Flow through vegetation I

Effects of biomechanical properties and density

Luca van Duren

22 August 2010

Crash-course boundary layer hydrodynamics

Boundary layer structured by friction drag

U_0 (free stream velocity)

U = 0

Turbulent log layer (i)

Boundary layer theory

\[ U(Z) = \frac{U_*}{\kappa} \ln \left( \frac{Z}{Z_0} \right) \]

Where:
- \( U(Z) \) = average horizontal velocity at height Z
- \( U_* \) = shear velocity
- \( \kappa \) = Von Karman constant (=0.41)
- \( Z_0 \) = roughness length

Important parameters

\[ \tau = \rho U_*^2 \]

Reynolds stress: \( \rho U' W' \)

\[ K_j = -\frac{\overline{WW}}{\overline{UU}} \]
Example

\[ U_1 = 0.20 \text{ m s}^{-1} \]
\[ U_2 = 0.20 \text{ m s}^{-1} \]

\[ U_1 = 0.010 \text{ m s}^{-1} \quad \tau = 0.10 \text{ N m}^{-2} = 0.10 \text{ Pa} \]
\[ U_2 = 0.013 \text{ m s}^{-1} \quad \tau = 0.18 \text{ N m}^{-2} = 0.18 \text{ Pa} \]

\[ t_{cr} \text{ for erosion of silt} = 0.13 \text{ Pa} \]

Turbulence parameters

- Momentum is transferred from high velocity layers to low velocity layers
- Flux of momentum: Reynolds stress \( \left< u'' \right> \)
- Sign (+/-) indicates direction of transport

There should be a direct relationship between:
- The velocity gradient
- Turbulence
- Momentum transfer

\[ u'^2 \approx \left< u'' \right> \approx c \cdot \text{TKE} \]
Turbulence over rough structures

- Flow over Crassostrea gigas ridge

Independent, interactive and skimming flow

- Plants
- Animals
- Mimics

Bio-fluid dynamic Research

- Flume tank: channel to create controlled flow for experiments
- NIOO flume: 10 m³, working section 12 m
- Robot for positioning equipment
- ADV equipment to measure $U_0$ and turbulence
Effect of density on TKE

High density patch

Effect of density on TKE

Low density patch - near the cases

Effect of density on TKE

Low density patch - away from the cases
Effect of density on Reynolds Stress

High density patch:

Effect of density on Reynolds Stress

Low density patch - near the cases:

Low density patch - away from the cases:

Within a canopy, biomass is not uniformly distributed through the water column.

**Effect of vertical biomass distribution**

- *Spartina*, *Salicornia* / *Suaeda*

**Flow reduction – turbulence enhancement**

- Drag exerted by stems reduce flow velocity through the canopy
- This reduces the volume flux of water through the canopy
- Drag increases turbulence
- Force on the bed depends on the balance between flow velocity and turbulence
Dislodgement: stiff v.s. flexible structures

Spartina

Zostera

Resisting breaking / dislodgement: drag

Stiff structures

Flexible structures

What strategy works best to avoid drag?

Artificial plants

- stiff strips
- Flexible strips

- low density
- high density
- Zostera noltii

- flat bed
- high density
- low density
- Zostera noltii

- low density
- high density
- Zostera noltii
**Drag avoidance**

- Plot showing drag (N m^{-2}) against bending angle (°)
- Data points for Spa & Sal, Zs, Sp a, & Sal

**Benefits: ecosystem engineering**

- Diagram of ecosystem engineering changes
  - STRONG hydrodynamics
  - REDUCED hydrodynamics

**Ecosystem engineering**

- Ecosystem engineering: modification of the abiotic environment by biological activity (Jones 1994)
Reduction of wave energy

Stiffness + density increase wave attenuation

Trade-offs shoot stiffness
Trade-offs shoot stiffness

Vegetation characteristics

Effects of shape
Wave attenuation as a function of vegetation type and density

All Spartina
\[ y = 5.8739e^{-0.3131x} \]
\[ R^2 = 0.947 \]
1st cut Spartina
\[ y = 6.3158e^{-0.2093x} \]
\[ R^2 = 0.973 \]
2nd cut Spartina
\[ y = 6.548e^{-0.1099x} \]
\[ R^2 = 0.890 \]

All Puccinellia
\[ y = 6.812e^{-0.457x} \]
\[ R^2 = 0.9944 \]
1st cut Puccinellia
\[ y = 6.4168e^{-0.1472x} \]
\[ R^2 = 0.932 \]
2nd cut Puccinellia
\[ y = 6.6637e^{-0.0937x} \]
\[ R^2 = 0.885 \]

Identify simple relations between biology & physics

Wave attenuation:
\[ D = \frac{1}{H} + D(x-x_0) \]

Drag (per m²) as a function of flexibility and wave height

[Diagram showing wave energy vs. drag with different types of strips (steel, flex., Spa., Puc.)]
**Effects of biomechanical properties on flow**

*drag (per g DM) as function of wave height & stiffness*

- Drag vs. wave energy graph showing:
  - Puc. and Spa. categories.
  - Drag values for different wave energy levels.

*Ecosystem engineering efficiency (EEF)*

- Ecosystem engineering efficiency (EEF) as a function of distance in vegetation.
- EEF values plotted for different vegetation densities.
- Distance in vegetation (m) vs. ecosystem eng. efficiency (J N m^-1 m^-2).

**Trade-offs shoot flexibility**

- *Spartina vs. Zostera noltii*
  - Stiffness increases dependence of drag on velocity by lack of reconfiguration → costs.
  - Stiffness + density increases wave attenuation → benefits.

- *Spartina vs. Puccinellia*
  - Per g DM, similar wave attenuation may explain sediment trapping Puccinellia.
  - Per g DM, EEF is higher for stiff Spartina.

*Spartina* → efficient, rather than effective ecosystem eng.

*Spartina* → most economic strategy to modify the environment.
Transport through seagrasses

Trade off between flow reduction and supply

Particle trapping

- Caulerpa racemosa
- C. prolifera
- C. taxifolia
- Posidonia oceanica
- Cymodocea nodosa

1 cm
Flow profiles

Flow reduction

Re stress
Particle capture

Particle loss rate in a race track flume with a 2 m canopy

\[ N_t = a + N_0 \cdot e^{-kt} \]

- \( N_0, N_t \) concentrations at time 0 and \( t \)
- \( a \) = background particle concentration
- \( k \) = first order rate constant (s\(^{-1}\))

\[ k = k_v + k_{SAND} \]

- \( k_v \) = vegetation specific loss rate

Particle retention

<table>
<thead>
<tr>
<th></th>
<th>( k )</th>
<th>( k_v )</th>
<th>Time required to retain 50% of the sediment</th>
<th>% retained after 5 min. per m(^2) leaf area</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sand (control)</td>
<td>0.0007</td>
<td>0.0007</td>
<td>990</td>
<td>-</td>
</tr>
<tr>
<td>C. racemosa</td>
<td>0.0009</td>
<td>0.0290</td>
<td>24</td>
<td>304.01</td>
</tr>
<tr>
<td>C. proliferata</td>
<td>0.0010</td>
<td>0.0910</td>
<td>8</td>
<td>101.04</td>
</tr>
<tr>
<td>C. taxifolia</td>
<td>0.0011</td>
<td>0.0270</td>
<td>28</td>
<td>22.60</td>
</tr>
<tr>
<td>Cymodocea nodosa</td>
<td>0.0013</td>
<td>0.0360</td>
<td>19</td>
<td>69.63</td>
</tr>
<tr>
<td>Posidonia oceanica</td>
<td>0.0006</td>
<td>0.0380</td>
<td>18</td>
<td>106.67</td>
</tr>
</tbody>
</table>

- C. racemosa can tolerate high sedimentation rates
- C. taxifolia has largest retention rate per m\(^2\), i.e. strongest ecosystem engineer

Particle trapping

Trapping is linked to species-specific canopy properties

\( k \) = probability that particles are removed from the water column
Bed protection

Reduction of stresses at sediment surface is important for sediment dynamics, i.e., storm events.

Nutrient uptake by seagrasses

Cymodocea nodosa

Zostera noltii

Volumetric flux and nutrient uptake

Effects of biomechanical properties on flow
Nutrient uptake related to various factors

• Canopy architecture of *C. nodosa* allows higher canopy flux and higher nutrient uptake per g biomass
• Higher biomass per m² of *Z. noltii* results in similar areal uptake

Waves

- NH₄ uptake is spatially explicit
- Linked to canopy flow and turbulence
- Waves add high turbulence, open up canopy

Monami

- K-H instabilities cause vortices to develop
- Results in undulation motion of a flexible canopy
Fluctuations not caused by ambient flow, but by hydro-elasticity of plants
Mixing in flexible canopies is reduced
Consequences for e.g. feeding organisms, but also sub-aquatic pollination and fertilisation.