Joint Nature Conservation Committee

Model development to assess the vulnerability of the Cayman Islands to storm surge and inland flooding, and the role and value of natural capital in mitigating the impacts – Phase 2

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SWAN model user guide

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Report for

Government of the Cayman Islands

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Executive summary

This model user guide has been prepared to accompany the SWAN models of Grand Cayman, Little Cayman, and Cayman Brac developed by Wood as part of the Phase 2 "*Model development to assess the vulnerability of the Cayman Islands to storm surge and inland flooding, and the role and value of natural capital in mitigating the impacts Cayman Islands Natural Capital Assessment*" project.

The user guide provides an overview of the existing model sources and elements, in addition to general SWAN background and training to provide modelling theory and background.

A number of possible user-defined model configurations are described, in the event of new data or should there be the desire to assess a specific scenario using the model.

The user guide also covers the functionality of the Wood TUFLOW SWAN Toolbox developed as part of Phase 2 of the project to aid the running of models from a GIS interface and details the common output checks to carry out following a simulation.

Contents

1. Introduction

SWAN wave models have been developed for the Cayman Islands to help assess the value of the coastal natural capital (coral reefs, mangroves, and seagrass) in mitigating flood risks for the islands. These SWAN wave models are used to evaluate wave conditions given a variety of hurricane wind forcing conditions as well as natural capital states, including accounting for potential reef degradation. Resulting wave conditions are subsequently passed on to a TUFLOW model to look at coastal inundation flooding. A bespoke ESRI ArcGIS geoprocessing toolbox has been developed to facilitate the running of the TUFLOW models for various scenarios and to facilitate the exchange of information between the SWAN wave model and TUFLOW, hereafter referred to as the "Wood TUFLOW SWAN Toolbox".

This user guide has been produced to support a training workshop provided to representatives of the Government of the Cayman Islands on 31st March 2022, and as a reference document for future use. This user guide provides the following:

- Background on the SWAN wave model (Chapter 2)
- Overview of the Cayman Islands models presently available (Chapter 3)
- Model updates that can be made using the accompanying GIS tool (Chapter 4)
- Overview of how to run the models (Chapter 5)
- Conclusions (Chapter 6)

2. SWAN background

2.1 Overview

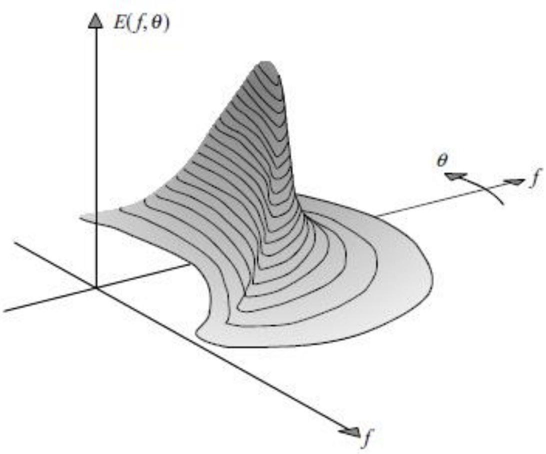
SWAN (**S**imulating **Wa**ves **N**earshore) is a third-generation spectral wave model developed at the Delft University of Technology. It is used for simulating wave generation (wind), propagation (shoaling, refraction, diffraction), transformation (non-linear wave-wave interactions), and dissipation (breaking, white-capping, bottom friction, vegetation). It is based on solving the spectral action balance equation (or energy balance in the absence of currents) accounting for the previously mentioned sources and sinks. It uses state-of-the-art formulations to describe the physical processes and is continually updated as new research improves upon the previous formulations.

2.2 Background

Waves can be described as the vertical motion of the ocean surface. There are several different types of waves present in the oceans around the world (including tsunami, tides, surges, etc.) with wind-generated waves (wave periods < 30 seconds) being the types of waves modelled by SWAN. Wind-generated waves consist of wind-sea and swell, where wind-sea are locally generated waves and swell are generated by a distant storm. In the case of the Cayman Islands models, the type of waves being modelled are regionally generated wind-sea waves, forced by a uniform wind field of hurricane wind speeds tracking directly towards the islands.

Wave parameters can be described statistically by means of a wave spectrum, which describes the wave energy as a function of wave frequency (inverse of wave period) and wave direction (Figure 2.1). Wave parameters (significant wave height, wave period) can be derived from this statistical description of the waves. Therefore, instead of looking at individual waves (and the corresponding movement of the water surface) one considers statistically representative wave properties. This is the premise of the SWAN model.

Figure 2.1 Two-dimensional spectrum of wind-generated waves (Figure 3.11 from Holthuijsen (2007))



SWAN then considers the transformation of this wave energy both in space and in time and considers additional energy sources and sinks. Some included processes are as follows.

Wave generation:

- Wind growth (input of energy due to wind field forcing)

Wave propagation:

- Wave shoaling (wave amplitude increases as waves propagate into shallower water)
- Wave refraction (turning of waves toward shallower water due to depth or current induced changes in the phase speed of the waves)
- Wave diffraction (not applicable to the current model runs; this is the turning of waves towards areas of lower amplitude, relevant when looking at waves in the shadow zone of obstacles)

Wave transformation:

- Non-linear wave interactions (triad and quadruplet, redistribute wave energy over the frequency spectrum, do not add or remove energy)

Wave dissipation:

- Depth induced wave breaking (waves breaking that occurs as the waves enter shallower water)
- White-capping (wave breaking that occurs in deeper water)
- Bottom friction (wave dissipation due to the roughness of the bed surface, e.g. coral reefs and mangroves)
- Vegetation (wave dissipation due to vegetation, e.g. seagrass)

Some relevant documents to review for further background information on waves and the SWAN wave model are:

- Waves in Oceanic and Coastal Waters by Leo H. Holthuijsen (general waves and wave modelling background)
- SWAN user manual and technical documentation, https://swanmodel.sourceforge.io/

2.3 Modelling concept

SWAN standalone does not use a graphical user interface (GUI). It has been incorporated into the Delft3D software as part of Delft3D-Wave and has a GUI as part of this package; however, this version is more limited with respect to available options. Therefore, the models for the Cayman Islands were set-up using SWAN standalone and model set-up was done using a text editor and run using the SWAN executable file.

The fundamental software required for building and viewing SWAN models are listed below, in addition to recommended software (but not limited to):

- Text editor (Notepad is an open source option)

- Programming software (Python is an open-source option, alternatively Matlab)
- GIS software for import and export of XYZ (position and value) data and for viewing results (QGIS is an open-source option, alternatively ArcGIS)

2.4 Suggested folder structure

It is recommended to store all files (inputs and outputs) for a particular run in one folder. This will allow easier functionality with the Wood TUFLOW SWAN Toolbox described in Section 5. If multiple runs are done in the same folder, a unique version number should be used to identify which files belong to which run.

2.5 File types

The file types and their extensions used in the Cayman Island SWAN models are listed in Table 2.1 below. For a full list of file types compatible with SWAN, refer to the SWAN user manual[1]. The file types can generally be classified into the following categories:

- Input files – contains the input files required for the simulation
- Intermediate files – files that are generated during one simulation (coarse model run) and that are needed for another simulation (fine model run, Grand Cayman or Cayman Brac/Little Cayman)
- Output files – files containing the wave results
- QA/QC files – Text files to check to ensure the model finished properly and without any errors.

[1] https://swanmodel.sourceforge.io/

Table 2.1 Most commonly used file types

File	Extension	Description	Format
Input Files			
Gridded Data	.dep	Gridded data files. These can contain roughness values, bathymetry, seagrass density.	Text
Main Input File	.swn	Main input file that specifies all the parameter settings and files to be used for the simulation.	Text
Output Location File	.loc	File used to specify output locations. This is not included in the current SWAN models.	Text
Intermediate Files			
Nesting file	.nest	This is output from the coarse model and provides input boundary conditions for the finer nested models.	Text
Data output			
Tabular Output	.tab	Contains output parameters at requested output points. This is not included in the current SWAN models.	Text
Matrix Output	.mat	Contains output parameters at all grid points and all time periods during the simulation	Matlab output file
QA/QC Files			
Log File	.prt (PRINT)	File contains a summary of the completed run and any errors. This file is used for diagnostic purposes.	Text
Run Completion File	norm_end	File created if the simulation finishes normally	Text

3. Cayman Islands models overview

3.1 Purpose

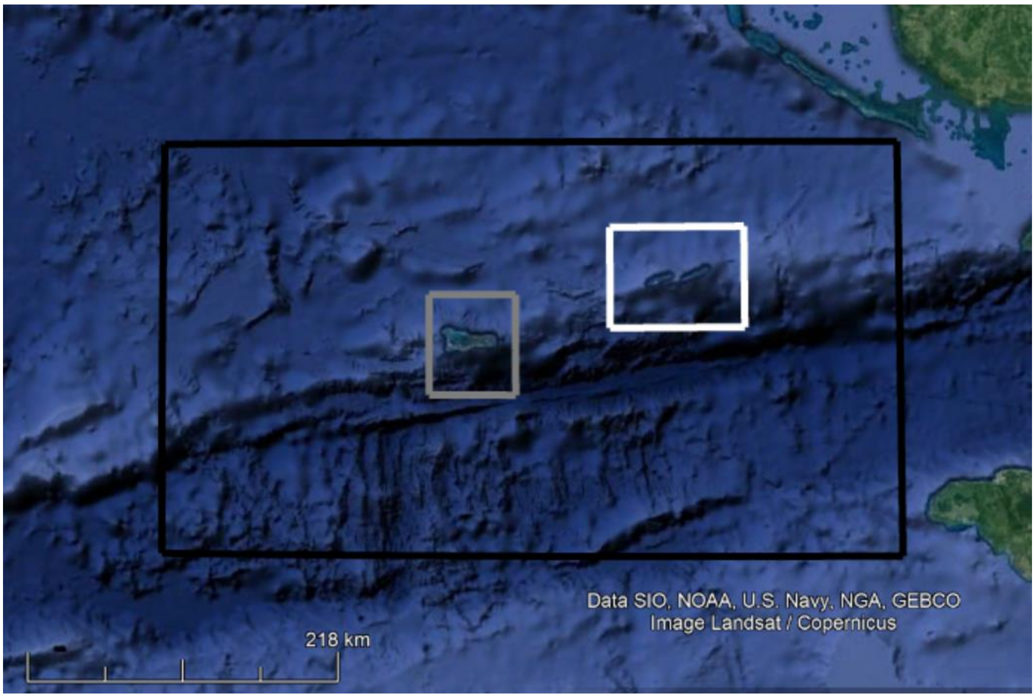
Several SWAN models have been generated for the Cayman Islands (Grand Cayman, Little Cayman, and Cayman Brac) to assess extreme waves at these islands during hypothetical hurricane events (Category 1, Category 3 and Category 5 and directions north, south, and southwest).

Three models have been generated (Figure 3.1):

- Coarse Cayman Islands model (black)
- Higher-Resolution Grand Cayman Island model (grey)
- Higher-Resolution Little Cayman and Cayman Brac (white)

The coarse model provides the boundary conditions (.nest file) for both the Grand Cayman Island model and the Little Cayman and Cayman Brac model.

Figure 3.1 Cayman Islands SWAN models, black (coarse model), grey (Grand Cayman Model), white (Little Cayman and Cayman Brac)



3.2 Scenarios and events

The models have been run for a baseline (present day) scenario, several degraded scenarios simulating the effect of natural capital degradation (loss of coral reef, mangroves, and seagrass), and an enhanced scenario where coral reef health improves. The outputs from the wave modelling scenarios have been analysed to assess the flood mitigation value of the coastal natural capital (i.e. wave height reduction). The following natural capital scenarios are considered (Table 3.1):

Table 3.1 Natural Capital Scenarios

Scenario	Coral Reefs	Mangroves	Sea Grass
Baseline	n = 0.176	n = 0.32	400 /m^2
Degraded	n = 0.110	n = 0.20	400 /m^2
Severe degraded	n= 0.110 Loss of 1 m depth along reef cells	n = 0.20	400 /m^2
Severe degraded – no seagrass	n= 0.110 Loss of 1 m depth along reef cells	n = 0.20	none
Enhanced	n = 0.22	n = 0.4	400 /m^2

The following hurricane scenarios were considered (Table 3.2) for the above-mentioned wind directions (north-0°, south-180°, and southwest-225°).

Table 3.2 Hurricane Scenarios Considered

Hurricane Category	Wind Speed	Surge
Category 1	42.5 m/s	1 m
Category 3	57.6 m/s	1.5 m
Category 5	72 m/s	3 m

3.3 Data inputs

Several data inputs have been prepared for the various scenarios and models (coarse Cayman Islands, Grand Cayman, Little Cayman and Cayman Brac).

Three template input files (.swn) were created for the three model domains (Table 3.3). These are meant as templates only and will be modified using the Wood TUFLOW SWAN Toolbox for the scenario of interest. These template files are example input files that can be modified using the GIS tool, which will do a search and replace of certain keywords contained within these files. For a description of what all the keywords mean in the input files please refer to the SWAN user manual[2].

[2] https://swanmodel.sourceforge.io/

Table 3.3 Available Input files

File Name	Purpose	Model
caymanislands_NEST.swn	Template input file	Overall Coarse Cayman Islands
grandcayman.swn	Template input file	Grand Cayman
littlecayman_caymanbrac.swn	Template input file	Little Cayman and Cayman Brac

Several different depth files are available (Table 3.4). These files represent the bathymetry (depth) of water above the sea bottom. Two of these files represent a scenario where the reef height is reduced by 1m.

Table 3.4 Available Depth Files

File Name	Purpose	Model
coarse_A.dep	Depth File, present day	Overall Coarse Cayman Islands
grandcayman1f.dep	Depth File, present day	Grand Cayman
gc_nest_reef_2.dep	Depth File, with 1 m reduction in reef height	Grand Cayman
lcayman_fine.dep	Depth File, present day	Little Cayman and Cayman Brac
lc_reef_bathy.dep	Depth File, with 1 m reduction in reef height	Little Cayman and Cayman Brac

Several different roughness files are available (Table 3.5), each representing different amounts of degradation of the reefs as well as the reefs in their current state.

Table 3.5 Available Roughness Files

File Name	Purpose	Model
gc_mannings_1p0_ext.dep	Roughness map representing enhanced scenario	Grand Cayman
gc_mannings_0p8_ext.dep	Roughness map representing baseline scenario	Grand Cayman
gc_mannings_0p5_ext.dep	Roughness map representing degraded/ severe degraded scenario	Grand Cayman
lc_mannings_1p0_ext.dep	Roughness map representing enhanced scenario	Little Cayman and Cayman Brac
lc_mannings_0p8_ext.dep	Roughness map representing baseline scenario	Little Cayman and Cayman Brac
lc_mannings_0p5_ext.dep	Roughness map representing degraded/ severe degraded scenario	Little Cayman and Cayman Brac

One seagrass map file is available for each of the smaller nested model runs (Table 3.6). These map files represent the seagrass density.

Table 3.6 Available Seagrass Density Maps

File Name	Purpose	Model
gc_nplants1.dep	Seagrass map file	Grand Cayman
lc_nplants1.dep	Seagrass map file	Little Cayman and Cayman Brac
gc_nplants_zero.dep	Seagrass map file, no seagrass	Grand Cayman

4. Potential user-defined model updates

The below sub-sections detail common model updates that could be made if, for instance, new improved data is available, to modify existing model representation or to establish new run scenarios. Potential model updates, however, are by no means limited to those detailed here. The sub section outlines how the updates may be implemented, making use of the bespoke Wood TUFLOW SWAN Toolbox or modifying/ creating new input data files.

Some potential model updates have been built into the Wood TUFLOW SWAN Toolbox to allow for easy updating (Table 4.1).

Table 4.1 Model Updates Built into the Wood TUFLOW SWAN Toolbox

File Name	Units (if any)	Description
Water Level Offset (surge)	m	The user can update the surge level considered in the model.
Wind Speed	m/s	Storm wind speed (spatially constant). By increasing the wind speed higher waves can be generated.
Wind Direction	Nautical degrees	Storm wind direction (spatially constant). 0 degrees is from North and 180 degrees is from South)
Depth File	m	The user can update the depth file used in the model. Several depth files have been prepared and can be selected (Table 3.4). If new bathymetry becomes available, or the user wants to look at different reef height scenarios this file will need to be updated. The update of this file is not covered within the tool.
Bed Friction File	m	The user can update the Madsen roughness coefficient. Several roughness files have been prepared and can be selected (Table 3.5). If the user wants to look at different reef scenarios this file will need to be updated. The update of this file is not covered within the tool.
Vegetation Density File	# stems per m^2	The user can update the seagrass plant density. One plant density file has been prepared for both Grand Cayman and Little Cayman and Cayman Brac and can be selected (Table 3.6). If the user wants to look at different seagrass scenarios this file will need to be updated. The update of this file is not covered within the tool.

5. Running the model

The model can be run with the accompanying Wood TUFLOW SWAN Toolbox. The following scenarios were run through during the training on 31st March (Table 5.1).

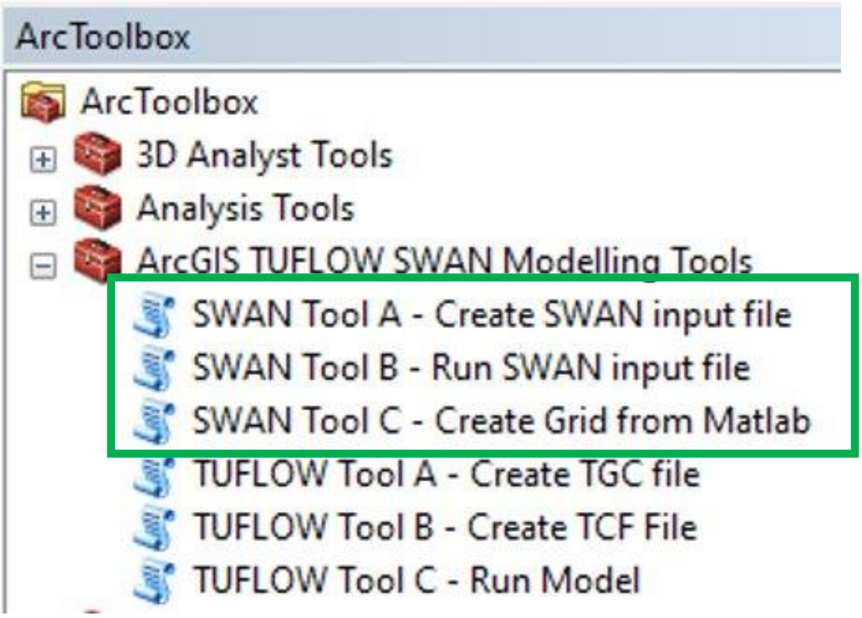
Table 5.1 Scenarios for the Training

File Name	Scenario 1 Cat 5, SW, enhanced	Scenario 2 Cat 5, SW, degraded scenario
Water Level Offset (surge)	3 m	3 m
Wind Speed	72 m/s	72 m/s
Wind Direction	225 ° (southwest)	225 ° (southwest)
Depth File (Cayman Islands Coarse Model)	coarse_A.dep	coarse_A.dep
Depth File (Grand Cayman Fine Model)	grandcayman1f.dep	grandcayman1f.dep
Bed Friction File	gc_mannings_1p0_ext.dep	gc_mannings_0p5_ext.dep
Vegetation Density File	gc_nplants1.dep	gc_nplants1.dep

The Wood TUFLOW SWAN Toolbox contains three processing tools (**Error! Reference source not found.**)

- Tool A – Create SWAN input file (creates the .swn SWAN input file)
- Tool B – Run SWAN input file (runs the SWAN model)
- Tool C – Create Grid from Matlab (converts the SWAN output .mat into both x-y-wave height data and raster data)

Figure 5.1 Wood TUFLOW SWAN Toolbox geoprocessing tools



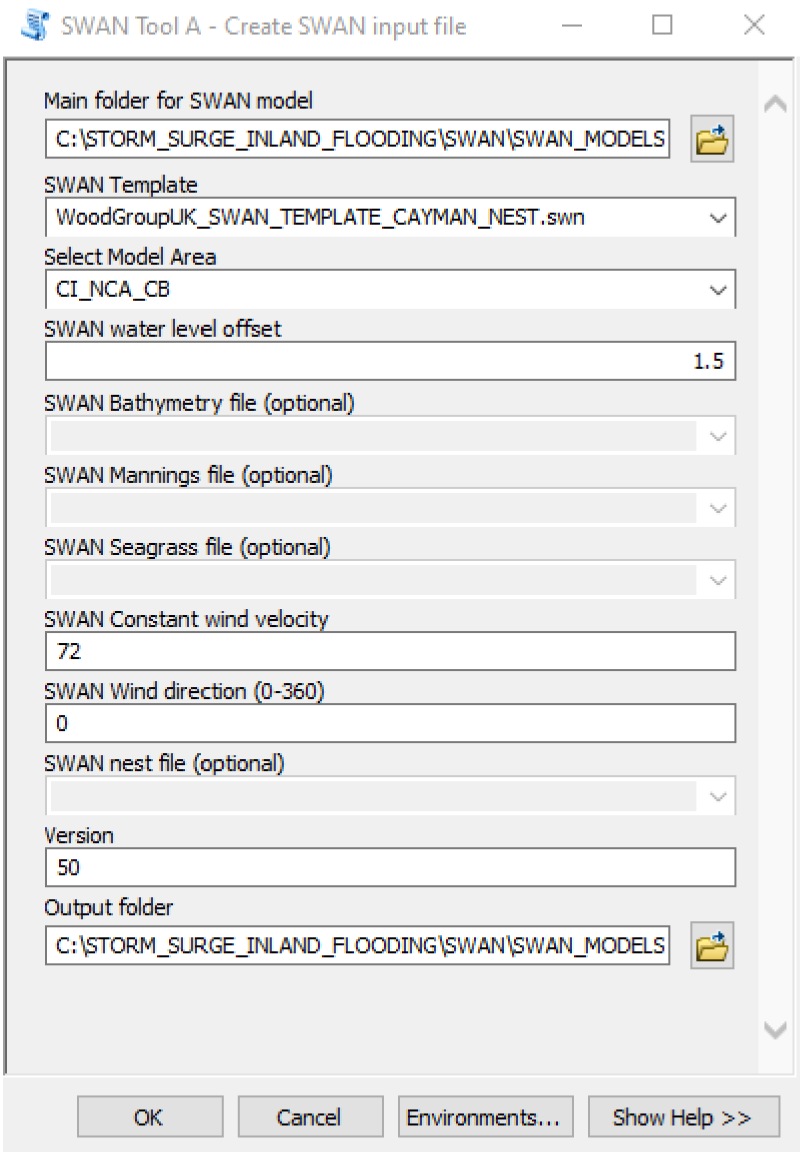
5.1 SWAN Tool A – Create SWAN input file

This tool creates the (.swn) input file by modifying a selected template file based on inputs specified by the user. Three template files have been provided, see Table 3.3. These files are located by default in the same location as the related SWAN model files. Depending on the input file selected, a different drop-down menu will be displayed.

If the caymanislands_NEST.swn file (or any template file with '_NEST') is selected, the following menu will appear (Figure 5.2). The '_NEST' indicates that the SWAN template file corresponds to the coarse model domain (Figure 3.1), which is used to provide boundary conditions (wave parameters) to the fine Grand Cayman and Little Cayman and Cayman Brac models. The input values that can be adjusted are:

- Model Area (a descriptive model name)
- SWAN water level offset (surge level)
- SWAN Constant wind velocity
- SWAN Wind direction
- Version (a number to indicate the run version)
- Output folder (where the output and input files are stored)

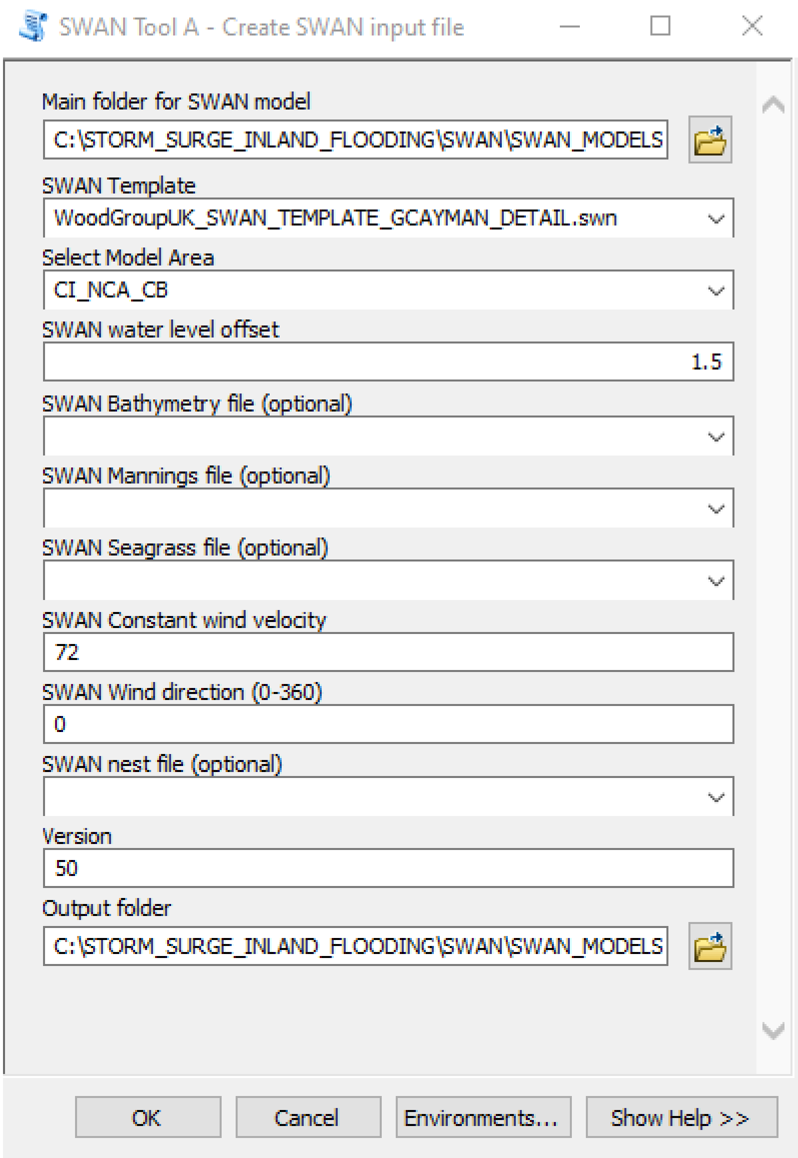
Figure 5.2 SWAN Tool A – Create SWAN input file (coarse grid)



If '_NEST' is not in the filename the following menu will appear (Figure 5.3). Additional input parameters that will need to be specified are:

- SWAN Bathymetry file (see Table 3.4 for options)
- SWAN Mannings file (see Table 3.5 for options)
- SWAN Seagrass file (see Table 3.6 for options)
- SWAN nest file (file generated by running, Tool B, for the coarse Cayman Islands model)

Figure 5.3 SWAN Tool A – Create SWAN input file (fine grids)

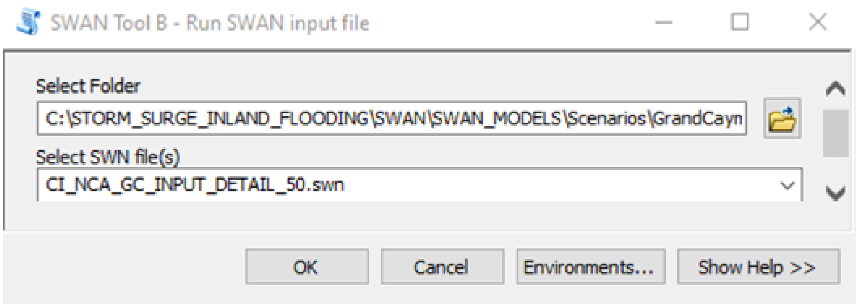


After the user selects OK, the related Python code is used to retrieve the SWAN template, run a python search / replace routine and then save a new SWAN input (.swn) file. The new input file will be saved in the folder defined at the bottom of the form.

5.2 SWAN Tool B – Run SWAN input file (runs the SWAN model)

This tool runs the selected model. The interface of the SWAN Tool B consists of two user parameters. The first enables the user to pick a local folder containing a SWAN input file (.swn) and the associated model files needed to run the SWAN model. The second user parameter enables the user to pick a single SWAN input file (.swn) which will be run.

Figure 5.4 SWAN Tool B – Run SWAN input file

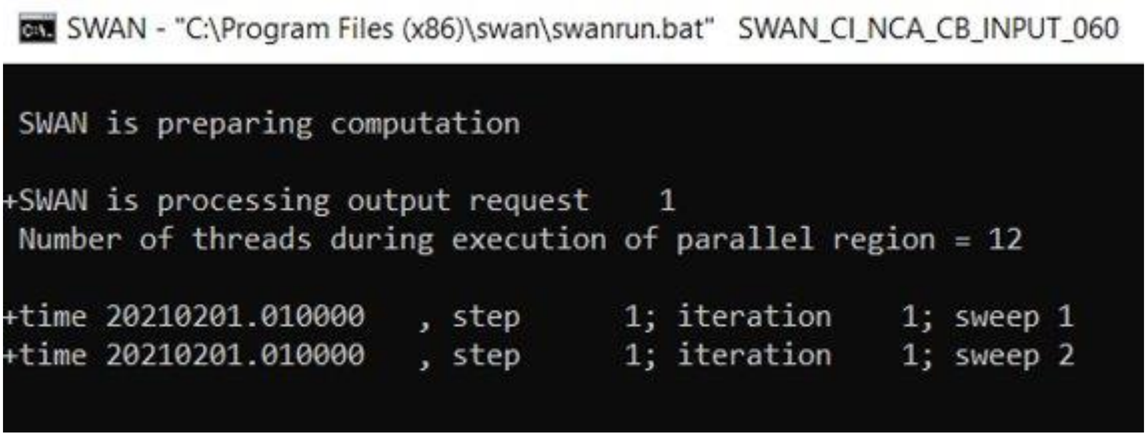


After the user selects OK, the code will generate a batch file to run the selected SWAN input (.swn) file using the SWAN executable. The location of the executable is defined using an environment variable set on the modelling computer.

The SWAN model will then start to run and develop the Matlab (.mat) output, Figure 5.5.

This file output files (.mat and .prt) will be saved in the same folder location selected in the tool interface.

Figure 5.5 Example of SWAN running



Some quality control measures to keep in mind are as follows:

- Several files are produced that help detect whether there are errors, or the SWAN results are of lower quality. If there is an error that occurs during the simulation a “Errfile” will be created. This file will contain a description of why the error occurred. Sometimes there is limited information in this file and the .prt file contains more information about the error. If the model simulation finishes ok a “norm_end” file will be created.
- Another aspect that can be easily checked with the output files created, is whether the model results have converged. During the simulation the model will keep iterating until a convergence criterion is met (in this case 97% of grid points considered converged). It is possible that the simulation completes without convergence being met.

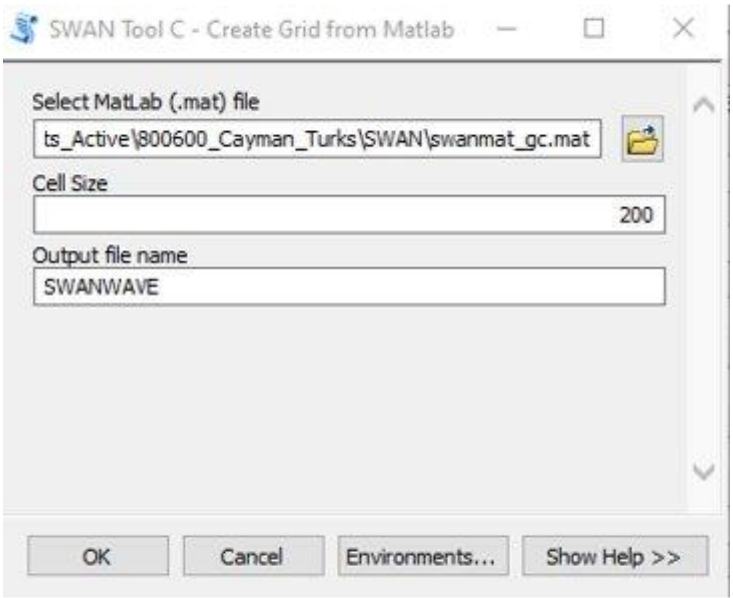
5.3 SWAN Tool C – Create Grid from Matlab (converts the SWAN output .mat into both x-y-value data and raster data)

The SWAN Tool C interface enables the user to create a final ESRI grid file of wave heights from the MATLAB (.mat) output created from running the SWAN model using Tool B. The key processing steps delivered by Tool C are:

- Converts the selected Tool B MATLAB file into a three column (lat, long, wave height) csv file;
- Creates points from the CSV using the geographic WGS 84 projection system (latitude and longitude) and reprojects the points to the projected WGS 84 projection system (meters); and
- Creates a final ESRI grid (raster file) from the projected points. The cell size of the grid is determined by the value entered in the form

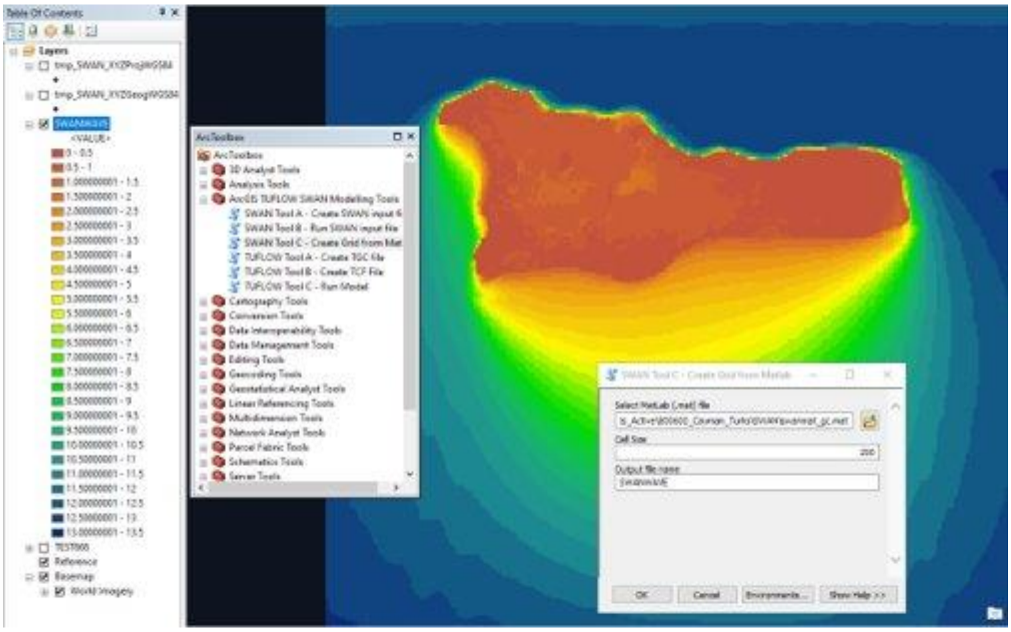
The output files are saved in the same folder location at the input MATLAB (.mat) file.

Figure 5.6 SWAN Tool C – Create Grid from Matlab



The final grid of wave heights can be visualized in ArcGIS, example shown in Figure 5.7.

Figure 5.7 Example Wave Height Output (m)



6. Conclusions

This user guide provides background on the SWAN wave model, the specific models developed for the Cayman Islands, and provides some guidance for utilizing the Cayman Islands models with the Wood TUFLOW SWAN Toolbox .

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