# MANUAL

# Database of Beach Retreat/Inundation Projections

## Beach retreat predictions methodology

Sea level rise represents a most significant threat to beaches, forcing their retreat/erosion; a sea level rise *α* will result in a shoreline retreat *S* due to erosion of the beach face, the sediments of which are transported/deposited offshore, with the extent/rates of the cross-shore retreat controlled (amongst others) by bed slope, the texture and supply of beach sediments and the hydrodynamic conditions (e.g. Dean, 2002).

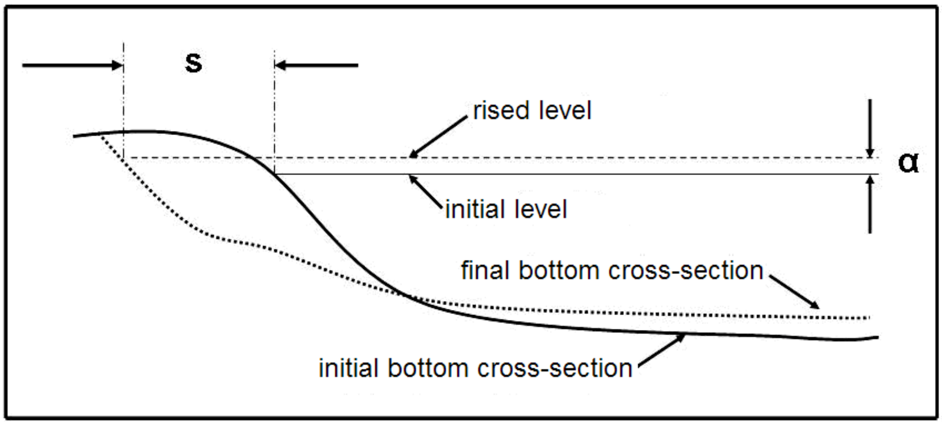



***Fig. 1:*** *Sketch of beach response to sea level rise. A rise α produces erosion of the beach face sediment which is transferred to the adjacent sea bed, resulting in a beach retreat S.*

1-D cross-shore morphodynamic models are used in an ensemble mode in order to assess the range of long- and short-term beach retreat/erosion for different beach slopes, sediment textures (grain size) and wave conditions, and under different scenarios of MSL changes and/or storm induced SLRs. The models that were used to create this database are: 3 analytical (Edelman, Bruun, Dean) (Edelman, 1972; Bruun, 1988; Dean, 1991) and 4 numerical models (SBEACH, Leont'yev, Xbeach and Boussinesq) (Larson and Kraus, 1989; Leont'yev, 1996; Roelvink et al., 2010; Karambas and Koutitas, 2002). Two model ensembles can be created, a 'long-term' ensemble consisting of the analytical models Bruun, Dean and Edelman and a 'short-term' ensemble comprising the numerical SBEACH, Leont'yev, XBEACH and Boussinesq models; the former is used to assess beach retreat/erosion under MSLR, whereas the latter retreat is due to temporary SLR (i.e. episodic storm-induced). With regard to combined SLRs (i.e. storm-induced SLR superimposed on MSLRs), the long-term and short-term ensembles were used consecutively (see also Monioudi et al, 2017). The above approach is designed to project beach retreat/erosion, but not temporary inundation/flooding due to wave run-up. Although wave run–up is dealt within the numerical models of the ensemble, its effects are manifested in the results only if it induces sediment transport that forces morphological changes (e.g. Leont'yev, 1996). Yet, wave run up-induced temporary flooding that does not result in beach retreats is also a significant management issue (e.g. Jiménez et al., 2012; Hoeke et al., 2013); therefore, estimations of wave run up excursion/inundation are also undertaken. Run up heights are estimated for all tested conditions, using the expressions of Stockdon et al. (2006) (Vousdoukas et al., 2009):

$$R_{2\%} = 1.1\left(0.35\beta(H_o/L_o)^{1/2} + \frac{\left[H_o L_o (0.563\beta^2 + 0.004)\right]^{1/2}}{2}\right) \quad \text{(all data)}$$

$$R_{2\%} = 0.043(H_o/L_o)^{1/2} \quad \text{for dissipative beaches } (\xi < 0.3)$$

where $R_{2\%}$, the 2 % exceedance of the peak run-up height $H_o$, $L_o$ are the deep water wave height and length, $\beta$ the beach slope and $\xi$ the Iribarren number ($\xi=\beta/(H_o/L_o)^{1/2}$).

Wave run up excursions are then calculated from the wave run up heights ($R_{2\%}$) for all tested bed slopes and wave conditions and added to the beach erosion/retreat projections of the seven 1-D cross-shore morphodynamic models to project final flooding excursions.

### ***Input data***

The input data for the application of this approach are the following:

#### Beach characteristics database

The geo-spatial characteristics of the "dry" beaches can be obtained, using images and other optical information available in the Google Earth Pro application. "Dry" beaches are defined as the low-lying coastal sedimentary bodies bounded on their landward side by either natural boundaries (vegetated dunes and/or cliffs) or permanent artificial structures (e.g. coastal embankments, seawalls, roads, and buildings) and on their seaward side by the shoreline, i.e. the median line of the foaming swash zone shown on the imagery.

The lateral extent of individual beaches is delimited by natural barriers, such as rock promontories. Tiny beaches (length less than 50 m) can be neglected in the data set. Beaches are digitized as polygons. Geo-rectification is not necessary as the aim of the exercise is not to provide definitive locations and elevations of beach features, but to extract/record (horizontal) geo-spatial characteristics.

In addition to beach dimensions, other relevant information is recorded/codified, including: the presence of (a) natural features, such as river mouths, vegetation and (b) artificial features, such as coastal protection schemes and backshore infrastructure/assets.

#### Environmental forcing

This methodology is suitable for large scale applications thus the input data of the models are not based on in situ measurements. The models are set up using a plausible range of environmental conditions. As accurate bathymetry data is often not available, initial linear bathymetric profiles are considered with different profile slopes. However, validation of the models against physical experiments in GWK in Germany showed that the results of the models set with the equivalent linear profile were reasonably close to those of the physical experiments (Monioudi et al. 2017). The wave forcing can be provided though the analysis of ERA-INTERIM wave data. With regard to the sediment texture, descriptive information (e.g. sand, gravel) can be collected from photos available on the Google Earth Pro application and other available information from the relevant literature.

***Table 1:*** *Input data*

| Data | Source | Publicly Available | Expertise Needed | Required Software or Other Resources |
|---|---|---|---|---|
| Beach location and width | Manually digitized from Google Earth | Yes | None | Google Earth Pro, Arc GIS |
| Beach slope | Plausible range of beach slopes | No | None | None |
| Wave conditions | Plausible wave condition range based on ERA-INTERIM wave data (1979-2015) | Yes | Manipulation of NetCDF Data | Software for Manipulating or Displaying NetCDF Data |
| Median sediment size $D_{50}$ | Optical information (Google Earth and other available information)/collated from scientific literature/reports | Yes | None | None |
| Mean Sea Level Rise Projections | Integrated Climate Data Centre - ICDC | Yes | None | None |
| Total Water Level Projections | Joint Research Centre (JRC) | Yes | Manipulation of NetCDF Data | Software for Manipulating/ Displaying NetCDF Data |

## Sea level projections

MSLR projections from literature and available databases (e.g. Integrated Climate Data Centre - ICDC, Church et al., 2013) are used. Projections of episodic extremes (due to the combined effect of storm surges and wave set up) can be obtained from the Joint Research Centre (JRC) or from literature.

## *Outputs*

This approach outputs the following:

- Potential ranges of beach retreat/erosion and temporary inundation/flooding
- Ranges of decreases in 'dry' beach widths projected through the comparison between the ranges of beach retreat/erosion (S) and the maximum widths of the Saint Lucia beaches
- Ranges in beach temporary inundation/flooding
- Numbers and percentages of beaches where backshore infrastructure/assets are projected to be affected by beach retreat/erosion and flooding.

## *Special expertise needed to apply the methodology*

A toolbox is constructed in order to simplify the developed approach. The toolbox is provided as a Guide User Interface (GUI) suite, is user- friendly, fast and requires no great expertise for its operation. This tool can bridge the gap between coastal scientists/engineers and coastal managers and stakeholders and can be used in building capacities in coastal regions with scarce human resources and little relevant expertise.

It must be noted that the use of the toolbox may reduce flexibility in the use of the models; for full control in the use of the models, experience in morphodynamic modeling and scientific programming is needed. Nevertheless, it can be used easily for a first assessment of the beach erosion risk.

### *Benefits*

The present approach provides reasonable assessments of potential ranges of beach retreat under marine forcing (i.e. sea levels and waves) on the basis of (minimal) environmental information that can be obtained relatively easily. It provides ranges (maximum and minimum) of the horizontal excursion of cross-shore beach retreat/inundation, which could be then compared to the beach width that could be easily determined by remote-sensed imagery.

Beach erosion is amongst the first issues to consider when planning for the sustainable development of coastal zones, particularly in areas where beaches function as natural 'armor' to valuable coastal infrastructure and assets and/or as significant environments of leisure. Assessments of the beach morphological evolution at different spatio-temporal scales are required, based on advanced numerical, analytical, and/or empirical models constructed and applied by experienced operators, set up/validated using appropriate field data and backed by expert analysis. However, such efforts are usually hampered by the (a) scarcity of relevant information in many coastal areas, and (b) dearth in the necessary human and financial resources (e.g. Parker et al., 2013); this is particularly true when assessments of beach erosion are carried out over larger spatial scales.

Existing methodologies/tools for rapid assessment of coastal/beach erosion due to MSLR and extreme events at large scales (e.g. Hinkel et al., 2010) have limitations stemming from (amongst others): (a) their requirements for coastal Digital Elevation Models (DEMs) of high resolution/accuracy; and (b) the generally limited consideration of major controls (e.g. hydrodynamics). At the same time, advanced modeling approaches (e.g. Vousdoukas et al., 2016) in addition to detailed environmental information commonly require experienced operators and high computation costs that may make them impractical to coastal planners/managers in SIDS (e.g. McLeod et al., 2010).

The present approach, which compares ranges of SLR induced beach retreat and flooding under different initial conditions and hydrodynamic forcing with beach maximum widths, is not limited by the resolution/accuracy of available coastal DEMs or the availability of detailed environmental information (e.g. Jiménez et al., 2012) and can be used in areas with limited human resources. Nevertheless, there are also constraints. Projections are based on the assumption that beaches comprise inexhaustible sediment reservoirs, with no lateral sediment losses; cross-shore modeling obviously cannot resolve such issues. In addition, the approach is not designed to account for other erosion-controlling factors, such as: geological controls, coastal sedimentary budgets, and extreme event duration and sequencing (e.g. Corbella and Stretch, 2012); the presence of artificial beach protection schemes and/or protecting nearshore ecosystems (e.g. Peduzzi et al., 2013); and the effects of coastal use (e.g. Bi et al., 2013). However, the aim of the exercise is not to replace detailed modeling studies for individual beaches, but to provide ranges of beach erosion and flooding at a large scale.

### *Additional data or resource needs*

Models displayed differential behaviour for almost all tested conditions, showing as expected significant ranges of results due to the varying initial conditions and forcing used i.e. different bed slopes, sediment sizes and wave conditions. Generally, all model results have been found to be very sensitive to beach slope, which makes the beach slope the most responsible parameter for the wide range of the beach retreat results. The "high" predictions of that range reflect the calculations with mild beach slope (1/30), heavy wave conditions and fine beach material ("low" predictions are for the other ends). Then, high and low predictions are applied to each beach to drive the results, assuming that all beaches have either mild slope ("high" prediction) or steep slope ("low" prediction). The predictions can be improved if more information is available for the environmental conditions (especially for the beach slope) of each beach from previous studies or from literature, then this information can be used to narrow the envelope of the maximum and minimum retreat ranges through the interactive GUIs and apply a different range of beach retreat/inundation to each beach. If such information is not available, in situ measurements are required, which in large spatial scale are impractical to be performed, especially by coastal planners/managers.

### *Relationship between beach retreat and erosion, and transport infrastructure vulnerability*

Transport is a demand-driven industry; thus, whatever effects climate variability and change (CV &C) has on tourism will also affect the demand for tourism-related transportation. The tourist industry in St Lucia is based on the 3S model (Sea, Sand and Sun). A most critical component of 3S tourism is the availability of beaches that are environmentally and aesthetically sound and retain adequate carrying capacity (e.g. McArthur, 2015; Cisneros et al., 2016). Carrying capacity is defined as the “maximum number of people that may visit a tourism destination at the same time, without causing destruction of the physical, economic and socio-cultural environment and an unacceptable decrease in the quality of the visitor’ satisfaction” (WTO, 1981). Beach erosion due to e.g. sea level rise might significantly reduce the carrying capacity and the quality of the beaches as environments of leisure. Therefore, beach erosion may reduce the attractiveness of the country to tourism, with potentially important (indirect) impacts on the major gateways of the international tourism, i.e. airports, and to a lesser extent, seaports).

## The toolbox

In order to create the database of this toolbox all models were applied for the case of beaches (low coasts consisted of unconsolidated sediments) using linear profiles with slopes of 1/10, 1/15, 1/20, 1/25 and 1/30. Experiments were carried out using varying wave conditions, i.e. wave heights (H) of 1 – 4 m and periods (T) 4- 8 s and 7 different sediment grain sizes ($d_{50}$ of 0.2, 0.33, 0.50, 0.80, 1, 2 and 5 mm). For all cases (totally 101), 12 sea level rise scenarios (0.05, 0.10, 0.15, 0.22, 0.30, 0.40, 0.50, 0.75, 1, 1.25, 1.50 and 2 m) were tested.

The toolbox includes 2 simplified platforms created using the MATLAB Guide. One platform for the beach retreat projections (Beach_Retreat_Projections.exe) and another platform for the beach inundation projections (Beach_Inundation_Projections.exe). Both platforms are used in the exact same way; the only difference is in the data that they contain. The users of these platforms can search in the database for the environmental conditions (beach slope, wave height, wave period, sediment size) of their interest. They can use specific conditions (one value for each parameter) and obtain (if these conditions are found in the database) the beach retreat/inundation (for small spatial scale e.g. one beach) given by the 7 models (Leont'yev, SBEACH, Xbeach, Boussinesq, Edelman, Bruun and Dean) for 12 sea level scenarios (0.05, 0.10, 0.15, 0.22, 0.30, 0.40, 0.50, 0.75, 1, 1.25, 1.50 and 2 m) and the polynomial equation that describes the relation between sea level rise and beach retreat. Users can select all or some of these models to create an ensemble and then they can obtain the mean values (by selected models) of beach retreat and the polynomial equation that fits in the mean values of the retreat. For large (spatial) scale applications, users can enter a range of environmental conditions in the platform and obtain the lower and upper limit of the beach retreat, projected by the models. They can also select models to create an ensemble and obtain the mean (by selected models) lower and mean upper limits of the projected retreat. A criterion for the selection of models can be the classification of the models to short-term and long-term for short-term and long-term projections respectively.

### *How to use this program*

First, install MATLAB Compiler Runtime (MCR) version 7.14 by running MCRInstaller. MCR - MATLAB Compiler uses the MATLAB Compiler Runtime (MCR), which is a standalone set of shared libraries that enable the execution of M-files. The MCR provides complete support for all features of MATLAB without the MATLAB GUI (see readme file). Once MCR has been installed the user can run the platform by simply double-clicking on the Beach_Retreat_Projections.exe or Beach_Inundation_Projections.exe, and then he/she should see the following screens (it might take some time to open):

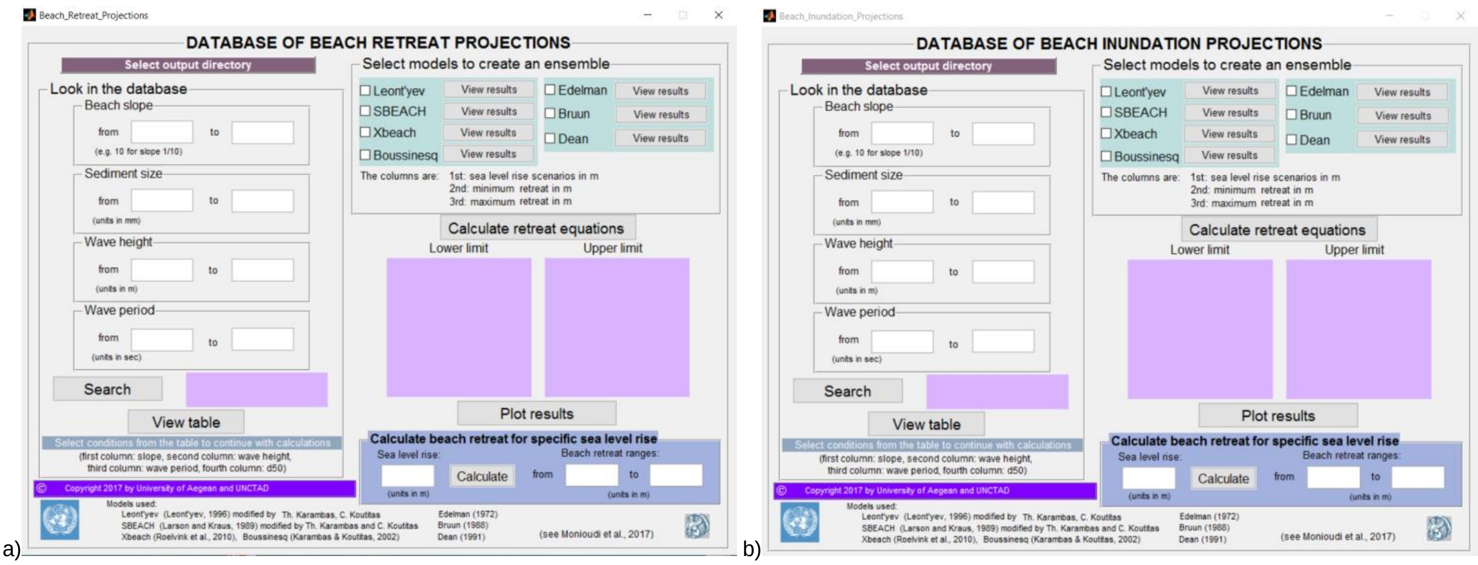



***Fig. 2****: (a) The Beach_Retreat_Projections and (b) the Beach_Inundation_Projections.exe GUI figures.*

This GUI consists of a big panel named 'Database of beach retreat projections'

('Database of beach inundation projections'), which contains all components of the GUI. By pressing the button 'select output directory' the user can select the directory where the output files are going to be saved automatically. In the panel entitled 'Look in the database', the user enters information about the beach slope, the sediment size, the wave height, and the wave period (Fig. 2). For each parameter 2 edit boxes exist. In the first box, the user enters the smaller value of the parameter and in the second box the larger value in order to insert a range of values, or he/she can enter the same value in the 2 boxes in order to insert a specific value; examples of input values are shown in Figure 3. Once all edit boxes are filled the user can press the button 'Search' and a text appears in text field next to the button.

If the conditions inserted by the user are found in the database, the number of conditions is written in the text field next to the button 'Search' (Fig. 3a). The program is first searching for the beach slope. If beach slope is not found, then the program stops the quest for the other parameters and informs the user that the slope is not found and suggests close values, if there are any in the data base (Fig. 3b). If the inserted beach slope is found, but not the sediment size, then the program stops the quest for the other parameters and informs the user that the sediment size is not found and suggests close values, if there are any in the data base (Fig. 4a). The same procedure is also applied for the other parameters.

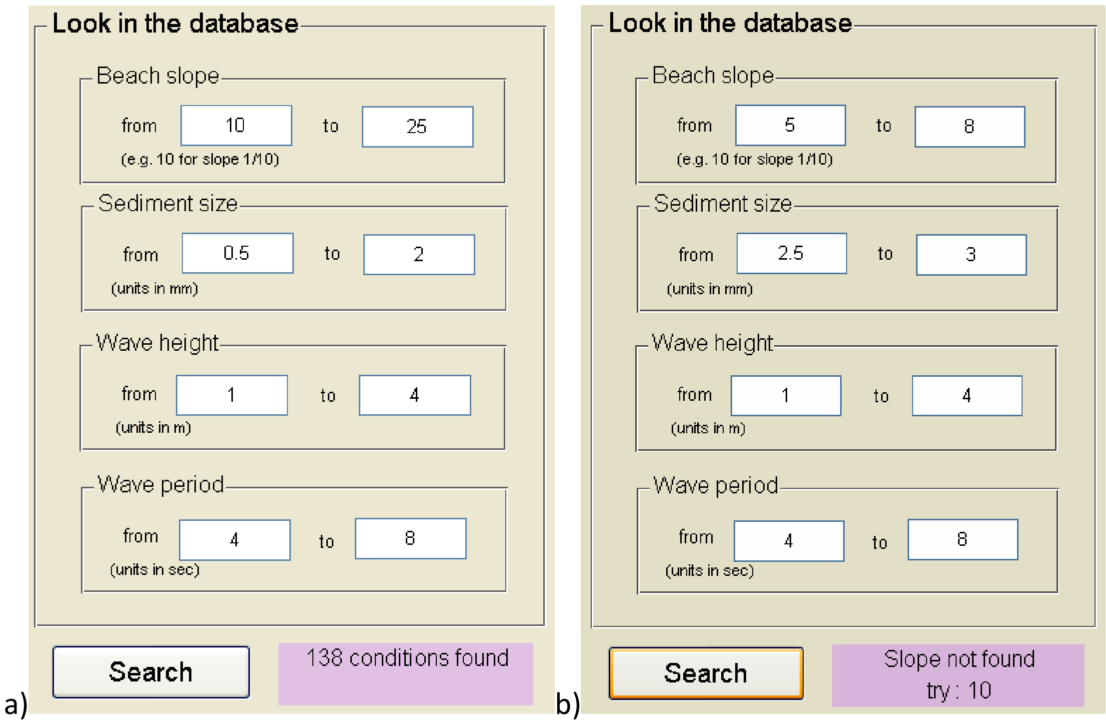



***Fig. 3:*** *Examples of input values.*

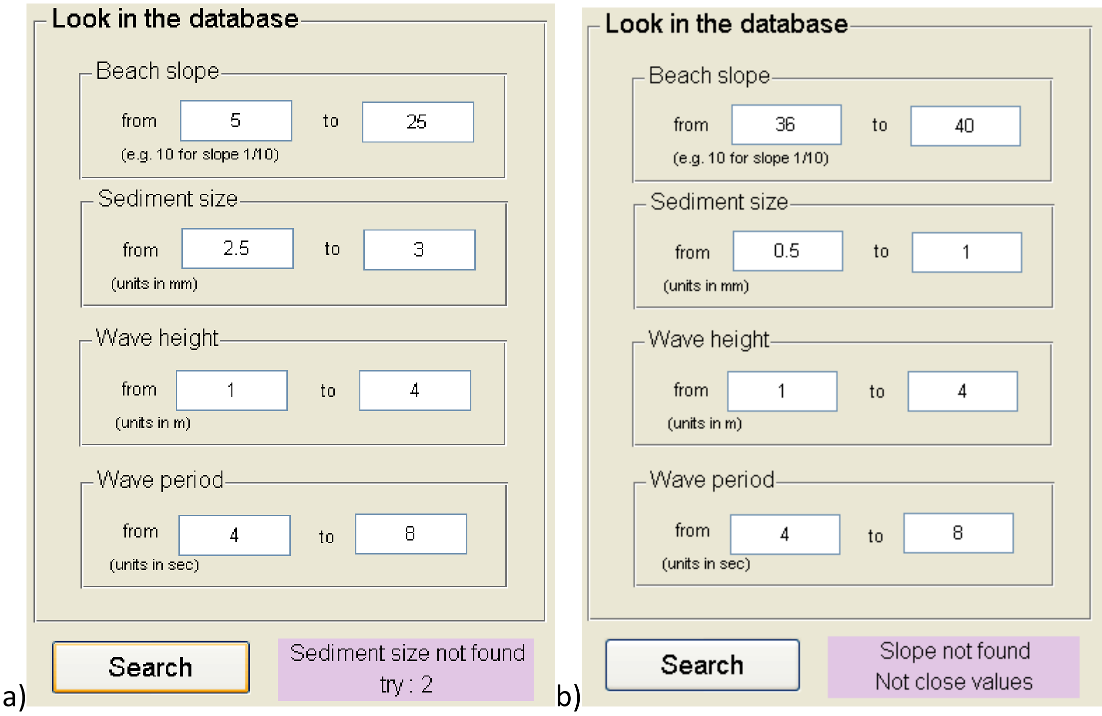



***Fig. 4:*** *Examples of input values not found.*

Once the desired conditions are found, the user can use the button 'View table', which prompts a list box to appear (Fig. 5) with all the condition combinations found in the database, enabling the user to view the results of his/her quest and make a new selection from the list. Now that the environmental conditions are determined, the user can select models to create an ensemble, by clicking in the corresponding checkboxes (Fig. 6a). The user has the option to view the lower and upper limit of beach retreat estimations made by each model individually by pressing the button 'View results' next to the model (the checkbox of the model should be clicked on) (Fig. 6b). When the 'View results' button is pressed, a message box is displayed with a table consisting of 3 columns. The first column is the sea level rise scenarios (in m), the second is the lower limit of beach retreat estimations (in m) made by the model and the third column is the upper limit.

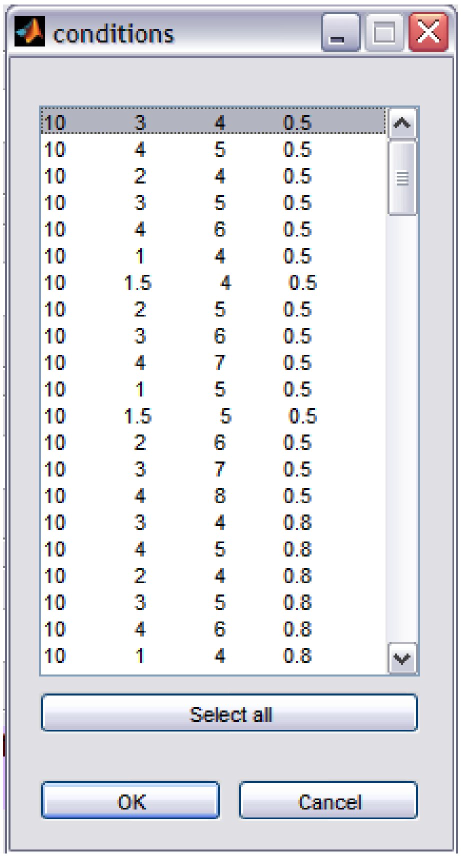
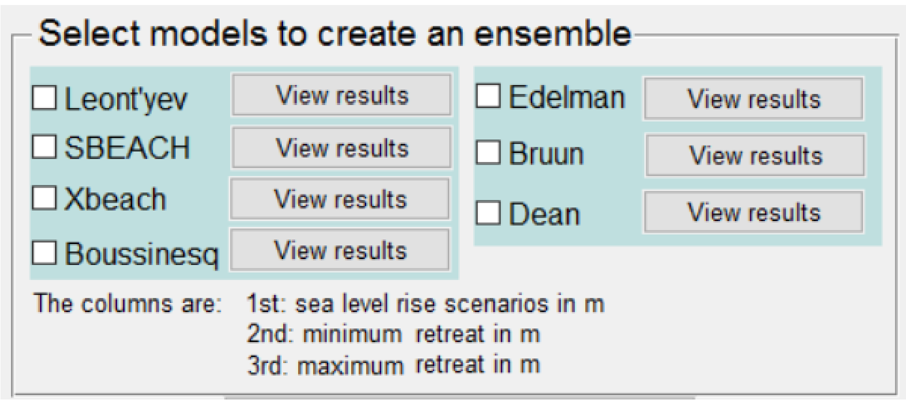



***Fig. 5:*** *The list box of the environmental conditions, 1st column: beach slope (m), 2nd column: wave height (m), 3rd column: wave period (sec), 4th column: sediment size (mm).*

Once the models that comprise the ensemble are selected, the user can use the button 'Calculate retreat equations'; then the polynomial equations describing the mean lower and mean upper limits of beach retreat estimations appear in the text fields below the texts 'Lower limit' and 'Upper limit', respectively (e.g. Fig. 7). These equations have the form: $s = p_1a^2 + p_2a + p_3$, where $s$: is the beach retreat, $p_1$, $p_2$ and $p_3$: are the polynomial coefficients and $a$: is the sea level rise. The value of $R^2$ is also given in the text field.




a)

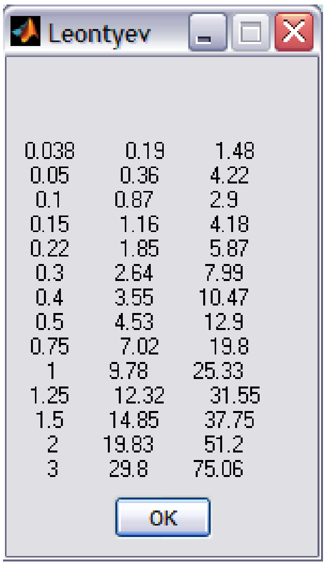
b) 


***Fig. 6:*** *a) An example of model selection. b) An example of a message box with the results of Leont'yev model.*

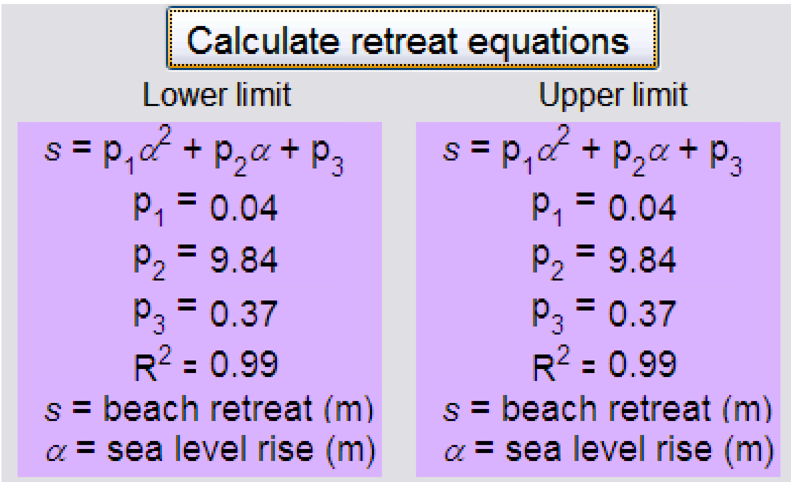



***Fig. 7:*** *An example of the resulting equations.*

By pressing the button 'Plot results' the polynomials equations of the lower and upper limit of all selected model are calculated and plotted together with the mean (non-weighed) limits (e.g. Fig. 8).

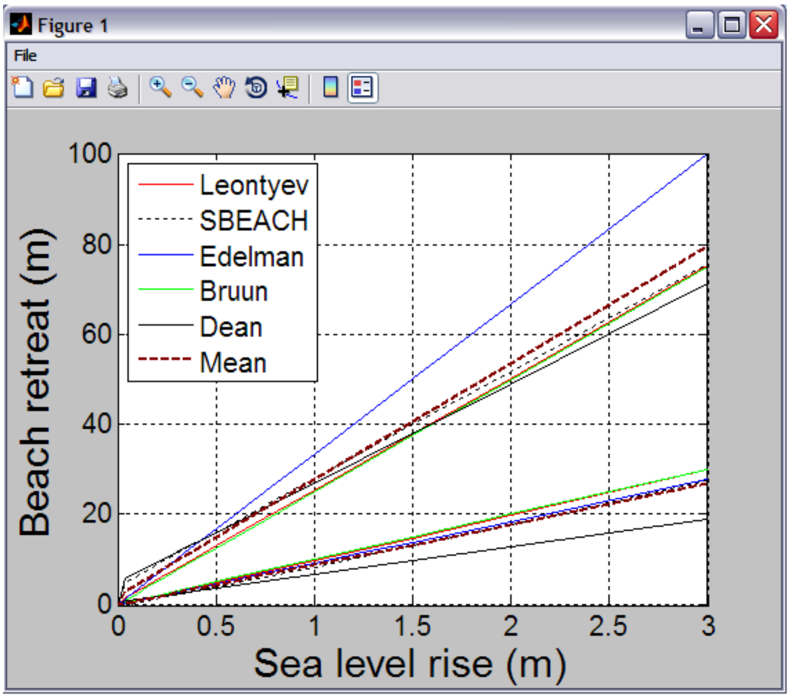



***Fig. 8:*** *An example of a plotting result.*

From the resulting equations, the range of beach retreat due to sea level rise can be calculated. This program gives the user the option to calculate the range of retreat only by clicking on the button 'Calculate' inside the panel 'Calculate the retreat for a specific sea level rise'. An example is given in Figure 9.

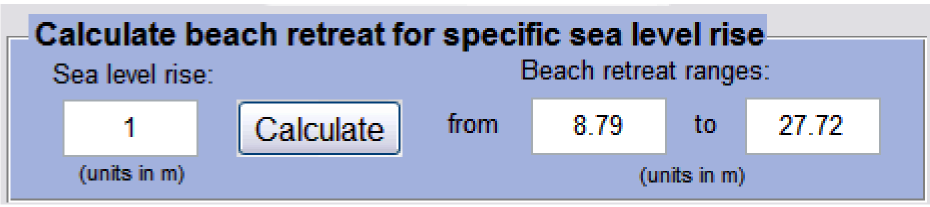



***Fig. 9:*** *An example of beach retreat range calculation for a specific sea level rise scenario.*

*<u>The output files of this platform are</u>*:

***L_limit.txt***: is a table with 7 rows and 12 columns and contains the lower limits of beach retreat projections made by Leont'yev (1st row), SBEACH (2nd row), Edelman (3rd row), Bruun (4th row), Dean (5th row), Xbeach (6th row) and Boussinesq (7th row) models. Each column corresponds to a different sea level rise scenario. If one or more models are not selected by the user, the values of the corresponding row are set to zeros.
***U_limt.txt***: is a table with 6 rows and 14 columns and contains the upper limits of beach retreat projections made by Leont'yev (1st row), SBEACH (2nd row), Edelman (3rd row), Bruun (4th row), Dean (5th row), Xbeach (6th row) and Boussinesq (7th row) models. Each column corresponds to a different sea level rise scenario. If one or more models are not selected by the user, the values of the corresponding row are set to zeros.
***Dif_cod.txt***: is a table that contains the combinations of conditions (selected by the user)

for which the models were applied. The first column is the beach slope (viz. 10 for a beach slope 1/10), the second is the wave height in meters, the third is the wave period in sec and the fourth is the sediment size (viz. $d_{50}$) in millimeters.

***Beach retreat estimations.tiff***: is the figure of the lower and upper limits of beach retreat projections of the models selected by the user. Mean lower and upper limit is also depicted in the figure.

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