MODELLING WAVE ATTENUATION DUE TO SALT MARSH VEGETATION USING A MODIFIED SWAN MODEL

Elizabeth K Christie[1], Iris Möller[1], Tom Spencer [1], Marissa Yates[2]

Vegetated shorelines have been increasingly recognized for their contribution to natural coastal protection due to their ability to dissipate wave energy. Within the UK, salt marshes are beginning to be included in flood defence schemes. Predicting wave dissipation over vegetation requires accurate representation of salt marsh canopies and the feedback relationship between vegetation and wave conditions. We present a modification to the SWAN vegetation model, which includes a variable drag coefficient and a spatially varying vegetation height. Its application is demonstrated by modelling wave propagation over UK salt marshes. The third generation wave model, SWAN includes a vegetation module for calculation of wave attenuation over vegetation. Wave dissipation is determined based on the vegetation properties and a drag coefficient. This drag coefficient, C_D, is used to calibrate the model, and a fixed value is used per model run. Empirically the drag coefficient has been found to vary with ambient wave conditions. Typically the drag coefficients are defined empirically as a function of either the stem Reynolds number, Re_v, or the Keulegan-Carpenter number, K_C. The parameter values have been shown to vary with vegetation type. In this paper, we modify the SWAN vegetation module to include a temporally varying C_D. This allows the drag coefficient to vary with ambient wave parameters, which gives an improved prediction under time varying wave conditions (e.g. passage of a storm) and includes the change in wave conditions as they travel through the vegetation. We also incorporate spatially varying vegetation height into the model to further improve the representation of the complexity of vegetated shorelines. Using the new formulation we find improved prediction of wave dissipation over both idealized laboratory and field salt marsh vegetation.

Keywords: salt marsh; vegetation; wave dissipation; SWAN; wave modelling

INTRODUCTION

Recent years have seen the increasing recognition of wave dissipation by vegetation in aquatic and coastal environments. This realization stems from growing field evidence of wave attenuation, both in salt marshes (Möller et al., 1999, 2001) and other types of vegetation (Kobayashi et al., 1993; Méndez et al., 1999; Paul and Amos, 2011; Bouma et al., 2014). The ability of vegetation particularly salt marsh to dissipate waves provides an important coastal protection function during storms. It has widely been argued that the restoration of new coastal wetlands can, alongside existing coastal defences, increase coastal resilience to climate change (Temmerman et al., 2013; Spalding et al., 2014). For incorporation into coastal management and planning, the prediction of wave dissipation due to vegetated wetlands must be rigorously studied under a range of conditions to ensure accurate prediction of the impacts of the vegetation.

Wave dissipation due to coastal wetland vegetation is typically calculated based on the Morison equation, which assumes that the vegetation can be represented as a cylinder. The Morison equation describes the force of a wave on a cylinder to calculate the energy dissipation due to the cylinder. This equation has been adapted for use in vegetated wetlands by Dalrymple et al. (1984) and Mendez and Losada (2004), where the energy dissipation is calculated based on the properties of the plants including the plant height, plant diameter, number of plants and a drag coefficient. The drag coefficient, C_D, is a simple method for parameterizing the approximations and physical processes not explicitly calculated.

Predicting the wave dissipation due to vegetation relies on accurate representation of marsh vegetation canopies within existing shallow water wave models. One of the difficulties in doing so arises from the complex nature of these vegetation canopies. Salt marsh vegetation often consists of mixed plant canopies with a mosaic of plant assemblages controlled by surface elevation and the related parameters of inundation frequency/duration (hydroperiod) and salinity gradients. In addition, canopies are often characterized by vegetation clumps forming spatially varied (on scales of metres) canopy characteristics, and are occupied, at least in the higher elevation zones of more mature marshes by often complex (woody/shrubby) vegetation types (such as *Atriplex spp*). Existing studies have shown that submergence ratio, i.e. the ratio between water depth and plant height, is critical in determining wave dissipation over salt marshes (Mendez and Losada, 2004; Möller et al., 2001). Vegetation height is thus a critical parameter.

[1]Department of Geography, University of Cambridge, UK
[2]Laboratoire d'Hydraulique Saint-Venant, Cerema, France

The drag coefficient is typically given a fixed value and used to calibrate models of waves across coastal wetlands, and is dependent on the plant species. However, empirically the drag coefficient has been shown to vary with the ambient wave conditions (Kobayashi et al., 1993; Méndez et al., 1999; Mendez and Losada, 2004; Möller et al., 2014). The empirical drag coefficient for various types of vegetation has been shown to vary with the vegetation Reynolds number (Re_v) and the Keulegan-Carpenter number (K_c), defined as:

$$Re_v = U_m \left(\frac{D_v}{\nu} \right) \tag{1}$$

where D_v is the vegetation diameter and ν is the kinematic viscosity defined as $\left(\nu = 1 \times 10^{-6} m^2 s^{-1} \right)$

$$K_C = \frac{U_m T}{D_v} \tag{2}$$

where T is the wave period. Figure 1 presents empirical relationships found for different vegetation types between the drag coefficient and Re_v and K_C. Kobayashi et al. (1993), Méndez et al. (1999), and Paul and Amos (2011) found an empirical relationship between the drag coefficient and the Re_v number for kelp, seaweed, and seagrass, respectively. Mendez and Losada (2004) and Jadhav et al. (2013) determined an empirical relationship between the drag coefficient and K_C number for kelp and salt marsh, respectively. Augustin et al. (2009) compared empirical relationships between Re_v and K_C over a salt marsh, finding that the drag coefficient showed greater correlation with the Re_v number under emergent conditions, whilst under near-emergent conditions the drag coefficient had a better correlation with K_C. Bradley and Houser (2009) found the drag coefficient is better described by the Re_v in low energy conditions for seagrass. Whilst Sánchez-González et al. (2011) showed the drag coefficient correlates closer to K_C than Re_v over a seagrass meadow.

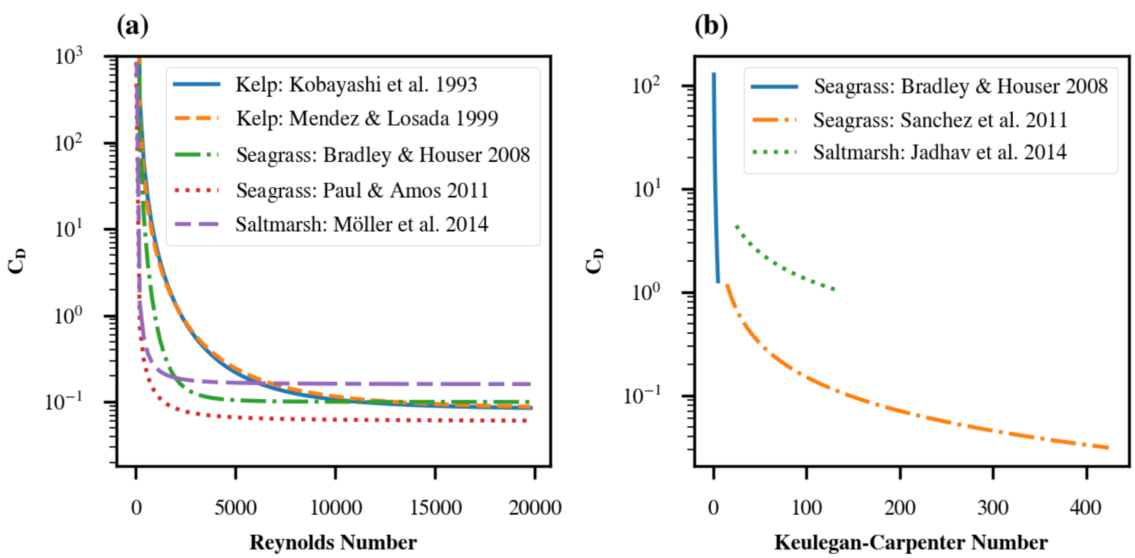

Figure 1: Relationship between C_D and a) vegetation Reynolds number (Re_v) and b) the Keulegan-Carpenter number (K_C) for empirical studies of wave dissipation over a range of vegetation types.

In this paper we improve the calculation of wave dissipation over vegetated wetlands by introducing a temporally varying drag coefficient. Additionally, we extend the representation of coastal wetlands in the SWAN wave model by introducing a spatially varying vegetation height.

METHODOLOGY

Current SWAN Vegetation module

SWAN is a third generation wave model (Booij et al., 1999) based on the wave action balance equation and includes source and sink terms for energy generation, dissipation and non-linear interactions. The dissipation due to vegetation, $S_{ds,veg}$, is calculated within a vegetation module, SWAN-Veg. The current formulation for vegetation dissipation (Suzuki et al., 2012) uses a modified version of the Dalrymple et al. (1984) wave dissipation formula by Mendez and Losada (2004).

Mendez and Losada (2004) determined the energy dissipation based on the properties of the vegetation. The vegetation characteristics include plant height (H_v), plant diameter (D_v), number of plants per m^2 (N_v) and the drag coefficient (C_D). The mean rate of energy dissipation due to vegetation per unit horizontal area (Mendez and Losada, 2004) is expressed as:

$$\langle \epsilon \rangle = \frac{1}{2\sqrt{\Pi}} \rho C_D D_v N_v \left(\frac{gk}{2\sigma} \right)^3 \frac{\sinh^3 kH_v + 3 \sinh kH_v}{3k \cosh^3 kh} H_{rms}^3 \tag{3}$$

where ρ is the water density, C_D is the drag coefficient, k is the mean wave number, σ is the mean wave frequency, h is the water depth, and H_{rms} is the root mean square wave height. As such the drag coefficient is commonly used to calibrate the wave model.

The SWAN vegetation module can differentiate between emergent and submergent vegetation, if emergent the height of the plant is specified as the water depth. The vegetation characteristics can be varied vertically, by dividing the vegetation into layers and specifying different vegetation characteristics for each layer. This allows the module to be used for vegetation which varies significantly with height, such as mangrove trees. In this case the energy dissipation for a layer i is defined. All the vegetation parameters (D_v, N_v and C_D) can be varied vertically. The vegetation density can be varied spatially, which allows the plant diameter to also vary spatially, however, the vegetation height is fixed spatially.

Modifications to the SWAN Vegetation Module

We modified the SWAN-Veg module to introduce a temporally varying C_D and a spatially varying H_v. This allows the vegetation height to be input as a grid over the model domain in an ascii format. We extended the wave dissipation to include a new formulation where the drag coefficient is calculated internally based on the vegetation Reynolds number (Eq.1), instead of the fixed user input parameter. This formulation requires knowledge of the relationship between $C_D \sim Re_v$, which, as shown earlier, is dependent on the vegetation properties and will vary by vegetation type. The relationship between the drag coefficient and Reynolds number is usually expressed (Kobayashi et al., 1993; Méndez et al., 1999; Bradley and Houser, 2009; Paul and Amos, 2011; Möller et al., 2014) in the form :

$$C_D = a + \left(\frac{b}{Re_v} \right)^c \tag{4}$$

where a, b, and c are empirically derived constants, which, are user defined in the SWAN steering file.

We use the empirical work of Möller et al. (2014) to define the $C_D \sim Re_v$ relationship for a typical North West European salt marsh. Möller et al. (2014) used the Hydralab Large Wave Flume, GWK Hannover, to observe waves over a $\sim$ 40 m long test section of transplanted salt marsh in a 300 m long, 5 m wide flume under 2 m water depth. They found a relationship between C_D & Re_v for irregular waves with:

$$C_D = 0.159 + \left(\frac{227.3}{Re_v} \right)^{1.615} \tag{5}$$

This equation is based on the Re_v at the front of the marsh section. For inclusion in the new module in SWAN, the calculation of vegetation Reynolds must be completed at each grid cell, therefore, the $C_D \sim Re_v$ calculation needs to take into account the change in Re_v over the salt marsh surface. We instead modify the relationship of Möller et al. (2014) and calculate the drag coefficient based on the median vegetation Reynolds number (i.e. $((Re_{v,0} - Re_{v,n})/2) + Re_{v,n}$), where 0 indicates the front of the marsh section and n is the end of the transect). Using the large wave flume data we calculated the new relationship as:

$$C_D = 0.174 + \left(\frac{170.489}{Re_{v,med}} \right)^{1.922} \tag{6}$$

Figure 2 presents the relationship between C_D and Re_v using data from the flume study showing the relationship for the $Re_{v,0}$ calculated by Möller et al. (2014) (Figure 2a) and the relationship for the median vegetation Reynolds number $Re_{v,med}$ (Figure 2b). The fit to the data is good, with r^2 = 0.99 for both cases.

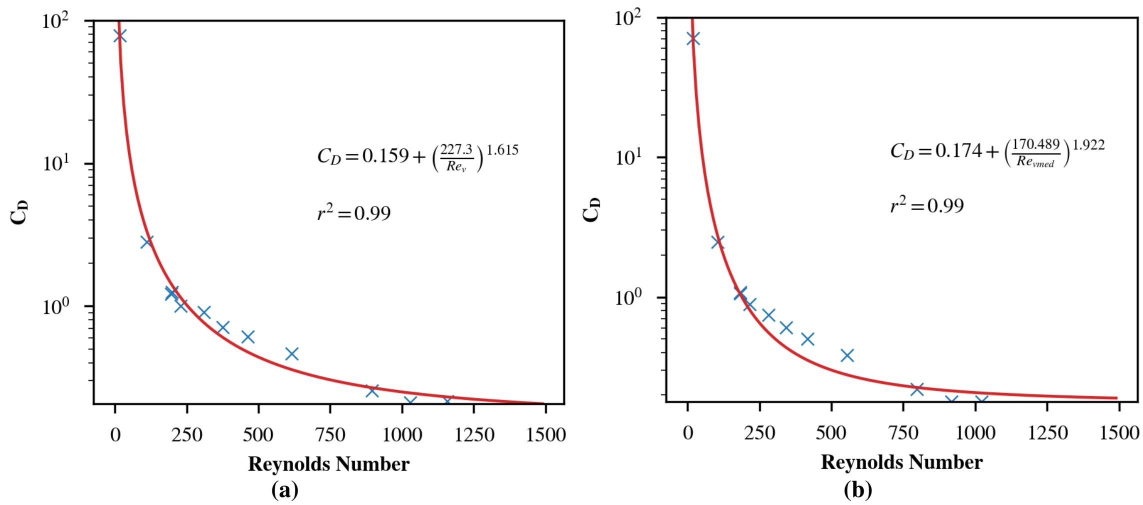

Figure 2: Relationship between C_D and a) Re_v calculated from the maximum wave orbital velocity at the front the salt marsh transect of Möller et al. (2014), and b) the $Re_{v,med}$ calculated from the median maximum wave orbital velocity.

MODEL VALIDATION AND RESULTS

Validation: Wave Flume Data

We validated the new SWAN-Veg module using the empirical data of Möller et al. (2014). The SWAN model was run in 1D mode with waves from a JONSWAP spectrum, wave setup and wave breaking were included with default parameters. The model input conditions were calibrated to reproduce the wave conditions at the initial wave gauge. The model was run for both the fixed drag coefficient, with C_D calculated for each test condition determined by Eq. 5, and for the temporally varying drag coefficient using the relationship between C_D and Re_v determined by Eq. 6. The vegetation used in the experiment is typical of upper intertidal zone North West European salt marsh, consisting of *Elymus athericus*, *Puccinellia maritima*, and *Atriplex prostrata*. The relevant plant characteristics, as mean values for the marsh section were, D_v = 0.00125 m, H_v = 0.7 m, N_v = 1225. The model was run for 11 wave conditions, with a water depth of 2 m and irregular waves with H_s = 0.111-0.909 m and T_p = 1.44-6.26 s.

The measured and predicted significant wave height reduction for the different wave conditions are presented in Figure 3. The measured experimental values show the significant wave height reduction increases with increasing initial wave height. The wave height reduction predicted by the original SWAN-Veg module, with a fixed C_D, shows a good fit to the measured data at low initial wave heights ($\leqslant$ 0.3 m), but underestimates the wave dissipation over the higher initial wave heights. Whereas the new SWAN-Veg module, with varying C_D, overestimates the wave dissipation for the small values of $H_{s,0}$ ($\leqslant$ 0.3 m), and agrees well with the measured data for the high initial significant wave heights representing storm waves. Overall, RMSE errors are 0.027 m, and 0.022 m for the fixed and temporally varying C_D, respectively, giving a slightly better fit with the new formulation.

Validation: Field Data

We validated the new SWAN-Veg formulation using the wave dissipation field measurements of Möller et al. (1999), providing a dataset for a natural salt marsh setting. Möller et al. (1999) measured the wave conditions at the seaward margin and at the end of a 197 m salt marsh transect at Stiffkey, North Norfolk, UK. Along the transect the marsh surface is characterised by the halophytes *Limonium vulgare*, *Aster tripolium*, *Atriplex portulacoides*, *Salicornia spp.* and *Spartina spp.* At the landward end the same species occur alongside *Suaeda maritima*, *Plantago maritima* and *Puccinellia maritima*.

Only experimental data with onshore winds within 45° of the transect orientation were used for the validation test; wind conditions were taken from the Weybourne station, 12 km east of the study site (BADC MIDAS wind database). A spatially invariant vegetation height was used, derived from side-on photography

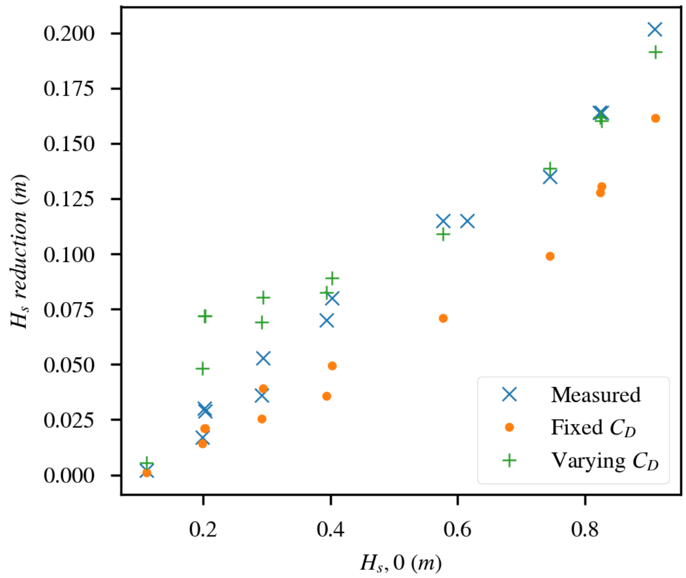

Figure 3: Observed and modelled wave height reduction over a 40 m long section of transplanted salt marsh in a 300 m wave flume (Möller et al., 2014). Modelled data compares calculation of wave dissipation using a fixed C_D and temporally varying C_D.

Run	Water Depth (m)	Significant wave height (m)	Peak Period (s)	Mean wind direction (°)	Mean wind speed (ms^{-1})
1	0.77	0.29	6.83	60	15
2	0.76	0.28	5.39	60	15
3	0.74	0.27	1.86	60	15
4	0.96	0.30	2.73	90	14
5	0.98	0.45	2.73	80	22
6	1.19	0.52	4.18	70	25

Table 1: Experimental conditions of wave dissipation measurements over a salt marsh transect at Stiffkey, North Norfolk, UK (Möller et al., 1999)

of the canopy (Möller et al., 1999), where $H_v = 0.11$ m. Plant diameter was assumed to be $D_v = 0.00125$ m (representative of North West European salt marsh (Möller et al., 2014)) and plant density, $N_v = 1061$ stems/m^2 (similar to marsh vegetation at Tillingham, Essex, UK (Möller, 2006)).

We set the 1D transect up with an elevational slope of 0.00196. The model was forced with 6 individual wave bursts (using a JONSWAP spectrum) with a fixed water depth. The model conditions are presented in Table 1 and cover water depths ranging from $h = 0.74-1.19$ m, significant wave heights of $H_s = 0.27-0.52$ m, and peak periods of $T_p = 1.86-6.83$ s. The measured significant wave height reduction is compared with the predicted wave height reduction by the new SWAN-Veg module in Figure 4. The field observations for these 6 wave bursts suggest that the wave height reduction is fairly constant over the range of initial wave heights, this pattern is also shown in the modelled results. The predicted wave height reduction by the new SWAN-Veg model shows a very good agreement with the measured results ($RMSE = 0.0274$ m), the agreement is best under the larger waves.

Sensitivity Testing

We ran a series of sensitivity tests to investigate the impact of the new SWAN-Veg formulations on the modelled wave dissipation over vegetation. All sensitivity tests were run using a hypothetical salt marsh wave flume experiment, we used a 1-D transect, with an initial water depth of 1 m. Wave setup and wave breaking were included, using default parameters, and bottom friction was included using the Collins

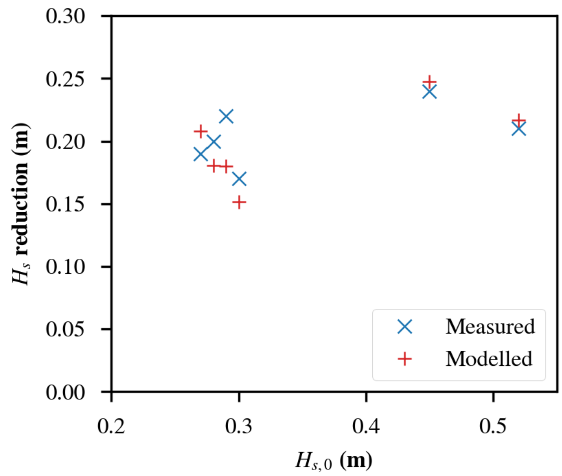

Figure 4: Observed and modelled wave height reduction over a 197 m long section of salt marsh at Stiffkey, North Norfolk, UK (Möller et al., 1999)

formula (friction coefficient = 0.015). In all cases wave conditions were input as parameters and calculated using the JONSWAP spectrum.

A synthetic storm event is used to test the temporally varying C_D over a 200 m salt marsh transect. A 28 hr synthetic storm event was generated with water level range of 1.80 – 4.0 m and maximum significant wave height of 2.77 m . The vegetation parameters were defined as H_v = 0.4 m, D_v = 0.00125 m and N_v = 1061 stems/m^2, giving vegetation parameters typical of UK East coast salt marshes in and around the Tillingham, Essex marsh location.

The synthetic storm conditions are presented in Figure 5a. The timeseries of normalised wave height reduction for both a fixed C_D, calculated using the maximum wave orbital velocity during the storm, and the new temporally varying C_D are presented in Figure 5b. At the peak wave heights the normalised wave height reduction is the same for both the fixed and temporally varying C_D, for all other wave conditions the fixed C_D predicts a lower wave height dissipation than the temporally varying C_D.

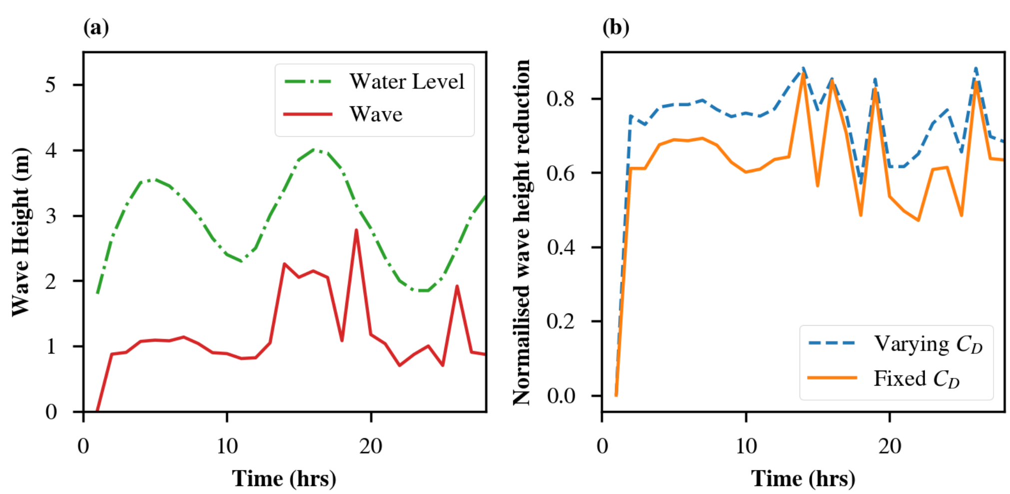

Figure 5: Modified SWAN-Veg formulation sensitivity testing for a storm event on a 100 **m section of salt marsh. a) Storm water level and significant wave height, b) normalised wave height reduction for a fixed** C_D **and a temporally varying** C_D

Sensitivity to the spatially varying vegetation height was tested across four 100 m salt marsh transects with different vegetation patterns in hypothetical wave tank experiments. The model vegetation patterns are displayed in Figure 6 and include a constant plant height (6a), gradually increasing plant height (6b), a stepped plant height (low-high) (6c) and tufts of plants (6d). In all cases the mean vegetation height is $H_v = 0.25$ m, plant diameter is $D_v = 0.0045$ m, and plant density is $N_v = 1061$ stems/m^2. The model is forced with a significant wave height of $H_s = 0.5$ m and peak period of $T_p = 4$ s.

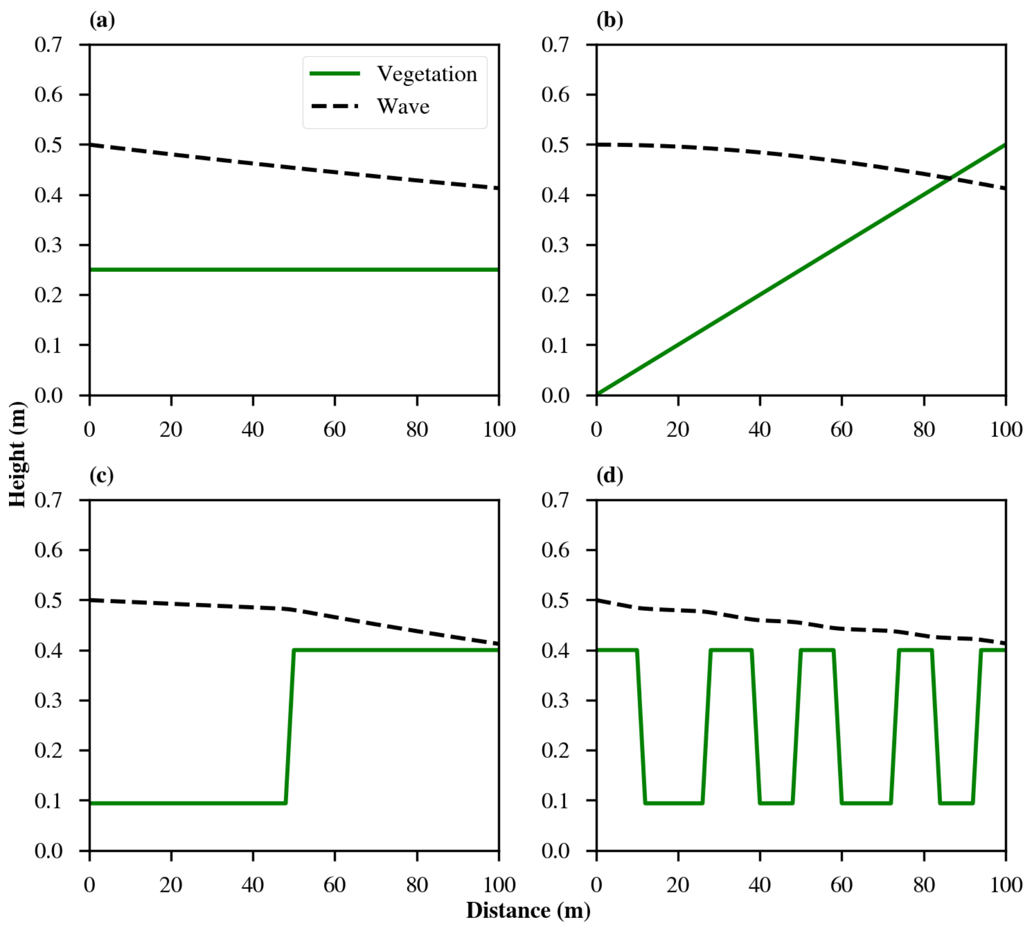

Figure 6: Modified SWAN-Veg formulation sensitivity testing for spatially varying vegetation height. Significant wave height variation over a) constant plant height, b) gradually increasing plant height, c) stepped plant height, d) tufted plants.

As shown in Figure 6, the spatially varying plant height does not influence the wave height reduction seen at the end of the 100 m transect. However, the significant wave height is clearly reduced at a faster rate as the wave travels over larger plants generating differences in the spatial pattern of wave height over the 100 m distance between the four cases.

DISCUSSION AND CONCLUSIONS

In this paper we present modifications to the SWAN-Veg module to better incorporate the complex hydrodynamics and varied vegetation structure across coastal vegetated wetlands. Firstly, the spatially varying vegetation height was added to the SWAN-Veg module. The sensitivity of wave dissipation over a 100 m long salt marsh was tested under a range of different vegetation structures. Whilst the different heights do not impact the final wave height over a transect they do impact at other points over the marsh. The spatially varying vegetation is difficult to validate as there are limited studies that have measured the required vegetation characteristics, due to labour intensive techniques required for this in the field. Current advances in sensors mounted on unmanned aerial vehicles (UAVs) and in methods for extracting vegetation community type information from remotely sensed imagery, however, may offer ways to acquire such information with greater ease in the future. Our new formulation will have the most impact in a 2D rather than a 1D case, and we plan future work to compare the results presented here to 2D empirical data of wave dissipation over vegetation.

Secondly, the module was extended to include a temporally varying drag coefficient, which, when used to compute wave dissipation has shown a good agreement with experimental data on salt marsh vegetation from a wave flume under simulated storm conditions and in the field. The new formulation has the advantage over the fixed C_D as the user does not have to either change the drag coefficient for each wave condition or use C_D as a calibration parameter to get the best fit of wave energy dissipation due to vegetation over all conditions. The new module can be used for modelling situations over longer periods of time where the wave conditions are likely to vary significantly, such as during storms. Additionally, it can be used for other types of vegetation using empirically derived constants from the literature.

The new wave dissipation calculation fit to empirical data was shown to be better for larger waves. This is due to two reasons i) the empirical data of Möller et al. (2014) used to derive the $C_D \sim Re_v$ relationship was acquired for simulated extreme storm events, therefore, includes predominantly large waves, and ii) the vegetation Reynolds numbers have a large range, and particularly high values at low wave heights. Therefore, the drag coefficient is particularly sensitive to small wave heights. To improve the formulation future work will test the model against further empirical data sets both in wave flumes and in the field. Additionally we will investigate the effect of including an additional SWAN-Veg formulation based on the relationship between $C_D \sim K_C$. For the prediction of the coastal protection function provided by salt marsh, however, we are mostly interested in wave dissipation under storm waves. The fact that the best model fit is achieved at higher water depths and for more energetic wave conditions thus makes our results highly relevant to the needs of coastal managers and engineers.

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