Technical Information of the Numerical Model Developed for the Research

Missing the forest for the trees: how focusing on local bio-morphodynamic feedbacks compromises estuary-scale coastal management

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Competing Interests

The authors declare no competing interests.

Model Availability Statement

The dynamic vegetation code with a representative model set-up is available at: https://github.com/xiedanghan/EstuarineMangroves. Delft3D is an open-source code available online (at https://oss.deltares.nl).

Overview

This Technical Information offers a detailed explanation on the use of bio-morphodynamic numerical model developed for a recent PhD research focusing on the interactions between mangrove dynamics and sediment transport. Specifically, the model aims to investigate the effects of changing sediment supply on estuarine bio-geomorphic landscape development and to explore whether local measures, like mangrove removal, can reduce mud infilling and potentially restore ecosystems in estuaries. The basic principles and equations used in this model can refer to the attached research paper, here I mainly focus on the interpretation of the usage of this model.

The bio-morphodynamic model contains two parts which interact with each other (Fig. 1). The first part is the hydro-morphodynamic model realized by Delft3D (Deltares, 2014) and the other part is the dynamic vegetation model realized by Matlab. Tidal flow, sediment transport and bathymetric changes are calculated by the Delft3D model suite, while vegetation responses to the changing environment is evaluated by Matlab so as to offer extra flow resistance in Delft3D hydrodynamic calculations. By implementing the morphological acceleration factor (morfac), long-term profile changes and vegetation behaviors can be obtained by simulating a short-term period of hydrodynamic calculations (Roelvink, 2006; Coco et al., 2013).

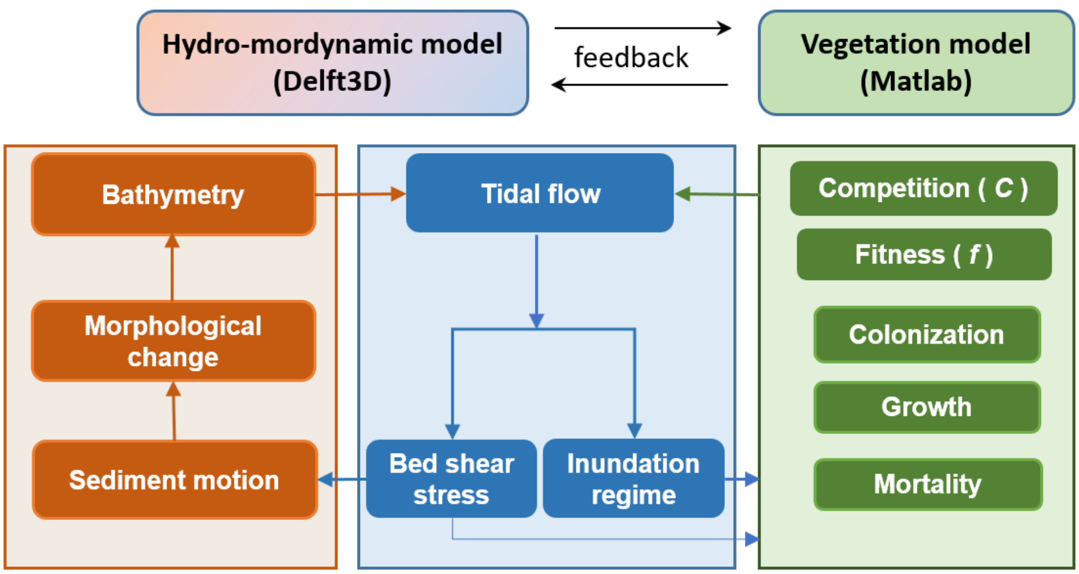

Figure 1. Overview of bio-morphodynamic interactions incorporated into the model. The modelling approach couples a hydro-morphodynamic model and a new dynamic vegetation model so that the interaction between tidal flow, sediment motion, morphological change and mangrove vegetation can be investigated. The vegetation model receives information on the bed shear stress and inundation regime from the hydro-morphodynamic model and then regulates the colonization, growth and mortality of mangrove trees. Information on mangrove vegetation characteristics is in turn exchanged with the hydro-morphodynamic model which then accounts for vegetation effects on tidal flow resistance.

Time scales of the model

The time defined in this model could be different from each inner model and I use 3 different times to describe different processes. First, the time that relates to tides/waves applying in the seaward boundary is called hydrodynamic time, which can be regarded as the real time we experience now. Second, to enable long-term simulation, morphological evolution is accelerated by applying morfac and the corresponding time is called morphological time. Based on the sensitivity analysis, I apply a morfrac of 90 in this research. Therefore, to achieve a 90 morphological-year profile evolution, we only need to define a one-year hydrological signal on the seaward boundary. The outcome of sensitivity analysis on different morfac values can be referred to the attached research paper. Last, I use the ecological time to describe the mangrove dynamics and this time scale is set to the same as morphological time. Every ecological year has been further divided into four ecological seasons to account for the responses of mangrove forests to specific seasons. For instance, mangroves are assumed to only colonize in the first season while mortality occurs at the end of the fourth season when trees are growing under consistently depressed conditions. In addition, mangroves grow over 4 seasons depending on their surrounding environments (e.g. inundation frequency and competition stress). Thus, mangroves growing within one ecological season would experience the same period of morphological evolution (i.e. 90 morphological days), which requires the hydrodynamic model to be driven by a hydrological signal lasting for one hydrodynamic day (Fig. 2).

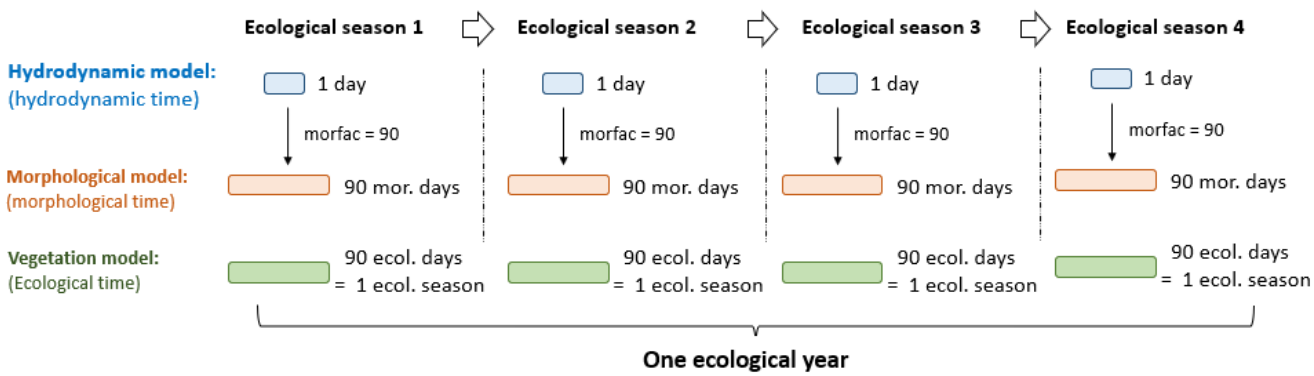

Figure 2. An example of model time scales when the morfac is set to 90. Morphological changes and vegetation dynamics are under the same time frame, which is driven by a much shorter time (hydrodynamic time) of hydrodynamic simulation due to the application of morphological acceleration factor. mor. = morphological, ecol. = ecological.

Preparation before model simulations

1) Install Delft3D and Matlab

   When it is the first time for the users to run this model, the software including Delft3D 4 Suite and Matlab should be installed correctly. A prior test should be implemented by running Delft3D example cases in order to check the successfully set up of Delft3D.

2) Set up parallel simulation working environment

This research is based on extensive computation workloads due to a large number of cases and fine grid cells. To enhance the computation efficiency, a parallel simulation method is implemented to run the model based on mpich2 (High-Performance Portable Message Passing Interface; https://www.mpich.org/). Set up of the mpich2 for the first time can be found online, or follow the steps indicated in the executive file ("*run_flow2d3d_parallel.bat*") within the *initial_files* folder. When the mpich2 has been successfully downloaded and activated in one machine, the subsequent modelling work on this machine can skip this step.

3) Check initial files

Each modelling case is set up in a main folder, as the example provided below, the main folder is named *3riversQ18EquSandMud30*, within which there are three subfolders calling *initial_files*, *Matlab_functions* and *Matlab_vegetation_modules* (Fig. 3). The *initial_files* folder documents all required files to run a Delf3D model, and it is the hydro-morphodynamic model that should be running directly through Delft3D executive file. Two cases are provided depending on the system that is used. If the model is running on a Windows system, the executive file will be '*run_flow2d3d_parallel.bat*'. However, if the model is running on a Linux system, the executive file will be '*run_flow2d3d_parallel_eejit.sh*'. Proper adjustments on the contents of these two executive files are needed, for example, update the path to the directory where the Delft3D has been installed. In order to include the vegetation effects on the hydrodynamics during simulation, in the *mdf* file (here, *3rivers.mdf*), the following keywords should be included in the end:

Trtrou = #Y#

Trtdef = #veg.trd#

Trtu = #veg.trv#

Trtv = #veg.trv#

The values of Trtrou determine whether or not to include the vegetation effects ("Yes" or "No"), and Trtdef and Trtu/Trtv indicate the vegetation files that will be used during the simulation. The vegetation files *veg.trd* and *veg.trv* store vegetation parameters including grid cell number, vegetation height, vegetation density, drag coefficient and bed roughness, etc. These two files will be generated and updated through the vegetation model, but the basic vegetation information should be provided beforehand in the *Veg.txt* file. Please refer to the explanation within the *Veg.txt* file to set up the basic information of the modelling vegetation, such as initial stem diameter, maximum stem diameter, shoot height, etc. When the research needs to consider the impacts of multiple vegetation species within one research area, different vegetation files with corresponding vegetation information should be created (e.g. *Veg1.txt*, *Veg2.txt*, *Veg3.txt*, *etc.).*

It is important to note Matlab will call the hydro-morphodynamic simulation through executive file and the xml-file, so the directory within the executive file should be carefully checked and the name of *.mdf file should be matched with the name in the xml-file (here, *config_flow2d3d.xml*).

The *Matlab_functions* folder includes several functions supporting the process of data extraction and update. For example, the code *d3d_admin_v5.m* helps to update the time after an ecological season of simulation has been done by Delft3D. Both *pctl.m* and *prctile.m* are the codes used to extract a percentile number from a sequence of values, especially when the Matlab Statistic tool is not installed.

The *Matlab_vegetation_modules* folder is an important folder containing all the key files to run the vegetation model. A detailed explanation of each module will be introduced in the following section.

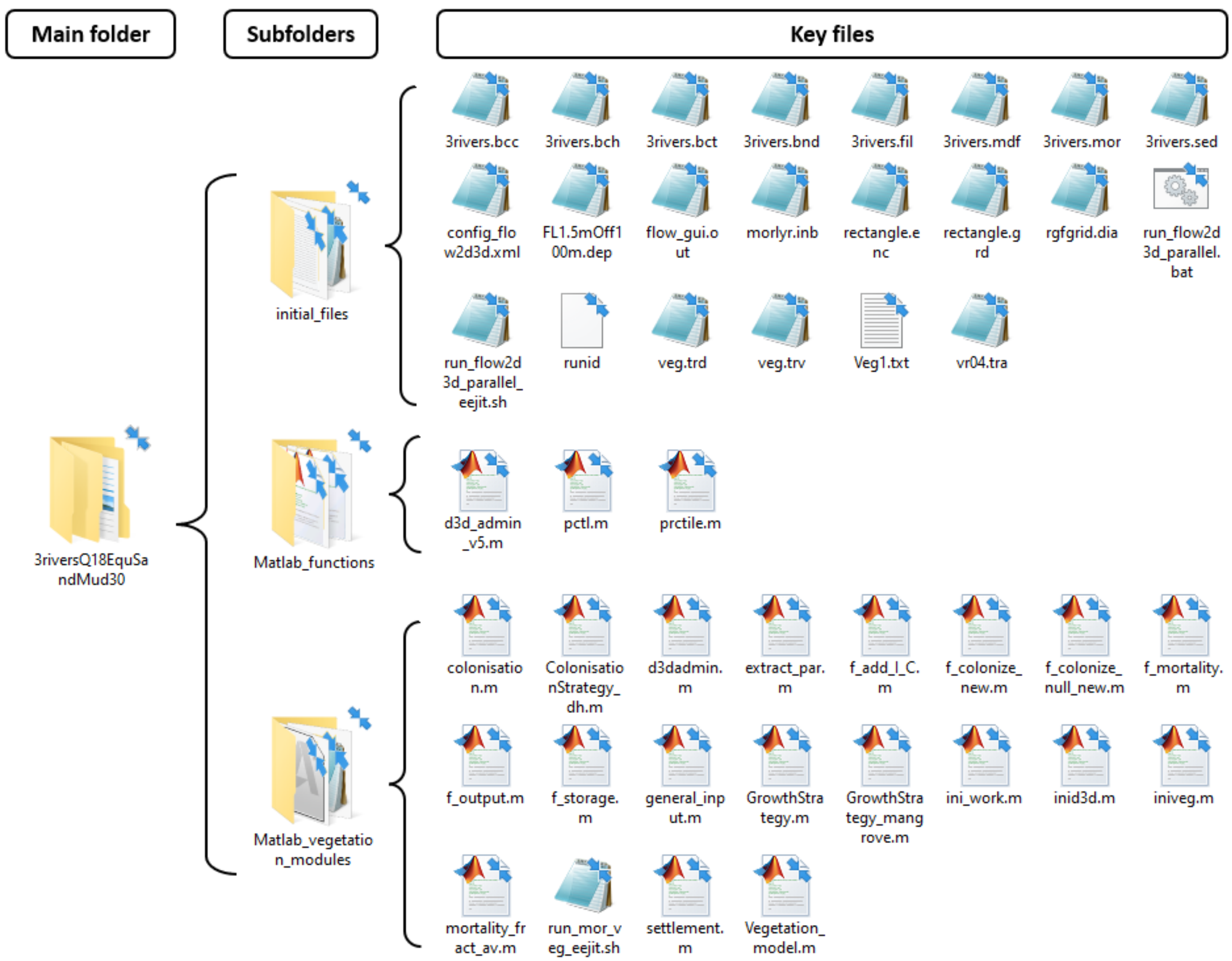

Figure 3. Hierarchy of folders and their corresponding files used to initialize a bio-morphodynamic model. The folder *initial_files* contains a Delft3D hydro-morphodynamic model, and the vegetation model is processed through the Matlab code assembled within the folders *Matlab_functions* and *Matlab_vegetation_modules*.

Vegetation model structures

Although a detailed explanation has been already included in each of the vegetation codes, to help readers quickly understand the process and compositions of the dynamic vegetation model, here I further explain the meaning and the connections between each module by using a flow chart below (Fig. 4). The whole dynamic vegetation model contains 10 main modules coded by Matlab. The core parts of the mangrove model such as their colonization, growth and mortality are based on previous studies using a biomass carrying capacity concept and allometric scaling approach (Berger & Hildenbrandt, 2000; van Maanen et al., 2013). The amount of mangrove biomass is traced and updated every ecological season, and the reduction of mangrove biomass is either due to a prolong inundation or severe competition. See the following description for a general explanation of each main module.

1) general_input.m

This is the main module defining the path of simulation, key parameters of vegetation (with/without vegetation, with/without roots) and how the model starts (from the beginning/a restarted file). The example case I provided is the model running on a Linux system, and it can be easily changed to a Windows system by renaming the "bat_file" keyword in the Line 14.

2) inid3d.m

This module is used to import data from *.mdf file, including domain scales, morfac and initial time information.

3) iniveg.m

This module is initialized if the effects of vegetation are taken into account, which in my cases it is always needed to run this module because we study mangroves. Its main work is to read vegetation information defined in vegetation files (i.e., veg[No.].txt). In my mangrove models, coefficients related to inundation stress, competition stress, growth function and initial vegetation sizes are defined in the vegetation files and will be imported through this module. A comprehensive analysis and explanation of how these growth functions influence vegetation growth can be further referred to my previous modelling work (Xie et al., 2020; Xie et al., 2022).

4) ini_work.m

This module creates the "*work*" folder where all initial files will be copied. By modifying the time slots in the *.mdf file, the simulation period will be changed to cover one ecological season. Generally, the very first simulation regarding the hydro-morphodynamic process without vegetation information will be started here based on initial settings. However, if the model is asked to make a restart from the previous run, then the last stored vegetation information will be imported to supplement files needed before the simulation starts.

As an initial setup, the codes including *general_input*, *inid3d*, *iniveg* and *ini_work* are only carried out once at the beginning of each simulation (Fig. 4). The outcome of Delft3D results and vegetation files are temporarily calculated at the '*work*' folder, both of which will be stored in a new folder under the main folder '*3riversQ18EquSandMud30*' following with a specific name on their ecological year (e.g. 'results_1', 'results_2', 'results_3', etc.).

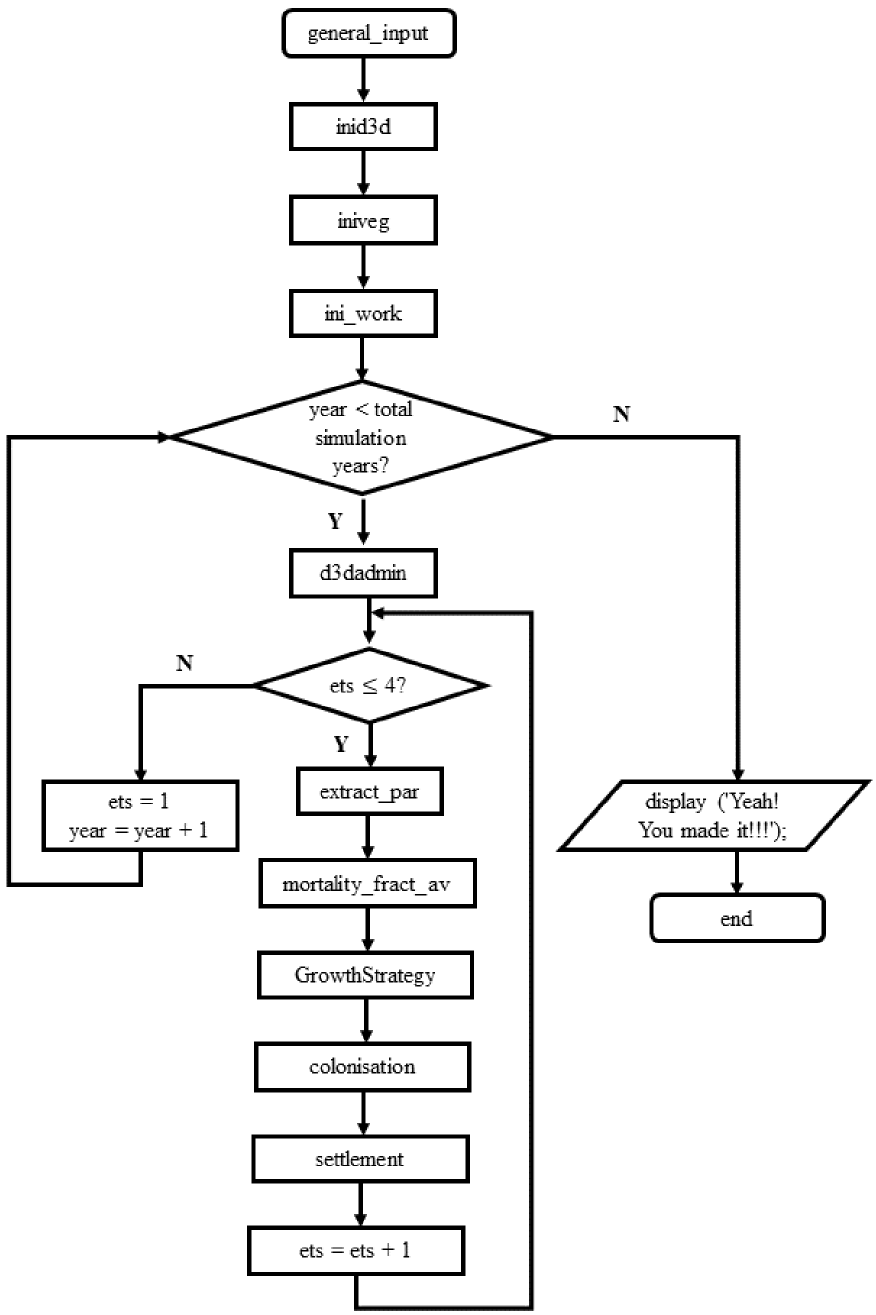

Figure 4. Flow chart of dynamic vegetation models. ets is the abbreviation of the ecological time step, in my current research, each ets represents one ecological season as shown in Fig. 2.

5) d3dadmin.m

This module moderates the time slots of simulation in *.mdf file for the next simulation.

6) extract_par.m

This module extracts and calculates data from Delft3D output, i.e. trim-*.dat file, for the coming vegetation dynamic process, including water depth and bed shear stress. These data will be stored in a specific matrix every ecological season time step.

7) mortality_fract_av.m

The mortality process is realized in this module when the growth rate of one vegetation is continually lower than 0.5 for 5 years. The growth rate is dependent on the fitness factor and competition stress factor. In one cell, mangroves with different sizes/species are allowed to co-exist. When mortality occurs among different mangroves, the number of mangroves in different species that is reduced from that cell is dependent on the relative value of their fitness function, with higher fitness values less vegetation will be removed. The young vegetation is assumed to be more vulnerable than other older age groups, so they will be the first vegetation group to be removed until no mortality vegetation exists in that cell.

8) GrowthStrategy.m

This module is used to update the size of vegetation (stem height and diameter) for a new ecological season time step. The growth rate is dependent on the fitness function and competition stress factor, which have been calculated in the previous module (mortality_fract_av). Different vegetation species may have different parameters for their growth function and these functions have been recognized in the module *iniveg.m*.

9) colonization.m

This module allows new seedlings to settle down in a suitable location. The conditions of one specific location are evaluated based on both inundation frequency (named as ‘relative hydroperiod’ in the research paper) and the 90th percentile bed shear stress. The number of new seedlings assigned to the cell is dependent on the existing vegetation number and the capacity of one cell can hold. When different vegetation species are all applicable to colonize in one cell, the number of seedlings for each species will be calculated based on the relative value of their fitness function. The cells where the mortality process occurs in the previous module will be excluded from this module.

10) settlement.m

This module summarizes all vegetation information that Matlab calculates in previous processes and add a number of pneumatophores according to the number and size of vegetation stems. At the same time, output files for the new hydro-morphodynamic simulation will be generated, such as *veg.trd* and *veg.trv*.

Run the vegetation model

After preparation all the files and particularly update the path in 1) executive file ('run_flow2d3d_parallel.bat' or 'run_flow2d3d_parallel_eejit.sh') in the *initial_files* folder, which links to the installing Delft3D bat file, and 2) case path in the code general_input.m in the *Matlab_vegetation_modules* folder, the vegetation code can be started. The way to start the vegetation code depends on the system that is used. When the model is running on a Windows system with Matlab-GUI, the code "*general_input.m*" should be opened and users can easily press 'RUN' to initialize the simulation. However, when the model is running on a Linux system, a bash shell script file (*.sh) should be created and submit to the system. An example of a shell script file has been attached in the folder, *Matlab_vegetation_modules* (see Fig. 3, "*run_mor_veg_eejit.sh*").

Model development history

This mangrove model has undergone three main upgrades since its development. Based on an earlier framework on salt marsh model (Brückner et al., 2019), I developed the first-generation model on a one-dimensional coastal profile to investigate the dynamics of multi-species mangrove assemblages under sea-level rise and human barriers (Xie et al., 2020). By considering the feedback between multi-species mangrove vegetation and the coastal profile, the research shows for the first time shifts in mangrove species zonation linked to a dynamic coastal system and environmental change impacts.

Then, I developed the second-generation model by widening the environmental conditions, including tides, small wind waves, sediment supply and coastal slopes to identify which combinations are most determinantal for mangrove forests (Xie et al., 2022). Although it was still a one-dimensional modelling study, the study systematically explored mangrove vulnerability to sea-level rise under various coastal environmental conditions. It is an important step because it not only highlights the need to consider the essential nonlinear feedbacks when assessing ecosystem resilience, but also proves that the model can be applied widely in different coastal environment conditions.

As a step further, I have now extended the one-dimensional model to a two-dimensional model to investigate the impacts of human actions on the development of coastal bio-geomorphic landscapes (attached research paper; in preparation). Different from the previous two model generations, this new model simulation has been set up based on the New Zealand estuarine systems with a history of anthropogenically increased fine sediment supply and an ongoing approach to remove coastal mangroves. Model simulations were conducted to assess the impacts of human-induced changes in sediment supply and mangrove removal, and to unravel anthro-bio-morphodynamic feedbacks. The outcome of the model, calibrated with publicized data, shows how the local management may compromise coastal ecosystem restoration, highlighting the necessity to incorporate the source-to-sink trajectories in coastal management.

Overall, the bio-morphodynamic model provided in this repository has been gradually improved over my PhD study. It has included functions to model multi-species mangrove assemblages, to be used in different coastal environment conditions and to interpret anthro-bio-morphodynamic feedbacks at different scales. The application of current modelling framework in other ecosystems is possible but requests a more detailed model adjustment and calibration.

Thank you for your time!

Sincerely,

Danghan

2023-Jan-11

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