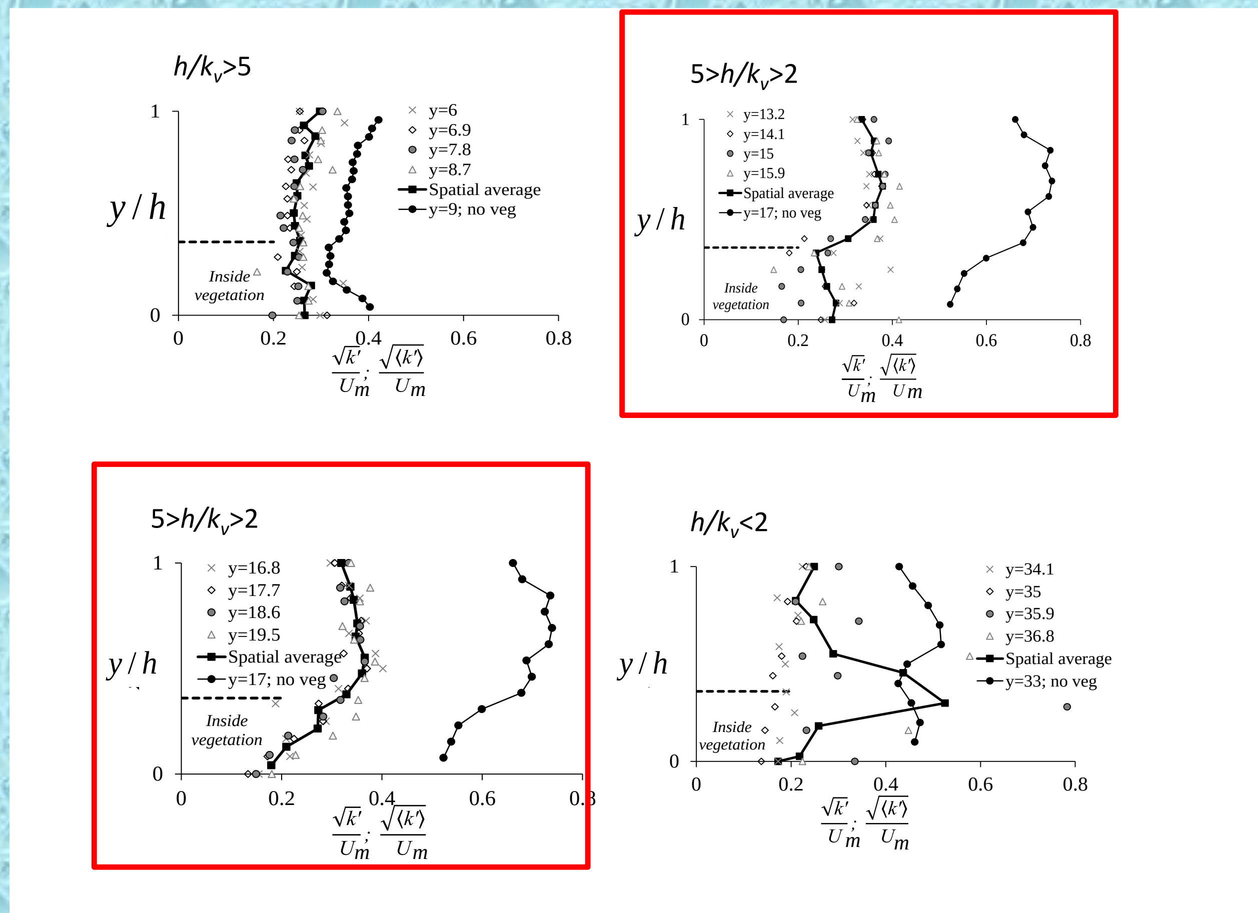

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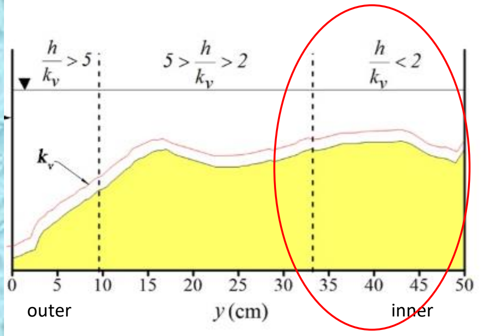

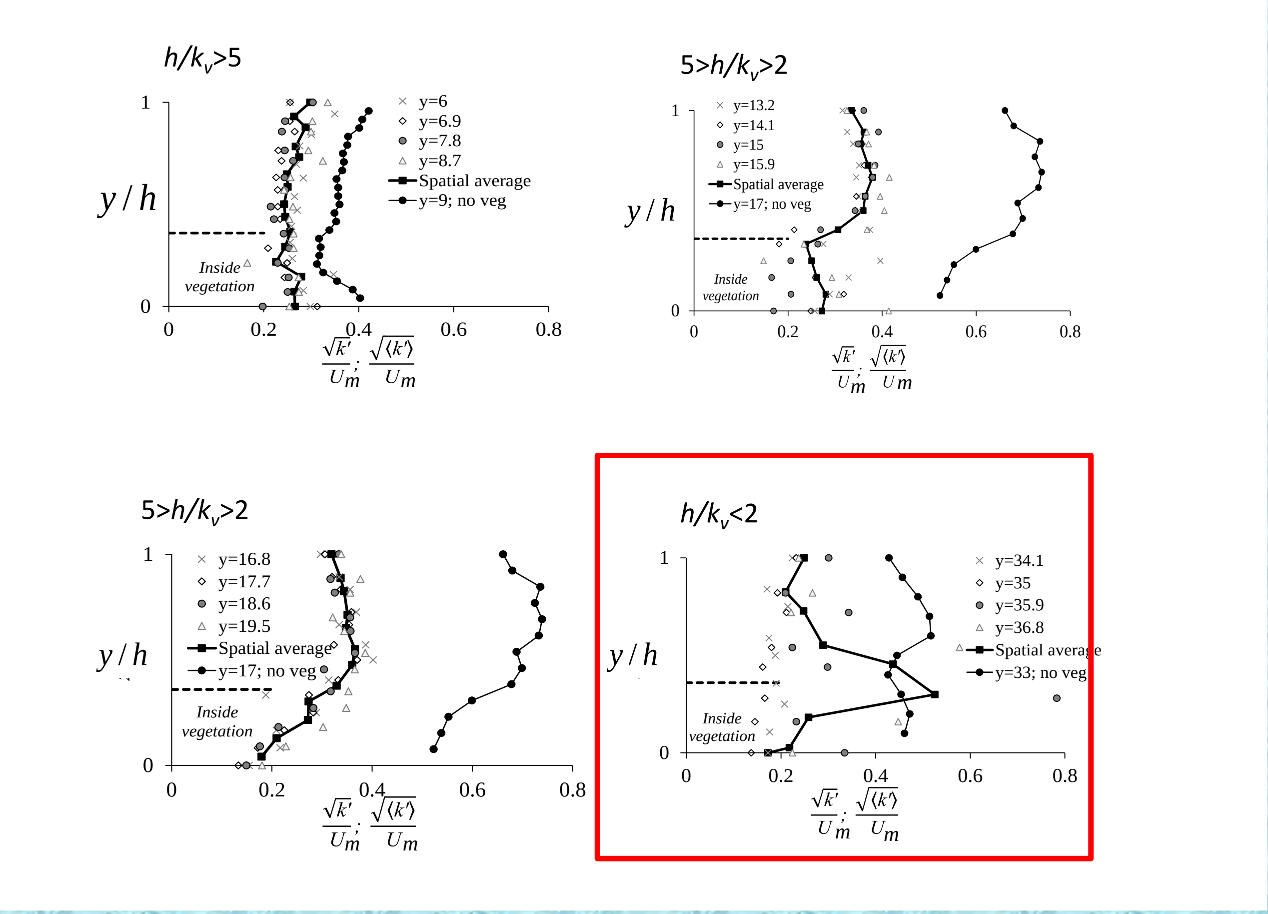

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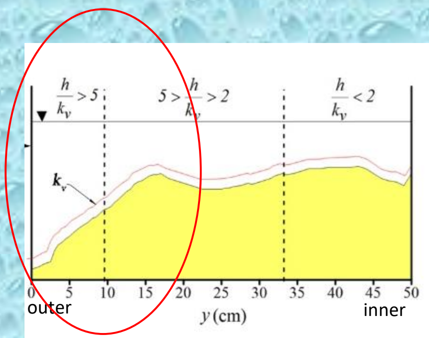
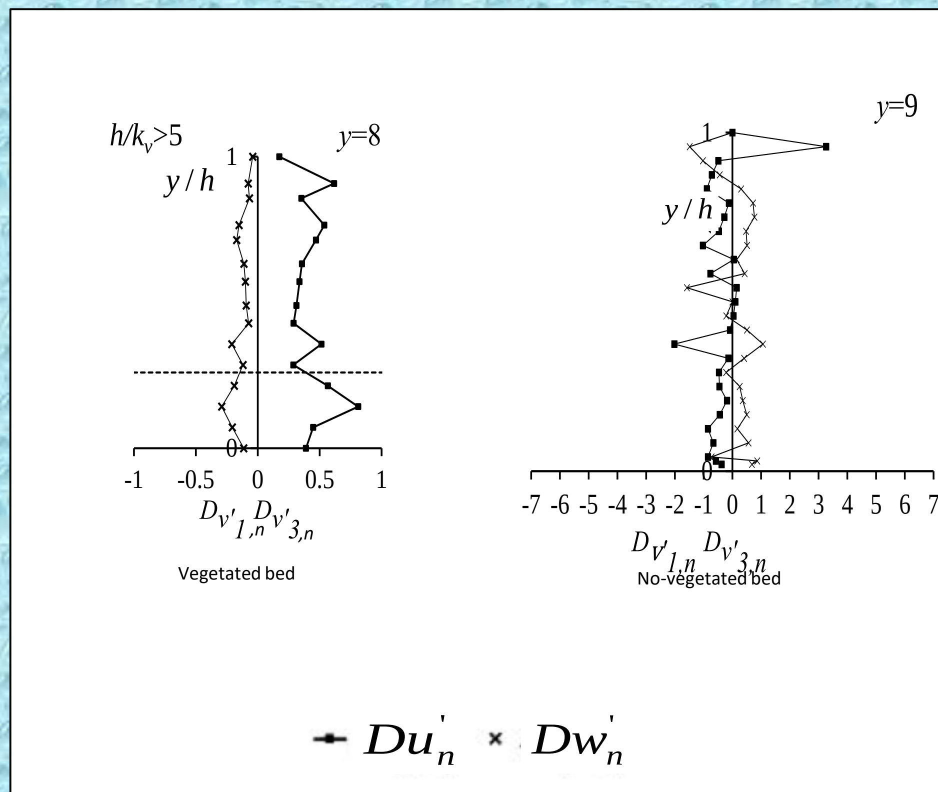
II: EFFECT ON TRANSPORT AND DIFFUSION

STREAMWISE AND VERTICAL NORMALIZED TURBULENT DIFFUSION

$$Du'_n = \overline{u'(t)^3} / \overline{u'(t)^2}^{3/2} \qquad Dw'_n = \overline{u'(t)^2 w'_3(t)} / \overline{u'(t)w'(t)}^{3/2}$$





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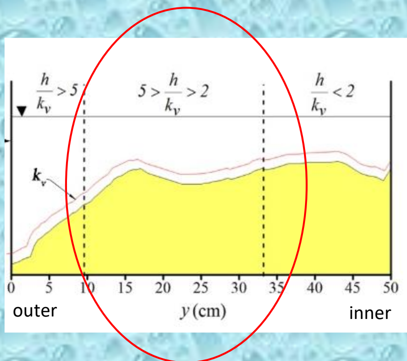

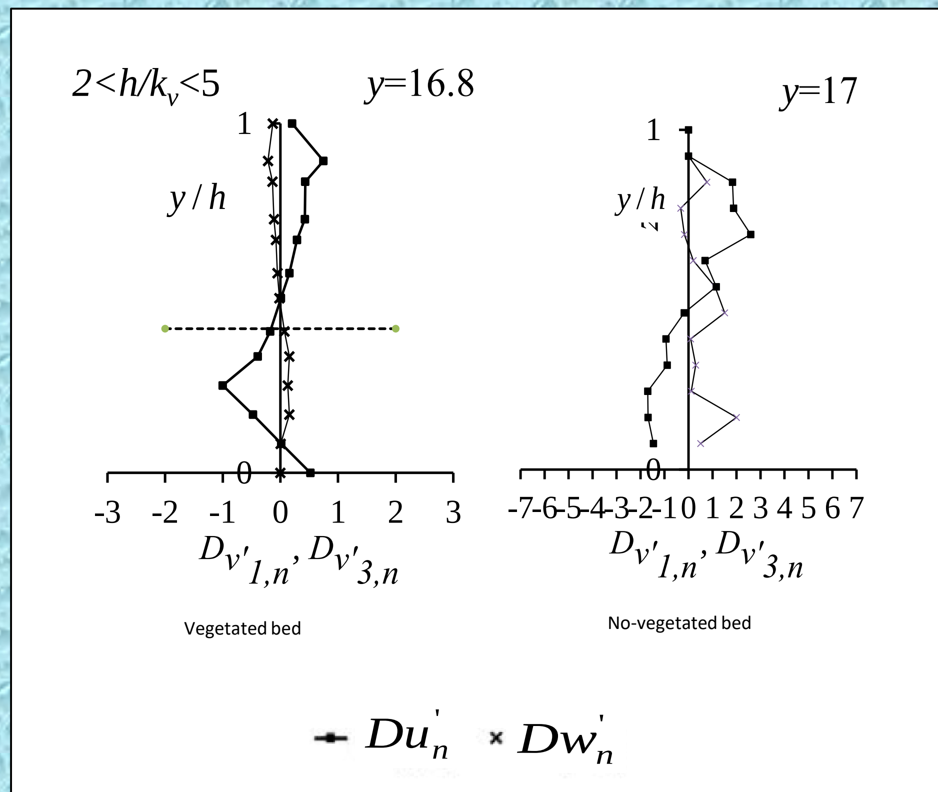

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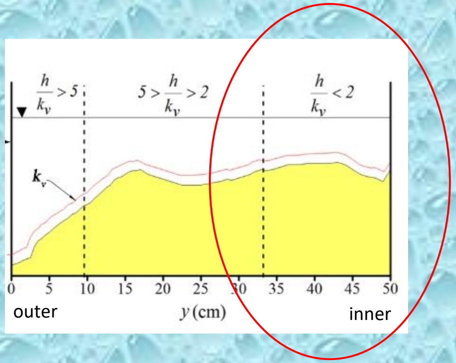

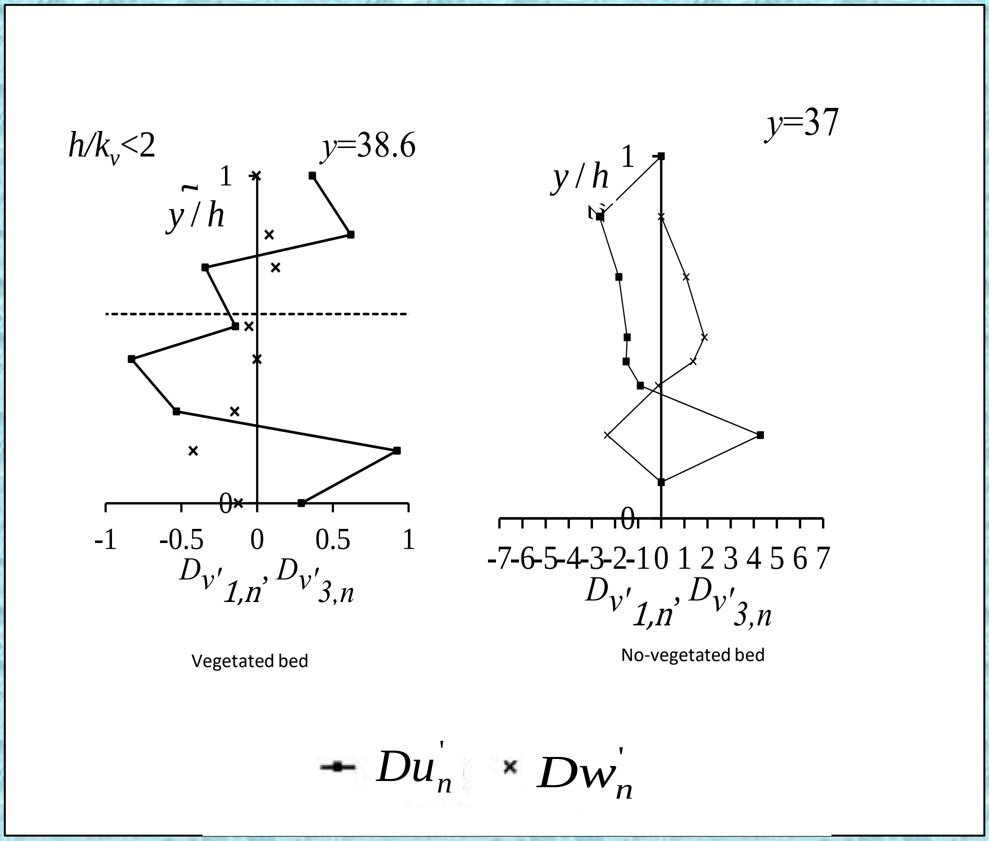

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INDICATIONS - II

EFFECT ON FLOW CONVEYANCE

The flow conveyance affected by concentration and on the relative submergence.

Low values of stems concentrations: the friction factor Um/v^* does not vary significantly with h/k_v.

As the stems concentration increases, the flow submergence exerts the major role on flow behavior and the ratio Um/v^* tends to increase as h/k_v increase.

High values of stems concentrations the increase with as h/k_v is not significant

Existence of two different regions of flow motion:

within $1<h/k_v<2$ (i.e. in “depth-limited submerged vegetation”)
the flow behavior is more complicated and the parameter h/k_v does not exert an important role on the friction factor Um/v^*;

for $h/k_v>2$ (i.e. in “submerged vegetation”) where the vertical momentum transport drives the flow within the vegetation and this effect increases the friction factor as the flow depth increases.

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INDICATIONS - II

EFFECT ON TRANSPORT AND DIFFUSION

- *Integral length scales*:
while in the absence of vegetation the longitudinal turbulent scale *lx* is of O(*h*);
in the presence of vegetation it is O(*d)* in all the directions.

In the case of dense canopy, turbulence seems to be characterized by isotropy.

- *Dispersion coefficients* follow those of the turbulent scales

-transversal and vertical directions:
the spatially averaged value is very small (around zero)

-longitudinal direction:
the spatially averaged value is reduced with respect to that obtained without vegetation and it assumes a maximum close to the vegetated layer.

For high values of vegetation density, the transport and dispersion within the vegetated layer seems to be reduced along all directions.

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INDICATIONS - II

EFFECT ON TRANSPORT AND DIFFUSION: effect of curvature

- Variation of lateral dispersion coefficient with variable *h/kv*:

a) For ***h/kv*>2**:

For **2<*h/kv*<5**

strong turbulent activity and vertical transport in the mixing layer

lateral dispersion could be important just over the vegetation

For ***h/kv*>5:**

possible suspension of substances in the flow transported downstream

transversal spatial averaged of turbulent diffusion assumes low values

b) For ***h/kv*<2** (in the inner-bank region)

interaction of the turbulent structures with the main flow in the hole flow depth

lateral dispersion assumes high values inside the vegetation

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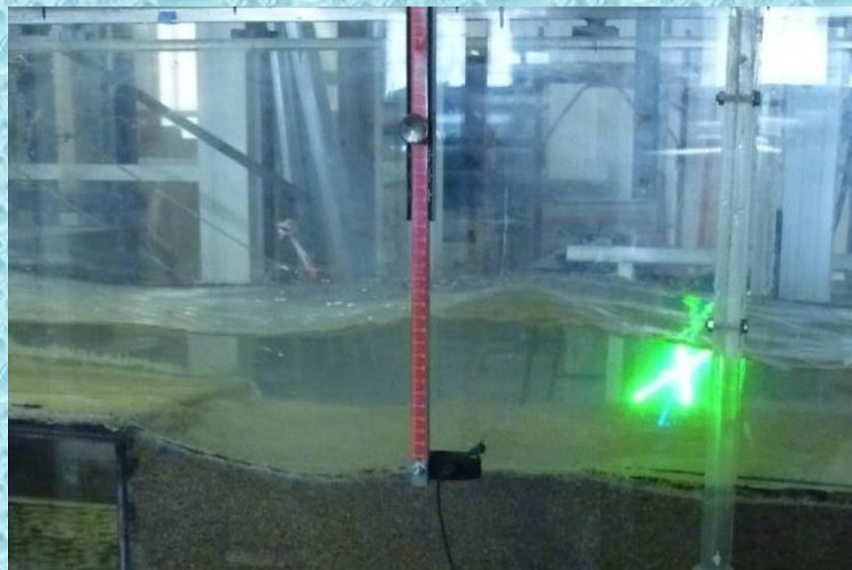
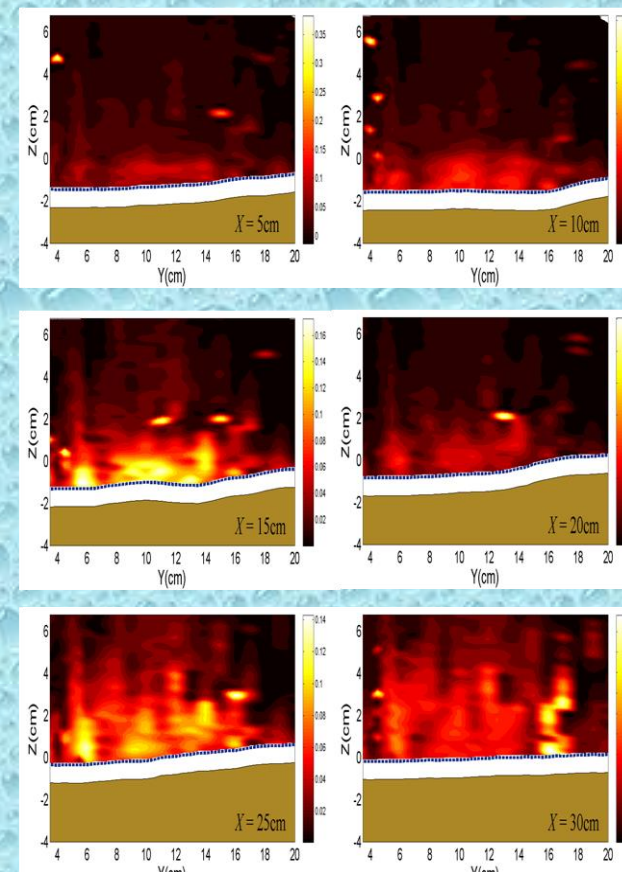
PRACTICAL IMPLICATIONS!





THANK YOU FOR YOUR ATTENTION!

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