Formulaciones para estimar la atenuación de energía del oleaje producida por SbN

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1 **Disipación de energía**

2 Coeficiente de arrastre

3 Nuevas aproximaciones

Disipación de energía

- Over the years, energy dissipation induced by coastal vegetation has been analyzed using different approaches.
- Initial approaches computed wave energy dissipation using an analytical formulation based on the conservation of energy equation assuming steady flow.
- The energy flux gradient produced along the vegetation field is related to the dissipation induced by the plants considering the drag force exerted on the vegetation.
- This drag force is computed assuming a constant drag coefficient and a constant characteristic stem width per unit height along the entered vegetation height. Dalrymple et al. (1984) presented first this conservation of energy approach for regular waves following linear wave theory and Mendez and Losada (2004) extended the formulation for irregular waves.
- This approach computes wave height decay as a function of an attenuation coefficient as follows:

$$\frac{H}{H_0} = \frac{1}{1 + \beta x}$$

Disipación de energía

$$\frac{H}{H_0} = \frac{1}{1 + \beta x}$$

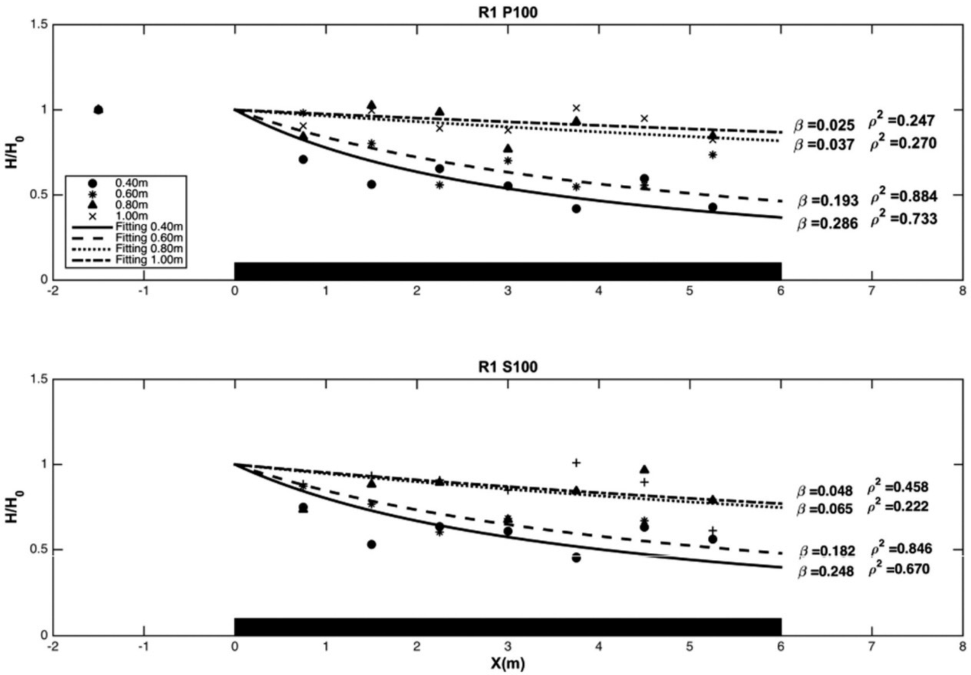
- H_0 is the incident wave height
- H the wave height at a distance x from the beginning of the vegetation field
- β is the attenuation coefficient

- Most of the studies in the literature fit this attenuation coefficient using experimental data

R & D + i for sustainable development

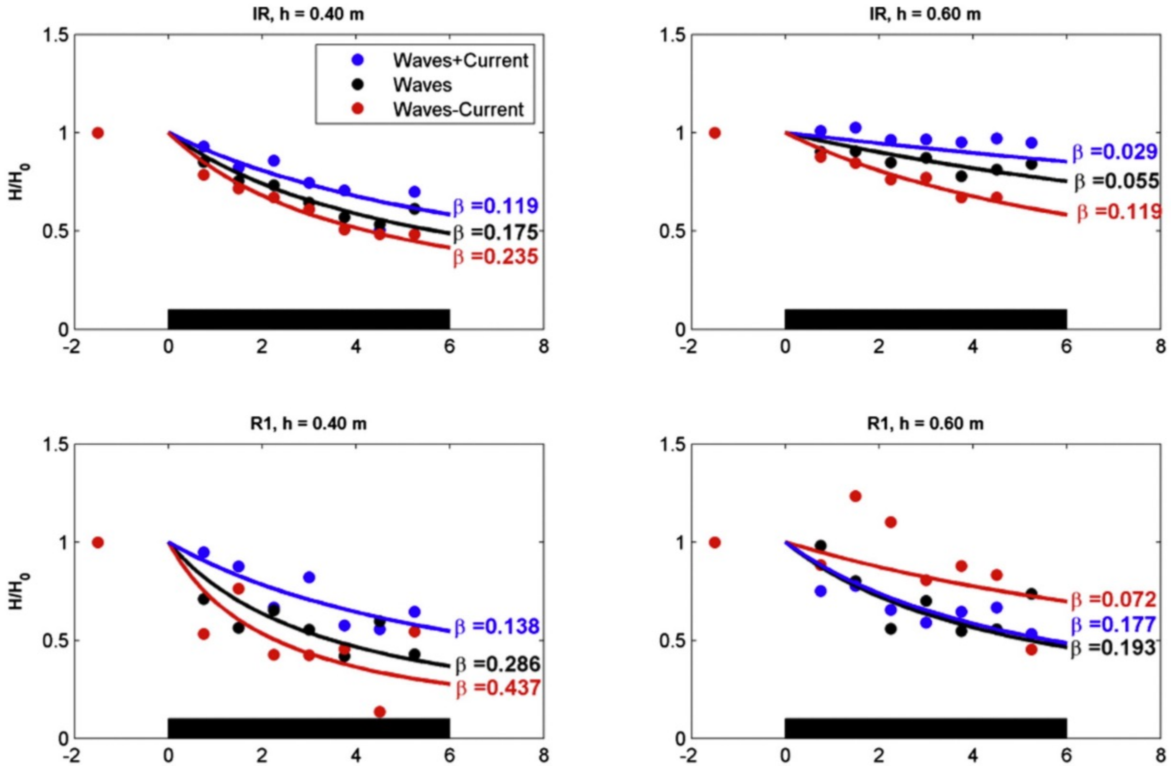
Disipación de energía

- Ejemplo: Maza et al. 2015



Disipación de energía

- Ejemplo: Maza et al. 2015



Disipación de energía

- There are some studies that give an analytical expression for this coefficient as a function of
  - flow parameters (wave height, wave period, water depth)
  - vegetation geometrical characteristics (representative diameter, density and height)
  - drag coefficient, C_D.

- Dalrymple et al. (1984) proposed the first β formulation for regular waves
- Mendez and Losada (2004) give the expression for irregular waves
- Losada et al. (2016) derive the formulas for waves and current conditions.

Paper	Study	Vegetation	Formulation	Variables and considerations
Dalrymple (1984)	Analytical	Generic	$\frac{H}{H_0} = \frac{1}{1+\beta x}$ $\beta = \frac{4aNH_0k}{9\pi} \frac{sinh^3kl + 3sinhkl}{(sinh2kh + 2kh)sinhkh} C_D$	H: wave height at the meadow (m) H_0: incident wave height (m) β: attenuation coefficient (1/m) x: separation between positions (m) a: stem diameter (m); N: number stems per square meter (1/m^2); h: water depth (m); k: wave number (1/m); l: vegetation length; C_D: drag coefficient - Wave decay for regular waves
Mendez and Losada (2004)	Lab	Seagrass (polypropylene strips, Asano et al. 1988)	$\frac{H_{rms}}{H_{rms,0}} = \frac{1}{1+\beta x}$ $\beta = \frac{aNH_{rms,0}k}{3\sqrt{\pi}} \frac{sinh^3kl + 3sinhkl}{(sinh2kh + 2kh)sinhkh} C_D$	H_{rms}: root-mean-square wave height at the meadow (m) $H_{rms,0}$: root-mean-square incident wave height (m) β: attenuation coefficient (1/m) x: separation between positions (m) a: stem diameter (m); N: number stems per square meter (1/m^2); h: water depth (m); k: wave number (1/m); l: vegetation length; C_D: drag coefficient - Wave decay for irregular waves

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Paper	Study	Vegetation	Formulation	Variables and considerations
Kobayashi et al. (1993) / Bradley and Houser (2009)	Lab / Field	Seagrasses (polypropylene strips) / Seagrass (Thalassia testudinum and Halodule wrightii)	$\frac{H_{rms}}{H_{rms,0}} = exp(-k_i \Delta x)$	H_{rms}: root-mean-square wave height at the meadow (m) $H_{rms,0}$: root-mean-square incident wave height (m) k_i: attenuation coefficient (1/m) Δx: separation between positions (m) - First proposed by Kobayashi et al. (1993) and later extended by Bradley and Houser (2009) considering flexible vegetation.
Koch et al. (2006)	Field	Seagrass (Ruppia maritima)	$AT = \frac{H_s}{H_0} \sqrt{\frac{c_g}{c_{g0}}} * 100$	AT: wave attenuation (%) H_s: wave height in the seagrass bed (m) H_0: wave height offshore seagrass bed (m) c_g: group velocity in the seagrass bed (m/s) c_{g0}: group velocity offshore the seagrass bed (m/s) - Consideration of group velocity to account for shoaling between two analyzed points.

Paper	Study	Vegetation	Formulation	Variables and considerations
Mazda et al. (2006)	Field	Mangrove forest dominated by Sonneratia sp.	$r = -\frac{\Delta H}{H}\frac{1}{\Delta x}$	r: attenuation rate (1/m) H: wave height (m) x: distance along the meadow (m) - Application for mangrove forests.
Coulombier et al. (2012)	Field	Saltmarsh, many species (e.g. Spartina patens, Carex spp., Spartina pectinata, Salicornia europaea)	$a = \frac{-ln\left(\frac{E_2}{E_1}\right)}{d}$	a: wave attenuation coefficient (1/m) E_1: wave energy at point 1 (J/m^2) E_2: wave energy at point 2 (J/m^2) d: distance between points (m) - Exponential attenuation between points is assumed to relate wave energy at two locations.

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Paper	Study	Vegetation	Formulation	Variables and considerations
Losada et al. (2016)	Lab	Saltmarshes (Spartina anglica and Puccinellia maritima)	$\frac{H}{H_0} = \frac{1}{1+\beta_{wc}x}$ Regular waves $\frac{H_{rms}}{H_{rms,0}} = \frac{1}{1+\beta'_{wc}x}$ Irregular waves $\beta_{wc} = \left(\frac{3\pi}{2aN\left(\frac{gk}{2(\sigma - U_0 k)}\right)^3 H_0} \frac{3k cosh^3 kh}{sinh^3 kl_D + 3 sinh kl_D} \left[\frac{g}{8}\left(1 + \frac{2kh}{sinh2kh}\right)\left(\frac{g}{k} tanhkh\right)^{\frac{1}{2}} + \frac{g}{8} U_0 \left(3 + \frac{4kh}{sinh2kh}\right) + \frac{3k}{8} U_0^2 \left(\frac{g}{k} cothkh\right)^{\frac{1}{2}} \right] \left[U_0 + \frac{1}{2}\left(1 + \frac{2kh}{sinh2kh}\right)\left(\frac{g}{k} tanhkh\right)^{\frac{1}{2}} \right] \right)^{-1} C_{Dwc}$ $\beta'_{wc} = \left(\frac{2\sqrt{\pi}}{aN\left(\frac{gk}{2(\sigma - U_0 k)}\right)^3 H_{rms,0}} \frac{3k cosh^3 kh}{sinh^3 kl_D + 3 sinh kl_D} \left[\frac{g}{8}\left(1 + \frac{2kh}{sinh2kh}\right)\left(\frac{g}{k} tanhkh\right)^{\frac{1}{2}} + \frac{g}{8} U_0 \left(3 + \frac{4kh}{sinh2kh}\right) + \frac{3k}{8} U_0^2 \left(\frac{g}{k} cothkh\right)^{\frac{1}{2}} \right] \left[U_0 + \frac{1}{2}\left(1 + \frac{2kh}{sinh2kh}\right)\left(\frac{g}{k} tanhkh\right)^{\frac{1}{2}} \right] \right)^{-1} C'_{Dwc}$	H, H_{rms}: wave height and root-mean-square wave height at the meadow (m) H_0, $H_{rms,0}$: incident wave height and root-mean-square incident wave height (m) β_{wc}, β'_{wc}: attenuation coefficient for regular and irregular waves respectively (1/m) x: separation between positions (m) a: stem diameter (m); N: number stems per square meter (1/m^2); h: water depth (m); σ: wave frequency (1/s); U_0: current velocity (m/s); k: wave number (1/m); l_D: deflected vegetation length; g: gravity acceleration (m/s^2); C_{Dwc}, C'_{Dwc}: drag coefficient for regular and irregular waves respectively. - Wave height decay for waves and current conditions and regular and irregular wave trains.

1 Disipación de energía

2 **Coeficiente de arrastre**

3 Nuevas aproximaciones

Coeficiente de arrastre

- For these studies where an expression of β is proposed accounting for vegetation characteristics, C_D is an unknown and it is obtained using existing formulas in the literature based on experimental and field data.

- These formulations have been commonly presented as a function of Reynolds number, Re, or Keulegan Carpenter number, KC, calculated using mean stem diameter.

- This conservation of energy approach as been also applied in spectral models (Suzuki et al. 2011) where spectral energy dissipation induced by vegetation is related to a bulk drag coefficient following Mendez and Losada (2004).

Paper	Study	Vegetation	Formulation	Considerations
Kobayashi et al. (1993)	Lab	Seagrasses (artificial Zostera noltii from Asano et al. 1988)	$C_D = 0.08 + \left(\frac{2200}{Re}\right)^{2.4}$	- Re: Reynolds number considering vegetation diameter - Re range: 2000 – 18000 - Regular waves
Mendez et al. (1999)	Lab	Seagrasses (artificial Zostera noltii from Asano et al. 1988)	$C_D = 0.08 + \left(\frac{2200}{Re}\right)^{2.2}$ no movement $C_D = 0.40 + \left(\frac{4600}{Re}\right)^{2.9}$ considering movement	- Two drag coefficients: one considering vegetation motion by introducing relative velocity between plants and fluid in the drag force calculation and another one without considering plant motion. - Re: Reynolds number considering vegetation diameter - Re range: 200 – 15500 - Regular waves
Mendez and Losada (2004)	Lab	Kelp (artificial Laminaria hyperborea from Dubi and Torum, 1995; Lovas and Torum, 2001)	$C_D = 0.47 exp(-0.052KC)$ $C_D = \frac{exp\left(-0.0138\, {KC}/{(h_v/h)^{0.76}}\right)}{\left({KC}/{(h_v/h)^{0.76}}\right)^{0.3}}$	- Two formulations as a function of Keulegan Carpenter number (KC): second one accounts for relative vegetation height (h_v/h: h_v is vegetation height and h water depth). - KC: Keulegan Carpenter number considering vegetation diameter - KC range: 3 – 59; $KC(h_v/h)^{-0.76}$ range: 7 - 172

Paper	Study	Vegetation	Formulation	Considerations
Augustin et al. (2009)	Lab	Artificial submerged and emergent wooden dowels	$C_D = C'_D \left(\frac{l_s d}{\Delta S h}\right)$	- Bulk drag coefficient per unit width - C'_D: individual stem drag coefficient - l_s: stem height (equal to h for emergent conditions); d: stem diameter; ΔS: stem spacing; h: water depth. - Regular waves
Myrhaug et al. (2009)	Analytical	Generic	$C_{D,rms} = r\sqrt{B}\left(1 + k_p a_{rms} \frac{sA}{rB}\right)$	- Stochastic method to get root-mean-square drag coefficient - k_p: wave number associated with the spectral peak; a_{rms}: root-mean-square wave amplitude; s, r, A, B: variables function of wave parameters - Irregular waves
Paul and Amos (2011)	Field	Seagrass (Zostera noltii)	$C_D = 0.06 + \left(\frac{153}{Re}\right)^{1.45}$	- Re: Reynolds number considering vegetation diameter - Formulation valid for significant wave height $H_s \geq 0.1$ m - Re range: 100 - 1000

Paper	Study	Vegetation	Formulation	Considerations
Jadhav and Chen (2012)	Field	Saltmarshes (Spartina alterniflora)	$C_D = 0.36 + \frac{2600}{Re}$	- Re: Reynolds number considering vegetation diameter - Re range: 600 - 3200
Jadhav et al. (2013)	Field	Saltmarshes (Spartina alterniflora)	$C_{D,j} = \overline{C_D}\alpha_{n,j}^2$	- Spectrally variable drag coefficient - $\overline{C_D}$: spectrally-averaged drag coefficient - α: normalized velocity attenuation parameter obtained as the ratio of vegetation-affected velocity and velocity in the absence of vegetation. - subindex j represents the jth frequency component of wave spectrum.
Maza et al. (2013)	Lab	Seagrasses (artificial Posidonia oceanica fron Stratigaki et al. 2011)	$C_D = 0.87 + \left(\frac{2200}{Re}\right)^{0.88}$ no movement $C_D = 1.61 + \left(\frac{4600}{Re}\right)^{1.9}$ considering movement	- Two drag coefficients: one considering vegetation motion by introducing relative velocity between plants and fluid in the drag force calculation and another one without considering plant motion. - Re: Reynolds number considering vegetation diameter - Re range: 2500 – 8500 - Regular waves

Paper	Study	Vegetation	Formulation	Considerations
Pinsky et al. (2013)	Review lab and field	Seagrasses, saltmarshes, mangroves	$log(C_D) = \beta_0 + \beta_1 log(c * Re)$	- Statistical analysis - Fitted parameters: β_0= -1.72; β_1=-1.67; c = 3*10^{-4} - Re: Reynolds number considering vegetation diameter
Ozeren et al. (2013)	Lab	Saltmarshes (J. roemerianus)	$C_D = \left(\frac{55.2}{KC(h_v/h)^{-2}}\right)^{0.817}$ Regular waves $C_D = \left(\frac{58.5}{KC(h_v/h)^{-2}}\right)^{0.641}$ Irregular waves	- Drag coefficient introducing vegetation height and water depth – KC: Keulegan Carpenter number as a function of vegetation diameter – h_v: vegetation height; h: water depth - $KC(h_v/h)^{-2}$ range: 5 - 80 for regular waves; 5 – 40 for irregular waves
Möller et al. (2014)	Lab	Saltmarshes (Elymun athericus)	$C_D = -0.046 + \left(\frac{305.5}{Re}\right)^{0.977}$ Regular waves $C_D = 0.159 + \left(\frac{227.3}{Re}\right)^{1.615}$ Irregular waves	- Drag coefficient for regular and irregular waves - Re: Reynolds number considering vegetation diameter - Re range: 100 - 1100

Paper	Study	Vegetation	Formulation	Considerations
Anderson and Smith (2014)	Lab	Saltmarshes (artificial Spartina made using cross linked polyolefin tubes)	$C_D = 0.76 + \left(\frac{744.2}{Re}\right)^{1.27}$ Submerged conditions $C_D = 1.10 + \left(\frac{27.4}{KC}\right)^{3.08}$ Submerged conditions $C_D = 0.11 + \left(\frac{2067.7}{Re(l_s/h)^{-1.5}}\right)^{0.64}$ $C_D = 0.97 + \left(\frac{744.2}{KC(l_s/h)^{-1.5}}\right)^{1.69}$	- Drag coefficient as a function of Re or KC for submerged conditions and new formulations to account for submergence ratio (l_s/h). - Re and KC considering vegetation diameter - Re range: 500 – 2300; $Re(l_s/h)^{-1.5}$ range: 550 - 2650 - KC range: 25 – 110; $KC(l_s/h)^{-1.5}$ range: 30 - 130
Hu et al. (2014)	Lab	Saltmarshes, Mangroves (stiff wooden rods)	$C_D = 1.04 + \left(\frac{730}{Re}\right)^{1.37}$	- Drag coefficient for wave and current conditions - Re: Reynolds number considering vegetation diameter and maximum velocity that is spatially averaged waves velocity for wave conditions and spatially averaged velocity field for waves and current conditions. - Re range: 300 - 4700
Losada et al. (2016)	Lab	Saltmarshes (Spartina anglica and Puccinellia maritima)	$C_D = 0.08 + \left(\frac{50000}{Re^D}\right)^{2.2}$ Regular waves $C_D = 0.25 + \left(\frac{75000}{Re^D_{wc}}\right)^{9}$ Regular waves + current $C_D = 0.50 + \left(\frac{50000}{Re^D_{wc}}\right)^{9}$ Regular waves – current $C_D = 0.08 + \left(\frac{22000}{Re^D}\right)^{2.2}$ Irregular waves $C_D = 0.25 + \left(\frac{35000}{Re^D_{wc}}\right)^{9}$ Irregular waves + current $C_D = 0.50 + \left(\frac{27000}{Re^D_{wc}}\right)^{9}$ Irregular waves - current	- Drag coefficient for wave and current conditions considering regular and irregular waves. - Re^D; Re^D_{wc}: Reynolds number obtained considering the deflected vegetation length and maximum velocity at the beginning of the vegetation field for wave conditions and waves and current conditions respectively. - Re^D range: 50000 – 145000 (regular waves); 2000 – 55000 (irregular waves) - Re^D_{wc} range: 135000 – 200000 (regular waves); 2500 – 55000 (irregular waves)

1 Disipación de energía

2 Coeficiente de arrastre

3 **Nuevas aproximaciones**

Nuevas aproximaciones

COHESION 30

Problem

- The characterization of a vegetated ecosystem by measuring leaf traits, biomechanical properties and the number of individuals involves a lot of effort and is case-specific. C_D is unknown for many cases.

Objective

- Find a parameter easy to be quantified that allows estimating the coastal protection service provided by different ecosystems. **Submerged Solid Volume Fraction** and **Standing Biomass** are explored.

Benefits

- A new relationship that allows quantifying the coastal protection service provided by different species, avoiding the use of parameters that need to be calibrated.

Nuevas aproximaciones

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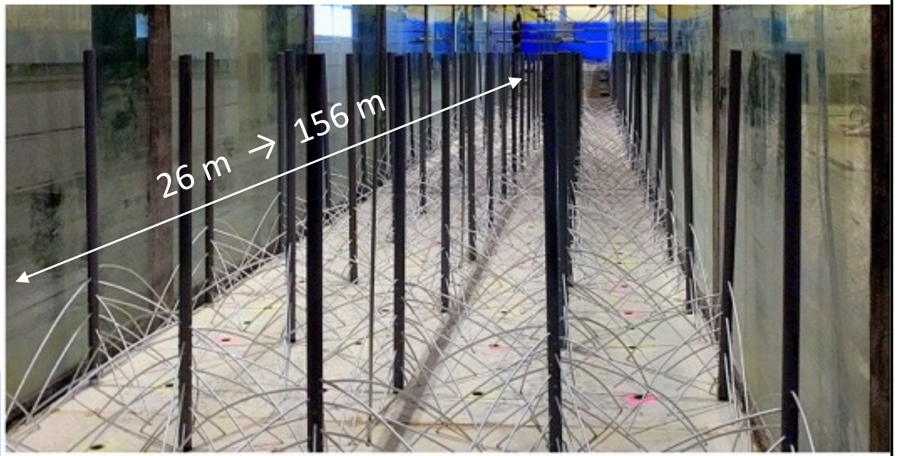
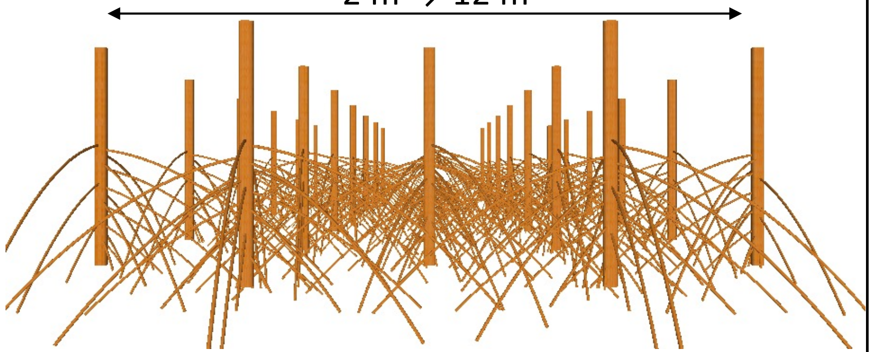
- Wave-Current-Tsunami Flume (COCOTSU)

Rhizophora mature tree





Nuevas aproximaciones

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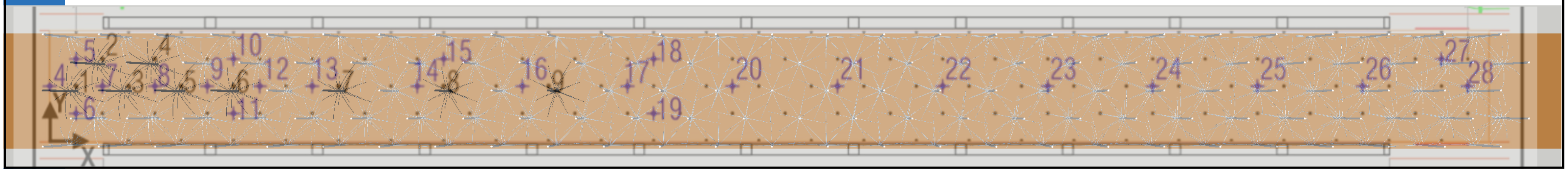
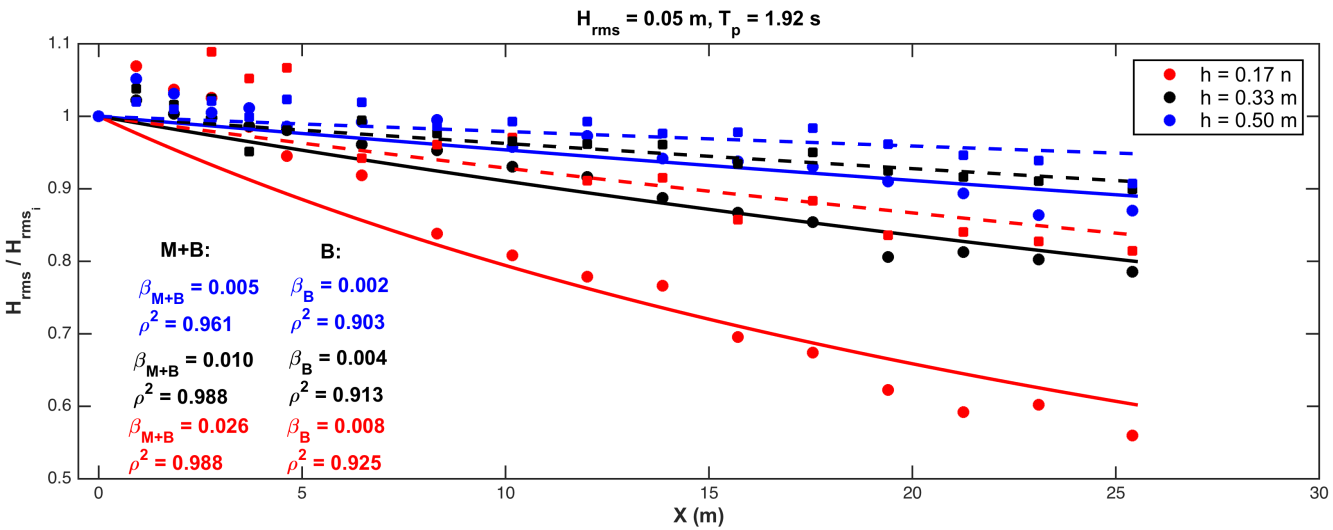
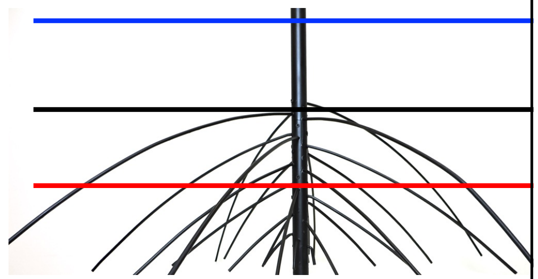


Nuevas aproximaciones

Nuevas aproximaciones

- Wave damping: $$\frac{H_{rms}}{H_{rms,i}} = \frac{1}{1+\beta X}$$





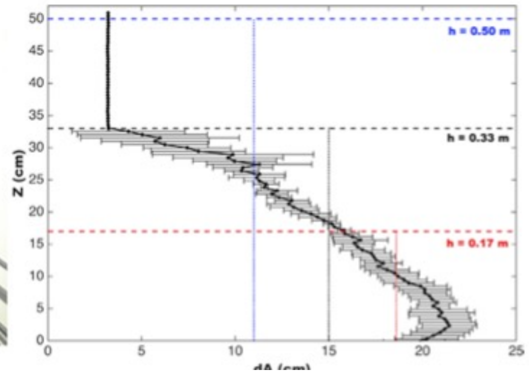
Solid lines: wave height attenuation for the flume full of mangroves

Dashed lines: wave height attenuation for the empty flume cases

R & D + i for sustainable development

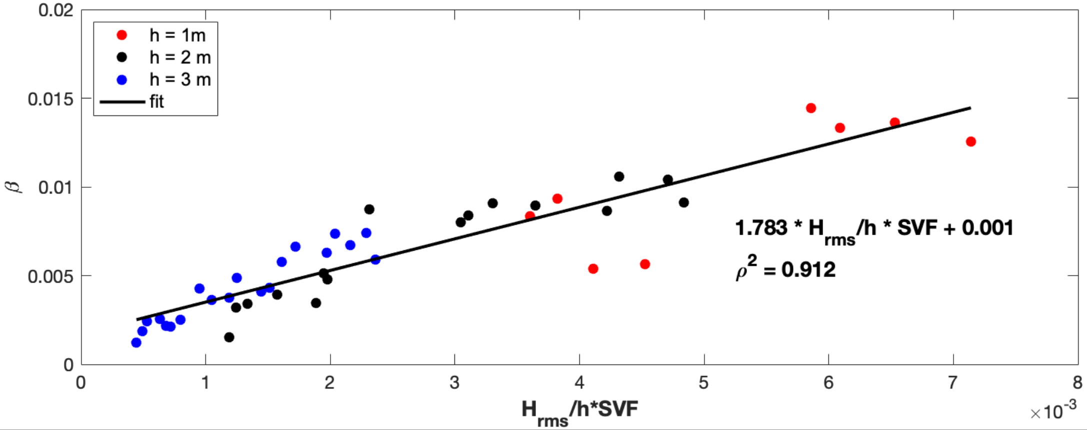
Nuevas aproximaciones

- Submerged solid volumen fraction (SVF)



$$SVF = \frac{\text{Solid Volume}}{\text{Water Volume}} = \frac{h * \frac{\pi * d^{*2}}{4} * N}{A_h * h}$$

$$\beta = 1.783 \frac{H_{rms}}{h} SVF$$



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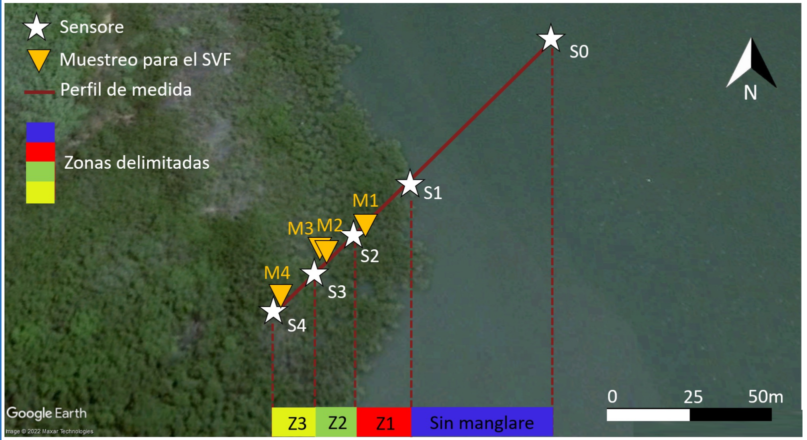
Experimental analysis of wave attenuation and drag forces in a realistic fringe *Rhizophora* mangrove forest

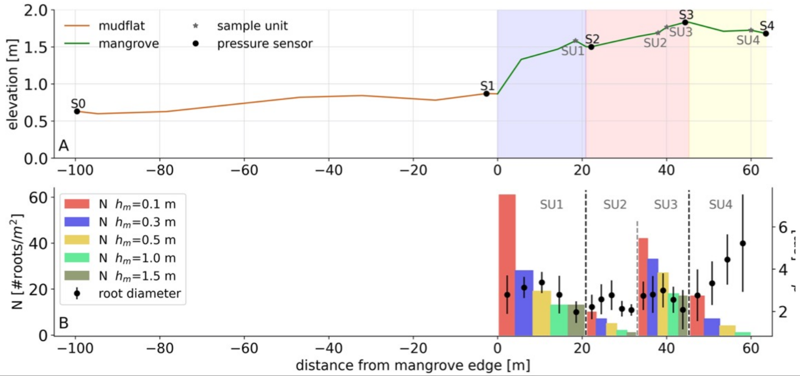
Maria Maza*, Javier L. Lara, Iñigo J. Losada

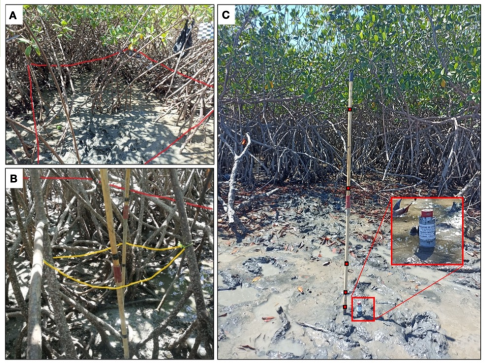
Environmental Hydraulics Institute (IHCantabria), Universidad de Cantabria, Isabel Torres 15, 39011 Santander, Spain

Nuevas aproximaciones

- Numerical tool







frontiers | Frontiers in Marine Science

Integrated drag coefficient formula for estimating the wave attenuation capacity of *Rhizophora* sp. mangrove forests

Fernando Lopez-Arias[1,2], Maria Maza[1*], Felipe Calleja[2], Georges Govaere[2] and Javier L. Lara[1]

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Nuevas aproximaciones

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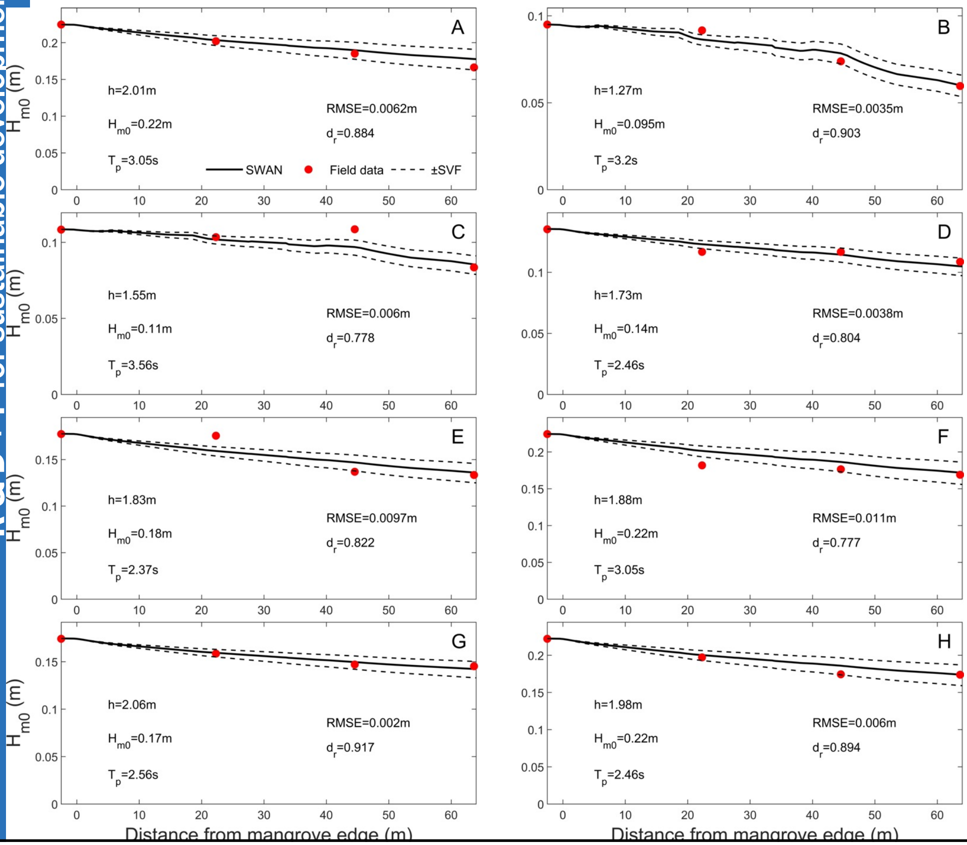
Numerical tool

- Implementación en el modelo SWAN de la nueva formulación:



$$S_{ds,veg} = -\sqrt{\frac{2}{\pi}}g^2\,\tilde{C}_D\,b_v\,N\left(\frac{\tilde{k}}{\tilde{\sigma}}\right)^3\frac{\sinh^3\tilde{k}h_v + 3\sinh\tilde{k}h_v}{3\,\tilde{k}\cosh^3\tilde{k}h}\sqrt{E_{tot}}\,E(\sigma,\theta)$$

$$S_{ds,veg} = -\frac{3\sqrt{2}g^2}{\tilde{k}\sqrt{8E_{tot}}}\left(\frac{\tilde{k}}{\tilde{\sigma}}\right)^3\frac{\left(\sinh 2\tilde{k}h + 2\tilde{k}h\right)\sinh\tilde{k}h}{3\tilde{k}\cosh^3\tilde{k}h}\left(A\cdot SVF\cdot\frac{\sqrt{8E_{tot}}}{h} + B\right)\sqrt{E_{tot}}E(\sigma,\theta) \quad (4.3)$$

Modeling wave height attenuation by mangroves in SWAN: a new approach without calibration parameters

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Nuevas aproximaciones

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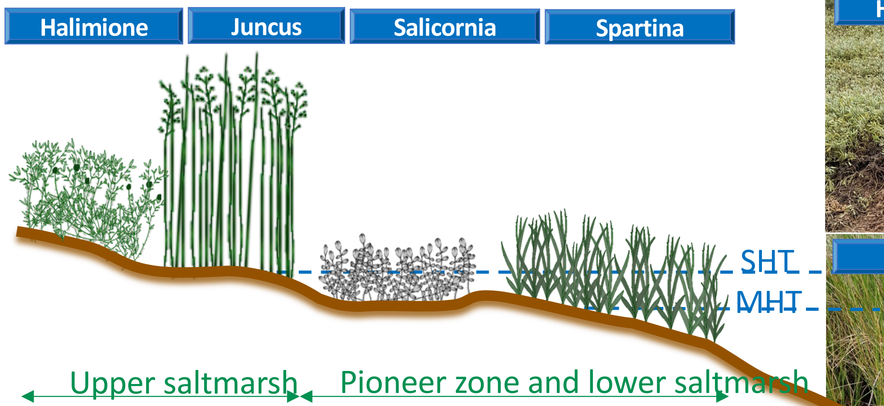
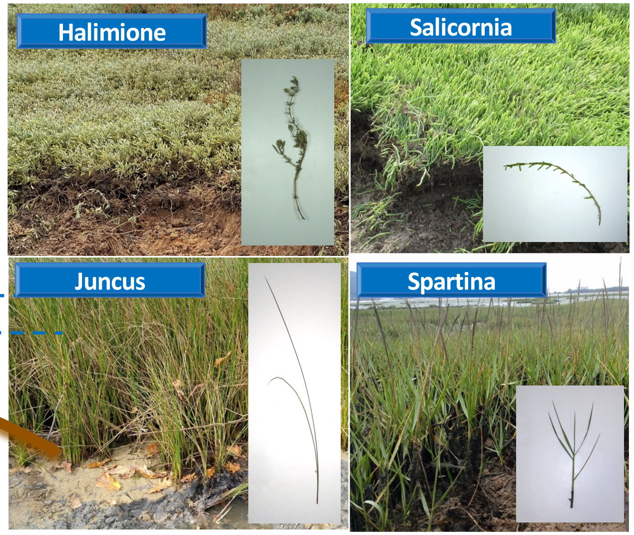
Vegetation species selection → Field campaign → Experimental set-up → Results





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Nuevas aproximaciones

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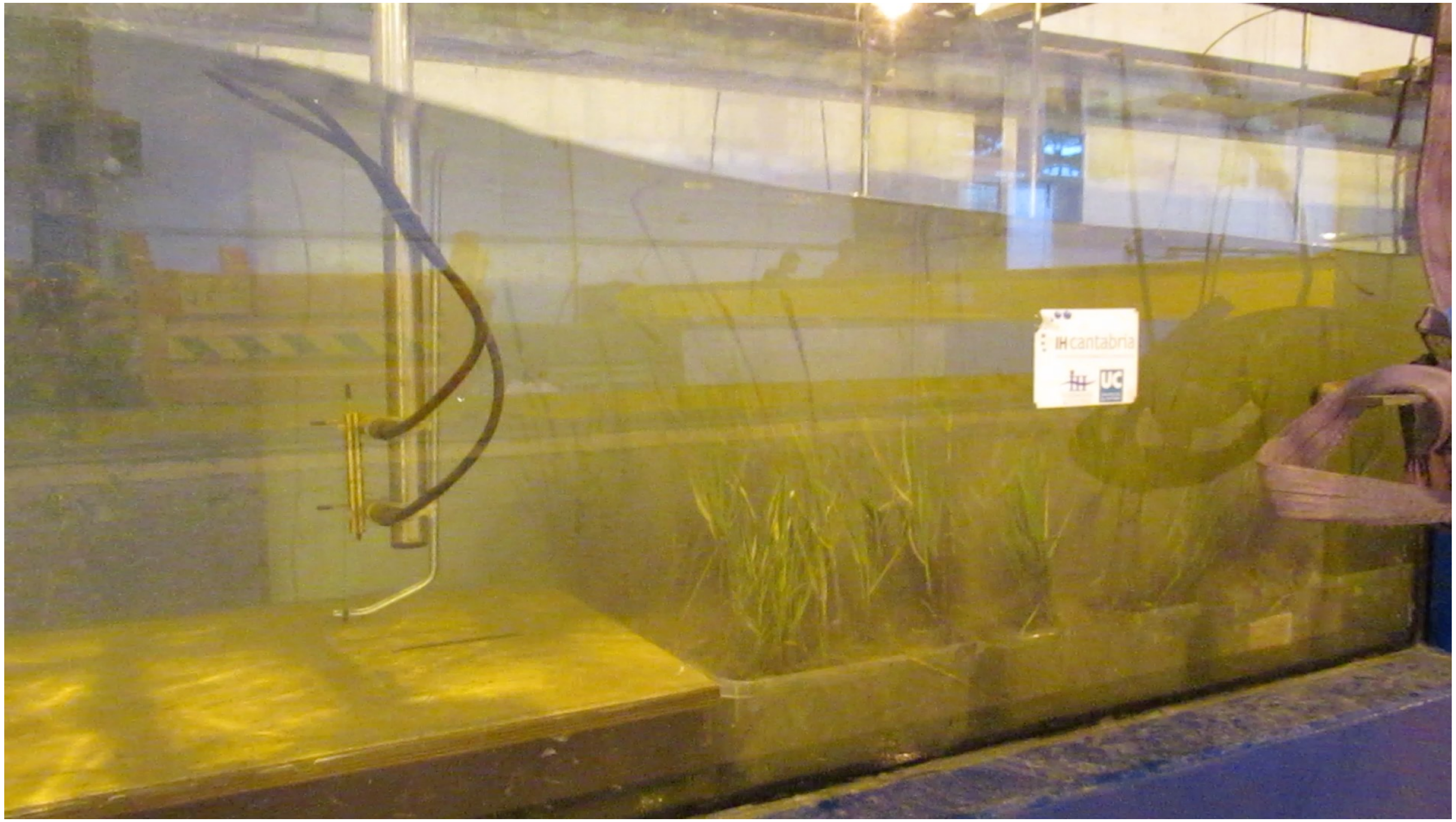
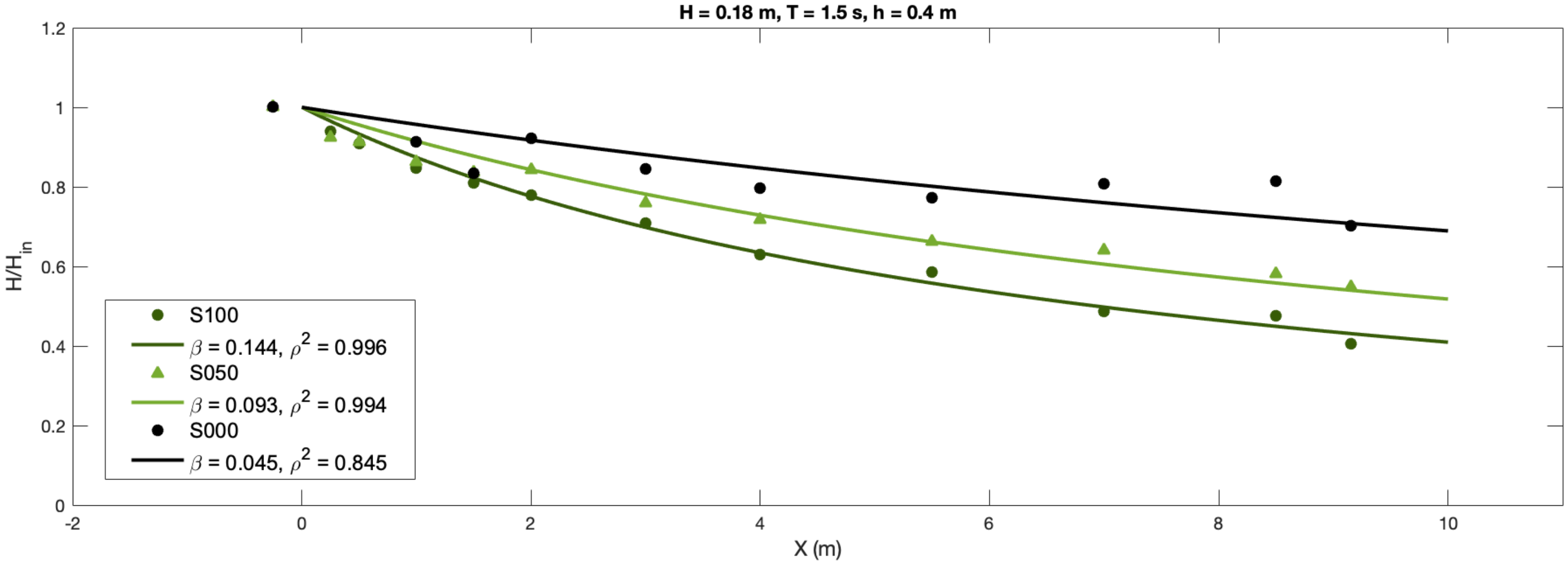
Nuevas aproximaciones



Nuevas aproximaciones

$$\frac{H}{H_i} = \frac{1}{1 + \beta X}$$



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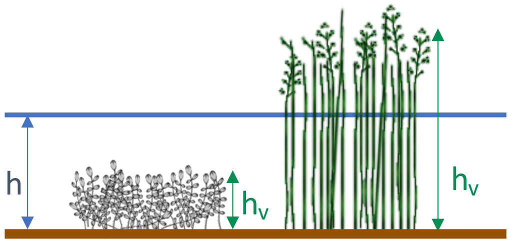
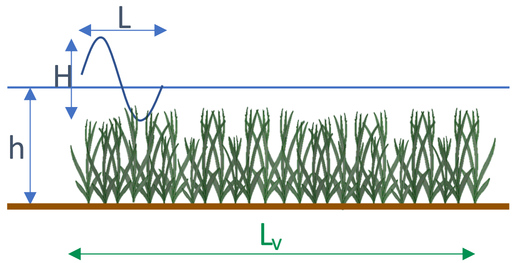
Nuevas aproximaciones



$$Effective\ Standing\ Biomass = \frac{Dry\ Weight}{h_v} * min\{h_v, h\} * SR$$

$$SR = \frac{h_v}{h}, where\ SR = 1\ if\ h_v > h$$



$$\boldsymbol{Hydraulic\ Standing\ Biomass\ (HSB)} =$$
$$= VSB * L_v/L * H/h$$

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Nuevas aproximaciones

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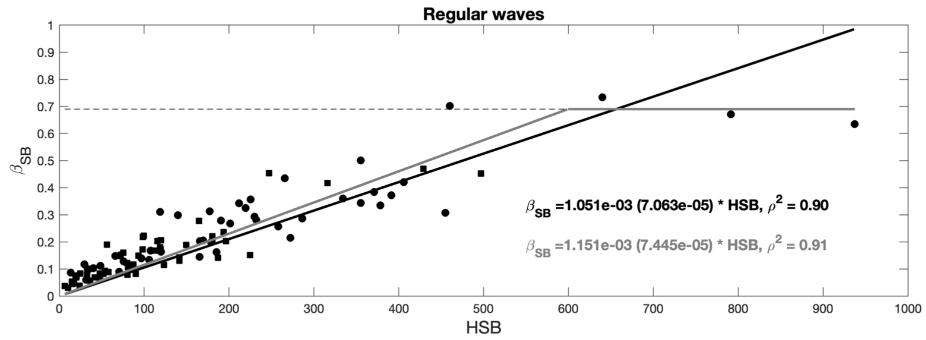

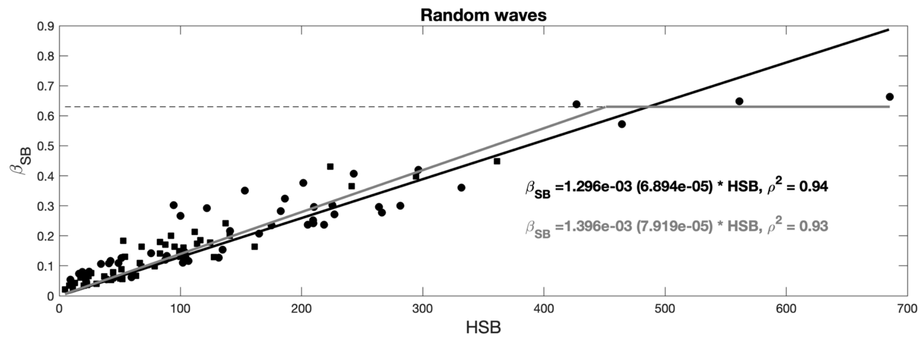

scientific reports

OPEN **A paradigm shift in the quantification of wave energy attenuation due to saltmarshes based on their standing biomass**

Maria Maza, Javier L. Lara & Iñigo J. Losada

$$\beta = f(Hydraulic\ Standing\ Biomass)$$

From **C_D calibration** to the use of the **standing biomass** of the ecosystem

Common linear relationship for 96 cases including 4 species, 2 meadow densities, 12 wave conditions.

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Nuevas aproximaciones

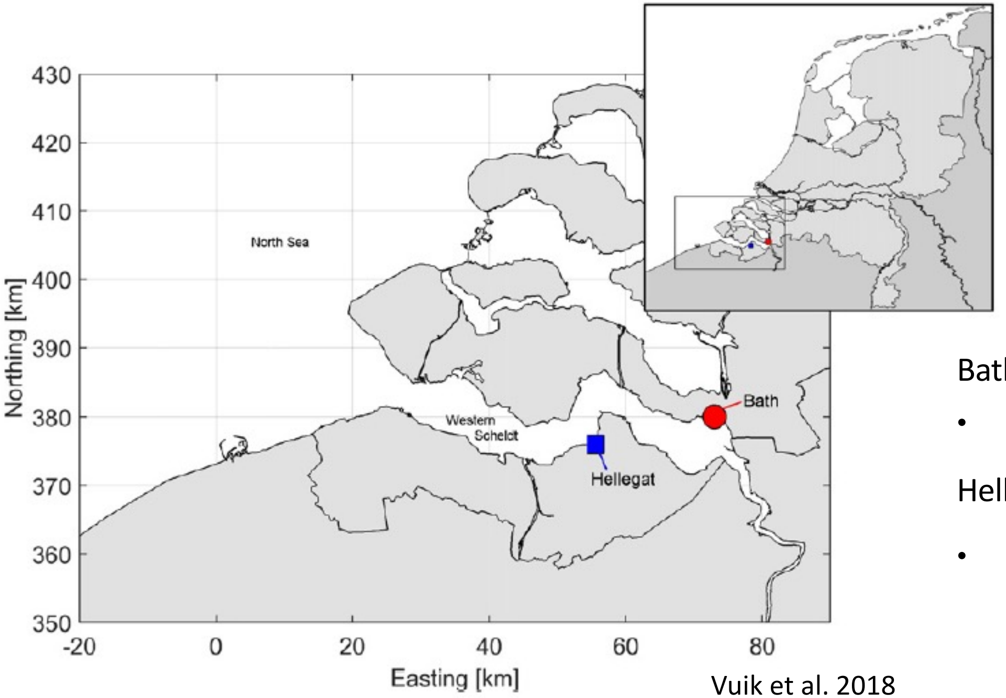
Empirical formulation → Numerical Tool

- Implementación en el modelo SWAN de la nueva formulación:

$$S_{ds,veg} = -\sqrt{\frac{2}{\pi}} g^2 \, \underline{\widetilde{C}_D \, b_v \, N} \left(\frac{\widetilde{k}}{\widetilde{\sigma}}\right)^3 \frac{\sinh^3 \widetilde{k} h_v + 3 \sinh \widetilde{k} h_v}{3 \, \widetilde{k} \cosh^3 \widetilde{k} h} \sqrt{E_{tot}} \, E(\sigma, \theta)$$

$$S_{ds,veg} = -\frac{3\sqrt{2} g^2}{\tilde{k}\sqrt{8E_{tot}}} \left(\frac{\tilde{k}}{\tilde{\sigma}}\right)^3 \frac{\left(\sinh 2\tilde{k}h + 2\tilde{k}h\right) \sinh \tilde{k}h}{3\tilde{k} \cosh^3 \tilde{k}h} \underline{(A \cdot HSB + B)} \sqrt{E_{tot}} E(\sigma, \theta)$$

- Validación de la herramienta: Scheldt estuary



Vuik et al. 2018

Fig. 3. Location of the salt marshes Hellegat and Bath in the Western Scheldt estuary, the Netherlands.

Scirpus maritimus

Spartina anglica

Bath:

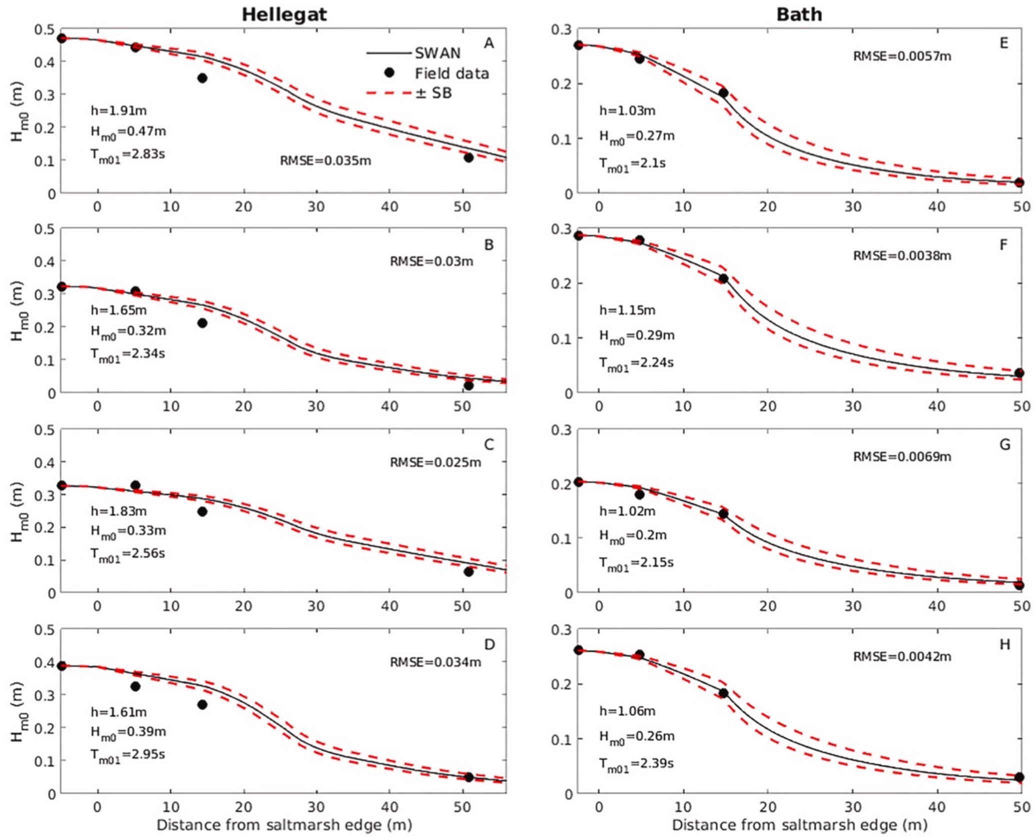
- $$biomasa\ (g/m^2) = \begin{cases} 228, & 0m - 5m \\ 609, & 5m - 15m \\ 1778, & > 15m \end{cases}$$

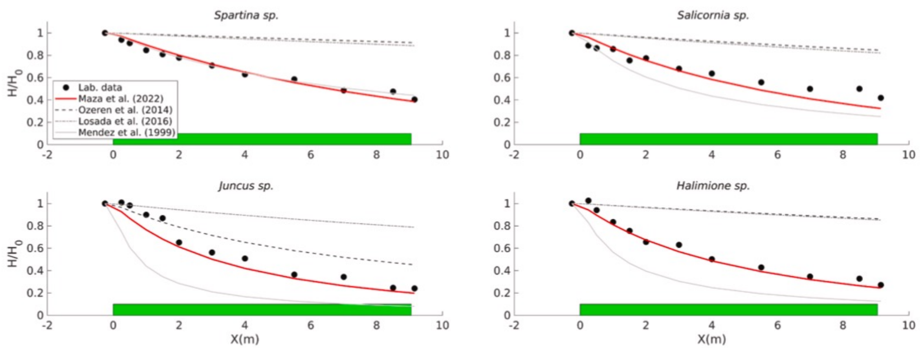
Hellegat:

- $$biomasa\ (g/m^2) = \begin{cases} 1102, & 0 - 15m \\ 1650, & > 15m \end{cases}$$

Heuner et al. (2015) and Schulze et al. (2019)

Nuevas aproximaciones





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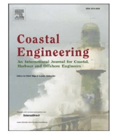

A new predictive tool for modeling wave attenuation produced by saltmarshes in SWAN based on standing biomass

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¡GRACIAS POR SU ATENCIÓN!
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