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NUMERICAL STUDY OF SEDIMENTATION IN UNIFORMLY VEGETATED WETLANDS

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Outline

- Free water surface wetlands
- The numerical model:
  - hydrodynamics
  - solute transport
  - sedimentation processes
- Model application
- Results

Wetlands as wastewater treatment options

- Alternative for conventional treatment plants
- High ecological value (increase of ecological diversity)
- Environmentally friendly (energy consumption, material)
- Economical (building, maintanance)

→ Sustainable effective solution

Free Water Surface Constructed Wetlands (FWS)

Sediment transport processes

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- Soil particles retention
- Water transparency
- Interactions between pathogens
- DO exchanges in the water-sediment interface

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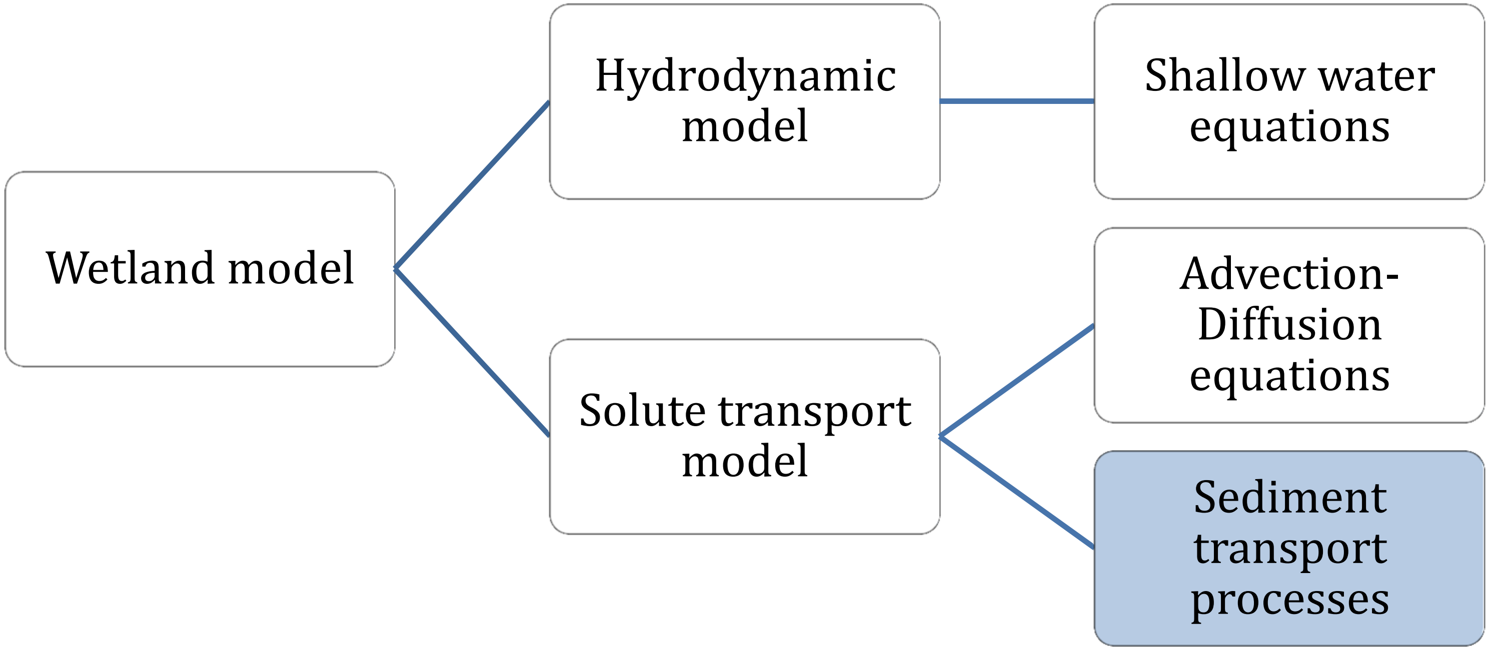
Performance in contaminal removal
Morphological evolution

Effect of vegetation density on sedimentation?

Numerical model

→ A coupled model to simulate wetland flow dynamics and transport of suspended sediments



Wetland model

Hydrodynamic model

Shallow water equations

Solute transport model

Advection-Diffusion equations

Sediment transport processes

Hydrodynamic model

- depth-averaged velocity field
- water depth

$$\frac{\partial(hU_x)}{\partial x}+\frac{\partial(hU_y)}{\partial y}=0$$

Mass conservation eq.

$$\frac{\partial(hU_x{}^2)}{\partial x}+\frac{\partial(hU_xU_y)}{\partial y}=-gh\frac{\partial(z_s)}{\partial x}-\frac{\tau_{bx}}{\rho}-\frac{\tau_{vx}}{\rho}$$

$$\frac{\partial(hU_xU_y)}{\partial x}+\frac{\partial(hU_y{}^2)}{\partial y}=-gh\frac{\partial(z_s)}{\partial y}-\frac{\tau_{by}}{\rho}-\frac{\tau_{vy}}{\rho}$$

Linear momentum conservation eq.

(Wu, 2007)

Assumptions: hydrostatic pressure, stationary flow, negligible wind & Coriolis forces

Hydrodynamic model - Stresses

Bed shear stress

$$\tau_{bx} = \rho C_b U_x \sqrt{{U_x}^2 + {U_y}^2}$$

$$\tau_{by} = \rho C_b U_y \sqrt{{U_x}^2 + {U_y}^2}$$

$$C_b = \frac{3\mu}{h\rho\sqrt{{U_x}^2+{U_y}^2}} + \frac{M^2 g}{h^{\frac{1}{3}}} = \frac{3}{Re_b} + \frac{M^2 g}{h^{\frac{1}{3}}}$$

Vegetation drag

$$\tau_{vx} = \frac{1}{2}\rho C_{vD} n_v d l U_x \sqrt{{U_x}^2 + {U_y}^2}$$

$$\tau_{vy} = \frac{1}{2}\rho C_{vD} n_v d l U_y \sqrt{{U_x}^2 + {U_y}^2}$$

$$C_{vD} = \frac{10\mu}{\rho d\sqrt{{U_x}^2+{U_y}^2}} + 1 = \frac{10}{Re_d} + 1 = \frac{10}{Re_h}\frac{h}{d} + 1$$

(Kadleck and Wallace, 2008)

In fully vegetated area, the vegetation drag provides the dominant flow resistance.

Mass transport model

Transport of suspended sediment :

$$\frac{\partial(hC)}{\partial t}+\frac{\partial(hU_xC)}{\partial x}+\frac{\partial(hU_yC)}{\partial y}=\frac{\partial}{\partial x}\left(hE_{xx}\frac{\partial C}{\partial x}+hE_{xy}\frac{\partial C}{\partial y}\right)$$

$$+\frac{\partial}{\partial y}\left(hE_{yx}\frac{\partial C}{\partial x}+hE_{yy}\frac{\partial C}{\partial y}\right)-KC$$

2D depth-averaged advection-dispersion eq. + First order source/sink term for resuspension/settling

$$K=k_s-k_r$$

Sediment transport model

$$\boxed{K = k_s - k_r}$$

Settling

$$k_s = \frac{w_s}{h}$$

(w_s: Stoke’s law)

Resuspension

(a threshold process)

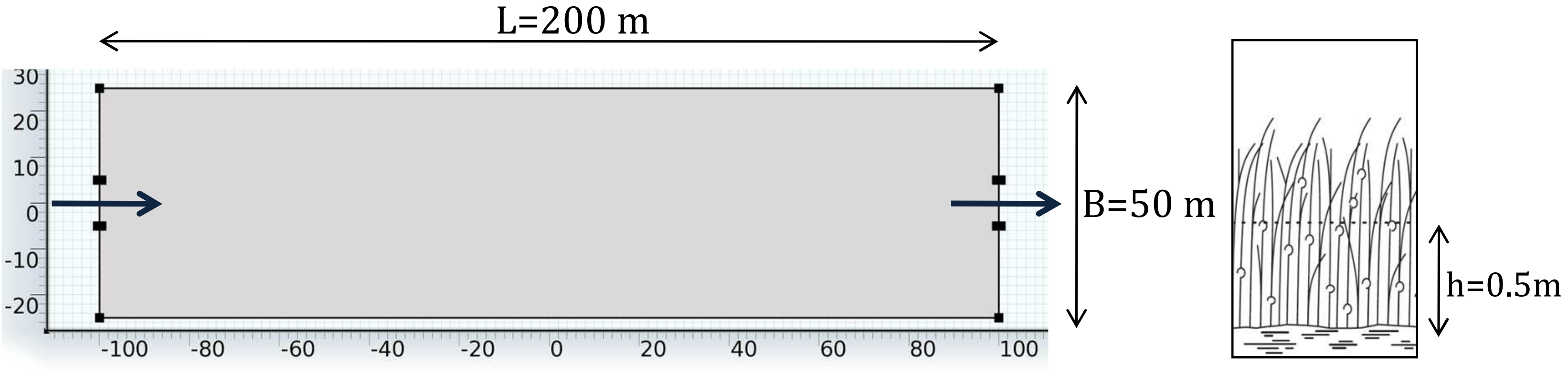
$$r = \frac{w_s}{k u^*} < 2.5$$

$$w_s = u^*$$

Assumption: $$\begin{cases} u^* < u^*_{th} \Rightarrow k_r = 0 \\ u^* \geq u^*_{th} \Rightarrow k_r = k_s \end{cases}$$

$$\boxed{K = k_s - k_r = \begin{cases} k_s & if\ u^* < u^*_{th} \\ 0 & if\ u^* \geq u^*_{th} \end{cases}}$$

Model application



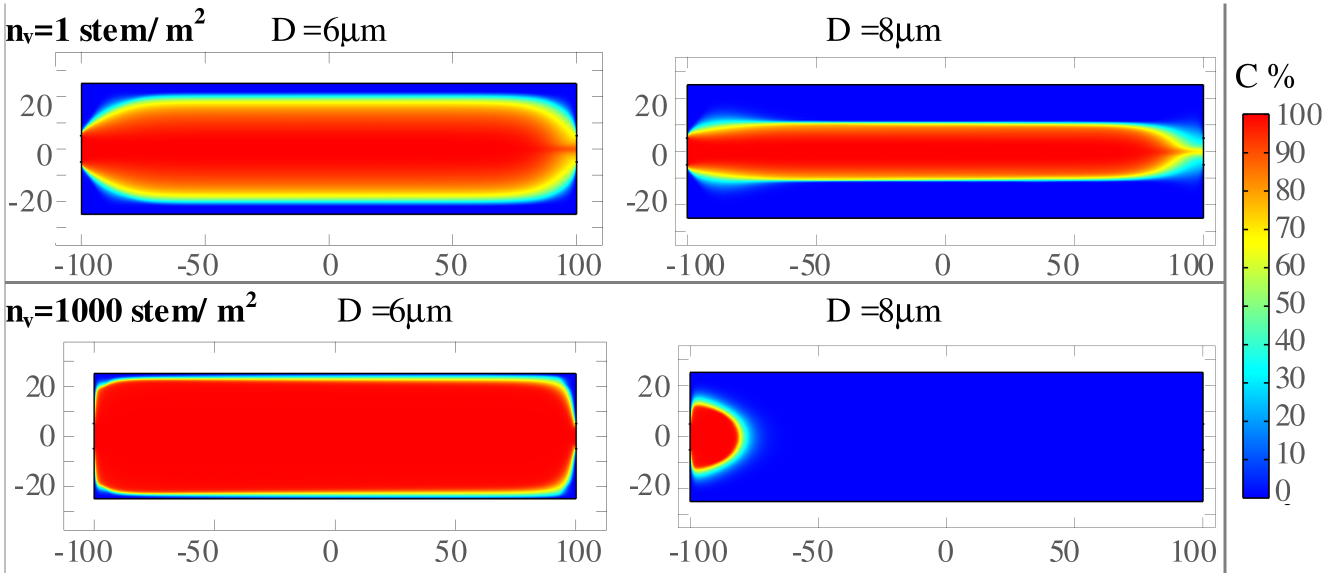
Tested conditions:

- $t_n \cong 7$ days
- $d = 10$ mm
- C_{in}= const = 100
- n_v= 1 – 10 – 100 – 1000 stem/m^2
- $D = 1 \div 10$ μm

Removal efficiency: $\boxed{E=C_{out}/C_{in}}$

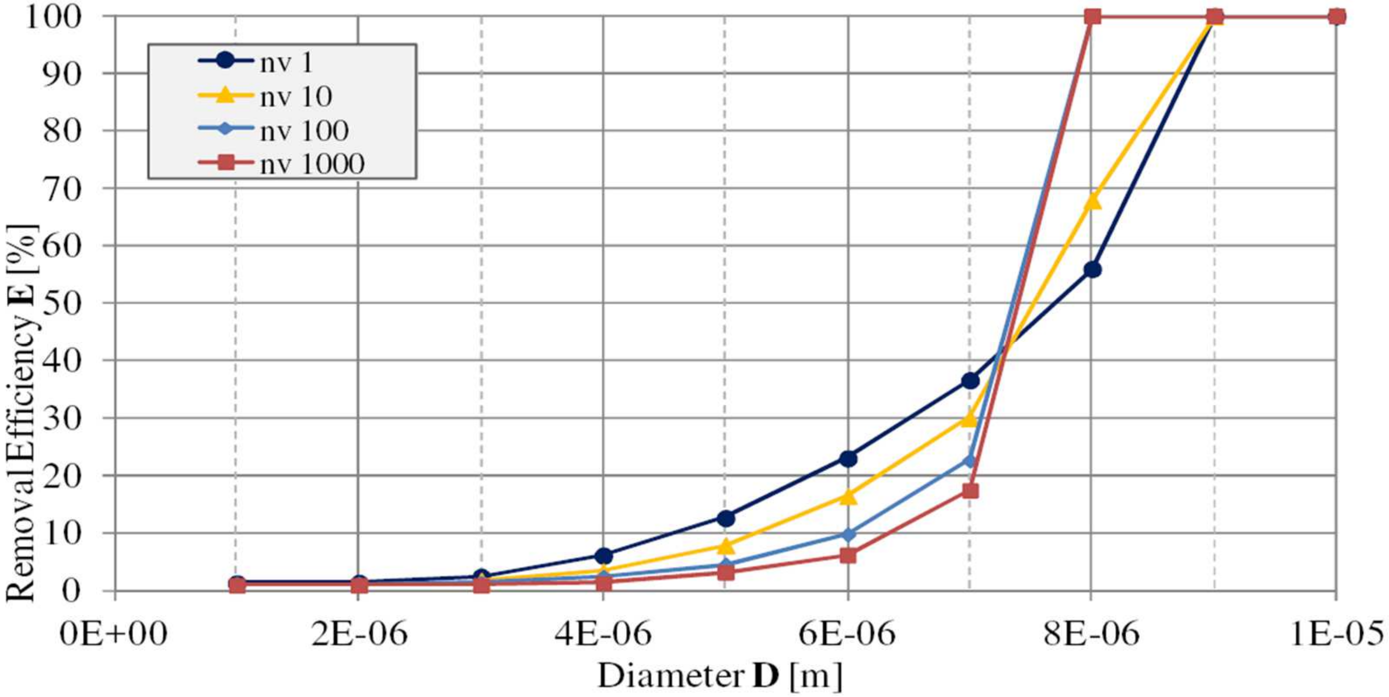
Results

Concentration distribution - Removal Efficiency



D [× 10^{-3}]	1	2	3	4	5	6	7	8	9	10
w_s [× 10^{-6} m/s]	0.9	3.5	7.8	13.9	21.8	31.4	42.7	55.8	70.6	87.1
E[%], n_v 1 stems/m^2	1.3	1.3	2.4	6.1	12.6	22.9	36.5	55.9	100.0	100.0
E [%], n_v 10 stems/m^2	1.5	1.5	1.7	3.3	7.9	16.4	29.9	67.9	100.0	100.0
E [%], n_v 100 stems/m^2	1.2	1.2	1.3	2.4	4.5	9.8	22.6	100.0	100.0	100.0
E [%], n_v 1000 stems/m^2	0.9	0.9	1.0	1.4	3.2	6.2	17.4	100.0	100.0	100.0

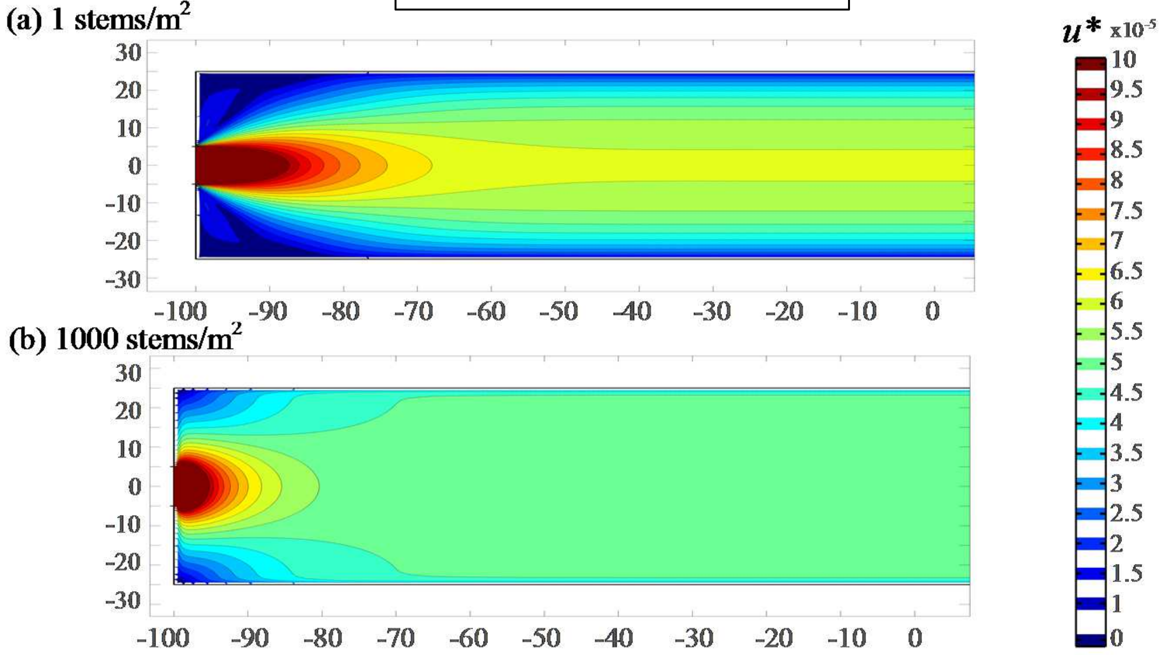
Results



- for different n_v, similar general trend
- for small particles, higher removal for lower n_v
- reverse trend just before the condition of total removal

Results

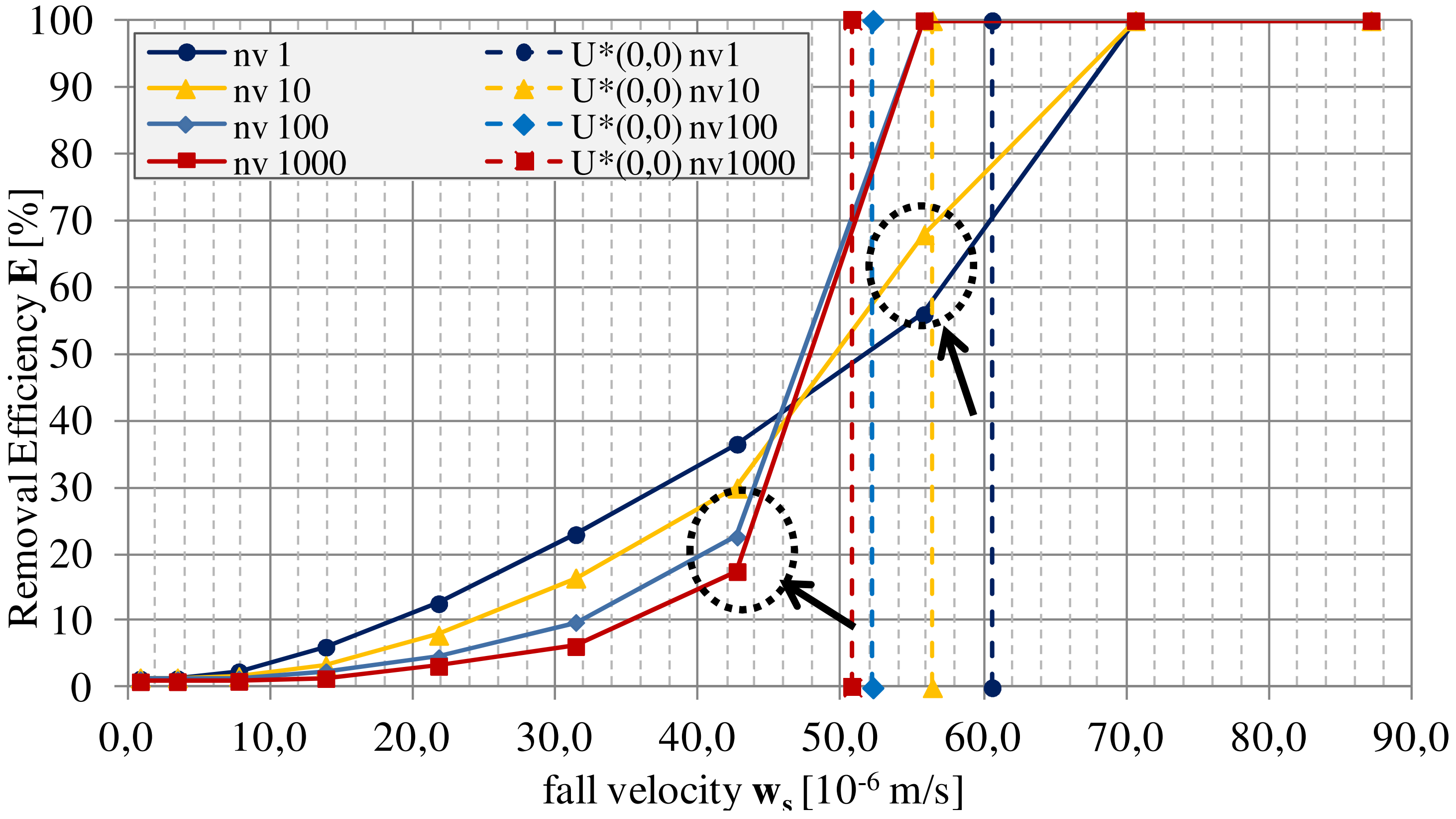
velocity field



Considerations on:
- Velocity averaged over the entire domain u_{mean}
- Velocity at the central point of the domain u(0,0)

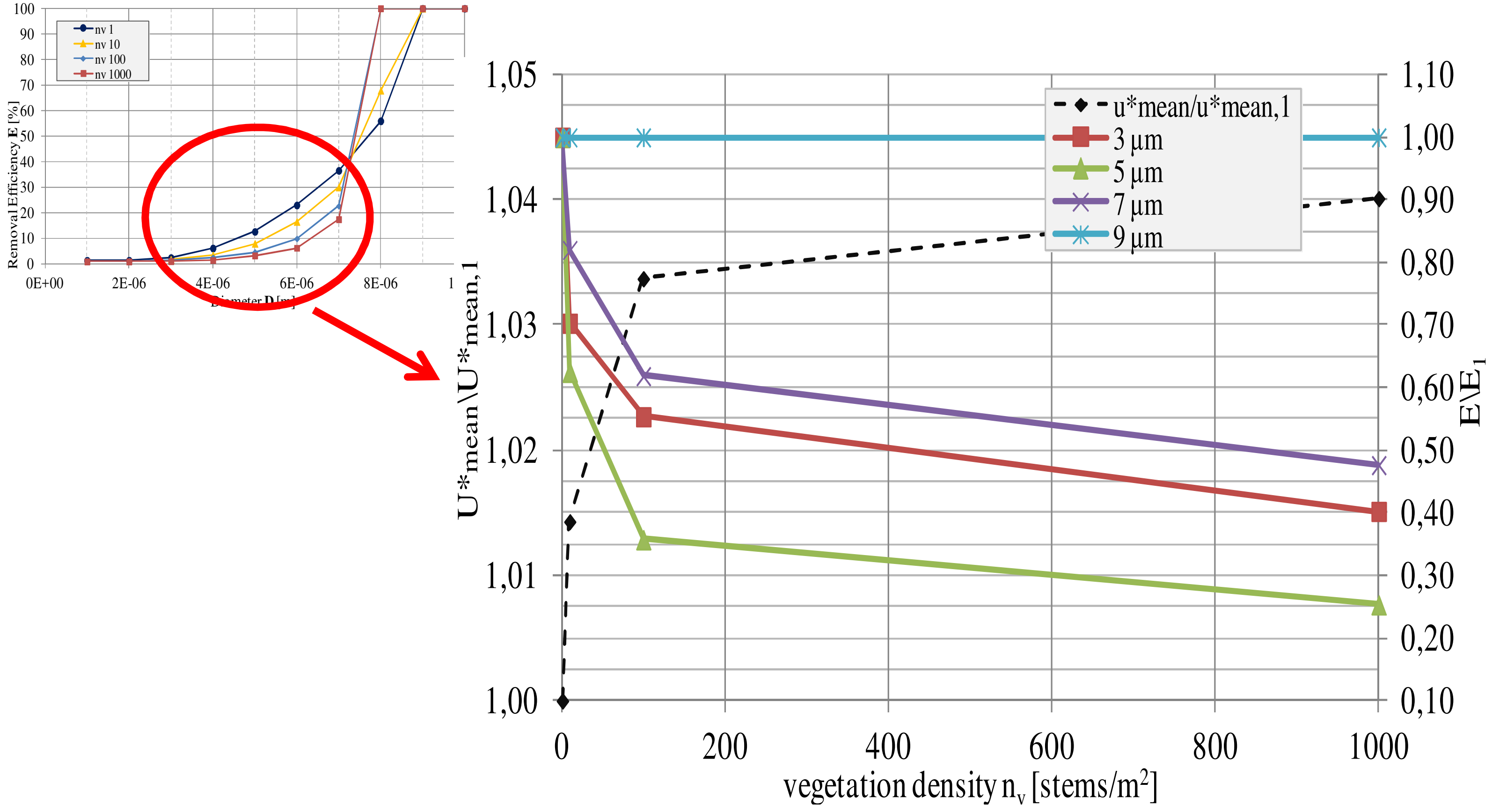
n_v [stems/m^2]	1	10	100	1000
u^*_{mean} [$\times 10^{-6}$ m/s]	48.9	49.6	50.5	50.8
$u^*(0,0)$ [$\times 10^{-6}$ m/s]	60.6	56.4	52.2	50.8

Results



Higher n_v → smaller u(0,0) → Complete removal for smaller D

Results



Higher n_v → higher u_{mean} → lower removal for finer D

Conclusion

Under the conditions simulated in the present numerical model

- for smaller particles, removal efficiency decreases as vegetation density increases
- total removal for finer particles is achieved for higher vegetation density
- behavior of removal efficiency is explained by velocity distribution

→ Vegetation affects removal of suspended sediments

Future developments

- Refined settling and resuspension formulations
- Different vegetation distribution

Thanks for your attention