Appendix F: TUFLOW model description

1. Modelling software description

1.1 Model selection

T&T applied a dynamic sea level as a downstream boundary condition to a previously constructed city-wide stormwater model in order to predict the extent of tidal inundation over Christchurch.

In development of this city-wide stormwater model, T&T selected the TUFLOW software package, running the GPU engine, largely because of the significant reduction in run-times over that using a classic CPU processor (such as that used in previous overland flow modelling). The faster run-times made sensitivity testing more feasible within the project timeframe. Sensitivity testing was undertaken to improve confidence in model results. The TUFLOW GPU engine also enables for smaller grid sizes to be viable for a large city size model domain. Smaller grid sizes are desirable because they provide better (finer) resolution, which provides more accurate modelling of flowpaths.

The TUFLOW model is well respected in Australasia, where it is used as a tool for identifying flood hazard and for planning flood mitigation works. The TUFLOW GPU engine is also accepted by the UK Environment Agency for flood modelling as a result of a 2D hydraulic modelling benchmarking exercise.

1.2 Software description

TUFLOW is a suite of numerical engines for simulating water flow in urban waterways, rivers, floodplains, estuaries and coastlines. There are three main numerical engines under the TUFLOW software suite:

- TUFLOW 2D grid based and linked 1D network solver
- TUFLOW GPU, a 2D only grid based solver using the parallel processing power of the modern GPU for fast simulations
- TUFLOW FV, a 2D/3D flexible mesh finite volume solution.

For the modelling outlined in this report, the TUFLOW GPU engine was used. TUFLOW GPU is an explicit solver of the full 2D Shallow Water Equations. TUFLOW GPU utilises the multiple cores on graphics card(s) to provide faster runtimes than the standard CPU based TUFLOW.

The solution scheme computes the volume flows across cell boundaries and is volume and momentum conserving. The scheme utilises a sub-grid scale eddy viscosity model and the default method is a Smagorinksy approach.

TUFLOW GPU is available in 1st, 2nd and 4th order time integration (the default is 4th order which is used in the modelling outlined in this report). Either an adaptive timestep or fixed timestep can be utilised, with an adaptive timestep applied in this work. TUFLOW GPU is available in both single and double precision versions. TUFLOW GPU is a cell centred scheme and one elevation per 2D cell is used.

TUFLOW GPU version 2014-03-AG (64 bit Single Precision) has been used in this modelling. This is the latest version at the time of writing. As the GPU engine is used in calculation of depth (as opposed to level), and given that the area of interest in this investigation is coastal, single precision (7 significant figures) was deemed suitable.

2. Data

2.1 Topography data

A bare earth digital elevation model (DEM) at 2 m resolution was created using a combination of LiDAR and estuary bathymetry files stitched together to make one DEM. The majority of the model uses LiDAR data flown following the December 2011 Christchurch earthquake. Where LiDAR data were not available the model uses LiDAR flown following the June 2010 Earthquake. The Avon-Heathcote Estuary bathymetry was surveyed in March/April 2011 and January 2013 by NIWA.

For each 2 m x 2 m cell containing point data, the mean elevation of the LiDAR data points is assigned to the cell. Cells containing no point data are assigned an elevation linearly interpolated from the nearest points. All DEMs are clipped to the respective survey extents (data area).

The DEM and LiDAR surveys are to Lyttelton Vertical Datum 1937 and New Zealand Transverse Mercator 2000. Refer to T&T (2014b) for a more detailed description of the LiDAR including its accuracy.

2.2 Streams

The model in-bank bathymetry for all waterways was derived from the network data held by CCC, which comprises stream cross sections at intervals of between 5 and 30m (for most streams and channels). The channel thalweg (channel invert) was converted into a breakline in TUFLOW (i.e. the horizontal location was defined from the channel centreline, and the thalweg level along this alignment was then “burned into” the DEM).

The levels of the channels are based on the latest available cross-section data. In some locations the pre-earthquake cross sections are the latest available information. In other locations there are post-earthquake surveys. The cross-sections used for the TUFLOW modelling for all events were converted from the latest information held by CCC at the time of model development.

The widths of channels are based on cross sections and from estimates from the aerial photos. The methodology used in TUFLOW is to drop the entire width of the channel to the level specified in the breakline (based on the thalweg level), which resulted in a rectangular cross section instead of the actual cross section with side slopes. This means that the channel network volume is larger in the TUFLOW model than in reality. An increased roughness allowance to counter this effect was made. It is recognised that this approach reduces accuracy for the channel and immediate surrounds, but is a trade-off with other advantages including better (finer) cell resolution. It is considered that, provided that adequate allowance is made for conveyance within the main channels, the overland flow path results will be relatively insensitive to the absolute accuracy in the main channels. For the tidal inundation being considered this approach was deemed appropriate.

Breaklines have also been used to preserve key hydraulic controls. Where required, additional topography modifiers were created based on the DEM to ensure that hydraulic controls, especially culverts, allow conveyance of water. For example, where major culverts were known to exist, the DEM was checked to ensure that breaklines were of suitable depth to allow flow.

2.3 Pipes

During calibration runs of the 4 and 5 March flood event it was found that the model predicted flooding in some areas where flooding was not expected to occur. Simulated pipe networks were trialled and found to give more realistic flooding in these areas. For consistency, simulated pipes were adopted for all areas of the city.

Simulated pipes were applied to the TUFLOW model for all pipes of diameter 600 mm and greater. Simulated pipes are an approximation of pipe conveyance capacity made by insertion of rectangular open channels of dimension calculated to deliver equivalent conveyance. Simulated pipes were adopted because the actual drainage network includes pipes and catchpits that cannot readily be modelled in TUFLOW GPU. Simulated pipes allow inflow/outflow along their length, similar to what occurs with regular spacing of catch pits and downpipes.

The pipes are modelled by lowering the cell elevation by 0.886 times the pipe diameter. The cell flow width is restricted to 0.886 times the diameter. The value of 0.886 was chosen as this gives an equivalent flow area when representing a circular pipe using a “flat” 2D cell.

In addition to provision of equivalent flow area, Manning’s n roughness was adjusted to ensure a proper scaling of conveyance is maintained through the simulated pipe representation. This roughness scaling was based on pipe full hydraulic radius being compared against 2D flow depth. By doing this, it emerged that once the flow area approximation has been made (as described above), the roughness scaling increased from n = 0.013 for a concrete pipe to n = 0.03 for the simulated pipes.

Of significance is that no flap gates were included in the model, which means that reverse flow (i.e. from estuary inland) was able to occur up all simulated pipes and open channels. This represents a reasonably conservative approach.

2.4 Land use (roughness) areas

Land roughness adopted in the model was based on land use. Land use was obtained from Landcare Research Land Cover Database version 3 (LCDB3). This data is available free from the Land Research Information Systems portal (https://lris.scinfo.org.nz). Details of specific roughness values applied to different land use is provided in Table 2-1. The Avon-Heathcote Estuary and coastline were given manning's 'n' values of 0.022 (Estuarine open waters) and 0.025 (coastal sands and gravels) respectively.

Roughness along roads was superimposed, as this is not detailed in LCDB3. The road centrelines were supplied by DHI, GHD and NIWA. These were buffered according to the road hierarchy (for the DHI and GHD supplied road centrelines), or the number of lanes (for the NIWA data). Road widths adopted are as follows:

- 5 m for private and single lane roads;
- 10 m for local, minor arterial roads, collector and two lane roads; and
- 20 m for major arterial roads, motorways and four lane roads.

Once buffered, these road areas had Manning's n roughness of 0.020 applied which superimposes the roughness from the LCDB3. In this way roughness of roads was differentiated from surrounding land.

Table 2-1 Manning's n values and impervious fractions for land use types

Land use description	Manning's value	Fraction impervious
Built-up area	0.100	0.3
Urban parkland/open space	0.033	0.0
Surface mine	0.028	0.0
Dump	0.060	0.0
Transport infrastructure	0.016	0.0
Coastal sand and gravel	0.025	0.0
River and lakeshore gravel and rock	0.028	0.0
Alpine gravel and rock	0.039	0.0
Lake and pond	0.020	0.0
River	0.035	0.0
Estuarine open water	0.022	0.0

Short-rotation cropland	0.100	0.0
Vineyard	0.070	0.0
Orchard and other perennial crops	0.050	0.0
High producing exotic grassland	0.050	0.0
Low producing grassland	0.090	0.0
Herbaceous freshwater vegetation	0.100	0.0
Herbaceous saline vegetation	0.100	0.0
Fernland	0.160	0.0
Gorse and broom	0.125	0.0
Manuka and or kanuka	0.100	0.0
Broadleaved indigenous hardwoods	0.100	0.0
Mixed exotic shrubland	0.080	0.0
Grey scrub	0.080	0.0
Major shelterbelts	0.120	0.0
Afforestation (not imaged)	0.200	0.0
Afforestation (imaged, post-LCDB 1)	0.340	0.0
Forest harvested	0.160	0.0
Pine forest – Open canopy	0.100	0.0
Pine forest – Closed canopy	0.200	0.0
Other exotic forest	0.150	0.0
Deciduous hardwoods	0.125	0.0
Indigenous forest	0.150	0.0
Road layer	0.020	1.0
Default land use type	0.050	0.0

2.5 Boundary data

A tidal boundary has been applied to the model. The model tide is based on a sinusoid with a maximum of RL 1.4 m (HAT) and a minimum of -0.88 m (MLWS). Sea level rise tide boundaries are outlined in Section 4.2.

3. Model coverage

3.1 Avon catchment

The Avon catchment is depicted in pink in Figure 3-1. The main channels from CCC data, which have been added into the model as breaklines, are shown in blue. Significant channels and culverts based on CCC GIS, which have been modelled as channels are depicted in red. Pipes which have been modelled as simulated pipe are depicted in purple.

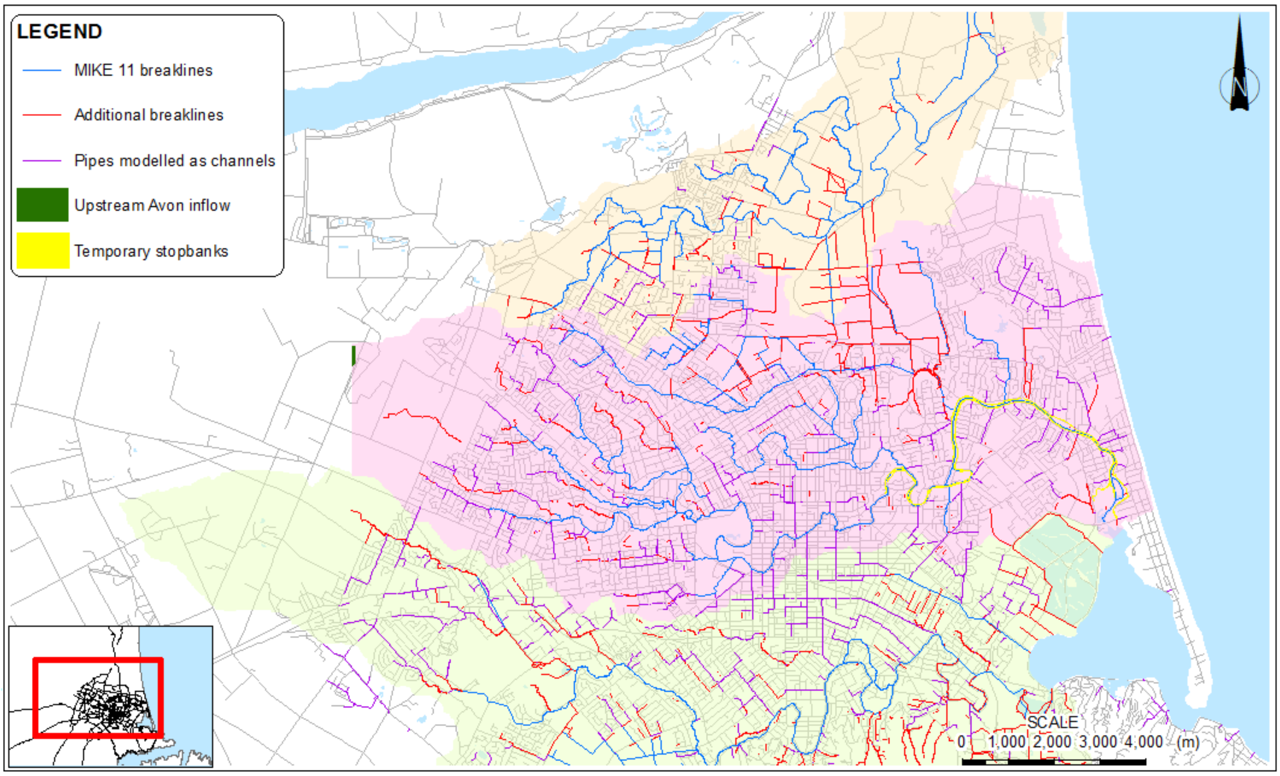

Figure 3-1 Avon catchment

3.2 Heathcote catchment

The Heathcote catchment is depicted in light green in Figure 3-2. The main channels from CCC data, which have been added into the model as breaklines, are shown in blue. Significant channels and culverts based on CCC GIS, which have been modelled as channels are depicted in red. Pipes which have been modelled as simulated pipes are depicted in purple.

3.3 Styx catchment

The Styx catchment is depicted in orange in Figure 3-3. The main channels from CCC data, which have been added into the model as breaklines, are shown in blue. Significant channels and culverts based on CCC GIS, which have been modelled as channels are depicted in red. Pipes which have been modelled as simulated pipes are depicted in purple.

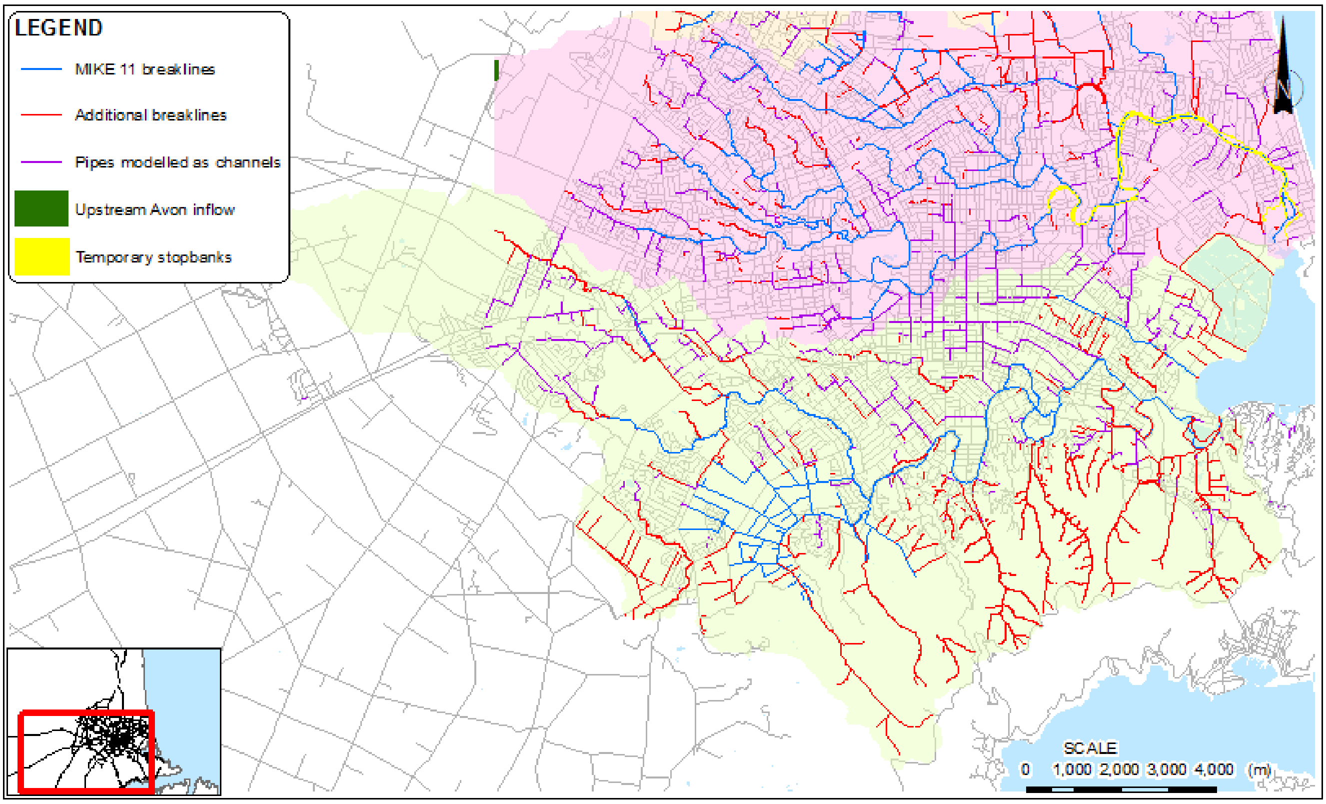

Figure 3-2 *Heathcote catchment*

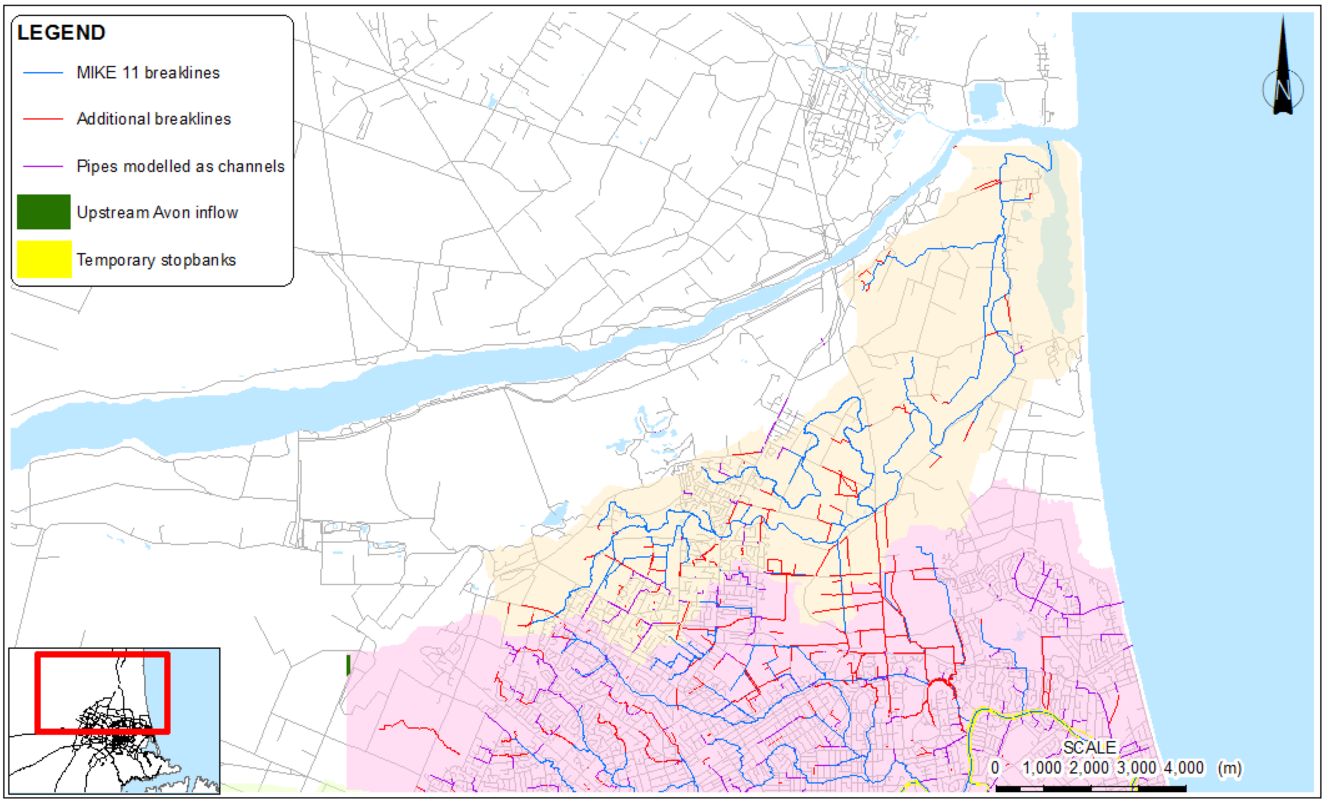

Figure 3-3 *Styx catchment*

4. Starting parameters

4.1 Model parameters

This section details the starting parameters used in the TUFLOW as the base model for sensitivity assessments. The key hydraulic parameters used in the TUFLOW model are outlined in Table 4-1 below.

Table 4-1 Summary hydraulic model parameters

Parameter	Value
Model cell size	A cell size of 5 m was used.
Timestep	The TUFLOW GPU model utilises an adaptive timestep. Rather than specifying timestep, a maximum Courant number is specified in TUFLOW. The adopted value (Adopted Maximum Courant Number = 1.0), this is the default value for TUFLOW GPU simulations. A test was performed to ensure that the results were consistent with lower Courant criteria. For this test a maximum Courant number of 0.8 was applied and the results compared, these were found to be consistent.
Viscosity	The default viscosity approach in TUFLOW GPU is a Smagorinsky method. The default Smagorinsky coefficient of 0.20 has been adopted for this modelling.
Manning's n	The Manning's values are defined for the land use areas defined in the model. The values used in the modelling are outlined in Table 2-1.
Topography	The model DEM is based on a combination of LiDAR flown post the December 2011 earthquake and bathymetry surveyed in March/April 2011 and January 2013 by NIWA.
Rainfall and River Flows	No rainfall or base river flows are used in the model

4.2 Sea level rise scenarios

For sea level rise the tides have been raised 0.4 m for the 50 year and 1.0 m for the 100 year horizons. The tidal time series are shown in Figure 4.1. An additional two inundation tides where run to model coastal inundation over the 50 year and 100 year horizons. The four model run tide scenarios are outlined below:

- Sea level rise to 2065 (RL 1.8 m peak)
- Sea level rise to 2115 (RL 2.4 m peak)
- Sea level rise to 2065 and 2% AEP storm tide with 0.4 m freeboard (RL 2.6 m peak)
- Sea level rise to 2115 and 1% AEP storm tide with 0.4 m freeboard (RL 3.3 m peak).

All four scenarios use the same in-bank bathymetry data (Section 2.1). The tidal boundary is located along the coast from Taylors Mistake in the south to the Waimakariri River in the north.

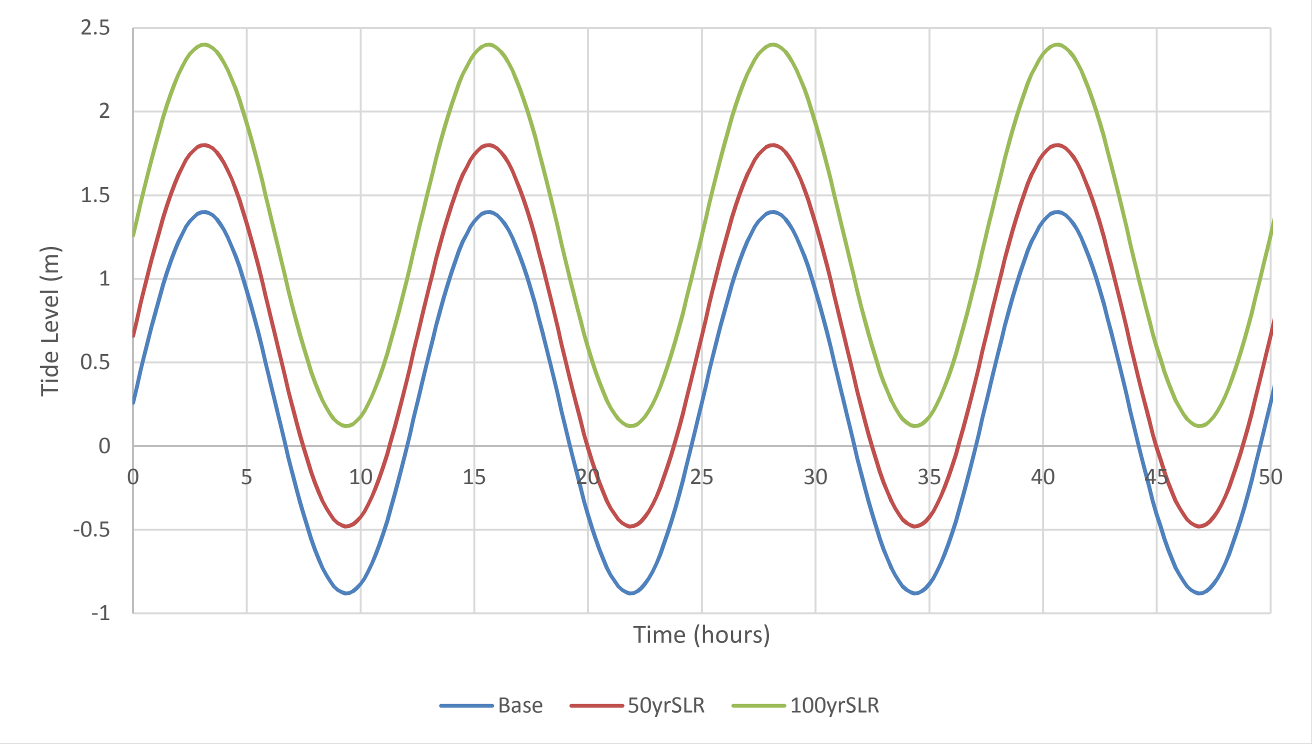

Figure 4.1: TUFLOW Model Tides including sea level rise

4.3 Validation

The model was validated using recorded tide levels and comparing the model results to the recorded tides.

Input level

The validation model was run with a tide sourced from the Sumner Head Gauge. The validation run tide and comparison tides are shown below in Figure 4.2 and Figure 4.3. The recorded tide was then compared to the model Ferrymead tide.

Figure 4.3 shows the comparison between the modelled Ferrymead tide level and the recorded tide for the same period. The first of the two peaks in this plot has model results showing some initial condition stabilisation, and the focus should rather be on the second high tide peak. As can be seen, the modelled behaviour differs from the measured in the following ways:

- Modelled peak is lower than measured peak level;
- Slope of the rising limb in the model result is flatter than that in the measured data;
- Slopes of the recession limbs is similar for modelled and measured;
- Time of the peak is similar, with the modelled peak lagging slightly behind the measured peak.

The reason for the differences between modelled and measured behaviour can largely be explained by the absence of river flow in the modelled result. With the inclusion of river flow it would be expected that the modelled water level would rise more quickly, to a higher level at an earlier time than is shown for the zero river flow scenario modelled. The close match between modelled and measured outflow rates (indicated by the slope of the recession limb, is indicative of the hydraulic simulation being reasonable within the estuary.

For the design runs using this model, the assumption of zero river, stream or stormwater system inflow is likely to be conservative, in that tidal effects may be propagated further upstream than would occur with some flow in these systems. Furthermore, this model takes no account of likely groundwater inflow to the estuary, with all of the water volume within the estuary being tidal. Results obtained using this model and this modelling approach are likely to represent a reasonably conservative upper bound in the likely tidal inundation.

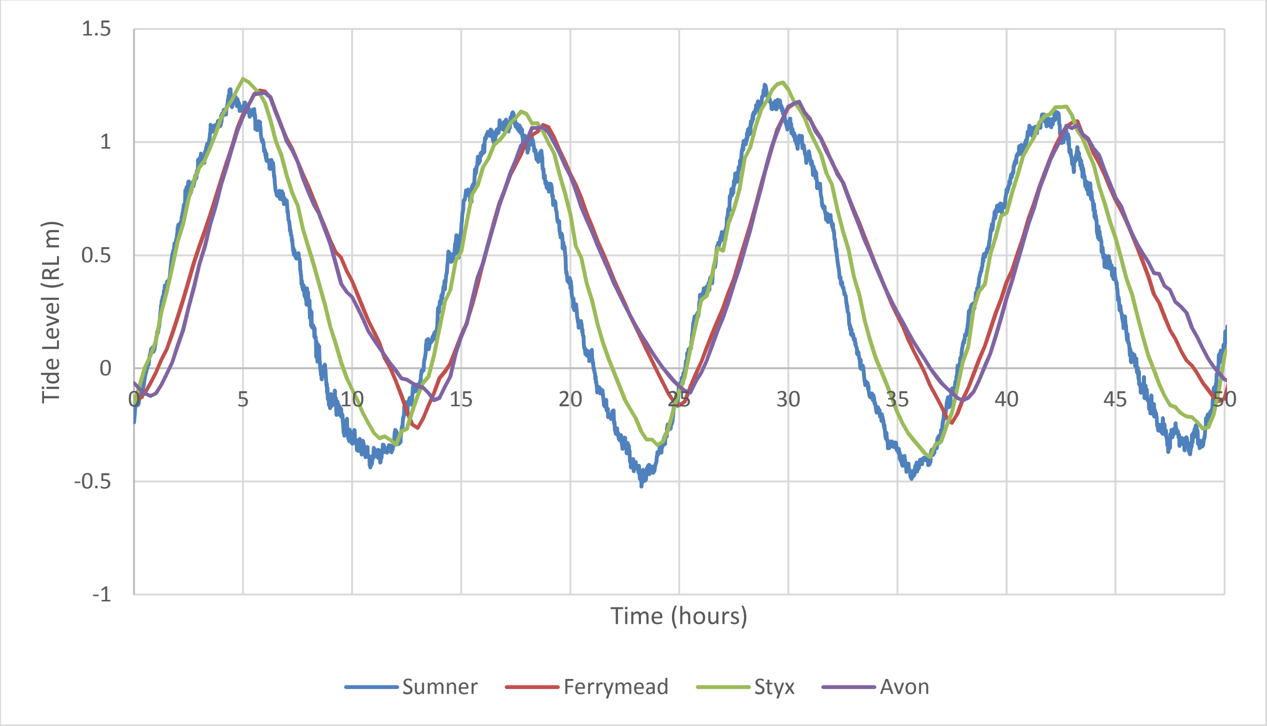

Figure 4.2: Sumner Gauge tide and comparison tides.

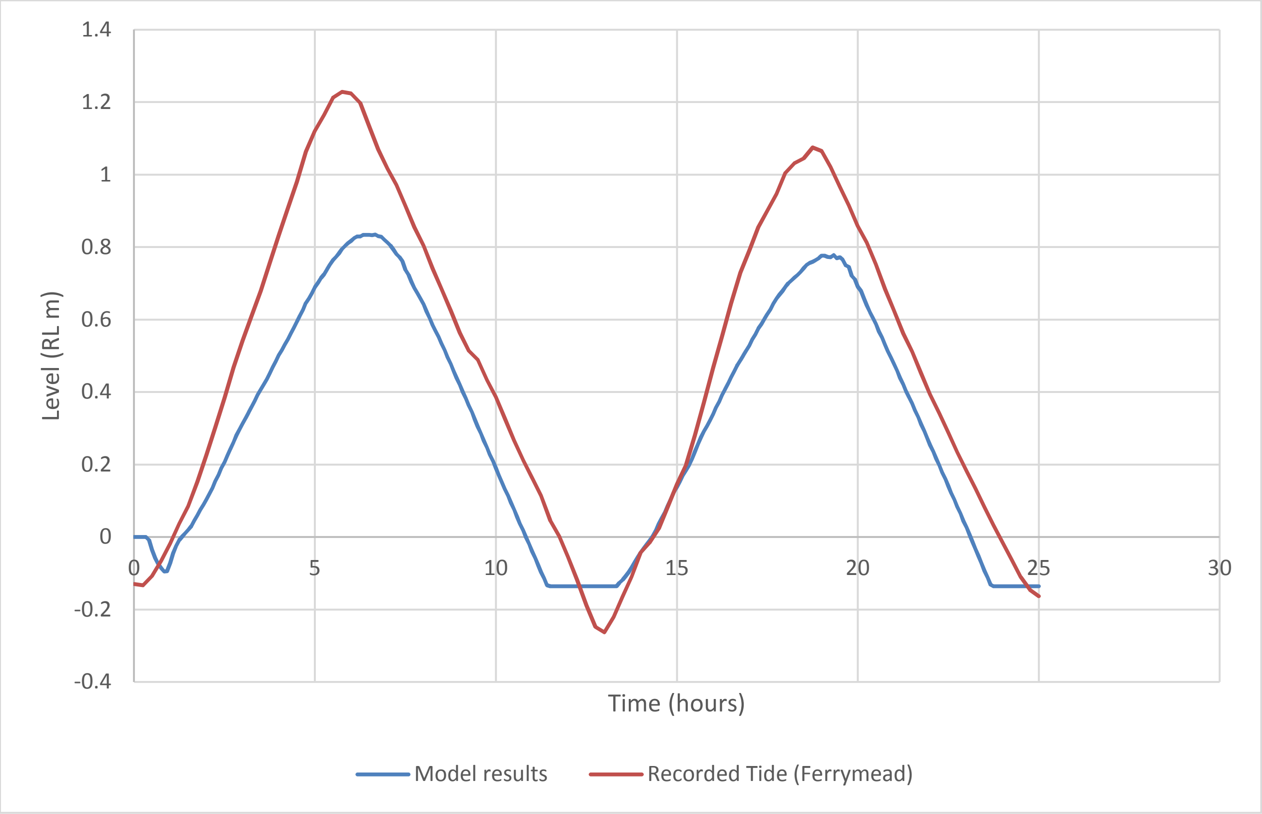

Figure 4.3: Validation comparison between model output and recorded tide levels