Dear Editor,

On behalf of my coauthors, I am pleased to resubmit the manuscript "Sensitivity Analysis of a Coupled Hydrodynamic-Vegetation Model Using the Effectively Subsampled Quadratures Method (ESQM v5.2)" to be considered for publication in Geophysical Model Development.

The manuscript provides an evaluation of a model to simulate 3D effects of submerged aquatic vegetation within a coupled hydrodynamics and wave model. Using a novel method to perform sensitivity analysis, we analyse the sensitivity of the vegetation model to provide guidance to optimizing efforts and reducing parameter space for future observational and modeling work. We think that the manuscript has the potential to be useful for the coastal modeling community in general and more specifically scientists trying to provide informed advice to coastal managers about the benefits of green infrastructure in reducing the impacts of large storms in coastal environments.

Following the publishing process at USGS, the discussion paper was internally reviewed by a USGS scientist. After the suggestions of the internal reviewer and external reviewers were incorporated, it was reviewed to ensure that the standards of USGS policy of peer review were met.

The issues raised with the previous submission have been addressed following the Reviewers' guidance. The reviewers major concern was to address the issue of describing the vegetation model and the sensitivity method. Along with the clarification that these models were not developed as a part of this study and were only being used, we have added additional text to clarify this point to the readers. We have incorporated all the other changes based on the reviewers' suggestions and addressed their comments in details. Please find the documents that address the suggestions and comments from all the referees. The sub-sections in the document contain the following:

     1.1 Comments from referee 1, Page 2
     1.2 Comments from referee 2, Page 3
     2.1 Authors' point by point response from referee 1, Page 4-9
     2.2 Authors' point by point response from referee 2, Page 9-15
     3.1 Authors' changes in the manuscript with markups, Page 16-49
     4.1 Final manuscript with all the changes included, Page 50-76

     In addition, we want to specifically mention that a comment by the anonymous reviewer 2 was made to add a reference that was used in selecting the range of "vegetation thickness". We had responded to reviewer 2 during the interactive discussion that that we had used personal communication from Jeremy Testa, who is an assistant professor at the University of Maryland's Center for Environmental Science. However, the USGS Bureau pointed out that personal communication was no longer allowed in USGS publications. Therefore, we have replaced the reference of personal communication to the citing of a paper that contains the relevant information on the range of "thickness".

Sincerely,

Tarandeep

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## 1.1 <u>Comments from Referee 1</u>

This paper details a sensitivity analysis of aquatic vegetation in the COAWST model using a novel
Effective Quadratures method. The model uses a three-dimensional drag term and generates TKE in
presence of vegetation. The paper does not detail the implementation details of the vegetation module
(though equations are given in Table 1), but evaluates the sensitivity of the model via novel Effective
Quadratures method.
The outcome of this paper is guidance on setting parameters in similar vegetation modules.

Major corrections ⸻⸻

The paper is not focused in its current state. The details of the EQ methods are not given and neither are
details of the vegetation model. In order to properly judge the conclusions more details on the EQ
methodology are required. The paper therefore lacks a clear aim: is it detailing the EQ method (no - this
is cited as Seshadri et al, 2017b, although as a paper in JOSS it lacks detail), the coupling of vegetation
to
COAWST (no - this is Beudin et al 2017). The paper should therefore be refocused along the lines of:
"new methods for assessment of models, including work on developing new metrics for assessing
model performance and novel ways of comparing model results with observational data" as to my
knowledge EQ has not been used in a coastal model and as such this would represent an advance. More
details of the implementation would greatly improve the paper.

Minor corrections ⸻⸻

Title: Change as requested by Editor

Line 4 - extra ) after parameters

Line 15 40 CPU hours. Is that 40 hours * 24 cores? Or 40/24 hours? Not clear.

Figures 4 to 7: Colour scheme is not suitable for colour-blind readers and also has the potential to
produce artificial "highlights" due to the luminosity changes. For a continuous scales as used in all plots

a continuous colour scheme should be used. See https://matplotlib.org/users/colormaps.html and https://bids.github.io/colormap/ for
examples

5  Figure 8: Difficult to differentiate the lines, especially those with pale colours (e.g. sim 13).

Can the lines have a label placed on them (or nearby) to aid the reader? Code availability: https://coawstmodel-trac.sourcerepo.com/ gave an error

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### 1.2 Comments from Referee 2

15  General comments Indeed, this type of models are needed for coastal studies. And the general idea of having more efficient sensitivity analysis methods for this type of models is very attractive. But: the real benefits are not imminent from this MS, as the real details of both model and method are not described (i.e. not informative) - it is too easy to lay this MS aside as just another paper describing some sort of method.
20  Remember that the people interested in using (the results of) this type of models are not necessarily interested in complicated sensitivity studies; what can you do to make their life easier?
COAWST contains the word sediment, but the effects of vegetation on sediment are not mentioned in

the abstract (or dealt with in the MS?)

The abstract describes the results very vaguely without any causality, and does not say anything we did
25  not expect already.

For the demonstration of this technique, seagrass properties -which can be measured quite well, i.e. do not have large uncertainty- have been varied over a relatively small range, whereas the environmental conditions have not been varied. Rather than learning which details matter, it would be interesting to see
30  when (under which conditions) these details matter; try to compare the combinations of veg parameters to literature on flow regimes, e.g. Mitul & Nepf 2013. My gut feeling says more uncertain parameters like $C_d$ (=1 which is ok for a rigid cylinder, not for flexible, flat-bladed seagras!!) and $z_0$ can have stronger effects. Such considerations are mentioned in section 4.4, but should be discussed earlier to avoid loosing your public.
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Why use pct change from the minimum value? That is a rather extreme situation.

Specific comments p2_l20 no drag coefficient or spatial density? Note that in the SWAN implementation (Suzuki et al), some parameters have exactly the same effect in the energy dissipation equations, see
http://swanmodel.sourceforge.net/online_doc/swantech/node21.html.

p3_l1-15 what is the overall message of these loose examples? p4 why not refer to Table 1 for the equations?

p4_l29 , instead of ; p5_l28-31 is this the stem density or the leaf density? Typically, Zostera marina has multiple leaves, and as the stem is usually short it may be the leaves that interact with the flow. For leaf density, this is a very low number but it matches the diameter (=leaf width?). The thickness of the leaves is rather large in my opinion, given the small length of these plants. How has this been measured? With a caliper or estimated? (personal comm is not published data!)

p18, Table 2 What about ah (as in Nepf, 2012)? p20, Fig 1 Are the Drag force, mixing and streaming calculated by the vegetation module? I would think these are hydrodynamic properties computed by ROMS, based on the same set of veg parameters that go to SWAN. p28, in caption: where can I find the conditions for these sims? I am surprised the classical S shape for flow in/over canopies is missing.

## 2.1 Author response to Referee 1

The response to the Reviewer's comments are in black while the original comments are in blue.

This paper details a sensitivity analysis of aquatic vegetation in the COAWST model using a novel Effective Quadratures method. The model uses a three-dimensional drag term and generates TKE in the presence of vegetation. The paper does not detail the implementation details of the vegetation module (though equations are given in Table 1), but evaluates the sensitivity of the model via novel Effective Quadratures method. The outcome of this paper is guidance on setting parameters in similar modules.

Major corrections ——————
The paper is not focused in its current state. The details of the EQ methods are not given and neither are details of the vegetation model. In order to properly judge the conclusions more details on the EQ methodology are required. The paper therefore lacks a clear aim: is it detailing the EQ method (no - this is cited as Seshadri et al, 2017b, although as a paper in JOSS it lacks detail), the coupling of vegetation to COAWST (no - this is Beudin et al 2017). The paper should therefore be refocused along the lines of: "new methods for assessment of models, including work on developing new metrics for assessing model performance and novel ways of comparing model results with observational data" as to my knowledge EQ has not been used in a coastal model and as such this would represent an advance. More details of the implementation would greatly improve the paper.

The paper does not detail the implementation details of the vegetation module because a reference paper also published by the part of the same group of authors (Beudin et al., 2017) contains the details of the implementation of the vegetation model. We have attempted to summarize the physical processes and related equations in Table 1 of the paper. The goal of the current paper is to provide guidance to the setting up of the parameters for the vegetation model by performing the sensitivity analysis.

The Reviewer states that the JOSS paper (Seshadri et al., 2017b) lacks details of the EQ method. This is true, however, the JOSS paper is simply for the software release. The underlying methodology is cited in the SIAM paper (Seshadri et al., 2017a) in Section 2.2, where more details as to what the subsampling strategy entails are provided. The computation of the Sobol' indices is outlined in Surdet et al., but is also provided in the appendix of the SIAM paper (Seshadri et al., 2017a). The purpose of the present paper is to demonstrate the computation of sensitivity metrics using an approach that is amenable to multi-physics simulations that are not computationally cheap. The EQ method has not been developed as a part of this study and we are not comparing the model results with observational data as well.

In the final version of the manuscript we will modify the introduction and conclusions to clarify the focus following the Reviewer's suggestions. Specific additions to the text include:

Line 25-29 Page 3 in introduction: These tools are implemented in the open source package, Effective Quadratures method (EQ) (Seshadri et al., 2017b) and the current work provides one of the first applications of this methodology to quantify sensitivity of input parameters in coastal models.
Therefore, the goal of this work is to use the EQ method to estimate Sobol' indices to estimate the sensitivity of the flow and wave dynamics to vegetation parameters in COAWST model.
Line 32 Page 10 in conclusions: We use an existing tool comprising of polynomial quadrature method to investigate the sensitivity of plant input properties for the vegetation module in COAWST model.

Minor Corrections:
1. Title: Change as requested by Editor
   Changed the title of the paper upon Editor's suggestion to include the version of EQ method

"Sensitivity Analysis of a Coupled Hydrodynamic-Vegetation Model Using the Effectively Subsampled Quadratures Method (ESQM v5.2) "

2. Line 4 fixed the typo

3. Line 15, Yes it is 40 CPU hours for 24 cores. Alternatively, we can use the word "Core hours". So the current simulations required 24*40 core hours.

4. Color scheme in Figures 4-7 is now using a continuous color scheme "viridis" from the matplotlib tool kit options. As an example, Figure 4 is shown on Page 3 of this document:

5. Figure now contains the individual legend on the line. Also, replaced the lines with different colors with symbols and markers for clarity. Please see the new figure at the end of this response document.

6. Code availability link has been modified to contain the right information.
https://coawstmodel-trac.sourcerepo.com/coawstmodel_COAWST

References

- Beudin, A., Kalra, T. S., Ganju, N., K., and Warner, J.C.: Development of a Coupled Wave-Current-Vegetation Interaction, Computers & Geosciences, 100, 76-86, 2017.
- Seshadri, P., Narayan, A., and Mahadevan, S.: Effectively Subsampled Quadratures for Least Squares Polynomial Approximations, arXiv: 1601.05470, 2017a.
- Seshadri, P., Parks, G. T.: Effective Quadratures (EQ): Polynomials for Computational Engineering Studies, Journal of Open Source Software, 2(11), DOI: 10.21105/joss.00166, 2017b.
- Sudret, B.: Global sensitivity analyzing using polynomial chaos expansions, Reliability Engineering and System Safety, 93, pp. 964-979, 2008.
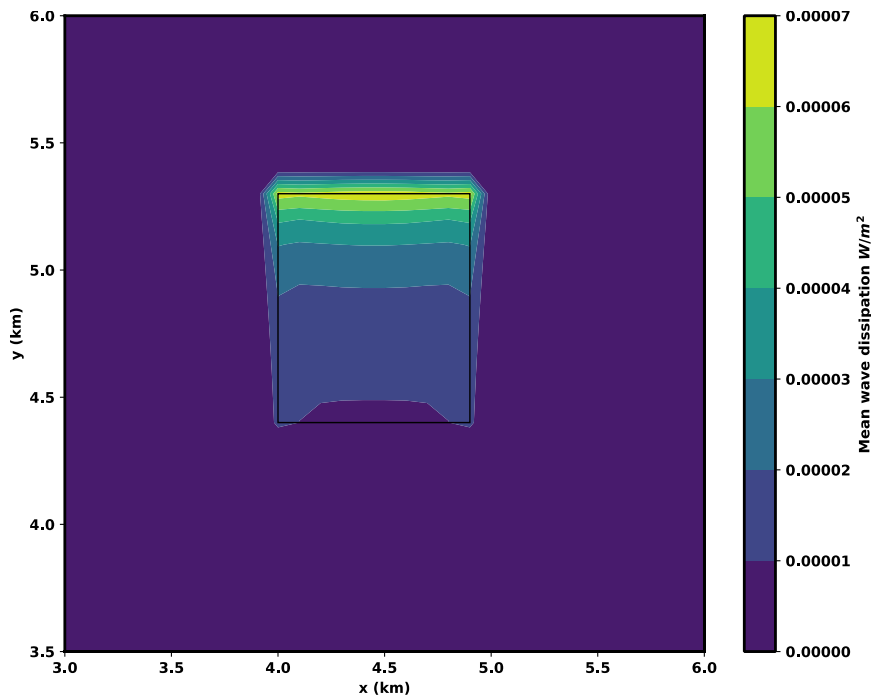
**Figure 4: Standard deviation from wave dissipation (W m⁻²) in presence of vegetation (Plan view). The area of the vegetation patch is highlighted in the middle of the domain.**
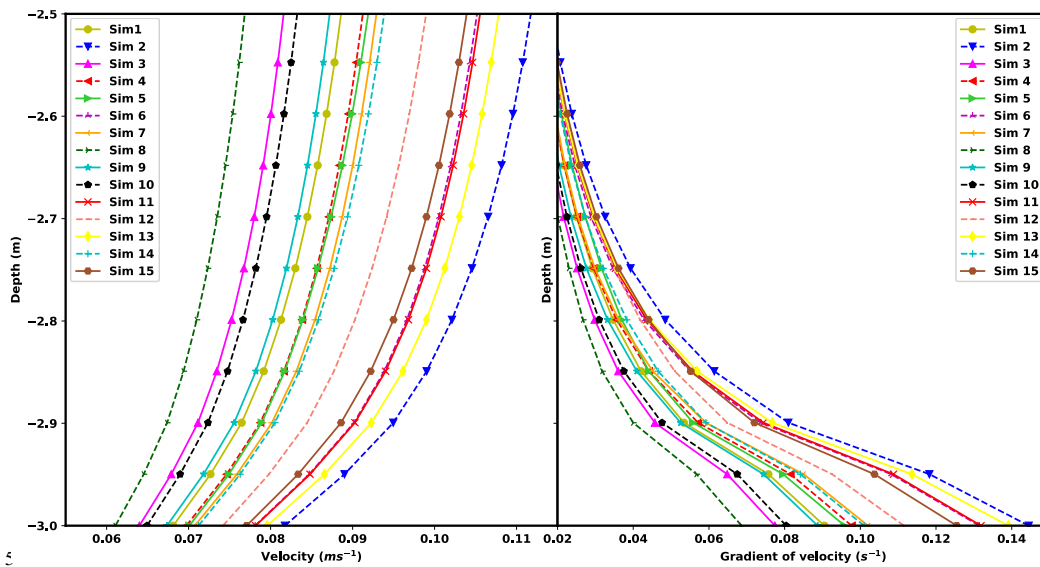
**Figure 8: (a) Velocity (m s⁻¹) profile and (b) Vertical gradient (s⁻¹) of velocity profile varying with depth in front of the vegetation patch at a particular time instance during flood for different simulations.**

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### 2.2 <u>Author response to Referee 2</u>

5  The response to the Reviewer's comments are in black while the original comments are in blue.

*General comments Indeed, this type of models are needed for coastal studies. And the general idea of having more efficient sensitivity analysis methods for this type of models is very attractive. But: the real benefits are not imminent from this MS, as the real details of both model and method are not described (i.e. not informative) - it is too easy to lay this MS aside as just another paper describing some sort of*
10  *method. Remember that the people interested in using (the results of) this type of models are not necessarily interested in complicated sensitivity studies; what can you do to make their life easier?*

Response 1: The goal of the current paper is to provide guidance to the setting up of the parameters for the vegetation model by performing sensitivity analysis. The paper does not detail the implementation details of the vegetation module because a referenced paper also published by the same group of authors
15  (Beudin et al., 2017) contains the details of the implementation of the vegetation model. We have attempted to summarize the physical processes and related equations in Table 1 of the paper. While the Beudin et al. paper was able to describe the details of the vegetation module, as the Reviewer mentions, users need some guidance to "make their life easier" when choosing the parameters of a model. The present MS provides that guidance and evaluates the repercussions of the parameter choice through
20  sensitivity analysis.

The chosen methodology of sensitivity analysis is detailed and cited in the Seshadri et al. 2017a paper of one of the co-authors, where more details as to what the subsampling strategy entails are provided. The computation of the Sobol' indices is outlined in Surdet et al., but is also provided in the appendix of the SIAM paper (Seshadri et al., 2017a). The purpose of the present paper is to demonstrate
25  the computation of sensitivity metrics using an approach that is amenable to multi-physics simulations that are not computationally cheap.

In the new version of the manuscript we have modified the introduction and conclusions to clarify the idea of the paper. Specific additions to the text include:

"Page 3 Line 25-29 in introduction: "These tools are implemented in the open source package, Effective Quadratures Method (EQ) (Seshadri et al., 2017b) and the current work provides one of the first applications of this methodology to quantify sensitivity of input parameters in coastal models.

Therefore, the goal of the present work is to take advantage of the EQ method to provide Sobol' indices that quantify the sensitivity of the flow and wave dynamics to vegetation parameters in COAWST model."

Page 10 Line 32 in conclusions: "We use a recently developed tool that formulates the Effective Quadratures method to quantify the sensitivity of plant input properties for the vegetation module in COAWST."

*COAWST contains the word sediment, but the effects of vegetation on sediment are not mentioned in the abstract (or dealt with in the MS?)*

Response 2: It is true that COAWST can model the transport of sediment. It is also able to model atmospheric conditions (WRF), but both sediment and atmospheric processes go beyond the scope of the present paper. The chosen output parameters for sensitivity analysis such as kinetic energy highlight the first order effects of introducing vegetation in the flow domain. While the model is capable of coupling the effects of vegetation with sediment model, the idea of the current study is not to model physical mechanisms due to the presence of vegetation. The focus of the current study remains to demonstrate the influence of vegetation parameter choice on the flow field. The resulting sediment transport effects are left for future work.

*For the demonstration of this technique, seagrass properties -which can be measured quite well, i.e. do not have large uncertainty- have been varied over a relatively small range, whereas the environmental conditions have not been varied. Rather than learning which details matter, it would be interesting to see when (under which conditions) these details matter; try to compare the combinations of veg parameters to literature on flow regimes, e.g. Mitul & Nepf 2013.*

Response 3: We believe the present work is relevant as it characterizes the sensitivity to seagrass properties because they do entail large uncertainty for measurement purposes and also exhibit a large range of spatial and temporal variability. Adding to the uncertainty, the seagrass growth is dynamic depending on nutrient supply, light quality and availability, and algal presence.

In Mitul & Nepf (2013), the focus is on creating situations ranging from blade scale to reach scale to understand the changes in resulting flow field. This kind of study is relevant for theoretical understanding of vegetation effects. The purpose of the vegetation module in COAWST is to be able to include the vegetation effects in realistic model applications for areas with known seagrass characteristics. The future goal is to use the model for the study of realistic changes in water level and wave attenuation triggered by the presence of vegetation.

*My gut feeling says more uncertain parameters like C_d (=1 which is ok for a rigid cylinder, not for flexible, flat-bladed seagras!!) and z_0 can have stronger effects. Such considerations are mentioned in section 4.4, but should be discussed earlier to avoid loosing your public.*

Response 4: We agree with the Reviewer that the sensitivity of drag coefficient can be studied. The determination of drag coefficient is usually done in controlled environments (laboratory scale). However, the purpose of the current work is to provide guidance for the vegetation parameters that are measured in physical systems and are required in the COAWST model for modeling the effect of seagrass. Variations on C_d are unlikely to be measured in the field and thus users could rely on the published literature for an appropriate choice based on the type, shape, and flexibility of the vegetation under study.

Following the reviewer's comment, we have added the reasons for not considering the input of C_d in the sensitivity of vegetation model in an earlier section on Page 6, Lines 2-6 (Section 2.3) as: "In addition to these four vegetation properties, the vegetative model requires an input of drag coefficient $(C_D)$ in the flow model and the wave model. However, variations on $C_D$ are unlikely to be measured in the field and thus users could rely on the published literature for an appropriate choice based on the type, shape, and flexibility of the vegetation under study."

*Why use pct change from the minimum value? That is a rather extreme situation.*

Response 5: The thoughts behind using a minimum value is to show a relative change from each of the simulations with different vegetation parameters. Also, the mean of the simulations might not be as relevant, if response is non-linear.

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*Specific comments p2_l20 no drag coefficient or spatial density? Note that in the SWAN implementation (Suzuki et al), som parameters have exactly the same effect in the energy dissipation equations, see http://swanmodel.sourceforge.net/online_doc/swantech/node21.html.*

10   Response 6: The bulk drag coefficient required in the SWAN parameterization in COAWST model assumes a constant drag coefficient. The spatial stem density is variable. Following the reviewer's specific comments Page 4 line 16-17 include the following text: "The parameterization of SWAN to account for wave dissipation implemented by Suzuki et al. 2012 has the same effect as energy dissipation."

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*p3_l1-15 what is the overall message of these loose examples?*

Response 7: The overall message of providing previous literature on sensitivity studies involving physical systems is to lead to the idea that the choice of sensitivity analysis method depends on multiple factors such as computational costs, characteristics of the model, number of input parameters, and/or
20   potential interactions between parameters. The authors have rephrased the paragraph to make the context of providing the examples in the new version on Page 3 Line 12 to 18 in Introduction as:

"One of the challenges associated with a Monte Carlo approach to computing the Sobol' indices is the large number of model evaluations required for approximating conditional variance.

All these studies highlight various approaches to perform sensitivity analysis. Saltelli et al.
25   (2008) provided a comparison of different sensitivity analysis methodologies and the optimal setup for specific combinations of parameters and model.   Ultimately, the choice of sensitivity analysis methodology depends on multiple factors such as the computational cost of running the model, the

characteristics of the model (e.g., nonlinearity), the number of input parameters, and/or the potential interactions between parameters."

*p4 why not refer to Table 1 for the equations? p4_l29 , instead of ;*

Response 8: We have added the reference to table 1 on page 4 in line 18 as:

"The parameterizations used to implement the effect of vegetation in both ROMS and SWAN models are mentioned in Table 1 and detailed in Beudin et al. (2017)."

*p5_l28-31 is this the stem density or the leaf density? Typically, Zostera marina has multiple leaves, and as the stem is usually short it may be the leaves that interact with the flow. For leaf density, this is a very low number but it matches the diameter (=leaf width?).*

Response 9: It is the stem density. Hence the units are stems/m$^2$. We have replaced the word "density" by "stem density" in the paper for clarity. The leaf width = diameter.

*The thickness of the leaves is rather large in my opinion, given the small length of these plants. How has this been measured? With a caliper or estimated? (personal comm is not published data!*

Response 10: This has been an estimation. Considering that the chosen range is large, even then the sensitivity analysis shows that thickness is not causing any changes to the flow field (i.e. the chosen model output parameters are the least sensitive to thickness).

Jeremy Testa is a Assistant Professor in the Chesapeake Biological Laboratory at University of Maryland Center for Environmental Science. Some of the relevant literature of Jeremy Testa includes:

1. "Temporal responses of coastal hypoxia to nutrient loading and physical controls", Biogeosciences 6 (12), 2985-3008, 2009.
2. "The metabolism of aquatic ecosystems: history, applications, and future challenges", Aquatic Sciences 74 (1), 15-29, 2012.
3. "Submersed aquatic vegetation in Chesapeake Bay: sentinel species in a changing world", BioScience, Volume 67, Issue 8, 1 August 2017, Pages 698–712, 2017.

*p18, Table 2 What about ah (as in Nepf, 2012)?*

Response 11: In Nepf, 2012; "ah" helps in distinguishing the different flow regime where "a" is the frontal area per unit canopy volume. The canopy volume is based on the spacing between elements. The

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implementation of vegetation model does not work on the scales to resolve the spacing between the elements and only considers vegetation height "h" in the equations for modeling seagrass.

*p20, Fig 1 Are the Drag force, mixing and streaming calculated by the vegetation module? I would think these are hydrodynamic properties computed by ROMS, based on the same set of veg eparameters that go to SWAN.*

Response 12: This is absolutely correct. The equations of drag, mixing and streaming computed in ROMS use the same vegetation parameters as SWAN. There are two parts of the vegetation module, one in SWAN and one in ROMS and the two exchange information in the coupled system, thus resolving the wave-current modifications.

*p28, in caption: where can I find the conditions for these sims?*

Response 13: The different simulations are characterized by varying the vegetation properties (mentioned in Table 2.) while keeping the baseline setup similar in all cases for the purpose of studying their sensitivity. The discussion on the choice of the vegetation properties is detailed in Section 2.3. The domain setup, initial, and boundary conditions are the same for all simulations (except for the variation of vegetation properties). This setup is described in details in Section 2.4 (and schematically described in figure 2).

*I am surprised the classical S shape for flow in/over canopies is missing*

Response 14: The reason we are missing a S shape in the flow in/over the canopy is because the chosen vegetation stem density range is not large enough to cause that shape. The original paper showing the vegetation model implementation by the current authors (Beudin et al., 2017) shows this shape when a vegetation stem density of 2500 stems/m$^2$ is chosen (Figure 4a).
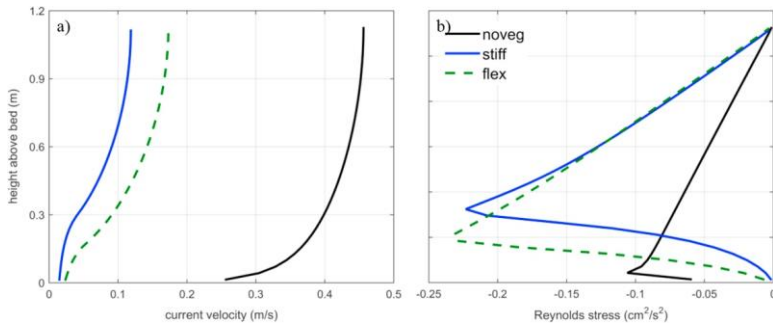
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Figure adapted from Beudin et al. (2017) showing vertical profiles of a) mean flow velocity, and b) turbulent Reynolds shear stress $(\overline{v'w'}=-KM\delta v\delta z)$ in the middle of the patch at peak flood without vegetation (solid black), with stiff vegetation (solid blue), and with flexible vegetation (dash green).

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**3.1 Marked up manuscript that tracks changes in MS-Word Format including the changes:**

# Sensitivity Analysis of a Coupled Hydrodynamic-Vegetation Model Using the Effectively Subsampled Quadratures ~~Method~~Method (ESQM v5.2)

Tarandeep S. Kalra[1], Alfredo Aretxabaleta[1], Pranay Seshadri[2], Neil K. Ganju[1], and Alexis Beudin[3]

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*Correspondence to*: Tarandeep S. Kalra (tkalra@usgs.gov)

**Abstract.** Coastal hydrodynamics can be greatly affected by the presence of submerged aquatic vegetation. The effect of vegetation has been incorporated into the Coupled-Ocean-Atmosphere-Wave-Sediment Transport (COAWST) Modeling System. The vegetation implementation includes the plant-induced three-dimensional drag, in-canopy wave-induced

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streaming, and the production of turbulent kinetic energy by the presence of vegetation. In this study, we evaluate the sensitivity of the flow and wave dynamics to vegetation parameters using Sobol' indices and a least squares polynomial approach referred to as Effective Quadratures method. This method reduces the number of simulations needed for evaluating Sobol' indices and provides a robust, practical, and efficient approach for the parameter sensitivity analysis. The evaluation of Sobol' indices shows that kinetic energy, turbulent kinetic energy, and water level changes are affected by plant stem density, height, and to a lesser degree, diameter. Wave dissipation is mostly dependent on the variation in plant stem density. Performing sensitivity analyses for the vegetation module in COAWST provides guidance to optimize efforts and reduce exploration of parameter space for future observational and modeling work.

## 1 Introduction

The presence of aquatic vegetation (e.g., mangroves, salt marshes, and seagrass meadows) provides several ecological benefits including nutrient cycling, habitat provision, and sediment stabilization (Costanza et al., 1997). Vegetation provides habitat for many species of epiphytes, invertebrates, and larval and adult fish (Heck et al., 2003). Seagrass meadows reduce sediment resuspension, thereby stabilizing bottom sediment, increasing light penetration, and improving water clarity in a positive feedback loop (Carr et al., 2010). In addition, aquatic vegetation provides coastal protection by absorbing wave energy (Wamsley et al., 2010).

One approach to implement the influence of aquatic vegetation on circulation is by increasing the bottom roughness coefficient (Ree, 1949; Morin et al., 2000). Increased computational power has led toMore recently, the effect of vegetation being studied through parameterization as form drag as opposed to skin friction in 2-D depth averaged models (Chen et al., 2007; Le Bouteiller and Venditti, 2015). To account for 3-D vertical structures, estuary-scale models have implemented both mean and turbulent flow impacts of vegetation (Temmerman et al., 2005; Kombiadou et al. 2014; Lapetina and Sheng, 2015). In addition to impacts on the flow-field, the presence of vegetation also results in wave attenuation. The decay of wave height over vegetation has been simulated by enhancing bed roughness (Möller et al., 1999; de Vriend, 2006; Chen et al., 2007). A more physical description of wave attenuation due to vegetation was developed by Dalrymple et. al (1984), who approximated wave energy loss due to stalks approximated as cylinders.s . This approach has been applied in spectral wave models and calibrated against flume experiment results (Mendez and Lozada, 2004; Suzuki et al., 2012; Wu, 2014; Bacchi et al., 2014).

Recently, Beudin et al. (20162017) implemented the effects of vegetation in a vertically varying water column through momentum extraction and turbulence dissipation and generation using a 3D hydrodynamic model and accounting for wave dissipation due to vegetation in a spectral wave model. The modeling approach was implemented and tested within the open source COAWST (Coupled-Ocean-Atmospheric-Wave-Sediment Transport) modeling system that couples the hydrodynamic and wave models (Warner et al., 2010). The vegetation module was based on modifications to the flow field resulting from three-dimensional drag, in-canopy wave-induced streaming, and production of turbulent kinetic energy in the

hydrodynamics model (ROMS), along with energy dissipation and resultant hydrodynamic feedback from the wave model (SWAN).

The vegetation module requires the user to input a given set of plant properties (stem density, height, diameter, and thickness). These vegetation properties can be highly variable depending on the season and environment, yet obtaining a full set of measurements in realistic settings is impractical. Identifying which properties have the greatest influence on the resulting flow dynamics can reduce the amount of observational data required to robustly parameterize the model, and/or reduce the number of runs required in a model ensemble to quantify the uncertainty associated with data gaps. Our study~~The current work~~ aims to perform a systematic sensitivity analysis~~study~~ to quantify the effect of changing the vegetation properties on the resulting hydrodynamic output. The results of the sensitivity analysis can be used to select and rank the most important parameters for calibration. Two conditions are required for the model to display a significant sensitivity: (1) a sufficient modification of one of the forcing parameters, and (2) a change in the leading terms of the dynamic equations of the model. While modifying the forcing parameters by a sufficient amount is required, the modification should remain within the natural range of variability of the parameters.

Several mathematical techniques have been utilized to perform sensitivity analysis. Bryant (1987) applied scaling analysis to an idealized domain and forcing and found that closure parameters such as vertical diffusivity and wind stress curl were important controlling factors in thermohaline circulation. Bastidas et al. (1999) used multicriteria methods to find the sensitivity of ~~a~~ land surface scheme models that couple biosphere-atmosphere interactions. The input variables such as precipitation, air temperature and humidity etc.) predict the evolution of soil skin temperature, soil moisture etc.  The input parameters obtained from the sensitivity analysis of the model showed consistency with physical properties for two different field sites and helped identifying insensitive parameters that led to an improvement in model description. Fennel et al. (2001) incorporated adjoint methods to perform sensitivity studies to refine ecological model parameters ~~and illustrated that it could be applied on a wider range of problems than …~~ such that the underlining model can be applied to a wider range of conditions~~(it was designed/calibrated for?)~~. Mourre et al. (2008) performed multiple simulations based on realistic variation of a forcing field to calculate the influence of model parameters on sea surface salinity. ~~The metric used to measure the sensitivity was based on RMS difference between the reference and modified model parameter.~~ The results showed that lateral salt diffusivity had the strongest impact on surface salinity model response. Rosero et al. (2009) investigated the sensitivity of three different versions of a land satellite model (Noah LSM) applied to nine different sites based on different conditions (soil, vegetation, and climate). They utilized the Monte Carlo method to generate the first order Sobol' indices (Sobol', 1993), to estimate the model sensitivity. The results showed that the optimal parameter values ~~differed~~ varied between different versions of the models and for different sites along with quantifying the nature of interactions between parameters. One of the challenges associated with a Monte Carlo approach to computing the Sobol' indices is the large number of model evaluations required for approximating conditional variance.

All these studies highlight various approaches to perform sensitivity analysis. Saltelli et al. (2008) provided a comparison of different sensitivity analysis methodologies and the optimal setup for specific combinations of parameters and

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model.  Ultimately, the choice of sensitivity analysis methodology depends on multiple factors such as the computational cost of running the model, the characteristics of the model (e.g., nonlinearity), the number of input parameters, and/or the potential interactions between parameters. Saltelli et al. (2008) described variance-based techniques as providing the most complete and general pattern of sensitivity for models with a limited number of parameters, such as the vegetation module in COAWST. Sobol' indices, as a form of variance-based sensitivity analysis, provide a decomposition of the variance of a model into fractions that can be assigned to inputs or combinations of inputs. However, techniques involving the estimation of Sobol' indices (such as Monte Carlo methods) are expensive.

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To reduce the computational cost and have desirable accuracy, techniques that involve approximating the global response of the model with a polynomial, and then using its coefficients to estimate the Sobol' indices can be utilized (Sudret, 2008). In this paper, we use a set of least squares polynomial tools based on subsampling to estimate our global polynomial response (Seshadri et al., 2017a). Then, the coefficients of the polynomial are used to compute the Sobol' indices. These tools are implemented in the open source package, Effective Quadratures method (EQ) (Seshadri et al., 2017b) and the current work provides one of the first applications of this methodology to quantify sensitivity of parameters involved coastal models. These tools are implemented in the open source package, Effective Quadratures Method (EQ) (Seshadri et al., 2017b) and our current work provides one of the first applications of this methodology to quantify sensitivity of input parameters in coastal models. Therefore, the goal of the present work is to take advantage of the EQ method to provide Sobol' indices that quantify the sensitivity of the flow and wave dynamics to vegetation parameters in COAWST model.

Therefore, the goal of this work is to use the EQ method to estimate Sobol' indices to estimate the sensitivity of the flow and wave dynamics to vegetation parameters in COAWST model. The paper is organized as follows: the methods are discussed in section 2, including the numerical model with vegetation model (COAWST), Effective Quadratures method to estimate Sobol' indices, and simulation design; iIn section 3, we present the results of sensitivity analysis from various simulations;

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and in section 4, we discuss the impact of these results; and . Ffinally, in section 5,we summarize ourthe work in section 5 and outline areas of future research.

## 2 Methods

### 2.1 COAWST implementation of vegetation model parameterization

Beudin et al. (20162017) implemented a hydrodynamic-vegetation routine within the open-source Coupled Ocean-Atmosphere Wave Sediment Transport (COAWST) numerical modeling systemm (Warner et al., 2008). The COAWST framework utilizes ROMS (Regional Ocean Modeling System) for hydrodynamics and SWAN (Simulating WAves Nearshore) for modeling waves coupled via the Model Coupling Toolkit (MCT) (Warner et al., 2008).

ROMS (Regional Ocean Modeling System) is a three-dimensional, free surface, finite-difference, terrain-following model that solves the Reynolds-Averaged Navier-Stokes equations using the hydrostatic and Boussinesq assumptions (Haidvogel et al., 2008). The transport of turbulent kinetic energy and generic length scale are computed with a generic length scale (GLS) two-equation turbulence model. SWAN (Simulating WAves Nearshore) is a third-generation spectral wave model based on the action balance equation (Booij et al., 1999). The effect of submerged aquatic vegetation in ROMS is to extract momentum, add wave-induced streaming, and generate turbulence dissipation. Similarly, the wave dissipation due to vegetation modifies the source term of the action balance equation in SWAN. Sub-grid scale parameterizations account for changes due to vegetation in the water column extending from the bottom layer to the height of the vegetation in the flow model, while SWAN accounts for wave dissipation due to vegetation at the seafloor. The parameterization of SWAN to account for wave dissipation implemented by Suzuki et al. 2012 has the same effect as energy dissipation.

The parameterizations used to implement the effect of vegetation in both ROMS and SWAN models are mentioned in Table 1 and detailed in Beudin et al. (2017). The parameterizations used to implement the effect of vegetation in both ROMS and SWAN models are overviewed in Table 1 and detailed in Beudin et al. (2016).

The coupling between the two models occurs with an exchange of water level and depth averaged velocities from ROMS to SWAN and wave fields from SWAN to ROMS after a fixed number of time steps (Fig. 1). The vegetation properties are separately input in the two models at the beginning of the simulations.

### 2.2 Method for Sensitivity Analysis: Polynomial Least Squares

Polynomial techniques are ubiquitous in the field of uncertainty quantification and model approximation. They estimate the response of some quantity of interest with respect to various input parameters using a global polynomial. From the coefficients of the polynomial the mean, variance, skewness and higher order statistical moments can be calculated (see Smith 2014; Geraci et al. 2016). In this paper, our interest lies in statistical sensitivity metrics called first order Sobol' indices (Sobol', 1993) that are derived from the conditional variances of the parameters of the model. These indices are the same in number as the input parameters to the model and quantitatively rank the input parameters based on their contribution

to the resultant model output. Thus, model output is more sensitive to parameters that exhibit higher first order Sobol' index value. Second order and third order Sobol' indices may also be computed. The sum of the first, second, and third order Sobol' indices should sum to unity, therefore if the first order indices are themselves close to unity, it indicates the higher order interaction between model input parameters is weak.

5      ~~In this paper, the first order indices are computed from a global polynomial model using Effective Quadratures.~~ In this paper, the first order indices are computed from a global polynomial model using Effectively Subsampled Quadratures Method (ESQM v5.2; Seshadri et al., 2017b). There are two attributes to any data-driven polynomial model: the choice of the polynomial basis and the strategy for estimating the coefficients of the polynomial. The basis~~es~~ used in Effective Quadratures are orthogonal polynomials; i.e. orthogonal with respect to the weight of the input parameter. For example, if

10     one of the input parameters is prescribed with a Gaussian distribution, then a Hermite orthogonal polynomial basis would be used; likewise for a uniform distribution, Legendre polynomials are used. In the current work, a uniform distribution is assumed for the input parameter space. The rationale behind selecting polynomials that are orthogonal with respect to the input weight is that it reduces the number of model evaluations required for estimating statistical moments. Details on the exponential convergence in moments when matching the orthogonal polynomial with its corresponding weight can be found

15     in Xiu et al. (2002).

The coefficients for the polynomial expansion are typically approximated using an integral over the input parameter space using quadrature rules. When the number of input parameters is greater than one, tensor grid or sparse grid based quadrature rules may be used to approximate these integrals. However, the cost of tensor grids grows exponentially with dimension, i.e., a four-point quadrature rule in three dimensions has $5^3$ points, in four dimensions has $5^4$ points and so on.

20     While some alleviation can be obtained using sparse grids, in this paper a more efficient sampling technique is used: effectively subsampled quadratures (abbreviated to Effective Quadratures).

The method of Effective Quadratures determines points for approximating the integral by subsampling well-chosen points from a tensor grid, and evaluating the model at those subsamples. These well-chosen points are obtained via a QR column pivoting heuristic (Seshadri et al. 2017a). Once the coefficients are estimated, the Sobol' indices can be readily

25     computed (Sudret 2008).

**2.3 Range of input vegetation properties for sensitivity analysis**

Prior to performing the simulations for estimating Sobol' indices described above, a range of vegetation inputs that would impact the model response needs to be chosen. Kennish et al. (2011) constrained annual variation of three of the four

30     vegetation properties (stem density, height, diameter) based on *Zostera marina* growth in the Barnegat Bay-Little Egg Harbor estuary. ~~The thickness of Z. Marina is an order of magnitude lower than its diameter (J. Testa, personal communication). Based on the published data, the range of the vegetation model inputs evaluated is as follows:~~ The thickness of *Z. Marina* is selected to be an order of magnitude lesser than its diameter based on Lakrum et al., 2007. Based on this, the range of the vegetation model inputs evaluated is as follows:

1. Stem dDensity $(n_v)$= [38.2 - 250.4] stems/m$^2$.
2. Height $(l_v) = [0.16 - 0.32]$ m.
3. Diameter $(b_v) = [1.0 - 102.0]$ mem.
3.4. Thickness $(t_v) = [0.1 - 1.0]$ mm.

For the sensitivity analysis, a combination of these ranges of inputs (Table 2) is chosen to configure different simulations in an idealized test case, described below.

In addition to these four vegetation properties, the vegetative model requires an input of drag coefficient $(C_D)$ in the flow model and the wave model. However, variations on $C_D$ are unlikely to be measured in the field and thus users could rely on the published literature for an appropriate choice based on the type, shape, and flexibility of the vegetation under study.

**Commented [KTS3]:** Following the reviewer 2's suggestion, have added the reasons for not considering the input of C_d in t sensitivity of vegetation model.

**2.4 Test case configuration**

An idealized rectangular model domain of 10 km by 10 km with a 3 m deep basin is chosen. The grid is 100 by 100 in the horizontal (100 m resolution) and has 60 vertical sigma-layers (uniformly distributed) leading to 0.05 m resolution in the vertical. The vertical resolution of 0.05 m allows a plant height of 0.27 m to be distributed over 6 vertical layers while the shortest height is restricted to 2 vertical layers. A square patch of vegetation (1 km by 1 km) is placed in the middle of the domain. The ROMS barotropic and baroclinic time steps are respectively *0.05 s and 1 s*, while the SWAN time step and the coupling interval between ROMS and SWAN are 10 min. The friction exerted on the flow by the bed is calculated using the SSW bbl in the bottom boundary layer formulation (Warner et al., 2008). The bottom boundary layer roughness is increased by the presence of waves that produce enhanced drag on the mean flow (Madsen, 1994; Ganju and Sherwood, 2010). The vegetative drag coefficients $(C_D)$ in the flow model and the wave model are set to 1 (typical value for a cylinder at high Reynolds number). ). The bed roughness is set to $z_0$=0.05 mm, which corresponds to a mixture of silt and sand (Soulsby, 1997). The turbulence model selected is the $k - \varepsilon$ scheme (Rodi, 1984).

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The model is forced by oscillating the water level on the northern edge with a tidal amplitude of 0.5 m and a period of 12 h. Waves are also imposed on the northern edge with a height of 0.5 m, directed to the south (zero angle), with a period of 2 s. The test case setup is similar to the one used by Beudin et al., (2017). The test case setup is simulated for 2 days to obtain a tidally steady state solution. These simulations require 40 CPU hours on Intel Xeon(R) X5650 2.67 GHz processors running on 24 parallel processors.

**2.5 Choice of COAWST model response to vegetation inputs**

The output parameters used to investigate the vegetation model sensitivity are chosen to reflect the first order effects of vegetation on the hydrodynamics and waves. The results for the model response are computed for the last tidal cycle (a total

of 3 tidal cycles are required for achieving steady state). The presence of vegetation affects the output parameters in different physical ways (Table 1) as:

1. Wave dissipation: Vegetation dissipates wave energy by reducing wave height, increasing wavelength, and reducing wave steepness. ~~The presence of vegetation dissipates wave energy, thereby reducing the wave height, increasing the wavelength, and reducing wave steepness.~~

2. Kinetic energy: A drag force is generated by plants. This leads to a decrease in kinetic energy within and behind the vegetation patch. ~~The presence of vegetation generates a drag force. This leads to a decrease in kinetic energy within and behind the vegetation patch.~~

3. Water level: As the wave energy (and momentum) flux decreases due to bottom friction, the mean water level increases to balance the decrease in wave and kinetic energy. The flow decelerates in front of the patch and in the wake of the patch while it accelerates around the edges of the patch, leading to a water level gradient.

4. Turbulent kinetic energy (TKE): Reduced turbulent kinetic energy in front and within the patch. ~~The presence of vegetation leads to a reduced turbulent kinetic energy in front and within the patch.~~ The enhancement of TKE inside the boundary layer is not captured with the current resolution.

The response impact to change in the inputs during each simulation is computed by calculating the percentage difference of model response for each simulation from the minimum value of all the simulations. The model response is obtained in and around the vegetation patch and averaged over the last tidal cycle. The change in model response of water level is computed by finding the maximum water level difference in and around the vegetation patch. In addition, the variability of model response with given vegetation inputs in different simulations is calculated through standard deviation of model response in and around the vegetation patch over the last tidal cycle. The standard deviation in TKE is depth averaged to provide a 2-D field.

## 3 Results

### 3.1 Setting up simulations with different vegetation inputs

Using the range of input parameters described above (section 2.3), and assuming all the inputs are uniformly distributed over their ranges, a matrix of design of experiment values (Table 2) was determined using Effective Quadratures. A total of 15 simulations were found to be required, corresponding to the number of coefficients in a 4D polynomial with a maximum order of 2. In general, the number of coefficients $n$, is given by the formula

$$n = \binom{d + o}{d},$$

where $d$ is the number of dimensions and $o$ is the maximum order (assuming it is isotropic across all dimensions).

### 3.2 Model response from all the simulations

The 15 simulations (parameter choice of each simulation in Table 2) are performed to provide model response from the four chosen output variables.

1. Wave dissipation: The percentage change in wave dissipation from all simulations relative to the minimum value of wave dissipation varied between 75 and 600% (Fig. 3(a)). Simulation 2, which includes the combination of smallest~~lowest~~ stem density ($n_v$= 62.1 stems/m²) and shortest height (0.174m), incurred the least ~~lowest~~ wave dissipation, while simulation 3, which involved the combination of greatest~~highest~~ stem density ($n_v$= 226.5 stems/m²) and tallest height (0.295 m), resulted in highest wave dissipation. The greatest~~highest~~ amount of variability in wave dissipation occurs in front of the vegetation patch (Fig. 4)~~.~~, where the greatest~~highest~~ amount of wave energy is dissipated due to the presence of the vegetation patch.

2. Kinetic energy: The percentage change in kinetic energy from all simulations relative to the minimum kinetic energy varied between 5.0 and 34.0 % (Fig. 3b). Simulation 8, performed with an intermediate value of stem density along with the largest~~highest~~ values of height, diameter, and thickness, results in the least amount of kinetic energy (lowest velocities). Simulation 2 causes the least amount of extraction of momentum with a combination of smallest~~lowest~~ plant stem density, height, and diameter values, resulting in the greatest~~highest~~ kinetic energy in and around the vegetation patch. The variability in kinetic energy from all the simulations is observed at a cross section along the vegetation patch (Fig. 5). Variability is observed throughout the water column where the vegetation patch exists. Similar to the variability in wave dissipation, the greatest~~highest~~ amount of variability occurs in front of the vegetation patch. The region of maximum variability occurs at a distance of (0.25 – 1.25) m above bed.

3. Water level: The percentage change in maximum water level difference from all simulations relative to the minimum of the maximum water level difference varied between 3.0 and 18.0 % (Fig. 3c). The minimum water level gradient is obtained from simulation 13 that includes a combination of plant inputs ($n_v$= 62.1 stems/m² (minimum), $l_v$= 0.174 m (intermediate), diameter=6 mm (minimum), and $t_v$= 0.3 mm (minimum). Simulations 2, 6, and 11 also give ~~a~~ relatively low values of water level gradient.~~.~~ Simulations 2 and 6 both involve the smallest~~lowest~~ plant stem density values (i.e. $n_v$= 62.1 stems/m²). On the other hand, simulation 8 ($n_v$=144.3 stems/m², $l_v$= 0.3 m (maximum), $b_v$=9 mm, and $t_v$= 0.9 mm) accounts for the greatest~~highest~~ value of maximum water level difference. The variability in water level (Fig. 6) is highest around the lobes of the vegetation patch where the water level adjusts owing to ~~a~~ changes in velocity around the patch. ~~Behind the vegetation patch, the variability also increases as the water level adjusts due to a decrease in values result in the highest variation in water level.~~ Behind the vegetation patch, the variability increases as the water level adjusts to the change in flow conditions.

4. Turbulent Kinetic Energy (TKE): The percentage change in TKE from all simulations relative to the minimum TKE varied between 0.5 and 10.0 % (Fig. 3d). Simulation 8 (combination of plant $n_v$= 144.3 stems/m², $l_v$= 0.3 m, $b_v$= 9 mm and $t_v$= 0.9 mm ) gives the most greatest ~~amount~~ of TKE, similar to what was observed with kinetic energy change . The smallest value of ~~lowest~~ TKE is obtained in and around the vegetation patch in simulation 2 with a combination of plant inputs ($n_v$ = 62.1 stems/m², $l_v$ = 0.2 m, $b_v$= 3 mm and $t_v$ = 0.6 mm). Simulation 2 causes the least amount of dissipation of turbulence with a combination of smallest~~lowest~~ plant stem density, height and diameter. The variability in TKE peaks occurs in front of the vegetation patch (Fig. 7) where the different simulations dissipate turbulence to substantially different

degrees. The changes in turbulence mixing caused by the presence of the vegetation patch are close to zero inside the patch (all simulations dissipate similar amounts of turbulence).

### 3.3 Quantifying sensitivity using Sobol' Indices

5 Following the variability in model response from different simulations, the sensitivity to input vegetation parameters can be quantified with the use of first order Sobol' indices that are obtained by taking advantage of the Effective Quadratures approach. Sobol' indices are individually computed for all the model responses. The first order Sobol' indices for all the model responses (Table 3) add up to ~~above~~ more than 0.9. This results indicates they account for 90% of the variability in model response for the given vegetation property inputs, and the variability captured by second order and third order indices is relatively low. The model is most sensitive (Table 3) to ~~vegetation~~ plant stem density ($n_v$) and height ($l_v$) over the range of parameters considered; these two inputs ~~that~~ account for over 80% of the sensitivity to all model outputs. The vegetation diameter ($b_v$) accounts for 12-15 % of model sensitivity to kinetic energy, water level change, and turbulent kinetic energy. Thickness ($t_v$) showed the least impact on all the chosen model outputs.

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## 4 Discussion
### 4.1 Variability in model response from sensitivity analysis

From the different simulations performed during sensitivity analysis, there is a great~~high~~ amount of variability in front of the vegetation patch in wave dissipation, KE, and TKE (Figs. 4, 5 and 7). This is a result of large~~high~~ amount of wave

20 dissipation and flow deceleration in front of the vegetation patch. The cross-sectional plane of the domain illustrates that the variability in KE occurs throughout the water column (Fig. 5), highlighting the 3-D impact of vegetation inputs. Interestingly, the greatest~~highest~~ amount of variability in KE (Fig. 5) occurs at distance above the bed ~~between~~ 0.4 – 1.3 m at y = 5.6 km, while the maximum vegetation height in all the simulations is 0.3 m. This result indicates that variation in vegetation height results in the greatest~~highest~~ amount of KE variability above the vegetation patch. The variability in water

25 level change is large~~high~~ around the lobes and behind the vegetation patch (Fig. 6). The variability in these regions is because the change in local flow velocity is adjusted by a change in water level around the vegetation patch.

~~————~~This is further confirmed by observing the variation in velocity profiles with depth (Fig. 8a) at a particular time instance during flood tide. Simulation 8 results in the lowest velocity of 0.06 m/s while simulation 2 results in the peak flood velocity of 0.11 m/s. Consequently, the gradient of velocity with respect to depth is greatest~~highest~~ at all depths for

30 simulation 8 while least~~lowest~~ for simulation 2 (Fig. 8b). The gradient reaches a maximum value at the bottom layer.

### 4.2 Understanding vegetation parameterization to interpret Sobol' Indices

The parameterizations involving extraction of momentum, turbulence production and turbulence dissipation are directly affected by vegetation stem density ($n_v$), diameter~~width~~ ($b_v$) and thickness ($t_v$) (Table 1). Because these mechanistic

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**Commented [KTS5]:** Modified this figure as per reviewer 1 comments

processes occur at the blade scale, the dependence on vegetation height ($l_v$) is implicitly included in the parameterizations. Sobol' indices provide quantifiable information and show that vegetation height, stem density and diameterwidth (in decreasing order of importance) are pertinent in accurately computing kinetic energy (KE), turbulent kinetic energy (TKE) and water level. An accurate representation of KE and TKE has direct ramifications on estimating sediment transport while water level estimates can affect storm surge predictions.

The high sensitivity of wave dissipation to vegetation stem density highlights the need of accurate density representation to attain wave attenuation estimates, especially in open coasts. SWAN computes wave dissipation due to vegetation as a bottom layer effect. Therefore, the height of the vegetation does not affect wave dissipation to the same extent as other model outputs: KE, TKE, and water level. In addition, the equation representing wave dissipation process in SWAN is independent of vegetation thickness, thus corresponding to the lowest Sobol' index. Vegetation thickness only appears in the turbulence dissipation term (Table 1) while modifying the turbulence length scale and consequently it has the least effect on any of the model response.

**4.3 Linear curve fitting to complement Effective Quadratures based sensitivity analysis**

To complement the results of the Sobol' indices calculation linear fits to the data are conducted. The main parameter contributing to the wave dissipation variability is the shoot stem density explaining over 80% of the variability ($R^2$=0.81). The least squared fit to wave dissipation that included all parameters combined explains 98% of the variability. When fitting models, it is possible to increase the explained variance by using more complex fitting models adding parameters, but doing so may result in over-fitting. The Bayesian Information Criterion (BIC; Schwarz, 1978; Aretxabaleta and Smith, 2011) provides a non-subjective metric for the best fit by penalizing over-parameterization. BIC resolves over-fitting by introducing a penalty term for the number of parameters in the model. For wave dissipation, the BIC approach identified a fit based exclusively on density as the model that best match the data while preventing over-fitting. The selection of density as the single most relevant parameter is consistent with the Sobol' indices result (Table 3).

The kinetic energy variability is also associated with stemshoot density changes, but the percentage of explained variability (42%) is smaller than for wave dissipation. Diameter and height also contributed to changes in kinetic energy. The combination of stem density, height, and diameter provided the optimal fit of the data (selected by minimizing BIC) and explained 89% of variability in kinetic energy. Similar results were obtained for TKE with density explaining 45% of the variability but the combination of stem density, height, and diameter providing the optimal fit to TKE (selected by minimizing BIC) and explained 87% of the variability. The model response of water level variability is also best explained by a combination of stem density, height, and diameter (96% of water level variance explained). Thickness was not correlated with wave dissipation, kinetic energy or TKE and only contributed to water level gradient variability.

**4.4 Limitations of the current sensitivity methodology**

The model configuration chosen includes vegetation covering a small fraction of the water column to allow for proper wave dissipation. Many species of seagrass have a larger vertical footprint and can also exhibit much higher shoot densities. The goal of the study is to provide estimates on the relative importance of the different parameters through a robust sensitivity approach. The current work assumed rigid vegetation blades, while the model is capable of including flexible vegetation by altering the blade scale. The expected effect of flexible blades would be to reduce the relative importance of vegetation length ($l_v$) on the model outputs. In addition, the present work assumes a constant drag coefficient for cylindrical vegetation shape; the influence of a variability drag coefficient can be a subject of a future sensitivity study. Other model parameters such as vertical and horizontal resolution, mixing parameterization, and wave and hydrodynamic forcings will also affect model results, but were beyond the scope of the current study.

**5 Conclusions**

The coupled wave-flow-vegetation module in the COAWST modeling system provides a tool to study vegetated flows in riverine, lacustrine, estuarine and coastal environments. The resulting flow field in the presence of vegetation depends on its properties, including vegetation stemshoot density, height, diameter, and thickness. The sensitivity of the hydrodynamic and wave conditions to changes in vegetation parameters is investigated. The sensitivity analysis helps in understanding the multiparameter/multiresponse of various interactions within the model. We use an existing tool comprising of polynomial quadrature method to investigate investigate the sensitivity of plant input properties for the vegetation module in COAWST model. that formulates the Effective Quadratures method to quantify the sensitivity of plant input properties for the vegetation module in COAWST model. the sensitivity of plant properties on the resulting output. The decomposition of the variance of the model solution given by the Sobol' indices is assigned to plant parameters.

The method of using Sobol' indices to quantify sensitivity can be computationally expensive. One of the goals of this work is to demonstrate a robust, practical, and efficient approach for the parameter sensitivity analysis. We show that the approach of using Effective Quadratures method to select a parameter space that is consistent with physical understanding significantly reduces the computational time required to obtain the Sobol' indices.

The evaluation of Sobol' indices shows that the input values of plant stem density, height and to a lesser degree, diameter are consequential in determining kinetic energy, turbulent kinetic energy and water level changes. Meanwhile, the wave dissipation is mostly dependent on the variation in plant density.

The sensitivity analysis for the vegetation model in COAWST presented here provides guidance for observational and modelling work by allowing future efforts to focus on constraining the most influential inputs without having to explore the entire parameter space. An accurate representation of processes causing kinetic energy and turbulent kinetic energy leads to enhanced understanding of sediment processes while accurate water level computations help to predict coastal flooding caused by storm surge. Similarly, wave attenuation measurements in open coasts are better understood with a correct representation of wave dissipation. In the future, we intend to perform a similar sensitivity analysis with the inclusion of a biological model that will affect plant growth, thus allowing a time dependence of model input and response. In addition,

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the influence of vegetation on sediment transport will be explored. As model complexity increases with more parameters representing additional processes, input parameter sensitivity is required for the model to be applied on practical applications.

## 6 Code availability

The Effective Quadratures methodology is an open source Python based tool designed to perform sensitivity analysis for a given physical system. The instructions to install the code along with all the open source files for this tool are detailed here: https://github.com/Effective-Quadratures/Effective-Quadratures. For any further inquiries about the Effective Quadratures methodology, please contact the corresponding author Dr. P. Seshadri (ps583@cam.ac.uk). ps583@cam.ac.uk.

The COAWST model is an open source coupled hydrodynamics and wave model containing vegetation effects mainly coded in Fortran 77. This model provided the physical setting to perform the sensitivity analysis. The code is available from https://coawstmodel-trac.sourcerepo.com/coawstmodel_COAWST after registration via email with J. C. Warner (jcwarner@usgs.gov).

## 7 Data availability

The model output from various simulations used to perform sensitivity analysis in this study are available at: http://geoport.whoi.edu/thredds/catalog/clay/usgs/users/tkalra/senstivity_study/catalog.html. The link contains a "README.txt" file that explains how the folder is organized to contain model output.

## 8 Author contribution

T. S. Kalra, and N. K. Ganju designed and simulated the numerical experiment space for sensitivity analysis. P. Seshadri developed the Effective Quadratures methodology to quantify the model sensitivity. A. Beudin provided inputs on the mechanistic processes involving the vegetation model. T. S. Kalra and A. Arextabaleta performed the data analysis from the output of sensitivity study and prepared the manuscript with contributions from all co-authors. We also thank you P. Soupy Daylander at U. S. Geological Survey, St. Petersburg Coastal and Marine Science Center for providing her feedback to improve the clarity of the paper. We thank the anonymous reviewers for their careful reading of our manuscript and their insightful comments and suggestions.

## 9 Disclaimer

Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the U.S. Government.

## 10 Acknowledgement

5 **11 References**

Aretxabaleta A.L., Smith K.W.: Analyzing state-dependent model-data comparison in multi-regime systems, Computers & Geosciences, 15, 627–636, 2011.

Baptiste M., Ballabrera-Poy J., García-Ladona E., and Font, J.: Surface salinity response to changes in the model parameters and forcings in a climatological simulation of the eastern North-Atlantic Ocean, Ocean Modeling, 23, 21-32, 2008.

10 Bastidas, L. A., Gupta, H. V., Sorooshian, S., Shuttleworth, W. J., and Yang, Z. L.: Sensitivity analysis of land surface scheme using multicriteria methods, Journal of Geophysical Research, 104, 481-490, 1999.

Beudin, A., Kalra, T. S., Ganju, N., K., and Warner, J.C.: Development of a Coupled Wave-Current-Vegetation Interaction, Computers & Geosciences, 100, 76-86, 2017.

Bryan, F.: Parameter Sensitivity of Primitive Equation Ocean General circulation models, Journal of Physical oceanography, 15 17, 970-985, 1986.

Booij, N., Ris, R. C., and Holthuijsen, L. H.: A third-generation wave model for coastal regions, Part I, Model description and validation, Journal of Geophysical Research C4, 104, 7649-7666, 1999.

Carr, J., D'Odorico P., McGlathery K., and Wiberg, P.: Stability and bistability of seagrass ecosystems in shallow coastal lagoons: role of feedbacks with sediment resuspension and light attenuation, Journal of Geophysical Research, 115, G03011, 20 2010.

Chen, S. N., Sanford L., Koch E. W., Shi F., and North, E. W.: A nearshore model to investigate the effects of seagrass bed geometry on wave attenuation and suspended sediment transport, Estuaries and Coasts, 30(2), 296-310, 2007.

Costanza, R., d'Arge, R., de Groot, R., Farberk, S., Grasso, M., Hannon, B., Limburg, K., Naeem, S., O'Neill, R.V., Paruelo, J., and Raskin, R.G.: The value of the world's ecosystem services and natural capital, Nature 387, 253-260, 1997.

25 Dalrymple, R. A., Kirby, J. T., and Hwang, P. A.: Wave diffraction due to areas of energy dissipation. Journal of Waterway, Port, Coastal, and Ocean Engineering, 110, 67-79, 1984.

de Vriend, H. J.: Integrated research results on hydrobiosedimentary processes in estuaries: algorithm for vegetation friction factor, Defra R&D Technical Report FD1905/TR3, 2006.

Fennel, K., Losch, M., Schroter, J., and Wenzel, M.: Testing a marine ecosystem model: sensitivity analysis and parameter 30 optimization, Journal of Marine Systems, 28, 45–63, 2000.

Geraci, G., Congedo, P. M., Abgrall, R., and Iaccarino, G.: High-order statistics in global sensitivity analysis: Decomposition and model reduction. Computer Methods in Applied Mechanics and Engineering, *301*, 80-115, 2016.

Heck, K.L., Hays, G. and Orth, R.J.: Critical evaluation of the nursery role hypothesis for seagrass meadows, Marine Ecology Progress Series, 253, 123-136, 2003.

Hemming, M. A., and Duarte, C. M.: Seagrass Ecology, Cambridge, UK: Cambridge University Press, 2000.

Lapetina A., and Sheng, Y. P.: Three-dimensional modeling of storm surge and inundation including the effects of coastal vegetation, Estuaries and Coasts, 37, 1028-1040, 2014.

Larkum, A. W. D, Orth, R. J., and Duarte, C. M.: In Seagrasses: Biology, Ecology and Conservation, Springer Netherlands, 2007.

5    Luhar M., Coutu S., Infantes E., Fox S., and Nepf H. M.: Wave-induced velocities inside a model seagrass bed, Journal of Geophysical Research, 115, C12005, 2010.

Luhar, M., and Nepf, H. M.: Flow-induced reconfiguration of buoyant and flexible aquatic vegetation. Limnology and Oceanography, 56(6), 2003-2017, 2011.

10   Luhar, M., and Nepf, H. M.: Wave-induced dynamics of flexible blades. Journal of Fluids and Structures, 61, 20-41, 2016.

Le Bouteiller, C., and Venditti, J. G.: Sediment transport and shear stress partitioning in a vegetated flow. Water Resources Research, 51, 2901-2922, 2014.

Madsen, O.S.: Spectral wave–current bottom boundary layer flows. Proceedings of the 24th International Conference on Coastal Engineering Research Council, Kobe, Japan, 384-398, 1994.

15   Marjoribanks, T. I., Hardy, R. J., and Lane, S. N.: The hydraulic description of vegetated river channels: the weaknesses of existing formulations and emerging alternatives, WIREs Water, 1, 549-560, 2014.

Mendez, F. M., and Losada, I. J.: An empirical model to estimate the propagation of random breaking and nonbreaking waves over vegetation fields, Coastal Engineering, 51, 103-118, 2004.

Möller, I., Spencer, T., French, J. R., Legget, D. J., and Dixon, M.: Wave transformation over salt marshes: a field and
20   numerical modeling study from Norfolk, England. Estuarine, Coastal and Shelf Science, 49, 411-426, 1999.

Morin, J., Leclerc, M., Secretan, Y., and Boudreau, P.: Integrated two-dimensional macrophytes-hydrodynamic modelling, Journal of Hydraulic Research, 38, 163-172, 2000.

Morison, J. R., O'Brien, M. P., Johnson, J. W., and Schaaf, S. A.: The force exerted by surface waves on piles, Petroleum Transactions, AIME, 189, 149-154.

25   Mourre, B., Ballabrera-Poy, J., García-Ladona, E., Font, J.: Surface salinity response to changes in the model parameters and forcings in a climatological simulation of the eastern North-Atlantic Ocean, Ocean Modeling, 23, 37-49, 2008.

Kennish, M. J., Fertig, M. B., and Sakowicz, G. P.: In situ Surveys of Seagrass Habitat in the Northern Segment of the Barnegat Bay-Little Egg Harbor Estuary, Barnegat Bay Partnership, Final Report, 2013.

Kombiadou, K., Ganthy, F., Verney, R., Plus, M., and Sottolichio, A.: Modelling the effects of Zostera noltei meadows on
30   sediment dynamics: application to the Arcachon lagoon, Ocean Dynamics, 64, 1499-1516, 2014.

Ree, W. O.: Hydraulic characteristics of vegetation for vegetated waterways, Agricultural Engineering, 30, 184-189, 1949.

Saltelli, A., Ratto, M., Andres, T., Campolongo, F., Cariboni, J., Gatelli, D., Saisana, M., and Tarantola, S.: Global sensitivity analysis: the primer, John Wiley & Sons, Chichester, 312 pp, 2008.

Rodi, W.: Turbulence models and their application in hydraulics, a state of the art review. Technical report, International

Association of Hydraulics Research, Delft, 1984.

Rosero, E., Yang, Z. L., Wagener, T., Gulden, L. E., Yatheendradas, S., and Niu, G. Y.: Quantifying parameter sensitivity, interaction, and transferability in hydrologically enhanced versions of the Noah land surface model over transition zones during the warm season, Journal of Geophysical Research 115, 2010.

5    Seshadri, P., Narayan, A., and Mahadevan, S.: Effectively Subsampled Quadratures for Least Squares Polynomial Approximations, arXiv: 1601.05470, 2017a.

Seshadri, P., Parks, G. T.: Effective Quadratures (EQ): Polynomials for Computational Engineering Studies, Journal of Open Source Software, 2(11), DOI: 10.21105/joss.00166, 2017b.

Sheng, Y. P., Lapetina, A., and Ma, G.: The reduction of storm surge by vegetation canopies: three-dimensional simulations,
10   Journal of Geophysical Research, 39, L20601, 2012.

Smith, R. C.: Uncertainty quantification: theory, implementation, and applications, Vol. 12. SIAM, 2013.

Soulsby, R. L.: Dynamics of Marine Sands, Thomas Telford, London, 249 pp, 1997.

Sobol', Ilya. M.: Sensitivity estimates for nonlinear mathematical models, Mathematical Modelling and Computational Experiments, 1.4, 407-414, 1993.

15   Sudret, B.: Global sensitivity analyzing using polynomial chaos expansions, Reliability Engineering and System Safety, 93, pp. 964-979, 2008.

Suzuki T., Zijlema, M., Burger, B., Meijer, M. C., and Narayan, S., Wave dissipation by vegetation with layer schematization in SWAN, Coastal Engineering, 59(1): 64-71, 2012.

Temmerman, S., Bouma, T. J., Govers, G., Wang, Z. B., De Vries, M. B., and Herman, P. M. J.: Impact of vegetation on flow
20   routing and sedimentation patterns: three-dimensional modeling for a tidal marsh, Journal of Geophysical Research, 110, F04019, 2005.

Uittenbogaard, R.: Modelling turbulence in vegetated aquatic flows, International workshop on Riparian Forest vegetated channels: hydraulic, morphological and ecological aspects, Trento, Italy, 2003.

Umlauf, L., and Burchard, H.: A generic length-scale equation for geophysical turbulence models, Journal of Marine
25   Research, 61, 235-265, 2003.

Van Katwijk, M. M., Bos, A.R., Hermus, D. C. R., and Suykerbuyk, W.: Sediment modification by seagrass beds: muddification and sandification induced by plants cover and environmental conditions, Estuarine, Coastal and Shelf Science, 89, 175-181, 2010.

Wamsley, T.V., Cialone, M.A., Smith, J.M., Atkinson, J.H. and Rosati, J.D.: The potential of wetlands in reducing storm
30   surge, Ocean Engineering, 37(1), 59-68, 2010.

Warner, J. C., Sherwood, C. R., Arango, H. G., and Signell, R. P.: Performance of four turbulence closure models implemented using a generic length scale method, Ocean Modelling, 8, 81-113, 2005.

Warner J. C., Sherwood, C. R., Signell, R. P., Harris, C. K., and Arango, H.G.: Development of a three-dimensional, regional, coupled wave, current, and sediment-transport model, Computer & Geosciences, 34, 1284-1306, 2008.

Warner, J. C., Perlin, N., and Skyllingstad, E. D.: Using the Model Coupling Toolkit to couple earth system models, Environmental Modelling & Software, 23, 1240-1249, 2008.

Warner, J. C., Armstrong, B., He, R., and Zambon, J. B.: Development of a Coupled Ocean-Atmosphere-Wave-Sediment Transport (COAWST) Modeling System, Ocean Modelling, 35, 230-244.

5 Warner, J. C., Defne, Z., Haas, K., and Arango, H. G.: A wetting and drying scheme for ROMS, Computer & Geosciences, 58, 54-61, 2013.

Wu, W.: A 3-D phase-averaged model for shallow-water flow with waves in vegetated water, Ocean Dynamics, 64, 1061-1071, 2014.

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| Process | Equation | $n_v$ | $l_v$ | $b_v$ | $t_v$ |
|---------|----------|-------|-------|-------|-------|
| Extraction of Momentum | $F_{d,veg,u} = \frac{1}{2} C_D b_v n_v u \sqrt{u^2 + v^2}$ <br> $C_D$ = Plant drag coefficient <br> u,v = Horizontal velocity components at each vertical level | X | | X | |

| Process | Equation | | | | |
|---|---|---|---|---|---|
| Turbulence Production<br><br>Uittenbogaard (2003) | $$P_{veg} = \sqrt{\left(F_{d,veg,u}u\right)^2 + \left(F_{d,veg,v}v\right)^2}$$ | X | | X | |
| Turbulence Dissipation<br><br>Uittenbogaard (2003) | $$D_{veg} = c_2 \frac{P_{veg}}{\tau_{eff}}$$ $$\tau_{eff} = min\left(\tau_{free}, \tau_{veg}\right)$$ $$\tau_{free} = \frac{k}{\varepsilon}$$ $$\tau_{veg} = \left(\frac{L^2}{c_k{}^2 P_{veg}}\right)^{1/3}$$ $$L(z) = c_l \left(\frac{1 - b_v t_v n_v}{n_v}\right)^{1/2}$$ $P_{veg}$ = Turbulence Production<br>$\tau_{free}$ = Dissipation time scale of free turbulence<br>$k$ = Turbulent kinetic energy<br>$\varepsilon$ = Turbulence dissipation<br>$\tau_{veg}$ = Dissipation time scale of free turbulence<br>$$c_k = \left(c_\mu^0\right)^4 \simeq 0.09$$ $L$ = typical length scale between the plants<br>$c_l$ = Lift coefficient of order unity | X | | X | X |
| Wave Dissipation<br><br>Mendez and Losada (2004)<br>Dalrymple et al. (1984) | $$S_{d,veg} = \sqrt{\frac{2}{\pi}} g^2 \widetilde{C_D} b_v n_v \left(\frac{\tilde{k}}{\tilde{\sigma}}\right)^3$$ $$\frac{sinh^3(\tilde{k}l_v) + 3\, sinh(\tilde{k}l_v)}{3\tilde{k}cosh^3(\tilde{k}h)} \sqrt{E_{tot}} E(\sigma, \theta)$$ $\widetilde{C_D}$ = Bulk drag coefficient<br>$\tilde{k}$ = Mean wave number<br>$\tilde{\sigma}$ = Mean wave frequency<br>$h$ = Water depth<br>$E_{tot}$ = Total wave energy<br>$E$ = Wave energy at frequency $\sigma$ and direction $\theta$ | X | X | X | |
| Wave induced streaming<br><br>Luhar et al., 2010 | $$F_{s,veg} = \frac{S_{d,veg,tot}\, \tilde{k}}{\rho_0\, \tilde{\sigma}}$$ $S_{d,veg,tot}$ = Total wave energy dissipation<br>$\tilde{k}$ = Mean wave number<br>$\tilde{\sigma}$ = Mean wave frequency<br>$\rho_0$ = Reference density of seawater | X | X | X | |

Table 1: Processes in ROMS and SWAN to model the presence of vegetation. The different input parameters (stem density, $n_v$; height, $l_v$; diameter, $b_v$; and thickness, $t_v$) affecting model wave and hydrodynamics are included.

| | Stem dDensity (stems/m²) $n_v$ | Height (m) $l_v$ | Diameter (mm) $b_v$ | Thickness (mm) $t_v$ |
|---|---|---|---|---|
| 1. | 144.3 | 0.24 | 6.0 | 0.6 |
| 2. | 62.1 | 0.17 | 3.0 | 0.6 |
| 3. | 226.5 | 0.3 | 6.0 | 0.3 |
| 4. | 144.3 | 0.17 | 9.0 | 0.9 |

| | | | | |
|---|---|---|---|---|
| 5. | 144.3 | 0.3 | 3.0 | 0.9 |
| 6. | 62.1 | 0.3 | 6.0 | 0.3 |
| 7. | 226.5 | 0.17 | 6.0 | 0.3 |
| 8. | 144.3 | 0.3 | 9.0 | 0.9 |
| 9. | 144.3 | 0.24 | 9.0 | 0.3 |
| 10. | 226.5 | 0.24 | 6.0 | 0.9 |
| 11. | 144.3 | 0.24 | 3.0 | 0.3 |
| 12. | 62.1 | 0.24 | 6.0 | 0.9 |
| 13. | 62.1 | 0.17 | 6.0 | 0.3 |
| 14. | 62.1 | 0.24 | 9.0 | 0.6 |
| 15. | 144.3 | 0.17 | 3.0 | 0.9 |

**Table 2: Plant property input combination for different simulations during sensitivity analysis.**

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| | Plant Stem Density Density $n_v$ | Plant Height $l_v$ | Plant Diameter $b_v$ | Plant Thickness $t_v$ |
|---|---|---|---|---|
| • Wave dissipation | • 0.68 | • 0.24 | • 0.032 | • 0.01 |
| • Kinetic energy | • 0.36 | • 0.44 | • 0.12 | • 0.03 |

| | | | |
|---|---|---|---|
| • Maximum water level change | • 0.38 | • 0.43 | • 0.15 | • 0.01 |
| • Turbulent kinetic energy | • 0.35 | • 0.42 | • 0.12 | • 0.03 |

**Table 3: Sobol Indices for all the outputs.**

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**Figure 1: Schematic showing the vegetation module implementation in COAWST model (Figure adapted from Beudin et. al, ~~2016~~2017)**
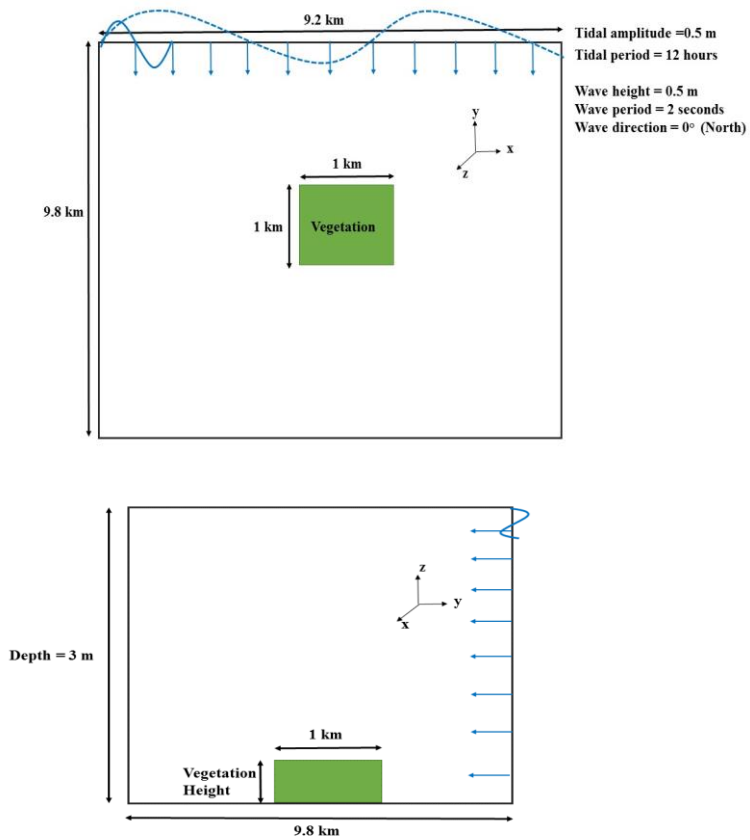
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9.2 km

Tidal amplitude =0.5 m
Tidal period = 12 hours

Wave height = 0.5 m
Wave period = 2 seconds
Wave direction = 0° (North)

1 km

9.8 km

1 km   Vegetation

Depth = 3 m

1 km

Vegetation
Height

9.8 km
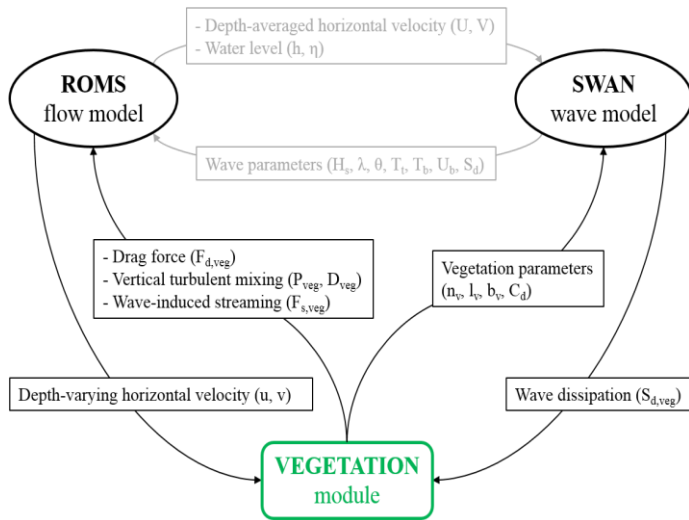
**Figure 2: Schematic showing the idealized domain (Not drawn to scale)**

**(a)  Plan view and (b) Cross-sectional view.**
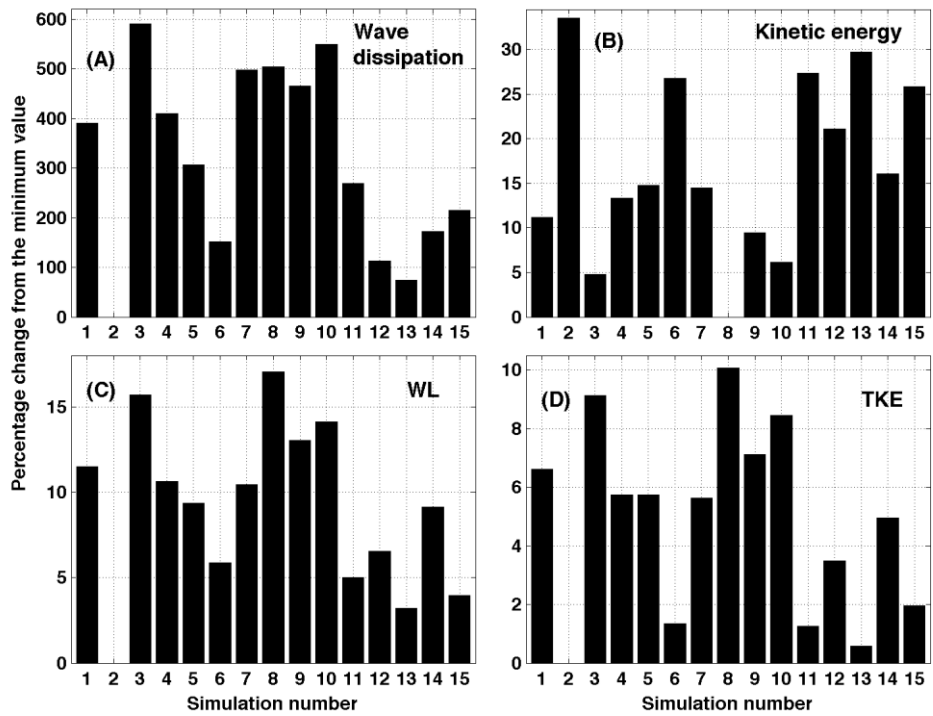
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**Figure 3: Percentage change from minimum for the four impact parameters: a) wave dissipation; b) kinetic energy; c) maximum water level change (WL); and d) Turbulent Kinetic Energy (TKE).**

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Standard deviation in wave dissipation $(Wm^{-2})$
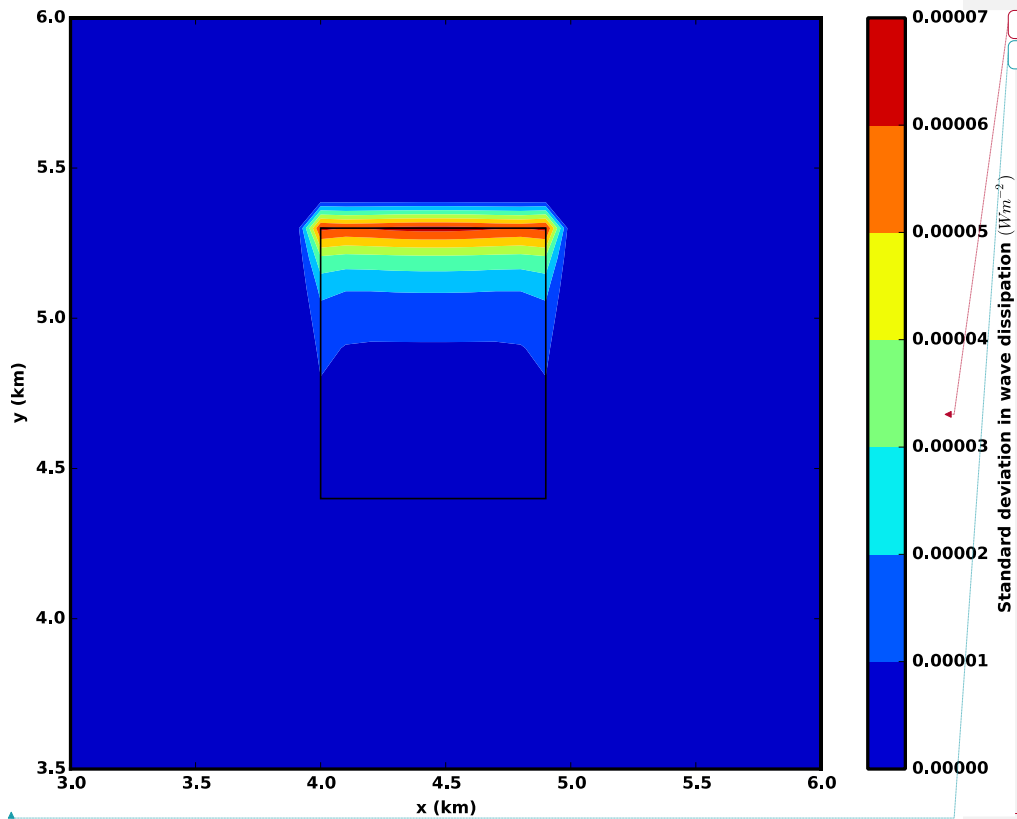
Figure 4: Standard deviation from wave dissipation (W m$^{-2}$) in presence of vegetation (Plan view). The area of the vegetation patch is highlighted in the middle of the domain.

**Figure 4: Standard deviation from wave dissipation (W m⁻²) in presence of vegetation (Plan view). The area of the vegetation patch is highlighted in the middle of the domain.**

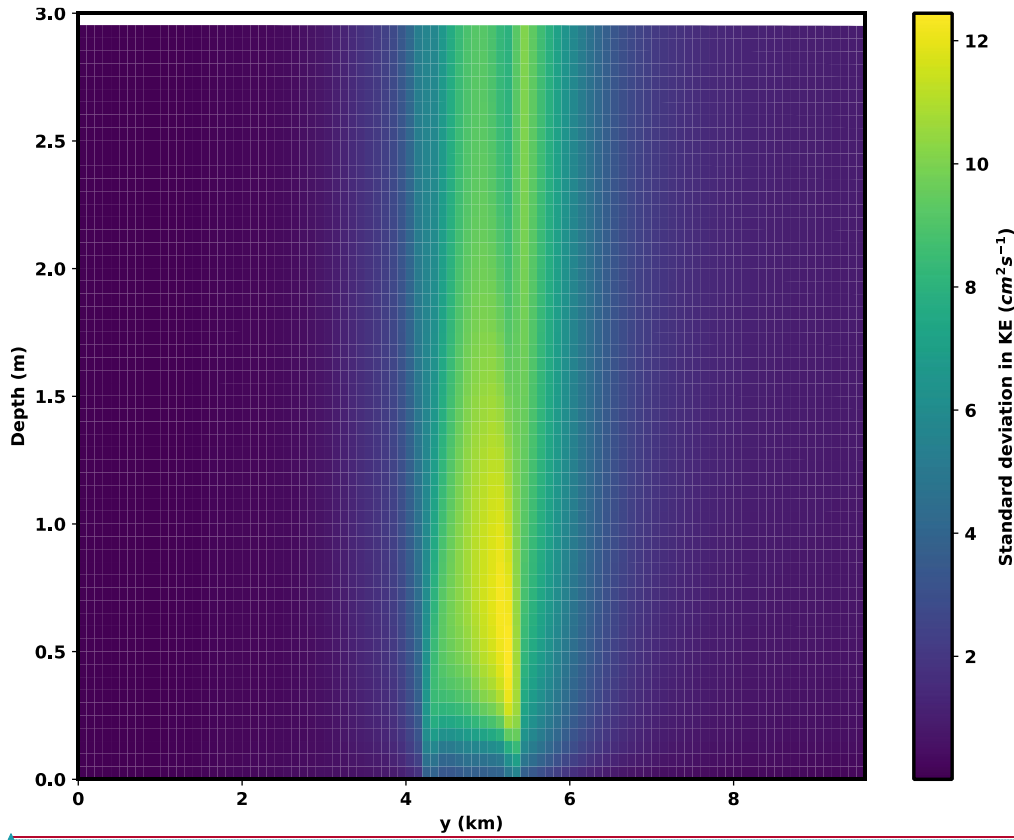**Figure 5: Standard deviation in kinetic energy (cm² s⁻¹) in presence of vegetation (cross-sectional view).**
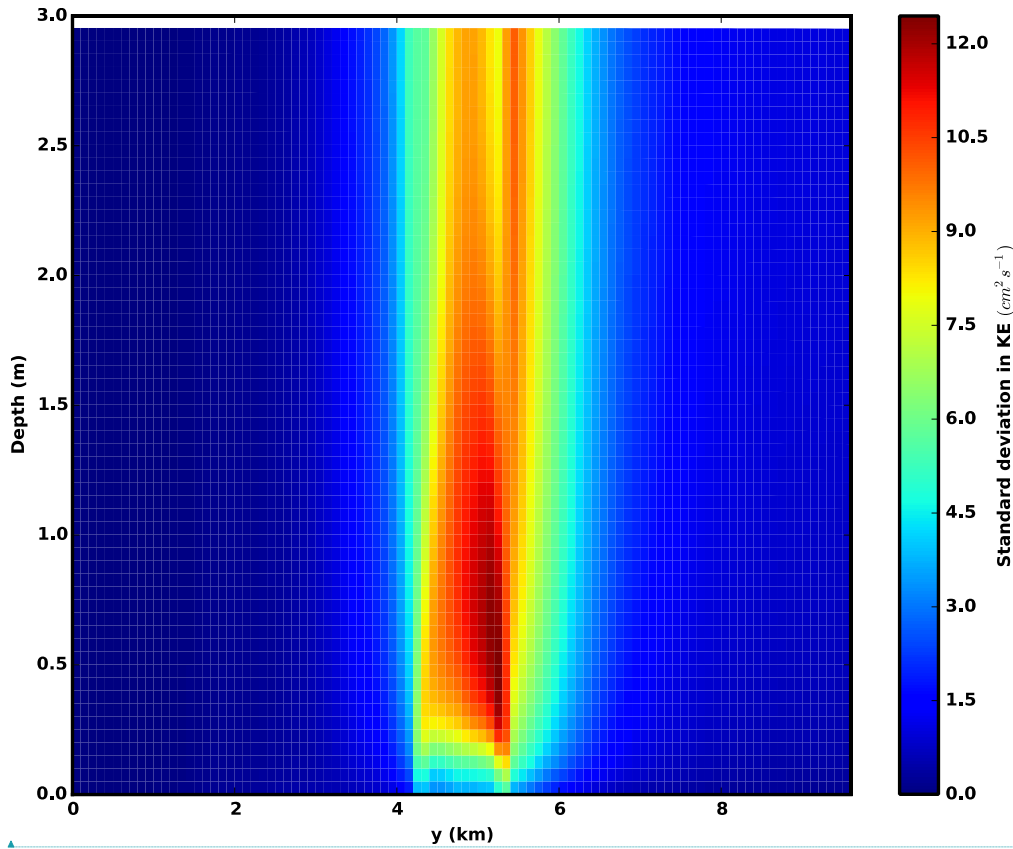
**Figure 5: Standard deviation in kinetic energy (cm² s⁻¹) in presence of vegetation (cross-sectional view).**
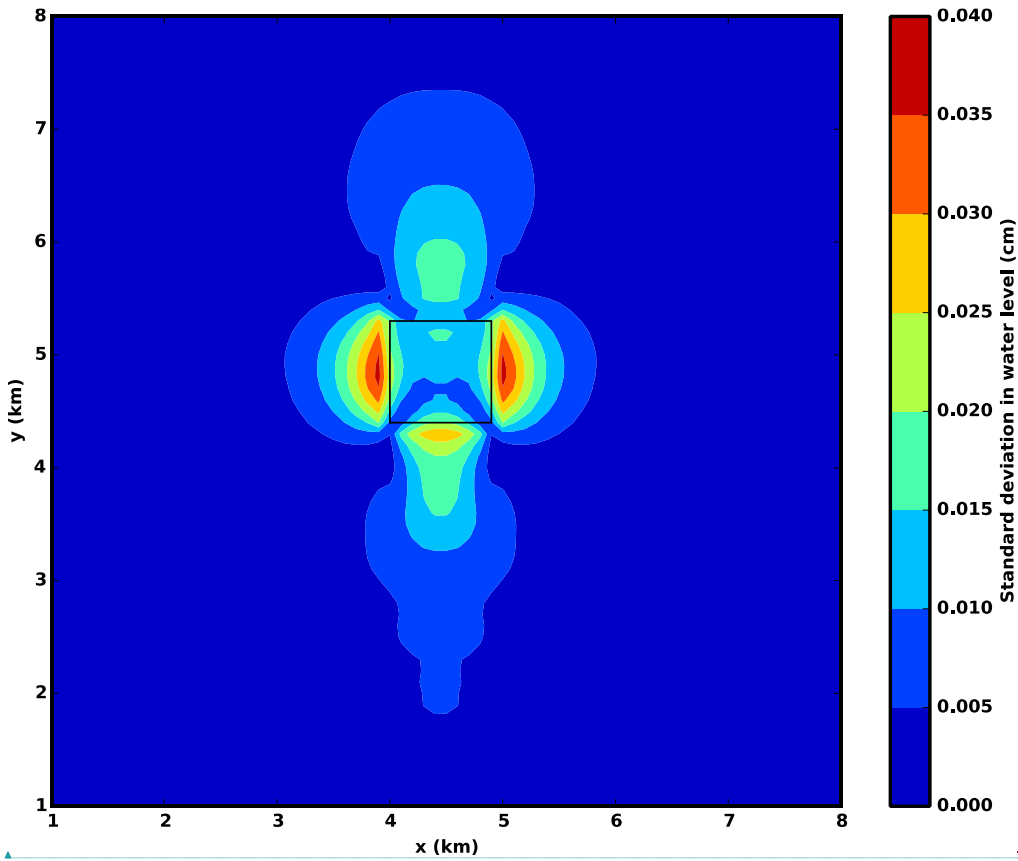
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**Figure 6: Standard deviation in water level in presence of vegetation (plan view). The area of the vegetation patch is highlighted in the middle of the domain.**

**F**
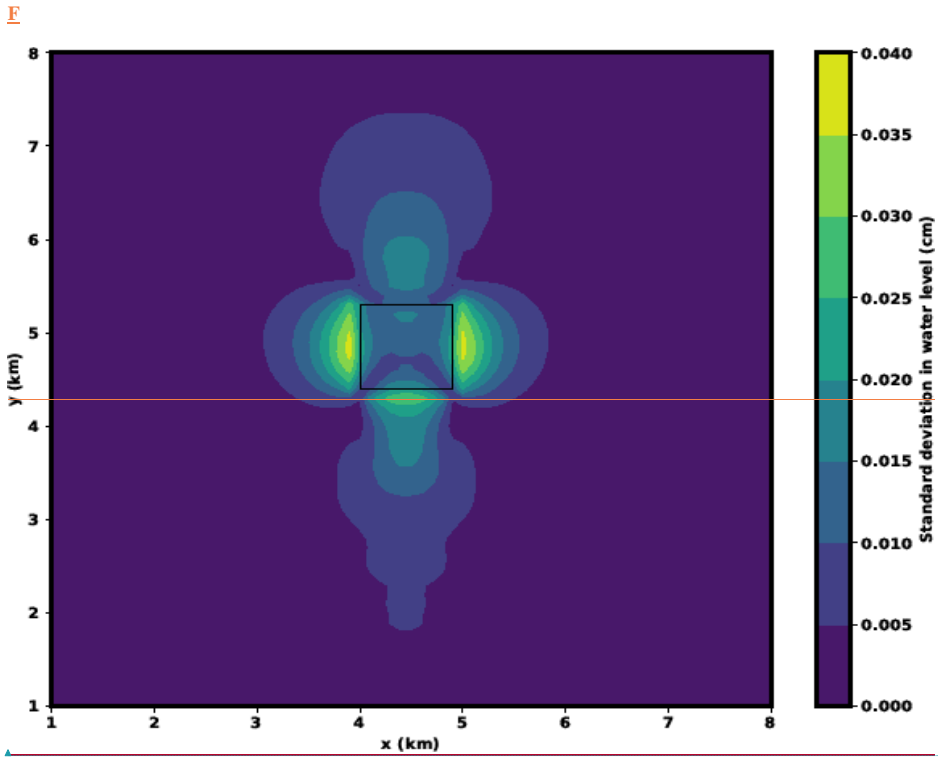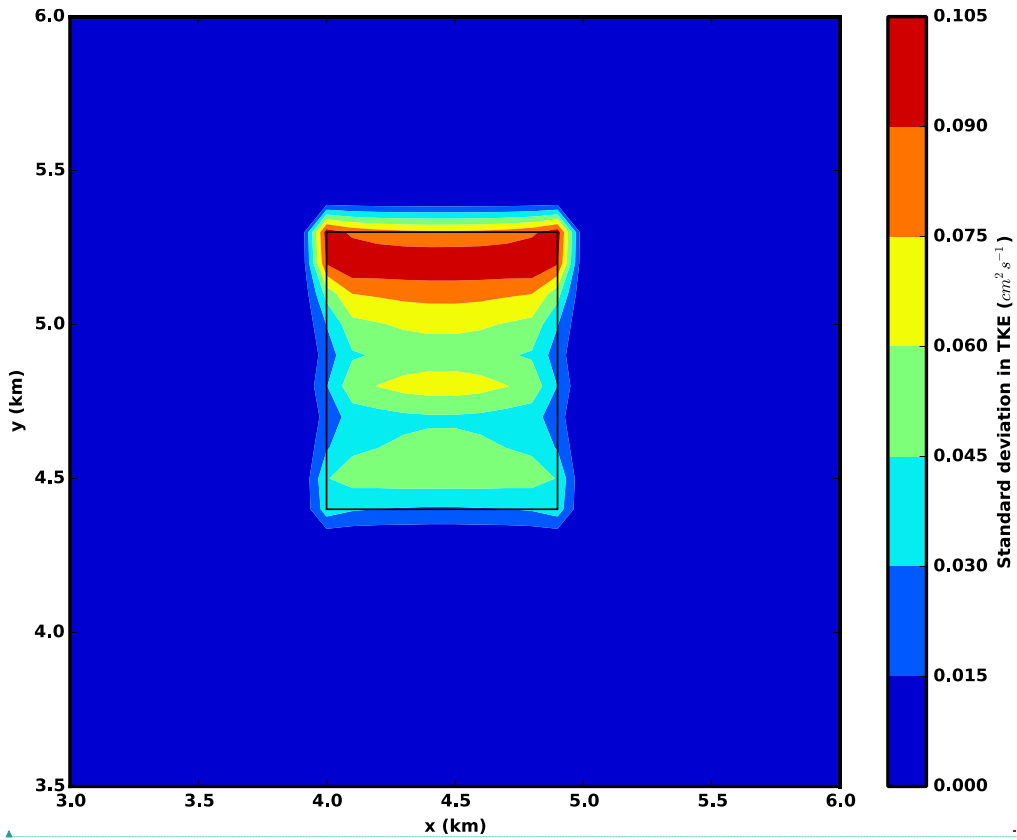


**Figure 6: Standard deviation in water level in presence of vegetation (plan view). The area of the vegetation patch is highlighted in the middle of the domain.**

Field Code Changed
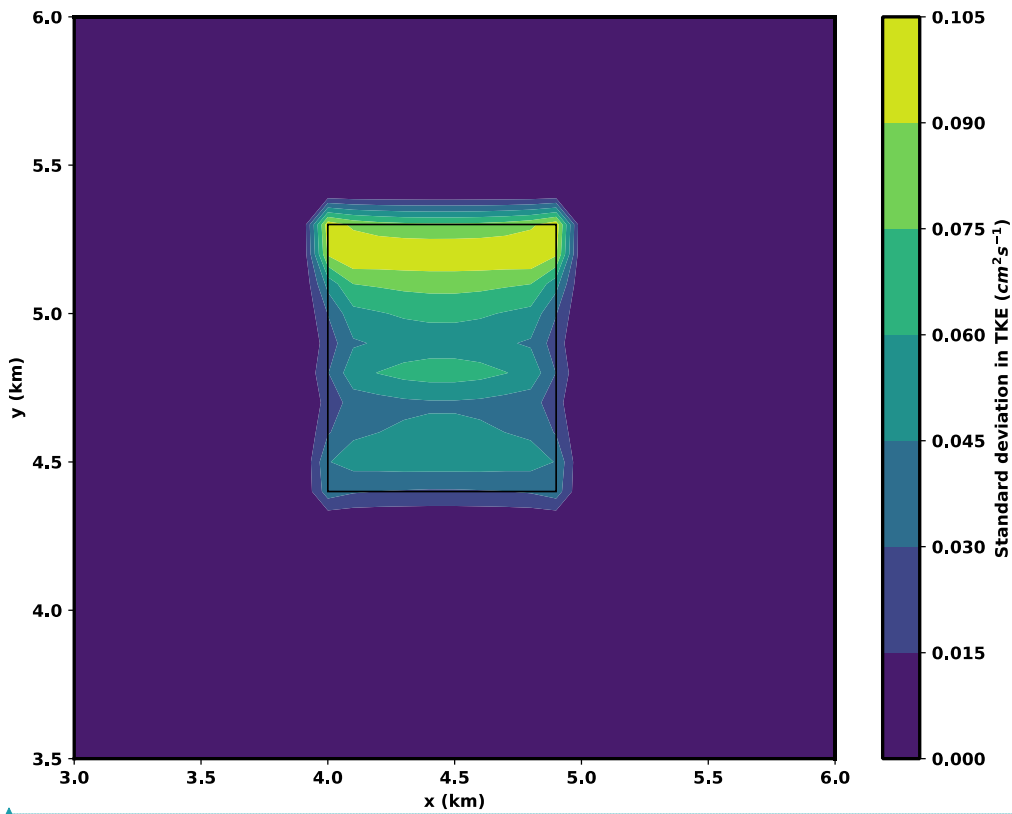
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**Figure 7: Standard deviation in Turbulent Kinetic Energy (TKE) (cm² s⁻¹) in presence of vegetation (plan view). The**
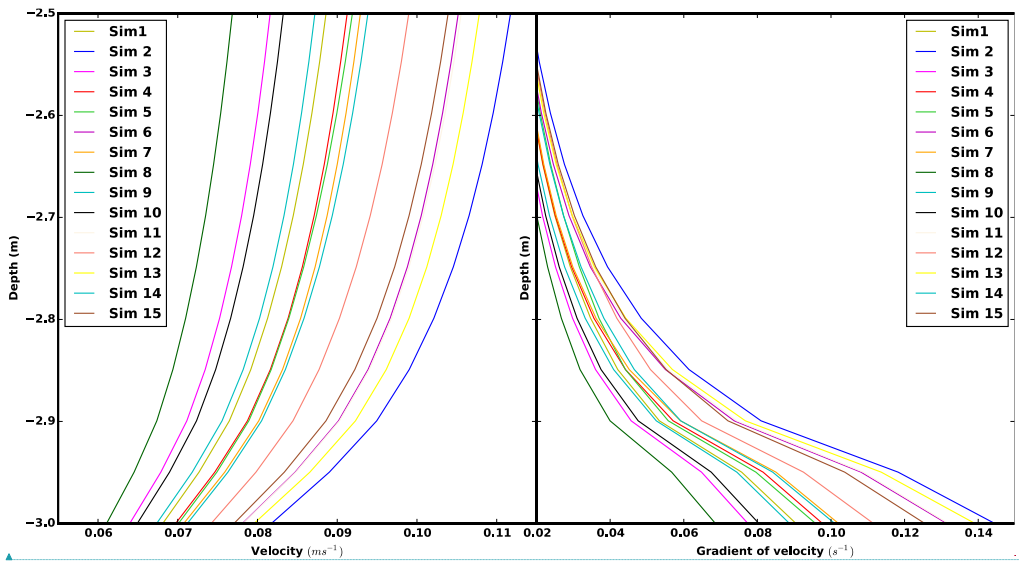10   **area of the vegetation patch is highlighted in the middle of the domain.**

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**Figure 7: Standard deviation in Turbulent Kinetic Energy (TKE) (cm$^2$ s$^{-1}$) in presence of vegetation (plan view). The area of the vegetation patch is highlighted in the middle of the domain.**

**Figure 8: (a) Velocity (m s⁻¹) profile and (b) Vertical gradient (s⁻¹) of velocity profile varying with depth in front of the vegetation patch at a particular time instance during flood for different simulations.**

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**Figure 8: (a) Velocity (m s⁻¹) profile and (b) Vertical gradient (s⁻¹) of velocity profile varying with depth in front of the vegetation patch at a particular time instance during flood for different simulations.**
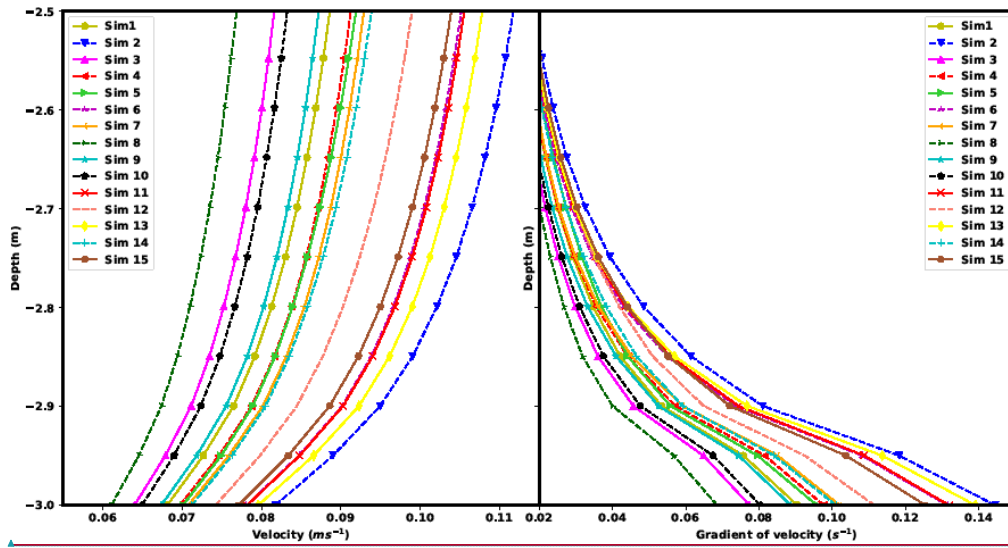
**4.1 Final draft of GMD paper without any markups**

# Sensitivity Analysis of a Coupled Hydrodynamic-Vegetation Model Using the Effectively Subsampled Quadratures Method (ESQM v5.2)

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**Abstract.** Coastal hydrodynamics can be greatly affected by the presence of submerged aquatic vegetation. The effect of vegetation has been incorporated into the Coupled-Ocean-Atmosphere-Wave-Sediment Transport (COAWST) Modeling System. The vegetation implementation includes the plant-induced three-dimensional drag, in-canopy wave-induced streaming, and the production of turbulent kinetic energy by the presence of vegetation. In this study, we evaluate the sensitivity of the flow and wave dynamics to vegetation parameters using Sobol' indices and a least squares polynomial approach referred to as Effective Quadratures method. This method reduces the number of simulations needed for evaluating Sobol' indices and provides a robust, practical, and efficient approach for the parameter sensitivity analysis. The evaluation of Sobol' indices shows that kinetic energy, turbulent kinetic energy, and water level changes are affected by plant stem density, height, and to a lesser degree, diameter. Wave dissipation is mostly dependent on the variation in plant stem density. Performing sensitivity analyses for the vegetation module in COAWST provides guidance to optimize efforts and reduce exploration of parameter space for future observational and modeling work.

## 1 Introduction

The presence of aquatic vegetation (e.g., mangroves, salt marshes, and seagrass meadows) provides several ecological benefits including nutrient cycling, habitat provision, and sediment stabilization (Costanza et al., 1997). Vegetation provides habitat for many species of epiphytes, invertebrates, and larval and adult fish (Heck et al., 2003). Seagrass meadows reduce

sediment resuspension, thereby stabilizing bottom sediment, increasing light penetration, and improving water clarity in a positive feedback loop (Carr et al., 2010). In addition, aquatic vegetation provides coastal protection by absorbing wave energy (Wamsley et al., 2010).

One approach to implement the influence of aquatic vegetation on circulation is by increasing the bottom roughness coefficient (Ree, 1949; Morin et al., 2000). More recently, the effect of vegetation being studied through parameterization as form drag as opposed to skin friction in 2-D depth averaged models (Chen et al., 2007; Le Bouteiller and Venditti, 2015). To account for 3-D vertical structures, estuary-scale models have implemented both mean and turbulent flow impacts of vegetation (Temmerman et al., 2005; Kombiadou et al. 2014; Lapetina and Sheng, 2015). In addition to impacts on the flow-field, the presence of vegetation also results in wave attenuation. The decay of wave height over vegetation has been simulated by enhancing bed roughness (Möller et al., 1999; de Vriend, 2006; Chen et al., 2007). A more physical description of wave attenuation due to vegetation was developed by Dalrymple et. al (1984), who approximated wave energy loss due to stalks approximated as cylinders. This approach has been applied in spectral wave models and calibrated against flume experiment results (Mendez and Lozada, 2004; Suzuki et al., 2012; Wu, 2014; Bacchi et al., 2014).

Recently, Beudin et al. (2017) implemented the effects of vegetation in a vertically varying water column through momentum extraction and turbulence dissipation and generation using a 3D hydrodynamic model and accounting for wave dissipation due to vegetation in a spectral wave model. The modeling approach was implemented and tested within the open source COAWST (Coupled-Ocean-Atmospheric-Wave-Sediment Transport) modeling system that couples hydrodynamic and wave models (Warner et al, 2010). The vegetation module was based on modifications to the flow field resulting from three-dimensional drag, in-canopy wave-induced streaming, and production of turbulent kinetic energy in the hydrodynamics model (ROMS), along with energy dissipation and resultant hydrodynamic feedback from the wave model (SWAN).

The vegetation module requires the user to input a given set of plant properties (stem density, height, diameter, and thickness). These vegetation properties can be highly variable depending on the season and environment, yet obtaining a full set of measurements in realistic settings is impractical. Identifying which properties have the greatest influence on the resulting flow dynamics can reduce the amount of observational data required to robustly parameterize the model, and/or reduce the number of runs required in a model ensemble to quantify the uncertainty associated with data gaps. Our study aims to perform a systematic sensitivity analysis to quantify the effect of changing the vegetation properties on the resulting hydrodynamic output. The results of the sensitivity analysis can be used to select and rank the most important parameters for calibration. Two conditions are required for the model to display a significant sensitivity: (1) a sufficient modification of one of the forcing parameters and (2) a change in the leading terms of the dynamic equations of the model. While modifying the forcing parameters by a sufficient amount is required, the modification should remain within the natural range of variability of the parameters.

Several mathematical techniques have been utilized to perform sensitivity analysis. Bryant (1987) applied scaling analysis to an idealized domain and forcing and found that closure parameters such as vertical diffusivity and wind stress curl were important controlling factors in thermohaline circulation. Bastidas et al. (1999) used multicriteria methods to find

the sensitivity of land surface scheme models that couple biosphere-atmosphere interactions. The input variables (such as precipitation, air temperature and humidity etc.) predict the evolution of soil skin temperature, soil moisture, etc. The input parameters obtained from the sensitivity analysis of the model showed consistency with physical properties for two different field sites and helped identifying insensitive parameters that led to an improvement in model description. Fennel et al. (2001)

5 incorporated adjoint methods to perform sensitivity studies to refine ecological model parameters such that the underlining model can be applied to a wider range of conditions. Mourre et al. (2008) performed multiple simulations based on realistic variation of a forcing field to calculate the influence of model parameters on sea surface salinity. The metric used to measure the sensitivity was based on RMS difference between the reference and modified model parameter. The results showed that lateral salt diffusivity had the strongest impact on surface salinity model response. Rosero et al. (2009) investigated the

10 sensitivity of three different versions of a land satellite model (Noah LSM) applied to nine different sites based on different conditions (soil, vegetation, and climate). They utilized the Monte Carlo method to generate the first order Sobol' indices (Sobol', 1993) to estimate the model sensitivity. The results showed that the optimal parameter values differed varied between different versions of the models and for different sites along with quantifying the nature of interactions between parameters. One of the challenges associated with a Monte Carlo approach to computing the Sobol' indices is the large

15 number of model evaluations required for approximating conditional variance.

All these studies highlight various approaches to perform sensitivity analysis. Saltelli et al. (2008) provided a comparison of different sensitivity analysis methodologies and the optimal setup for specific combinations of parameters and model. Ultimately, the choice of sensitivity analysis methodology depends on multiple factors such as the computational cost of running the model, the characteristics of the model (e.g., nonlinearity), the number of input parameters, and/or the

20 potential interactions between parameters. Saltelli et al. (2008) described variance-based techniques as providing the most complete and general pattern of sensitivity for models with a limited number of parameters, such as the vegetation module in COAWST. Sobol' indices, as a form of variance-based sensitivity analysis, provide a decomposition of the variance of a model into fractions that can be assigned to inputs or combinations of inputs. However, techniques involving the estimation of Sobol' indices (such as Monte Carlo methods) are expensive.

25 To reduce the computational cost and have desirable accuracy, techniques that involve approximating the global response of the model with a polynomial, and then using its coefficients to estimate the Sobol' indices can be utilized (Sudret, 2008). In this paper, we use a set of least squares polynomial tools based on subsampling to estimate our global polynomial response (Seshadri et al., 2017a). Then, the coefficients of the polynomial are used to compute the Sobol' indices. These tools are implemented in the open source package Effective Quadratures Method (EQ) (Seshadri et al.,

30 2017b), and our current work provides one of the first applications of this methodology to quantify sensitivity of input parameters in coastal models. Therefore, the goal of the present work is to take advantage of the EQ method to provide Sobol' indices that quantify the sensitivity of the flow and wave dynamics to vegetation parameters in COAWST model. The paper is organized as follows: the methods are discussed in section 2, including the numerical model with vegetation model (COAWST), Effective Quadratures method to estimate Sobol' indices, and simulation design; in section 3 we present the

results of sensitivity analysis from various simulations; in section 4 we discuss the impact of these results; and finally in section 5 we summarize our work and outline areas of future research.

## 2 Methods

5     **2.2  COAWST implementation of vegetation model parameterization**

Beudin et al. (2017) implemented a hydrodynamic-vegetation routine within the open-source COAWST numerical modeling system. The COAWST framework utilizes ROMS (Regional Ocean Modeling System) for hydrodynamics and SWAN (Simulating WAves Nearshore) for modeling waves coupled via the Model Coupling Toolkit (MCT) (Warner et al., 2008).

10     ROMS (Regional Ocean Modeling System) is a three-dimensional, free surface, finite-difference, terrain-following model that solves the Reynolds-Averaged Navier-Stokes equations using the hydrostatic and Boussinesq assumptions (Haidvogel et al., 2008). The transport of turbulent kinetic energy and generic length scale are computed with a generic length scale (GLS) two-equation turbulence model. SWAN (Simulating WAves Nearshore) is a third-generation spectral wave model based on the action balance equation (Booij et al., 1999). The effect of submerged aquatic vegetation in ROMS

15     is to extract momentum, add wave-induced streaming, and generate turbulence dissipation. Similarly, the wave dissipation due to vegetation modifies the source term of the action balance equation in SWAN. Sub-grid scale parameterizations account for changes due to vegetation in the water column extending from the bottom layer to the height of the vegetation in the flow model, while SWAN accounts for wave dissipation due to vegetation at the seafloor. The parameterization of SWAN to account for wave dissipation implemented by Suzuki et al. 2012 has the same effect as energy dissipation.

20     The parameterizations used to implement the effect of vegetation in both ROMS and SWAN models are mentioned in Table 1 and detailed in Beudin et al. (2017). The coupling between the two models occurs with an exchange of water level and depth averaged velocities from ROMS to SWAN and wave fields from SWAN to ROMS after a fixed number of time steps (Fig. 1). The vegetation properties are separately input in the two models at the beginning of the simulations.

25     **2.2 Method for Sensitivity Analysis: Polynomial Least Squares**

Polynomial techniques are ubiquitous in the field of uncertainty quantification and model approximation. They estimate the response of some quantity of interest with respect to various input parameters using a global polynomial. From the coefficients of the polynomial the mean, variance, skewness, and higher order statistical moments can be calculated (see Smith 2014; Geraci et al. 2016). In this paper, our interest lies in statistical sensitivity metrics called first order Sobol'

30     indices (Sobol', 1993) that are derived from the conditional variances of the parameters of the model. These indices are the same in number as the input parameters to the model and quantitatively rank the input parameters based on their contribution to the resultant model output. Thus, model output is more sensitive to parameters that exhibit higher first order Sobol' index value. Second order and third order Sobol' indices may also be computed. The sum of the first, second, and third order

Sobol' indices should sum to unity, therefore if the first order indices are themselves close to unity, it indicates the higher order interaction between model input parameters is weak.

In this paper, the first order indices are computed from a global polynomial model using Effectively Subsampled Quadratures Method (ESQM v5.2; Seshadri et al., 2017b). There are two attributes to any data-driven polynomial model: the choice of the polynomial basis and the strategy for estimating the coefficients of the polynomial. The basis used in Effective Quadratures are orthogonal polynomials; i.e. orthogonal with respect to the weight of the input parameter. For example, if one of the input parameters is prescribed with a Gaussian distribution, then a Hermite orthogonal polynomial basis would be used; likewise for a uniform distribution, Legendre polynomials are used. In the current work, a uniform distribution is assumed for the input parameter space. The rationale behind selecting polynomials that are orthogonal with respect to the input weight is that it reduces the number of model evaluations required for estimating statistical moments. Details on the exponential convergence in moments when matching the orthogonal polynomial with its corresponding weight can be found in Xiu et al. (2002).

The coefficients for the polynomial expansion are typically approximated using an integral over the input parameter space using quadrature rules. When the number of input parameters is greater than one, tensor grid or sparse grid based quadrature rules may be used to approximate these integrals. However, the cost of tensor grids grows exponentially with dimension, i.e., a four-point quadrature rule in three dimensions has $5^3$ points, in four dimensions has $5^4$ points and so on. While some alleviation can be obtained using sparse grids, in this paper a more efficient sampling technique is used: effectively subsampled quadratures (abbreviated to Effective Quadratures).

The method of Effective Quadratures determines points for approximating the integral by subsampling well-chosen points from a tensor grid, and evaluating the model at those subsamples. These well-chosen points are obtained via a QR column pivoting heuristic (Seshadri et al. 2017a). Once the coefficients are estimated, the Sobol' indices can be readily computed (Sudret 2008).

### 2.3 Range of input vegetation properties for sensitivity analysis

Prior to performing the simulations for estimating Sobol' indices described above, a range of vegetation inputs that would impact the model response needs to be chosen. Kennish et al. (2013) constrained annual variation of three of the four vegetation properties (stem density, height, diameter) based on *Zostera marina* growth in the Barnegat Bay-Little Egg Harbor estuary. The thickness of *Z. Marina* is selected to be an order of magnitude lesser than its diameter based on Lakrum et al., 2007. Based on this, the range of the vegetation model inputs evaluated is as follows:

1. Stem density $(n_v)$= [38.2 - 250.4] stems/m$^2$.
2. Height $(l_v)$ = [0.16 − 0.32] m.
3. Diameter $(b_v)$ = [1.0 − 10.0] mm.
4. Thickness $(t_v)$ = [0.1 − 1.0] mm.

For the sensitivity analysis, a combination of these ranges of inputs (Table 2) is chosen to configure different simulations in an idealized test case, described below. In addition to these four vegetation properties, the vegetative model requires an input of drag coefficient ($C_D$) in the flow model and the wave model. However, variations on $C_D$ are unlikely to be measured in the field and thus users could rely on the published literature for an appropriate choice based on the type, shape, and flexibility of the vegetation under study.

### 2.4 Test case configuration

An idealized rectangular model domain of 10 km by 10 km with a 3 m deep basin is chosen. The grid is 100 by 100 in the horizontal (100 m resolution) and has 60 vertical sigma-layers (uniformly distributed) leading to 0.05 m resolution in the vertical. The vertical resolution of 0.05 m allows a plant height of 0.27 m to be distributed over 6 vertical layers while the shortest height is restricted to 2 vertical layers. A square patch of vegetation (1 km by 1 km) is placed in the middle of the domain. The ROMS barotropic and baroclinic time steps are respectively *0.05 s and 1 s*, while the SWAN time step and the coupling interval between ROMS and SWAN are 10 min. The friction exerted on the flow by the bed is calculated using the SSW bbl in the bottom boundary layer formulation (Warner et al., 2008). The bottom boundary layer roughness is increased by the presence of waves that produce enhanced drag on the mean flow (Madsen, 1994; Ganju and Sherwood, 2010). The vegetative drag coefficients ($C_D$) in the flow model and the wave model are set to 1 (typical value for a cylinder at high Reynolds number). The bed roughness is set to $z_0$=0.05 mm, which corresponds to a mixture of silt and sand (Soulsby, 1997). The turbulence model selected is the $k - \varepsilon$ scheme (Rodi, 1984).

The model is forced by oscillating the water level on the northern edge with a tidal amplitude of 0.5 m and a period of 12 h. Waves are also imposed on the northern edge with a height of 0.5 m, directed to the south (zero angle), with a period of 2 s. The test case setup is similar to the one used by Beudin et al., (2017). The test case setup is simulated for 2 days to obtain a tidally steady state solution. These simulations require 40 CPU hours on Intel Xeon(R) X5650 2.67 GHz processors running on 24 parallel processors.

### 2.5 Choice of COAWST model response to vegetation inputs

The output parameters used to investigate the vegetation model sensitivity are chosen to reflect the first order effects of vegetation on the hydrodynamics and waves. The results for the model response are computed for the last tidal cycle (a total of 3 tidal cycles are required for achieving steady state). The presence of vegetation affects the output parameters in different physical ways (Table 1) as:

1. Wave energy dissipation: Vegetation dissipates wave energy by reducing wave height, increasing wavelength, and reducing wave steepness.

2. Kinetic energy: A drag force is generated by plants. This leads to a decrease in kinetic energy within and behind the vegetation patch.

3. Water level: As the wave energy (and momentum) flux decreases due to bottom friction, the mean water level increases to balance the decrease in wave and kinetic energy. The flow decelerates in front of the patch and in the wake of the patch while it accelerates around the edges of the patch, leading to a water level gradient.

4. Turbulent kinetic energy (TKE): Reduced turbulent kinetic energy in front and within the patch. The enhancement of TKE inside the boundary layer is not captured with the current resolution.

The response impact to change in the inputs during each simulation is computed by calculating the percentage difference of model response for each simulation from the minimum value of all the simulations. The model response is obtained in and around the vegetation patch and averaged over the last tidal cycle. The change in model response of water level is computed by finding the maximum water level difference in and around the vegetation patch. In addition, the variability of model response with given vegetation inputs in different simulations is calculated through standard deviation of model response in and around the vegetation patch over the last tidal cycle. The standard deviation in TKE is depth averaged to provide a 2-D field.

## 3 Results

### 3.1 Setting up simulations with different vegetation inputs

Using the range of input parameters described above (section 2.3), and assuming all the inputs are uniformly distributed over their ranges, a matrix of design of experiment values (Table 2) was determined using Effective Quadratures. A total of 15 simulations were found to be required, corresponding to the number of coefficients in a 4D polynomial with a maximum order of 2. In general, the number of coefficients $n$, is given by the formula

$$ n = \binom{d + o}{d}, $$

where $d$ is the number of dimensions and $o$ is the maximum order (assuming it is isotropic across all dimensions).

### 3.2 Model response from all the simulations

The 15 simulations (parameter choice of each simulation in Table 2) are performed to provide model response from the four chosen output variables.

1. Wave dissipation: The percentage change in wave dissipation from all simulations relative to the minimum value of wave dissipation varied between 75 and 600% (Fig. 3(a)). Simulation 2, which includes the combination of smallest stem density ($n_v$= 62.1 stems/m$^2$) and shortest height (0.174m), incurred the least wave dissipation, while simulation 3, which involved the combination of greatest stem density ($n_v$= 226.5 stems/m$^2$) and tallest height (0.295 m), resulted in greatest wave dissipation. The greatest amount of variability in wave dissipation occurs in front of the vegetation patch (Fig. 4), where the greatest amount of wave energy is dissipated due to the presence of the vegetation patch.

2. Kinetic energy: The percentage change in kinetic energy from all simulations relative to the minimum kinetic energy varied between 5.0 and 34.0 % (Fig. 3b). Simulation 8, performed with an intermediate value of stem density along with the

largest values of height, diameter, and thickness, results in the least amount of kinetic energy (lowest velocities). Simulation 2 causes the least amount of extraction of momentum with a combination of smallest plant stem density, height, and diameter values, resulting in the greatest kinetic energy in and around the vegetation patch. The variability in kinetic energy from all the simulations is observed at a cross section along the vegetation patch (Fig. 5). Variability is observed throughout the water column where the vegetation patch exists. Similar to the variability in wave dissipation, the greatest amount of variability occurs in front of the vegetation patch. The region of maximum variability occurs at a distance of $(0.25 - 1.25)$ m above bed.

3. Water level: The percentage change in maximum water level difference from all simulations relative to the minimum of the maximum water level difference varied between 3.0 and 18.0 % (Fig. 3c). The minimum water level gradient is obtained from simulation 13 that includes a combination of plant inputs ($n_v$= 62.1 stems/m$^2$ (minimum), $l_v$= 0.174 m (intermediate), diameter=6 mm (minimum), and $t_v$= 0.3 mm (minimum). Simulations 2, 6, and 11 also give relatively low values of water level gradient. Simulations 2 and 6 both involve the smallest plant stem density values (i.e. $n_v$= 62.1 stems/m$^2$). On the other hand, simulation 8 ($n_v$=144.3 stems/m$^2$, $l_v$= 0.3 m (maximum),$b_v$=9 mm, and $t_v$= 0.9 mm) accounts for the greatest value of maximum water level difference. The variability in water level (Fig. 6) is highest around the lobes of the vegetation patch where the water level adjusts owing to changes in velocity around the patch. Behind the vegetation patch, the variability increases as the water level adjusts to the change in flow conditions.

4. Turbulent Kinetic Energy (TKE): The percentage change in TKE from all simulations relative to the minimum TKE varied between 0.5 and 10.0 % (Fig. 3d). Simulation 8 (combination of plant $n_v$= 144.3 stems/m$^2$, $l_v$= 0.3 m, $b_v$= 9 mm and $t_v$= 0.9 mm) gives the greatest amount of TKE, similar to what was observed with kinetic energy change. The smallest value of TKE is obtained in and around the vegetation patch in simulation 2 with a combination of plant inputs ($n_v$ = 62.1 stems/m$^2$, $l_v$ = 0.2 m, $b_v$= 3 mm, and $t_v$ = 0.6 mm). Simulation 2 causes the least amount of dissipation of turbulence with a combination of smallest plant stem density, height and diameter. The variability in TKE peaks occurs in front of the vegetation patch (Fig. 7) where the different simulations dissipate turbulence to substantially different degrees. The changes in turbulence mixing caused by the presence of the vegetation patch are close to zero inside the patch (all simulations dissipate similar amounts of turbulence).


**3.3 Quantifying sensitivity using Sobol' Indices**

Following the variability in model response from different simulations, the sensitivity to input vegetation parameters can be quantified with the use of first order Sobol' indices that are obtained by taking advantage of the Effective Quadratures approach. Sobol' indices are individually computed for all the model responses. The first order Sobol' indices for all the model responses (Table 3) add up to more than 0.9. This results indicates they account for 90% of the variability in model response for the given vegetation property inputs, and the variability captured by second order and third order indices is relatively low. The model is most sensitive (Table 3) to plant stem density ($n_v$) and height ($l_v$) over the range of parameters considered; these two inputs account for over 80% of the sensitivity to all model outputs. The vegetation diameter ($b_v$)

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accounts for 12-15 % of model sensitivity to kinetic energy, water level change, and turbulent kinetic energy. Thickness ($t_v$) showed the least impact on all the chosen model outputs.

## 4 Discussion

### 4.1 Variability in model response from sensitivity analysis

From the different simulations performed during sensitivity analysis, there is a great amount of variability in front of the vegetation patch in wave dissipation, KE, and TKE (Figs. 4, 5 and 7). This is a result of large amount of wave dissipation and flow deceleration in front of the vegetation patch. The cross-sectional plane of the domain illustrates that the variability in KE occurs throughout the water column (Fig. 5), highlighting the 3-D impact of vegetation inputs. Interestingly, the greatest amount of variability in KE (Fig. 5) occurs at distance above the bed between 0.4 – 1.3 m at y = 5.6 km, while the maximum vegetation height in all the simulations is 0.3 m. This result indicates that variation in vegetation height results in the greatest amount of KE variability above the vegetation patch. The variability in water level change is large around the lobes and behind the vegetation patch (Fig. 6). The variability in these regions is because the change in local flow velocity is adjusted by a change in water level around the vegetation patch. This is further confirmed by observing the variation in velocity profiles with depth (Fig. 8a) at a particular time instance during flood tide. Simulation 8 results in the lowest velocity of 0.06 m/s while simulation 2 results in the peak flood velocity of 0.11 m/s. Consequently, the gradient of velocity with respect to depth is greatest at all depths for simulation 8 while least for simulation 2 (Fig. 8b). The gradient reaches a maximum value at the bottom layer.

### 4.2 Understanding vegetation parameterization to interpret Sobol' Indices

The parameterizations involving extraction of momentum, turbulence production, and turbulence dissipation are directly affected by vegetation stem density ($n_v$), diameter ($b_v$), and thickness ($t_v$) (Table 1). Because these mechanistic processes occur at the blade scale, the dependence on vegetation height ($l_v$) is implicitly included in the parameterizations. Sobol' indices provide quantifiable information and show that vegetation height, stem density, and diameter (in decreasing order of importance) are pertinent in accurately computing kinetic energy (KE), turbulent kinetic energy (TKE), and water level. An accurate representation of KE and TKE has direct ramifications on estimating sediment transport while water level estimates can affect storm surge predictions.

The high sensitivity of wave dissipation to vegetation stem density highlights the need of accurate density representation to attain wave attenuation estimates, especially in open coasts. SWAN computes wave dissipation due to vegetation as a bottom layer effect. Therefore, the height of the vegetation does not affect wave dissipation to the same extent as other model outputs: KE, TKE, and water level. In addition, the equation representing the wave dissipation process in SWAN is independent of vegetation thickness, thus corresponding to the lowest Sobol' index. Vegetation thickness only

appears in the turbulence dissipation term (Table 1) modifying the turbulence length scale has the least effect on any of the model responses.

### 4.3 Linear curve fitting to complement Effective Quadratures based sensitivity analysis

To complement the results of the Sobol' indices calculation, linear fits to the data are conducted. The main parameter contributing to the wave dissipation variability is the stem density explaining over 80% of the variability ($R^2=0.81$). The least squared fit to wave dissipation that included all parameters combined explains 98% of the variability. When fitting models, it is possible to increase the explained variance by using more complex fitting models adding parameters, but doing so may result in over-fitting. The Bayesian Information Criterion (BIC; Schwarz, 1978; Aretxabaleta and Smith, 2011) provides a non-subjective metric for the best fit by penalizing over-parameterization. BIC resolves over-fitting by introducing a penalty term for the number of parameters in the model. For wave dissipation, the BIC approach identified a fit based exclusively on density as the model that best match the data while preventing over-fitting. The selection of density as the single most relevant parameter is consistent with the Sobol' indices result (Table 3).

The kinetic energy variability is also associated with stem density changes, but the percentage of explained variability (42%) is smaller than for wave dissipation. Diameter and height also contributed to changes in kinetic energy. The combination of stem density, height, and diameter provided the optimal fit of the data (selected by minimizing BIC) and explained 89% of variability in kinetic energy. Similar results were obtained for TKE with density explaining 45% of the variability but the combination of stem density, height, and diameter providing the optimal fit to TKE (selected by minimizing BIC) and explained 87% of the variability. The model response of water level variability is also best explained by a combination of stem density, height, and diameter (96% of water level variance explained). Thickness was not correlated with wave dissipation, kinetic energy or TKE and only contributed to water level gradient variability.

### 4.4 Limitations of the current sensitivity methodology

The model configuration chosen includes vegetation covering a small fraction of the water column to allow for proper wave dissipation. Many species of seagrass have a larger vertical footprint and can also exhibit much higher shoot densities. The goal of the study is to provide estimates on the relative importance of the different parameters through a robust sensitivity approach. The current work assumed rigid vegetation blades, while the model is capable of including flexible vegetation by altering the blade scale. The expected effect of flexible blades would be to reduce the relative importance of vegetation length ($l_v$) on the model outputs. In addition, the present work assumes a constant drag coefficient for cylindrical vegetation shape; the influence of a variability drag coefficient can be a subject of a future sensitivity study. Other model parameters such as vertical and horizontal resolution, mixing parameterization, and wave and hydrodynamic forcings will also affect model results, but were beyond the scope of the current study.

### 5 Conclusions

The coupled wave-flow-vegetation module in the COAWST modeling system provides a tool to study vegetated flows in riverine, lacustrine, estuarine, and coastal environments. The resulting flow field in the presence of vegetation depends on its properties, including vegetation stem density, height, diameter, and thickness. The sensitivity of the hydrodynamic and wave conditions to changes in vegetation parameters is investigated. The sensitivity analysis helps in understanding the multiparameter/multiresponse of various interactions within the model. We use an existing tool that formulates the Effective Quadratures method to quantify the sensitivity of plant input properties for the vegetation module in COAWST model. The decomposition of the variance of the model solution given by the Sobol' indices is assigned to plant parameters.

The method of using Sobol' indices to quantify sensitivity can be computationally expensive. One of the goals of this work is to demonstrate a robust, practical, and efficient approach for the parameter sensitivity analysis. We show that the approach of using Effective Quadratures method to select a parameter space that is consistent with physical understanding significantly reduces the computational time required to obtain the Sobol' indices.

The evaluation of Sobol' indices shows that the input values of plant stem density, height and to a lesser degree, diameter are consequential in determining kinetic energy, turbulent kinetic energy and water level changes. Meanwhile, the wave dissipation is mostly dependent on the variation in plant density.

The sensitivity analysis for the vegetation model in COAWST presented herein provides guidance for observational and modelling work by allowing future efforts to focus on constraining the most influential inputs without having to explore the entire parameter space. An accurate representation of processes causing kinetic energy and turbulent kinetic energy leads to enhanced understanding of sediment processes while accurate water level computations help to predict coastal flooding caused by storm surge. Similarly, wave attenuation measurements in open coasts are better understood with a correct representation of wave dissipation. In the future, we intend to perform a similar sensitivity analysis with the inclusion of a biological model that will affect plant growth, thus allowing a time dependence of model input and response. In addition, the influence of vegetation on sediment transport will be explored. As model complexity increases with more parameters representing additional processes, input parameter sensitivity is required for the model to be applied on practical applications.

**6 Code availability**

The Effective Quadratures methodology is an open source Python based tool designed to perform sensitivity analysis for a given physical system. The instructions to install the code along with all the open source files for this tool are detailed here: https://github.com/Effective-Quadratures/Effective-Quadratures. For any further inquiries about the Effective Quadratures methodology, please contact the corresponding author Dr. P. Seshadri (ps583@cam.ac.uk).

The COAWST model is an open source coupled hydrodynamics and wave model containing vegetation effects mainly coded in Fortran 77. This model provided the physical setting to perform the sensitivity analysis. The code is available from https://coawstmodel-trac.sourcerepo.com/coawstmodel_COAWST after registration via email with J. C. Warner (jcwarner@usgs.gov).

**7 Data availability**

The model output from various simulations used to perform sensitivity analysis in this study are available at: http://geoport.whoi.edu/thredds/catalog/clay/usgs/users/tkalra/senstivity_study/catalog.html. The link contains a
5    "README.txt" file that explains how the folder is organized to contain model output.

**8 Author contribution**

T. S. Kalra, and N. K. Ganju designed and simulated the numerical experiment space for sensitivity analysis. P. Seshadri developed the Effective Quadratures methodology to quantify the model sensitivity. A. Beudin provided inputs on the
10    mechanistic processes involving the vegetation model. T. S. Kalra and A. Arextabaleta performed the data analysis from the output of sensitivity study and prepared the manuscript with contributions from all co-authors.

**9 Disclaimer**

Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the U.S.
15    Government.

**11 References**

Aretxabaleta A.L., Smith K.W.: Analyzing state-dependent model-data comparison in multi-regime systems, Computers &
25    Geosciences, 15, 627–636, 2011.

Baptiste M., Ballabrera-Poy J., García-Ladona E., and Font, J.: Surface salinity response to changes in the model parameters and forcings in a climatological simulation of the eastern North-Atlantic Ocean, Ocean Modeling, 23, 21-32, 2008.

Bastidas, L. A., Gupta, H. V., Sorooshian, S., Shuttleworth, W. J., and Yang, Z. L.: Sensitivity analysis of land surface scheme using multicriteria methods, Journal of Geophysical Research, 104, 481-490, 1999.

30    Beudin, A., Kalra, T. S., Ganju, N., K., and Warner, J.C.: Development of a Coupled Wave-Current-Vegetation Interaction, Computers & Geosciences, 100, 76-86, 2017.

Bryan, F.: Parameter Sensitivity of Primitive Equation Ocean General circulation models, Journal of Physical oceanography, 17, 970-985, 1986.

Booij, N., Ris, R. C., and Holthuijsen, L. H.: A third-generation wave model for coastal regions, Part I, Model description

and validation, Journal of Geophysical Research C4, 104, 7649-7666, 1999.

Carr, J., D'Odorico P., McGlathery K., and Wiberg, P.: Stability and bistability of seagrass ecosystems in shallow coastal lagoons: role of feedbacks with sediment resuspension and light attenuation, Journal of Geophysical Research, 115, G03011, 2010.

5  Chen, S. N., Sanford L., Koch E. W., Shi F., and North, E. W.: A nearshore model to investigate the effects of seagrass bed geometry on wave attenuation and suspended sediment transport, Estuaries and Coasts, 30(2), 296-310, 2007.

Costanza, R., d'Arge, R., de Groot, R., Farberk, S., Grasso, M., Hannon, B., Limburg, K., Naeem, S., O'Neill, R.V., Paruelo, J., and Raskin, R.G.: The value of the world's ecosystem services and natural capital, Nature 387, 253-260, 1997.

Dalrymple, R. A., Kirby, J. T., and Hwang, P. A.: Wave diffraction due to areas of energy dissipation. Journal of Waterway, 10  Port, Coastal, and Ocean Engineering, 110, 67-79, 1984.

de Vriend, H. J.: Integrated research results on hydrobiosedimentary processes in estuaries: algorithm for vegetation friction factor, Defra R&D Technical Report FD1905/TR3, 2006.

Fennel, K., Losch, M., Schroter, J., and Wenzel, M.: Testing a marine ecosystem model: sensitivity analysis and parameter optimization, Journal of Marine Systems, 28, 45–63, 2000.

15  Geraci, G., Congedo, P. M., Abgrall, R., and Iaccarino, G.: High-order statistics in global sensitivity analysis: Decomposition and model reduction. Computer Methods in Applied Mechanics and Engineering, *301*, 80-115, 2016.

Heck, K.L., Hays, G. and Orth, R.J.: Critical evaluation of the nursery role hypothesis for seagrass meadows, Marine Ecology Progress Series, 253, 123-136, 2003.

Hemming, M. A., and Duarte, C. M.: Seagrass Ecology, Cambridge, UK: Cambridge University Press, 2000.

20  Lapetina A., and Sheng, Y. P.: Three-dimensional modeling of storm surge and inundation including the effects of coastal vegetation, Estuaries and Coasts, 37, 1028-1040, 2014.

Larkum, A. W. D, Orth, R. J., and Duarte, C. M.: In Seagrasses: Biology, Ecology and Conservation, Springer Netherlands, 2007.

Luhar M., Coutu S., Infantes E., Fox S., and Nepf H. M.: Wave-induced velocities inside a model seagrass bed, Journal of 25  Geophysical Research, 115, C12005, 2010.

Luhar, M., and Nepf, H. M.: Flow-induced reconfiguration of buoyant and flexible aquatic vegetation. Limnology and Oceanography, 56(6), 2003-2017, 2011.

Luhar, M., and Nepf, H. M.: Wave-induced dynamics of flexible blades. Journal of Fluids and Structures, 61, 20-41, 2016.

Le Bouteiller, C., and Venditti, J. G.: Sediment transport and shear stress partitioning in a vegetated flow. Water Resources 30  Research, 51, 2901-2922, 2014.

Madsen, O.S.: Spectral wave–current bottom boundary layer flows. Proceedings of the 24th International Conference on Coastal Engineering Research Council, Kobe, Japan, 384-398, 1994.

Marjoribanks, T. I., Hardy, R. J., and Lane, S. N.: The hydraulic description of vegetated river channels: the weaknesses of existing formulations and emerging alternatives, WIREs Water, 1, 549-560, 2014.

Mendez, F. M., and Losada, I. J.: An empirical model to estimate the propagation of random breaking and nonbreaking waves over vegetation fields, Coastal Engineering, 51, 103-118, 2004.

Möller, I., Spencer, T., French, J. R., Legget, D. J., and Dixon, M.: Wave transformation over salt marshes: a field and numerical modeling study from Norfolk, England. Estuarine, Coastal and Shelf Science, 49, 411-426, 1999.

5   Morin, J., Leclerc, M., Secretan, Y., and Boudreau, P.: Integrated two-dimensional macrophytes-hydrodynamic modelling, Journal of Hydraulic Research, 38, 163-172, 2000.

Morison, J. R., O'Brien, M. P., Johnson, J. W., and Schaaf, S. A.: The force exerted by surface waves on piles, Petroleum Transactions, AIME, 189, 149-154.

Mourre, B., Ballabrera-Poy, J., García-Ladona, E., Font, J.: Surface salinity response to changes in the model parameters and

10   forcings in a climatological simulation of the eastern North-Atlantic Ocean, Ocean Modeling, 23, 37-49, 2008.

Kennish, M. J., Fertig, M. B., and Sakowicz, G. P.: In situ Surveys of Seagrass Habitat in the Northern Segment of the Barnegat Bay-Little Egg Harbor Estuary, Barnegat Bay Partnership, Final Report, 2013.

Kombiadou, K., Ganthy, F., Verney, R., Plus, M., and Sottolichio, A.: Modelling the effects of Zostera noltei meadows on sediment dynamics: application to the Arcachon lagoon, Ocean Dynamics, 64, 1499-1516, 2014.

15   Ree, W. O.: Hydraulic characteristics of vegetation for vegetated waterways, Agricultural Engineering, 30, 184-189, 1949.

Saltelli, A., Ratto, M., Andres, T., Campolongo, F., Cariboni, J., Gatelli, D., Saisana, M., and Tarantola, S.: Global sensitivity analysis: the primer, John Wiley & Sons, Chichester, 312 pp, 2008.

Rodi, W.: Turbulence models and their application in hydraulics, a state of the art review. Technical report, International Association of Hydraulics Research, Delft, 1984.

20   Rosero, E., Yang, Z. L., Wagener, T., Gulden, L. E., Yatheendradas, S., and Niu, G. Y.: Quantifying parameter sensitivity, interaction, and transferability in hydrologically enhanced versions of the Noah land surface model over transition zones during the warm season, Journal of Geophysical Research 115, 2010.

Seshadri, P., Narayan, A., and Mahadevan, S.: Effectively Subsampled Quadratures for Least Squares Polynomial Approximations, arXiv: 1601.05470, 2017a.

25   Seshadri, P., Parks, G. T.: Effective Quadratures (EQ): Polynomials for Computational Engineering Studies, Journal of Open Source Software, 2(11), DOI: 10.21105/joss.00166, 2017b.

Sheng, Y. P., Lapetina, A., and Ma, G.: The reduction of storm surge by vegetation canopies: three-dimensional simulations, Journal of Geophysical Research, 39, L20601, 2012.

Smith, R. C.: Uncertainty quantification: theory, implementation, and applications, Vol. 12. SIAM, 2013.

30   Soulsby, R. L.: Dynamics of Marine Sands, Thomas Telford, London, 249 pp, 1997.

Sobol', Ilya. M.: Sensitivity estimates for nonlinear mathematical models, Mathematical Modelling and Computational Experiments, 1.4, 407-414, 1993.

Sudret, B.: Global sensitivity analyzing using polynomial chaos expansions, Reliability Engineering and System Safety, 93, pp. 964-979, 2008.

Suzuki T., Zijlema, M., Burger, B., Meijer, M. C., and Narayan, S., Wave dissipation by vegetation with layer schematization in SWAN, Coastal Engineering, 59(1): 64-71, 2012.

Temmerman, S., Bouma, T. J., Govers, G., Wang, Z. B., De Vries, M. B., and Herman, P. M. J.: Impact of vegetation on flow routing and sedimentation patterns: three-dimensional modeling for a tidal marsh, Journal of Geophysical Research, 110, F04019, 2005.

Uittenbogaard, R.: Modelling turbulence in vegetated aquatic flows, International workshop on Riparian Forest vegetated channels: hydraulic, morphological and ecological aspects, Trento, Italy, 2003.

Umlauf, L., and Burchard, H.: A generic length-scale equation for geophysical turbulence models, Journal of Marine Research, 61, 235-265, 2003.

Van Katwijk, M. M., Bos, A.R., Hermus, D. C. R., and Suykerbuyk, W.: Sediment modification by seagrass beds: muddification and sandification induced by plants cover and environmental conditions, Estuarine, Coastal and Shelf Science, 89, 175-181, 2010.

Wamsley, T.V., Cialone, M.A., Smith, J.M., Atkinson, J.H. and Rosati, J.D.: The potential of wetlands in reducing storm surge, Ocean Engineering, 37(1), 59-68, 2010.

Warner, J. C., Sherwood, C. R., Arango, H. G., and Signell, R. P.: Performance of four turbulence closure models implemented using a generic length scale method, Ocean Modelling, 8, 81-113, 2005.

Warner J. C., Sherwood, C. R., Signell, R. P., Harris, C. K., and Arango, H.G.: Development of a three-dimensional, regional, coupled wave, current, and sediment-transport model, Computer & Geosciences, 34, 1284-1306, 2008.

Warner, J. C., Perlin, N., and Skyllingstad, E. D.: Using the Model Coupling Toolkit to couple earth system models, Environmental Modelling & Software, 23, 1240-1249, 2008.

Warner, J. C., Armstrong, B., He, R., and Zambon, J. B.: Development of a Coupled Ocean-Atmosphere-Wave-Sediment Transport (COAWST) Modeling System, Ocean Modelling, 35, 230-244, 2010.

Warner, J. C., Defne, Z., Haas, K., and Arango, H. G.: A wetting and drying scheme for ROMS, Computer & Geosciences, 58, 54-61, 2013.

Wu, W.: A 3-D phase-averaged model for shallow-water flow with waves in vegetated water, Ocean Dynamics, 64, 1061-1071, 2014.

| Process | Equation | $n_v$ | $l_v$ | $b_v$ | $t_v$ |
|---------|----------|-------|-------|-------|-------|
| Extraction of Momentum | $F_{d,veg,u} = \dfrac{1}{2} C_D b_v n_v u \sqrt{u^2 + v^2}$<br>$C_D$ = Plant drag coefficient<br>u,v = Horizontal velocity components at each vertical level | X | | X | |
| Turbulence Production<br><br>Uittenbogaard (2003) | $P_{veg} = \sqrt{\left(F_{d,veg,u}u\right)^2 + \left(F_{d,veg,v}v\right)^2}$ | X | | X | |
| Turbulence Dissipation<br><br>Uittenbogaard (2003) | $D_{veg} = c_2 \dfrac{P_{veg}}{\tau_{eff}}$<br>$\tau_{eff} = min\left(\tau_{free}, \tau_{veg}\right)$<br>$\tau_{free} = \dfrac{k}{\varepsilon}$<br>$\tau_{veg} = \left(\dfrac{L^2}{c_k{}^2 P_{veg}}\right)^{1/3}$<br><br>$L(z) = c_l \left(\dfrac{1 - b_v t_v n_v}{n_v}\right)^{1/2}$<br>$P_{veg}$ = Turbulence Production<br>$\tau_{free}$ = Dissipation time scale of free turbulence<br>$k$ = Turbulent kinetic energy<br>$\varepsilon$ = Turbulence dissipation<br>$\tau_{veg}$ = Dissipation time scale of free turbulence<br>$c_k = \left(c_\mu^0\right)^4 \simeq 0.09$<br>$L$ = typical length scale between the plants<br>$c_l$ = Lift coefficient of order unity | X | | X | X |

| | | | | | |
|---|---|---|---|---|---|
| Wave Dissipation<br><br>Mendez and Losada (2004)<br>Dalrymple et al. (1984) | $S_{d,veg} = \sqrt{\dfrac{2}{\pi}} g^2 \widetilde{C_D} b_v n_v \left(\dfrac{\tilde{k}}{\tilde{\sigma}}\right)^3$ $\dfrac{sinh^3(\tilde{k}l_v) + 3\, sinh(\tilde{k}l_v)}{3\tilde{k}cosh^3(\tilde{k}h)} \sqrt{E_{tot}} E(\sigma, \theta)$<br>$\widetilde{C_D}$ = Bulk drag coefficient<br>$\tilde{k}$ = Mean wave number<br>$\tilde{\sigma}$ = Mean wave frequency<br>$h$ = Water depth<br>$E_{tot}$ = Total wave energy<br>$E$ = Wave energy at frequency $\sigma$ and direction $\theta$ | X | X | X | |
| Wave induced streaming<br><br>Luhar et al., 2010 | $F_{s,veg} = \dfrac{S_{d,veg,tot}\,\tilde{k}}{\rho_0\,\tilde{\sigma}}$<br>$S_{d,veg,tot}$ = Total wave energy dissipation<br>$\tilde{k}$ = Mean wave number<br>$\tilde{\sigma}$ = Mean wave frequency<br>$\rho_0$ = Reference density of seawater | X | X | X | |

**Table 1: Processes in ROMS and SWAN to model the presence of vegetation. The different input parameters (stem density, $n_v$; height, $l_v$; diameter, $b_v$; and thickness, $t_v$) affecting model wave and hydrodynamics are included.**

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|      | Stem density (stems/m²) $n_v$ | Height (m) $l_v$ | Diameter (mm) $b_v$ | Thickness (mm) $t_v$ |
|------|------------------------------|------------------|---------------------|----------------------|
| 1.   | 144.3 | 0.24 | 6.0 | 0.6 |
| 2.   | 62.1  | 0.17 | 3.0 | 0.6 |
| 3.   | 226.5 | 0.3  | 6.0 | 0.3 |
| 4.   | 144.3 | 0.17 | 9.0 | 0.9 |
| 5.   | 144.3 | 0.3  | 3.0 | 0.9 |
| 6.   | 62.1  | 0.3  | 6.0 | 0.3 |
| 7.   | 226.5 | 0.17 | 6.0 | 0.3 |
| 8.   | 144.3 | 0.3  | 9.0 | 0.9 |
| 9.   | 144.3 | 0.24 | 9.0 | 0.3 |
| 10.  | 226.5 | 0.24 | 6.0 | 0.9 |
| 11.  | 144.3 | 0.24 | 3.0 | 0.3 |
| 12.  | 62.1  | 0.24 | 6.0 | 0.9 |
| 13.  | 62.1  | 0.17 | 6.0 | 0.3 |
| 14.  | 62.1  | 0.24 | 9.0 | 0.6 |
| 15.  | 144.3 | 0.17 | 3.0 | 0.9 |

**Table 2: Plant property input combination for different simulations during sensitivity analysis.**

| | Plant Stem Density $n_v$ | Plant Height $l_v$ | Plant Diameter $b_v$ | Plant Thickness $t_v$ |
|---|---|---|---|---|
| Wave dissipation | 0.68 | 0.24 | 0.032 | 0.01 |
| Kinetic energy | 0.36 | 0.44 | 0.12 | 0.03 |
| Maximum water level change | 0.38 | 0.43 | 0.15 | 0.01 |
| Turbulent kinetic energy | 0.35 | 0.42 | 0.12 | 0.03 |

**Table 3: Sobol Indices for all the outputs.**

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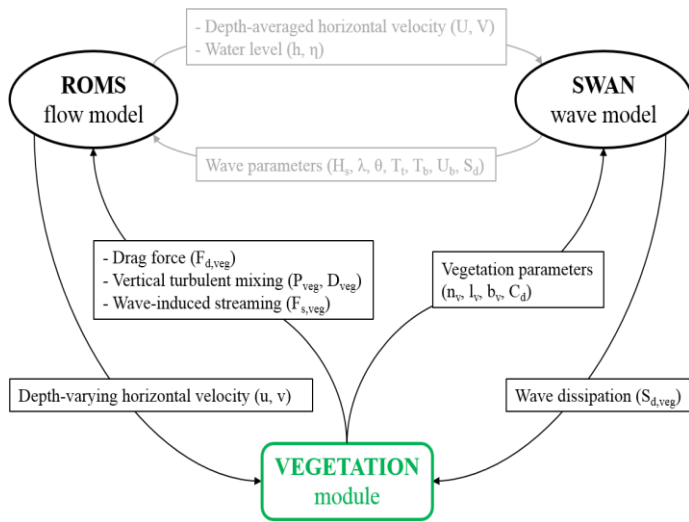


**Figure 1: Schematic showing the vegetation module implementation in COAWST model (Figure adapted from Beudin et. al, 2017)**

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Tidal amplitude =0.5 m
Tidal period = 12 hours

Wave height = 0.5 m
Wave period = 2 seconds
Wave direction = 0° (North)

9.2 km

9.8 km

1 km

1 km  Vegetation

Depth = 3 m

1 km

Vegetation Height

9.8 km
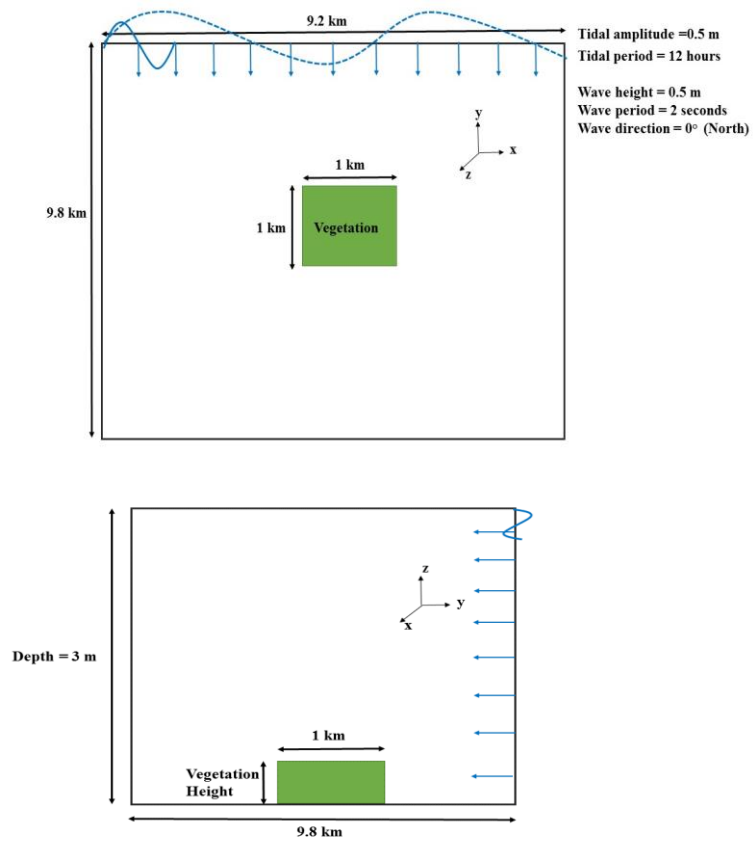
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**Figure 2: Schematic showing the idealized domain (Not drawn to scale)**

**(b) Plan view and (b) Cross-sectional view.**

**Figure 3: Percentage change from minimum for the four impact parameters: a) wave dissipation; b) kinetic energy; c) maximum water level change (WL); and d) Turbulent Kinetic Energy (TKE).**

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**Figure 4: Standard deviation from wave dissipation (W m⁻²) in presence of vegetation (Plan view). The area of the vegetation patch is highlighted in the middle of the domain.**
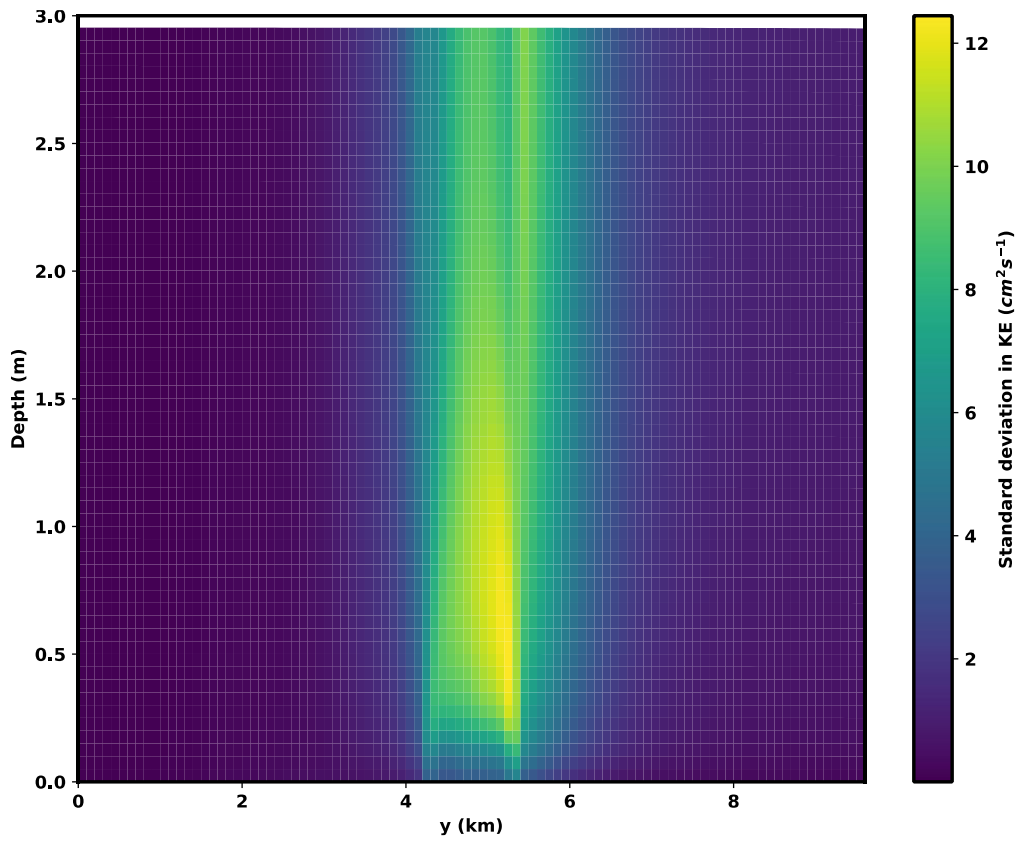
**Figure 5: Standard deviation in kinetic energy (cm² s⁻¹) in presence of vegetation (cross-sectional view).**
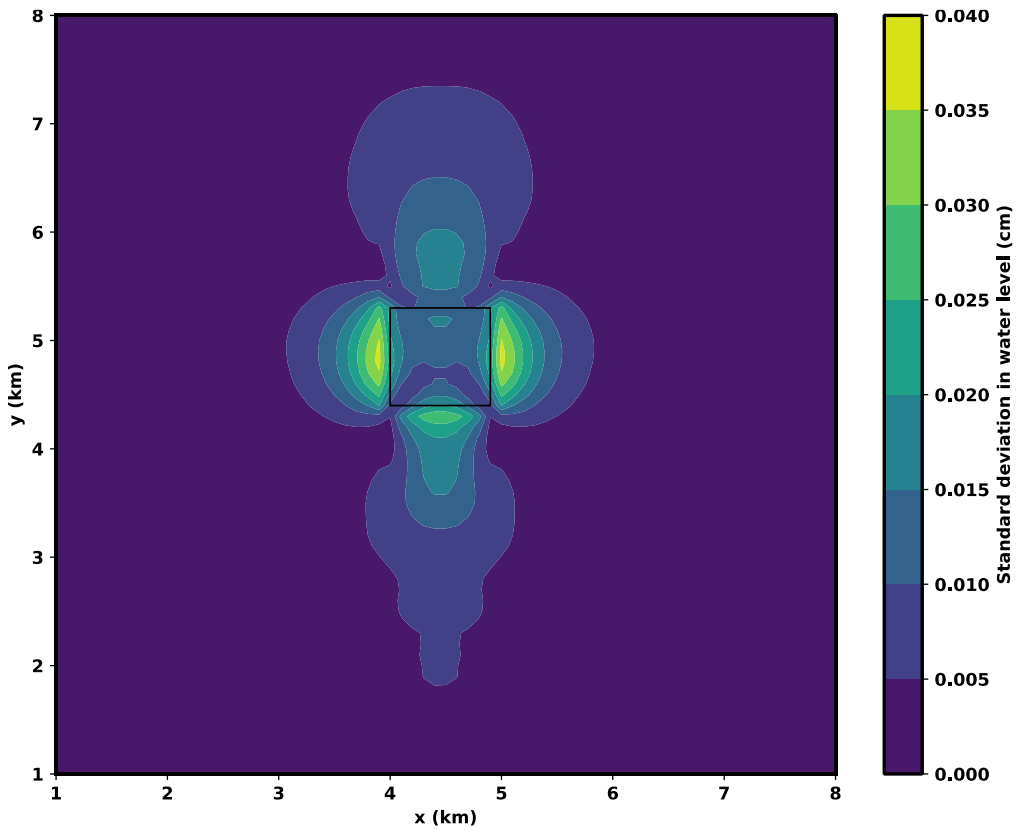
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**Figure 6: Standard deviation in water level in presence of vegetation (plan view). The area of the vegetation patch is highlighted in the middle of the domain.**
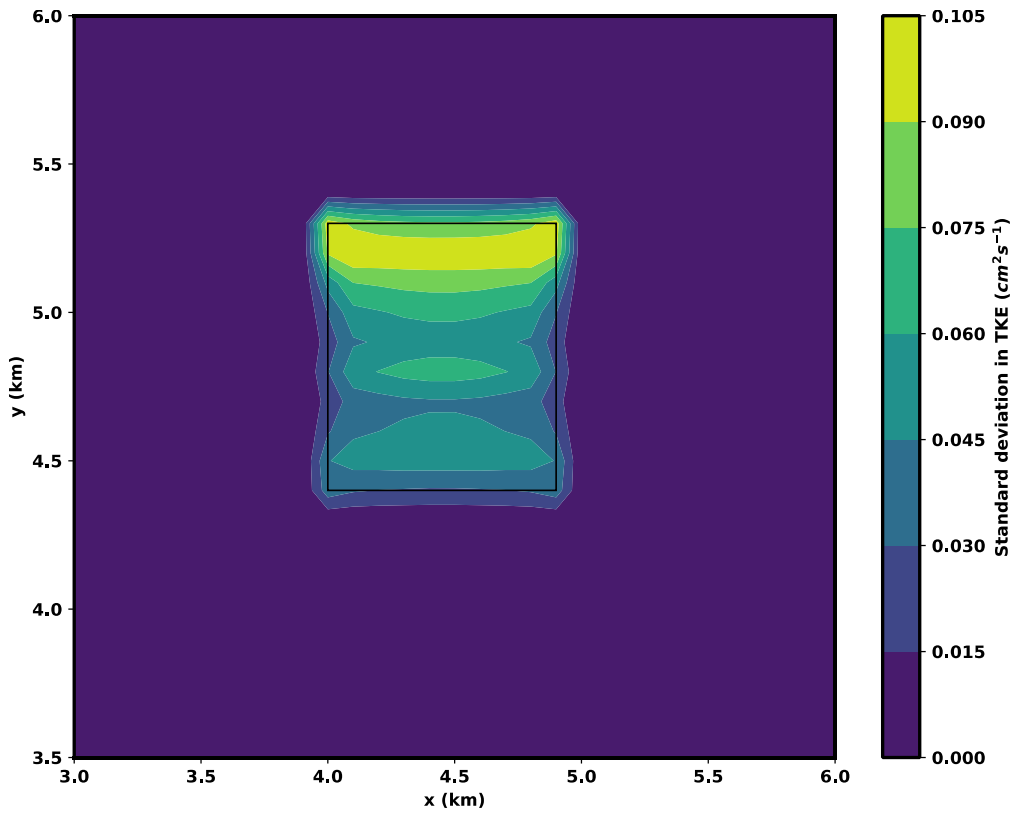
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**Figure 7: Standard deviation in Turbulent Kinetic Energy (TKE) (cm² s⁻¹) in presence of vegetation (plan view). The area of the vegetation patch is highlighted in the middle of the domain.**

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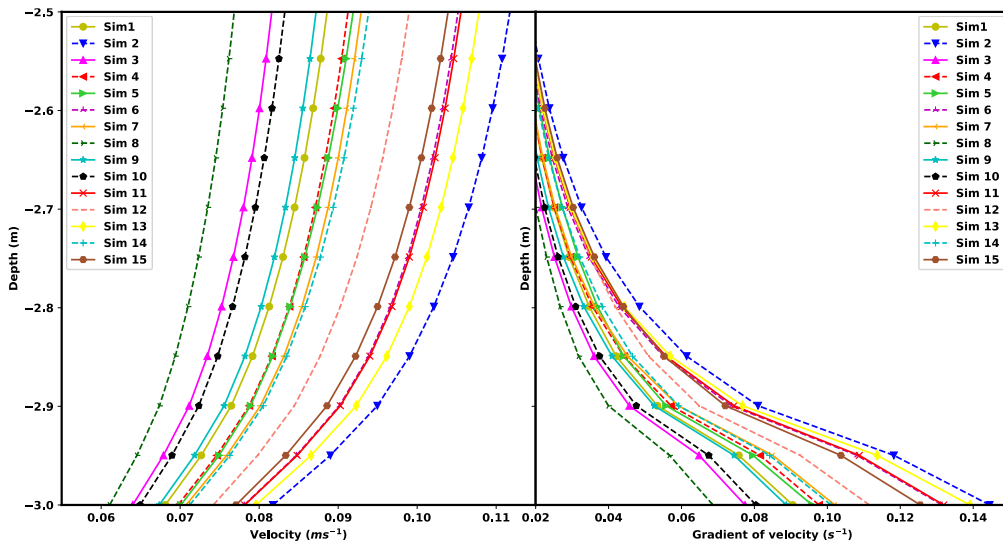**Figure 8: (a) Velocity (m s⁻¹) profile and (b) Vertical gradient (s⁻¹) of velocity profile varying with depth in front of the vegetation patch at a particular time instance during flood for different simulations.**

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