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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TUFLOW model user guide

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Report for

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Executive summary

This model user guide has been prepared to accompany the island-wide TUFLOW 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 TUFLOW background and training to provide modelling theory and background.

A number of possible model updates 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.

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Contents

1. Introduction

TUFLOW models have been developed for the Cayman Islands to help assess the value of the inland and coastal natural capital in mitigating flood risks for the islands. The TUFLOW models are used to evaluate inland flood risk from intense rainfall and coastal inundation given a variety of hurricane wind forcing conditions as well as natural capital states. 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 1st April 2022, and as a reference document for future use. This user guide provides the following:

- Background on the TUFLOW modelling software (Chapter 2**Error! Reference source not found.**)
- Overview of the Cayman Islands models developed for this project (Chapter 3)
- Model updates that can be made using the accompanying GIS toolbox (Chapter 4)
- Overview of how to run the models (Chapter 5)
- Discussion on the results output and visualisation (Chapter 6)
- Conclusions (Chapter 7)

2. TUFLOW background

2.1 Overview

TUFLOW (Two-Dimensional Unsteady Flow) is a world-leading computer program for simulating depth averaged, one-dimensional (1D) and two-dimensional (2D) free surface flows from floods and tides. TUFLOW incorporates two fixed-grid based solvers:

- TUFLOW Classic: A second order semi-implicit solution available for computations using CPU hardware on a single core, and;
- TUFLOW HPC (Heavily Parallelised Compute): A second order explicit solver. HPC can be run on multiple CPU cores or on GPU hardware for high-speed execution.

The two fixed grid schemes (in addition to TUFLOW's 2D and 3D flexible mesh solver; TUFLOW FV) have been extensively benchmarked as part of the UK Environment Agency (EA) software benchmarking studies and proven to demonstrate consistent results.

TUFLOW offers advanced functionality in terms of dynamic infiltration and the representation of rainfall losses, allowing for detailed representation of natural capital scenarios for this project.

TUFLOW is a licensed software and requires the purchase of an appropriate license to utilize its functionality. The Government of the Cayman Islands currently hold a TUFLOW Classic license.

2.2 Background

TUFLOW solves the full 2D depth-averaged Shallow Water Equations (SWE) for modelling 'long waves' such as tides, storm surges and inland floods (rivers and surface water). The SWE include a mathematical description of all the physical processes thought to control the movement of flood waves in two spatial dimensions. These include acceleration, pressure, bottom slope and friction slope terms. The SWE are derived from: the Navier-Stokes equations which describe the motion of fluids;, and the equations for conservation of mass and linear momentum.

Flow regimes through structures and 1D channels are handled by ESTRY, which is the primary 1D engine used by TUFLOW. ESTRY solves the full 1D free-surface St Venant flow equations (momentum and continuity) including the inertia terms. The equations contain the essential terms for modelling periodic long waves in estuaries and rivers, that is: wave propagation; advection of momentum (inertia terms) and bed friction (Manning's equation).

Relevant documents to review for further background information include the TUFLOW manual[1].

2.3 Modelling concept

TUFLOW does not use a graphical user interface (GUI) but utilises GIS and other third-party GUI software for the creation, manipulation and viewing data. Text files are used for controlling simulations and defining simulation parameters, and much of the data input is in GIS formats.

[1] TUFLOW Manual https://www.tuflow.com/downloads/

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

- Text editor (recommend Notepad++ due to advanced colour highlighting and given that it is open source);
- Spreadsheet software (Microsoft Excel), and;
- GIS software for import and export of .mif or .shp files and for viewing results (recommend ArcGIS or QGIS due to advanced functionality with the TUFLOW viewer plugin and given that it is open source).

2.4 Suggested folder structure

The recommended set of sub-folders for a model is shown in Table 2.1. Files are located relative to the file they are referenced from. For example, the path and filename of a file referred to in a .tgc is sourced relative to the .tgc file.

All TUFLOW models developed as part of this project follow this file structure, outlined in more detail in Section 3.

Table 2.1 Recommended sub-folder structure

Sub-folder	Description
Locate folders below on the system network under a folder named "TUFLOW"	
bc_dbase	Boundary condition database and time-series data for the model domain
model	Stores the TUFLOW Geometry Control (.tgc), TUFLOW Boundary Control (.tbc) and other model data files. GIS layers are located in the model\gis\ folder (see below)
model\gis	GIS layers that are inputs to the model domain
runs	TUFLOW Simulation Control File (.tcf) and TUFLOW Event File (.tef) simulation control files
runs\log	Stores TUFLOW Log File (.tlf) log files and _messages.shp files
results	Output folder to store results
check	Stores GIS and other check files to carry out model review and checks

2.5 File types

The file types and their extensions used in the Cayman Island TUFLOW models are listed in Table 2.2. For a full list of file types compatible with TUFLOW, refer to Table 2-3 of the TUFLOW manual[1]. The file types can generally be classified into the following categories:

- Control files – used for directing inputs to the simulation and setting parameters in the form of free-form commands.

- Data input files – primarily GIS layers defining the spatial data of the model and comma-delimited files specifying parameters such as the boundary conditions.
- Data output files – files containing the 2D (and 1D) hydraulic results of the simulation in a variety of formats (GIS raster, GIS vector, text files and .csv).
- Check files – GIS and text files representing the final model dataset used in the simulation calculations to allow for model review and checks.

Table 2.2 Most commonly used file types

File	Extension	Description	Format
Control Files			
TUFLOW Simulation Control File	.tcf	Controls the overarching data input and output for simulations. Mandatory for all simulations.	Text
TUFLOW Boundary Control File	.tbc	Controls the 2D boundary condition data input. Mandatory for a 2D simulation.	Text
TUFLOW Event File	.tef	Database of .tcf (and .ecf) file commands for different events.	Text
TUFLOW Geometry Control File	.tgc	Controls the 2D spatial and topographic data input. Mandatory for a 2D simulation.	Text
ESTRY Control File	.ecf	Controls the data input and output for 1D domains (not used in the TUFLOW models developed as part of this project given no 1D elements, though will be needed for any subsequent 1D updates if required.)	Text
Data input			
ArcGIS Shapefile Layers	.shp .dbf .shx .prj	The .shp file contains information on the GIS object and coordinates.	Binary
Comma delimited files	.csv	Used for boundary condition databases.	Text
TUFLOW Materials File	.tmf .csv	Sets the Manning's n values for different bed material categories (land covers). Also used to define initial and continuing rainfall losses and impervious percentage.	Text
TUFLOW Soils File	.tsoilf	Sets the infiltration method and parameters for different soil types in the 2D domain.	Text
Data output			
Binary Float Grid	.flt	Gridded data in the binary versions of the .asc format (see below). This data is recognised by most GIS packages and is much faster to read in than the .asc format.	Raster

File	Extension	Description	Format
ASCI Raster Grid	.asc	Gridded data in the widely used ESRI format. (not used in the TUFLOW models developed as part of this project given preference for .flt format)	Raster
SMS XMDF File	.xmdf	Contains all TUFLOW map output within a single file. Used for results animation using the TUFLOW Viewer plugin available within QGIS.	Binary
Comma Delimited Files	.csv	Used for 2D (and 1D) time-series data output.	Text
ArcGIS Shapefile Layers	.shp .dbf .shx .prj	Used for GIS based output of 1D and 2D time-series results within GIS.	Binary
Check Files			
TUFLOW Log File	.tlf	Log file containing all 1D and 2D data input process and 2D simulation.	Text
TUFLOW Summary File	.tsf	Log file containing a concise summary of the simulation.	Text
ESTRY Output File	.eof	ESTRY output file containing all 1D input data and results. (not used in the TUFLOW models developed as part of this project given no 1D elements)	Text
Comma Delimited Files	.csv	Output of processed time-series boundaries and other data for checking.	Text
ArcGIS Shapefile Layers	.shp .dbf .shx .prj	A range of 1D and 2D domain check files are produced for checking processed input data within GIS.	Binary

2.6 Naming conventions

Given the large number of GIS layers that form the basis of TUFLOW models, efficient management of the datasets is essential.

Different TUFLOW input files require different GIS attributes to define the various input parameters. TUFLOW input files are given different recommended prefixes depending on their purpose. A full range of the TUFLOW GIS input types and predefined layer prefixes are defined in Table 2-4 of the TUFLOW manual[2]. TUFLOW empty files can be generated to provide template files which use the recommended GIS data naming convention (these are supplied for each Cayman Island model), and this greatly enhances data management efficiency.

[2] https://downloads.tuflow.com/_archive/TUFLOW/Releases/2018-03/TUFLOW%20Manual.2018-03.pdf (Accessed 16/03/22)

2.7 Version numbering

Establishing a sound naming and numbering convention is highly recommended throughout model development, aiding quality control and creating an audit trail throughout model development. The TUFLOW Simulation Control File (.tcf) is used as a basis for version numbering given its name determines the prefix assigned for result and check files.

The below naming convention is presented as guidance (and has been used throughout the development of the Cayman Island models developed for this project), though users are free to deviate from that suggested:

- Increment the .tcf number sequentially whenever a change is made anywhere in the model;
- If a change is made in a sub-control file such as the TUFLOW Geometry Control File (.tgc) or Boundary Control File (.tbc), then the version number of that sub-control file should be incremented. However, the number of these files should be incremented to correspond to the revised .tcf version number, and;
- If a change is made to any input GIS files listed in any of the control files, then the version number of that input file should be incremented, corresponding to the revised .tcf iteration. This provides an indication at which point in the model development a GIS layer was introduced.

It is recommended to keep a model log, documenting any changes made for each version of the model, to further aid quality control and model review.

3. Cayman Islands model overview

3.1 Purpose

A 2D only island-wide TUFLOW model has been generated for each of the Cayman Islands; Grand Cayman, Little Cayman and Cayman Brac, to assess both the inland risk of flooding from rainfall sources and the risk of flooding from coastal storm surges.

The models have been run to evaluate inland flood risk from intense rainfall and coastal inundation.

Flood risk from intense rainfall has been assessed through running two rainfall events of 48-hour duration (based on hurricane Ivan) with annual exceedance probabilities (AEP) of 4% (1 in 25) and 1% (1 in 100). Scenarios have been established to represent a baseline (present day) scenario, and a degraded scenario simulating the effect of natural capital degradation (conversion of forest, shrubland, and mangrove to grassland). The outputs from the rainfall scenarios have been analysed to assess the flood mitigation value of the inland natural capital.

Flood risk from coastal inundation has been evaluated by running three different storm categories (Categories 1, 3 and 5) and considering three dominant wind directions (north, south, and southwest). Scenarios have been established to represent a baseline (present day) scenario, two separate degraded scenarios and an enhanced scenario. The first degraded scenario considers a reduced friction coefficient to represent the loss of existing reef structure, whilst a second, more extreme scenario has been considered also representing a physical loss of 1m reef structure. The enhanced scenario represents the enhancement of coral reef structure through an increased roughness coefficient. Coastal boundary conditions applied to the model for the storm surge scenarios have been established using a separate SWAN wave model (as used in Phase 1 of the project), and discussed further in sub-section below and Section 4.4.

3.2 Data inputs

The spatial GIS elements that make up each of the island-wide TUFLOW models are listed in **Error! Reference source not found.**, **Error! Reference source not found.** and **Error! Reference source not found.**. The associated source(s) and description is provided for each layer.

Table 3.1 Grand Cayman model input data - GIS

Data Input Layer	Source	Description
Simulation Control File (.tcf)		
Cayman_WGS84_Projection.prj	User generated	Sets the projection of the GIS elements to UTM17N (ESPG 32617)
Geometry control file (.tgc)		
2d_loc_grand_cayman_001_L.shp	User generated	Defines the orientation of the 2D model domain
2d_code_grand_cayman_001_R.shp	Department of	Defines the 2D model extent, based on a coastline

Data Input Layer	Source	Description
	Environment	shapefile provided for the island
gc_dtm_m_utm17_1m.flt	Land and Surveys Department	DTM of the island defining the underlying topography. Raw data has been converted into metric units and resampled to 1m resolution.
2d_mat_grand_cayman_a_002_R.shp	Department of Environment	Defines the spatial materials definition (surface roughness, rainfall losses, and fraction impervious) for baseline land cover across the model extent. Based on detailed land cover data and simplified into 10 broad land covers prevalent across the island. The parameters for each material are defined in the Materials File detailed in Table 3.4 Features 1-10,000 (TUFLOW limits to a maximum of 10,000 features per layer).
2d_mat_grand_cayman_b_002_R.shp	Department of Environment	As above. Features 10,000-20,000 (TUFLOW limits to a maximum of 10,000 features per layer).
2d_mat_grand_cayman_c_002_R.shp	Department of Environment	As above. Features 20,000-30,000 (TUFLOW limits to a maximum of 10,000 features per layer).
2d_mat_grand_cayman_d_002_R.shp	Department of Environment	As above. Features 30,000-36,000 (TUFLOW limits to a maximum of 10,000 features per layer).
2d_mat_grand_cayman_DEG_a_024_R.shp	Department of Environment	Defines the spatial materials definition (surface roughness, rainfall losses, and fraction impervious) for the degraded scenario across the model extent. The parameters for each material are defined in the Materials File detailed in Table 3.4. Features 1-10,000 (TUFLOW limits to a maximum of 10,000 features per layer).
2d_mat_grand_cayman_DEG_b_024_R.shp	Department of Environment	As above. Features 10,000-20,000 (TUFLOW limits to a maximum of 10,000 features per layer).
2d_mat_grand_cayman_DEG_c_024_R.shp	Department of Environment	As above. Features 20,000-30,000 (TUFLOW limits to a maximum of 10,000 features per layer).
2d_mat_grand_cayman_DEG_d_024_R.shp	Department of Environment	As above. Features 30,000-36,000 (TUFLOW limits to a maximum of 10,000 features per layer).
2d_mat_GC_buildings_a_008_R.shp	Department of Environment	Defines the spatial materials definition (surface roughness, rainfall losses, and fraction impervious) for buildings across the model extent. Based on dataset provided by Department of Environment (DoE). The parameters for the buildings are defined in the Materials File detailed in Table 3.4. Features 1-10,000 (TUFLOW limits to a maximum of 10,000 features per layer).
2d_mat_GC_buildings_b_008_R.shp	Department of Environment	As above. Features 10,000-20,000 (TUFLOW limits to a maximum of 10,000 features per layer).

Data Input Layer	Source	Description
2d_mat_GC_buildings_c_008_R.shp	Department of Environment	As above. Features 20,000-26,000 (TUFLOW limits to a maximum of 10,000 features per layer).
2d_soil_GC_geology_017_R.shp	SoilGrids[3] Jones (2019)[4]	Defines the infiltration parameters across the model extent based on underlying soil texture data obtained from SoilGrids[3], and spatial geology data obtained from Jones (2019)[4].
Boundary control file (.tbc)		
2d_rf_grand_cayman_rainfall_002_R.shp	Department of Environment	Defines the spatial extent of the rainfall boundary to be applied. Based on coastline shapefile provided for the island matching the 2d_code layer. Linked to hyetograph timeseries detailed in the bc_dbase as outlined in Table 3.4.
2d_bc_Grand_Cayman_stormsurge_TEXG_023_L.shp	Department of Environment	Defines the coastline boundary conditions for the baseline (TEXG) storm surge scenario. Based on coastline shapefile provided for the island matching the 2d_code layer. Linked to storm surge timeseries detailed in the bc_dbase as outlined in Table 3.4.
2d_bc_Grand_Cayman_stormsurge_TDEG_023_L.shp	Department of Environment	Defines the coastline boundary conditions for the degraded (TDEG) storm surge scenario. Based on coastline shapefile provided for the island matching the 2d_code layer. Linked to storm surge timeseries detailed in the bc_dbase as outlined in Table 3.4.
2d_bc_ Grand_Cayman_stormsurge_TENH_023_L.shp	Department of Environment	Defines the coastline boundary conditions for the enhanced (TENH) storm surge scenario. Based on coastline shapefile provided for the island matching the 2d_code layer. Linked to storm surge timeseries detailed in the bc_dbase as outlined in Table 3.4.
2d_bc_ Grand_Cayman_stormsurge_TXDEG_023_L.shp	Department of Environment	Defines the coastline boundary conditions for the extreme degraded (TXDEG) storm surge scenario. Based on coastline shapefile provided for the island matching the 2d_code layer. Linked to storm surge timeseries detailed in the bc_dbase as outlined in Table 3.4.

[3] https://www.isric.org/explore/soilgrids (Accessed: 26/01/22)

[4] Jones, B. (2019). Recycled insular phosphates and coated grains: Case Study from Little Cayman, British West Indies. Available at: Recycled insular phosphates and coated grains: Case study from Little Cayman, British West Indies - Jones - 2020 - Sedimentology - Wiley Online Library (Accessed: 26/01/22)

Data Input Layer	Source	Description
2d_bc_grand_cayman_DSBDY_001_L.shp	Department of Environment	Defines the downstream boundary (coastal) conditions for the rainfall scenarios. Based on coastline shapefile provided for the island matching the 2d_code layer. Set to approximate spring high tide level of 0.44m Above Mean Sea Level (AMSL) (defined in the bc_dbase as outlined in Table 3.4).

Table 3.2 Little Cayman model input data - GIS

Data Input Layer	Source	Description
Simulation Control File (.tcf)		
Cayman_WGS84_Projection.prj	User generated	Sets the projection of the GIS elements to UTM17N (ESPG 32617)
Geometry control file (.tgc)		
2d_loc_little_cayman_001_L.shp	User generated	Defines the orientation of the 2D model domain
2d_code_little_cayman_001_R.shp	Department of Environment	Defines the 2D model extent, based on a coastline shapefile provided for the island
lc_dtm_m_utm17_1m.flt	Land and Surveys Department	DTM of the island defining the underlying topography. Raw data has been converted into metric units and resampled to 1m resolution.
2d_mat_little_cayman_001_R.shp	Department of Environment	Defines the spatial materials definition (surface roughness, rainfall losses, and fraction impervious) for baseline land cover across the model extent. Based on detailed land cover data and simplified into 10 broad land covers prevalent across the island. The parameters for each material are defined in the Materials File detailed in Table 3.5.
2d_mat_little_cayman_DEG_009_R.shp	Department of Environment	Defines the spatial materials definition (surface roughness, rainfall losses, and fraction impervious) for the degraded scenario across the model extent. The parameters for each material are defined in the Materials File detailed in Table 3.5.
2d_mat_LC_buildings_008_R.shp	Department of Environment	Defines the spatial materials definition (surface roughness, rainfall losses, and fraction impervious) for buildings across the model extent. Based on dataset provided by DoE. The parameters for the buildings are defined in the Materials File detailed in Table 3.5.

Data Input Layer	Source	Description
2d_soil_LC_geology_022_R.shp	SoilGrids[3] Jones (2019)[4]	Defines the infiltration parameters across the model extent based on underlying soil texture data obtained from SoilGrids[3], and spatial geology data obtained from Jones (2019)[4].
Boundary control file (.tbc)		
2d_rf_little_cayman_rainfall_001_R.shp	Department of Environment	Defines the spatial extent of the rainfall boundary to be applied. Based on coastline shapefile provided for the island matching the 2d_code layer. Linked to hyetograph timeseries detailed in the bc_dbase as outlined in Table 3.5.
2d_bc_little_cayman_stormsurge_TEXG_028_L.shp	Department of Environment	Defines the coastline boundary conditions for the baseline (TEXG) storm surge scenario. Based on coastline shapefile provided for the island matching the 2d_code layer. Linked to storm surge timeseries detailed in the bc_dbase as outlined in Table 3.5.
2d_bc_little_cayman_stormsurge_TDEG_028_L.shp	Department of Environment	Defines the coastline boundary conditions for the degraded (TDEG) storm surge scenario. Based on coastline shapefile provided for the island matching the 2d_code layer. Linked to storm surge timeseries detailed in the bc_dbase as outlined in Table 3.5.
2d_bc_little_cayman_stormsurge_TENH_028_L.shp	Department of Environment	Defines the coastline boundary conditions for the enhanced (TENH) storm surge scenario. Based on coastline shapefile provided for the island matching the 2d_code layer. Linked to storm surge timeseries detailed in the bc_dbase as outlined in Table 3.5.
2d_bc_little_cayman_stormsurge_TXDEG_028_L.shp	Department of Environment	Defines the coastline boundary conditions for the extreme degraded (TXDEG) storm surge scenario. Based on coastline shapefile provided for the island matching the 2d_code layer. Linked to storm surge timeseries detailed in the bc_dbase as outlined in Table 3.5.
2d_bc_little_cayman_DSBDY_001_L.shp	Department of Environment	Defines the downstream boundary (coastal) conditions for the rainfall scenarios. Based on coastline shapefile provided for the island matching the 2d_code layer. Set to approximate spring high tide level of 0.44m Above Mean Sea Level (AMSL) (defined in the bc_dbase as outlined in Table 3.5).

Table 3.3 Cayman Brac model input data – GIS

Data Input Layer	Source	Description
Simulation Control File (.tcf)		
Cayman_WGS84_Projection.prj	User generated	Sets the projection of the GIS elements to UTM17N (ESPG 32617)
Geometry control file (.tgc)		
2d_loc_cayman_brac_001_L.shp	User generated	Defines the orientation and extent of the 2D model domain
2d_code_cayman_brac_001_R.shp	Department of Environment	Defines the 2D model extent, based on a coastline shapefile provided for the island
cb_dtm_m_utm17_1m.flt	Land and Surveys Department	DTM of the island defining the underlying topography. Raw data has been converted into metric units and resampled to 1m resolution.
2d_mat_cayman_brac_001_R.shp	Department of Environment	Defines the spatial materials definition (surface roughness, rainfall losses, and fraction impervious) for baseline land cover across the model extent. Based on detailed land cover data and simplified into 10 broad land covers prevalent across the island. The parameters for each material are defined in the Materials File detailed in Table 3.6.
2d_mat_cayman_brac_DEG_009_R.shp	Department of Environment	Defines the spatial materials definition (surface roughness, rainfall losses, and fraction impervious) for the degraded scenario across the model extent. The parameters for each material are defined in the Materials File detailed in Table 3.6.
2d_mat_CB_buildings_008_R.shp	Department of Environment	Defines the spatial materials definition (surface roughness, rainfall losses, and fraction impervious) for buildings across the model extent. Based on dataset provided by DoE. The parameters for the buildings are defined in the Materials File detailed in Table 3.6.
2d_soil_CB_geology_014_R.shp	SoilGrids[2] Jones (2019)[3]	Defines the infiltration parameters across the model extent based on underlying soil texture data obtained from SoilGrids, and spatial geology data obtained from Jones (2019).
Boundary control file (.tbc)		
2d_rf_cayman_brac_rainfall_001_R.shp	Department of Environment	Defines the spatial extent of the rainfall boundary to be applied. Based on coastline shapefile provided for the island matching the 2d_code layer. Linked to hyetograph timeseries detailed in the bc_dbase as

Data Input Layer	Source	Description
		outlined in Table 3.6.
2d_bc_cayman_brac_stormsurge_TEXG_019_L.shp	Department of Environment	Defines the coastline boundary conditions for the baseline (TEXG) storm surge scenario. Based on coastline shapefile provided for the island matching the 2d_code layer. Linked to storm surge timeseries detailed in the bc_dbase as outlined in Table 3.6.
2d_bc_cayman_brac_stormsurge_TDEG_019_L.shp	Department of Environment	Defines the coastline boundary conditions for the degraded (TDEG) storm surge scenario. Based on coastline shapefile provided for the island matching the 2d_code layer. Linked to storm surge timeseries detailed in the bc_dbase as outlined in Table 3.6.
2d_bc_cayman_brac_stormsurge_TENH_019_L.shp	Department of Environment	Defines the coastline boundary conditions for the enhanced (TENH) storm surge scenario. Based on coastline shapefile provided for the island matching the 2d_code layer. Linked to storm surge timeseries detailed in the bc_dbase as outlined in Table 3.6.
2d_bc_cayman_brac_stormsurge_TXDEG_019_L.shp	Department of Environment	Defines the coastline boundary conditions for the extreme degraded (TXDEG) storm surge scenario. Based on coastline shapefile provided for the island matching the 2d_code layer. Linked to storm surge timeseries detailed in the bc_dbase as outlined in Table 3.6.
2d_bc_cayman_brac_DSBDY_001_L.shp	Department of Environment	Defines the downstream boundary (coastal) conditions for the rainfall scenarios. Based on coastline shapefile provided for the island matching the 2d_code layer. Set to approximate spring high tide level of 0.44m Above Mean Sea Level (AMSL) (defined in the bc_dbase as outlined in Table 3.6).

Additional text file and comma separated value (.csv) inputs to the models are outlined in **Error! Not a valid bookmark self-reference.**,

Table 3.5 and

Table 3.6.

Table 3.4 Grand Cayman model input data – text and csv

Data Input	Source	Description
Event file (.tef)		
CI_NCA_GC_013.tef	Wood	Defines all possible events to be run through the same .tcf (avoiding the need for multiple control files for different runs). Two types of events (~e1~ and ~e2~) are defined for each run, relating to the magnitude (AEP (rainfall) or storm category (tidal), and either duration (rainfall) or wind direction (tidal). For information regarding events, refer to Section 11.3 of the TUFLOW manual[1].
Boundary Control Database (bc_dbase)		
CI_NCA_GC_bc_dbase_024.csv	Wood	Specifies the source data for boundary conditions applied within the .tbc file. These are the rainfall hyetograph and storm surge timeseries (detailed below) and the coastal high tide level of 0.44m Above Mean Sea Level (AMSL).
CI_NCA_100R_48hr_008.csv **CI_NCA_025R_48hr_008.csv**	Wood	Rainfall hyetographs generated for 1% (1 in 100) and 4% (1 in 25) AEP of 48-hour duration (based on the Hurricane Ivan storm profile).
GC_Tidal_Curves_05x_026.csv	Wood	Storm surge timeseries generated along the coastline segments using wave height results from the SWAN wave model and incorporating a storm surge allowance as detailed in Section 4.4.
Materials File		
CI_NCA_GC_Materials_011.csv	Wood	Specifies the material (land cover) manning's n roughness values, the initial loss (mm) and continuing loss (mm/h) and the fraction impervious. The initial and continuing losses have been applied as a rainfall loss (associated with interception) and are independent of the infiltration losses detailed below. The fraction impervious for each land cover dictates the rate of infiltration (if at all).
Soils File		
CI_NCA_GC_Soil_017.tsoilf	Wood	Specifies the infiltration method for each soil ID (defined spatially by the 2d_soil GIS layer). TUFLOW is parameterised with in-built USDA soil textures using the Green-Ampt method.

Table 3.5 Little Cayman model input data – text and csv

Data Input	Source	Description
Event file (.tef)		
CI_NCA_LC_020.tef	Wood	Defines all possible events to be run through the same .tcf (avoiding the need for multiple control files for different runs). Two types of events (~e1~ and ~e2~) are defined for each run, relating to the magnitude (AEP (rainfall) or storm category (tidal), and either duration (rainfall) or wind direction (tidal). For information regarding events, refer to Section 11.3 of the TUFLOW manual[1].
Boundary Control Database (bc_dbase)		
CI_NCA_LC_bc_dbase_029.csv	Wood	Specifies the source data for boundary conditions applied within the .tbc file. These are the rainfall hyetograph and storm surge timeseries (detailed below) and the coastal high tide level of 0.44m Above Mean Sea Level (AMSL).
CI_NCA_100R_48hr_008.csv **CI_NCA_025R_48hr_008.csv**	Wood	Rainfall hyetographs generated for 1% (1 in 100) and 4% (1 in 25) AEP of 48-hour duration (based on the Hurricane Ivan storm profile).
LC_Tidal_Curves_05x_029.csv	Wood	Storm surge timeseries generated along the coastline segments using wave height results from the SWAN wave model and incorporating a storm surge allowance as detailed in Section 4.4.
Materials File		
CI_NCA_LC_Materials_011.csv	Wood	Specifies the material (land cover) manning's n roughness values, the initial (mm) and continuing loss (mm/h) and the fraction impervious. The initial and continuing losses have been applied as a rainfall loss (associated with interception) and are independent of the infiltration losses detailed below. The fraction impervious for each land cover dictates the rate of infiltration (if at all).
Soils File		
CI_NCA_LC_Soil_022.tsoilf	Wood	Specifies the infiltration method for each soil ID (defined spatially by the 2d_soil GIS layer). TUFLOW is parameterised with in-built USDA soil textures using the Green-Ampt method.

Table 3.6 Cayman Brac model input data – text and csv

Data Input	Source	Description
Event file (.tef)		
CI_NCA_CB_012.tef	Wood	Defines all possible events to be run through the same .tcf (avoiding the need for multiple control files for different runs). Two types of events (~e1~ and ~e2~) are defined for each run, relating to the magnitude (AEP (rainfall) or storm category (tidal), and either duration (rainfall) or wind direction (tidal). For information regarding events, refer to Section 11.3 of the TUFLOW manual[1].
Boundary Control Database (bc_dbase)		
CI_NCA_CB_bc_dbase_020.csv	Wood	Specifies the source data for boundary conditions applied within the .tbc file. These are the rainfall hyetograph and storm surge timeseries (detailed below) and the coastal high tide level of 0.44m Above Mean Sea Level (AMSL).
CI_NCA_100R_48hr_008.csv **CI_NCA_025R_48hr_008.csv**	Wood	Rainfall hyetographs generated for 1% (1 in 100) and 4% (1 in 25) AEP of 48-hour duration (based on the Hurricane Ivan storm profile).
CB_Tidal_Curves_05x_020.csv	Wood	Storm surge timeseries generated along the coastline segments using wave height results from the SWAN wave model and incorporating a storm surge allowance as detailed in Section 4.4.
Materials File		
CI_NCA_CB_Materials_011.csv	Wood	Specifies the material (land cover) manning's n roughness values, the initial (mm) and continuing loss (mm/h) and the fraction impervious. The initial and continuing losses have been applied as a rainfall loss (associated with interception) and are independent of the infiltration losses detailed below. The fraction impervious for each land cover dictates the rate of infiltration (if at all).
Soils File		
CI_NCA_CB_Soil_014.tsoilf	Wood	Specifies the infiltration method for each soil ID (defined spatially by the 2d_soil GIS layer). TUFLOW is parameterised with in-built USDA soil textures using the Green-Ampt method.

SWAN model boundary conditions

The coastline of each island has been segmented based on the SWAN model wave height results, to apply spatially varying tidal conditions along the coast taking into account the variable vulnerability. For each coastline segment, the nearshore mean wave heights have been sampled and incorporated with a storm surge allowance, which has been fitted to a 48-hour tidal cycle. A symmetrical storm surge shape has been assumed, with total duration of 6 hours. A range of scenarios have been run simulating offshore reef degradation and enhancement to assess the value of the offshore reef systems from a flood risk mitigation perspective.

The derivation of the synthetic storm surge boundary conditions is discussed further in Section 4.4.

3.3 Scenarios and events

The TUFLOW models have been developed incorporating scenario and event logic to allow for multiple different scenarios (model configurations) and events (input boundary conditions, ie. event magnitude, storm duration) to be run from one TUFLOW Simulation Control File (.tcf). This minimises the number of simulation files required and improves the efficiency of model checks and review.

The Cayman models use two scenarios and two events; hence, each model run requires these to be defined. The scenarios are defined using a 3-4 letter acronym, each relating to a separate model configuration with the use of additional commands within the TUFLOW files. A summary is provided below:

- Scenario 1 (~s1~): **RFL** (Inland RainFfaLl scenario) | **TDL** (Coastal TiDaL scenario)
- Scenario 2 (~s2~): **REXG** (Rainfall EXistinG (baseline)) | **RDEG** (Rainfall DEGraded) | **TEXG** (Tidal EXistinG (baseline)) | **TDEG** (Tidal DEGraded) | **TENH** (Tidal ENHanced) | **TXDEG** (Tidal EXtreme DEGradation)

Similarly, the events are defined using a 3-4 letter acronym and depending on the Scenario 1 selected above. A summary is provided below:

- Event 1 (~e1~): Event magnitude (RFL - Average Recurrence Interval; TDL – Storm magnitude)
  - RFL: **100R** (100-year Recurrence interval or 1% AEP) | **025R** (25-year Recurrence interval or 4% AEP)
  - TDL: **CAT1** (CATegory 1) | **CAT3** (CATegory 3) | **CAT5** (CATegory 5)
- Event 2 (~e2~): Rainfall duration (for RFL runs) or Wind direction (for TDL runs)
  - RFL: **048HR** (48-HouR rainfall event based on the Hurricane Ivan profile)
  - TDL: **NOR** (NORth) | **SOU** (SOUth) | **SWE** (SouthWEst)

The defined events are discussed in more detail in the Event File sub-section, Section 0.

3.4 Control files

The below sub-sections detail the key elements of each of the control files within the Cayman models. Extracts of the Little Cayman model control file commands have been used as a reference, though these remain the same for each of the models.

Control File (.tcf)

> **Comment out (!)**
>
> The addition of an exclamation mark (!) in front of any command or text within the control files will mean the subsequent text is not read by TUFLOW. Comments have been added at each command line to add context.

Simulation parameters

The Cayman models provided to the Government of the Cayman Islands have been set-up using the TUFLOW Classic solver, which is the default 2D fixed grid solver. TUFLOW Classic is an implicit scheme and can only be run using a single CPU core.

TUFLOW Classic uses a fixed computational timestep (in seconds), generally in the range of 1/2 to 1/5 of the model cell size (in metres). The model timestep has been defined as 2.5 seconds (half the model cell size) using the command below:

```
Timestep == 2.5
```

This differs from the initial model development and runs carried out by Wood, which was carried out using the TUFLOW HPC (Heavily Parallelised Compute) solver and using GPU (Graphics Processing Units) hardware. The added benefits of using HPC and graphics cards are significantly shorter model run times, allowing for increased modelling capabilities. TUFLOW HPC solver can be run using CPU hardware, however, TUFLOW Classic is a more efficient scheme when run on a single CPU core. As a result, and given the specialised computer hardware requirements, the models delivered as part of this project have been updated to run in Classic and using CPU hardware as default.

The different solvers will result in minor changes to the results, hence, if the models are re-run in TUFLOW Classic for a given scenario, the results will not perfectly match the model results supplied by Wood. However, sensitivity testing has established that for the vast majority of the model extent the peak flood depth results remain within 0.01m difference. Any differences to resultant peak flood depths are typically minor (<0.05m) and isolated in extent. For more detail on the differences between TUFLOW solvers, see Section 1.2 of the TUFLOW manual[1].

Should access to a suitable GPU card be available, it is recommended the model simulation hardware and solution scheme be reverted to HPC as detailed in Section 4.2.

The start time of the model has been defined at 0 hours, using the command below:

```
Start Time == 0
```

Output formats

The map output format has been defined as binary grid (.flt) format and eXtensible Model Data Format Data (.xmdf) format using the command below.

```
Map Output Format == GRID XMDF
```

The output data types for each format are specified using the commands below. For more information regarding the below acronyms, refer to Section 3.6. Only maximum values have been stored within the .flt output results, whist the .xmdf output stores outputs at a user-specified time interval as defined within the TUFLOW Event File (.tef) for this model (dependent on the event and simulation run time).

```
XMDF Map Output Data Types == d v h ZUK2 CI IR RFR

GRID Map Output Data Types == d v h ZUK2

Store Maximums and Minimums == ON MAXIMUMS ONLY

Maximums and Minimums Only for GRID == ON
```

GIS output format has been set as .shp, and the output location for results, checks and log files is defined by the commands below. The below output location has been used by Wood for Little Cayman as an example, however, the Wood TUFLOW SWAN Toolbox developed as part of this project (discussed further in Section 5.1) defines the result and check output folders to subfolders within the main TUFLOW 'model' folder. Updates to the output folders are discussed further in Section 4.2.

```
GIS Format == SHP

Output Folder == D:\807909_Cayman_PhaseII\LC\results\<<~s1~>>\2d\

Write Check Files == D:\807909_Cayman_PhaseII\LC\checks\<<~s1~>>\2d\

Log Folder == Log
```

Initial water level

A global initial water level (IWL) has been set across the model, corresponding to an approximate spring high water level (AMSL). This assumes a conservative approach, assuming all tidal and low-lying regions below this level are inundated at the start and throughout the model simulation.

```
Set IWL == 0.44
```

Geometry Control File (.tgc)

Extent and cell size

The computational model domain is defined by the 2d location (2d_loc) layer and grid size dimensions (metres) in the command lines below. The 2d_loc layer defines the orientation of the x-axis to set the X and Y dimensions for the computational model domain. After establishing the computational model domain origin and orientation and extent, the cell size command is used to define the model resolution of 5m.

Filepaths

The Cayman Island models use relative filepaths for input files, hence the path is relative to the file that is referring to it. The '..\' signifies to 'go up' one folder level.

```
Read GIS Location == gis\2d_loc_little_cayman_001_L.shp

Grid Size (X,Y) == 17200,3400

Cell Size == 5
```

Within the above computational domain, the active cells (to define the 2D model extent) are defined using the 2d_code layer via the command lines below. Initially all cells within the computational domain are set as inactive (value of zero), and the 2d_code layer (with an attribute value of 1) subsequently defines the active cells across the island.

```
Set Code == 0
Read GIS Code == gis\2d_code_little_cayman_001_R.shp
```

Topography

The model topography has been defined using the supplied high-resolution DTM data from the Cayman Island Government Land and Surveys Department (LSD) using the command lines below. A value of zero (assumed to be the Mean Sea Level) is initially set to apply a sea level value across tidal inlets and foreshore which are not covered by the DTM data.

```
Set Zpts == 0
Read Grid Zpts == Topography\lc_dtm_m_utm17_1m.flt
```

Materials

Land cover data supplied by the Cayman Island Government DoE has been used as a basis to define the spatial materials across the model extent and combined with buildings data supplied from the Cayman Island Government LSD. The 2d_mat layers are linked to the Materials File (.csv) discussed below, which sets the roughness parameters, rainfall losses and fraction impervious for each materials ID.

The commands below are layered, such that a 'Set Mat' command is initially used to apply a common materials definition across the 2D domain, and sequentially overwritten by the 'Read GIS Mat' commands below. This approach ensures that any minor gaps (if any) within the land cover dataset are accounted for.

In this case, the baseline 2d_mat file has been applied. This is used to define the materials for the rainfall existing (REXG) and all tidal (TDL) scenarios (since the coastal natural capital scenarios relate to changes to the offshore reef system in isolation, not in combination with inland degradation). A separate 2d_mat file is used to represent the rainfall degraded (RDEG) scenario.

TUFLOW has a limit of 10,000 features per layer, hence, given the size of Grand Cayman, several 2d_mat files are needed to define the materials across the entire model extent.

```
Set Mat == 99
Read GIS Mat == gis\2d_mat_little_cayman_001_R.shp
Read GIS Mat == gis\2d_mat_LC_buildings_008_R.shp
```

The Materials File is referenced within the .tcf using the Read Materials File command, and can be in either .tmf (text) or .csv format. The .csv format has been used in this case given that it offers greater functionality. A breakdown of the format of the file is provided in Table 3.7.

Table 3.7 Materials File .csv format

Column no.	Description
1	Material ID in integer format. 11 simplified land covers have been used to categorise the materials across the model extent.
2	Manning's n bed resistance values. Manning's n values have been defined based on documentation and modeller judgement.
3	Rainfall loss parameters on an initial (mm) and continuing loss (mm/hr) basis. These are separated by a single comma (,). Loss values have been set based on available literature and guidance[5], with reference to the climate classification of the Cayman Islands.
4	Landuse Hazard ID (not used).
5	Storage Reduction Factor (SRF) value (not used).
6	Defines the Fraction Impervious of the overlying material type. The value is a number between 0 and 1, whereby 0 is fully pervious and 1 is fully impervious. The feature is used to influence the amount of water that is infiltrated into the ground with the soil infiltration feature. Values of 1 have been assigned to urban, water, wetland and mangrove materials.

Soil

Infiltration parameters across the model extent have been defined using a combination of soils data and geology data. The International Soil Reference and Information Centre (ISRIC) soils data[6] identifies Clay Loam soil texture as dominant across the islands. However, further research has established that soil coverage is in fact typically sparse across the islands, and the exposed limestone typically has a high porosity with limited drainage issues[7]. A soil type of Clay Loam (consistent with the ISRIC data) has been defined for areas underlain by the Ironshore Formation dominant across low-lying coastal regions, known to have typically poor infiltration rates and a greater coverage of soils). Elsewhere, a Sand soil type has been assigned as a proxy for the high infiltration rates known over regions underlain by the Bluff Group limestones.

The 2d_soil layer command below provides the spatial definition of soil type across the model extent, and is linked to the .tsoilf file described below. The below commands have also been layered, such that a default soil type is initially applied using the 'Set Soil' command to account for gaps (if any) within the 2d_soil file.

```
Set Soil == 99

Read GIS Soil == gis\2d_soil_LC_geology_022_R.shp
```

[5] Ball J, Babister M, Nathan R, Weeks W, Weinmann E, Retallick M, Testoni I, (Editors) Australian Rainfall and Runoff: A Guide to Flood Estimation, © Commonwealth of Australia (Geoscience Australia), 2019.
[6] https://www.isric.org/explore/soilgrids (Date accessed: 01/03/22)
[7] Smith Water International Ltd (2015). Storm Water Management Plan Report for the Cayman Islands Government Cruise Berthing Facility.

The .tsoilf file is referenced within the .tcf, and similarly to the Materials File it provides a breakdown of the soil infiltration parameters per soil type. The Green-Ampt method has been applied using the default USDA soil types that are hardwired into TUFLOW. An overview of the format is provided in Table 3.8.

Table 3.8 Soils File format

Column no.	Description
1	Soil ID in integer format.
2	Infiltration type – 'GA' specifies Green Ampt
3	Default USDA soil type

The amount of water that enters the soil is also dependent on the fraction impervious value of the overlying soil type, as discussed in the Materials section above.

Boundary Control File (.tbc)

Rainfall boundary

The spatial rainfall boundary is applied using the command below, and the 2d_rf polygon which is a duplicate of the 2d_code (island) polygon.

```
Read GIS RF == gis\2d_rf_little_cayman_rainfall_001_R.shp
```

The Name attribute 'rainfall' specifies the source ID linked to the boundary control database discussed in the below sub-section.

Coastal boundary

The spatial coastal boundary applying the coastal inflows to the model are defined using the command below. Scenario logic has been used within the .tbc such that a different boundary is applied depending on the scenario.

```
Read GIS BC == gis\2d_bc_little_cayman_stormsurge_TEXG_028_L.shp
```

As per the rainfall boundary above, the Name attribute specifies the source ID linked to the boundary control database discussed in the below sub-section.

Boundary Condition Database

The Boundary Condition (BC) database (bc_dbase) is made up of two file types:

- The database providing a list of BC events and location of the BC data, and;
- One or more files containing the boundary data (rainfall hyetographs and coastal water level time series).

The BC database must be in .csv format and is referenced within the .tcf. The database format is summarised in Table 3.9.

Table 3.9 BC database format

Column ID	Description
Name	Name of the BC data event – matching those used specified within the 2d_rf and 2d_bc layers. Summarised below: - 'Rainfall' (linked to 2d_rf) - 'LC_DSBDY' (linked to downstream boundary 2d_bc) - 'LC_TID_TEXG_XXX' (linked to baseline storm surge 2d_bc) - 'LC_TID_TDEG_XXX' (linked to degraded storm surge 2d_bc) - 'LC_TID_TENH_XXX' (linked to enhanced storm surge 2d_bc) - 'LC_TID_TXDEG_XXX' (linked to 'extreme' degradation storm surge 2d_bc)
Source	The file from which to extract the BC data (ie. the rainfall hyetographs and coastal timeseries). The source names use wildcards '_ARI_' (Average Recurrence Interval), '_DUR_' (Duration), '_CAT_' (storm category) and '_DIR_' (Direction) defined in the .tef (and discussed in the sub-section below).
Column 1 or Time	Name of the first column of data in the .csv source files – Time (hr)
Column 2 or Value or ID	Name of the second column of data in the .csv source files – Rainfall (mm) or Level (m), or the value (high tide level applied for rainfall simulations)
TimeAdd	An amount to add (usually a time shift) to Column 1 (not used)
ValueMult	A multiplication factor to apply to Column 2 values (not used)
ValueAdd	An amount to add to column 2 values (not used)
Column 3	Name of the third column of data when a third column of data is used (not used)
Column 4	Name of the fourth column of data when a fourth column of data is used (not used)

Event File (.tef)

The event file allows for numerous different events to be run through the same control file (.tcf). The .tef is referenced in the .tcf command using the command Event File, and allows for up to nine different types of events for a simulation. The event names are automatically inserted into the output file names using the wildcards '~e~' in the same way as scenarios (as detailed in section 3.3). Each model run in this case requires two events (-e1 and -e2) to be defined, detailed in Table 3.10.

Table 3.10 Event file events

Event	Tidal (TDL)	Rainfall (RFL)
-e1 (Event 1)	Storm magnitude (ie. Cat5)	Average Recurrence Interval/ AEP (ie. 100R)
-e2 (Event 2)	Storm direction (ie. NOR)	Rainfall duration (ie. 48hr)

The .tef has been set up with two possible event magnitudes (-e1) for a rainfall scenario (025R or 100R; 4% 1 in 25 AEP or 1% 1 in 100 AEP), and one rainfall duration (-e2) (48-hour) based on the hurricane Ivan rainfall hyetograph profile developed as part of Phase 1 of the project. The .tef defines three possible storm magnitudes for the tidal scenarios (CAT1, CAT3, or CAT5), and three storm directions (NOR, SOU, SWE) referencing the coastal scenarios run through the SWAN model.

Example .tef commands are shown below defining Event 1 for Rainfall and Tidal scenario runs, in this case a 1% (1 in 100) AEP rainfall event and a Category 5 storm coastal event. The 'Define Event' and 'End Define' commands establishes a new event, and any event specific commands are contained between these two commands. The BC Event Source command sets up a wildcard in the bc_dbase and replaces the wildcard with a second argument (e.g. 100R/CAT1) wherever it is found. In these examples, wildcards '_ARI_' and '_CAT_' denote Average Recurrence Interval (AEP) and the Storm Category, respectively. This will look in the bc_dbase and replace each wildcard in the BC source(s) with '100R' or 'CAT1'. The Write Check Files Exclude command is used in this case to exclude certain (typically large) check files from being written for every run, given the size of the datasets and the fact only one set of check files is typically needed per Scenario. For further information relating to these check files, refer to Section 12 of the TUFLOW manual[1].

```
Define Event == 100R
      BC Event Source == _ARI_ | 100R
      Write Check Files Exclude == zpt uvpt grd DEM_Z DEM_M
End Define


Define Event == CAT1
      BC Event Source == _CAT_ | CAT1
      Write Check Files Exclude == zpt uvpt grd DEM_Z DEM_M
End Define
```

The example .tef commands shown below are used to define Event 2 for Rainfall and Tidal scenario runs, in this case a 48-hour rainfall event and a Northern wind direction for the coastal event. The events are defined using the same commands, and similarly make use of wildcards; '_DUR_' and '_DIR_' denoting the rainfall duration and storm direction, respectively. Additional commands have been used in this case to define the model end time and map output interval, given that these will vary for the rainfall duration in particular. Sufficient simulation time is needed to capture the full hyetograph or tidal timeseries data, plus an allowance to allow for floodwater to be routed and reach a peak across the model extent.

```
Define Event == 48hr
      BC Event Source == _DUR_ | 48hr
      End Time (h) == 52
      Map Output Interval == 900.
End Define


Define Event == NOR
      BC Event Source == _DIR_ | NOR
      End Time (h) == 52
```

```
    Map Output Interval == 900.
End Define
```

3.5 Model runs

A breakdown of all the model runs undertaken is provided Table 3.11. A total of 36 tidal (TDL) runs have been carried out for Grand Cayman considering all scenarios and wind directions. However, for Little Cayman and Cayman Brac, the full suite of scenarios have only been run for a North wind direction storm which was deemed to be the worst case based on the existing/baseline results.

Table 3.11 Model runs

Island	Scenario 1 (Source)	Scenario 2	Event 1 (Magnitude)	Event 2 (Duration or Direction)
Grand Cayman	Rainfall (RFL)	Existing (REXG)	4% AEP (1 in 25)	48-hour
			1% AEP (1 in 100)	
		Degraded (RDEG)	4% AEP (1 in 25)	
			1% AEP (1 in 100)	
	Tidal (TDL)	Existing (TEXG)	Category 1	North
				South
				Southwest
			Category 3	North
				South
				Southwest
			Category 5	North
				South
				Southwest
		Degraded (TDEG)	Category 1	North
				South
				Southwest
			Category 3	North
				South

Island	Scenario 1 (Source)	Scenario 2	Event 1 (Magnitude)	Event 2 (Duration or Direction)
				Southwest
			Category 5	North
				South
				Southwest
		Extreme Degradation (TXDEG)	Category 1	North
				South
				Southwest
			Category 3	North
				South
				Southwest
			Category 5	North
				South
				Southwest
		Enhanced (TENH)	Category 1	North
				South
				Southwest
			Category 3	North
				South
				Southwest
			Category 5	North
				South
				Southwest
Little Cayman	Rainfall (RFL)	Existing (REXG)	4% AEP (1 in 25)	48-hour
			1% AEP (1 in 100)	
		Degraded (RDEG)	4% AEP (1 in 25)	

Island	Scenario 1 (Source)	Scenario 2	Event 1 (Magnitude)	Event 2 (Duration or Direction)
			1% AEP (1 in 100)	
	Tidal (TDL	Existing (TEXG)	Category 1	North
			Category 3	North
			Category 5	North
			Category 1	South
			Category 3	South
			Category 5	South
			Category 1	Southwest
			Category 3	Southwest
			Category 5	Southwest
		Degraded (TDEG)	Category 1	North
			Category 3	North
			Category 5	North
		Extreme Degraded (TXDEG)	Category 1	North
			Category 3	North
			Category 5	North
		Enhanced (TENH)	Category 1	North
			Category 3	North
			Category 5	North
Cayman Brac	Rainfall (RFL)	Existing (REXG)	4% AEP (1 in 25)	48-hour
			1% AEP (1 in 100)	
		Degraded (RDEG)	4% AEP (1 in 25)	
			1% AEP (1 in 100)	
	Tidal (TDL	Existing (TEXG)	Category 1	North
			Category 3	North

Island	Scenario 1 (Source)	Scenario 2	Event 1 (Magnitude)	Event 2 (Duration or Direction)
			Category 5	North
			Category 1	South
			Category 3	South
			Category 5	South
			Category 1	Southwest
			Category 3	Southwest
			Category 5	Southwest
		Degraded (TDEG)	Category 1	North
			Category 3	North
			Category 5	North
		Extreme Degraded (TXDEG)	Category 1	North
			Category 3	North
			Category 5	North
		Enhanced (TENH)	Category 1	North
			Category 3	North
			Category 5	North

3.6 Results

The models have been parameterised to output results to binary grid (.flt) and XMDF formats. A full overview of the output results and associated acronyms is provided in Table 3.12.

Table 3.12 Model result types

Results acronym	Description	Results format	
		XMDF	Binary grid
D	Depth (m)	✓	✓
V	Velocity (m/s)	✓	✓
H	Water level / Head (m AMSL)	✓	✓
ZUK2	Hazard rating (based on UK guidance on flood risk to people[8])	✓	✓
TMAX_H	Time to max water level (hours)	✓	✓
DT_MIN	Minimum timestep (s)	✓	✓
TDUR	Duration of flooding above user specified threshold (hours)	✓	✓
TEXC	Time of first exceedance of user specified threshold (hours)	✓	✓
CI	Cumulative infiltration (mm)	✓	×
IR	Infiltration rate (mm/hr)	✓	×
RFR	Rainfall rate (mm/hr)	✓	×

Further information regarding results visualisation is provided in Section 6.2.

[8] DEFRA and EA (2006). The Flood Risks to People Methodology, Flood Risks to People Technical Report 1. FD2321/TR1.

4. Potential model updates

4.1 Purpose

This chapter details 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 sections outline how a series of example updates may be implemented to the various control files, making use of the bespoke "Wood TUFLOW SWAN Toolbox" or modifying the commands within the control files using a text editor. An overview is also provided of the open-source ArcTUFLOW toolbox (developed by BMT), which provides several useful features to update TUFLOW GIS layers in particular. Finally, a sub-section has been provided detailing the necessary processing steps in order to generate a cut-down, refined model for a smaller portion of the island.

4.2 Control File (.tcf)

Simulation parameters

Solver

As detailed in Section 0, the model solution scheme has been updated in the supplied models to run using TUFLOW Classic rather than TUFLOW HPC (as used for model simulations carried out by Wood) given the specialised computer hardware requirements. Should access to a suitable GPU card be available, and a HPC license obtained, the .tcf can be updated to run using TUFLOW HPC and make use of the GPU hardware with the addition of the commands below.

```
Solution Scheme == HPC

Hardware == GPU
```

The solver can be updated manually within an existing .tcf, or within the supplied TUFLOW templates which are used by the Wood TUFLOW SWAN Toolbox discussed further in section 5.1. The above commands should be situated at the top of the .tcf, above any subsequent commands.

Timestep

If the model cell size is adjusted (as detailed in Section 4.3), the fixed timestep applied using TUFLOW Classic should be adjusted accordingly (typically 1/2 to 1/5 of the mode cell size).

Rather than use a fixed computational timestep, TUFLOW HPC (by default) uses an adaptive timestep based on the hydraulic conditions during a simulation. The explicit nature of TUFLOW HPC generally requires a smaller timestep than TUFLOW Classic, and hence it is recommended that a lower timestep of 1s be applied should the model be updated to run in TUFLOW HPC.

The model timestep can be manually updated within an existing .tcf, or within the default settings (.set) file for the Wood TUFLOW SWAN Toolbox as outlined in Section 5.1.

Initial water level

The global IWL applied in the .tcf can be simply updated or removed using the command below. This is currently set to provide a conservative approach for the rainfall scenarios, assigning an approximate spring high water level throughout the duration of the simulation.

```
Set IWL == 0.44
```

This can be modified within the existing .tcf, or within the default settings (.set) file for the Wood TUFLOW SWAN Toolbox as outlined in Section 5.1.

4.3 Geometry Control File (.tgc)

Cell size

The cell size of 2D domains must be sufficiently small to reproduce the hydraulic behaviour yet be large enough to minimise run times. Given the scale and high-resolution cell size used for the models (making use of TUFLOW HPC and GPU hardware to minimise run times), it may be desired to increase the cell size to minimise run times.

Sensitivity testing of the model using TUFLOW Classic suggests that run times are in the order of 10-14 times longer (~35 hours total run time) using Classic compared to HPC for a model cell size of 5m. However, the model has been tested using a 10m cell size in TUFLOW Classic which yielded more reasonable run times comparable to the original HPC runs. Results are broadly comparable to the 5m cell size and suitable for island-wide flood mapping. Some detail is compromised at the small scale, as the lower resolution cell size generally results in wider regions of surface water flooding with reduced definition in comparison to the 5m cell size results.

The cell size can be adjusted simply using the command below, or within the Wood TUFLOW SWAN Toolbox discussed further in Section 5.1.

```
Cell Size == X
```

Should the cell size be increased or decreased, it is recommended that the timestep also be adjusted accordingly (generally 1/5th to 1/2 of the model cell size). The impact of a coarser cell size on model results should be assessed to satisfy that the cell size is appropriate for the purpose of the model.

Topography

The topography data forms the fundamental basis of the 2D model, and hence the quality of the data has a direct impact to the results.

The existing Cayman models use high-resolution DTM data supplied from the Cayman Islands LSD as a basis. The topographic data read into TUFLOW can be updated using the Wood TUFLOW SWAN Toolbox as described in Section 5.1. Any new topography data in binary grid (.flt) format will become selectable within the 'model\Topography' file directory. Alternatively, the topography data can be updated manually using the command below and replacing the existing dataset, or additional commands can be specified below if, for instance, new data becomes available for only a portion of the island. TUFLOW is able to build 2D elevations from any number of GIS layers and/or TIN layers. For more information see Sections 6.6 and 6.8 within the TUFLOW manual[1].

```
Read Grid Zpts == <<Filepath>>
```

Grid formats supported by TUFLOW include the ESRI ASCII grid (.asc) format and binary grids (.flt).

Modifications

No topographic modifications have been applied to the existing Cayman models. However, TUFLOW has advanced functionality for manipulating and modifying the 2D elevation values. Modifications can be applied to represent new developments, remove channel obstructions or interpolate missing elevation data for example.

Modifications are most typically applied using Z shape features (2d_zsh), in the form of regions or polygons (_R), lines (_L), or points (_P). Multiple Z shape features can be read in combination, for instance, one layer may contain elevation points coincident with a polygon feature. Topographic modifications are used most commonly to represent buildings, new developments and to remove any 2D flow obstructions (for instance to remove a bridge deck from the topography).

The Wood TUFLOW SWAN Toolbox has been developed based on the existing TUFLOW models, without allowance for any topographic modifications to be incorporated. Therefore, any topographic modifications will need to be generated within GIS and incorporated into the control files manually.

Single Z shape features are applied using the command below:

```
Read GIS Z Shape == <<Filepath>>
```

A maximum of nine layers per command is allowed, with each layer separated by a vertical bar ("|"). For example, to read a Z shape layer with both lines and points, the below command may be used:

```
Read GIS Z Shape == gis\2d_zsh_LC_002_L.shp | gis\2d_zsh_LC_002_P.shp
```

For more information relating to topographic modifications refer to section 6.8.5 of the TUFLOW manual[1].

Materials (roughness)

The 2d_mat layer defines the surface roughness for each land cover spatially across the 2D model domain using the Manning's n equation, in addition to the rainfall losses and fraction impervious specified within the linked Materials File.

Updates can be made to the 2d_mat GIS layers to amend the spatial representation of land cover within the model, or to assess specific land cover change scenarios for instance. The 2d_mat layers representing the current inland scenarios and buildings can be simply updated and incorporated into the model using the Wood TUFLOW SWAN Toolbox discussed further in Section 5.1. Alternatively, the 2d_mat file can be updated manually using the command below:

```
Read GIS Mat == <<Filepath>>
```

The Wood TUFLOW SWAN Toolbox has been developed currently using the above command to specify just one 2d_mat file to represent the main landcover across the models. This is limited to the existing and degraded scenario 2d_mat files. Two separate .tgc files will therefore be needed to represent the inland existing (baseline) and degraded scenarios, respectively. The .tgc files could be developed further to incorporate scenario logic such that the existing scenarios and any subsequent additional scenarios could be run from the same .tgc.

Example commands are given below to run both the existing and degraded rainfall scenarios, plus an additional hypothetical scenario 'SSBD' (South Sounds Basin Development) of landcover change in South Sound Basin. The existing scenario 2d_mat file is read in as default but is subsequently overwritten should the RDEG or SSBD scenarios be defined within the run batch file. Any number of 'If/Else' commands can be incorporated into the control files.

```
Read GIS Mat == gis\2d_mat_Grand_Cayman_001_R.shp
If Scenario == RDEG
      Read GIS Mat == gis\2d_mat_Grand_Cayman_DEG_001_R.shp
Else If Scenario == SSBD
      Read GIS Mat == gis\2d_mat_Grand_Cayman_SSBD_001_R.shp
End If
```

In addition to spatial updates to the 2d_mat GIS layers, the Materials File (.csv) can be updated to amend the existing roughness, rainfall loss and fraction impervious parameters shown in Table 4.1. Any new Materials File can be defined manually within the .tcf, or referenced using the Wood TUFLOW SWAN Toolbox discussed further in Section 5.1.

Table 4.1 Materials File parameters

! Material ID	Manning's n	Initial/Continuing Loss	Fraction Impervious
1	0.025	5,1	
2	0.12	30,5	
3	0.04	10,2	
4	0.12	30,5	1
5	0.07	20,4	1
6	0.05	20,4	
7	0.03	5,1	
8	0.017	2,0	1
9	0.035		1
10	0.04	20,2	1
11	1	2,0	1
99	0.04	5,2	

4.4 Boundary Control File (.tbc)

The supplied model has been run with two hyetograph events of 1% (1 in 100) and 4% (1 in 25) AEP and 48-hour duration as default based on the Hurricane Ivan storm profile. The coastal tidal scenarios have been run with coastal tidal boundaries relating to category 1, 3 and 5 storms for three different wind directions. Both the rainfall hyetographs and tidal boundaries have been generated by Wood as part of phases 1 and 2 of this project and have not been incorporated as an option to update within the Wood TUFLOW SWAN Toolbox. However, it would be possible to update the model boundary conditions with manual edits to the control files and run different rainfall hyetographs and tidal boundaries through the model, should these become available. The conversion of SWAN wave height output result into TUFLOW boundary conditions is summarised in the sub-section below.

Boundary Condition Database (bc_dbase)

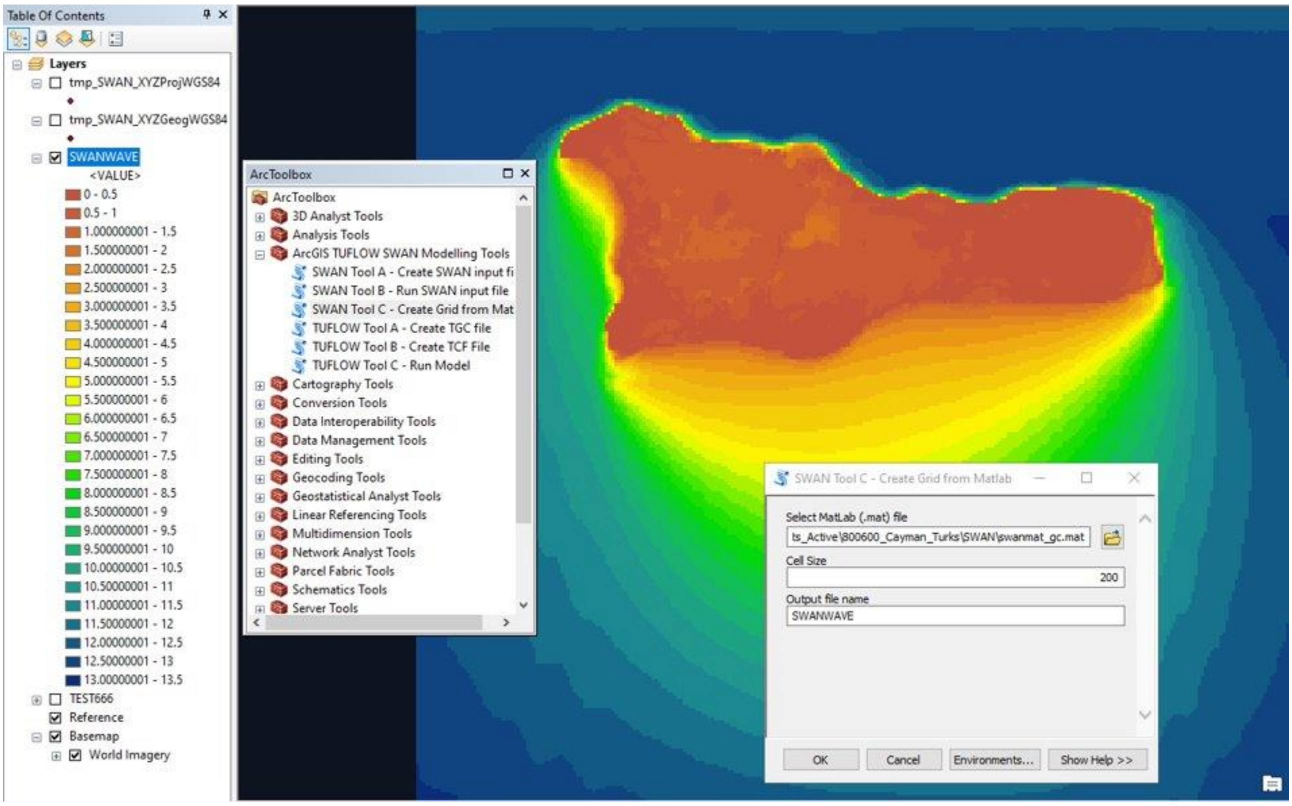
The BC database format is described in detail in Table 3.9. Should new rainfall hyetographs or coastal boundary data become available to be run through the model (further detail is provided below for generating coastal boundary conditions from any additional SWAN runs undertaken), the data will need to be in .csv format and conform to the Column 1 and Column 2 formats within the BC database. If the data does not conform to the pre-defined events within the .tef (Table 3.10), additional commands will be needed to define the new event(s) and associated parameters.

SWAN to TUFLOW

The link between the separate SWAN and TUFLOW models requires some manual processing in order to generate new TUFLOW boundary conditions from any new SWAN runs undertaken. The processing steps are summarised below.

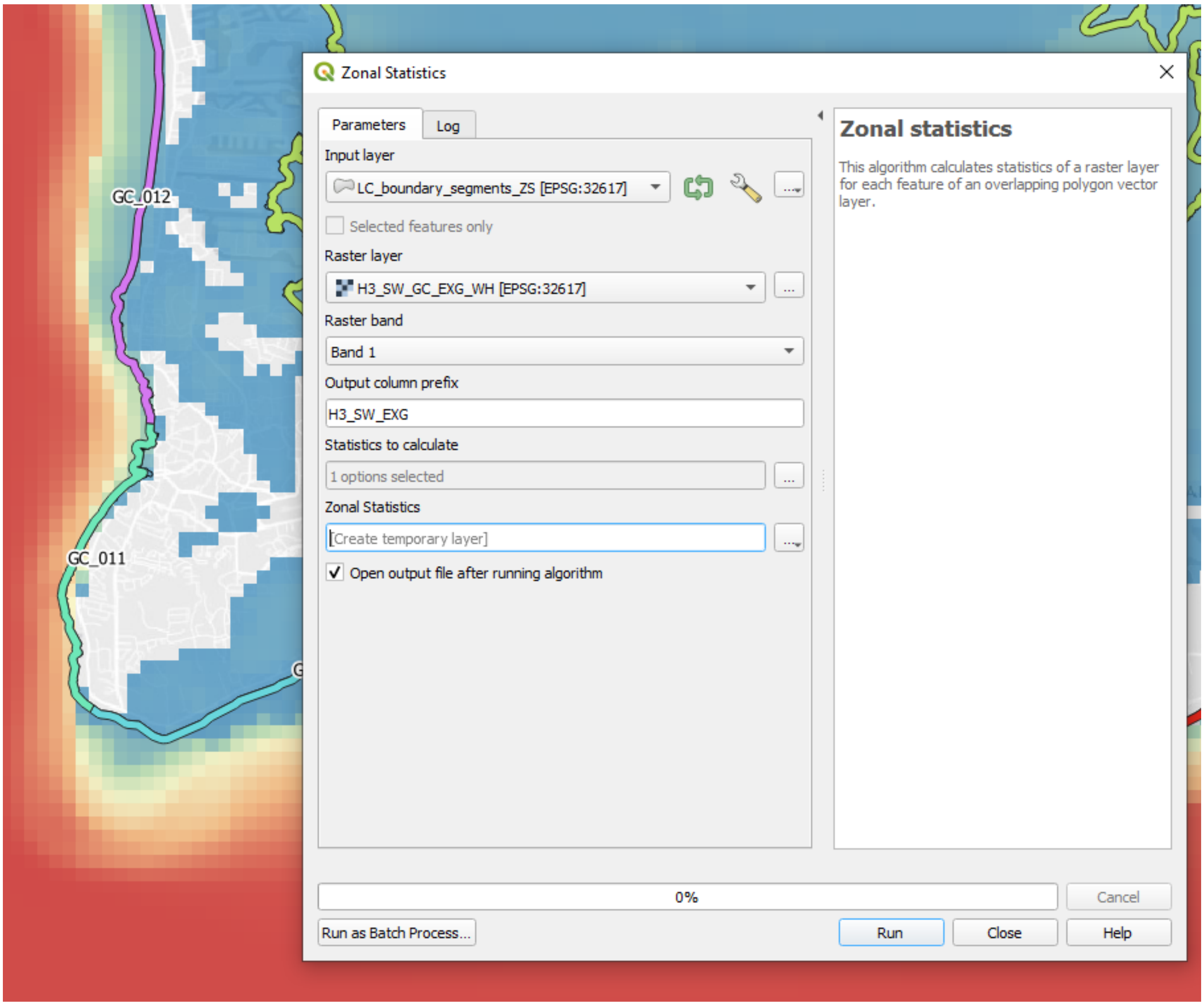
The 'SWAN Tool C' within the bespoke Wood TUFLOW SWAN Toolbox should be used to generate SWAN outputs in GRID format, able to be viewed and interrogated within GIS software (Figure 4.1).

Figure 4.1 SWAN Tool C – Create Grid from Matlab



The coastline boundary segments described in Section 3.2 have been buffered seaward by a set distance (relative to the SWAN model resolution) in order to form polygon features. These polygons have been used to sample the mean underlying SWAN wave heights, which has been deemed to be representative of the nearshore wave heights to be applied into the TUFLOW model. This is carried out using the Zonal Statistics processing tool (available in both QGIS and ArcGIS) and should be repeated for each SWAN results output (Figure 4.2).

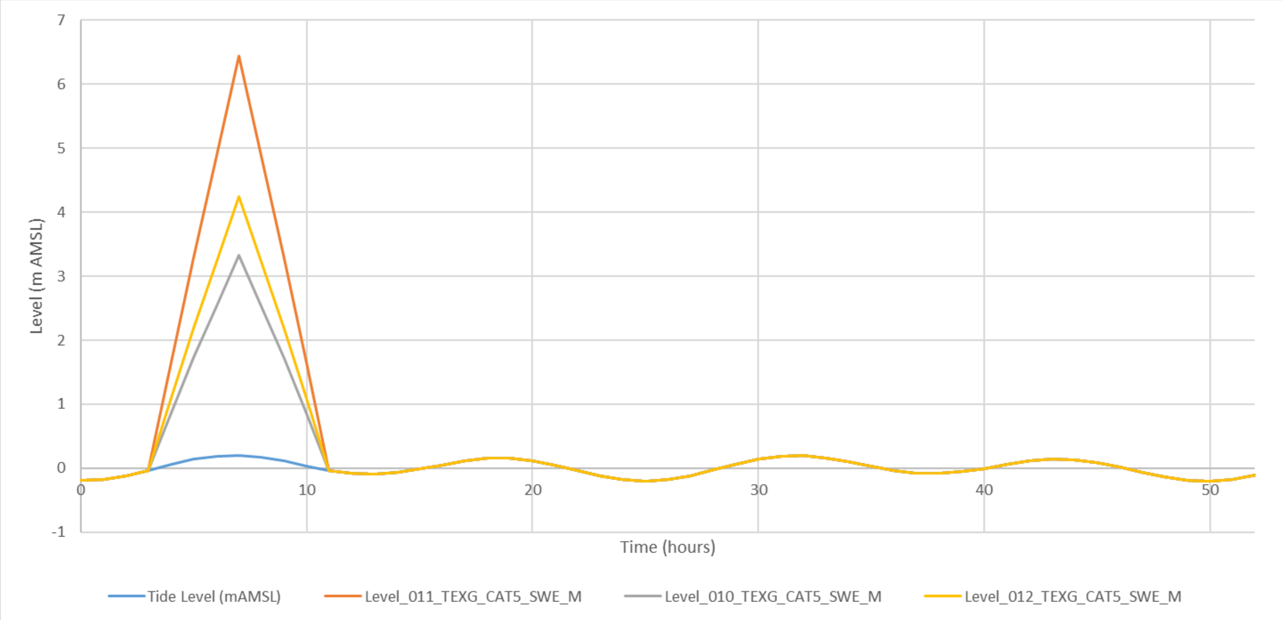
Figure 4.2 Zonal Statistics – SWAN nearshore wave heights



The resultant wave height results for each boundary ID should be tabulated and exported into excel for incorporation with the appropriate storm surge allowance and base tidal curve. The spreadsheets used to generate the storm surge timeseries for Phase 2 of this project have been supplied separately for reference.

Wave height (Hs) represents the wave trough to peak height, and therefore has been halved to provide the wave amplitude (relative to mean sea level). The wave amplitude has been combined with the storm surge allowance to provide a maximum 'surge height', which is used to scale the base tidal curve to generate a synthetic storm surge timeseries for each boundary segment. Example timeseries are shown in Figure 4.4 for three boundary segments on the southwest coastline of Grand Cayman. The resultant timeseries should be saved in .csv format using the existing file format, and referenced within the bc_dbase.

Figure 4.3 Synthetic storm surge timeseries



4.5 ESTRY Control File (.ecf)

ESTRY is the in-built 1D solver used by TUFLOW. Any 1D elements incorporated into the existing models will need to be manually incorporated using an ESTRY control file (.ecf), and referenced within the TCF. ESTRY offers advanced functionality for representing a range of elements within 1D such as channels, operational structures and pipes. For the purposes of the Cayman Island models, a brief overview is provided below for incorporating nested 1D culverts within the 2D domain. For a full overview of the 1D ESTRY capabilities, refer to Section 5 of the TUFLOW manual.

Nested 1D culverts

Culverts or pipe channels are most commonly represented using a 1d_nwk TUFLOW feature, and can be either rectangular, circular, or irregular in shape and vary in size. For a full overview of the required GIS attributes refer to Table 5-3 of the TUFLOW manual[1].

Any 1d_nwk features are read into TUFLOW using the below command:

```
Read GIS Network == <Filepath>
```

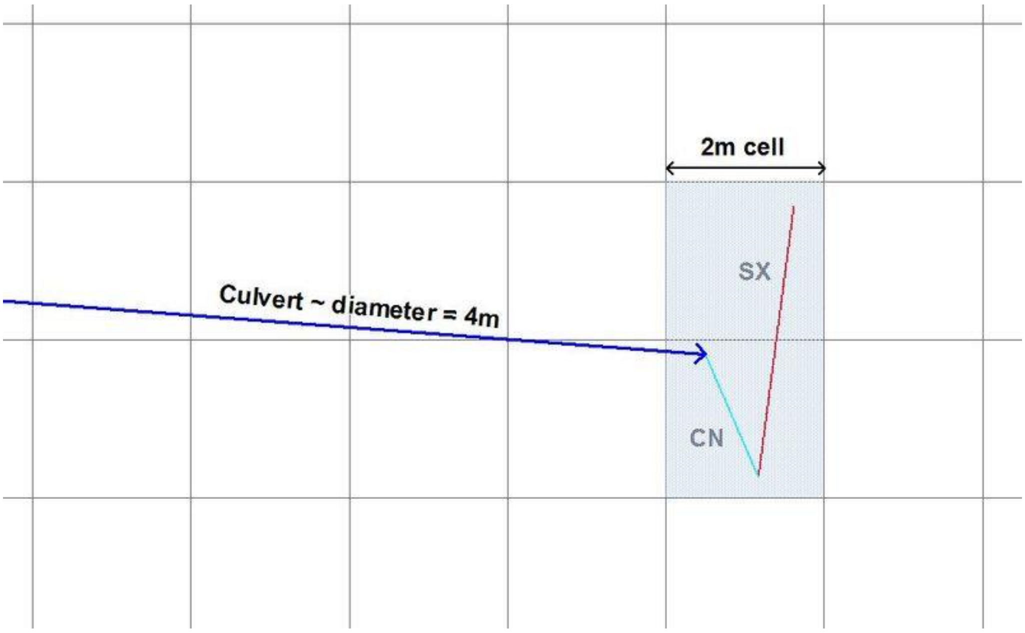
The 1d_nwk features need to be linked to the 2D model domain using 2d_bc features, read into the TUFLOW boundary control file (.tbc). This is most commonly done with the use of CN (**C**o**N**nection) and SX (**S**ource boundary from an e**X**ternal 1D scheme) 2d_bc features, which can be within a single 2d_bc GIS layer for any number of culverts.

An example command is provided below:

```
Read GIS BC == gis\2d_bc_little_cayman_culverts_001.shp
```

Figure 4.4 shows a typical 1D-2D schematisation for a 1d_nwk culvert feature. Consideration needs to be given to the cell size and culvert width – the 2D flow into and out of the culvert should be representative of the culvert dimensions to limit the doubling up of expansion and contraction losses. For more information relating to 1D-2D linking, refer to the TUFLOW wiki pages[9][10].

Figure 4.4 1D-2D culvert linking



4.6 BMT ArcTUFLOW toolbox

The open-source ArcTUFLOW toolbox developed by BMT, the developers of TUFLOW, provides several useful tools to help streamline the process of editing or updating a TUFLOW model using ArcMap (similarly, the TUFLOW plugin within QGIS provides the same functionality should QGIS be used). A full overview of the toolbox is available on the TUFLOW wiki page[11]. Of most relevance, the 'Insert TUFLOW attributes' and 'Increment layer' functions are recommended for any GIS layer updates as summarised in the following sub-sections.

Insert TUFLOW attributes

The 'Insert TUFLOW attributes' tool provides an efficient way of generating a new TUFLOW input layer from an existing GIS layer, rather than importing and copying features into an empty file. The tool inserts the relevant TUFLOW attributes required (for a specified TUFLOW file type) in front of an existing layer. For instance, a new habitat or land-cover dataset can be quickly transferred into a TUFLOW 2d_mat format to form a new materials layer. The tool requires an input GIS layer, the file directory of a TUFLOW 'empty' directory (included in the supplied models), the selected TUFLOW file format and an associated run ID which will be added to the name as a suffix. This method

[9] https://wiki.tuflow.com/index.php?title=TUFLOW_1D2D_SX_Advice (Accessed 16/03/22)
[10] https://wiki.tuflow.com/index.php?title=1D_Culverts (Accessed 16/03/22)
[11] https://wiki.tuflow.com/index.php?title=TUFLOW_ArcGIS_Toolbox_and_Toolbar_Installation (Accessed: 16/03/22)

avoids the need to use a TUFLOW empty file as a basis for any new input layers and retains all the previous attribute data from the original GIS file.

Increment layer

The 'Increment layer' tool is recommended for incrementing any existing TUFLOW layers should any updated be made. The tool generates a new revision number (which should be based on the .tcf version number, see Section 2.7) for an existing layer, and replaces the existing layer in ArcMap with the same style applied.

4.7 Refined models

Generating a cut-down version of the island-wide models opens numerous opportunities to model specific areas in more detail, whilst also minimising model run times and efficiency. This sub-section provides a general overview of the necessary steps to create a cut-down model from one of the existing island-wide models.

Folder structure

Any new model created should be built in a new 'TUFLOW' folder, conforming to the recommended structure as outlined in Section 2.4. This ensures good file management practice and separates any new model files from the existing models. The folder structure should also take into account the required folders as outlined in Section 5.1 for compatibility with the Wood TUFLOW SWAN Toolbox.

Catchment analysis

The refined model extent should be defined on a catchment basis, to include the full contributing catchment to an area. If the full catchment is not captured, the output results will likely underestimate the flood risk to a specific area as not all of the contributing runoff has been captured and accounted for.

Catchment analysis can be done based on the underlying DTM using either the watershed processing tools available in QGIS, or the ArcHydro toolbox available in ArcMap. An example is shown in Figure 4.5, outlining the entire contributing catchment to the South Sound Basin and surrounding sub-catchments.

The delineated catchment polygon will need to be converted into the required TUFLOW 2d_code format to define the active area, and into the TUFLOW 2d_rf format to define the rainfall area (across the entire active area defined by the 2d_code) using the TUFLOW empty files. The most efficient method to do this is using the 'Insert TUFLOW attributes' tool as outlined in Section 4.6.

Fundamental model updates

Model files such as the 2d_mat and 2d_soils can remain unchanged from the island-wide model and be simply copied across into the appropriate new model folders. However, other fundamental model input files will need to be amended from the existing models, as outlined in Table 4.2. Any number of additional updates as outlined in sections above could be further implemented.

Figure 4.5 Catchment delineation

Table 4.2 Materials File parameters

TUFLOW file type	Description	Required update
TUFLOW Geometry Control File (.tgc)		
2d_code	Sets the active 2D grid extent	Update based on delineated catchment (as outlined in Figure 4.5)
2d_loc	Sets the orientation and extent of the model domain	Update based on the new 2d_code layer. The associated grid dimensions will also need to be updated in accordance with the revised 2d_code.
TUFLOW Boundary Control File (.tbc)		
2d_rf	Sets the spatial extent of the rainfall boundary (same as 2d_code)	Update based on delineated catchment (as outlined in Figure 4.5)
2d_bc	Downstream boundary setting the sea level	Trim existing island-wide 2d_bc coastline layer to the new coastline boundary in the revised 2d_code

5. Running the model

An existing TUFLOW model can be run using a Windows batch (.bat) file. At the very least, a batch file needs only two arguments, the first specifying the path to the TUFLOW executable and the second argument specifying the TUFLOW control file (.tcf) to be run. For more information regarding batch files, refer to the TUFLOW wiki page[12].

The following subsections outline the steps to set-up and run the Cayman Island models using the bespoke Wood TUFLOW SWAN Toolbox .

5.1 Wood TUFLOW SWAN Toolbox

As part of this project, a bespoke Wood TUFLOW SWAN Toolbox has been developed to facilitate the set-up and running of the TUFLOW models, using the currently defined scenarios. The tools allow for some flexibility for potential future updates (as mentioned in Section 4) within the geometry control (.tgc) and control file (.tcf), though assume that the boundary control file (.tbc) and event file (.tef) will remain the same.

The model has been split into three separate tools, outlined in detail in the following sub-sections. Each tool requires the file path to the main 'TUFLOW' folder for the model (to provide a reference file directory location) and a 'global settings' file. The global settings file defines several default parameters for each of the TUFLOW models listed in Table 5.1. A unique global settings file is required for each model and should be saved within the main 'TUFLOW' folder in order for the tool dropdown to identify the file.

Table 5.1 TUFLOW global settings file (.set)

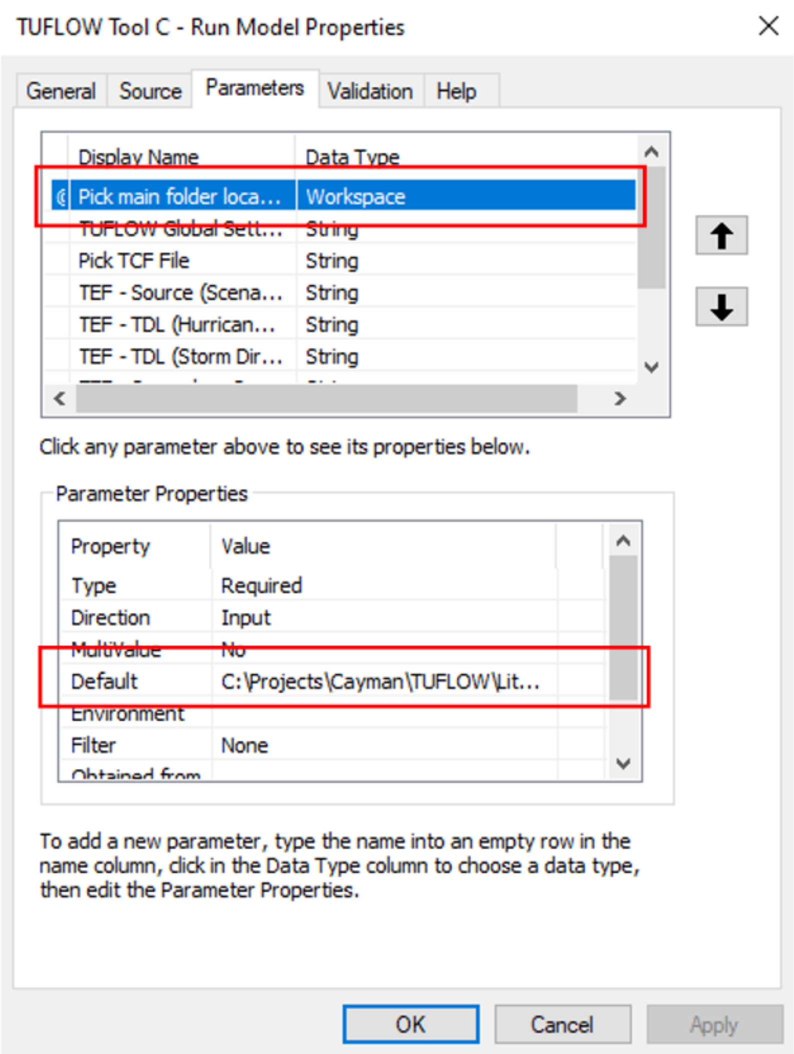
Row ID	Parameter
2	Project Name – name of project, commented out within TUFLOW.
3	Job number – internal (Wood) job number, commented out within TUFLOW.
4	Location – Model location/island, commented out within TUFLOW.
5	Shapefile projection – default of WGS UTM17N (EPSG 32617).
6	MapInfo projection (commented out within TUFLOW, update if MapInfo is used).
7	Model start time – default of 0.
8	Model timestep – set to 2.5s as default. Update depending on solver and cell size.
9	Map output types – set to GRID and XMDF as default.
10	Hazard approach – set as conservative as default.
11	Initial water level – set as 0.44m as default, representative of approximate spring high tide.

[12] https://wiki.tuflow.com/index.php?title=Run_TUFLOW_From_a_Batch-file (Accessed: 15/03/22)

Row ID	Parameter
12	Cell wet/dry depth – sets the wet/dry depth for determining when a cell wets and dries
13	Grid location – default 2d_loc line within the .tgc
14	Grid size – default grid dimensions within the .tgc
15	Active grid – default 2d_code within the .tgc
16	TUFLOW .exe filepath – update to align with local system.

If using the TUFLOW tool elements of the Wood TUFLOW SWAN Toolbox across different models, the default main folder location stored within the tools (Figure 5.1) will need to be manually updated in order for the different global settings files to be identifiable by the dropdown box. This can be updated in the tool parameters by right clicking on the tool and navigating to 'Parameters'.

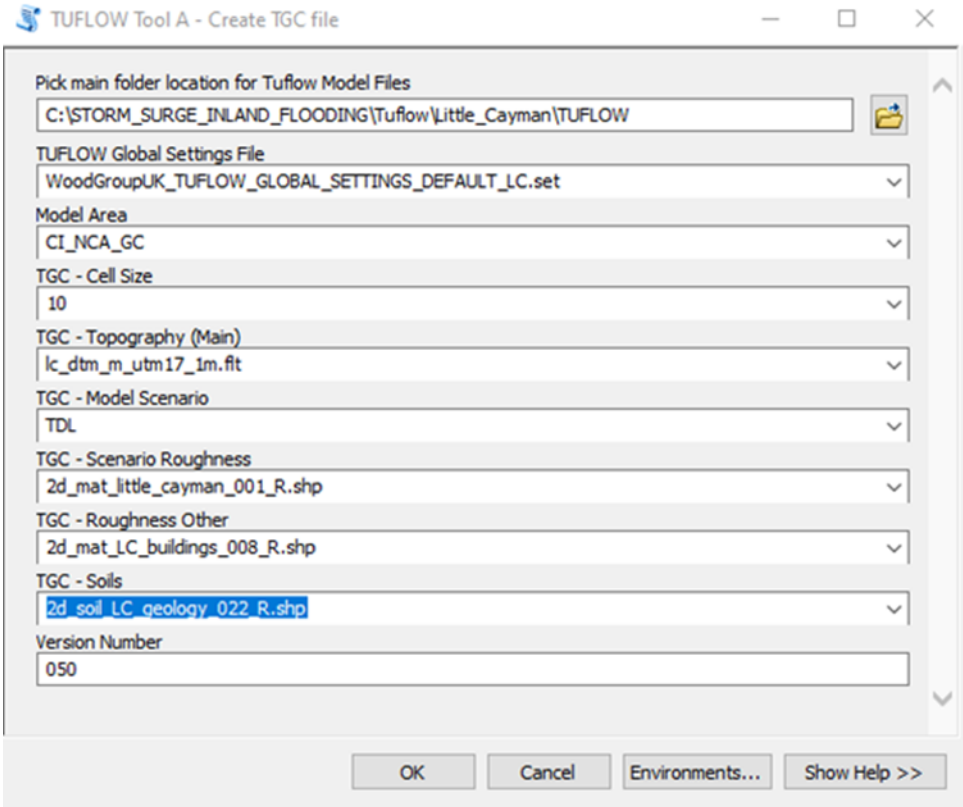
Figure 5.1 TUFLOW Tool Parameters – default main folder



01 Create TGC file

The ‘Create TGC file’ forms the initial step of the Wood TUFLOW SWAN Toolbox. The tool includes several dropdowns to define various model parameters as outlined in Figure 5.2 and following sub-sections.

Figure 5.2 TUFLOW Tool A – Create TGC File



Once the tool has been run, the resultant .tgc file should be checked using text editor to ensure the model parameters have been defined correctly. As noted in Section 0, the Grand Cayman model uses several 2d_mat files to cover the entire model, and hence additional command lines are needed to read in the extra layers (to be added manually). Any additional manual edits (ie. to incorporate z-shapes) can be made to the .tgc at this stage.

Model Area

Fixed acronym to form the base of the .tgc file name, relevant to the specific island. For example ‘CI_NCA_LC’ (Cayman Islands - Natural Capital Assessment – Little Cayman).

TGC – Cell Size

Select the model cell size. A range of cell sizes have been provided from 1m to 50m. Model runs carried out by Wood used a 5m cell size for the rainfall scenarios and 10m cell size for the tidal scenarios.

TGC – Topography (Main)

Select the underlying topography (DTM). Any new topography data in .flt format within the 'model\Topography' file directory will become available.

TGC – Model Scenario

Select the model scenario regarding the land cover materials (linked to the Scenario Roughness below). The rainfall existing/baseline (REXG) and all tidal (TDL) runs will use the baseline materials layer. The rainfall degraded scenario (RDEG) will use the degraded materials layer.

TGC – Scenario Roughness

Select the associated land cover materials layer for above scenario. These are stored in sub-folders for each scenario within the 'model\gis' file directory.

TGC – Roughness Other

Select the materials layer to represent buildings. This is stored in a sub-folder within the 'model\gis' file directory.

TGC – Soils

Select the soils layer. This layer is stored within the main 'model\gis' file directory.

Version Number

Add unique version number for resultant file. This is used to aid model development and quality assurance (see Section 2.7). This will be appended to the Model Area acronym.

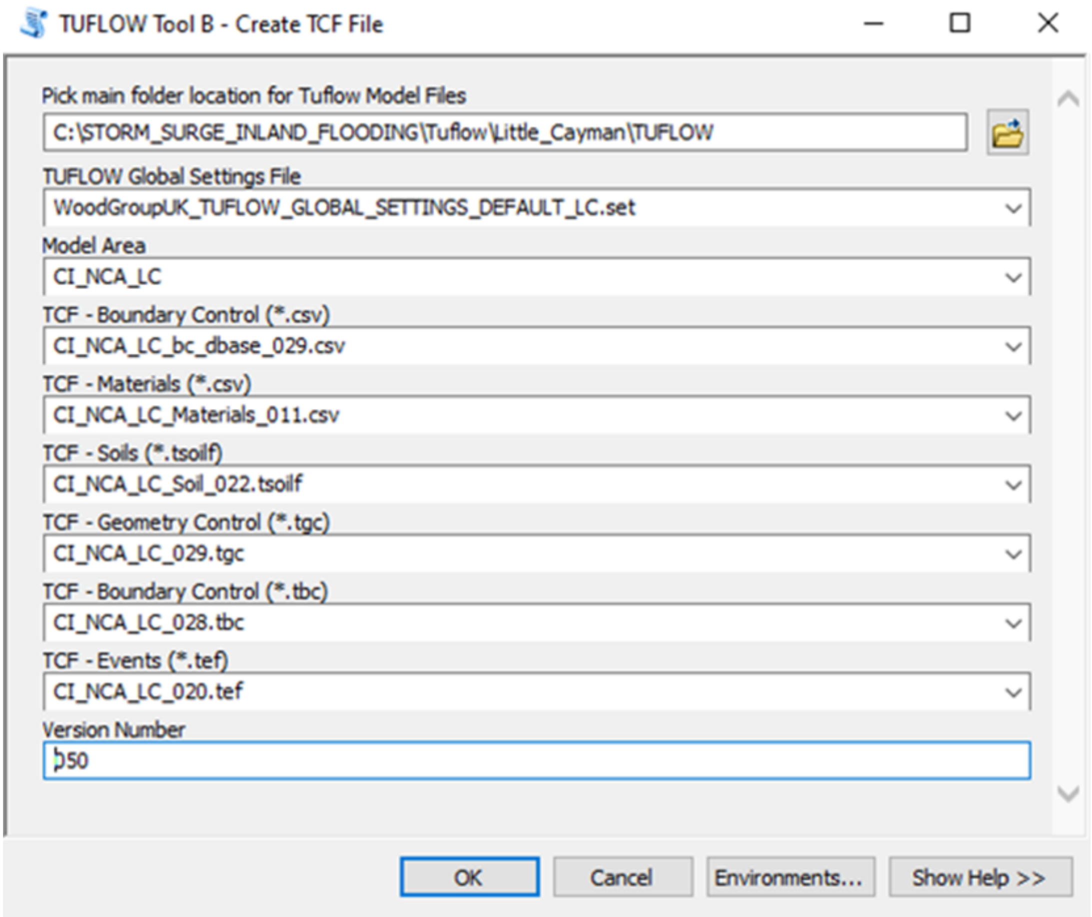
Given that a separate .tgc file will be needed to represent the different land cover configurations (REXG/TDL and RDEG), it is recommended a short prefix be added to distinguish between the two different configurations (ie. 'EXG_001').

02 Create TCF file

The 'Create TCF file' creates the final simulation file (.tcf) to be run, using the below dropdown options to define the model input files. Figure 5.3 provides an overview of the tool dropdowns.

Once the tool has been run, the resultant .tcf file should be checked using text editor to ensure the model parameters and input files have been defined correctly. Any additional manual edits can be made to the .tcf at this stage.

Figure 5.3 TUFLOW Tool B – Create TCF File



Model Area

Fixed acronym to form the base of the .tcf file name, relevant to the specific island. For example, 'CI_NCA_LC' (Cayman Islands - Natural Capital Assessment – Little Cayman).

TCF – Boundary Control (*.csv)

Select the boundary control database from the 'bc_dbase' file directory.

TCF – Materials (*.csv)

Select the Materials File from the 'model' file directory.

TCF – Soils (*.tsoilf)

Select the Soils File from the 'model' file directory.

TCF – Geometry Control (*.tgc)

Select the output TUFLOW geometry control file from the 'Create TGC File' tool. The .tgc file is output to the 'model' file directory.

TCF – Boundary Control (*.tbc)

Select TUFLOW boundary control file from the 'model' file directory.

TCF – Events (*.tef)

Select TUFLOW event file from the 'runs' file directory.

Version Number

Add unique version number for resultant file. This is used to aid model development and quality assurance (see Section 2.7). This will be appended to the Model Area acronym.

Given that separate .tcf files will be needed to represent the different land cover configurations (REXG/TDL and RDEG), it is recommended a short acronym be added to distinguish between the two different configurations (ie. 'EXG_001').

03 Run Model

The 'Run Model' tool creates a batch file to run a specified .tcf file, with defined scenarios and events. Once the tool has been run, a Windows dos window will open and the run will initiate.

Pick TCF File

Select .tcf file for the model run from the 'runs' file directory.

TEF Source (Scenario 1)

Select the flooding source (Scenario 1). These are Rainfall (RFL) or Tidal (TDL).

TEF – TDL (Hurricane Strength) or RFL (AEP)

Select the event magnitude (Event 1). Three hurricane categories (Categories 1, 3 and 5) can be run for a tidal scenario, and two possible AEPs of 1% (1 in 100) and 4% (1 in 25) can be run for a rainfall scenario.

TEF – TDL (Storm Direction) or RFL (Rainfall Duration)

Select Event 2. This is the storm direction for a tidal scenario (North, South, or Southwest), or the rainfall duration (48-hours) for a rainfall scenario. Figure 5.4 shows the possible event options, linked to the TEF Source selected above.

TEF – Secondary Scenario

Select the secondary scenario (Scenario 2). For a tidal run, these are existing (baseline) (TEXG), degraded (TDEG), extreme degraded (TXDEG) and enhanced (TEXG). For a rainfall run, these are existing (baseline) (REXG) or degraded (RDEG).

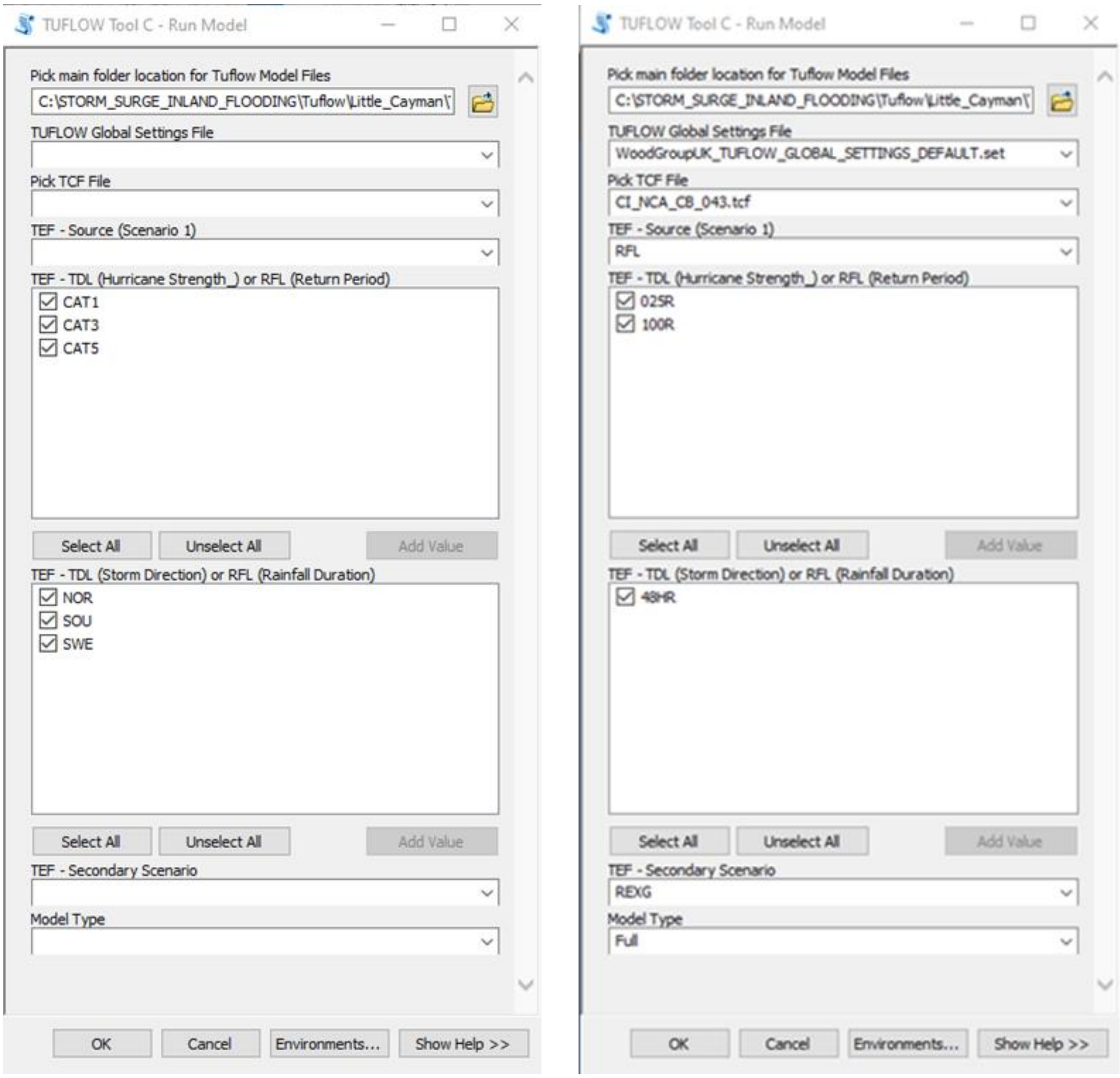
Model Type

Select the model run type. An 'Evaluation' run is a TUFLOW test run, which will compile the model and produce check files, without running the model. The resultant batch file produced by the tool will have a '-t' command to signify test. This is useful to check that the model inputs are correct, and any new model edits are working as intended by viewing the resultant check files before running the model fully.

A 'Full' model run will run the model to completion and output results.

Should an 'Evaluation' be run and the model compiles correctly and as intended, the '-t' command can be removed from the batch file rather than having to use the tool again to select the .tcf and associated scenarios and events. Batch files can be run by simply double clicking.

Figure 5.4 TUFLOW Tool C – Run Model



6. Results output

6.1 Quality control

Check Files and inputs

Check Files output from TUFLOW can be mapped within GIS to provide a visual representation of how the input data has been interpreted by the model. A review of check files is recommended particularly if any model updates are implemented at a later stage, to ensure the model representation is as intended.

Within the open-source BMT ArcTUFLOW toolbox (and QGIS TUFLOW plugin) the 'Load Simulation Input File' option provides an efficient way of reviewing all input and check files from a single run. The GIS layers will be loaded with predefined TUFLOW thematic styles based on the prefix of the file name to improve efficiency of the review process. A full list of TUFLOW check files is provided in Table 12-2 of the TUFLOW manual.

Model health

Key model health indicators are provided at the end of the simulation in the log file (.tlf) and summary file (.tsf). Table 6.1 provides an overview of common model health checks to carry out at the end of each run. However, these are only some of the main indicators and hence should be used in conjunction with good general review practices. A full overview of the wide range of model health indicators is provided in Section 14.2 of the TUFLOW manual[1].

Table 6.1 Model health checks

Item	Description
Total Negative Depths	Negative depths are often an indication that the solution has not converged or has over-stepped at that location in time. Repeated occurrences in the same location are often an indication of poor topography. Location of any warnings can be viewed using the _messages GIS layer.
WARNINGs and CHECKs prior to and during simulation	Details of any CHECKs and WARNINGs issued in a .csv and GIS format. CHECKs and WARNINGs should be reviewed and resolved where necessary.
Total Volume In and Out (m^3/s)	Review these numbers to ensure these are in accordance with expectations. Usually, the volume out is less than the volume in, as the model has a residual amount of water left in at the end of the simulation. Review within the .tsf.
Volume Error (m^3)	Volume Error is the loss or gain in water over the course of the simulation, equal to: (Total Volume In – Total Volume Out) – (Volume at End – Volume at Start) Volume Error % value is the Volume Error divided by the Volume In + Out. Final Cumulative Mass Error % is calculated throughout the simulation using a similar formula. A healthy

Item	Description
	model generally has a value of less than ±1 %, though higher values of 2-3% can be acceptable depending on the objectives of the modelling. Review within the .tsf.

If the model is run in TUFLOW HPC, several additional health checks should be carried out to check the model timestep throughout the simulation, detailed in Section 10.3.5 of the TUFLOW manual[1].

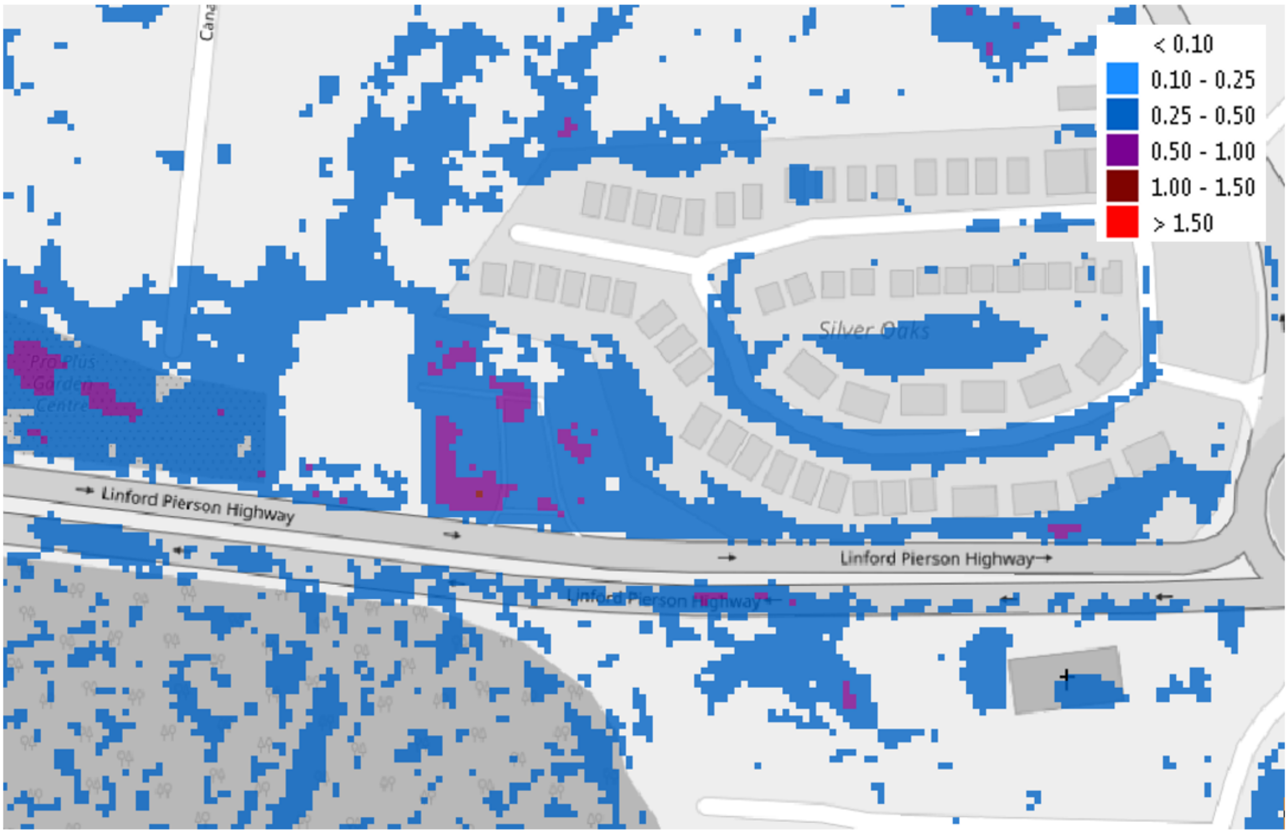
6.2 Visualisation

Result outputs in the form of max grids (.flt) can be loaded directly into GIS for visualisation. These represent the maximum recorded value across the model extent from any given point within the model simulation.

GIS styling

A number of QGIS style layers and Arc layer files have been supplied with the model, which provide suggested styles for some of the key TUFLOW max grid outputs (depth, velocity and hazard). Given that the rainfall scenario applied a rainfall depth across the entire model domain, it is recommended to use a threshold value to ignore minor depths, as seen in Figure 6.1.

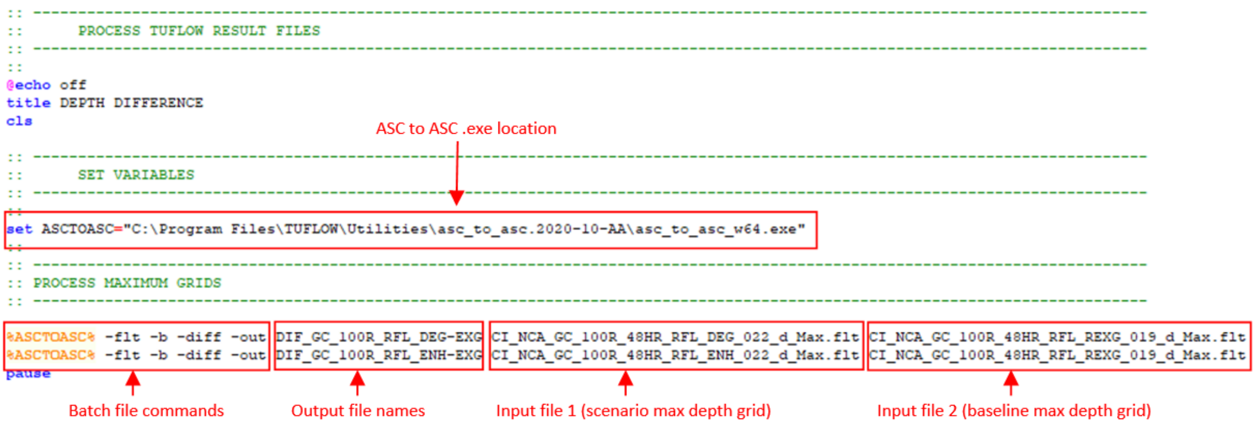
Figure 6.1 Suggested peak depth styling



Post-processing - depth difference

If running several different scenarios to assess against a baseline scenario, it is recommended to carry out a depth difference comparison. This can be carried out using GIS tools such as raster calculator within QGIS or ArcMap, or by making use of the TUFLOW ASC to ASC utility tool. The ASC to ASC utility tool is a freely-downloadable executable from the TUFLOW website[13], and is recommended given the batch functionality. An example batch file (shown in Figure 6.2) has been provided with the models as a reference to process depth differences in batch. The batch file will need to be in the same folder location as the input result files.

Figure 6.2 TUFLOW ASC to ASC depth difference



The example batch file above has been provided as an example to process both an enhanced and a degraded scenario depth difference, relative to the baseline. Running the file will output a GRID (.flt) depth difference file with the output file names, in addition to a 'wet/dry' file with the acronym '_wd' identifying any regions of change to the flood extent (as depth differences will only show where there is spatial overlap between the results). Note for any direct rainfall results, there will be no change in flood extent regardless of the scenario, as rainfall is applied across the entire model domain and hence each model cell will record a max flood depth (though in many cases negligible).

A suggested QGIS style and Arc layer file has been supplied for assessing depth differences.

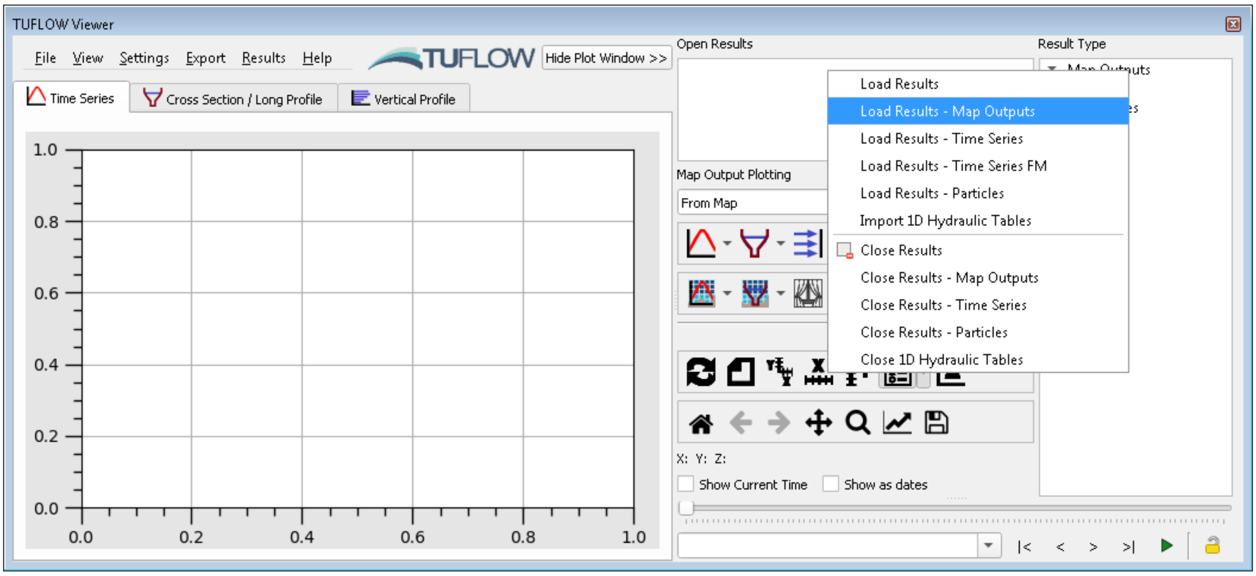
TUFLOW Viewer

The TUFLOW Viewer within the QGIS TUFLOW plugin provides a powerful tool to animate and query simulation results. The open-source BMT ArcTUFLOW toolbox (discussed in Section 4.6) includes the TUPLOT results viewer with functionality to view 1D and 2D timeseries results. However, the existing models developed for the Cayman Islands do not include any timeseries based results, and at this stage the BMT Arc toolbox has not been developed to incorporate the full functionality of the TUFLOW Viewer within the TUFLOW QGIS plugin. Hence, it is recommended that QGIS is used for animating and querying results. Results animation in combination with dynamic timeseries plots can be used to give an understanding of the flooding mechanisms and flood wave progression over an area.

13 https://www.tuflow.com/downloads/#utilities (Accessed 16/03/22)

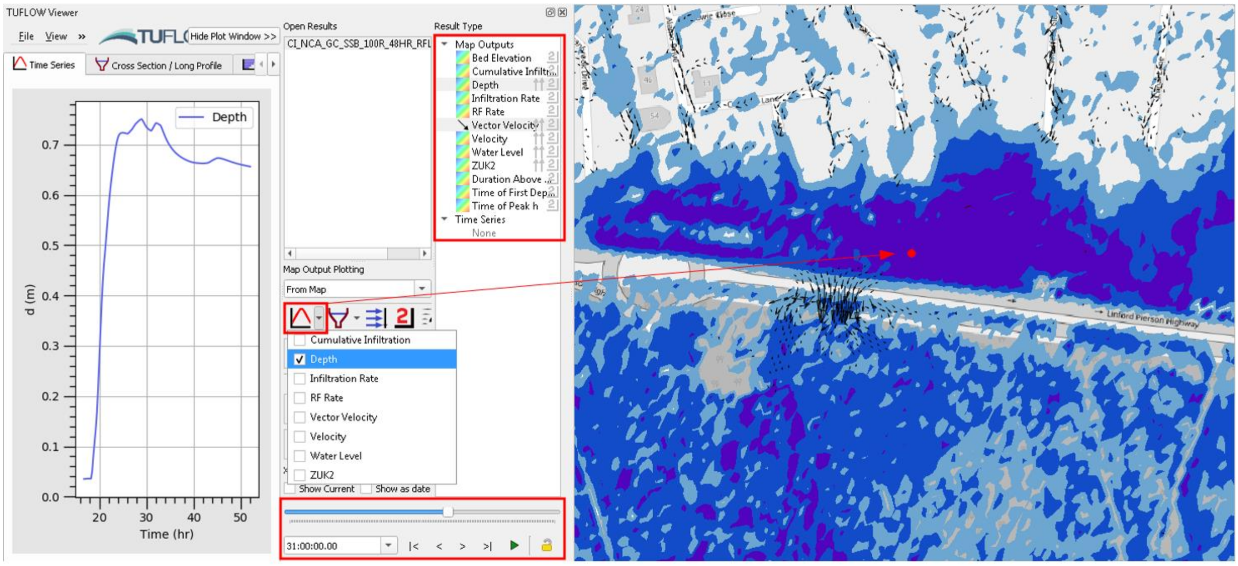
The steps to animating TUFLOW results are outlined in Figure 6.3 and Figure 6.4, demonstrating the overtopping flooding mechanisms of Linford Pierson Highway, George Town.

Figure 6.3 TUFLOW viewer – load results



Select 'Map Output' results type for results animation, and navigate to the relevant .xmdf results file (saved to the 2d results folder).

Figure 6.4 TUFLOW viewer – Animation and dynamic plots



Select results type from the various map outputs (typically depth and vector velocity are the most commonly used) and apply an appropriate style. The results can be animated using the timestep options at the bottom of the tool. Timeseries for various map outputs can be plotted directly from the GIS window.

For a full overview of the TUFLOW viewer functionality refer to the TUFLOW wiki page[14].

[14] https://wiki.tuflow.com/index.php?title=TUFLOW_Viewer (Accessed 24/04/22)

7. Conclusions

This user guide has been generated to provide an overview of the TUFLOW software and functionality, and to describe in detail the island-wide TUFLOW models developed for the Cayman Islands. There are endless possible updates that could be further implemented to the existing TUFLOW models, and this guide has given an overview of some of the possible updates that could be made to expand the model functionality.

As part of this project, a bespoke Wood TUFLOW SWAN Toolbox has been developed to help facilitate the set-up and running of TUFLOW model files and implement simple model updates for future runs.

An overview of some of the key model heath checks has been provided in order to check the health of any future simulations carried out and identify any instabilities.

Model results can be visualised in numerous ways, and this user guide has provided an overview of the key model result outputs and suggested visualisation within GIS software. The QGIS TUFLOW Viewer provides the most advanced functionality for animating results and viewing dynamic result plots across the model domain.

wood.