Tauranga Harbour inundation modelling

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Executive summary

Bay of Plenty Regional Council (BOPRC), Tauranga City Council (TCC) and Western Bay of Plenty District Council (WBOPDC) commissioned NIWA to calculate and model coastal inundation levels and their likelihood for the Tauranga Harbour coastline. This technical report details the data, models and methods employed in the study and presents the resulting inundation levels and mapping.

For hazard assessment purposes coastal inundation is defined as the combination of storm tide and wave setup plus any allowance for future sea-level rise. A previous report titled Tauranga Harbour Extreme Sea Level Analysis (Stephens 2017), calculated storm-tide frequency and magnitude by analysing extreme sea levels at all existing tide-gauge locations within Tauranga Harbour.

The purpose of this study is to map the overland extent of coastal inundation for the Tauranga Harbour coastline. This study expands on the previous extreme sea-level analysis by modelling storm-tide around the entire harbour and calculating the wave setup component.

The study used a calibrated hydrodynamic model (DelfFM) forced by tidal water levels, annual average river flows, wind, and air pressure (inverse barometer effect). The model used a flexible mesh with a high spatial resolution for populated areas of approximately 15 m cell edge. The model calculated storm–tide around the entire harbour shoreline and dynamically mapped the water depth overland.

The model's ability to simulate overland inundation was validated against post-inundation surveys from the 5 January 2018 storm event. The model validated well in locations sheltered from waves to within a few centimetres of observed elevations. The wave set up component was calculated at over 100 sites using empirical formulae and the results validated well with observed elevations in exposed locations.

Inundation maps were produced for the total inundation level based on both the storm-tide and wave setup for a set of annual exceedance probability likelihoods of 2%, 1% and 0.2% (50, 100 and 500-year average recurrence intervals). The inundation levels and maps were calculated relative to Moturiki Vertical Datum 1953 (MVD–53) and include a present day mean sea level of 0.13 m to the year 2020. Further inundation maps were produced for additional sea-level rise scenarios of 0.2, 0.4, 0.6, 0.8, 1.25 and 1.6 m MVD–53. These sea-level rise scenarios were designed to meet the requirements of the New Zealand Coastal Policy Statement, the Bay of Plenty Regional Policy Statement and the recently updated MfE 2017 guidance for local government on climate change and coastal hazards.

All resulting coastal inundation maps have been supplied to the clients as digital GIS layers. These inundation hazard map outputs can be used for RMA planning and climate change adaptation planning.

1 Introduction

Bay of Plenty Regional Council (BOPRC), Tauranga City Council (TCC) and Western Bay of Plenty District Council (WBOPDC) commissioned NIWA to calculate and model coastal inundation levels and their likelihood for the Tauranga Harbour coastline.

The purpose of the project is to identify areas of land surrounding the Tauranga Harbour exposed to coastal hazards within the jurisdictional boundaries of WBOPDC and TCC. The project includes the assessment of the following two coastal hazards:

1. Coastal erosion.
2. Coastal inundation.

NIWA partnered with Tonkin and Taylor Ltd (T&T), with T&T undertaking the coastal erosion study, and sub-contracting NIWA to undertake the coastal inundation study.

A Delft2D FM hydrodynamic model of the Tauranga Harbour was constructed from hydrographic charts, bathymetry survey data and LiDAR data. The model mesh was explicitly designed to incorporate the seabed and all land elevations up to the + 5 m contour above Moturiki vertical datum 1953 (MVD–53). The model used a grid size down to approximately 15 m (triangle) edge lengths over the heavily developed urban areas. The model was forced with tides, annual average river flows, wind and inverse-barometer (to account for air pressure).

This report describes the model (Section 2), its calibration and verification (Section 3), its validation for the 5 January 2018 storm-tide event (Section 4), the simulation of extreme sea levels (Section 5), and the simulation of extreme sea levels for future sea-level rise (SLR) scenarios (Section 6).

The key output required for the Project is a set of digital GIS layers showing the coastal inundation extents and magnitudes and this associated technical report. For each coastal inundation scenario, Project Partners were supplied with digital GIS files of maximum inundation depth.

All elevations referred to in this report are relative to Moturiki vertical datum 1953 (MVD–53) unless otherwise specified.

2 The hydrodynamic model

The Deltares flexible mesh modelling software (DelftFM) was used to simulate water level within the Tauranga Harbour. The finite element, semi-implicit model finds numerical solutions for the Navier-Stokes equations for momentum whilst conserving mass through the principle of continuity. Physical processes in the model can be parameterised / simulated through specifying for example, eddy scales, turbulent closure schemes, surface and bottom boundary conditions. The model open boundary is initialised and forced using tidal elevations. The finite element grid with the inclusion of a wetting and drying scheme makes the model ideal for simulating tidally driven flows in coastal regions with complex shoreline and/or embayments. The hydrodynamic model was set up in 2-dimensional mode to predicted depth-averaged flows, which is suitable for coastal-inundation modelling.

2.1 Model mesh development

The Delft FM model mesh of the Tauranga Harbour was developed with a focus on geographical regions of interest. For example, Mount Manganui, Waihi Beach, Bowentown, Katikati, Omokoroa, Takitimu Drive, Otumoetai, Welcome Bay, Greerton, Sulphur Point, Tauranga City and Tauranga Airport, urban areas are at the highest feasible resolution of approximately 15 m cell edge lengths (Figure 2-1). The model domain offshore area covers the coastline from Papamoa to Waihi Beach out to a depth of 300 m some 20 km offshore, but at a lower resolution. The model grid also includes all land below an elevation of +5 m Moturiki Vertical Datum–1953 (MVD–53) contour (as extracted from the 2017 LiDAR) and the grid explicitly resolved the river and stream channels for the Waimapu Stream, Wairoa River, Te Puna Stream, Waipapa River, Wainui River, Aongatete River, Uretara Stream and Tuapiro Stream.

The flexible mesh DelftFM model was established from bathymetry data sourced from:

- Light Detection And Ranging (LiDAR) and sub-tidal sounding data was supplied by the BOPRC, The University of Waikato, Ports of Tauranga, NIWA and Discovery Marine Ltd (DML).

- Offshore and intertidal soundings from Land Information NZ Hydrographic Chart NZ5413 (LINZ, 1961-1991) for approaches to Tauranga and NZ5411 (LINZ 1954-1998) Tauranga Harbour and Katikati Entrance to Mount Maunganui obtained in digital form from the LINZ Data Centre. These depths were relative to Chart datum established in 1993.

These baseline bathymetric datasets were then combined with high-resolution topography of the main intertidal banks of the central harbour and over land values up to +5 m in elevation on LiDAR, which is an aerial laser scanner system. Gridded LiDAR (2017) topography was made available by BOPRC.

Due to the varying quality and vertical and spatial resolution of the bathymetry data, ARC GIS software was used to post-process all bathymetric data. Data were imported into ARC GIS and re-projected to New Zealand Transverse Mercator (NZTM) coordinate system and all vertical datums were converted to MVD. Due to the large chronological diversity in the bathymetric data sets, each area was converted in ARC GIS into a raster surface, which represented the extent of the dataset.

Each new raster layer was then given a weighting and using the spatial analyst extension in ARC GIS, areas with the highest weighting. For example, where datasets overlapped the most recent survey data and LiDAR were preferentially chosen over that of the older data sets to create the model bathymetry. This means that overlapping data would not be skewed by the older bathymetry. The source of bathymetry datasets used in construction of the Tauranga Harbour model grid are listed in Table 2-1.

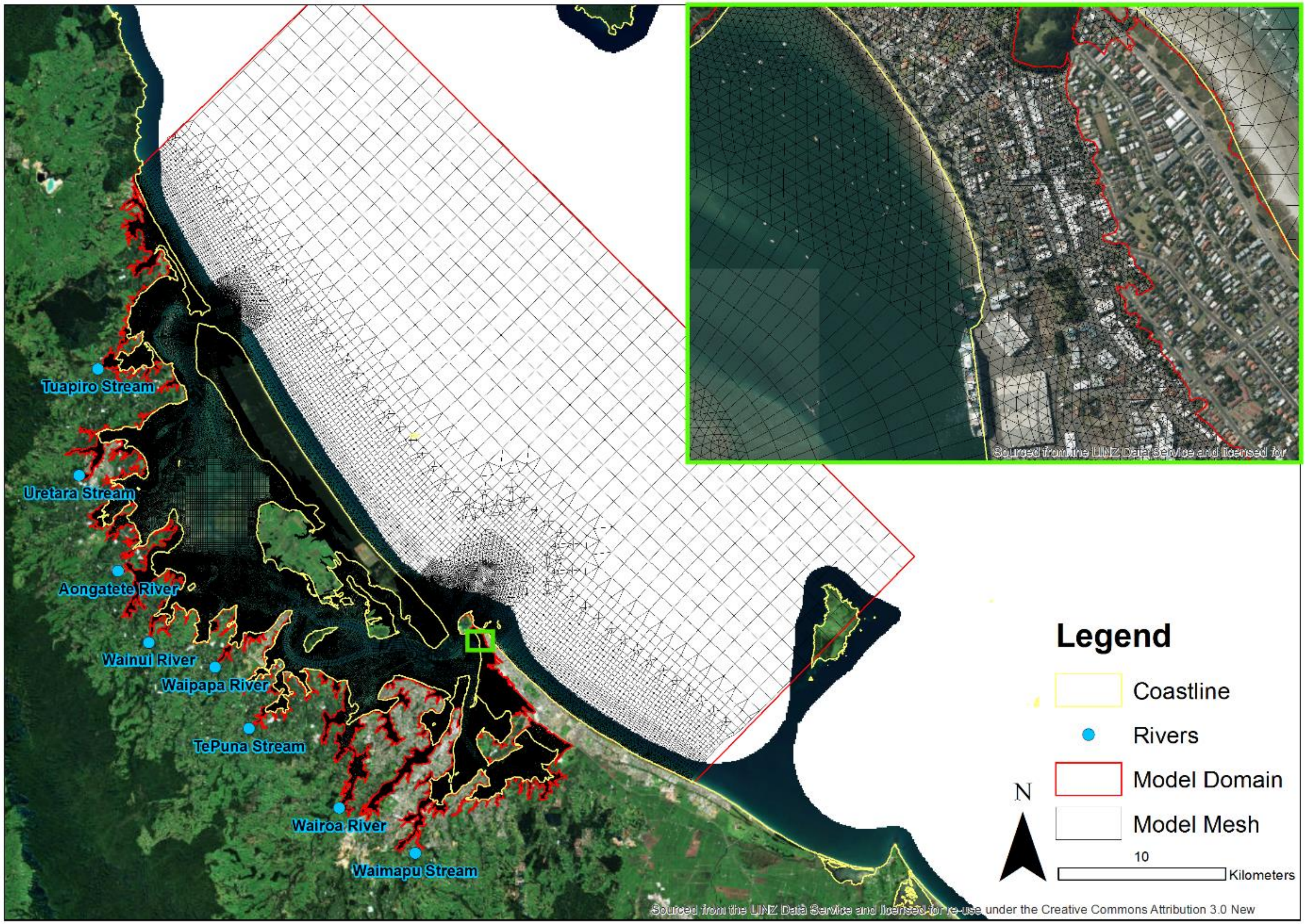

Figure 2-1: Tauranga Harbour flexible mesh model grid. Black rectangles and triangles represent the finite-element cells that make up the model grid. The red line represents the + 5m contour and model domain boundary while the yellow line represents the present land sea coastline. Blue dots mark the location of the freshwater boundary conditions. Note: in the areas inside Tauranga Harbour, the cells are much smaller and show up as mainly black. Green box illustrates the zoom area around Mount Manganui.

Table 2-1: Sources of seabed elevation data used to generate the bathymetry for the DelftFM model of Tauranga Harbour. Where; NZTM (New Zealand Transverse Mercator), NZMG (New Zealand Map Grid), WGS84 (World Geographic System), MVD (Moturiki Vertical Datum), NZVD (New Zealand Vertical Datum) and CD (Chart Datum).

Name	Projection	Original source datum	Survey Date	Data ownership
Bay of Plenty offshore bathymetry -5 to -300 m	WGS84	CD	1995	NIWA
LiDAR	NZTM	NZVD 2000	2017 and 2014	BOPRC
Central Bank to Katikati	NZTM	MVD	2007	NIWA
A Beacon to Tanea	NZMG	CD	2007	Ports of Tauranga
Stella to Railway bridge	NZMG	CD	2007	Ports of Tauranga
Cement Tanker	NZMG	CD	2007	Ports of Tauranga
Central Bank	NZMG	CD	2007	Ports of Tauranga
Mt Berth North	NZMG	CD	2007	Ports of Tauranga
Mt Berth South	NZMG	CD	2007	Ports of Tauranga
Sulphur Point	NZMG	CD	2007	Ports of Tauranga
Pilot Bay	NZMG	CD	2007	Ports of Tauranga
Matakana Bank	NZMG	CD	2007	Ports of Tauranga
Matahui – Waikareo	NZMG	CD	2007	Ports of Tauranga
DML fill survey Wairoa	NZTM	MVD	2017	BOPRC
DML fill survey Waimapu	NZTM	MVD	2017	BOPRC
DML fill survey Te Puna	NZTM	MVD	2017	BOPRC

2.2 Model forcing

For calibration of tidal water levels and currents, the model was forced by tidal water levels at the open offshore boundary, and annual-average flows from sources located at Waimapu Stream, Wairoa River, Te Puna Stream, Waipapa River, Wainui River, Aongatete River, Uretara Stream and Tuapiro Stream. For validation against the 5 January 2018 storm-tide event, and for inundation scenarios, the model was also forced using wind data, and with an inverse-barometer boundary forcing to account for drop in air pressure (described in Section 4).

To force the model at the offshore boundary, tidal constituents (13 in total), were extracted from the NIWA exclusive economic zone (EEZ) tide model (Walters et al. 2001), and used to generate the offshore boundary water levels to drive the hydrodynamic model. A phase-lagged tidal forcing file was generated to account for the north–south variation in the phase of the tide across the offshore boundary between the Tauranga and Katikati entrances.

2.3 Bed Roughness

For the subtidal area of the harbour a spatially varying bed roughness map was constructed. The model is run by specifying the bed-roughness coefficient Manning's n value *M*, which is derived using water depth and seabed roughness, using the Chezy formula:

Equation 2-1: Conversion from Manning's n to Chezy bed roughness. *M* = Manning's n, C is the Chezy coefficient calculated in Equation 2-2, *h* = water depth.

$$M = \frac{C}{\left(h^{(1/6)}\right)}$$

Equation 2-2: Chezy coefficient formula. *h* = water depth (m) and z_0 is the roughness length (m).

$$C = 18\log_{10}\left(\frac{0.37h}{z_0}\right)$$

Equation 2-3: Bed roughness formula. *H* and *L* represent bedform height and width (m), or if there are no bedforms use Equation 2-4.

$$z_0 = \frac{H^2}{2L} \text{ (m)}$$

Equation 2-4: Bed roughness formula if no bedforms are present *d* is the sand grainsize (m).

$$z_0 = \frac{d}{30}$$

Observations collated for the Tauranga Harbour Sediment Study suggest bedforms in the central harbour, the deeper channels in and the entrance and the flood tidal delta had a mean diameter of about 0.25–0.5 mm (> 60% sand) and to be very consistent throughout the inlet with some isolated shell patches in the deeper faster flowing main channels (Hancock et al. 2008). Therefore, it may be reasonable to assume a uniform bed-roughness length (z_0) throughout the inlet. The data also suggests that most of the sub-estuaries (where data existed) had a mean grainsize of 0.125−0.35 mm, except for the sub-estuary to the west of Ngakautuakina Point which was 0.013 mm.

Hancock and Hume et al. (2008) made observations during the Tauranga Harbour Sediment Study of large bedforms on the ebb tidal delta, therefore $z_0 \approx 0.01$ m was applied to this area. The assumption was made that tidal flow was fast enough in the channels to smooth out bedforms and a bed roughness length map was created, setting z_0 to 0.01 on the central harbour sand banks and the deeper harbour channels, and to 0.001 m everywhere else. A spatially varying bed roughness map was then created using z_0 and the model depth in Equation 2-1 and Equation 2-2.

2.3.1 Overland roughness classification

To accurately predict the extent of overland inundation, we need to incorporate representative land use and vegetation roughness values. This is important because different coastal land use, infrastructure and vegetation types can buffer the coast during high sea-level events by dissipating the incoming wave energy (Musleh & Cruise 2006; Zhang et al. 2012).

For the roughness values in the model which represent intertidal flats and land use (> −0.5 m MVD–53) we developed an ARCGIS categorising technique to define different vegetation and land use types. The process of mapping estuarine land use and vegetation uses the colour in aerial photos and elevation data from LiDAR following Allen (2016), and employed a sequence of classification algorithms (Principal Component Analysis, Image Segmentation, Support Vector Machine learning) (Frohn et al. 2011; Khatami et al. 2016). The land use and vegetation raster values were classified to differentiate land use types. Then, the overland manning roughness values in Table 2-2 and the seabed manning roughness values calculated for the harbour (Equation 2-1 – Equation 2-4; Figure 2-2), they were merged to create a spatially-varying Manning's n roughness values for the full model domain, using ArcMap 10.4. For a complete step by step explanation of the categorisation process see Townsend and Wadhwa (2017).

Table 2-2: Summary of Manning's n values for various land use classifications used in the Tauranga Harbour inundation model.

Vegetation land use classification	Manning's n	Reference/source
Muds	0.015	(Chow 1959)
Sands	0.026–0.035 (used range relative to depth)	(Chow 1959; Arcement & Schneider 1989)
Mangroves	0.01–0.22 (0.1 used)	(Musleh & Cruise 2006)
Wetlands	0.04–0.1 (0.04 used)	(Narayan et al. 2017)
Kiwifruit Orchards	0.025–0.12 (used 0.05) estimated low vegetation density	(Arcement & Schneider 1989)
Exotic forest	0.085–0.120 (0.11 used)	(Arcement & Schneider 1989)
Grass	0.01–0.08 (0.02 used)	(Henderson 1966; Engman Edwin 1986; Arcement & Schneider 1989)
Buildings	1	-
Roads	0.012–0.016 (0.013 used)	(Ali 2001)
Lakes/water bodies	0.02	(Narayan et al. 2017)

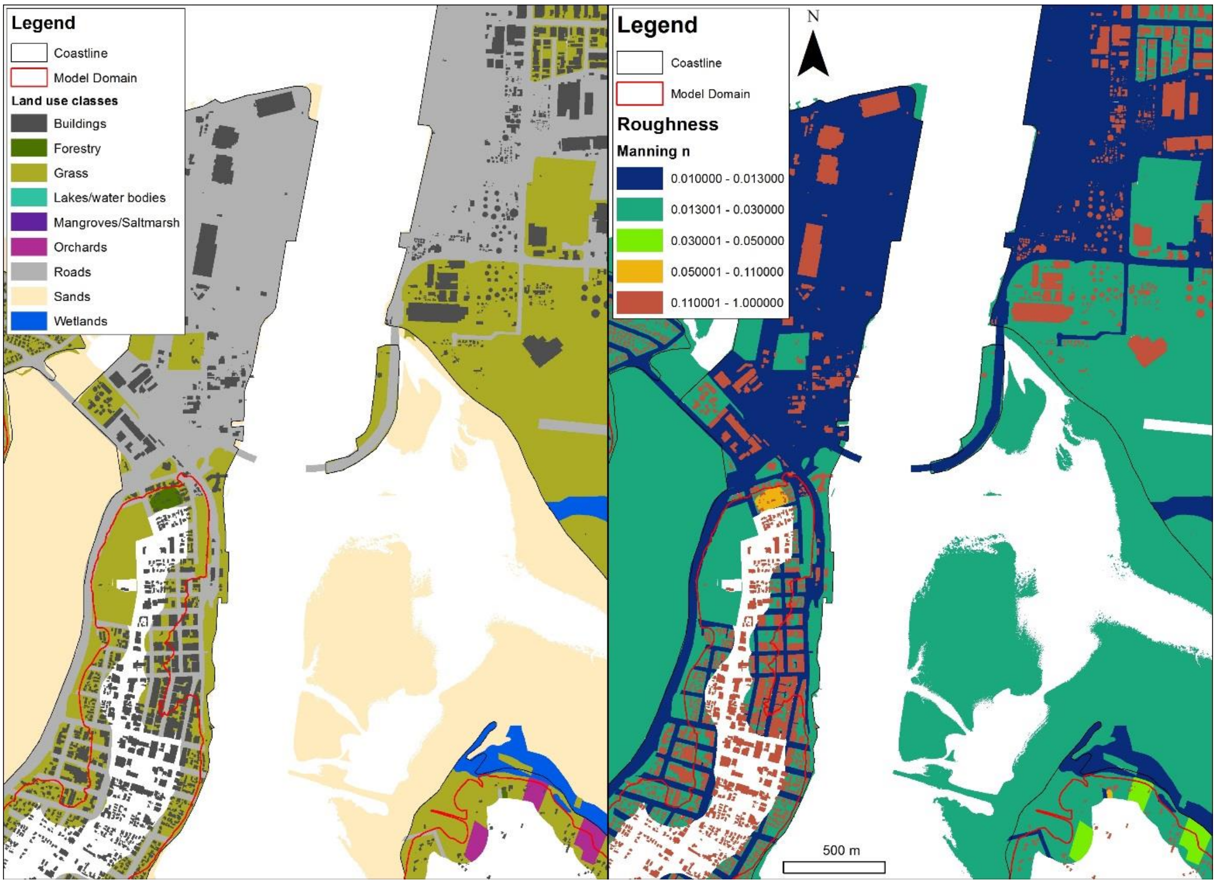

Figure 2-2: Spatially varying land use classification created from the support vector machine analysis (Left-hand-side), and illustration of the conversion from land use to Manning's n (Right-hand-side).

3 Model Calibration and Verification

Section 3 assesses the model's ability to accurately simulate tidal water levels and tidal currents. The model was calibrated and verified using tidal forcing only, atmospheric pressure, wind surface forcing, and waves were not included during the calibration or verification reported here in Section 3.

- Calibration involved comparing the model output to measured water levels and adjusting the model parameters (e.g., bed roughness) so that it accurately reproduced the observations. Calibration: is the model accurate?
- Verification involved comparing the output of the calibrated model to measured water levels and currents, and re-checking its accuracy, using observations made at a different place or time from those used in the calibration. Verification: is the model working correctly?
- Validation involved comparing the total water level and inundation extent predicted by the model, to observations during the 5 January 2018 storm-tide event. Validation: is the model's system function satisfactory; does it meet the needs of the study? Whereas verification focuses on the right operation of the model itself, the validation focuses on the right output of the model.

Storm surge validation is addressed in Section 4, where the model is compared to the 5 January 2018 storm-tide event, using sensitivity testing, and through validation against the 5 January 2018 storm-tide. Nevertheless, if the model can predict the propagation of the tide well, due to accurate bathymetry, and bed roughness and eddy viscosity parameters, for example, then it should also model the propagation of storm surge well.

The purpose of model calibration is to tune it so that it is accurate. The purpose of model verification is to re-check its accuracy, using observations made at a different place or time from those used in the calibration.

The model was calibrated by iteratively changing calibration parameters until modelled and predicted water levels and currents were in best agreement, by simulating hydrodynamic conditions over specific periods when field measurements were available, and comparing simulated water levels and current velocities, and tidal amplitudes and phase, with the measured data. Given a good fit between observed (measured) and predicted (modelled) values the model can be confidently used to make predictions of water levels at other sites in the Harbour.

The following parameters were adjusted in the hydrodynamic model to achieve a best fit between modelled and observed values:

Smagorinsky eddy coefficient: Simulates horizontal shear flows in the model and causes change in the amplitude of surface elevations and the magnitude of current speeds.

Sea-bed roughness (z_0): Controls the phase (timing) and magnitude of water levels and current flows.

The calibrated model was then verified, by taking the calibrated model, "freezing" the model parameters and testing how well the model reproduced a second data set. In this instance the verification was undertaking by comparing the model with measured data collected at a different time and/or place to the calibration dataset.

The measure of the 'goodness of fit' between observed and predicted was estimated using the following four statistical skill measures:

- SKILL – where values span 1 (high) to 0 (poor) skill decreases towards zero as described by Warner et al. (2005) and Haidvogel et al. (2008).
- Root mean square error (RMSE) – A measure of the difference in the variance between the observed and predicted signal.
- Cross-correlation function (R_{xy}) – A coefficient that describes the strength in the phase relationship (timing) between two oscillating signals. 0-1, with 0 being weak and 1 being strong.
- Bias: The residual offset between two time-series. ± bias indicates a positive/negative offset in time series data.

Further details on the goodness of fit measures used for calibration are provided in Appendix C.

3.1 Water level and current data for calibration and verification of tides

The hydrodynamic model was calibrated and verified using water level and current records at 27 sites in and around Tauranga Harbour. Figure 3-1 shows the locations of data used, and Table 3-1 provides details of each sites. The data records for the harbour ranged in date from 1974 to 2018.

The model was calibrated against water-level timeseries data collected between 17–21 August 2017; this coincided with the most recent instrument deployments at sites 10, 11 ,12, 13 and 14 and tidal records from sites 9 ,15, 17, 20 and 23, which cover the same period. The model was also calibrated against tidal harmonic constituents, fitted to sites 16, 19, 21 and 21 collected at other times. Table 3-1 explains how the data was used for calibration.

The purpose of model verification is to re-check the model's accuracy, using observations made at a different place or time from those used in the calibration. The model was verified against water-level measurements at sites 1, 4, 5, and 7 and against current measurements at sites 1–8 from instruments deployed from the 21 October to 19 November 2015.

For the calibration the model was run without any atmospheric forcing. This was a reasonable assumption as the wind conditions for the 17–21 August model calibration period were generally less than 10 m/s with the average wind speed for the period of 8.6 m/s. The maximum wind speed during the calibration period was 22 m/s, which occurred on the 19th August but was not a sustained period of high winds.

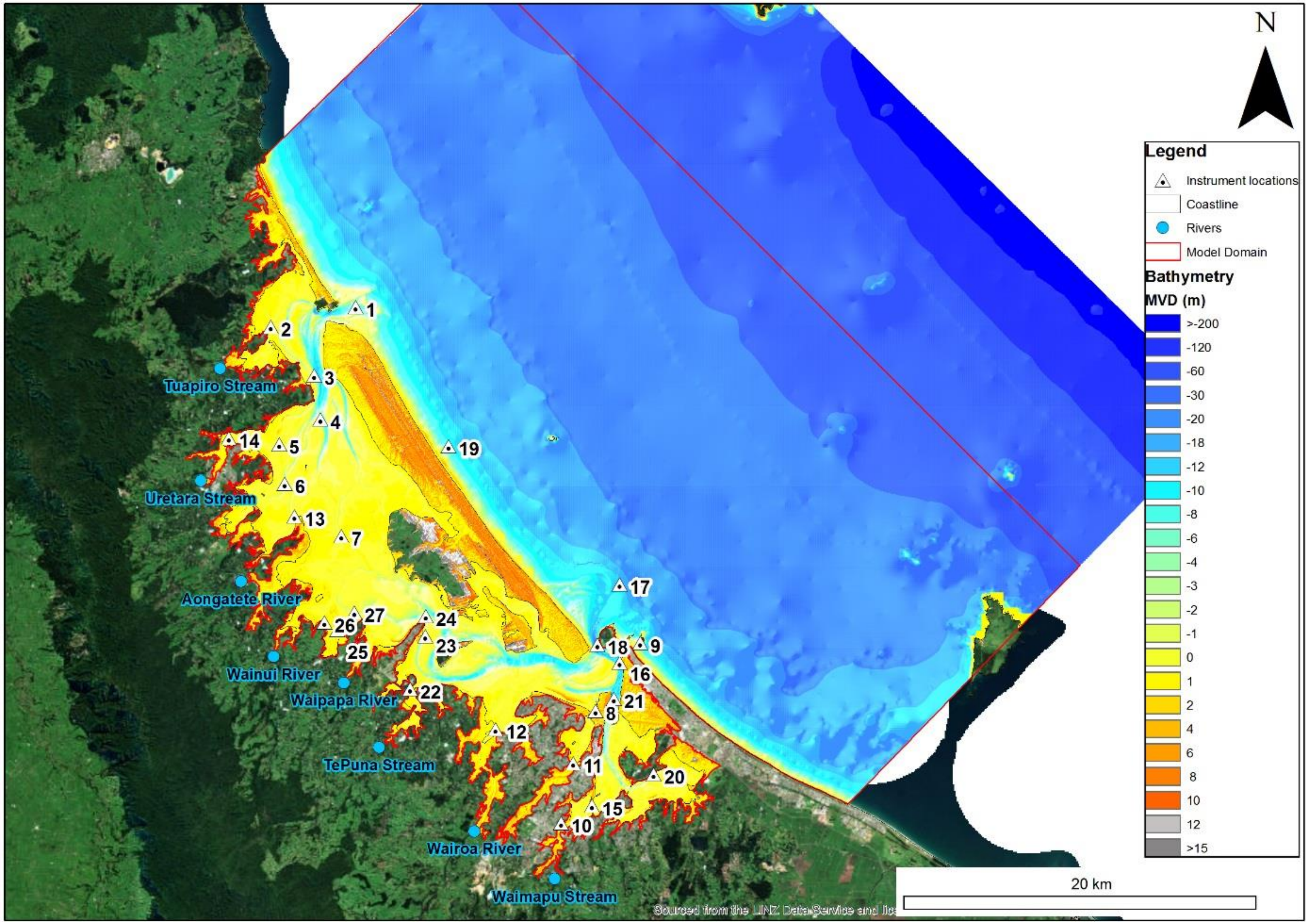

Figure 3-1: Tauranga Harbour inundation model bathymetry. The white triangles indicate the locations of available instrument data, the blue circles illustrate the most upstream river boundary locations incorporated into the model domain and the black line represents the model domain boundary. The bathymetry/digital elevation model overlays aerial photos and includes values of elevations from +15 m to depths < −200 m.

Table 3-1: Instrument deployment details. The last column explains how the data was used for calibration and/or verification. All model comparisons were made using depth-averaged currents.

Location (Figure 3-1)	Geographic Name	Northing (NZTM)	Easting (NZTM)	Measurement period	Water level	Current	How the instrument record was used
1	Katikati entrance	1865586	5849191	21/10/15 to 18/11/15	✓	✓	Calibration with M2 tide only and verification raw water levels and currents (Method 1 & 3 from section 3.2.1)
2	Tanners Point	1860764	5848060	21/10/15 to 18/11/15		✓	Verification raw currents (Method 1 from section 3.2.1)
3	Ongare Point channel	1863229	5845300	29/10/15 to 18/11/15		✓	Verification raw currents (Method 1 from section 3.2.1)
4	Katikati channel marker (GRG)	1863588	5842816	29/10/15 to 18/11/15	✓	✓	Calibration with M2 tide only and verification raw water levels and currents (Method 1 & 3 from section 3.2.1)
5	Katikati channel marker (BY)	1861239	5841389	21/10/15 to 18/11/15	✓	✓	Calibration with M2 tide only and verification raw water levels and currents Method 1 & 3 from section 3.2.1)
6	Tutaekaka	1861558	5839165	29/10/15 to 19/11/15		✓	Verification raw currents (Method 1 from section 3.2.1)
7	Centre Bank	1864783	5836179	22/10/15 to 18/11/15	✓	✓	Calibration with M2 tide only and verification raw water levels and currents Method 1 & 3 from section 3.2.1)
8	Sulphur Point	1879222	5826264	21/10/15 to 19/11/15		✓	Verification raw currents (Method 1 from section 3.2.1)
9	Moturiki	1881766	5830106	01/06/74 to present	✓		Calibration raw water levels and M2 tide (Method 1 & 4 from section 3.2.1)
10	Waimapu Stream	1877261	5819895	17/08/17 to 21/08/17	✓		Calibration raw water levels and M2 tide (Method 1 & 4 from section 3.2.1)
11	Waikareao Estuary	1877953	5823293	17/08/17 to 22/08/17	✓		Calibration raw water levels and M2 tide (Method 1 & 4 from section 3.2.1)
12	Wairoa River	1873541	5825229	17/08/17 to 21/08/17	✓		Calibration raw water levels and M2 tide (Method 1 & 4 from section 3.2.1)
13	Matahui Point	1862107	5837298	17/08/17 to 21/08/17	✓		Calibration raw water levels and M2 tide (Method 1 & 4 from section 3.2.1)
14	Uretara Stream	1858383	5841748	17/08/17 to 22/08/17	✓		Calibration raw water levels and M2 tide (Method 1 & 4 from section 3.2.1)
15	Hairini	1879014	5820867	05/04/02 to present	✓		Calibration raw water levels and M2 tide (Method 1 & 4 from section 3.2.1)
16	Tug Berth	1880579	5829002	02/08/08 to 01/11/16	✓		Calibration full tidal harmonic analysis and M2 tide (Method 2 & 4 from section 3.2.1)

Location (Figure 3-1)	Geographic Name	Northing (NZTM)	Easting (NZTM)	Measurement period	Water level	Current	How the instrument record was used
17	A Beacon	1880580	5833447	01/01/03 to present	✓		Calibration raw water levels and M2 tide (Method 1 & 4 from section 3.2.1)
18	Tauranga entrance	1879121	5829763	01/01/07 to present		✓	Not used (error in data)
19	Katikati WWTP	1870863	5841295	07/09/16 to 13/10/16	✓	✓	Calibration full tidal harmonic analysis and M2 tide (Method 2 & 4 from section 3.2.1)
20	Oruamatua	1882526	5822655	10/01/01 to present	✓		Calibration raw water levels and M2 tide (Method 1 & 4 from section 3.2.1)
21	Sulphur Point channel	1880246	5826944	01/06/89 to 04/10/04	✓		Calibration full tidal harmonic analysis and M2 tide (Method 2 & 4 from section 3.2.1)
22	Kotuku channel	1868681	5827494	24/11/00 to 18/08/14	✓		Calibration full tidal harmonic analysis and M2 tide (Method 2 from section 3.2.1)
23	Omokoroa Wharf	1869556	5830498	15/08/14 to present	✓		Calibration raw water levels and M2 tide Method 2 & 4 from section 3.2.1)
24	Omokoroa Point	1869568	5831631	08/06/17 to 12/07/17	✓	✓	Calibration with M2 tide only (Method 3 from section 3.2.1)
25	Pahoia Domain	1864542	5830865	08/06/17 to 19/07/17	✓	✓	Calibration with M2 tide only Method 3 from section 3.2.1)
26	Wainui River/ Te Hopai Island	1863797	5831279	08/06/17 to 19/07/17	✓	✓	Calibration with M2 tide only Method 3 from section 3.2.1)
27	Ngakautua kina Point	1865509	5831843	15/05/17 to 11/08/17	✓		Calibration with M2 tide only Method 3 from section 3.2.1)

3.2 Calibration of water levels

3.2.1 Calibration methods

The model was calibrated against water level using four methods, depending on the available data:

1. Raw measured water-level timeseries—the timeseries predicted by the model was calibrated against the raw measured water-level timeseries, for the period 17–21 August 2017, for the sites shown in (Table 3-2). This instrument data set was the primary focus of the calibration as it was the most recent and spatial diverse data set available at the time. A good calibration was achieved (Table 3-2), despite the model being forced only by tides at the offshore boundary, whereas the measured data included other effects such as the influence of weather.

2. Water-level timeseries from tidal harmonic prediction—for sea-level measurement records that were collected outside the model calibration period, but which were long enough (> 1 month), the model was compared to a water-level timeseries from a tidal harmonic prediction, for the calibration period (Table 3-3).

3. Water-level timeseries from M_2 tidal harmonic prediction—where sites have a short record (sites 1, 4, 5 & 7) (Table 3-4). This is because 1 month of data is required to resolve enough tidal constituents to make a meaningful timeseries comparison with the model timeseries generated using 13 tidal constituents. The M_2 component was extracted and an M_2 water level timeseries predicted from both the model and measured data, using tidal harmonic analysis (Foreman et al. 2009).

4. Comparison of modelled and measured M_2 tidal amplitudes and phase at all measured water-level locations (Table 3-5). To simulate M_2 tides, the model was forced at the open boundary using M_2 tidal amplitude and phase extracted from NIWA's tidal model, which were approximately 0.72 m and 198° respectively (they change a small amount across the model boundary).

Figures A-1 to A-11 (Appendix A) show model calibration time series plots of water levels for visual inspection.

3.2.2 Calibration results

The Tauranga Harbour model is predicting water levels with high skill, with the model reproducing the phase, amplitude and tidal asymmetry at the majority of the 22 calibration sites where water-level records exist. The results from the analysis between the measured and modelled sea surface elevations show a range of RSME 0.04–0.11 m and bias -0.04–0.05 m in the bias for the sea-surface elevations (Table 3-2, Table 3-3 and Table 3-4). A small negative bias means that overall the model is slightly over predicting the MSL for that period, and *vice versa*. High model skill measures of > 0.96 were achieved. Cross-correlation functions (R_{xy}) were greater than 0.97 indicating good phase (timing) agreement between the observed and modelled elevations e.g., at high and low tides.

The modelled M_2 tidal phases shown in Table 3-5 are in good agreement with measurements, but some of the amplitudes don't quite match. Omokoroa Wharf and Omokoroa Point are close together, so we expect the M_2 amplitude and phase to be similar. The model predicts them to be similar, but the measured amplitude seems low at Omokoroa Point. We think this is because the amplitudes were under-measured by an ADCP current meter; these instruments are designed primarily to measure currents and in the author's experience the pressure-sensors in them often aren't very accurate.

Katikati channel marker (BY) has a 0.09 m error. We think that the model bathymetry at this location is too shallow causing the tide to shoal. The depth measured by the instrument was 2.0 m and the depth in the model here is 1.73 m (including 0.13 m MSL) but most of the surrounding depths in the model are 1.1–1.3 m. Having said that, the model fit is very good at the instrument site 14 further upstream (Uretara Steam).

Table 3-2: Calibration results for raw water-level timeseries recorded in and around Tauranga Harbour and modelled tidal water levels. Root mean square error (RMSE), Skill, bias (field data minus model) and cross-correlation function (R_{xy}). See Appendix C for description of these calibration measures.

Location	RMSE (m)	SKILL	Bias (m)	R_{xy}
9	0.09	0.97	0.01	0.98
10	0.06	0.99	0.02	0.99
11	0.09	0.98	-0.02	0.98
12	0.06	0.99	-0.03	0.99
13	0.04	0.99	0.01	0.99
14	0.06	0.99	-0.01	0.99
15	0.1	0.99	-0.04	0.99
17	0.11	0.99	-0.012	0.98
20	0.12	0.98	-0.015	0.99
23	0.1	0.99	0.05	0.99

Table 3-3: Calibration results for water levels predicted using full tidal harmonic analysis of instrument data collected outside of the calibration period and the model predicted water levels in Tauranga Harbour. Root mean square error (RMSE), SKILL, bias (field data minus model) and cross-correlation function (Rxy). See Appendix C for description of these calibration measures.

Location	RMSE (m)	SKILL	Bias (m)	R_{xy}
16	0.09	0.97	0.01	0.98
19	0.06	0.99	0.02	0.99
21	0.09	0.98	-0.02	0.98
22	0.06	0.99	-0.03	0.99

Table 3-4: Calibration results for water levels predicted using the M2 tidal constituent, predicted from instrument data and model outputs in Tauranga Harbour. Root mean square error (RMSE), SKILL, bias (field data minus model) and cross-correlation function (Rxy). See Appendix C for description of these calibration measures. The bias is not applicable because both timeseries are generated from tidal harmonics.

Location	RMSE (m)	SKILL	Bias (m)	R_{xy}
1	0.06	0.98	NA	0.99
4	0.06	0.96	NA	0.99
5	0.07	0.99	NA	0.99
7	0.05	0.99	NA	0.99

Table 3-5: M_2 tidal phase and amplitude at all modelled locations where water level records were collected. Only locations with water-level data are shown (not sites with currents only).

Location (Figure 2-1)	Geographic Name	Measured		Modelled	
		M_2 Amp	M_2 Phase	M_2 Amp	M_2 Phase
1	Katikati entrance	0.729	191	0.741	186
4	Katikati channel marker (GRG)	0.644	229	0.667	228
5	Katikati channel marker (BY)	0.595	233	0.685	225
7	Centre Bank	0.69	240	0.666	237
9	Moturiki	0.743	190	0.762	183
10	Waimapu Stream	0.685	222	0.622	221
11	Waikareao Estuary	0.623	219	0.618	219
12	Wairoa River	0.681	222	0.638	217
13	Matahui Point	0.703	243	0.663	235
14	Uretara Stream	0.64	245	0.622	238
15	Hairini	0.762	213	0.754	213
16	Tug Berth	0.717	197	0.721	192
17	A Beacon	0.728	190	0.766	183
19	Katikati WWTP	0.731	189	0.762	184
20	Oruamatua	0.794	213	0.772	221
21	Sulphur Point channel	0.727	200	0.757	193
22	Kotuku channel	0.718	222	0.73	219
23	Omokoroa Wharf	0.761	220	0.735	219
24	Omokoroa Point	0.665	224	0.738	222
25	Pahoia Domain	0.684	235	0.629	237
26	Wainui River/ Te Hopai Island	0.693	237	0.623	242
27	Ngakautuakina Point	0.728	232	0.738	230

3.3 Model Verification

The purpose of model verification is to re-check its accuracy, using observations made at a different place or time from those used in the calibration. Sections 3.3.1 and 3.3.2 show that the model verifies well against both water-level and current measurements.

3.3.1 Verification of water levels

The calibrated model was verified against the measured water-level and current data from instruments deployed from 21 October to 18 November 2015 at sites 1–8 (Table 3-1) ; statistical skill measures are shown in Table 3-6 and Table 3-7.

Model predictions of tidal water level were verified against water-level measurements collected from 29 October to 4 November 2015 at sites 1, 4, 5, and 7. Data from these sites were also used for calibration, by using them to fit tidal harmonics and to predict the tides for the calibration period (17–21 August 2017), which is different from the verification period. The use of these data for verification differs from the calibration, because the verification compares the model with the measured water-level measurements at these sites, as opposed to tidal predictions based on the measurements.

The verification skill statistics for water level at sites 1, 4, 5 and 7 (Table 3-6), show that the model is predicting water levels well outside of the calibration period, and thus is suitable for the simulation of water levels in Tauranga Harbour.

Table 3-6: Verification statistics for measured water levels recorded at sites 1, 4, 5, and 7. Root mean square error (RMSE), Skill, bias and cross-correlation function (R_{xy}). See Appendix C for description of these calibration measures.

Location	RMSE (m)	SKILL	Bias (m)	R_{xy}
1	0.09	0.97	0.01	0.98
4	0.06	0.99	0.02	0.99
5	0.09	0.98	-0.02	0.98
7	0.06	0.99	-0.03	0.99

3.3.2 Verification of currents

Because of lack of available current data available during the 2017 calibration period, the model was not calibrated to currents in the Harbour. Also, the focus of the modelling work is the prediction of peak water levels. Furthermore, currents are difficult to calibrate because morphological changes between the bathymetry survey and current measurements can result in large directional differences between model and measurement. Nevertheless, we compared observed and modelled current velocities for verification purposes at sites 1–8 (Table 3-1), for the period 29 October to 4 November 2015. The skill statistics are shown in Table 3-7. The model was compared with depth-averaged currents for ADCP data and compared directly to point-source data. All current-meter data were corrected to true north before verification.

Measured and modelled currents at sites 1, 3, 4 and 5 had a RMSE of 0.01–0.14 m/s and bias 0–0.05 m/s indicating good agreement. However, currents at sites 2 and 8 are subject to strong topographical steering due to the confined channels located at Tanners point and near the Marina on the north-western side of Sulphur Point. An inspection of the “raw” fit at these sites (Appendix B Figure B-4 and Figure B-10) shows that the model generally reproduced the current speed but differed in direction. At site 7 (Appendix B, Figure B-9), the agreement is good considering that the model computational grid is large through the central harbour. Further, the comparison itself is between field measurements at a point (i.e., the current meter) and the modelled currents that are averaged over the area of the relevant grid cell in the model mesh, so there will always be some inherent error due to the different spatial scale.

Table 3-7: Verification results for current velocities at sites 1, 2, 3, 4, 5, 6, 7 and 8. Root mean square error (RMSE), Skill (skill is performed on the velocity magnitude therefore the U and V components are combined), bias and cross-correlation function (Rxy). See Appendix C for description of these calibration measures.

Location	Variable	RMSE (m/s)	SKILL	Bias (m/s)	R_{xy}
1	*u* component of velocity (m/s)	0.09	0.95	0.01	0.98
	v component of velocity (m/s)	0.07		0.02	0.99
2	*u* component of velocity (m/s)	0.09	0.58	-0.04	0.97
	v component of velocity (m/s)	0.19		-0.03	0.99
3	*u* component of velocity (m/s)	0.07	0.81	0.01	0.99
	v component of velocity (m/s)	0.16		0.05	0.99
4	*u* component of velocity (m/s)	0.05	0.92	0	0.99
	v component of velocity (m/s)	0.1		0.01	0.99
5	*u* component of velocity (m/s)	0.11	0.86	0.05	0.99
	v component of velocity (m/s)	0.14		0.02	0.98
6	*u* component of velocity (m/s)	0.08	0.61	-0.003	0.93
	v component of velocity (m/s)	0.32		-0.01	0.99
7	*u* component of velocity (m/s)	0.26	0.25	-0.04	0.98
	v component of velocity (m/s)	0.25		0.001	0.99
8	*u* component of velocity (m/s)	0.008	0.54	-0.003	0.93
	v component of velocity (m/s)	0.32		-0.02	0.99

4 Model validation: 5 January 2018 storm-tide

A large storm-tide on 5 January 2018 caused overland flooding within the Tauranga Harbour (and other parts of NZ). Within Tauranga Harbour, the water level was measured by sea-level gauges, and post-storm surveys captured the elevations and horizontal location of debris deposited on land. This event provided an ideal opportunity to validate the model's ability to reproduce observed water levels and spatial patterns of overland inundation.

There was a lot of rain before and during the 5 January storm, which caused water levels to rise in the streams entering the harbour. The model was calibrated and validated for mean annual freshwater discharge. The heavy rain during the verification period would affect water levels in the rivers themselves, but river discharge effects on water level dissipate very quickly away from the river mouths, because the river volumes, even in flood, are very small compared to the tide and surge prism.

It is important to note that the model does not include waves, so cannot simulate the effects of wave setup and runup. Therefore, we expect the model to under predict total inundation at wave-exposed locations. An allowance for wave setup was included in the extreme inundation levels and mapping, and is explained in Section 7.

Wave setup and runup raise the water level at the coast. Wave setup describes an average raised elevation of sea level at the shoreline when breaking waves are present, which is a more continuous rise in sea level, albeit temporary during a storm. Wave runup is the maximum vertical extent of wave "up-rush" on a beach or structure above the instantaneous still-water or storm-tide level (that would occur without waves), and thus constitutes only fluctuations in water level relative to wave-setup, tidal and storm-surge time scales. Wave runup includes the wave-setup component. Wave setup is an integral component of the total water level that potentially could cause direct or near-continuous inundation of "green water" onto coastal land. The combined storm-tide plus wave setup level is therefore important for direct and quick-response coastal inundation. Wave runup tends to dissipate within a few metres of the coast and does not result in significant inundation over a broad surface, although it may cause inundation through wave overtopping of coastal defences with lower-elevation land behind.

The expected amount of wave setup and runup were estimated using the fetch and depth-limited wave formula of Young and Verhagen (1996), and the wave-setup and runup formulae of Stockdon et al. (2006). For the Otumoetai coastline (which is exposed to wind blowing over the central harbour region) these formulae were applied assuming a 34.5 m/s peak wind speed (as measured), blowing over a 3.5 km fetch of ~9 m deep water, with waves breaking on a beach with slope of 1:10. The empirical formulae estimate a wave setup of ~0.2 m and wave runup of ~0.45 m. Thus, we can expect observed inundation elevations to be about 0.2–0.4 m above those modelled for the storm-tide validation, at these wave-exposed sites. Other wave setup formulae (e.g., Stephens et al. (2011) describes several) provide similar results. Gibb (1997) observed debris elevations of ~0.3 m above gauge-measured sea levels in Tauranga Harbour during cyclones Fergus and Drena (Stephens 2017).

4.1 Description of the 5 January storm-tide event

On 4–5 January 2018, an intense low-pressure weather system moved onto NZ, coinciding with a King Tide, one of the very highest tides of the year. The very high tide combined with low air pressure and strong onshore winds, causing seawater to flood many low-lying areas of Tauranga Harbour.

Table 4-1 shows the total water level reached at BOPRC's permanent sea-level recorders and gives a breakdown of the different components of sea level. Alongside the very high tides, the background mean sea-level anomaly (MSLA) was also high, related to seasonal warming of the ocean. Due to SLR over the intervening years, MSL is also considerably higher (0.1–0.2 m) than in 1968 when ex-tropical cyclone *Gisele* last caused widespread flooding in the Harbour (de Lange and Gibb, 2000). Skew-surge is like storm-surge and is the difference between the measured total water level and the predicted height of the closest high tide—known as skew-surge because the highest total water level can occur before or after high tide (skewed in time).

Comparing the gauge measurements on 5 January 2018 with the extreme-value estimates from Table 8–6 of Stephens (2017), the levels reached fell somewhere between a 2–10% annual exceedance probability (AEP) at Tug Berth (Mount Maunganui), Omokoroa, Oruamatua, and at Tauranga near Sulphur Point. Therefore, the 5 January 2018 storm-tide had an AEP of ~3% (30-year return period). This compares with an estimated AEP of ~2% (50-year return period) for cyclone *Gisele* (Stephens, 2017). The measurements fell between 1–2% AEP at Hairini Bridge (Stephens, 2017), but comparison of model sensitivity tests suggests that the extreme-value distribution derived from the gauge record by Stephens (2017), might under-predict the magnitude of extreme storm-tides at Hairini Bridge.

Table 4-1: Components of storm-tide water levels measured on 5 January 2018 by permanent sea-level gauges TWL = total water level; MSL = MSL; Projected 2020 MSL from Stephens (2017); NTR = non-tidal residual; MSLA = mean sea-level anomaly obtained from a 30-day running average.

Water-level recorder	TWL (m MVD–53)	Projected 2020 MSL (m MVD–53)	TWL – MSL	Predicted high tide	NTR (includes MSL)	Skew-surge	MSLA	Skew-surge – MSLA
Moturiki	1.64	0.13	1.51	1.14	0.5	0.37	0.01	0.36
Tug Berth	1.64	0.1	1.54	1.09	0.55	0.45	0.09	0.36
Hairini Bridge	1.84	0.19	1.65	1.12	0.72	0.53	0.1	0.43
Oruamatua	1.97	0.2	1.77	1.18	0.79	0.59	0.23	0.36
Omokoroa	1.73	0.18	1.55	1.08	0.65	0.47	0.07	0.4

The model was validated against post-storm survey locations and elevation of the inland flood extent, which were collected by Tonkin and Taylor and the University of Waikato (Figure 4-1). At the data comparison locations Figure 4-1 (sites A – I), the survey data was averaged to produce an area-averaged inundation level, which is shown in the "measured" column of Table 4-2.

Figure 4-1: Tauranga Harbour January 2018 storm inundation survey sites. Red dots show sites surveyed by Tonkin and Taylor and the University of Waikato. Black dots with white halo show model comparison sites. Green dots show water-level recorder locations. The letters A–J describe site-specific inundation locations used for model validation (presented in Table 4-2).

4.2 How the model was forced

The model was forced using observed wind data and predicted tidal boundary conditions. We used wind data collected by Port of Tauranga at Tug Berth, A-Beacon, Tanker Berth, Crane 6, air pressure recorded by the University of Waikato, and water level data collected by BOPRC inside the harbour and by NIWA at Moturiki Island.

To generate the wind speed and direction boundary conditions, wind velocities recorded at Tug Berth, A-Beacon, Tanker Berth and Crane 6 were averaged to get a median wind speed, and then a 1-hour running average was applied to smooth the averaged wind speeds (Figure 4-2). Wind speed records are usually adjusted to a 10 m height assuming a logarithmic wind profile before use in models. We did not do this correction before averaging the wind speeds, because we did not know at what height the wind records were collected. In other words, we averaged the "raw" wind records. There is ≤ 12% difference in wind speed for anemometer heights 5–25 m. The validation results shown below indicate that the approximation used was sufficiently accurate.

The hydrodynamic model can't simulate the effects of topographic wind sheltering—it "assumes" that the winds are blowing over a flat surface. There are several hills in the Tauranga Harbour that would slow the wind, and reduce the simulated wind setup, in Waikareao Estuary for example. To increase the model accuracy, areas partially sheltered from north–northeasterly winds were identified using the Viewshed 2 ARC GIS tool. The Viewshed 2 tool was run for winds from the north, north-northeast and north-easterly (onshore) directions, to show wind-shadow zones (Figure 4-3). At the locations which were identified as partially-sheltered, in this instance Waikareao Estuary, Waimapu Estuary, southern side Matua, Te Puna Estuary, Matakana Point (Flax Point) and the entrance to Uretara Stream (Katikati), the wind speed was modified. MATLAB® was used to create spatially and temporally varying wind fields which are based on the winds measured at the Port of Tauranga gauge sites (Figure 4-2). For the areas that were identified as being sheltered from onshore winds, the wind speed was reduced. This decrease in wind speed was assumed to be spatially constant and was applied as a percent change in the total wind for each area. The drop in speed was determined through sensitivity testing and was guided using the analytical solution discussed below.

To calculate the wind velocity required to achieve the correct wind setup in the sheltered areas the Zuider Zee equation (Equation 4-1) was used to relate wind speed to wind setup. We then tested the results using the numerical model.

Surveys undertaken, indicate that during the storm the water level reached approximately 1.72 m at the northern end of the Waikareao Estuary and 1.79 m at the south end (see Table 4-2), a difference of 0.07 m.

Using Equation 4-1, we can calculate the wind speed required to generate the 0.07 m wind setup measured in the Waikareao Estuary. Given a fetch of 2.8 km an average depth plus the tide height is -0.74 m and Kappa (κ) is an empirical friction factor, which was set to 3.5×10^{-6} (Van Rinsum 2015). The winds during the 2018 storm moved from parallel to Waikareao Estuary (0°) to onshore (22.5°). For the evaluation we assume the winds were parallel. This equates to a wind speed of approximately ~7.5 m/s or <30% of measured wind at Tauranga Port.

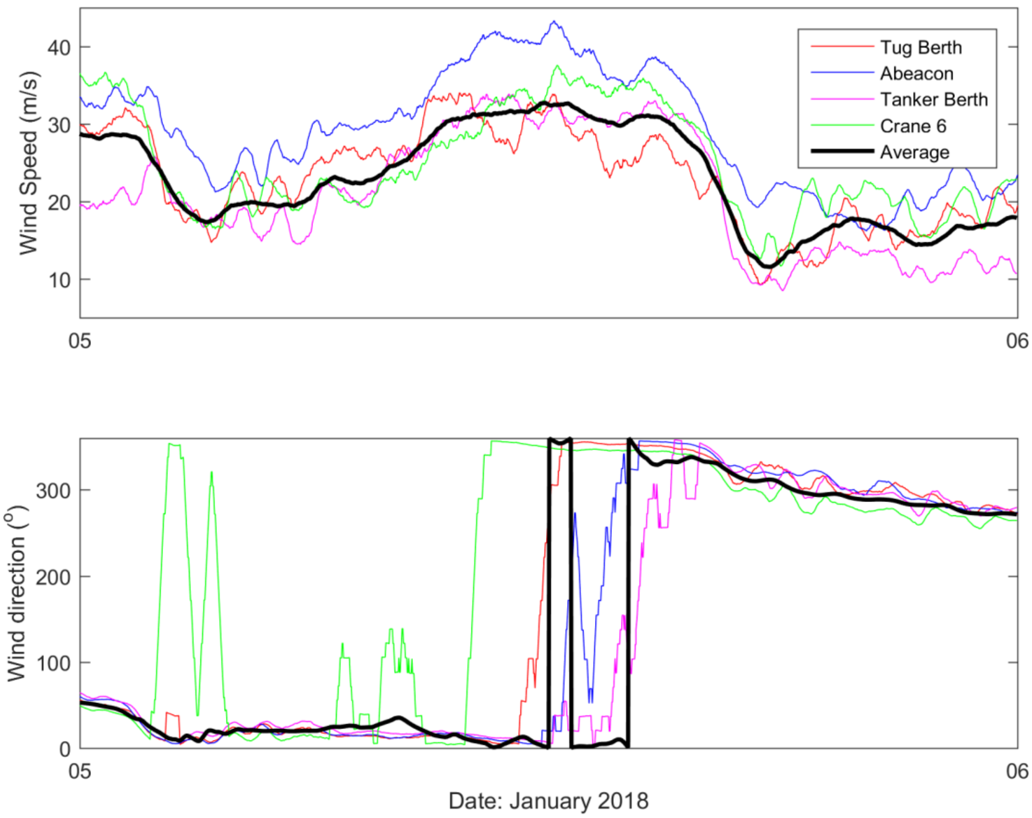

Figure 4-2: Wind speeds and directions recorded at Port of Tauranga weather stations on 5 January 2018. The bold line shows 1-hour running vector-average of the four sites, with peak wind speed of 32.7 m/s

Equation 4-1: Zuider Zee formula for wind setup.

$$u_{10} = \sqrt{\frac{gdW}{\kappa F cos\phi}}$$

For which:

u10 = wind velocity at 10-meter height	[ms^{-1}]
g = Gravity	[ms^{-2}]
κ = Friction constant	[-]
W = Wind setup	[m]
d = Water depth	[m]
F = Fetch	[m]
ϕ = Angle between land and wind	[-]

Sensitivity testing with the model in the Waikareao Estuary showed that reducing the wind speeds to be 30% of the original wind in sheltered areas produced a much better fit to the measured inundation extent than when the model was run with a constant high wind speed over the full domain. When the wind was held constant at 32.5 m/s, simulated water level at the south end of Waikareao Estuary was 2.15 m. A reduction in wind speed to 30% of the original saw water levels at the south end of Waikareao reduced to 1.81 m just slightly above the 1.78 m measured, so the wind-speed correction factor worked as intended. However, in the Waimapu estuary the 30% wind-speed reduction factor was too large, a better wind-speed reduction factor was found to be 60%, resulting in a good fit to observed water levels at Hairini Bridge. There wasn't sufficient data to calculate wind-speed reduction factors in other sheltered locations, so a uniform 50% reduction in wind speed was applied to the areas identified as sheltered including both Waikareao and Waimapu estuaries (Figure 4-3). Appling the uniform 50% reduction in wind-speeds saw water levels at the south end of Waikareao increase from the 30% level of 1.81 m to 1.9 m.

The model used the Smith and Banke (1975) wind stress formula with wind drag coefficients linearly varying between 0.00063 at 0 m/s and 0.00723 and 100 m/s.

Sensitivity testing showed that the model was under-representing the inverse-barometer (IB) effect when forced with air-pressure data collected at Omokoroa by the University of Waikato, probably due to the relatively small scale of the model domain compared to the scale of the weather system. We included IB in the simulation using Equation 4-2 to apply IB setup to the model boundary as an elevated water level, which is consistent with the observed shelf wave shown in weather forecasting models. Sensitivity testing showed that the elevated boundary propagated relatively uniformly, preserving the boundary elevation throughout the Harbour.

Equation 4-2: Equation for calculating inverse-barometer surge boundary. IB_{surge} = the inverse-barometer boundary (m); IB_{amp} = inverse-barometer amplitude (m); t = time (days); t_0 = time of inverse-barometer peak (days). N_{days} = time (days) between surge of magnitude IB_{amp}, and that of 1% × IB_{amp}, i.e., IB_{surge} × (t0 ± N_{days}) = 0.01 × IB_{amp}.

$$IB_{surge} = IB_{amp} \times sech^2[k(t - t_0)],\ k = \frac{3}{N_{days}}$$

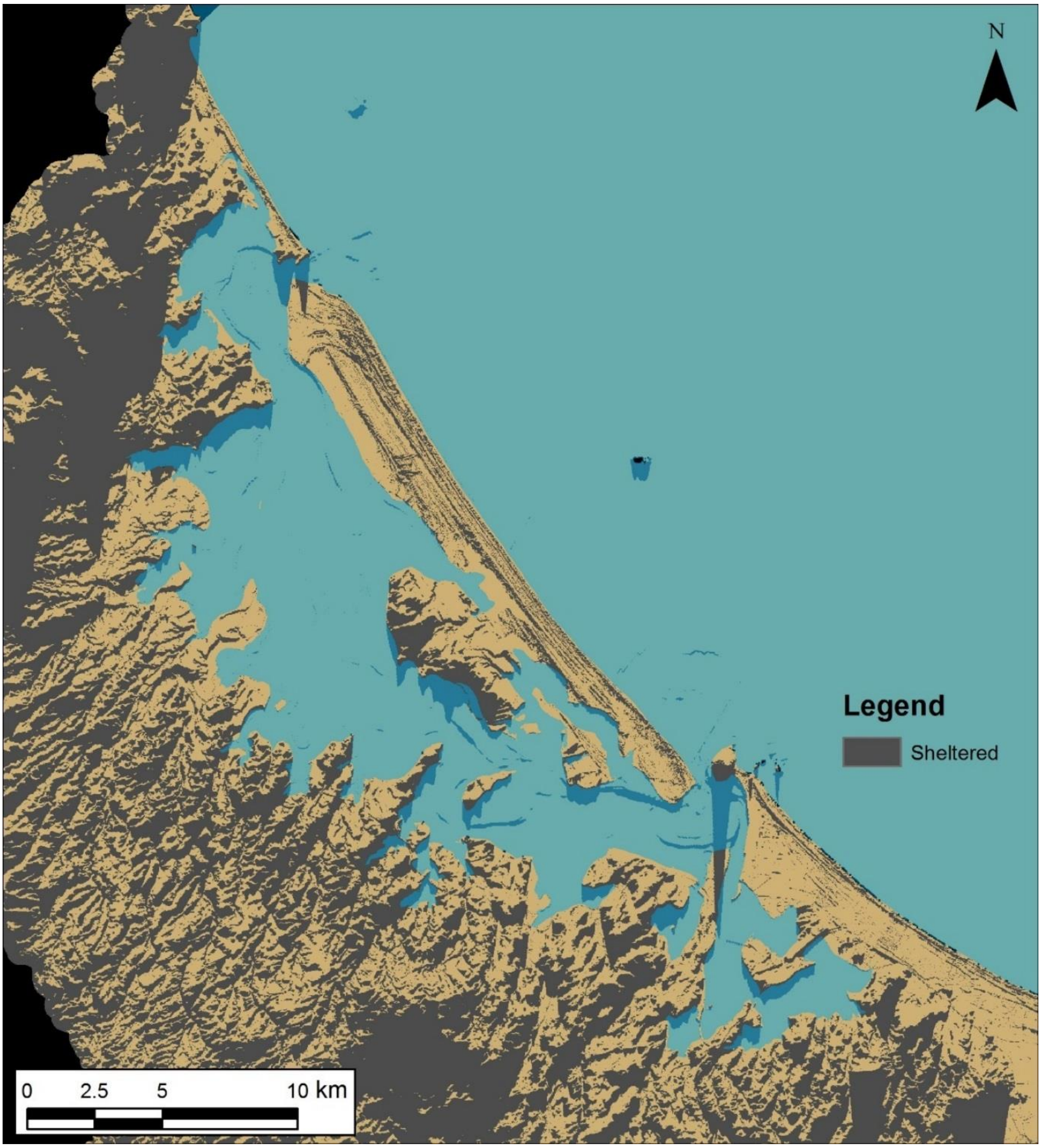

Figure 4-3: Example of the North wind shadowing. Using the Viewshed 2 ARC GIS tool locations sheltered from north, north-northeast and north-easterly (onshore) wind directions were identified.

4.3 Model validation

Figure 4-4 shows the modelled water levels during the 5 January 2018 storm-tide. Table 4-2 compares the modelled water level elevations to measured. Figure 4-5 – Figure 4-9 compare the location of the observed and modelled inundation, at sites A–E (Figure 4-1)—the sites shown are those for which water levels were surveyed post storm.

The modelled water levels at Omokoroa Golf course, Hairini Bridge (North), Maungatapu, Pahoia Beach, Sulphur point tide gauge and Tilby Point are all within 0.03 m of the measured values (Figure 4-4 and Table 4-2). Furthermore, the model reproduced the inundation extent and overland flow measured from the debris surveys at the Omokoroa Golf course and Tilby Point (Figure 4-5), which suggests that the overland bed roughness map used in the model (Figure 2-2) is giving good results over wide grassy flats.

In Rangataua Bay, where the Oruamatua sea-level recorder is located, the model appears to be predicting the inundation extent well (Figure 4-5), but under predicts the water level at Oruamatua tide gauge by 0.26 m (Figure 4-4). At this location the modelled showed wind to creates some set-down at the north-eastern end of Rangataua Bay around Oruamatua Point. The long-term Oruamatua gauge record shows that Rangataua Bay experiences periods where the water level is raised or lowered by several decimetres compared to the rest of Tauranga Harbour, possibly due to its narrow entrance and forced by seasonal wind stress (Stephens, 2017). On the 5 January 2018, the MSLA was +0.23 m (Table 4-1), which is similar to, and explains, the difference between the simulated and observed storm-tide elevations.

The model overpredicted water levels by ~0.11 m at the southern end of the Waikareao Estuary (Figure 4-4 and Table 4-2). This overprediction of the water level is also apparent in the inundation extent where the model inundation line is up to 20 m further inland than the surveyed debris. This is because we were deliberately allowed to model to over predict water levels by using the constant spatial reduction in wind speed as outlined in section 4.2.

The model validated well in locations sheltered from waves (Figure 4-5 – Figure 4-9). The largest differences between the survey and simulated inundation occurred at sites exposed to wave setup and runup; wave setup and runup were not included in the model. The model underpredicted the maximum water levels by 0.1–0.2 m on average at Otumoetai and up to 0.4 m at Pilot Bay when compared to the debris survey elevations. At Otumoetai, the modelled inundation extent differed from observed by less than 8 m on average, and up to 26 m at worst Figure 4-6.

An allowance for wave setup is described in Section 7.

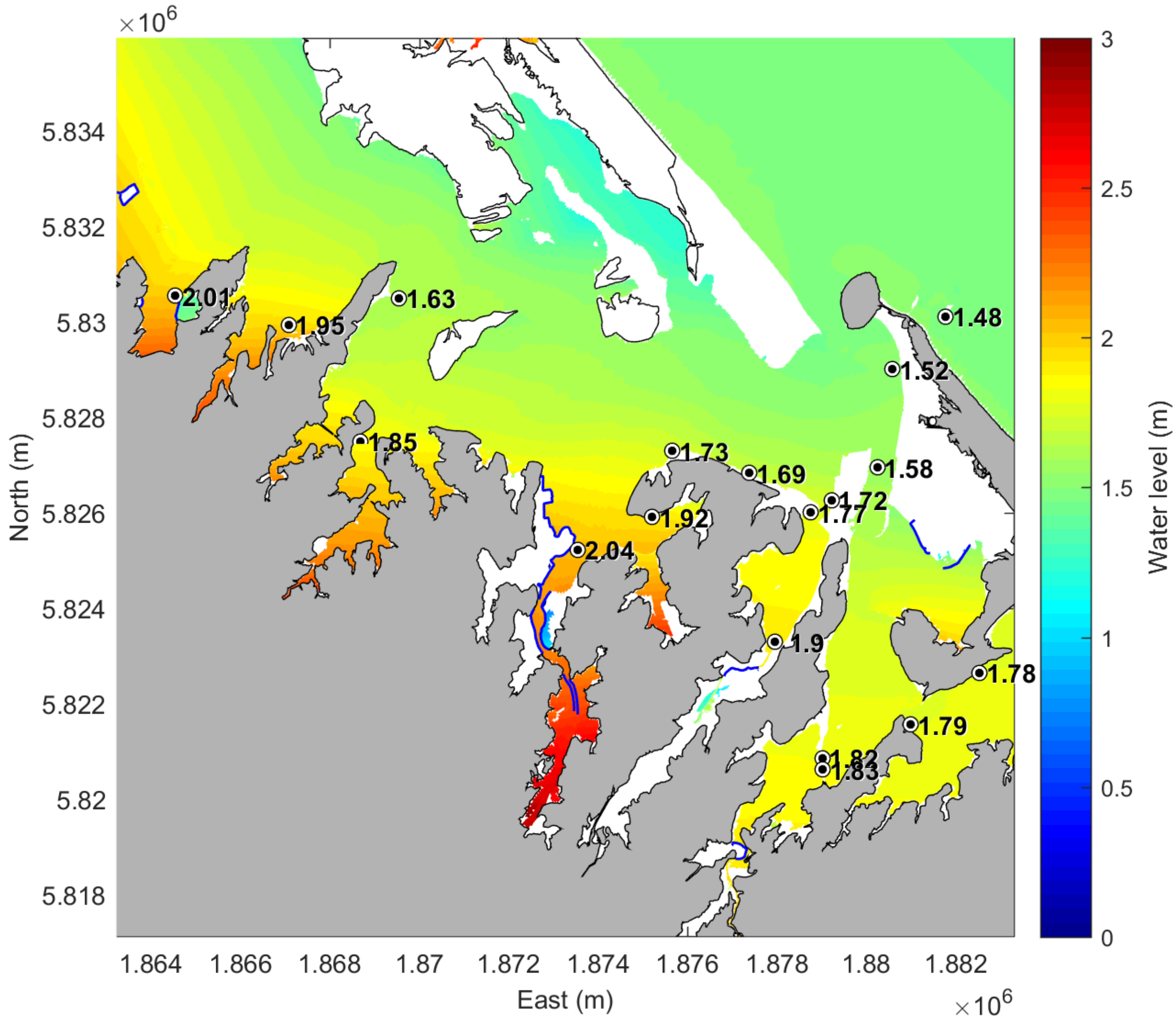

Figure 4-4: 5 January 2018 modelled water level elevation. The colour scale shows modelled water level elevation (where white is dry area within the 5 m contour), while the numbers show modelled water level location at selected sites for comparison with post-storm surveys or permanent water level recorders, see Figure 4-1. The grey outline represents the extent of the model and the 5 m MVD–53 contour and blue lines represent the stop banks used in the model. Water levels are specified relative to MVD–53.

Table 4-2: Measured and modelled water levels from the validation simulation of the 5 January 2018 storm. The post-storm flood elevation survey data are in normal font, while the permanent sea-level recorder data are bolded. Sites A–J are marked in Figure 4-1. The elevation 1.93 m at Pilot Bay was supplied by Peter Blackwood. Elevations are relative to MVD–53.

Location	Measurement type	Measured (averaged at location) [m]	Modelled maximum water level [m]
Hariri Bridge South (Site A)	Survey data	2.05	1.83
Hariri Bridge North (Site A)	Survey data	1.8	1.82
Hariri tide gauge	**Water level recorder**	**1.84**	**1.83**
Oruamatua tide gauge	**Water level recorder**	**1.95**	**1.78**
Maungatapu (Site B)	Survey data	1.75	1.79
Sulphur Point tide gauge	**Water level recorder**	**1.7**	**1.72**
Otumoetai (Site C)	Survey data	1.95	1.69
Tilby Point (Site D)	Survey data	1.75	1.73
South Waikareao Estuary (Site E)	Survey data	1.79	1.9
Omokoroa Golf Course (Site F)	Survey data	1.93	1.94
Omokoroa tide gauge	**Water level recorder**	**1.73**	**1.63**
North Waikareao Estuary (Site G)	Survey data	1.72	1.77
Te Puna Estuary entrance (Site K)	Survey data	1.91	1.85
Pilot Bay (Site H)	Survey data	1.93	1.52
Pahoia Beach (Site I)	Survey data	1.98	2.01
Wairoa River (Site J)	Survey data	1.88	2.2

Figure 4-5: Model validation for the horizontal extent of inundation during 5 January 2018 storm-tide, at sites A (Hairini Bridge) and B (Maungatapu). The light blue line represents the modelled predict inundation extent and the red dots are measured inundation heights and extents.

Figure 4-6: Model validation for the horizontal extent of inundation during 5 January 2018 storm-tide, at sites C (Otumoetai) and D (Tilby Point). The light blue line represents the modelled predict inundation extent and the red dots are measured inundation heights and extents.

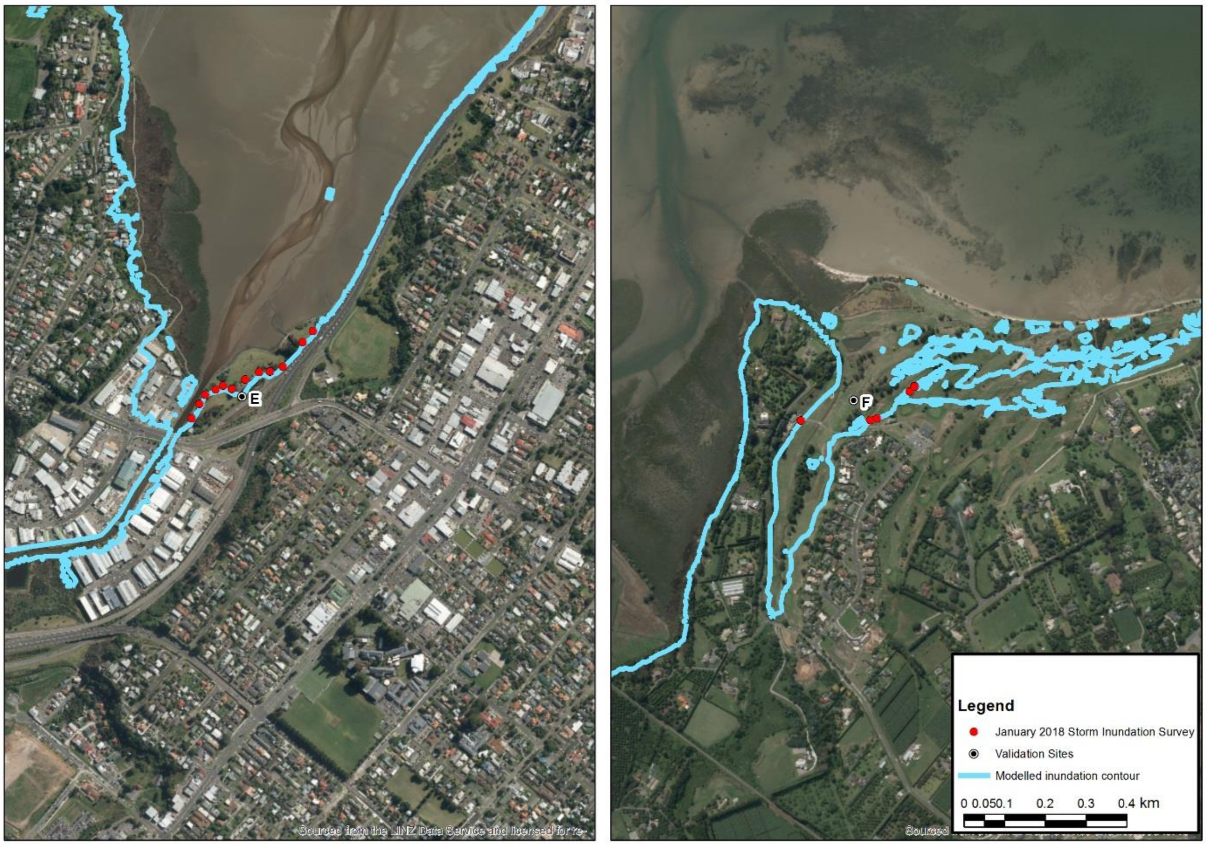

Figure 4-7: Model validation for the horizontal extent of inundation during 5 January 2018 storm-tide, at sites E (South Waikareao Estuary) and F (Omokoroa Golf Course). The light blue line represents the modelled predict inundation extent and the red dots are measured inundation heights and extents.

Figure 4-8: Model validation for the horizontal extent of inundation during 5 January 2018 storm-tide, at sites G (North Waikareao Estuary) and H (Pilot Bay). The light blue line represents the modelled predict inundation extent and the red dots are measured inundation heights and extents.

Figure 4-9: Model validation for the horizontal extent of inundation during 5 January 2018 storm-tide, at sites I (Waikareao Estuary) and J (Wairoa River). The light blue line represents the modelled predict inundation extent and the red dots are measured inundation heights and extents.

5 Present-day storm-tide hazard in Tauranga Harbour

We simulated storm-tides associated with 2%, 1% and 0.2% AEP, at present-day MSL. Table 5-1 shows the model forcing conditions used for each of the simulations. The model forcing conditions were based on trying to reproduce the extreme sea-level distributions shown in Figure 8-4 and Tables 8-5 and 8-6 of Stephens (2017) (reproduced in Appendix G), but recognising the uncertainty associated with those extreme sea-level distributions due to reliance on sparse cyclone observations.

The 5 January 2018 validation simulation used wind directions as measured during the storm, whereas the 2%, 1% and 0.2% AEP storm-tide scenario simulations used a constant wind from the north-northeast. This leads to some differences in the spatial pattern of surge response between the 5 January 2018 simulation and the other simulations—the results of all simulations are compared side-by-side in this Section. For demonstration purposes, this Section only shows results at sites areas west of Pahoia Beach where runup validation levels were available for the 5 January 2018 event. However, sea-level elevations were extracted throughout the whole harbour for the present-day MHWS–7, 2%, 1% and 0.2% AEP storm-tide scenarios, and for various SLR scenarios, and are reported in Section 6 and in Table D-1. The coastal inundation maps supplied to the client as digital GIS layers include the whole harbour.

MHWS–7 refers to the height of the tide exceeded only by the highest 7% of all high tides, which is about the highest tide every fortnight (Glossary Section 11). The line of MHWS provides legal definition of the land-sea boundary. For this study, the line of future MHWS–7, after SLR, will be used as a shoreline proxy for the coastal erosion study being undertaken by Tonkin and Taylor Ltd.

Table 5-2 shows the simulated water-level elevations at the output locations A–J in Figure 4-1, and simulated water levels throughout the southern harbour are shown in Figure 5-1 – Figure 5-3. The storm-tide elevations in Table 5-2 do not include wave setup or runup effects. Table 5-3 shows approximate wind-driven surge (or wind setup) magnitude inside the harbour at locations A–J. The average wind setup was approximately 0.45, 0.56 and 1.0 m respectively for the 2%, 1% and 0.2% AEP scenarios, and reached up to 1.5 m at Pahoia (I) in the 0.2% AEP scenario.

Figure 5-4 – Figure 5-9 show the simulated water level along several transects throughout the harbour, for the extreme sea-level at present-day MSL scenarios driven by north-northeast winds. Strong winds blowing along the axis of the Harbour can set down the water level adjacent to lee shores (e.g., Figure 5-9), but pile water up against exposed shores, and force water up into the narrow upper-harbour arms to reach very high elevations. Very high wind setups were simulated on the northern side of Omokoroa Peninsula, at the golf course and at Pahoia; these locations have been observed to respond strongly to wind in instrument records (Willem de Lange, *pers. comm.*) during historical ex-tropical cyclones (Gibb, 1997), and on 5 January 2018. The northern harbour has a relatively long fetch and is relatively shallow, making it highly responsive to wind setup. The along-transect response of the harbour depends on the alignment of the transect relative to the predominant wind direction, hence transects K and T (Figure 5-4) were highly responsive to the north-northeast winds. For production of storm-tide inundation maps, we simulated wind directions from NNE and SE and extracted the highest elevation water level throughout the harbour.

This paragraph, reproduced from (de Lange & Gibb 2000), gives observations from historical cyclones for comparison with the model simulations. "Gibb (1997) determined maximum observed sea levels of 2.3–2.5 m above MVD–53 associated with cyclones on 2 February 1936, 6–8 March 1954, and 9–10 April 1968 (Cyclone Gisele). With respect to the predicted tide elevations at the time, the maximum potential storm surges, generated by the three events were c. 1.1–1.7 m (Gibb 1997). Both the 1936 and 1968 cyclones occurred during neap tides and the 1954 event during spring tides (Gibb 1997). Had the 1936 and 1968 events coincided with spring tides, maximum observed sea levels would have been closer to 3 m. Such events are characterised by central barometric pressures down to 960–980 hPa and sustained winds of 50–80 knots which are most hazardous when they veer clockwise from east to west (Gibb 1997)".

The total water levels simulated for the 0.2% AEP scenario are close to 3 m in many locations, and above 3 m in places, in keeping with Gibb's theory of what would have occurred if the 1936 and 1968 cyclones had coincided with a spring tide. Central barometric pressures of 960–980 hPa are equivalent to inverse barometer of 0.42–0.26 m assuming an IB factor of 0.8 (which is between a factor of 1 for open ocean conditions, and average of 0.658 at Moturiki, Goring (1995)). Sustained winds of 50–80 knots are equivalently 26–41 m/s. These wind speeds and inverse-barometer are like those used in our extreme storm-tide scenarios (Table 6-1).

Table D-1 provides the modelled extreme storm-tide sea levels at sites throughout Tauranga Harbour, for present-day MSL and SLR scenarios. At present-day MSL, the minimum, median and maximum 1% AEP storm-tide elevation within the harbour were predicted as 1.88, 2.25 and 2.81 m MVD–53 respectively. The median and maximum difference between 1% and 2% AEP storm-tides at present-day MSL were 0.15 and 0.17 m respectively, and between 0.2% and 1% AEP storm-tides were 0.42 and 0.72 m respectively.

Table 5-1: Model boundary conditions used for the 5 January 2018 validation, and 2%, 1% and 0.2% AEP storm-tide simulations at present-day MSL. The annual exceedance probabilities (AEP) referred to in the table represent the AEP that the simulated model scenarios were intended to represent; as opposed to a statistical extreme-value model fitted to measured data.

AEP	MSL (m MVD–53)	MSLA (m)	High-tide amplitude (m)	Inverse barometer at offshore boundary (m)	Wind speed (m/s)
3% (5 January 2018)	0.13	0.1	1.1	0.20	32.5
2%	0.13	0.1	1.1	0.33	30
1%	0.13	0.1	1.1	0.4	34.5
0.2%	0.13	0.1	1.1	0.4	42

Table 5-2: Modelled storm-tide elevations at present-day (2020) MSL. Site locations shown in Figure 4-1. MSL was set to 0.13 m MVD–53 as projected for the year 2020 (Stephens, 2017). The storm-tide elevations in this table do not include allowance for wave setup or runup. The annual exceedance probabilities (AEP) referred to in the table represent the AEP that the simulated model scenarios were intended to represent; as opposed to a statistical extreme-value model fitted to measured data.

Location	3% AEP (5 January 2018)	2% AEP (Figure 5-1)	1% AEP (Figure 5-2)	0.2% AEP (Figure 5-3)
Hariri Bridge South (Site A)	1.83	2.13	2.3	2.74
Hariri Bridge North (Site A)	1.82	2.13	2.3	2.75
Hariri tide gauge	1.83	2.13	2.3	2.75
Oruamatua tide gauge	1.78	2.09	2.26	2.69
Maungatapu (Site B)	1.79	2.1	2.26	2.7
Sulphur Point tide gauge	1.72	2.02	2.18	2.58
Otumoetai (Site C)	1.69	2.01	2.18	2.58
Tilby Point (Site D)	1.73	2	2.19	2.58
South Waikareao Estuary (Site E)	1.9	2.16	2.32	2.78
Omokoroa Golf Course (Site F)	1.94	2.31	2.52	3.04

Location	3% AEP (5 January 2018)	2% AEP (Figure 5-1)	1% AEP (Figure 5-2)	0.2% AEP (Figure 5-3)
Omokoroa tide gauge	1.63	2.05	2.24	2.63
North Waikareao Estuary (Site G)	1.77	2.08	2.24	2.67
Te Puna Estuary entrance	1.85	2.23	2.47	2.99
Pilot Bay (Site H)	1.52	1.84	1.96	2.24
Pahoia Beach (Site I)	2.01	2.43	2.64	3.24

Table 5-3: Wind-driven storm-surge (wind setup) elevations. Wind setup elevations are approximate, and were derived by subtracting the MSL + MSLA + high tide + inverse barometer values shown in Table 5-1. Site locations shown in Figure 4-1. The annual exceedance probabilities (AEP) referred to in the table represent the AEP that the simulated model scenarios were intended to represent; as opposed to a statistical extreme-value model fitted to measured data.

Location	3% AEP (5 January 2018)	2% AEP (Figure 5-1)	1% AEP (Figure 5-2)	0.2% AEP (Figure 5-3)
Hariri Bridge South (Site A)	0.3	0.47	0.57	1.01
Hariri Bridge North (Site A)	0.29	0.47	0.57	1.02
Hariri tide gauge	0.3	0.47	0.57	1.02
Oruamatua tide gauge	0.25	0.43	0.53	0.96
Maungatapu (Site B)	0.26	0.44	0.53	0.97
Sulphur Point tide gauge	0.19	0.36	0.45	0.85
Otumoetai (Site C)	0.16	0.35	0.45	0.85
Tilby Point (Site D)	0.2	0.34	0.46	0.85
South Waikareao Estuary (Site E)	0.37	0.5	0.59	1.05
Omokoroa Golf Course (Site F)	0.41	0.65	0.79	1.31
Omokoroa tide gauge	0.1	0.39	0.51	0.9
North Waikareao Estuary (Site G)	0.24	0.42	0.51	0.94
Te Puna Estuary entrance	0.32	0.57	0.74	1.26
Pilot Bay (Site H)	-0.01	0.18	0.23	0.51
Pahoia Beach (Site I)	0.48	0.77	0.91	1.51

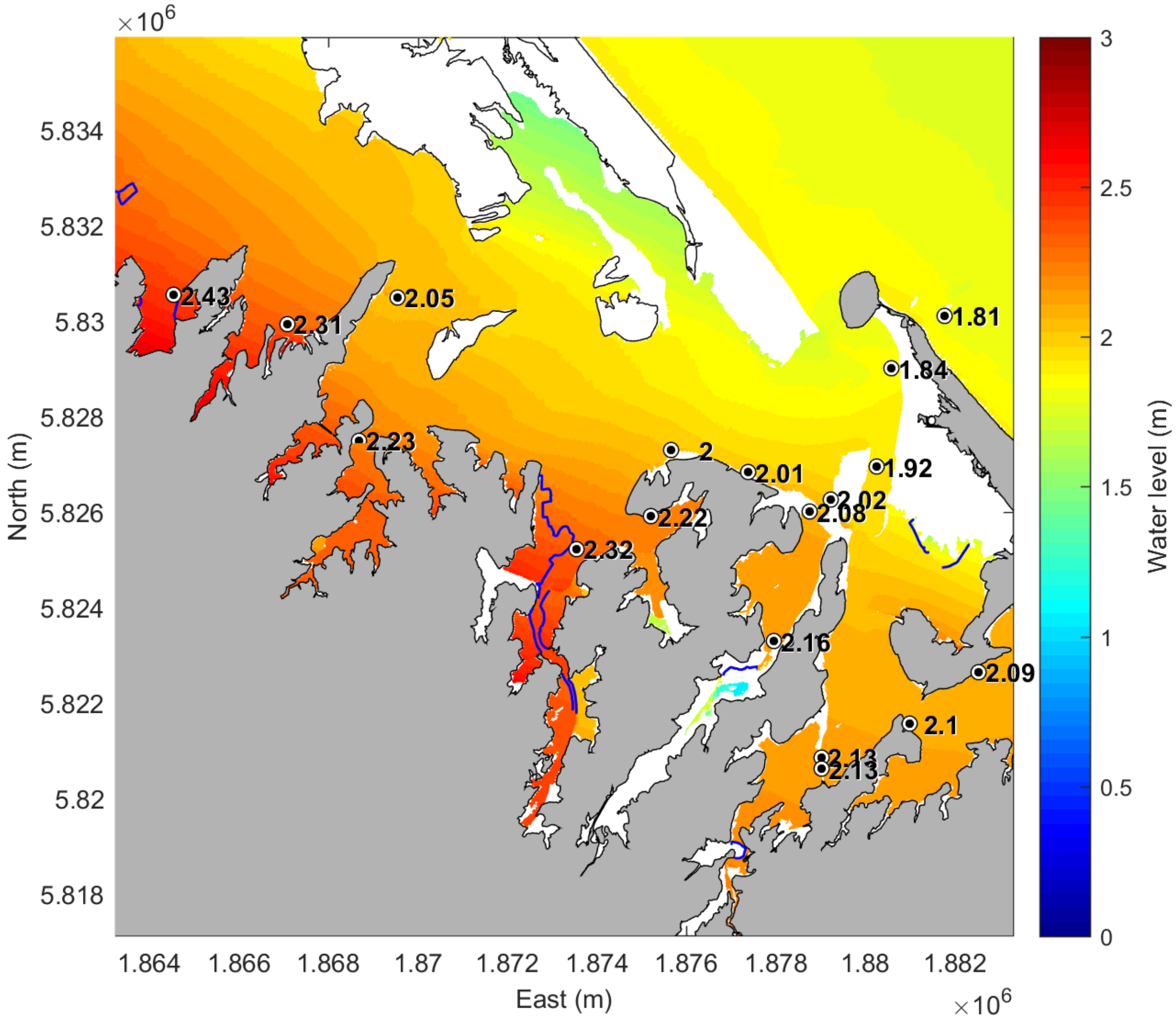

Figure 5-1: Modelled water-level elevations during a 2% AEP storm-tide at present-day MSL. The colour scale shows modelled water level elevation (where white is dry area within the 5 m contour). The grey outline represents the extent of the model and the 5 m MVD–53 contour and blue lines represent the stop banks used in the model. Water levels are specified relative to MVD–53. MSL was set to 0.13 m MVD–53 as projected for the year 2020 (Stephens, 2017). Simulation included a 1.1 m high-tide elevation, 0.1 m MSLA, 0.33 m inverse-barometer and wind speed that peaked at 30 m/s from north-northeast (22.5°) in direction.

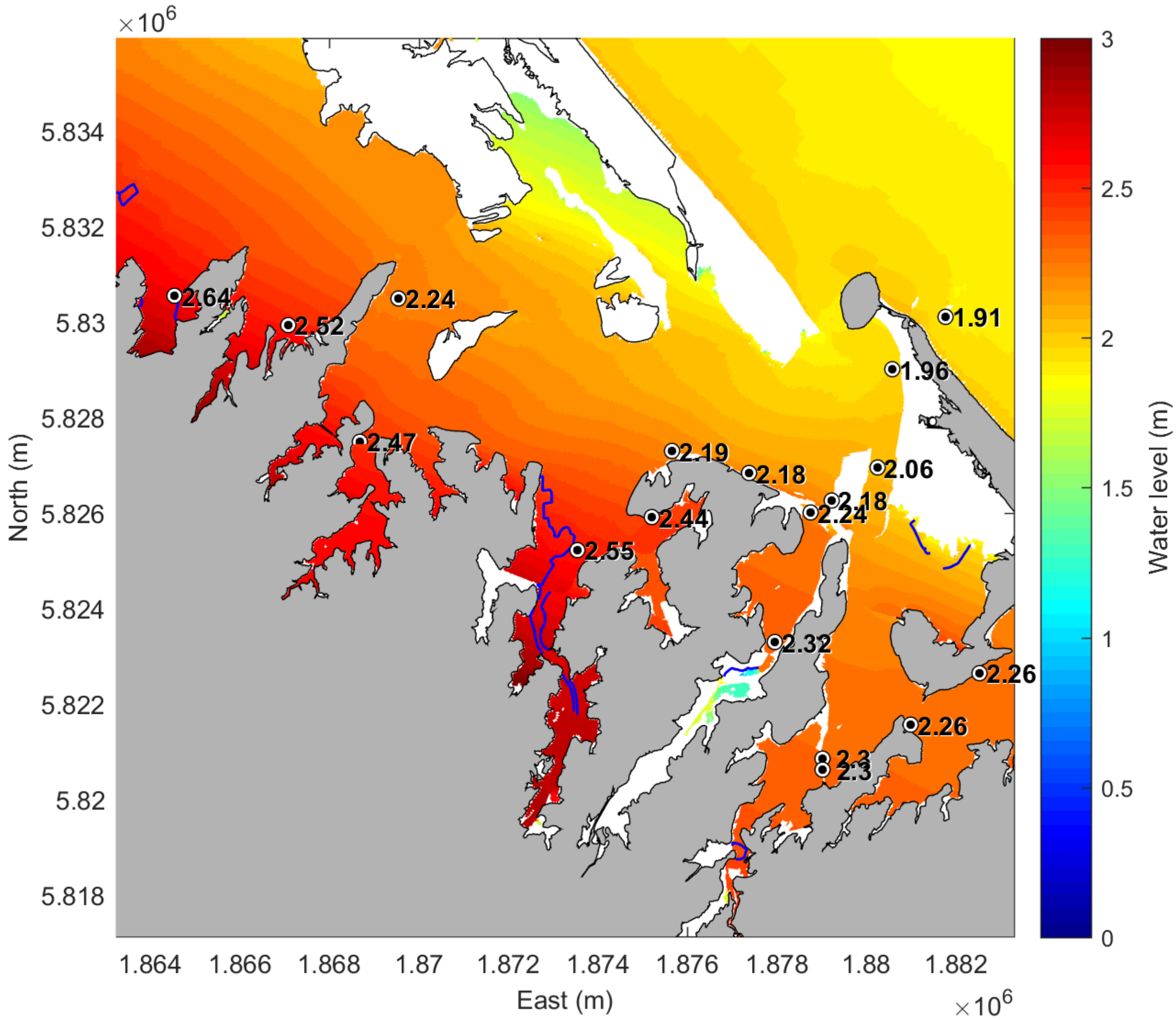

Figure 5-2: Modelled water-level elevations during a 1% AEP storm-tide at present-day MSL. The colour scale shows modelled water level elevation (where white is dry area within the 5 m contour). The grey outline represents the extent of the model and the 5 m MVD–53 contour and blue lines represent the stop banks used in the model. Water levels are specified relative to MVD–53. MSL was set to 0.13 m MVD–53 as projected for the year 2020 (Stephens, 2017). Simulation included a 1.1 m high-tide elevation, 0.1 m MSLA, 0.4 m inverse-barometer and wind speed that peaked at 34.5 m/s from north-northeast (22.5°) in direction.

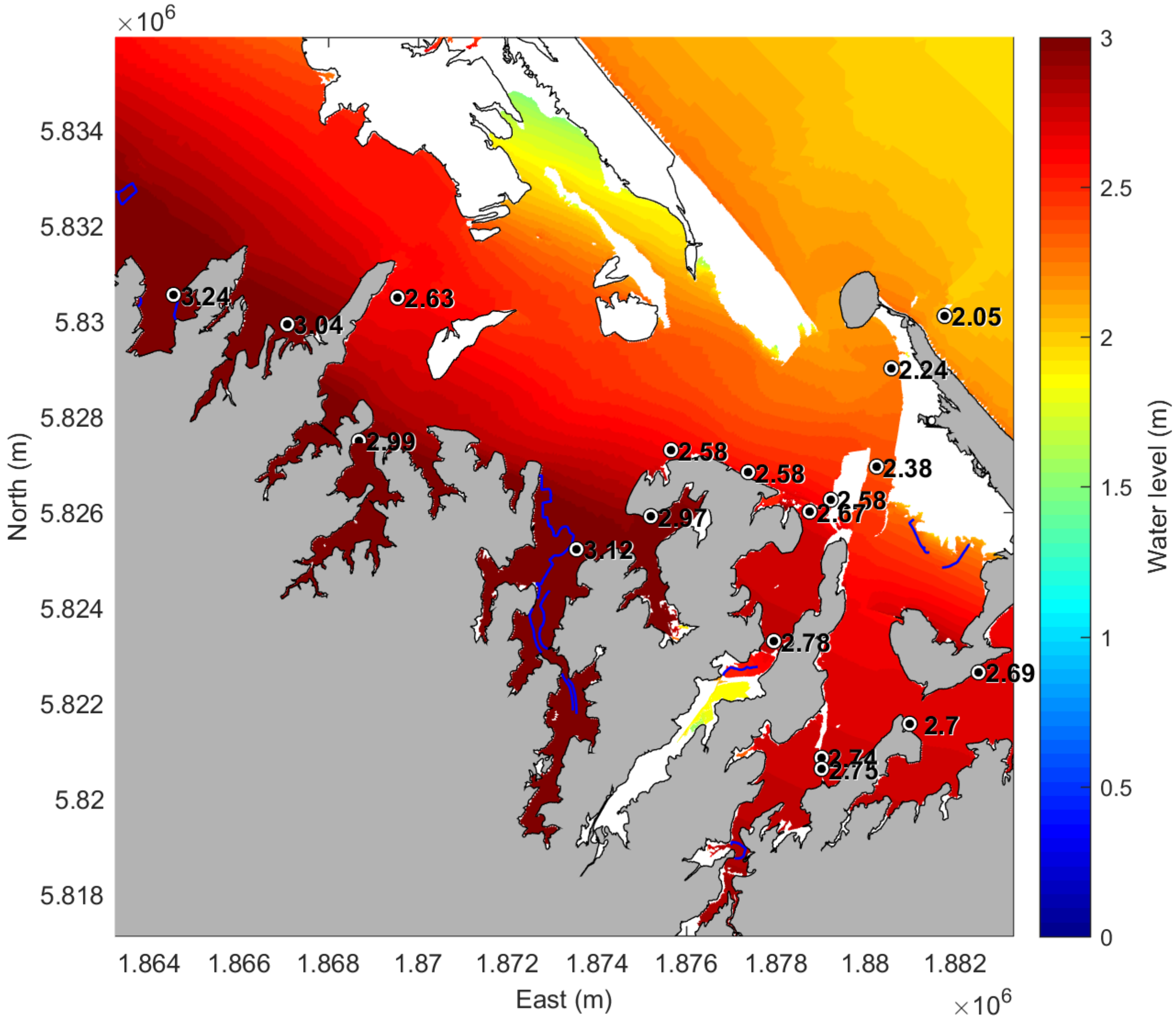

Figure 5-3: Modelled water-level elevations during a 0.2% AEP storm-tide at present-day MSL. The colour scale shows modelled water level elevation (where white is dry area within the 5 m contour). The grey outline represents the extent of the model and the 5 m MVD–53 contour and blue lines represent the stop banks used in the model. Water levels are specified relative to MVD–53. MSL was set to 0.13 m MVD–53 as projected for the year 2020 (Stephens, 2017). Simulation included a 1.1 m high-tide elevation, 0.1 m MSLA, 0.4 m inverse-barometer and wind speed that peaked at 42 m/s from north-northeast (22.5°) in direction.

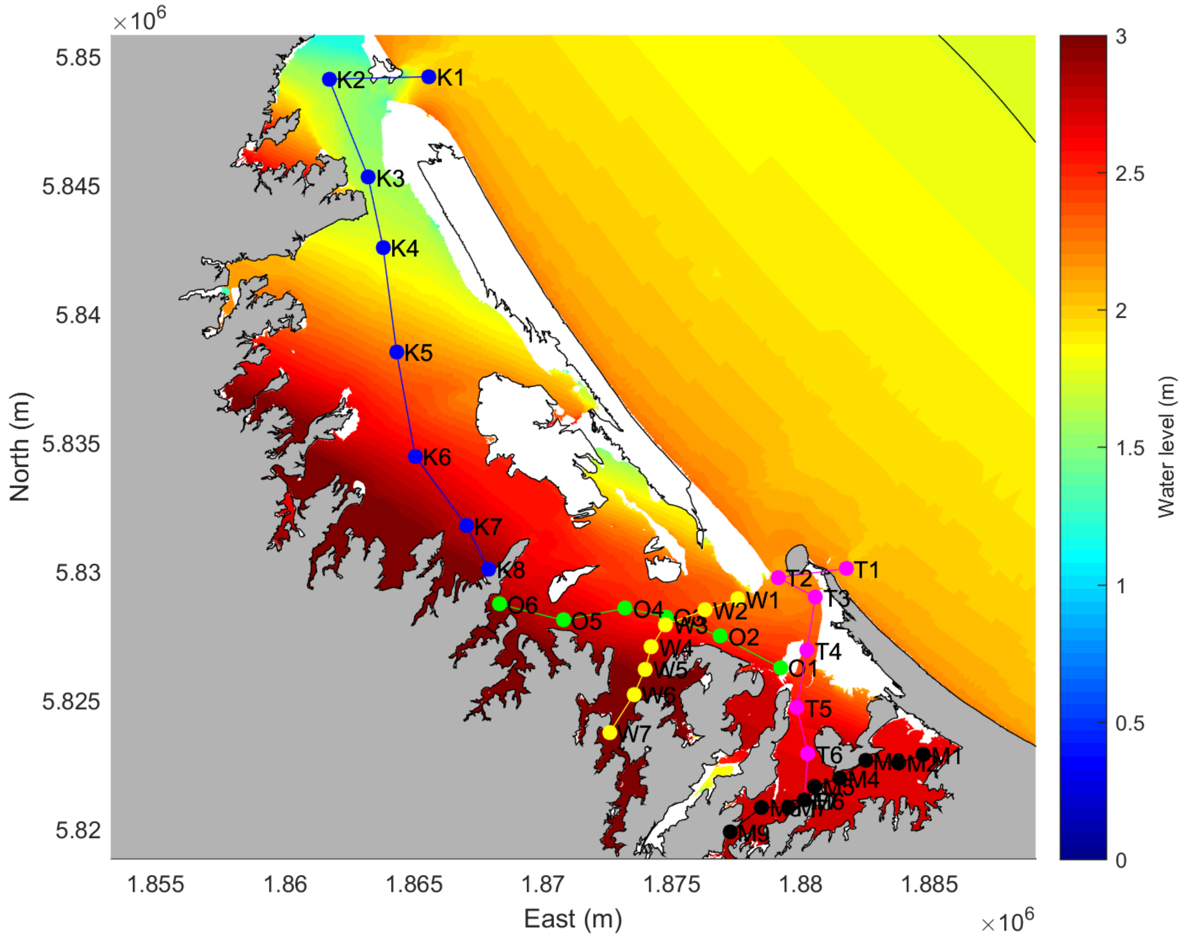

Figure 5-4: Transects for extraction of storm-tide elevation. The colour scale shows modelled water level elevation (where white is dry area within the 5 m contour). The grey outline represents the extent of the model and the 5 m MVD–53 contour and blue lines represent the stop banks used in the model. Water levels are specified relative to MVD–53. Coloured lines represent the data extraction transects K (Blue), O (Green), W (Yellow), T (Pink) and M (Black). Transects superimposed on modelled water-level elevations during a 0.2 % AEP storm-tide at present-day MSL.

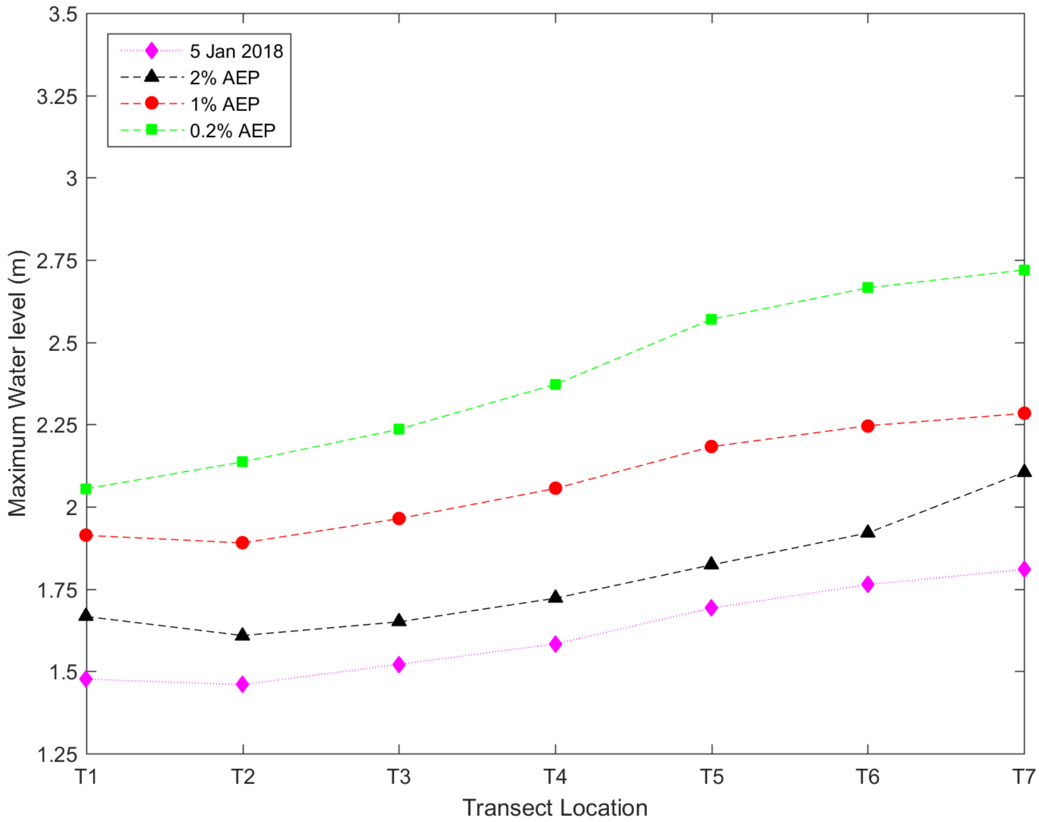

Figure 5-5: Maximum water elevations extracted from transect "T". Transect T runs from north (Tauranga Harbour entrance) to south (Maungatapu), Figure 5-4.

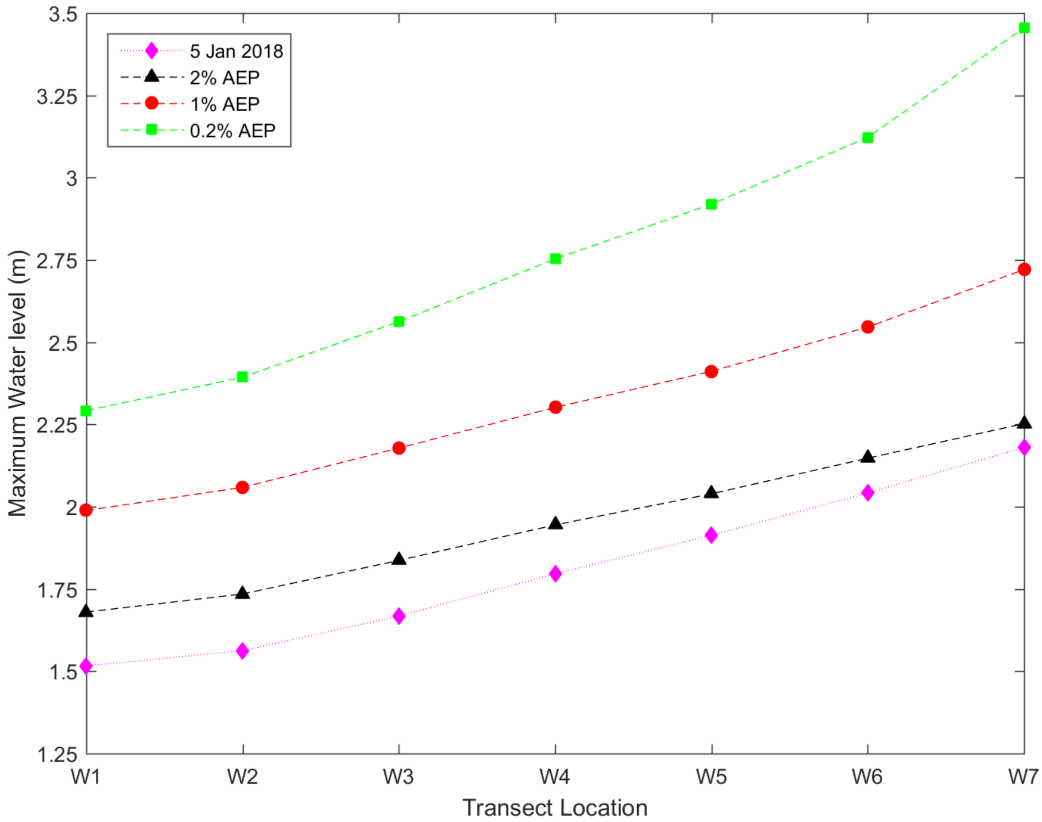

Figure 5-6: Maximum water elevations extracted from transect "W". Transect W runs from northeast (Matakana Island) to southwest (Wairoa River inlet), Figure 5-4.

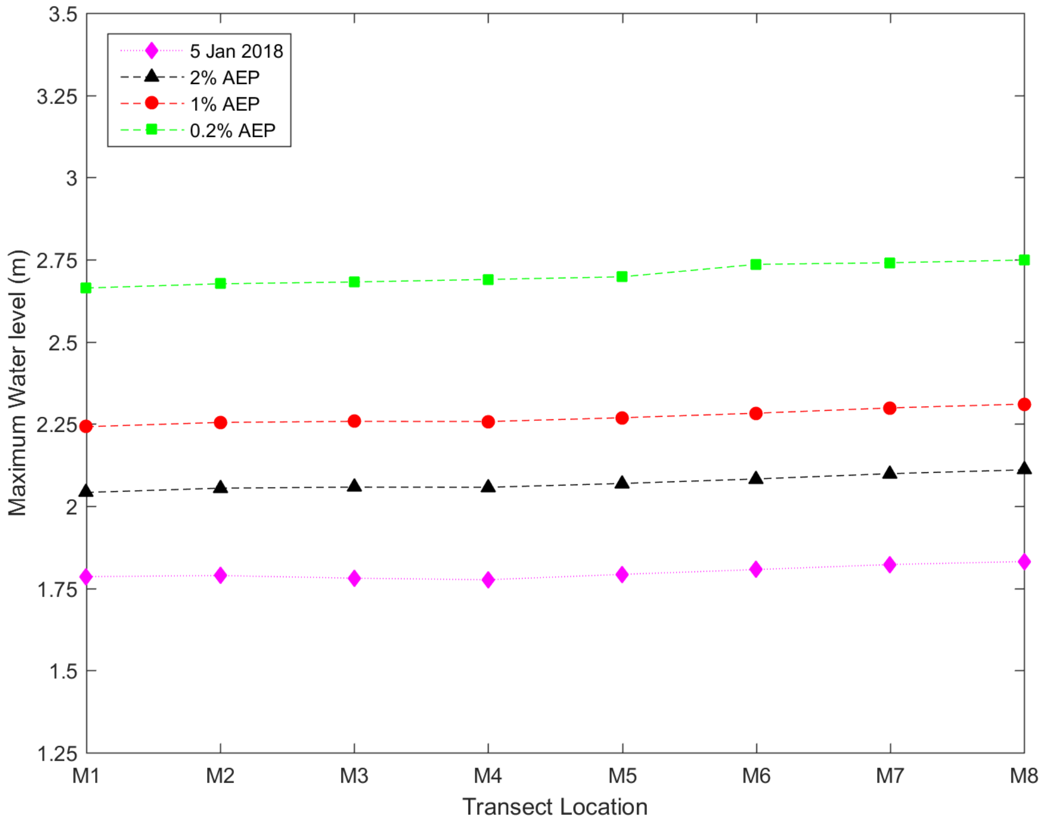

Figure 5-7: Maximum water elevations extracted from transect "M". Transect M runs from west (Rangataua Bay) to east (Waimapu Estuary), Figure 5-4.

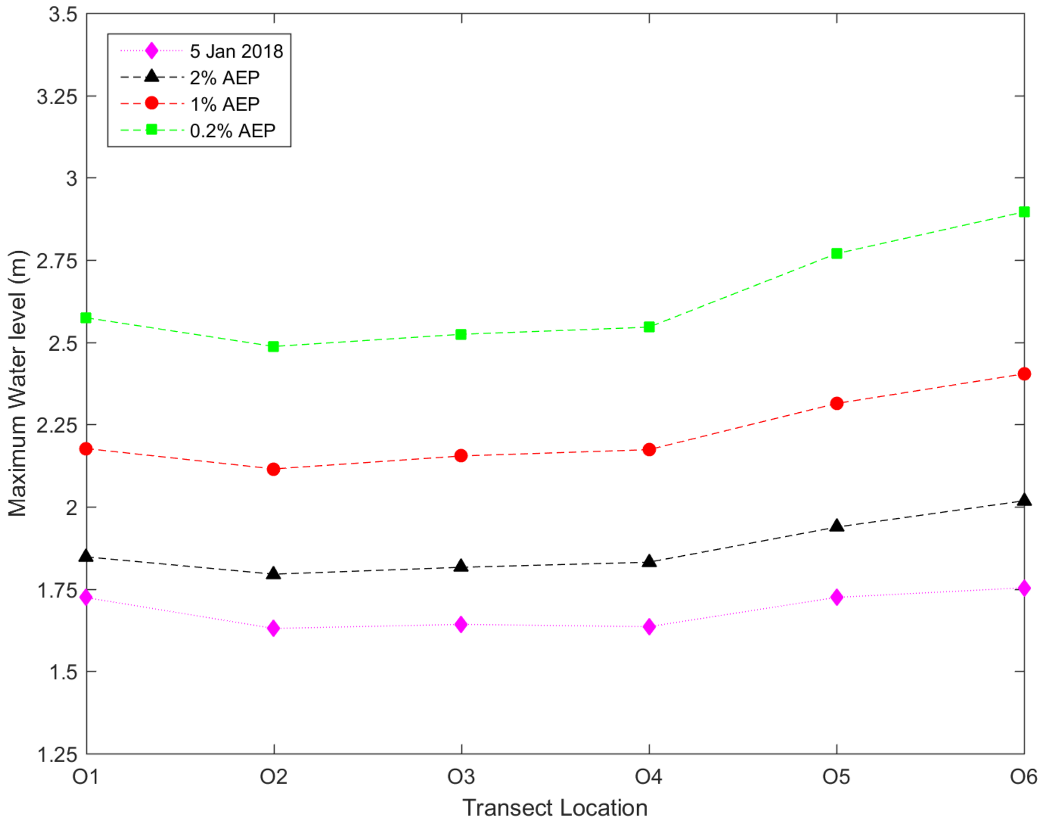

Figure 5-8: Maximum water elevations extracted from transect "O". Transect O runs from east (Sulphur Point) to west (Omokoroa), Figure 5-4.

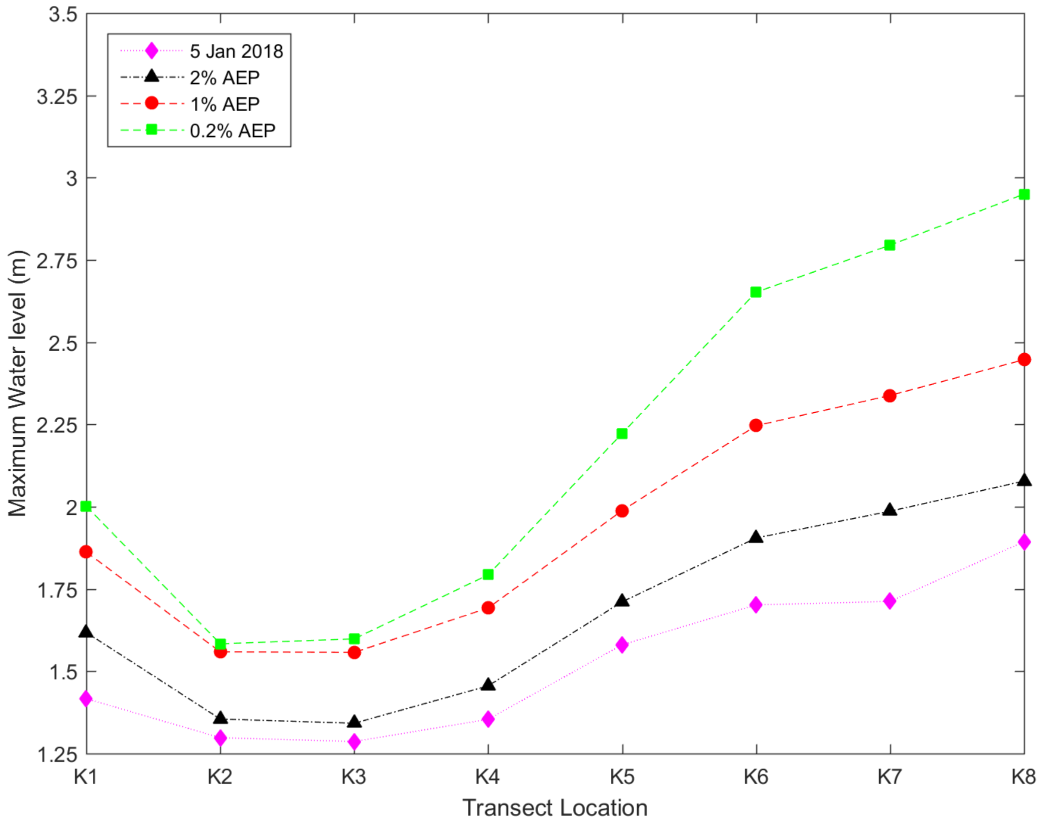

Figure 5-9: Maximum water elevations extracted from transect "K". Transect K runs from northwest (Katikati Entrance) to southeast (Omokoroa), Figure 5-4.

6 Impacts from SLR

6.1 SLR scenarios

Table 6-1 shows the model scenarios that were run. SLR are specified relative to MVD–53. 0.13 m is the projected MSL at Moturiki island in 2020 (Stephens 2017), which we refer to as "present-day" MSL. 0.13 m is the SLR that has occurred since the Moturiki MSL datum was established, based on 4 years of sea-level measurements from Feb 1949 to Dec 1952 (Hannah & Bell 2012). The results of the present-day simulations were presented in Section 5. This Section (6) reports on the SLR scenarios.

The upper three SLR scenarios of 0.8 m, 1.25 m and 1.6 m are based on Table 6-2 of Stephens (2017) for a 2130 timeframe. These three scenarios correlate to the RCP 4.5 median, RCP 8.5 median and RCP8.5 H^{+} (83rd percentile) projections respectively as set out in the MfE (2017) guidance for a 2130 timeframe. The use of other scenarios of 0.2, 0.4 and 0.6 m, is consistent with the recommended guidance to test adaptation plans against a range of SLR increments (MfE 2017).

Table 6-1: Model output scenarios. 0.13 m is the projected MSL at Moturiki island in 2020 (Stephens 2017), and represents "present day".

Likelihood (present day)	SLR scenario relative to MVD–53 (m)
0.2% AEP (500-year ARI)	0.13, 1.25, 1.6
1% AEP (100-year ARI)	0.13, 0.2, 0.4, 0.6, 0.8, 1.25, 1.6
2% AEP (50-year ARI)	0.13, 1.25
MHWS–7 (Occurs approximately once per fortnight)	0.13, 0.4, 0.6 0.8, 1.25, 1.6

Table 6-2: SLR projections (metres above MVD–53) in 2070 and 2130 for the Bay of Plenty region. Reproduced from Stephens (2017).

Year	NZ RCP2.6 *M* (median)	NZ RCP4.5 *M* (median)	NZ RCP8.5 *M* (median)	NZ RCP8.5 H^{+} (83rd percentile)
1986–2005	0.07	0.07	0.07	0.07
2070	0.39	0.43	0.52	0.68
2130	0.67	0.81	1.25	1.59

6.2 Simulated inundation from SLR

Here we report how the calibrated and validated Tauranga Harbour model was used to estimate the inundation hazard from extreme storm-tides and SLR in and around Tauranga Harbour. Table 6-1 outlines 18 scenarios that were modelled for this study. Scenarios 1–6 represent MHWS–7 + SLR and scenarios 7–18 represent extreme storm-tides + SLR (Table 6-3).

All stopbanks owned by BOPRC, TCC and WBOPDC and those that could be clearly identified through aerial photo analysis were incorporated into the hydrodynamic model for the simulations at present-day MSL. Stop banks that are not maintained by TCC, WBOPDC or BOPRC were removed from the simulations that contain a SLR component, to identify residual hazard. Remaining seawalls in the model were assumed to remain at present height and not change with SLR.

The maximum sea-level reached during each simulation was extracted at 106 locations throughout Tauranga Harbour (Figure 6-1 and Table D-1). For each of the storm-tide scenarios (7–18 in Table 6-3), two simulations were run, one with NE winds blowing from 22.5° and the other with SW winds blowing from 135°. The maximum water levels extracted into Table D-1 are the maximum of either simulation, and tend to divide at Katikati, with maximum elevations west of Katikati experienced during NE winds, *vice versa*.

Figure 6-2 – Figure 6-5 show the extent of inundation by spring tides (MHWS–7), at the same locations. The coastal marine area boundary is legally defined as the line of high-water springs. The plots show areas of land that will be "in the sea" after future SLR.

Figure 6-6 – Figure 6-9 show the extent of storm-tide inundation at the modelled grid cell resolution, at several locations around the harbour: Mount Maunganui, Ports of Tauranga and Tauranga Airport (Figure 6-6), Otumoetai and Waikareao Estuary (Figure 6-7), Katikati (Figure 6-8) and Waihi Beach (Figure 6-9). These figures are provided for illustrative purposes. All simulated model scenario outputs have been provided to the Project Partners in digital GIS format.

These figures are illustrative—GIS files have been supplied to Bay of Plenty Regional Council, which cover the full extent of the Harbour.

Table 6-3: Extreme storm-tide and level rise scenarios. SLR are specified relative to MVD–53. 0.13 m of SLR is projected by 2020 and is considered to be "present day". IB = inverse barometer.

Scenario	MHWS–7 AEP (%)	Tide (m)	SLR (m)	IB (m)	Wind Speed (m/s)
1	MHWS–7	0.96	0.13	0	0
2	MHWS–7	0.96	0.4	0	0
3	MHWS–7	0.96	0.6	0	0
4	MHWS–7	0.96	0.8	0	0
5	MHWS–7	0.96	1.25	0	0
6	MHWS–7	0.96	1.6	0	0
7	2% AEP	1.1	0.13	0.33	32
8	2% AEP	1.1	1.25	0.33	32
9	1% AEP	1.1	0.13	0.4	34.5
10	1% AEP	1.1	0.2	0.4	34.5
11	1% AEP	1.1	0.4	0.4	34.5
12	1% AEP	1.1	0.6	0.4	34.5
13	1% AEP	1.1	0.8	0.4	34.5
14	1% AEP	1.1	1.25	0.4	34.5
15	1% AEP	1.1	1.6	0.4	34.5
16	0.2% AEP	1.1	0.13	0.4	42

Scenario	MHWS−7 AEP (%)	Tide (m)	SLR (m)	IB (m)	Wind Speed (m/s)
17	0.2% AEP	1.1	1.25	0.4	42
18	0.2% AEP	1.1	1.6	0.4	42

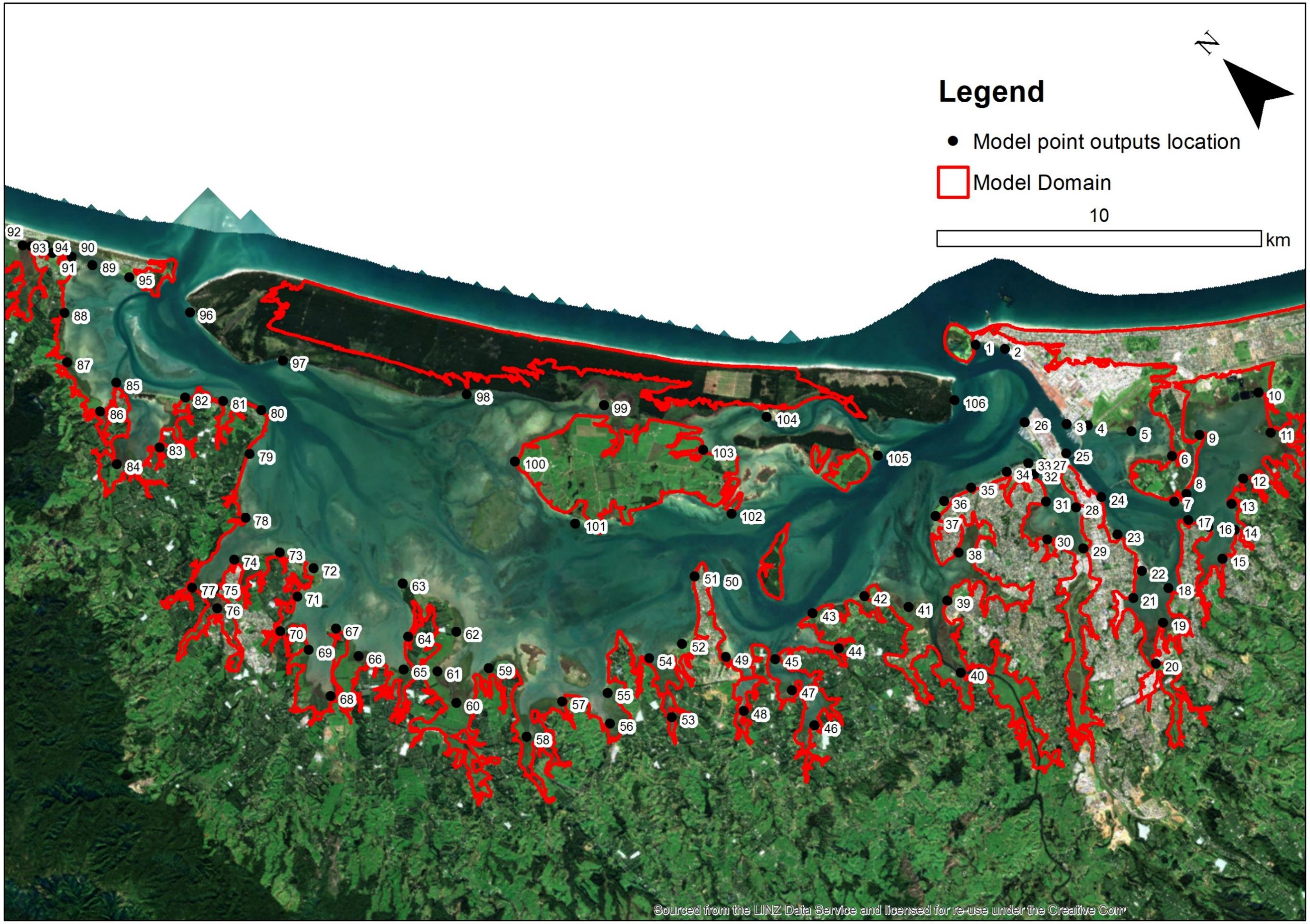

Figure 6-1: Water level extraction locations. (Table D-1 and Table E-1)

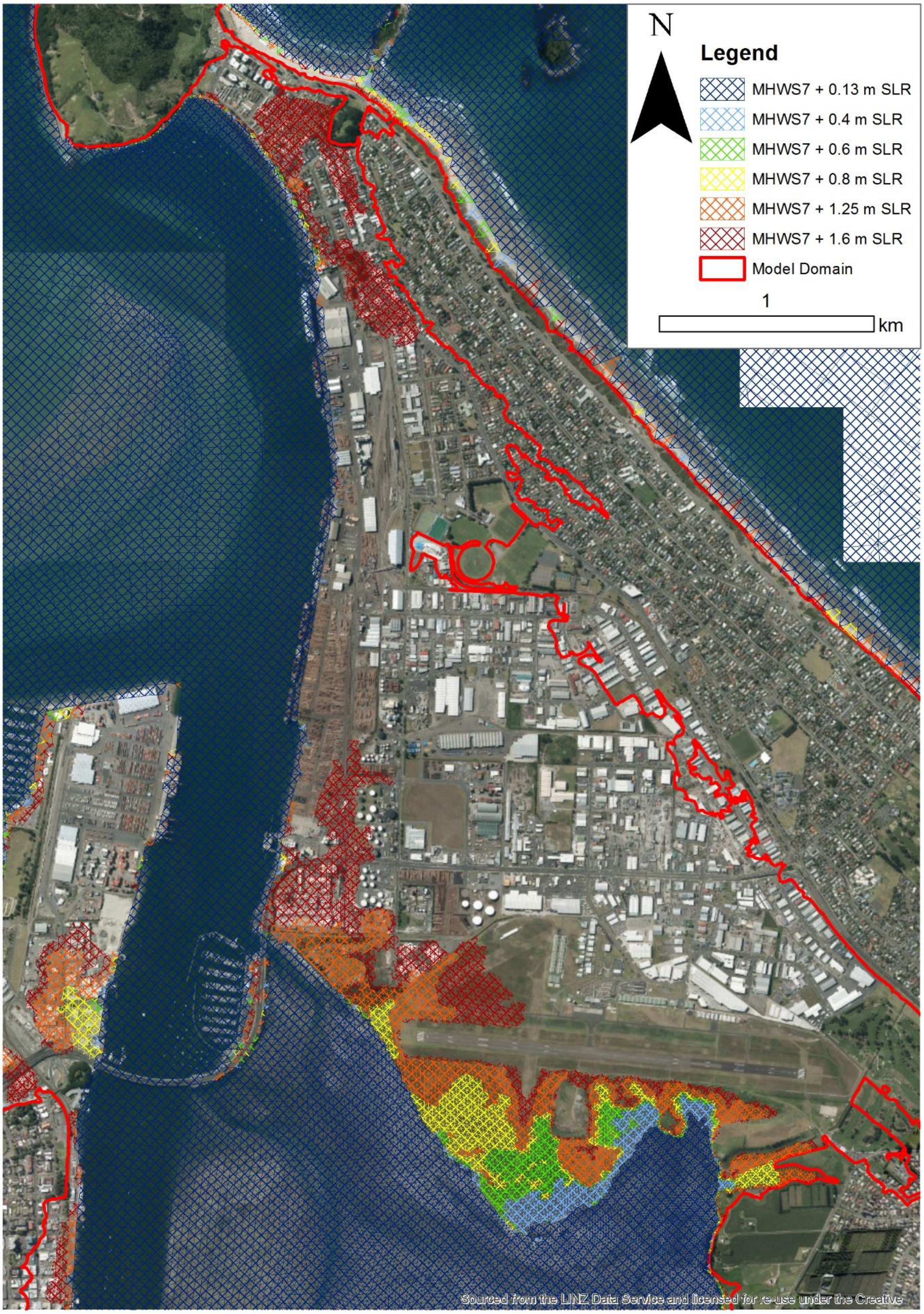

Figure 6-2: MHWS–7 + SLR inundation map, for Mount Maunganui, Ports of Tauranga and Tauranga Airport. SLR is specified relative to MVD–53 and 0.13 m SLR represents MSL in 2020, “present-day".

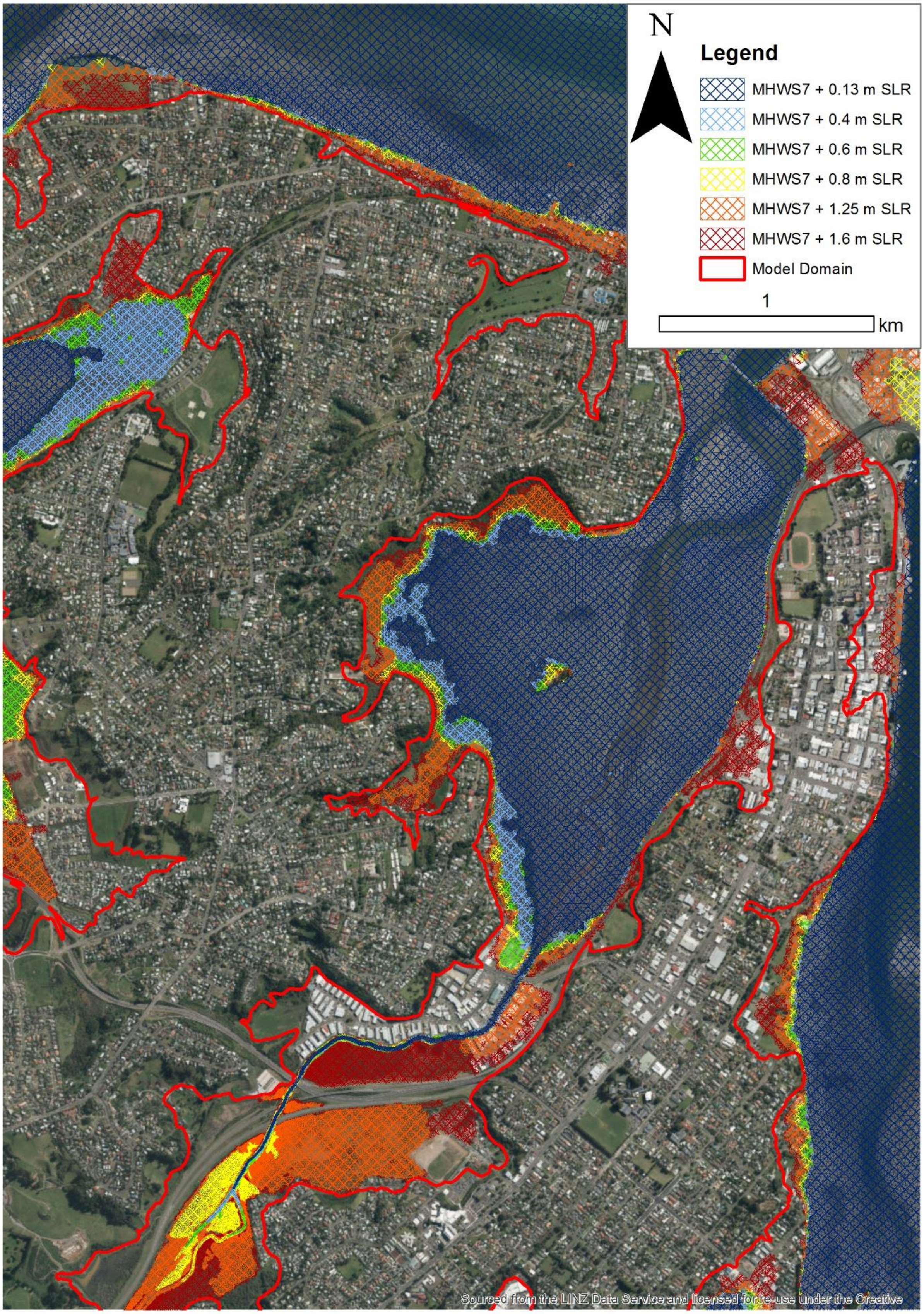

Figure 6-3: MHWS–7 + SLR inundation map, for Otumoetai and Waikareao Estuary. SLR is specified relative to MVD–53 and 0.13 m SLR represents MSL in 2020, “present-day".

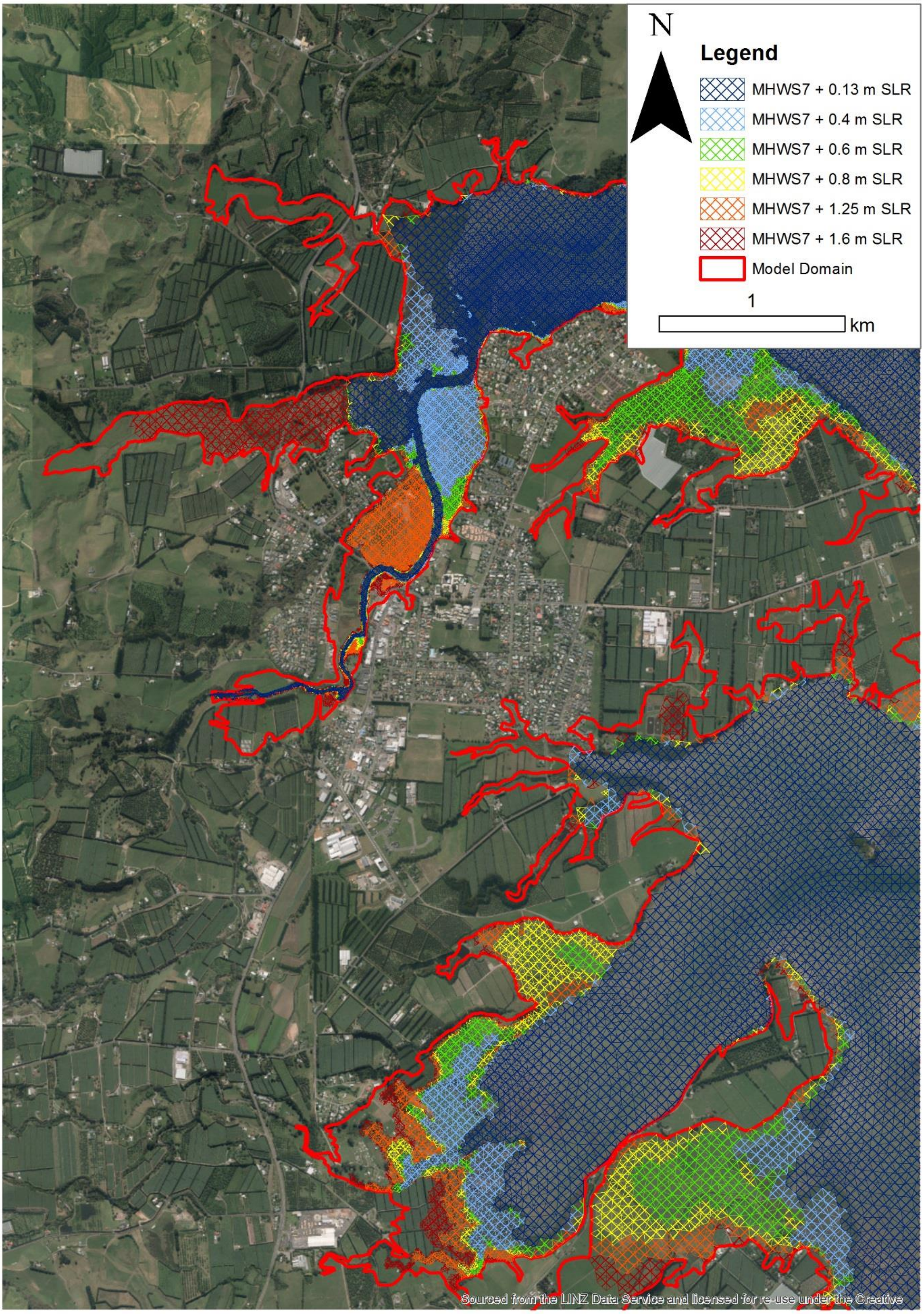

Figure 6-4: MHWS–7 + SLR inundation map, for Katikati. SLR is specified relative to MVD–53 and 0.13 m SLR represents MSL in 2020, “present-day".

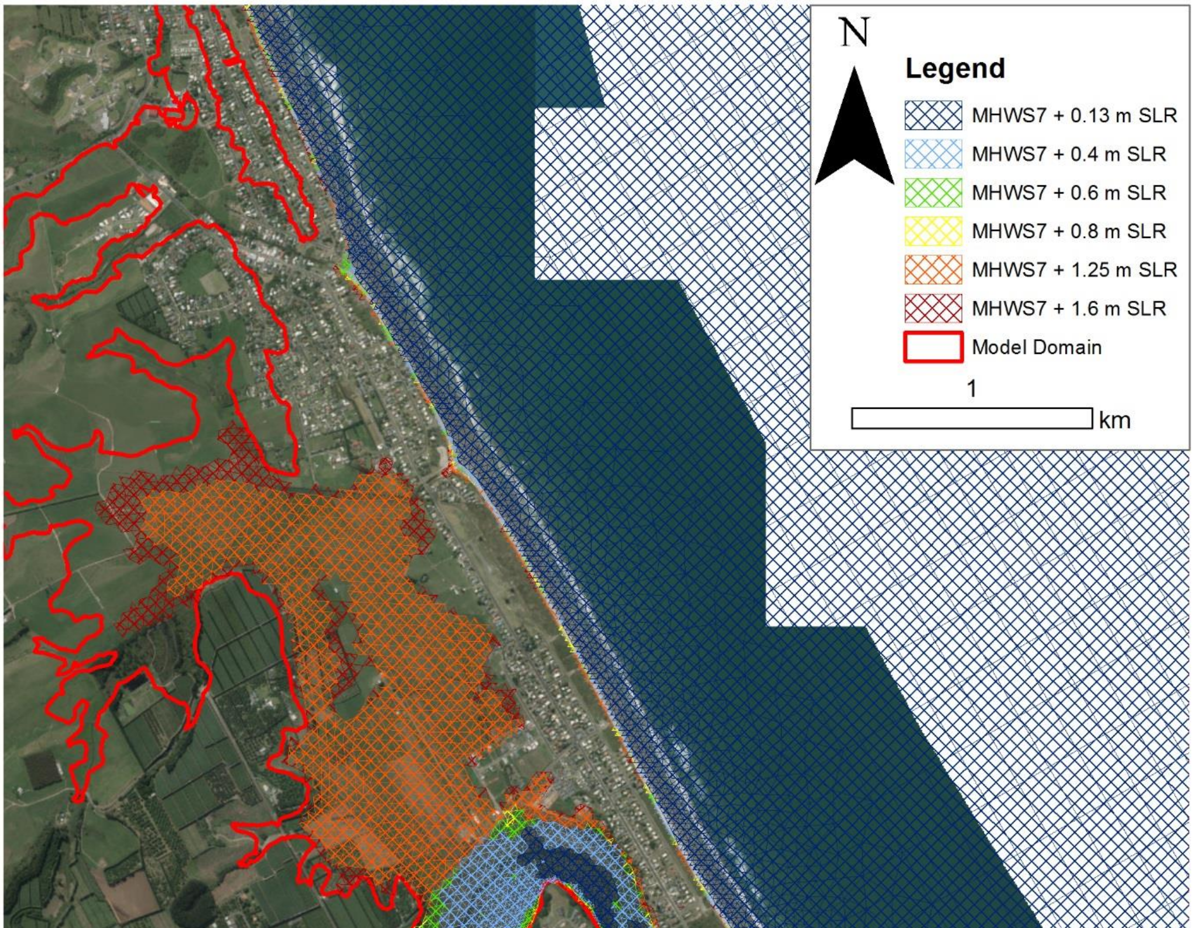

Figure 6-5: MHWS–7 + SLR inundation map for Waihi Beach. SLR is specified relative to MVD–53 and 0.13 m SLR represents MSL in 2020, "present-day".

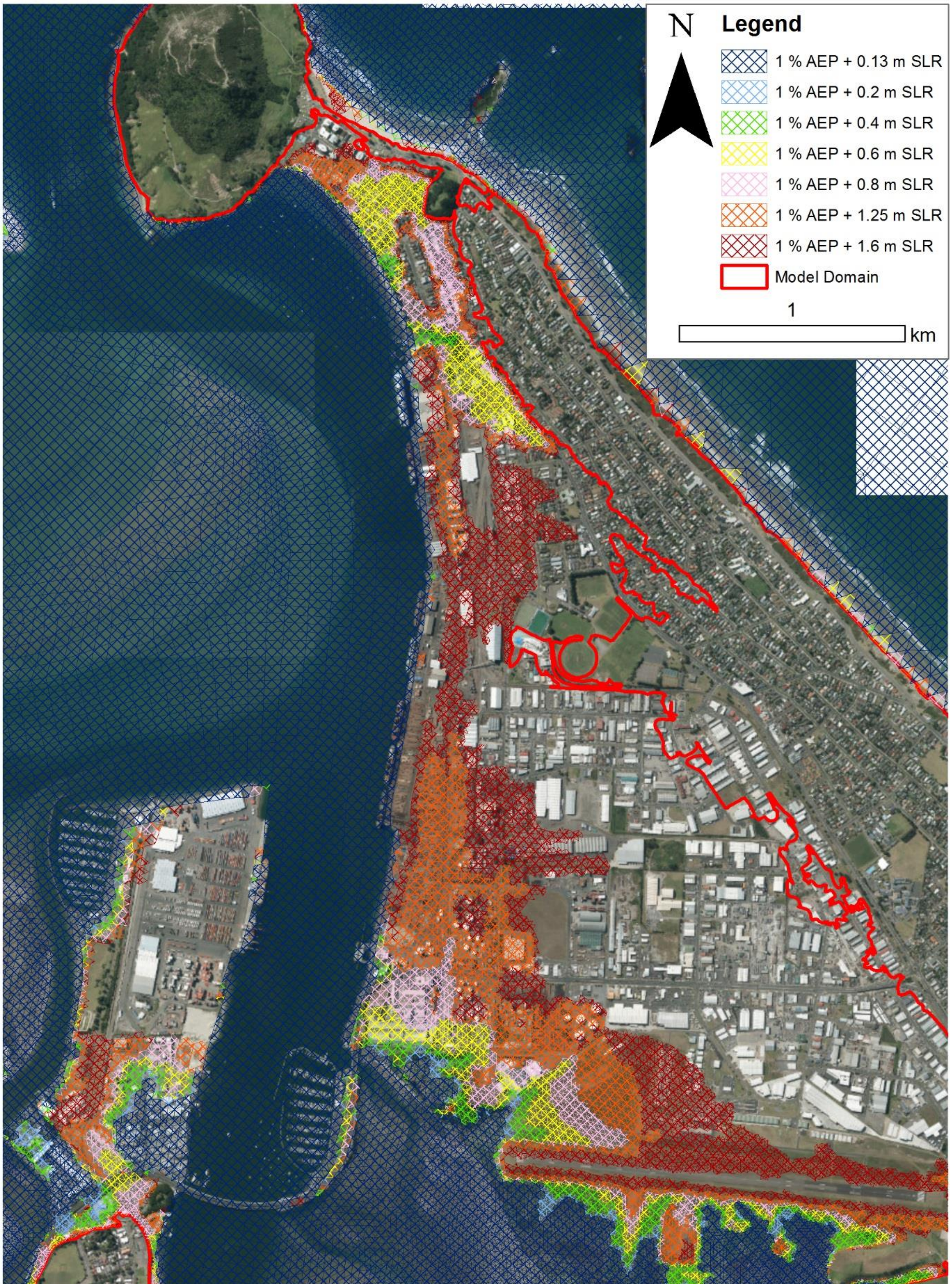

Figure 6-6: 1% AEP extreme storm-tide + SLR inundation map, for Mount Maunganui, Ports of Tauranga and Tauranga Airport. SLR is relative to MVD–53 and 0.13 m SLR represents MSL in 2020, "present-day".

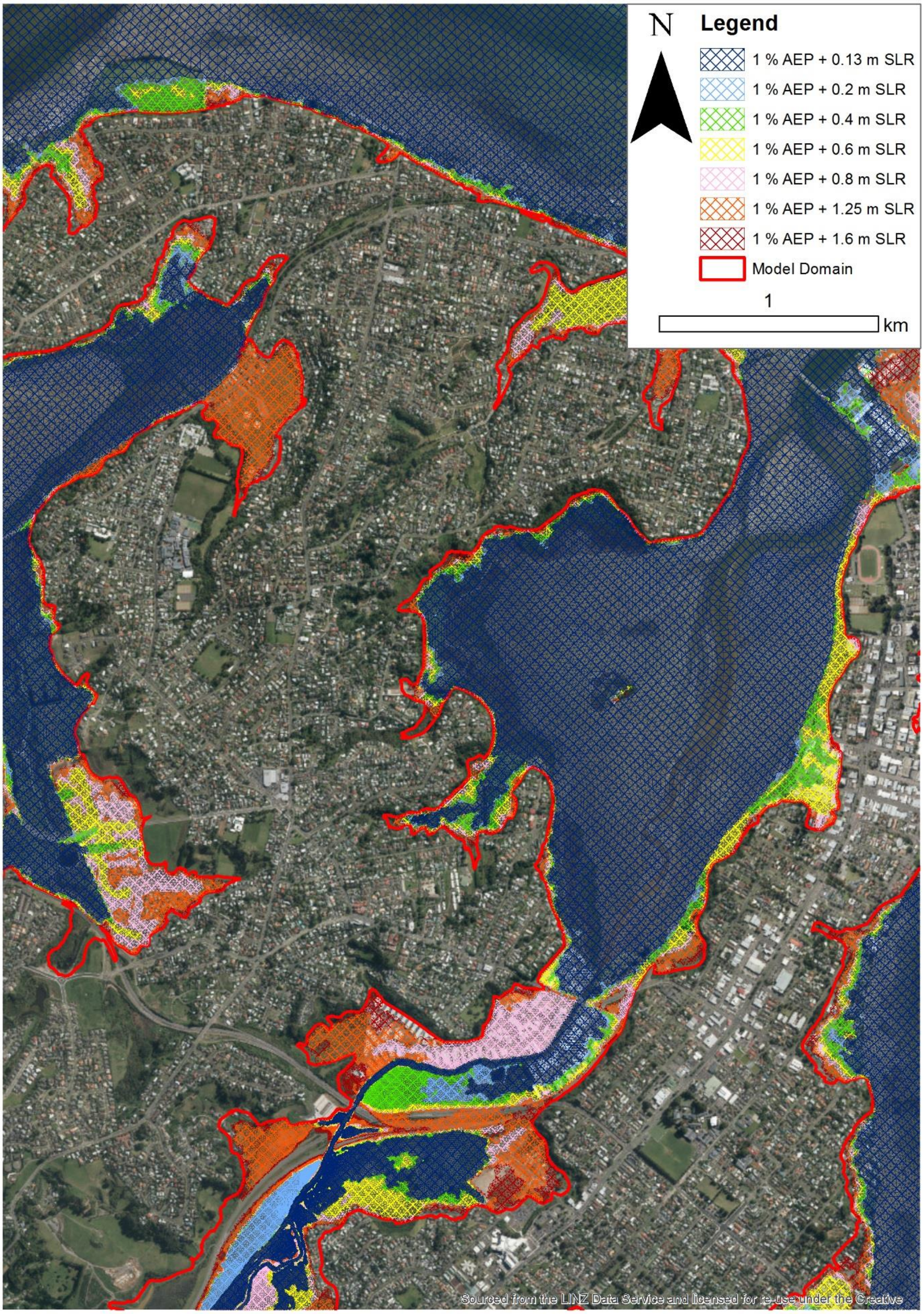

Figure 6-7: 1% AEP extreme storm-tide + SLR inundation map for Otumoetai and Waikareao Estuary. SLR is specified relative to MVD–53 and 0.13 m SLR represents MSL in 2020, "present-day".

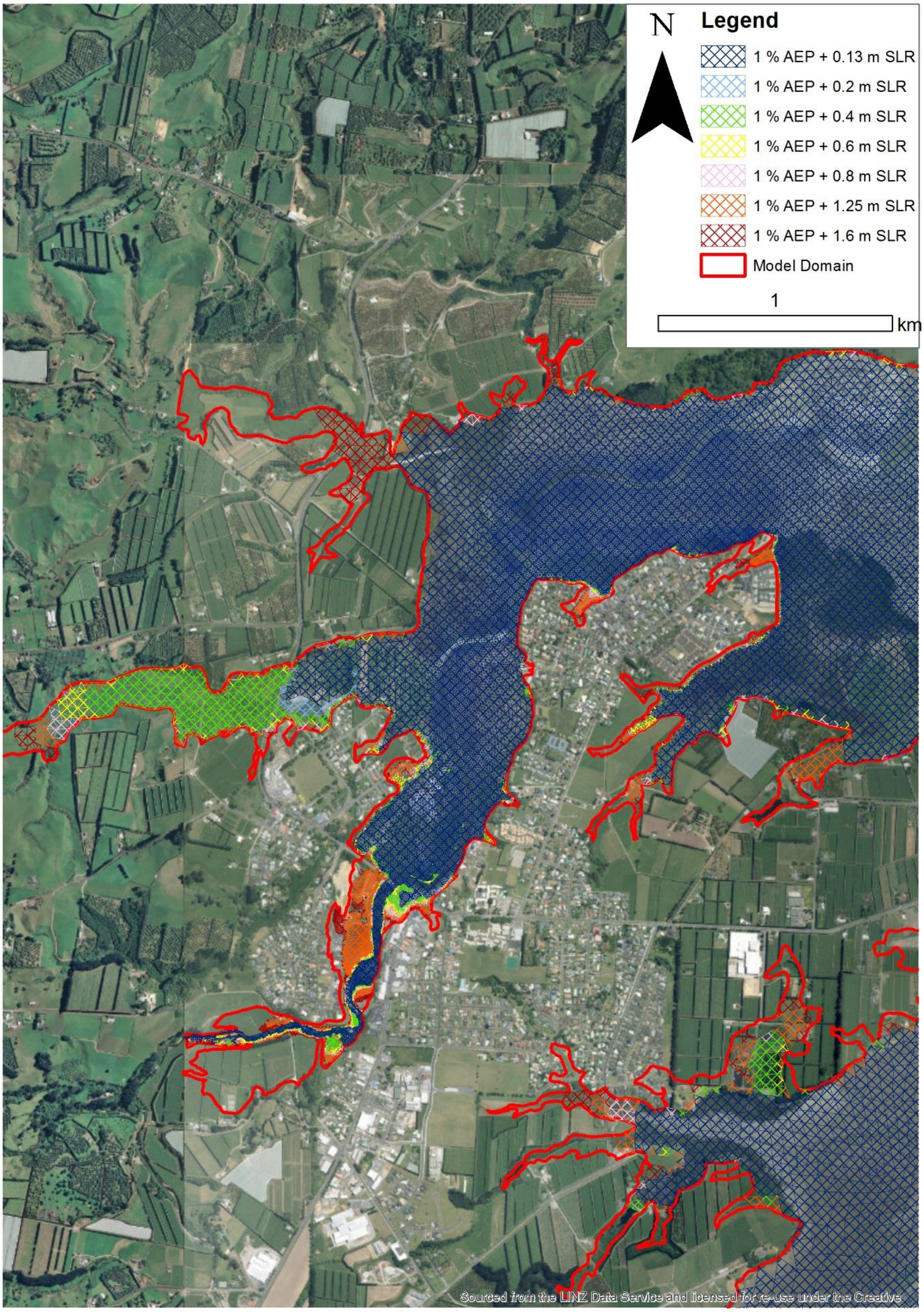

Figure 6-8: 1% AEP extreme storm-tide +SLR inundation map for Katikati. SLR is specified relative to MVD–53 and 0.13 m SLR represents MSL in 2020, "present-day".

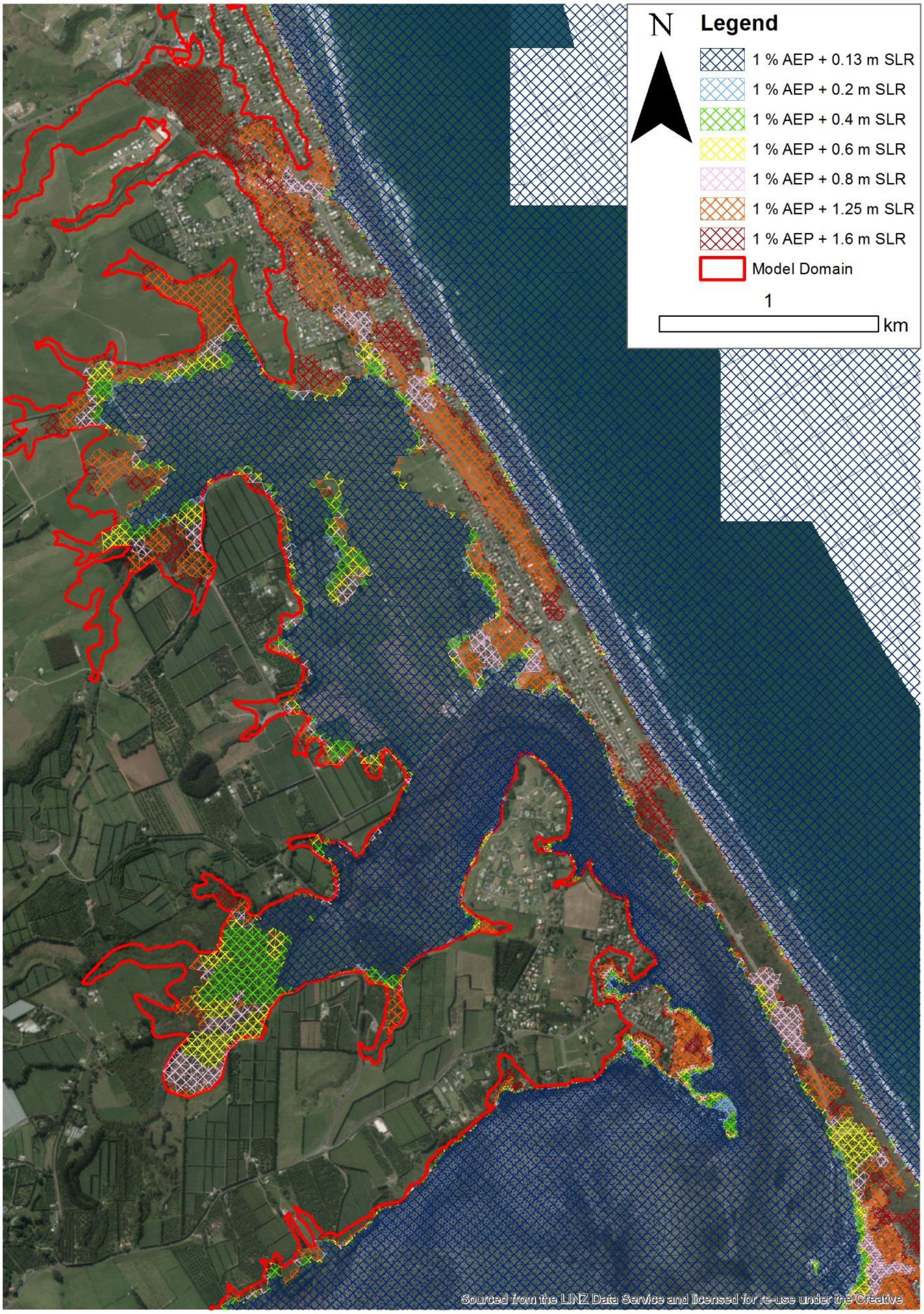

Figure 6-9: 1% AEP extreme storm-tide + SLR inundation map for Waihi Beach. SLR is specified relative to MVD–53 and 0.13 m SLR represents MSL in 2020, "present-day".

7 Wave setup allowance

The hydrodynamic model used to simulate storm-tide did not include wave effects. The largest differences between modelled and observed water levels occurred at sites exposed to wave setup and runup (Section 4). There were two main technical difficulties for extracting wave setup and runup from the hydrodynamic model:

1. The model contained 910,376 grid cells, and there was insufficient computer power to couple the wave module to the hydrodynamic model without crashing the model. Transfer to NIWA's super-computer could overcome this in future but was not available during the work.

2. Wave setup and runup are generated in the last few metres next to the shoreline or while running up a beach or seawall. The model had high spatial resolution for simulating storm tides, but the spatial resolution still would not have been high enough to accurately resolve wave setup and runup, even if the wave module was able to be run.

Empirical formulae were used to estimate wave setup, based on wind fetch and depth. The maximum fetch and average depth were estimated from the model bathymetry grid, for the same locations for which storm-tide elevations were calculated (Figure 6-1, Table D-1). Fetch and average depth along that fetch was calculated at each site for wind directions 0 : 22.5 : 337.5°.

For each fetch direction at each site, significant wave height and peak wave period were estimated using the empirical fetch and depth-limited formula of Young and Verhagen (1996), using the 1% AEP wind speed of 34.5 m/s (Table 6-3). The estimated wave parameters were used to calculate wave setup using several empirical formulae. The fetch direction giving the maximum wave setup was used. The empirical wave formulae used were: Guza and Thornton (1981), King et al. (1990), Hanslow and Nielsen (1993), Raubenheimer et al. (2001) and Stockdon et al. (2006).

Wave setup was estimated using an assumed beach slope of 1(V):10(H). Previous studies by Tonkin and Taylor show that while the inter-tidal zone is generally relatively flat throughout most of the harbour, the upper beach, where wave setup would be generated, is often steeper at between 1:7 and 1:25 (T&T 1999; T&T 2008). The 1:10 beach slope we used is nearer the steeper end of the 1:7–25 range provided by Tonkin and Taylor, so would tend to produce conservatively large wave setup for planning purposes.

Figure 7-1 shows the spread in wave setup calculated throughout the harbour using 7 empirical formulae. Some formulae predict higher wave setup than others. We chose to use the median wave setup, which is plotted on the right-hand side. The data underlying Figure 7-1 are detailed in Appendix E, Table E-1. The minimum, median and maximum (from all sites) of the Median wave setup (from all equations) were 0.06, 0.18 and 0.29 m respectively.

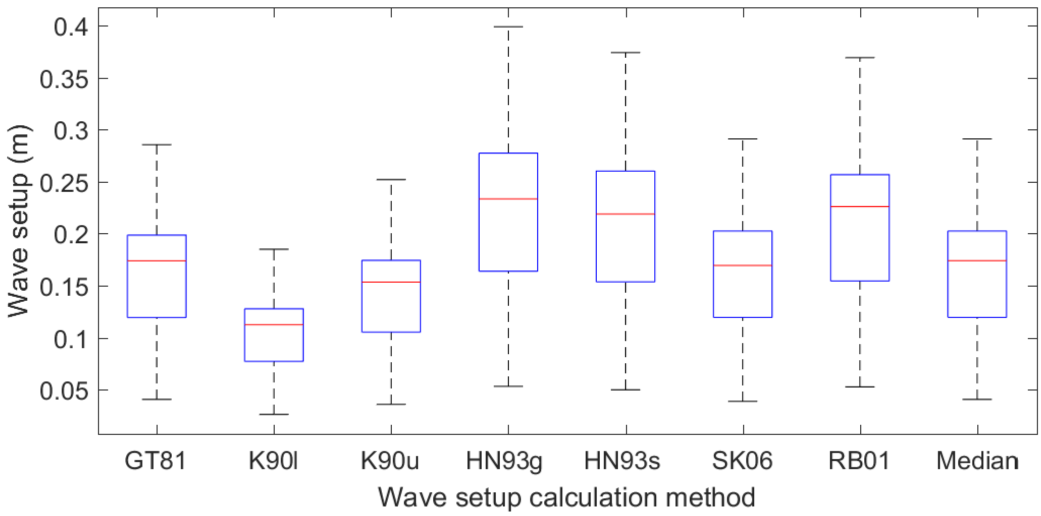

Figure 7-1: Spread of wave setup calculated at 106 sites throughout Tauranga Harbour, using different empirical formulae. The spread of the median of all methods is plotted on the right. Red line marks median, blue box marks 25–75% quantiles, and black bars contain ~99% of all data. GT81 = Guza and Thornton (1981), K90l,u = King et al. (1990) lower and upper, HN93g,s = Hanslow and Nielsen (1993) general and beach-slope dependent, RB01 = Raubenheimer et al. (2001), SK06 = Stockdon et al. (2006) and median = median of all methods. Wave setup was calculated using a 1:10 beach slope.

8 Inundation mapping

Section 6 explains how inundation maps were created for the 18 storm-tide scenarios shown in Table 6-1. Examples of inundation from the storm-tide scenarios are given in Figure 6-6 – Figure 6-9. The Project Partners were supplied with GIS polygons of storm-tide inundation at 10 × 10 m grid resolution. Table D-1 details storm-tide elevations at 106 locations throughout the harbour. The hydrodynamic model predicted dynamic inundation from each of the 18 storm-tide scenarios but did not include wave setup.

Wave setup will cause water levels to reach higher elevations and encroach further inland than for storm-tide alone. Section 7 describes how wave setup elevations were calculated at locations throughout the harbour—the wave setup elevations are detailed in Table E-1. Adding the elevations in Table D-1 and Table E-1 will give the total water level at 106 locations throughout the harbour, as detailed in Table F-1.

For the final mapping product, we wanted to make maximum use of the hydrodynamic model's ability to accurately simulate the storm-tide inundation at the fine scale, rather than rely on total water level outputs at only 106 discrete locations. Therefore, a GIS technique was developed to produce inundation maps from the combined storm-tide + wave setup elevations, as follows:

1. Merge the discrete wave setup elevations in Table E-1 by interpolating into a continuous 3-dimensional wave-setup-elevation line that follows the coastline.

2. For each scenario in Table 6-1, find all the wet cells. These are all the triangular model grid cells in which inundation occurred—there are dry cells inland (e.g., Figure 8-1). Extract the model grid cells along the inland boundary of the wet area, to create a strip of wet cells along the wet area boundary.

3. Create a buffer that extends inland from the wet area boundary cells. Merge the buffer with the wet area boundary cells into a single polygon. Convert that polygon into a 5 × 5 m grid, then convert the grid into points at 5 m spacing.

4. Assign water level elevation to the points within the buffer. The storm-tide water level is taken from the nearest model grid cell. The wave setup elevation is taken from the nearest location on the coastline (from step 1 above). The storm-tide elevation is added to the wave setup elevation within the buffer that extends inland from the wet area boundary cells. The wave setup was not added for the six MHWS–7 simulations (Table 6-1).

5. Convert the buffer points back into a 2 × 2 m grid that now has an associated elevation. Merge this buffer grid with a 2 × 2 m elevation grid created from the modelled storm tide. There is now a single 2 × 2 m grid of water level elevations, which extends throughout the harbour and inland from the original storm-tide simulation and includes the wave setup elevations within the inland buffer.

6. Create a grid of overland flow height reduction using the tsunami runup equation of Smart et al. (2016), based on a 0.2 m high wave and a friction coefficient consistent with undulating open ground. This reduced water levels within the wave-setup buffer by about 0.1 m in height for every 80 m of overland flow. The height reduction was applied only within the inland buffer extension, i.e. landward of the hydrodynamic model boundary.

7. Smooth the water-level grid to remove any sudden elevation changes in water level remaining after interpolation across the buffer, which occurred in a few places where the hydrodynamic-modelled water levels were quite different on either side of an obstacle.

8. Difference the 2 × 2 m water-level elevation grid from a 1 × 1 m LIDAR bathymetry to determine the inundation depths at 1 × 1 m resolution. The contour of zero difference represents the inundation boundary.

9. Removed all grid cells with depths less than 0.1 m.

10. Applied a clipping mask to remove wet areas along the open coast and the Bay Park stadium.

Figure 8-1 illustrates the process of buffering the combined storm-tide + wave setup elevation to intersect the DEM, to create the inundation maps.

The final set of inundation maps supplied to the Project Partners included both storm-tide + wave setup allowance at 1 × 1 m resolution. The Project Partners were also supplied with the storm-tide results interpolated onto a 10 × 10 m grid.

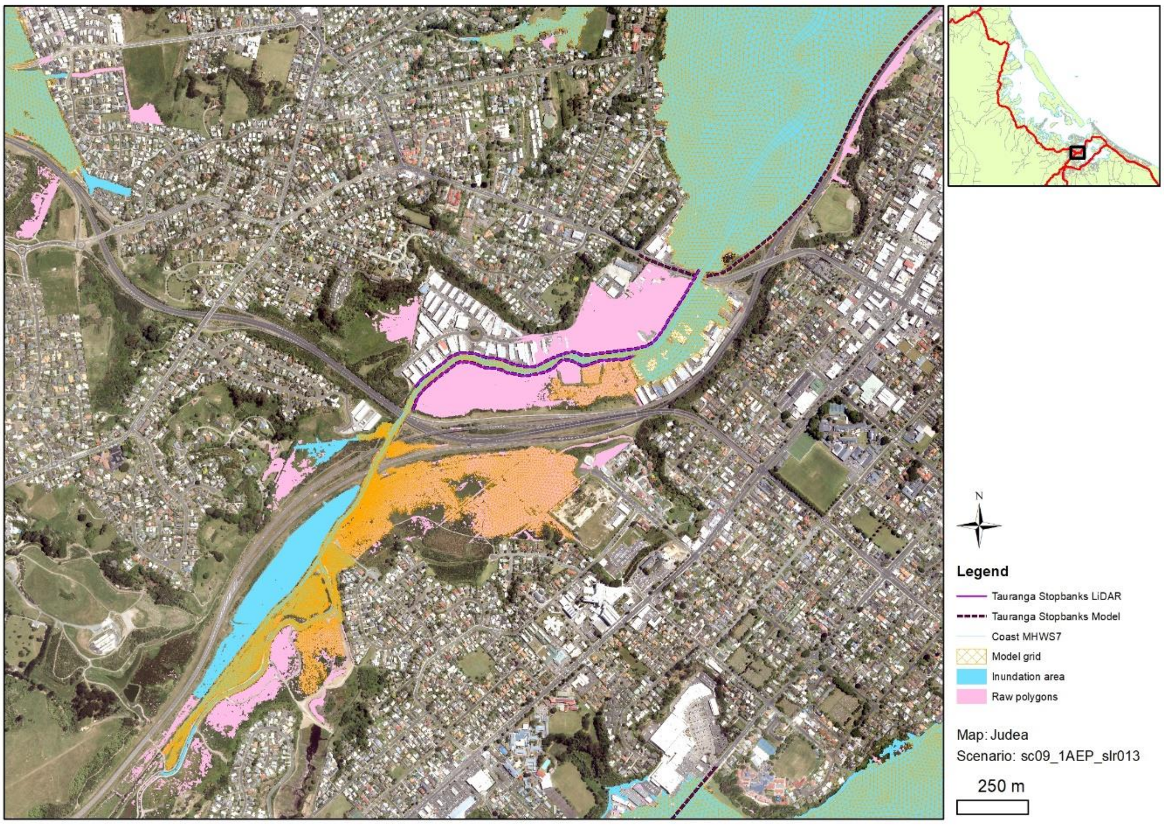

Figure 8-1: Ilustration of wave setup effect on the inundation maps. The inundated area is Judea and the scenario is 1% AEP storm-tide at present-day MSL. The map shows the extent of the "wet" cells within the hydrodynamic model grid (orange triangles), the raw polygons after applying the wave-setup extension (pink), and the final inundation area (blue) after accounting for non-connection to the sea, which includes all of the stopbanks in the hydrodynamic model that were also built into the LIDAR DEM to ensure they were accounted for during the wave-setup extension (stopbanks are also marked).

Figure 8-2: Modelled storm-tide inundation at Otumoetai. Blue marks inundation from 1% AEP storm-tide at 2020 MSL, green + 0.4 m SLR, orange +1.25 m SLR, red +1.6 m SLR.

Figure 8-3: Modelled storm-tide inundation at Port of Tauranga. Blue marks inundation from 1% AEP storm-tide at 2020 MSL, green + 0.4 m SLR, orange +1.25 m SLR, red +1.6 m SLR.

Figure 8-4: Modelled storm-tide inundation at Mount Maunganui. Blue marks inundation from 1% AEP storm-tide at 2020 MSL, green + 0.4 m SLR, orange +1.25 m SLR, red +1.6 m SLR.

9 Summary

This report describes the setup, calibration and verification of a hydrodynamic model of tides in Tauranga Harbour, and validation of the model's ability to reproduce inundation during the 5 January 2018 storm-tide event. The report describes simulations of MHWS–7, and 2%, 1% and 0.2% AEP storm-tide scenarios at present-day (year 2020) MSL, and for various SLR scenarios.

The hydrodynamic model was set up using the Deltares flexible mesh modelling software (DelftFM) and was run in 2-dimensional mode to predict depth-averaged flow, which is suitable for coastal-inundation modelling. The model grid has high spatial resolution, with cell edge-lengths of approximately 15 m in the heavily-populated areas of the harbour. The model was forced using tidal water levels at the open offshore boundary condition, annual average river flows, wind and inverse-barometer to account for the shelf wave induced by air pressure drop.

The model was calibrated and verified for accurate simulation of tidal water levels in the harbour. The report presents tables of five measures of model skill: root mean square error, skill score, bias, cross-correlation function, and M_2 tidal constituent amplitude and phase. Time series plots of modelled and measured water level and currents are presented in Appendix A and Appendix B, which make it possible to visually judge the skill of the model. The simulated tidal elevations compared well with measurement records from the 26 water-level recorder and pressure gauge sites around Tauranga harbour where the skill statistics are >95%. The plots of measured and modelled water level show that the model is reproducing the phase, amplitude and tidal asymmetry of the tidal wave in Tauranga harbour. The tidal water level verification also shows a good fit between predicted and observed water level where the skill statistics were >96%. The verification of modelled data with current meter measurements from 8 sites showed reasonable agreement at 6 of the sites. Generally, the magnitude of the currents at all sites were similar to the measured data. However, the modelled current directions at sites 2 and 8 were somewhat different to the measurement records due to bathymetric steering effects which the model didn't reproduce.

The model's ability to simulate overland inundation was validated against observations from the 5 January 2018 storm-tide. The model validated well in locations sheltered from waves. In wave-sheltered locations the modelled water-level elevations were within a few centimetres of those observed, and the horizontal extent of inundation was in most places within a few metres.

Inundation for MHWS and for extreme storm-tides was simulated for 2%, 1% and 0.2% AEP scenarios at present-day MSL. Strong winds blowing along the axis of the Harbour can set down the water level adjacent to lee shores, but pile water up against exposed shores, and force water up into the narrow upper-harbour arms to reach very high elevations. Simulations show very high wind setup on the northern side of Omokoroa Peninsula, at the golf course and at Pahoia. These locations have been observed to respond strongly to wind in instrument records during historical ex-tropical cyclones (Gibb, 1997), and on 5 January 2018. The total water levels simulated for the 0.2% AEP scenario are close to 3 m in many locations, and above 3 m in places, in keeping with Gibb's theory of what would have occurred if the 1936 and 1968 cyclones had coincided with a spring tide. The average amplitude of the wind setup component of sea level was approximately 0.45, 0.56 and 1.0 m respectively for the 2%, 1% and 0.2% AEP scenarios, and reached up to 1.5 m at Pahoia for the 0.2% AEP scenario.

The largest differences between the 5 January 2018 surveyed and simulated inundation occurred at sites exposed to wave setup and runup. Waves, wave setup and wave runup were not included in the storm-tide simulations, but wave setup was included during the mapping process. Before waves were included, the storm-tide model underpredicted the maximum water levels by 0.1–0.2 m on average at Otumoetai and up to 0.6 m at Pilot Bay when compared to the debris survey elevations. Despite the absence of waves, at wave-exposed locations around Otumoetai, the modelled horizontal extent of the inundation differed from observed by less than 8 m on average, and up to 26 m at worst.

Empirical formulae were used to estimate wind-wave generation and wave setup, based on wind fetch and mean water depth along that fetch. A wind speed of 34.5 m/s was used to calculate wave setup since this wind speed was applied in the 1% AEP storm-tide simulation. Wave setup was estimated using an assumed beach slope of 1(V):10(H), which is nearer the steeper end of the 1:7–25 range measured by T&T (1999), so would tend to produce conservatively large wave setup for planning purposes. The median wave setup from 7 empirical formulae was used. The minimum, median and maximum (from all sites) of the median wave setup (from 7 empirical formulae) were 0.06, 0.18 and 0.29 m respectively. Table E-1 provides wave setup elevations at 106 locations throughout the harbour.

In addition to simulations at present-day MSL, SLR scenarios of 0.2, 0.4, 0.6, 0.8, 1.25 and 1.6 m relative to MVD–53 were simulated, for MHWS and for 2%, 1% and 0.2% AEP storm-tide scenarios (Table 6-1). From these simulations, maximum storm-tide elevations were extracted at 106 sites throughout the harbour and are provided in Table D-1. Inundation mapping examples are provided that show the extent of inundation at the modelled grid cell resolution, at several locations around the harbour. Digital GIS shapefiles were supplied to the Project Partners, which show inundation from storm-tides throughout the harbour, for all modelled scenarios at 10 × 10 m grid spacing.

Table F-1 provides total water level at 106 locations throughout the harbour, obtained by adding the storm-tide elevations from Table D-1 to the wave setup elevations from Table E-1.

A GIS technique was applied to produce inundation maps from the combined storm-tide + wave setup elevations. The technique involved adding the wave setup elevations to the storm-tide elevations from the hydrodynamic model, within a buffer zone inland from the storm-tide wet-area boundary. This resulted in a single 5 × 5 m grid of water level elevations for each of the 18 storm-tide scenarios shown in Table 6-1. The grid extended throughout the harbour and inland from the original storm-tide simulation and includes the wave setup elevations within the inland buffer. For each scenario, this grid was differenced with a 1 × 1 m LIDAR bathymetry to determine the inundation depths at 1 × 1 m resolution. The contour of zero difference represents the inundation boundary.

The final set of inundation maps supplied to the Project Partners included both storm-tide + wave setup allowance at 1 × 1 m resolution, as digital GIS files of maximum inundation depth in Geotiff format, which is compatible with RiskScape software[6]. Metadata for the GIS maps is built into the GIS files and is summarised in Appendix H.

The following recommendations would help future modelling work:

- Collection of bathymetry data would improve the accuracy of model predictions in the upper Wairoa River. We consider that the modelled storm-tide levels are reliable downstream of the Rail Bridge located near Te Puna Station Road (1 km downstream from site J), as this is the upstream limit of the surveyed bathymetry data. We have not output inundation levels upstream of the Rail Bridge.

- The modelling used mean annual flow values, which were extracted from the NIWA WRENZ model for New Zealand. While this is OK when modelling storm-tides outside of the rivers, storm river flow data is required to simulate flood hazard inside the rivers, which is influenced by both storm-tides and rainfall. Sensitivity testing for the Wairoa River showed that maximum water levels in the upper portion of the river is sensitive to small changes in flow.
- There was no storm-tide validation data for high sea-level events in the northern harbour, collection of such would be helpful for model validation in here, particularly in Katikati and Waihi Beach. There are several permanent sea-level recorders within Tauranga Harbour, but none north of Omokoroa peninsula—we recommend one be installed.
- Model sensitivity testing, and examination of data collected in the southern harbour have shown that topographical wind steering and wind-sheltering is important to the accurate simulation of storm-surge in many of the Harbour's sub-estuaries. Collection of high-resolution spatial and temporal wind data would help to accurately simulate these localised wind set-up effects.
- To create inundation maps for the whole region, open coast inundation elevations from the Bay of Plenty Coastal Calculator could be used as input to a dynamic model to simulate inundation from the open coast. The open-coast inundation maps could be merged with the harbour inundation maps to create a seamless product.

10 Acknowledgements

The University of Waikato supplied sea-level, current and bathymetric data (Willem de Lange, Peter de Ruiter, John Montgomery and Dean Sandwell). Tonkin and Taylor Ltd and the University of Waikato (Michael Tyler) supplied inundation locations and elevations from the 5 January 2018 storm-tide. Port of Tauranga supplied wind, wave and sea-level data. Ben Robinson processed sea-level data.

11 Glossary of abbreviations and terms

Annual exceedance probability (AEP)	The probability of a given (usually high) sea level being equalled or exceeded in elevation, in any calendar year. AEP can be specified as a fraction of 1 (e.g., 0.01) or a percentage (e.g., 1%).
Average recurrence interval (ARI)	The average time interval (averaged over a long time period and many "events") that is expected to elapse between recurrences of an infrequent event of a given large magnitude (or larger). A large infrequent event would be expected to be equalled or exceeded in elevation, once, on average, every "ARI" years.
CD	Chart Datum.
Epoch	A period of history that is arbitrarily selected as a point of reference – used in connection with developing a baseline sea level.
Joint-probability	The probability of two separate processes occurring together (e.g., high tides and high storm-surge).
LiDAR	Light Detection And Ranging.
MHWS–7	Mean high water springs – The high tide height associated with higher than normal high tides that result from the beat of various tidal harmonic constituents. Mean high water springs occur every 2 weeks approximately. MHWS can be defined in various ways, and the MHWS elevation varies according to definition. MHWS–7 refers to the height of the tide exceeded only by the highest 7% of all high tides, which is about the highest tide every fortnight.
MSL	Mean sea level – the mean level of the sea relative to a vertical datum over a defined epoch, usually of several years.
MSLA	Mean sea-level anomaly – the variation of the non-tidal sea level about the longer term MSL on time scales ranging from a monthly basis to decades, due to climate variability. This includes ENSO and IPO patterns on sea level, winds and sea temperatures, and seasonal effects.
MVD-53	Moturiki Vertical Datum-1953 is the local vertical datum used in the Bay of Plenty region.
Skew-surge	The difference between the measured total water level and the predicted height of the closest high tide—known as skew-surge because the highest total water level can occur before or after high tide (skewed in time).
SLR	Sea-level rise.

Storm-surge	The temporary rise in sea level due to storm meteorological effects. Low-atmospheric pressure causes the sea-level to rise, and wind stress on the ocean surface pushes water down-wind and to the left up against any adjacent coast.
Storm-tide	Storm-tide is defined as the sea-level peak during a storm event, resulting from a combination of MSL + SLA + tide + storm-surge. In New Zealand this is generally reached around high tide.
Wave overtopping	Wave overtopping occurs when the wave runup exceeds the crest elevation of the beach. Overtopping by wave runup involves “wave splash”, “wind spray” and sporadic shallow overwash of “green water” over the beach crest and onto the backshore. Wave overtopping is measured in litres per second per metre length of crest. Wave overtopping may not necessarily cause substantial flooding depending on the back-shore drainage capacity.
Wave runup	The maximum vertical extent of sporadic wave “up-rush” or flowing water (“green water”) on a beach or structure above the still water or storm-tide level, and thus constitutes only a short-term upper-bound fluctuation in water level compared to wave setup.
Wave setup	The increase in mean still-water sea level at the coast, resulting from the release of wave energy in the surf zone as waves break.

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Appendix A Calibration figures

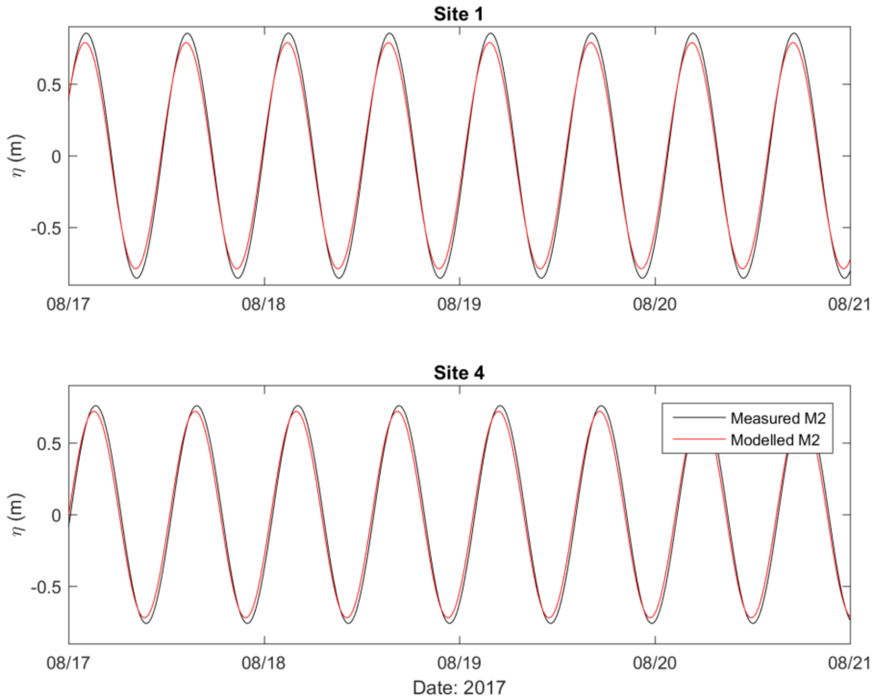

Figure A-1: Measured (black) and modelled (red) M_2 tidal elevation predictions for the period 17 - 21 August 2017 for: Site 1 and Site 4.

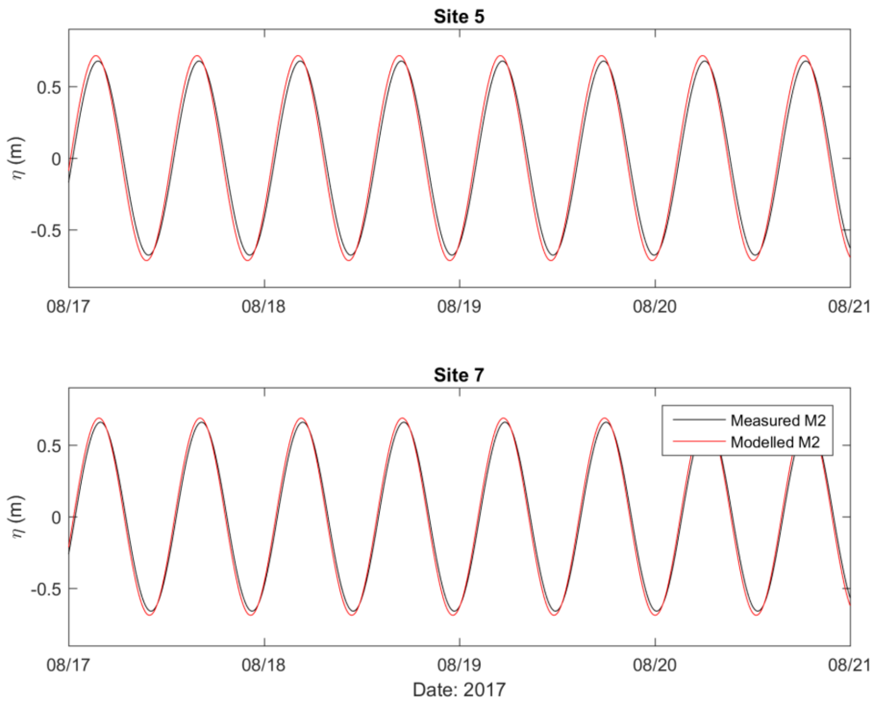

Figure A-2: Measured (black) and modelled (red) M_2 tidal elevation predictions for the period 17 - 21 August 2017 for: Site 5 and Site 7.

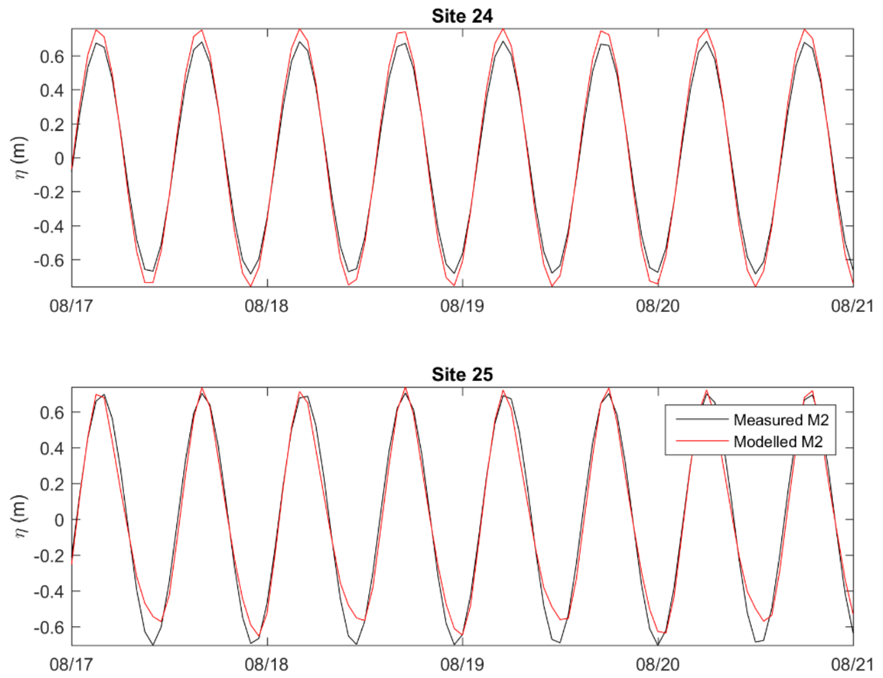

Figure A-3: Measured (black) and modelled (red) M_2 tidal elevation predictions for the period 17 - 21 August 2017 for: Site 24 and Site 25.

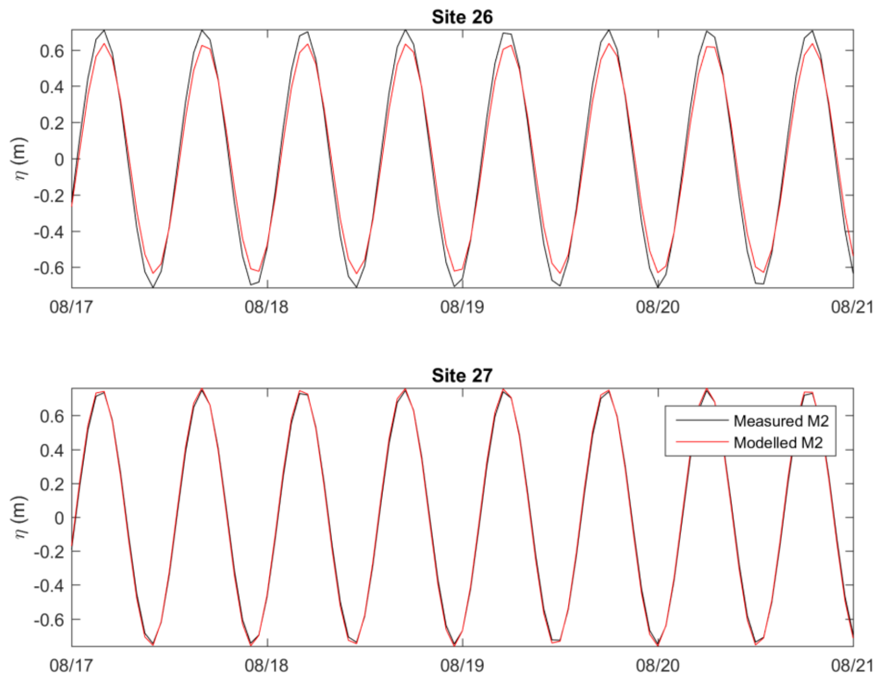

Figure A-4: Measured (black) and modelled (red) M_2 tidal elevation predictions for the period 17 - 21 August 2017 for: Site 26 and Site 27.

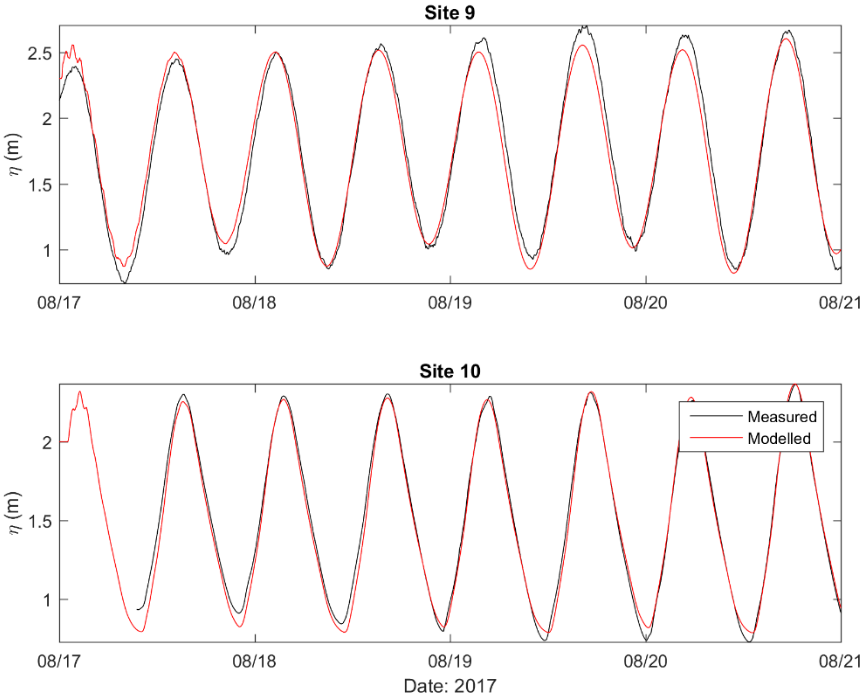

Figure A-5: Measured (black) and modelled (red) sea surface elevations for period 17 - 21 August 2017 for: Site 9 and Site 10.

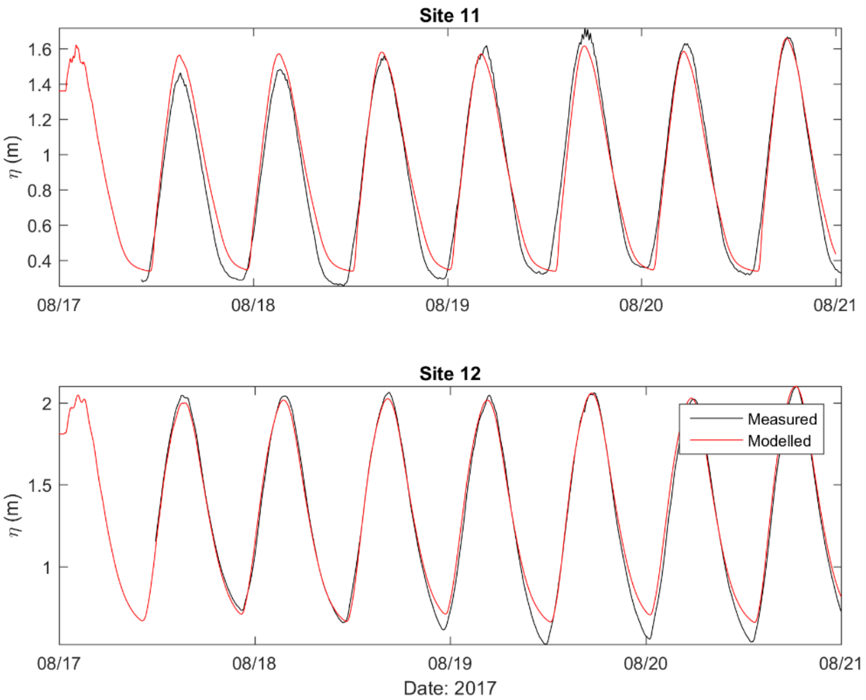

Figure A-6: Measured (black) and modelled (red) sea surface elevations for period 17 - 21 August 2017 for: Site 11 and Site 12.

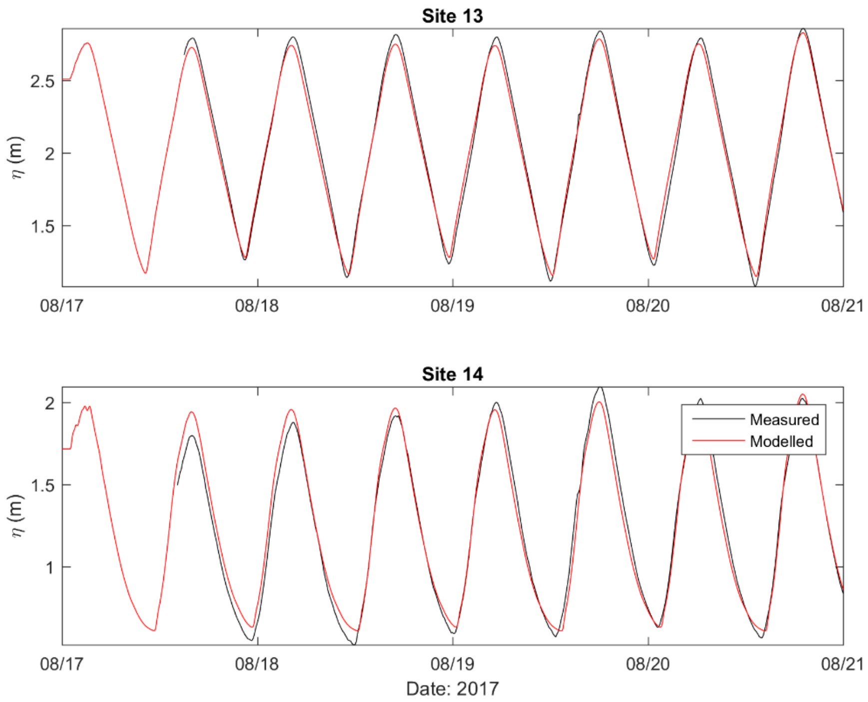

Figure A-7: Measured (black) and modelled (red) sea surface elevations for period 17 - 21 August 2017 for: Site 13 and Site 14.

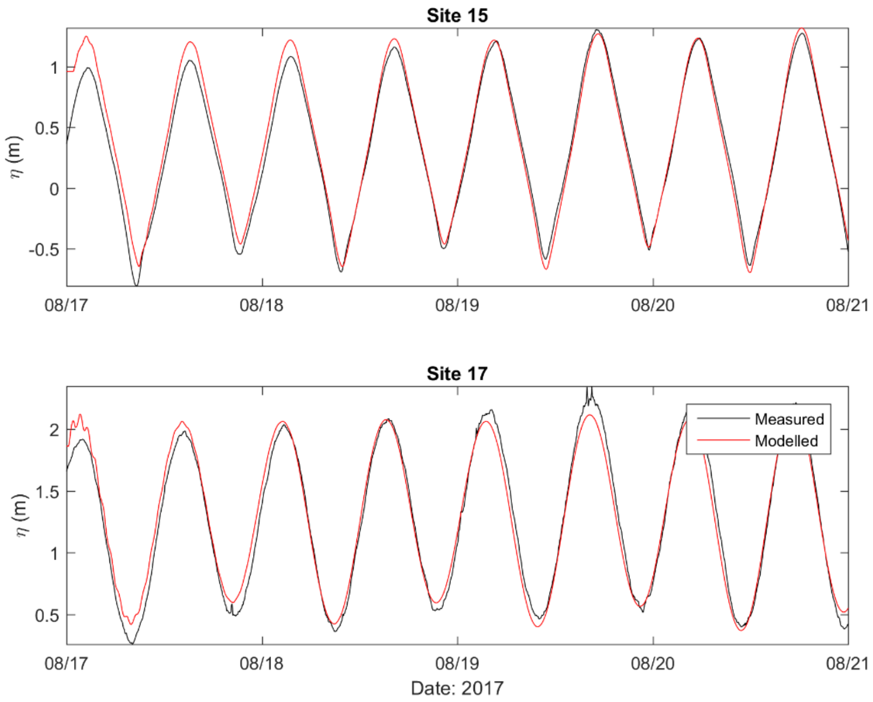

Figure A-8: Measured (black) and modelled (red) sea surface elevations for period 17 - 21 August 2017 for: Site 15 and Site 17.

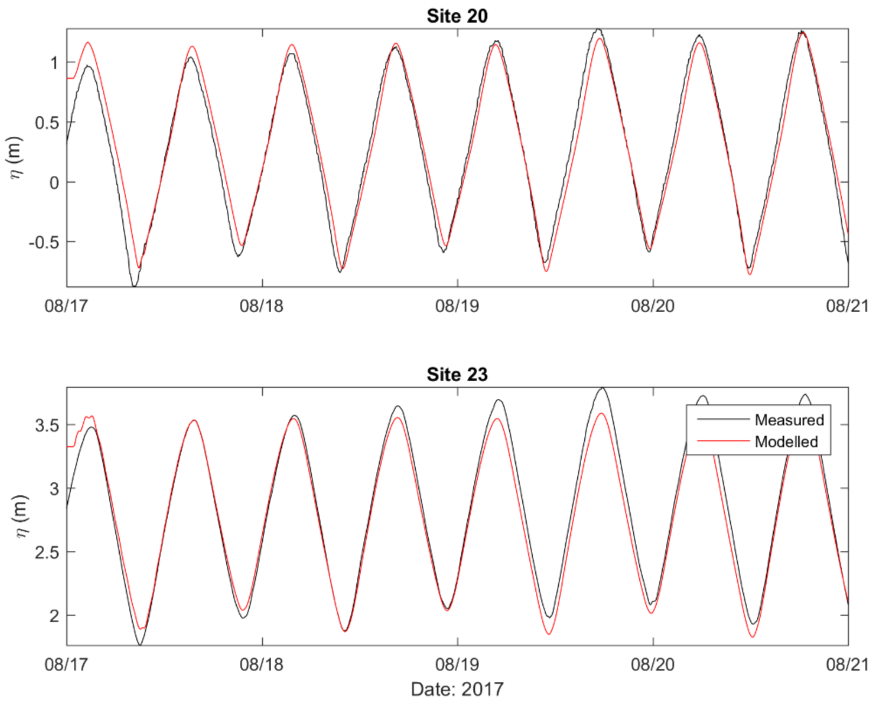

Figure A-9: Measured (black) and modelled (red) sea surface elevations for period 17 - 21 August 2017 for: Site 20 and Site 23.

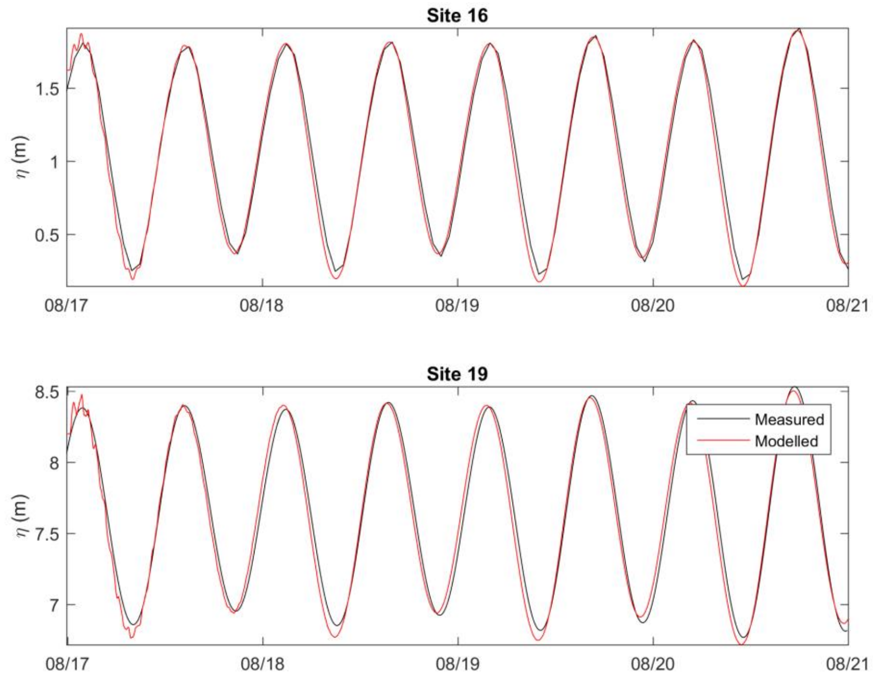

Figure A-10: Predicted (from tidal harmonic constituents) (black) and modelled (red) sea surface elevations for period 17 - 21 August 2017 for: Site 16 and Site 19.

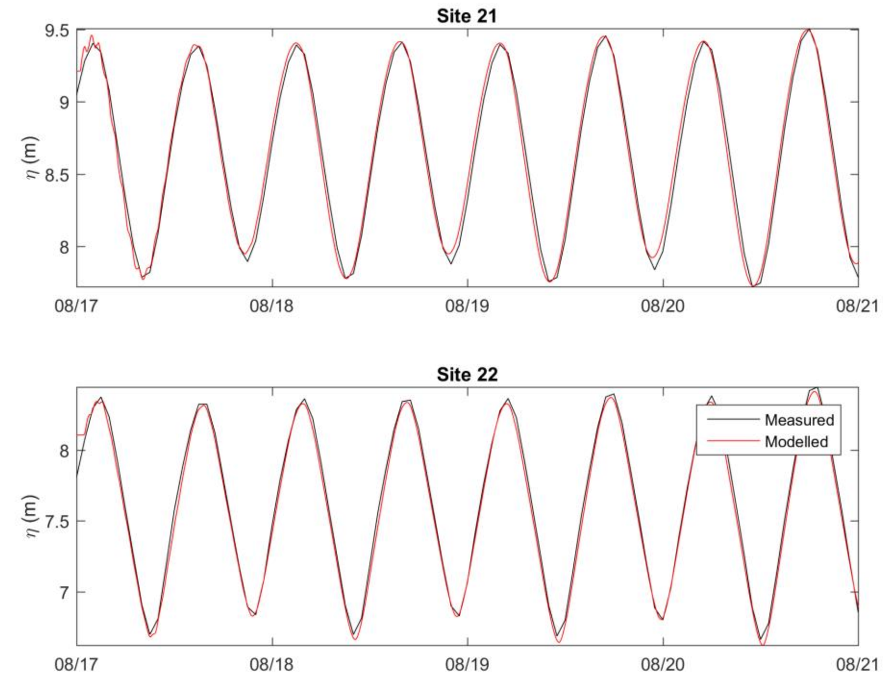

Figure A-11: Predicted (from tidal harmonic constituents) (black) and modelled (red) sea surface elevations for period 17 - 21 August 2017 for: Site 21 and Site 22.

Appendix B Verification figures

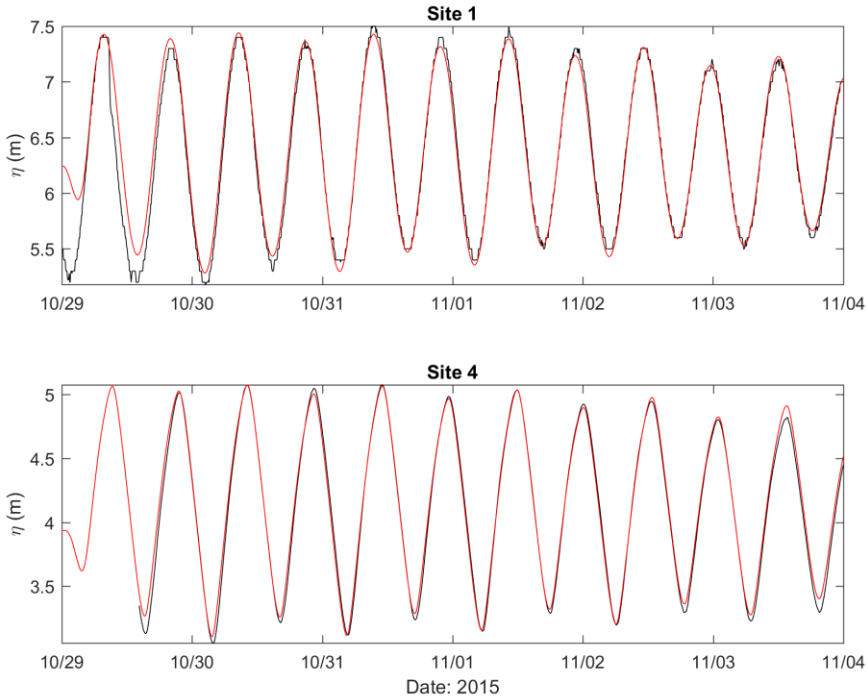

Figure B-1: Measured (black) and modelled (red) sea surface elevations for period 10 October - 4 November 2015 for: Site 1 and Site 4.

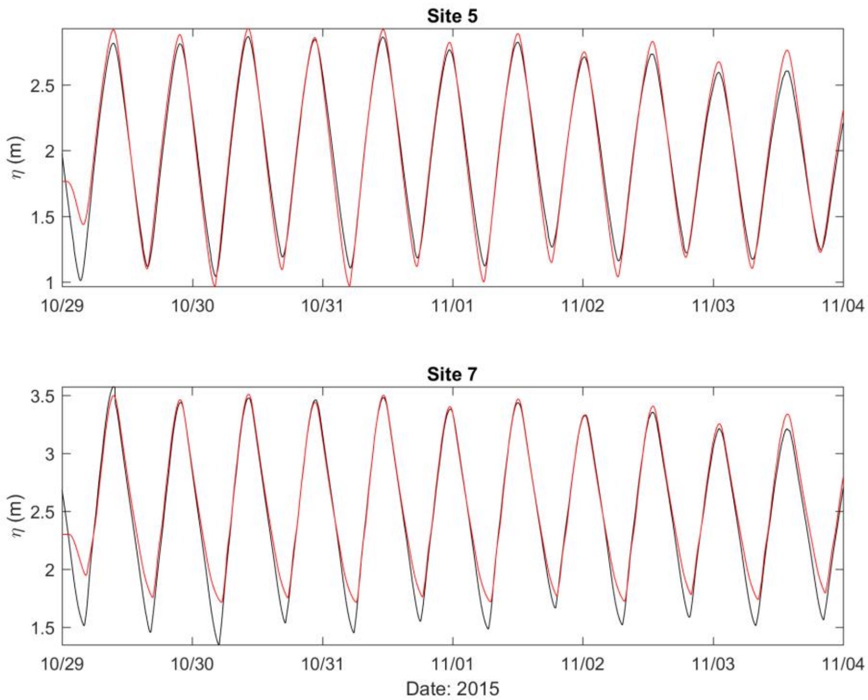

Figure B-2: Measured (black) and modelled (red) sea surface elevations for period 10 October - 4 November 2015 for: Site 5 and Site 7.

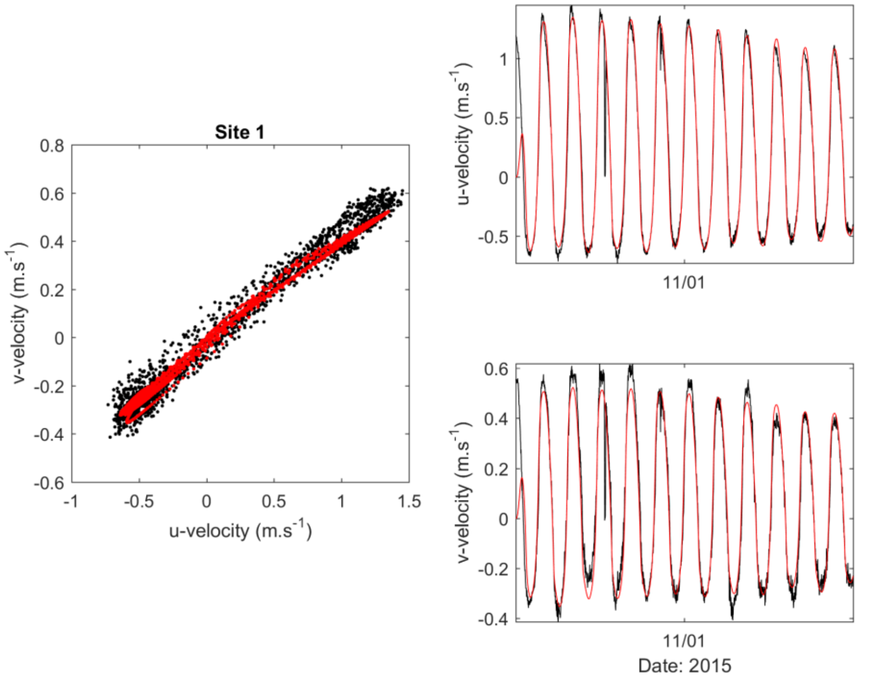

Figure B-3: Measured (red) and modelled (black) depth-averaged u and v components of velocity at Site 1 for the 10 October - 4 November 2015.

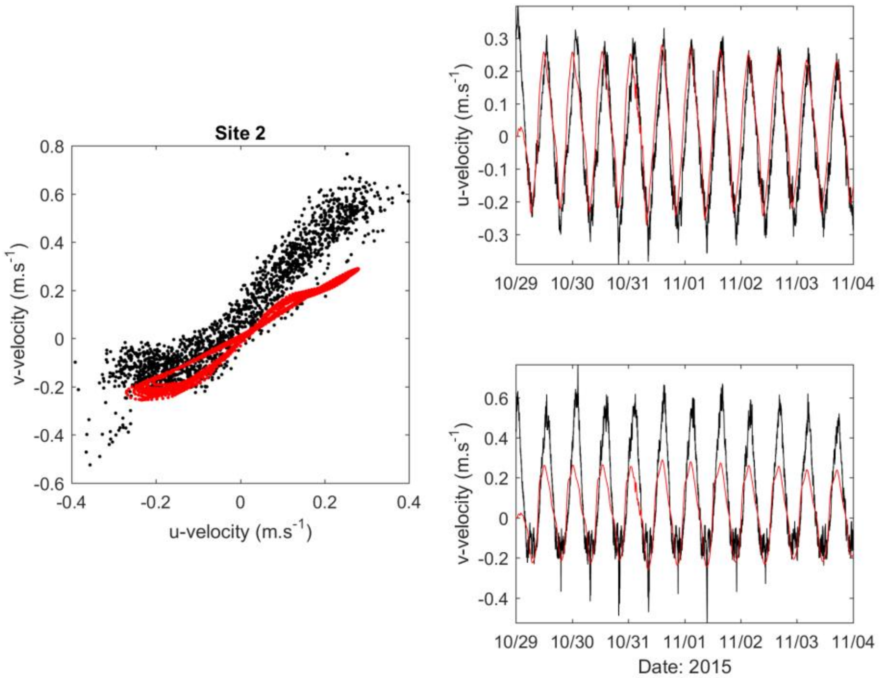

Figure B-4: Measured (red) and modelled (black) depth-averaged u and v components of velocity at Site 2 for the 10 October - 4 November 2015.

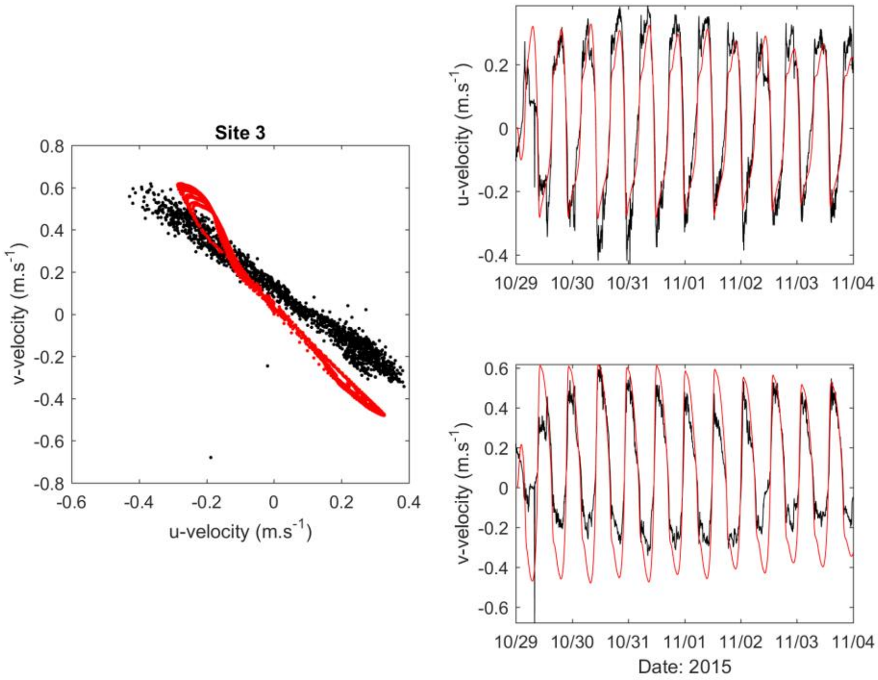

Figure B-5: Measured (red) and modelled (black) depth-averaged u and v components of velocity at Site 3 for the 10 October - 4 November 2015.

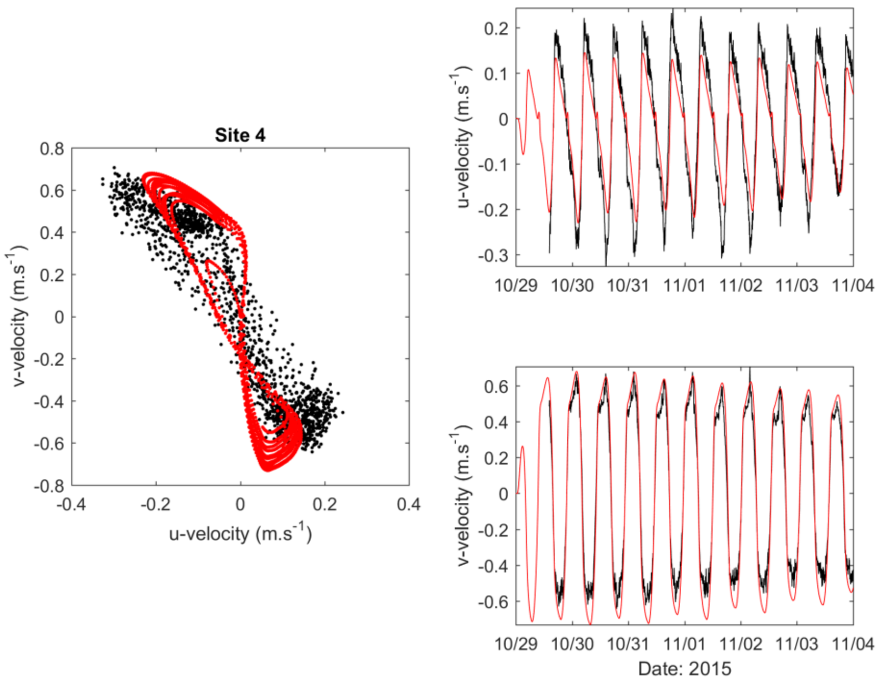

Figure B-6: Measured (red) and modelled (black) depth-averaged u and v components of velocity at Site 4 for the 10 October - 4 November 2015.

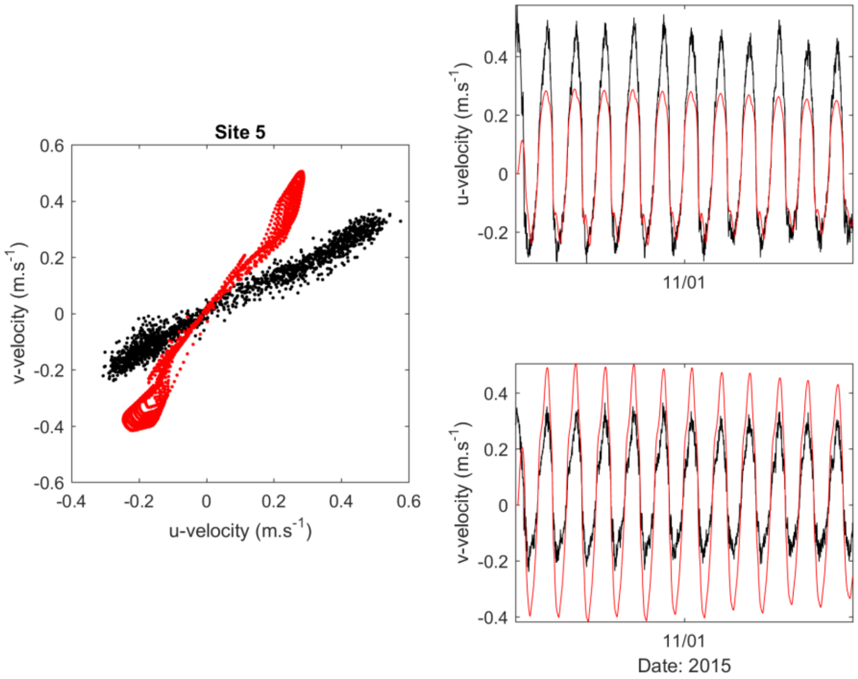

Figure B-7: Measured (red) and modelled (black) depth-averaged u and v components of velocity at Site 5 for the 10 October - 4 November 2015.

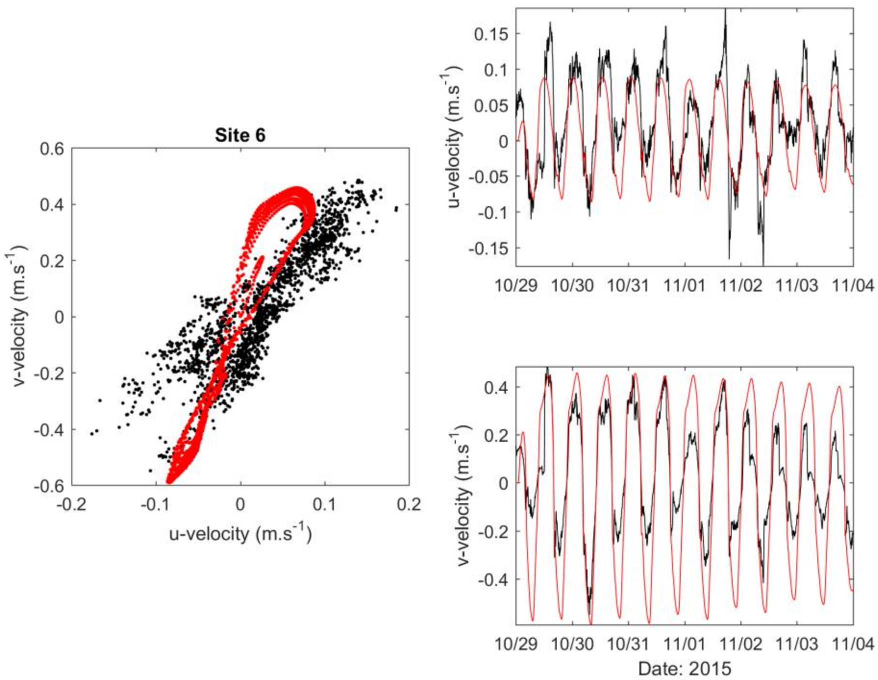

Figure B-8: Measured (red) and modelled (black) depth-averaged u and v components of velocity at Site 6 for the 10 October - 4 November 2015.

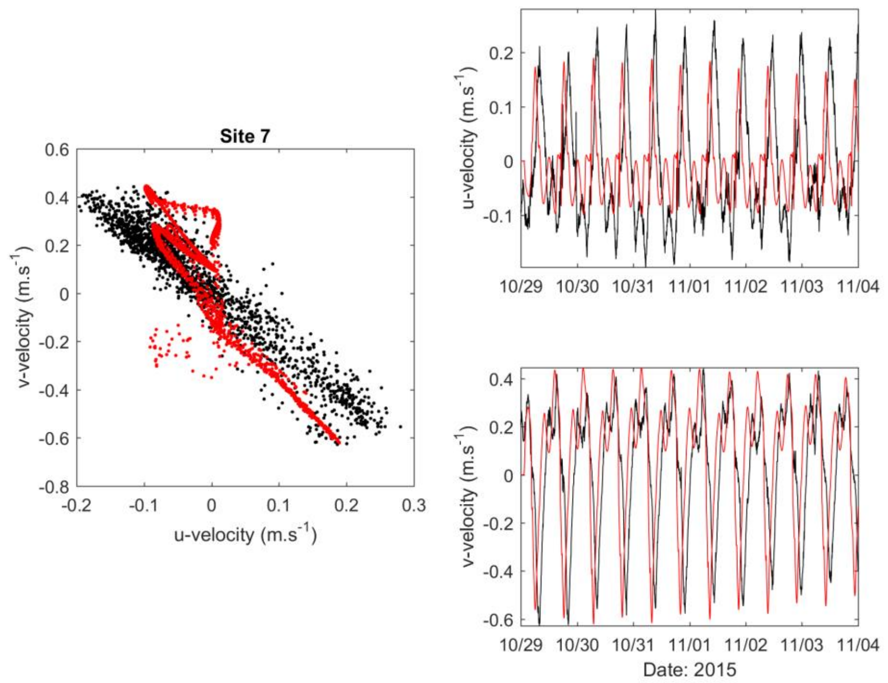

Figure B-9: Measured (red) and modelled (black) depth-averaged u and v components of velocity at Site 7 for the 10 October - 4 November 2015.

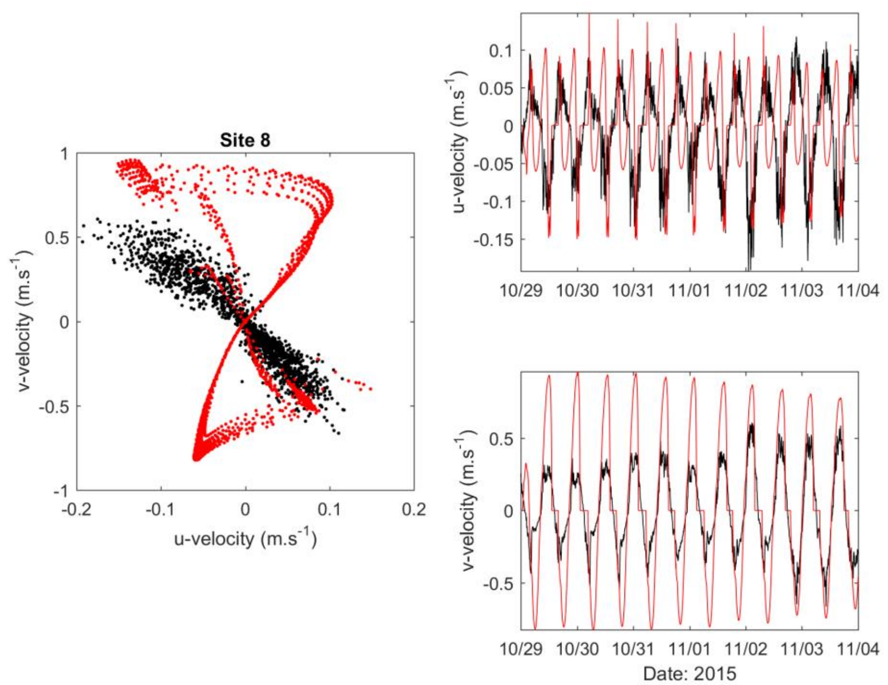

Figure B-10: Measured (red) and modelled (black) depth-averaged u and v components of velocity at Site 8 for the 10 October - 4 November 2015.

Appendix C Calibration statistics

Bias is a measure of the overall offset between the model predictions and the observations. The most common measure of bias uses the mean of the differences, although there are circumstances where using the median is appropriate. Bias is sometimes referred to as reliability. In this definition a "reliable" model does not consistently over-predict or under-predict, but is not necessarily accurate (Sutherland et al. 2004).

$$Bias = \frac{1}{n}\sum_{i=1}^{n}(y_i - x_i)$$

Where: x_i is the modelled, y_i the measured value, and n the number of values being compared.

Accuracy is a measure of difference between a prediction and the corresponding observations. The average accuracy can be represented in a dimensional or a non-dimensional (relative accuracy) manner.

The **root mean square error (RMSE)** has been used as a statistical measure of the dimensional model accuracy.

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(y_i - x_i)^2}$$

Where: x_i is the prediction and y_i the true value and n the number of values being compared.

Model skill is a measure **(*SKILL*)** where values span 1 (high) to 0 (poor) skill decreases towards zero as described by Warner et al. (2005) and Haidvogel et al. (2008). *SKILL* is defined as:

$$SKILL = 1 - [|X_m - X_o|^2] / \left[\sum_{i=1}^{N}(|X_{mi} - \overline{X_o}| + |X_{oi} - \overline{X_o}|)^2\right],$$

where X is a variable and $\bar{X}$ is a time average of the variable. Subscript m and o are for modelled and observed values respectively.

Cross correlation function (R_{xy}) is a statistical method of quantifying the similarity between two waveforms as a function of a time-lag between two time series data sets. For example, the timing of an observed and modelled tidal curve. This is computed from the cross-covariance function:

$$C_{xy}(\tau) \equiv E[\{y(t) - \mu_y\}\{x(t+\tau) - \mu_x\}]$$

Where: C_{xy} is the cross-covariance function, E is the expected value, $x(t)$ and $y(t)$ are discrete variables at time t, μ_y and u_x are means of the time series, and τ is the time lag.

The cross-correlation function (R_{xy}) is a non-dimensional summary of this analysis which ranges from 0 to 1, where 1 infers a strong phase agreement between the two signals.

$$R_{xy} \equiv \frac{C_{xy}(\tau)}{\sigma_x \sigma_y}$$

Where: σ_x, σ_y are the standard deviations of each time series.

Appendix D Modelled extreme storm-tide elevations, for present-day and SLR scenarios

Table D-1: Modelled storm-tide sea levels at sites throughout Tauranga Harbour, for present-day and SLR scenarios. Site locations are shown in Figure 6-1. Columns represent the 18 scenarios described in Table 6-3. SLR is specified relative to MVD–53, and 0.13 m SLR is the projected MSL in 2020, which is considered to be “present-day”.

Location	MHWS–7 + 0.13 m SLR	MHWS–7 + 0.4 m SLR	MHWS–7 + 0.6 m SLR	MHWS–7 + 0.8 m SLR	MHWS–7 + 1.25 m SLR	MHWS–7 + 1.6 m SLR	2% AEP + 0.13 m SLR	2% AEP + 1.25 m SLR	1% AEP + 0.13 m SLR	1% AEP + 0.2 m SLR	1% AEP + 0.4 m SLR	1% AEP + 0.6 m SLR	1% AEP + 0.8 m SLR	1% AEP + 1.25 m SLR	1% AEP + 1.6 m SLR	0.2% AEP + 0.13 m SLR	0.2% AEP + 1.25 m SLR	0.2% AEP + 1.6 m SLR
Location	Scenario 01	Scenario 02	Scenario 03	Scenario 04	Scenario 05	Scenario 06	Scenario 07	Scenario 08	Scenario 09	Scenario 10	Scenario 11	Scenario 12	Scenario 13	Scenario 14	Scenario 15	Scenario 16	Scenario 17	Scenario 18
1	1.04	1.30	1.50	1.70	2.15	2.5	1.79	2.94	1.89	1.96	2.17	2.38	2.59	3.06	3.42	2.12	3.32	3.68
2	1.04	1.30	1.49	1.69	2.14	2.5	1.83	2.98	1.94	2.01	2.21	2.42	2.63	3.11	3.46	2.21	3.40	3.75
3	1.06	1.32	1.52	1.72	2.18	2.53	1.92	3.08	2.03	2.11	2.32	2.52	2.73	3.21	3.58	2.37	3.57	3.94
4	1.06	1.32	1.52	1.72	2.18	2.54	1.86	3.06	1.98	2.06	2.27	2.49	2.70	3.20	3.58	2.28	3.55	3.94
5	1.06	1.33	1.52	1.73	2.19	2.54	1.94	3.12	2.07	2.15	2.35	2.56	2.78	3.26	3.64	2.43	3.66	4.04
6	1.06	1.33	1.53	1.73	2.19	2.54	2.13	3.24	2.28	2.35	2.54	2.73	2.93	3.40	3.76	2.74	3.87	4.24
7	1.07	1.34	1.54	1.75	2.21	2.57	2.08	3.26	2.22	2.29	2.49	2.71	2.93	3.42	3.79	2.65	3.90	4.28
8	1.08	1.35	1.55	1.76	2.22	2.58	2.08	3.26	2.22	2.29	2.51	2.71	2.93	3.42	3.81	2.65	3.91	4.30
9	1.09	1.37	1.57	1.78	2.23	2.6	2.08	3.26	2.21	2.28	2.50	2.71	2.94	3.43	3.81	2.63	3.90	4.29
10	1.10	1.37	1.57	1.77	2.24	2.6	2.07	3.26	2.21	2.27	2.49	2.70	2.93	3.42	3.80	2.62	3.89	4.28
11	1.09	1.37	1.57	1.78	2.23	2.6	2.09	3.27	2.24	2.29	2.51	2.73	2.95	3.44	3.81	2.66	3.91	4.30
12	1.09	1.36	1.56	1.77	2.23	2.59	2.10	3.28	2.24	2.31	2.52	2.73	2.95	3.44	3.82	2.68	3.92	4.31
13	1.08	1.36	1.56	1.76	2.22	2.59	2.10	3.27	2.24	2.31	2.53	2.73	2.95	3.44	3.82	2.68	3.93	4.32
14	1.08	1.36	1.56	1.76	2.23	2.59	2.11	3.28	2.25	2.32	2.54	2.75	2.96	3.45	3.83	2.70	3.95	4.33
15	1.08	1.36	1.56	1.77	2.23	2.59	2.13	3.29	2.27	2.34	2.55	2.76	2.97	3.47	3.84	2.73	3.96	4.35
16	1.08	1.35	1.56	1.76	2.22	2.58	2.10	3.28	2.25	2.32	2.53	2.74	2.95	3.45	3.82	2.69	3.94	4.32
17	1.07	1.34	1.54	1.75	2.21	2.57	2.08	3.26	2.23	2.30	2.50	2.71	2.93	3.43	3.80	2.66	3.92	4.30
18	1.07	1.34	1.54	1.75	2.21	2.57	2.12	3.29	2.27	2.34	2.54	2.75	2.96	3.46	3.82	2.72	3.96	4.32
19	1.08	1.35	1.55	1.75	2.21	2.57	2.15	3.31	2.29	2.36	2.56	2.77	2.98	3.48	3.84	2.76	3.99	4.35

Location	MHWS–7 + 0.13 m SLR	MHWS–7 + 0.4 m SLR	MHWS–7 + 0.6 m SLR	MHWS–7 + 0.8 m SLR	MHWS–7 + 1.25 m SLR	MHWS–7 + 1.6 m SLR	2% AEP + 0.13 m SLR	2% AEP + 1.25 m SLR	1% AEP + 0.13 m SLR	1% AEP + 0.2 m SLR	1% AEP + 0.4 m SLR	1% AEP + 0.6 m SLR	1% AEP + 0.8 m SLR	1% AEP + 1.25 m SLR	1% AEP + 1.6 m SLR	0.2% AEP + 0.13 m SLR	0.2% AEP + 1.25 m SLR	0.2% AEP + 1.6 m SLR
20	1.09	1.36	1.55	1.76	2.22	2.58	2.18	3.33	2.33	2.41	2.60	2.80	3.00	3.51	3.87	2.81	4.03	4.39
21	1.07	1.35	1.55	1.75	2.21	2.57	2.12	3.29	2.27	2.34	2.54	2.75	2.96	3.46	3.83	2.72	3.96	4.33
22	1.07	1.35	1.55	1.75	2.21	2.57	2.11	3.28	2.25	2.32	2.53	2.74	2.95	3.45	3.82	2.70	3.94	4.31
23	1.06	1.33	1.54	1.74	2.2	2.56	2.07	3.25	2.22	2.29	2.49	2.70	2.92	3.41	3.78	2.65	3.89	4.26
24	1.05	1.33	1.53	1.73	2.19	2.55	2.04	3.22	2.19	2.26	2.46	2.68	2.89	3.38	3.74	2.62	3.84	4.21
25	1.06	1.32	1.52	1.72	2.18	2.53	1.96	3.12	2.09	2.16	2.37	2.57	2.78	3.26	3.63	2.45	3.65	4.03
26	1.05	1.31	1.50	1.70	2.16	2.51	1.92	3.07	2.04	2.11	2.32	2.53	2.74	3.21	3.57	2.39	3.57	3.93
27	1.03	1.31	1.51	1.71	2.16	2.51	2.04	3.17	2.18	2.25	2.45	2.65	2.86	3.32	3.68	2.61	3.75	4.09
28	1.05	1.33	1.52	1.72	2.17	2.52	2.11	3.22	2.25	2.32	2.52	2.72	2.92	3.38	3.73	2.72	3.84	4.18
29	1.05	1.33	1.53	1.72	2.17	2.52	2.13	3.23	2.27	2.34	2.53	2.73	2.93	3.39	3.74	2.74	3.85	4.19
30	1.05	1.33	1.53	1.72	2.17	2.52	2.12	3.23	2.26	2.33	2.52	2.72	2.92	3.39	3.73	2.73	3.85	4.19
31	1.04	1.33	1.52	1.72	2.17	2.52	2.11	3.22	2.25	2.32	2.51	2.71	2.91	3.38	3.73	2.71	3.84	4.17
32	1.04	1.32	1.51	1.71	2.16	2.52	2.06	3.19	2.20	2.27	2.47	2.67	2.88	3.35	3.70	2.64	3.79	4.12
33	1.04	1.30	1.50	1.71	2.16	2.51	2.03	3.16	2.16	2.23	2.43	2.64	2.84	3.31	3.66	2.58	3.72	4.07
34	1.04	1.30	1.50	1.70	2.15	2.51	2.01	3.15	2.14	2.22	2.42	2.63	2.83	3.30	3.65	2.56	3.71	4.05
35	1.04	1.29	1.49	1.70	2.15	2.51	1.99	3.15	2.13	2.20	2.41	2.62	2.82	3.29	3.65	2.54	3.70	4.05
36	1.02	1.28	1.49	1.69	2.15	2.51	2.00	3.17	2.16	2.23	2.44	2.64	2.86	3.32	3.67	2.58	3.73	4.08
37	1.03	1.28	1.49	1.69	2.16	2.52	2.02	3.20	2.19	2.26	2.47	2.68	2.90	3.35	3.70	2.62	3.78	4.12
38	1.04	1.30	1.51	1.71	2.17	2.54	2.19	3.36	2.39	2.47	2.67	2.88	3.09	3.53	3.87	2.94	4.06	4.39
39	1.04	1.30	1.51	1.71	2.17	2.54	2.28	3.42	2.49	2.57	2.76	2.96	3.16	3.60	3.93	3.08	4.16	4.48
40	1.06	1.32	1.52	1.73	2.19	2.56	2.39	3.66	2.72	2.90	3.07	3.27	3.45	3.87	4.18	3.53	4.57	4.86
41	1.03	1.30	1.51	1.71	2.17	2.54	2.27	3.40	2.47	2.54	2.73	2.93	3.14	3.57	3.90	3.04	4.12	4.44
42	1.03	1.30	1.50	1.71	2.18	2.54	2.14	3.31	2.32	2.39	2.60	2.81	3.03	3.47	3.81	2.82	3.97	4.30
43	1.03	1.30	1.51	1.71	2.18	2.55	2.10	3.29	2.28	2.35	2.57	2.78	3.00	3.46	3.80	2.75	3.93	4.27
44	1.04	1.30	1.51	1.72	2.19	2.56	2.29	3.42	2.48	2.55	2.75	2.96	3.17	3.60	3.94	3.06	4.17	4.48
45	1.04	1.30	1.52	1.72	2.19	2.56	2.18	3.37	2.40	2.46	2.67	2.88	3.09	3.55	3.88	2.92	4.07	4.40

Location	MHWS−7 + 0.13 m SLR	MHWS−7 + 0.4 m SLR	MHWS−7 + 0.6 m SLR	MHWS−7 + 0.8 m SLR	MHWS−7 + 1.25 m SLR	MHWS−7 + 1.6 m SLR	2% AEP + 0.13 m SLR	2% AEP + 1.25 m SLR	1% AEP + 0.13 m SLR	1% AEP + 0.2 m SLR	1% AEP + 0.4 m SLR	1% AEP + 0.6 m SLR	1% AEP + 0.8 m SLR	1% AEP + 1.25 m SLR	1% AEP + 1.6 m SLR	0.2% AEP + 0.13 m SLR	0.2% AEP + 1.25 m SLR	0.2% AEP + 1.6 m SLR
46	1.05	1.32	1.53	1.74	2.2	2.57	2.30	3.47	2.55	2.59	2.79	3.00	3.21	3.65	3.98	3.12	4.23	4.54
47	0.92	1.29	1.52	1.73	2.19	2.56	2.34	3.47	2.56	2.61	2.81	3.01	3.22	3.66	3.99	3.15	4.25	4.56
48	1.01	1.30	1.51	1.73	2.2	2.56	2.43	3.53	2.65	2.70	2.89	3.09	3.29	3.72	4.04	3.28	4.33	4.64
49	1.01	1.31	1.51	1.72	2.19	2.56	2.22	3.37	2.42	2.48	2.69	2.90	3.10	3.55	3.88	2.94	4.07	4.39
50	1.03	1.30	1.51	1.72	2.19	2.56	2.05	3.22	2.21	2.28	2.50	2.71	2.92	3.37	3.72	2.61	3.77	4.11
51	1.04	1.31	1.52	1.73	2.21	2.58	2.07	3.24	2.23	2.31	2.53	2.74	2.95	3.39	3.74	2.65	3.80	4.13
52	1.05	1.32	1.53	1.74	2.22	2.59	2.28	3.40	2.47	2.53	2.75	2.95	3.14	3.57	3.90	2.99	4.08	4.40
53	1.07	1.27	1.53	1.75	2.23	2.6	2.57	3.59	2.76	2.81	3.01	3.20	3.38	3.79	4.11	3.42	4.42	4.72
54	1.05	1.32	1.53	1.74	2.22	2.59	2.29	3.40	2.48	2.54	2.76	2.96	3.15	3.58	3.91	3.01	4.09	4.41
55	1.07	1.34	1.55	1.76	2.23	2.61	2.43	3.50	2.60	2.69	2.89	3.08	3.27	3.69	4.02	3.22	4.26	4.57
56	1.07	1.34	1.53	1.76	2.23	2.61	2.64	3.63	2.81	2.88	3.08	3.26	3.43	3.83	4.15	3.50	4.49	4.78
57	1.07	1.32	1.53	1.76	2.24	2.61	2.41	3.50	2.60	2.69	2.89	3.08	3.26	3.68	4.01	3.20	4.24	4.55
58	1.06	1.30	1.48	1.70	2.26	2.61	2.40	3.56	2.69	2.79	2.98	3.16	3.34	3.75	4.07	3.34	4.35	4.65
59	1.07	1.34	1.55	1.76	2.23	2.61	2.29	3.38	2.44	2.54	2.73	2.92	3.11	3.55	3.89	2.97	4.01	4.34
60	1.07	1.29	1.54	1.74	2.24	2.61	2.37	3.46	2.50	2.67	2.86	3.04	3.22	3.64	3.97	3.17	4.16	4.48
61	1.06	1.31	1.55	1.75	2.24	2.61	2.23	3.34	2.37	2.48	2.68	2.88	3.06	3.50	3.85	2.88	3.95	4.29
62	1.06	1.33	1.54	1.76	2.23	2.6	2.11	3.25	2.24	2.34	2.55	2.76	2.95	3.40	3.75	2.67	3.78	4.13
63	1.02	1.30	1.52	1.73	2.21	2.59	2.03	3.13	2.16	2.23	2.42	2.62	2.81	3.27	3.63	2.50	3.56	3.92
64	1.02	1.30	1.52	1.74	2.21	2.59	2.20	3.25	2.36	2.41	2.59	2.78	2.97	3.40	3.75	2.83	3.79	4.12
65	1.03	1.31	1.52	1.74	2.21	2.59	2.40	3.37	2.57	2.61	2.77	2.94	3.12	3.54	3.88	3.17	3.99	4.31
66	1.02	1.31	1.52	1.74	2.21	2.59	2.25	3.28	2.41	2.46	2.64	2.82	3.00	3.44	3.78	2.91	3.83	4.16
67	1.02	1.30	1.52	1.73	2.21	2.59	2.08	3.17	2.22	2.28	2.47	2.67	2.86	3.31	3.67	2.59	3.63	3.98
68	1.03	1.31	1.53	1.74	2.21	2.6	2.31	3.33	2.49	2.54	2.71	2.89	3.07	3.50	3.84	3.04	3.92	4.25
69	1.03	1.31	1.52	1.74	2.21	2.6	2.11	3.19	2.26	2.32	2.50	2.70	2.89	3.34	3.70	2.66	3.67	4.01
70	1.02	1.31	1.52	1.74	2.21	2.59	2.04	3.22	2.17	2.24	2.45	2.66	2.88	3.35	3.71	2.50	3.63	4.00
71	1.02	1.30	1.52	1.73	2.21	2.59	1.95	3.16	2.07	2.14	2.36	2.57	2.80	3.28	3.65	2.36	3.51	3.88

Location	MHWS−7 + 0.13 m SLR	MHWS−7 + 0.4 m SLR	MHWS−7 + 0.6 m SLR	MHWS−7 + 0.8 m SLR	MHWS−7 + 1.25 m SLR	MHWS−7 + 1.6 m SLR	2% AEP + 0.13 m SLR	2% AEP + 1.25 m SLR	1% AEP + 0.13 m SLR	1% AEP + 0.2 m SLR	1% AEP + 0.4 m SLR	1% AEP + 0.6 m SLR	1% AEP + 0.8 m SLR	1% AEP + 1.25 m SLR	1% AEP + 1.6 m SLR	0.2% AEP + 0.13 m SLR	0.2% AEP + 1.25 m SLR	0.2% AEP + 1.6 m SLR
72	1.00	1.29	1.50	1.72	2.2	2.58	1.89	3.08	2.01	2.08	2.28	2.48	2.69	3.19	3.57	2.27	3.38	3.76
73	0.99	1.28	1.50	1.71	2.19	2.57	1.90	3.13	2.03	2.09	2.32	2.54	2.76	3.25	3.63	2.25	3.49	3.88
74	1.00	1.28	1.50	1.72	2.2	2.58	2.07	3.25	2.21	2.27	2.49	2.70	2.91	3.39	3.76	2.54	3.73	4.09
75	0.99	1.28	1.51	1.72	2.2	2.58	2.14	3.30	2.29	2.34	2.56	2.77	2.98	3.45	3.81	2.67	3.82	4.18
76	0.99	1.27	1.51	1.73	2.2	2.58	2.11	3.30	2.27	2.31	2.54	2.77	2.97	3.44	3.80	2.64	3.81	4.17
77	0.94	1.29	1.51	1.72	2.2	2.58	2.25	3.38	2.41	2.46	2.67	2.87	3.08	3.53	3.89	2.86	3.96	4.30
78	0.99	1.27	1.49	1.71	2.19	2.57	2.02	3.21	2.16	2.22	2.43	2.65	2.86	3.34	3.71	2.46	3.65	4.02
79	0.97	1.26	1.47	1.69	2.18	2.56	1.94	3.16	2.07	2.14	2.36	2.58	2.80	3.29	3.67	2.34	3.57	3.95
80	0.94	1.23	1.45	1.66	2.14	2.52	1.80	3.05	1.92	1.99	2.22	2.45	2.67	3.17	3.54	2.10	3.37	3.76
81	0.93	1.21	1.42	1.63	2.11	2.49	1.83	3.06	1.95	2.03	2.25	2.47	2.70	3.19	3.56	2.18	3.43	3.81
82	0.93	1.20	1.41	1.63	2.1	2.47	1.83	3.05	1.95	2.03	2.24	2.46	2.68	3.17	3.55	2.20	3.43	3.81
83	0.89	1.21	1.43	1.65	2.11	2.47	1.96	3.08	2.09	2.15	2.30	2.50	2.72	3.22	3.59	2.46	3.51	3.89
84	0.90	1.22	1.43	1.66	2.11	2.47	2.06	3.23	2.22	2.29	2.50	2.71	2.91	3.38	3.73	2.65	3.77	4.13
85	0.96	1.22	1.42	1.63	2.1	2.47	1.97	3.16	2.12	2.19	2.41	2.61	2.82	3.30	3.66	2.49	3.66	4.03
86	0.96	1.22	1.43	1.64	2.11	2.47	2.05	3.21	2.21	2.28	2.48	2.68	2.89	3.36	3.72	2.63	3.75	4.11
87	0.95	1.22	1.43	1.64	2.11	2.47	2.22	3.31	2.39	2.46	2.65	2.83	3.03	3.48	3.83	2.90	3.94	4.29
88	0.98	1.23	1.43	1.64	2.11	2.47	2.20	3.31	2.37	2.44	2.63	2.82	3.02	3.47	3.82	2.87	3.93	4.28
89	0.98	1.23	1.43	1.64	2.1	2.46	2.05	3.20	2.20	2.27	2.48	2.68	2.88	3.35	3.71	2.62	3.75	4.11
90	0.98	1.23	1.43	1.64	2.1	2.46	2.13	3.25	2.30	2.36	2.56	2.75	2.95	3.41	3.76	2.76	3.85	4.20
91	0.98	1.23	1.43	1.63	2.1	2.45	2.20	3.27	2.37	2.44	2.63	2.81	2.99	3.44	3.78	2.87	3.89	4.24
92	0.90	1.12	1.27	1.45	1.89	2.22	1.83	3.06	1.88	1.92	2.09	2.34	2.60	3.24	3.65	2.35	3.71	4.10
93	0.88	1.11	1.26	1.45	1.88	2.22	1.88	3.10	1.94	1.96	2.15	2.40	2.64	3.28	3.68	2.44	3.77	4.15
94	0.97	1.22	1.41	1.61	2.06	2.39	2.13	3.16	2.29	2.35	2.53	2.70	2.87	3.32	3.68	2.77	3.77	4.15
95	0.98	1.23	1.43	1.64	2.1	2.46	1.91	3.11	2.05	2.12	2.34	2.55	2.76	3.25	3.62	2.38	3.58	3.95
96	0.94	1.20	1.40	1.61	2.07	2.44	1.78	3.01	1.90	1.98	2.20	2.42	2.64	3.13	3.50	2.14	3.37	3.75
97	0.94	1.23	1.44	1.66	2.14	2.52	1.75	3.01	1.85	1.93	2.15	2.38	2.62	3.12	3.51	1.99	3.31	3.71

Location	MHWS–7 + 0.13 m SLR	MHWS–7 + 0.4 m SLR	MHWS–7 + 0.6 m SLR	MHWS–7 + 0.8 m SLR	MHWS–7 + 1.25 m SLR	MHWS–7 + 1.6 m SLR	2% AEP + 0.13 m SLR	2% AEP + 1.25 m SLR	1% AEP + 0.13 m SLR	1% AEP + 0.2 m SLR	1% AEP + 0.4 m SLR	1% AEP + 0.6 m SLR	1% AEP + 0.8 m SLR	1% AEP + 1.25 m SLR	1% AEP + 1.6 m SLR	0.2% AEP + 0.13 m SLR	0.2% AEP + 1.25 m SLR	0.2% AEP + 1.6 m SLR
98	1.01	1.30	1.51	1.72	2.21	2.59	1.59	2.82	1.67	1.75	1.97	2.19	2.42	2.91	3.29	1.76	2.99	3.38
99	1.04	1.34	1.54	1.74	2.24	2.60	1.82	2.99	1.91	1.98	2.17	2.40	2.62	3.09	3.46	2.10	3.27	3.64
100	1.01	1.31	1.52	1.73	2.21	2.59	1.84	2.99	1.95	2.02	2.22	2.42	2.63	3.10	3.48	2.16	3.30	3.66
101	1.06	1.33	1.53	1.74	2.22	2.59	1.95	3.13	2.08	2.17	2.39	2.60	2.80	3.26	3.62	2.40	3.56	3.92
102	1.03	1.30	1.51	1.71	2.19	2.56	1.94	3.13	2.09	2.16	2.39	2.61	2.82	3.27	3.63	2.42	3.62	3.97
103	1.02	1.32	1.52	1.71	2.18	2.55	2.22	3.05	2.37	2.41	2.54	2.68	2.82	3.17	3.46	2.82	3.49	3.72
104	1.00	1.31	1.51	1.71	2.17	2.54	1.98	2.88	2.10	2.14	2.29	2.44	2.60	2.98	3.36	2.39	3.15	3.52
105	1.02	1.28	1.49	1.69	2.15	2.51	1.85	3.06	2.00	2.07	2.29	2.50	2.73	3.19	3.55	2.30	3.51	3.87
106	1.01	1.27	1.46	1.66	2.12	2.47	1.76	2.96	1.89	1.96	2.17	2.38	2.59	3.08	3.45	2.16	3.38	3.74

Appendix E Wave setup and runup

Table E-1: Wave setup at 106 sites within Tauranga Harbour. Site locations are shown in Figure 6-1. Modelled results are shown for the fetch direction that produced maximum wave setup at that location, which was also the direction of maximum fetch at most sites. Depths are positive downward and are relative to 2 m (the height of a high storm-tide) above MVD–53. H_s = significant wave height (metres), T_p = peak wave period (seconds), GT81 = Guza and Thornton (1981), K90l,u = King et al. (1990) lower and upper, HN93g,s = Hanslow and Nielsen (1993) general and beach-slope dependent, RB01 = Raubenheimer et al. (2001), SK06 = Stockdon et al. (2006) and Median = median of all methods. Wave setup was calculated using a 1(V):10(H) beach slope. Sites 20, 40 and 53 are located inside river channels with no fetch and no waves.

Location	Easting (NZTM)	Northing (NZTM)	Fetch direction (°N)	Fetch (m)	Depth (m)	H_s (m)	T_p (s)	GT81	K90l	K90u	HN93g	HN93s	SK06	RB01	Median
1	1880171	5830048	180	4530	9.7	1.1	4.2	0.19	0.12	0.17	0.27	0.25	0.20	0.25	0.20
2	1880713	5829319	247.5	5170	6.2	1.2	4.3	0.20	0.13	0.17	0.28	0.26	0.20	0.26	0.20
3	1880425	5826337	0	3590	14.0	1.0	4.0	0.17	0.11	0.15	0.24	0.23	0.18	0.23	0.18
4	1880855	5825839	202.5	4390	2.9	1.0	3.9	0.17	0.11	0.15	0.23	0.21	0.17	0.21	0.17
5	1881681	5824765	247.5	2330	3.2	0.8	3.5	0.13	0.09	0.12	0.18	0.17	0.13	0.17	0.13
6	1882023	5823343	315	3230	2.7	0.9	3.7	0.15	0.10	0.13	0.20	0.19	0.15	0.19	0.15
7	1881083	5822302	225	2780	2.8	0.8	3.6	0.14	0.09	0.12	0.19	0.18	0.14	0.18	0.14
8	1881513	5822204	90	3540	2.7	0.9	3.7	0.15	0.10	0.13	0.21	0.20	0.15	0.20	0.15
9	1883082	5823206	90	1360	1.7	0.6	2.9	0.10	0.06	0.09	0.13	0.13	0.10	0.13	0.10
10	1885292	5822839	247.5	4350	2.6	0.9	3.8	0.16	0.10	0.14	0.22	0.21	0.16	0.21	0.16
11	1884686	5821707	270	3810	2.6	0.9	3.7	0.15	0.10	0.14	0.21	0.20	0.16	0.20	0.16
12	1883086	5821304	45	2410	2.3	0.8	3.4	0.13	0.08	0.11	0.18	0.17	0.13	0.17	0.13
13	1882286	5821003	247.5	2200	2.4	0.7	3.3	0.12	0.08	0.11	0.17	0.16	0.13	0.16	0.13
14	1881778	5820366	337.5	2830	2.9	0.8	3.6	0.14	0.09	0.12	0.20	0.18	0.14	0.18	0.14
15	1880886	5820000	45	4710	2.5	1.0	3.8	0.16	0.11	0.14	0.22	0.21	0.16	0.21	0.16
16	1881285	5821001	67.5	4420	2.4	0.9	3.8	0.16	0.10	0.14	0.22	0.21	0.16	0.21	0.16
17	1880984	5821601	337.5	3490	4.9	1.0	3.9	0.16	0.11	0.14	0.23	0.21	0.17	0.21	0.17
18	1879070	5820549	22.5	5400	2.8	1.0	4.0	0.18	0.11	0.15	0.24	0.23	0.18	0.23	0.18
19	1878194	5819907	22.5	1740	2.6	0.7	3.2	0.11	0.07	0.10	0.16	0.15	0.12	0.15	0.12
20	1877139	5819169													
21	1878082	5821096	157.5	1200	2.3	0.6	2.9	0.10	0.06	0.09	0.13	0.12	0.10	0.13	0.10
22	1878866	5821494	202.5	1740	2.6	0.7	3.2	0.11	0.07	0.10	0.16	0.15	0.11	0.15	0.11
23	1879128	5822813	112.5	3960	3.3	1.0	3.9	0.16	0.11	0.14	0.23	0.21	0.17	0.21	0.17
24	1879592	5823987	180	3330	3.2	0.9	3.7	0.15	0.10	0.13	0.21	0.20	0.15	0.20	0.15
25	1879776	5825702	180	4900	4.6	1.1	4.2	0.19	0.12	0.16	0.26	0.25	0.19	0.24	0.19
26	1879553	5827286	292.5	19570	4.7	1.7	5.1	0.29	0.18	0.25	0.40	0.37	0.29	0.37	0.29
27	1879075	5826001	0	10000	11.8	1.6	5.2	0.28	0.18	0.25	0.40	0.37	0.29	0.36	0.29
28	1878814	5824322	0	1600	2.2	0.6	3.1	0.11	0.07	0.10	0.15	0.14	0.11	0.14	0.11
29	1878079	5823261	22.5	2600	2.3	0.8	3.4	0.13	0.09	0.12	0.18	0.17	0.13	0.17	0.13

Location	Easting (NZTM)	Northing (NZTM)	Fetch direction (°N)	Fetch (m)	Depth (m)	H_s (m)	T_p (s)	GT81	K90l	K90u	HN93g	HN93s	SK06	RB01	Median
30	1877492	5824245	45	2110	2.1	0.7	3.3	0.12	0.08	0.11	0.17	0.15	0.12	0.16	0.12
31	1878276	5825099	180	1670	2.2	0.7	3.1	0.11	0.07	0.10	0.15	0.14	0.11	0.14	0.11
32	1878631	5825954	180	1970	2.2	0.7	3.2	0.12	0.08	0.10	0.16	0.15	0.12	0.15	0.12
33	1878735	5826322	315	4810	5.3	1.1	4.2	0.19	0.12	0.17	0.27	0.25	0.19	0.24	0.19
34	1878073	5826600	337.5	4520	5.5	1.1	4.2	0.18	0.12	0.16	0.26	0.24	0.19	0.24	0.19
35	1876966	5827034	292.5	6330	3.4	1.1	4.2	0.19	0.12	0.17	0.27	0.25	0.20	0.25	0.20
36	1876073	5827327	315	6120	5.0	1.2	4.4	0.21	0.13	0.18	0.29	0.27	0.21	0.27	0.21
37	1875566	5827183	315	9330	3.7	1.3	4.5	0.22	0.14	0.20	0.31	0.29	0.23	0.29	0.23
38	1875273	5825895	247.5	2470	2.5	0.8	3.4	0.13	0.09	0.12	0.18	0.17	0.13	0.17	0.13
39	1873973	5825092	22.5	6150	3.8	1.2	4.3	0.20	0.13	0.17	0.28	0.26	0.20	0.25	0.20
40	1872697	5823215													
41	1872988	5825796	45	5840	4.0	1.1	4.3	0.20	0.13	0.17	0.27	0.26	0.20	0.25	0.20
42	1872262	5826998	67.5	5790	4.0	1.1	4.3	0.19	0.13	0.17	0.27	0.26	0.20	0.25	0.20
43	1870764	5827744	90	9940	4.3	1.4	4.7	0.24	0.15	0.21	0.33	0.31	0.24	0.30	0.24
44	1870565	5826406	337.5	510	1.6	0.4	2.3	0.06	0.04	0.06	0.09	0.08	0.06	0.08	0.06
45	1868950	5827564	67.5	5620	4.5	1.2	4.3	0.20	0.13	0.17	0.28	0.26	0.20	0.25	0.20
46	1868359	5825262	45	1070	2.2	0.5	2.8	0.09	0.06	0.08	0.13	0.12	0.09	0.12	0.09
47	1868637	5826525	0	1030	2.1	0.5	2.8	0.09	0.06	0.08	0.12	0.11	0.09	0.12	0.09
48	1867129	5827115	45	980	1.8	0.5	2.8	0.09	0.06	0.08	0.12	0.11	0.09	0.11	0.09
49	1867914	5828690	90	10000	5.1	1.4	4.8	0.25	0.16	0.22	0.35	0.33	0.25	0.32	0.25
50	1869393	5830621	90	4520	5.2	1.1	4.1	0.18	0.12	0.16	0.26	0.24	0.19	0.24	0.19
51	1869001	5831130	337.5	21060	3.3	1.4	4.6	0.25	0.16	0.22	0.33	0.31	0.24	0.32	0.25
52	1867248	5829928	337.5	14580	2.8	1.3	4.2	0.21	0.14	0.19	0.29	0.27	0.21	0.28	0.21
53	1865426	5828558													
54	1866215	5830325	67.5	4850	4.4	1.1	4.2	0.19	0.12	0.16	0.26	0.24	0.19	0.24	0.19
55	1864557	5830488	315	2860	2.2	0.8	3.5	0.14	0.09	0.12	0.19	0.17	0.14	0.18	0.14
56	1863946	5829763	22.5	11180	2.2	1.1	3.9	0.18	0.12	0.16	0.24	0.23	0.18	0.24	0.18
57	1863378	5831279	45	5870	2.5	1.0	3.9	0.17	0.11	0.15	0.24	0.22	0.17	0.23	0.17
58	1861830	5831293	45	8040	1.9	1.0	3.7	0.17	0.11	0.15	0.22	0.20	0.16	0.21	0.17
59	1862507	5833612	22.5	9660	2.5	1.1	4.1	0.19	0.12	0.17	0.26	0.24	0.19	0.25	0.19
60	1861039	5833557	22.5	1320	1.3	0.6	2.8	0.09	0.06	0.08	0.13	0.12	0.09	0.12	0.09
61	1861317	5834666	112.5	10000	3.0	1.2	4.3	0.21	0.14	0.19	0.29	0.27	0.21	0.27	0.21
62	1862592	5835121	112.5	10000	3.4	1.3	4.4	0.22	0.14	0.19	0.30	0.28	0.22	0.28	0.22
63	1862476	5837335	22.5	7340	3.3	1.2	4.3	0.20	0.13	0.18	0.28	0.26	0.20	0.26	0.20
64	1861438	5836055	22.5	9240	3.5	1.3	4.4	0.22	0.14	0.19	0.30	0.28	0.22	0.28	0.22
65	1860624	5835435	22.5	10390	3.0	1.2	4.3	0.21	0.14	0.19	0.29	0.27	0.21	0.27	0.21
66	1859934	5836714	45	8630	2.8	1.2	4.2	0.20	0.13	0.17	0.27	0.25	0.20	0.26	0.20
67	1860033	5837806	45	7940	3.3	1.2	4.3	0.20	0.13	0.18	0.28	0.27	0.21	0.27	0.21

Location	Easting (NZTM)	Northing (NZTM)	Fetch direction (°N)	Fetch (m)	Depth (m)	H_s (m)	T_p (s)	GT81	K90l	K90u	HN93g	HN93s	SK06	RB01	Median
68	1858449	5836449	22.5	2080	1.7	0.7	3.2	0.12	0.07	0.10	0.16	0.15	0.11	0.15	0.12
69	1858980	5837939	67.5	1450	2.3	0.6	3.1	0.11	0.07	0.09	0.14	0.13	0.10	0.14	0.11
70	1858757	5838966	90	10000	2.5	1.1	4.1	0.19	0.13	0.17	0.26	0.24	0.19	0.25	0.19
71	1859893	5839349	112.5	8120	2.1	1.0	3.8	0.17	0.11	0.15	0.23	0.22	0.17	0.23	0.17
72	1860872	5839611	45	6290	3.6	1.1	4.2	0.19	0.13	0.17	0.27	0.26	0.20	0.25	0.20
73	1860467	5840690	135	15030	3.3	1.4	4.5	0.23	0.15	0.21	0.32	0.30	0.23	0.30	0.23
74	1859324	5841532	90	7350	3.2	1.2	4.2	0.20	0.13	0.17	0.27	0.26	0.20	0.26	0.20
75	1858253	5841317	67.5	2140	2.2	0.7	3.3	0.12	0.08	0.11	0.17	0.16	0.12	0.16	0.12
76	1857888	5840844	0	1090	1.0	0.5	2.6	0.08	0.05	0.07	0.11	0.10	0.08	0.11	0.08
77	1857792	5841833	90	8690	3.0	1.2	4.2	0.20	0.13	0.18	0.28	0.26	0.20	0.26	0.20
78	1860481	5842193	112.5	9740	2.8	1.2	4.2	0.20	0.13	0.18	0.27	0.26	0.20	0.26	0.20
79	1861968	5843495	157.5	14700	3.0	1.3	4.4	0.22	0.14	0.20	0.30	0.28	0.22	0.29	0.22
80	1863163	5844199	157.5	14470	3.5	1.4	4.6	0.24	0.15	0.21	0.32	0.30	0.24	0.31	0.24
81	1862534	5845228	135	10000	3.6	1.3	4.5	0.22	0.14	0.20	0.31	0.29	0.22	0.29	0.22
82	1861782	5846135	0	5080	3.1	1.0	4.0	0.18	0.11	0.16	0.25	0.23	0.18	0.23	0.18
83	1860137	5845601	22.5	1740	2.3	0.7	3.2	0.11	0.07	0.10	0.16	0.15	0.11	0.15	0.11
84	1858845	5846173	112.5	1050	1.6	0.5	2.8	0.09	0.06	0.08	0.12	0.11	0.09	0.11	0.09
85	1860608	5847953	112.5	3430	4.6	1.0	3.9	0.16	0.10	0.14	0.23	0.21	0.17	0.21	0.17
86	1859629	5847681	67.5	4050	3.2	1.0	3.9	0.16	0.11	0.14	0.23	0.21	0.17	0.21	0.17
87	1859986	5849469	135	5500	4.3	1.1	4.3	0.19	0.13	0.17	0.27	0.25	0.20	0.25	0.20
88	1860996	5850610	157.5	21050	3.5	1.5	4.6	0.25	0.16	0.22	0.34	0.32	0.25	0.32	0.25
89	1862658	5851041	180	6060	4.1	1.2	4.3	0.20	0.13	0.17	0.28	0.26	0.20	0.26	0.20
90	1862370	5851668	337.5	1480	1.4	0.6	2.9	0.10	0.06	0.09	0.13	0.12	0.10	0.13	0.10
91	1862036	5852181	0	500	1.6	0.4	2.3	0.06	0.04	0.06	0.09	0.08	0.06	0.08	0.06
92	1861726	5852787	135	1170	1.1	0.5	2.7	0.09	0.06	0.08	0.12	0.11	0.08	0.11	0.09
93	1861569	5852995	135	800	1.2	0.4	2.6	0.08	0.05	0.07	0.10	0.10	0.07	0.10	0.08
94	1862072	5852514	157.5	980	1.6	0.5	2.7	0.09	0.06	0.08	0.12	0.11	0.09	0.11	0.09
95	1863190	5849974	180	5880	5.9	1.2	4.4	0.21	0.13	0.18	0.29	0.28	0.21	0.27	0.21
96	1863751	5847882	180	16190	3.91	1.50	4.77	0.25	0.16	0.22	0.35	0.33	0.26	0.33	0.26
97	1864724	5844813	180	14150	3.03	1.31	4.38	0.22	0.14	0.20	0.30	0.28	0.22	0.29	0.22
98	1867998	5840064	315	6560	4.15	1.20	4.37	0.20	0.13	0.18	0.29	0.27	0.21	0.26	0.21
99	1870756	5836829	315	10760	3.46	1.32	4.48	0.22	0.14	0.20	0.31	0.29	0.23	0.29	0.23
100	1867581	5837557	337.5	8230	3.55	1.24	4.39	0.21	0.14	0.19	0.29	0.28	0.21	0.27	0.21
101	1867548	5834878	337.5	17080	3.52	1.44	4.63	0.25	0.16	0.22	0.33	0.31	0.24	0.32	0.25
102	1871166	5831696	270	9010	3.44	1.26	4.41	0.21	0.14	0.19	0.30	0.28	0.22	0.28	0.22
103	1871940	5833701	247.5	4930	3.46	1.05	4.06	0.18	0.12	0.16	0.25	0.23	0.18	0.23	0.18
104	1874044	5833039	315	2380	1.90	0.73	3.30	0.12	0.08	0.11	0.17	0.16	0.12	0.16	0.12
105	1875631	5829765	112.5	5480	9.38	1.23	4.45	0.21	0.14	0.18	0.30	0.28	0.22	0.27	0.22

Location	Easting (NZTM)	Northing (NZTM)	Fetch direction (°N)	Fetch (m)	Depth (m)	H_s (m)	T_p (s)	GT81	K90l	K90u	HN93g	HN93s	SK06	RB01	Median
106	1878502	5829295	135	3090	7.56	0.94	3.83	0.16	0.10	0.14	0.22	0.21	0.16	0.21	0.16
Minimum				500	1.0	0.4	2.3	0.06	0.04	0.06	0.09	0.08	0.06	0.08	0.06
Median				4850	3.0	1.0	4.0	0.18	0.11	0.16	0.24	0.23	0.18	0.23	0.18
Maximum				21060	14.0	1.7	5.2	0.29	0.18	0.25	0.40	0.37	0.29	0.37	0.29
2.5th percentile				684	1.1	0.4	2.5	0.07	0.05	0.06	0.10	0.09	0.07	0.09	0.07
10th percentile				1182	1.7	0.5	2.8	0.09	0.06	0.08	0.13	0.12	0.09	0.12	0.09
90th percentile				12962	5.1	1.4	4.5	0.23	0.15	0.20	0.31	0.29	0.23	0.30	0.23
97.5th percentile				20162	10.5	1.6	4.9	0.26	0.17	0.23	0.37	0.35	0.27	0.34	0.27

Appendix F Modelled storm-tide + wave-setup elevations

Table F-1: Modelled storm-tide + wave setup sea levels at sites throughout Tauranga Harbour, for present-day and SLR scenarios. These elevations are a combination of the storm-tide elevations in Table D-1 added to the median wave setup elevations on right-most column of Table E-1. Site locations are shown in Figure 6 1 and Table E-1. Columns represent the 18 scenarios described in Table 6-1. SLR is specified relative to MVD–53, and 0.13 m SLR is the projected MSL in 2020, which is considered to be "present-day".

Location	MHWS–7 + 0.13 m SLR	MHWS–7 + 0.4 m SLR	MHWS–7 + 0.6 m SLR	MHWS–7 + 0.8 m SLR	MHWS–7 + 1.25 m SLR	MHWS–7 + 1.6 m SLR	2% AEP + 0.13 m SLR	2% AEP + 1.25 m SLR	1% AEP + 0.13 m SLR	1% AEP + 0.2 m SLR	1% AEP + 0.4 m SLR	1% AEP + 0.6 m SLR	1% AEP + 0.8 m SLR	1% AEP + 1.25 m SLR	1% AEP + 1.6 m SLR	0.2% AEP + 0.13 m SLR	0.2% AEP + 1.25 m SLR	0.2% AEP + 1.6 m SLR
Location	Scenario 01	Scenario 02	Scenario 03	Scenario 04	Scenario 05	Scenario 06	Scenario 07	Scenario 08	Scenario 09	Scenario 10	Scenario 11	Scenario 12	Scenario 13	Scenario 14	Scenario 15	Scenario 16	Scenario 17	Scenario 18
1	1.04	1.30	1.50	1.70	2.15	2.50	1.99	3.14	2.09	2.16	2.36	2.57	2.78	3.26	3.62	2.32	3.52	3.88
2	1.04	1.30	1.49	1.69	2.14	2.50	2.04	3.18	2.14	2.21	2.42	2.62	2.83	3.31	3.67	2.41	3.60	3.96
3	1.06	1.32	1.52	1.72	2.18	2.53	2.09	3.25	2.21	2.29	2.49	2.70	2.91	3.39	3.76	2.55	3.75	4.12
4	1.06	1.32	1.52	1.72	2.18	2.54	2.03	3.23	2.15	2.22	2.44	2.65	2.87	3.37	3.75	2.45	3.72	4.11
5	1.06	1.33	1.52	1.73	2.19	2.54	2.08	3.25	2.20	2.28	2.49	2.70	2.91	3.40	3.77	2.56	3.79	4.17
6	1.06	1.33	1.53	1.73	2.19	2.54	2.28	3.39	2.43	2.50	2.69	2.88	3.08	3.55	3.91	2.89	4.02	4.39
7	1.07	1.34	1.54	1.75	2.21	2.57	2.22	3.40	2.36	2.43	2.63	2.85	3.07	3.56	3.93	2.79	4.05	4.42
8	1.08	1.35	1.55	1.76	2.22	2.58	2.23	3.41	2.37	2.44	2.66	2.87	3.09	3.58	3.96	2.81	4.06	4.45
9	1.09	1.37	1.57	1.78	2.23	2.60	2.18	3.36	2.31	2.38	2.60	2.81	3.04	3.53	3.91	2.73	4.00	4.39
10	1.10	1.37	1.57	1.77	2.24	2.60	2.23	3.42	2.37	2.43	2.65	2.87	3.09	3.58	3.96	2.78	4.05	4.45
11	1.09	1.37	1.57	1.78	2.23	2.60	2.25	3.43	2.39	2.45	2.67	2.89	3.11	3.59	3.97	2.81	4.07	4.46
12	1.09	1.36	1.56	1.77	2.23	2.59	2.23	3.41	2.37	2.44	2.65	2.86	3.08	3.57	3.95	2.81	4.05	4.44
13	1.08	1.36	1.56	1.76	2.22	2.59	2.23	3.40	2.37	2.44	2.65	2.86	3.07	3.57	3.95	2.81	4.06	4.44
14	1.08	1.36	1.56	1.76	2.23	2.59	2.26	3.42	2.40	2.47	2.68	2.89	3.10	3.60	3.97	2.85	4.09	4.47
15	1.08	1.36	1.56	1.77	2.23	2.59	2.29	3.46	2.43	2.50	2.72	2.92	3.13	3.63	4.00	2.89	4.13	4.51
16	1.08	1.35	1.56	1.76	2.22	2.58	2.26	3.44	2.40	2.47	2.69	2.90	3.11	3.60	3.98	2.85	4.10	4.48
17	1.07	1.34	1.54	1.75	2.21	2.57	2.25	3.43	2.40	2.47	2.67	2.88	3.10	3.60	3.97	2.83	4.08	4.46
18	1.07	1.34	1.54	1.75	2.21	2.57	2.30	3.47	2.45	2.52	2.71	2.93	3.14	3.63	4.00	2.90	4.13	4.50
19	1.08	1.35	1.55	1.75	2.21	2.57	2.26	3.42	2.41	2.48	2.68	2.88	3.09	3.59	3.96	2.87	4.10	4.46

Location	MHWS−7 + 0.13 m SLR	MHWS−7 + 0.4 m SLR	MHWS−7 + 0.6 m SLR	MHWS−7 + 0.8 m SLR	MHWS−7 + 1.25 m SLR	MHWS−7 + 1.6 m SLR	2% AEP + 0.13 m SLR	2% AEP + 1.25 m SLR	1% AEP + 0.13 m SLR	1% AEP + 0.2 m SLR	1% AEP + 0.4 m SLR	1% AEP + 0.6 m SLR	1% AEP + 0.8 m SLR	1% AEP + 1.25 m SLR	1% AEP + 1.6 m SLR	0.2% AEP + 0.13 m SLR	0.2% AEP + 1.25 m SLR	0.2% AEP + 1.6 m SLR
20	1.09	1.36	1.55	1.76	2.22	2.58	2.18	3.33	2.33	2.41	2.60	2.80	3.00	3.51	3.87	2.81	4.03	4.39
21	1.07	1.35	1.55	1.75	2.21	2.57	2.22	3.39	2.36	2.44	2.64	2.85	3.06	3.56	3.92	2.82	4.06	4.42
22	1.07	1.35	1.55	1.75	2.21	2.57	2.22	3.39	2.37	2.44	2.64	2.85	3.06	3.56	3.93	2.81	4.06	4.43
23	1.06	1.33	1.54	1.74	2.20	2.56	2.24	3.41	2.39	2.46	2.66	2.87	3.09	3.58	3.94	2.82	4.06	4.43
24	1.05	1.33	1.53	1.73	2.19	2.55	2.20	3.37	2.34	2.41	2.62	2.83	3.05	3.53	3.90	2.77	4.00	4.36
25	1.06	1.32	1.52	1.72	2.18	2.53	2.15	3.31	2.28	2.35	2.56	2.76	2.97	3.46	3.83	2.64	3.85	4.22
26	1.05	1.31	1.50	1.70	2.16	2.51	2.21	3.36	2.33	2.40	2.61	2.82	3.03	3.50	3.86	2.68	3.86	4.22
27	1.03	1.31	1.51	1.71	2.16	2.51	2.34	3.46	2.47	2.54	2.74	2.94	3.15	3.62	3.97	2.90	4.04	4.39
28	1.05	1.33	1.52	1.72	2.17	2.52	2.22	3.33	2.36	2.43	2.62	2.83	3.03	3.49	3.84	2.83	3.95	4.29
29	1.05	1.33	1.53	1.72	2.17	2.52	2.26	3.37	2.40	2.47	2.66	2.86	3.06	3.53	3.87	2.87	3.99	4.32
30	1.05	1.33	1.53	1.72	2.17	2.52	2.24	3.35	2.38	2.45	2.64	2.84	3.04	3.51	3.85	2.85	3.97	4.31
31	1.04	1.33	1.52	1.72	2.17	2.52	2.22	3.33	2.36	2.43	2.62	2.82	3.02	3.49	3.84	2.82	3.95	4.28
32	1.04	1.32	1.51	1.71	2.16	2.52	2.18	3.31	2.31	2.39	2.59	2.79	2.99	3.46	3.81	2.76	3.90	4.24
33	1.04	1.30	1.50	1.71	2.16	2.51	2.22	3.35	2.35	2.43	2.63	2.83	3.03	3.50	3.85	2.78	3.92	4.26
34	1.04	1.30	1.50	1.70	2.15	2.51	2.20	3.34	2.33	2.41	2.61	2.82	3.02	3.49	3.84	2.75	3.90	4.24
35	1.04	1.29	1.49	1.70	2.15	2.51	2.19	3.34	2.33	2.40	2.61	2.81	3.02	3.49	3.84	2.74	3.90	4.24
36	1.02	1.28	1.49	1.69	2.15	2.51	2.21	3.38	2.37	2.44	2.65	2.86	3.07	3.53	3.88	2.79	3.95	4.29
37	1.03	1.28	1.49	1.69	2.16	2.52	2.25	3.42	2.41	2.49	2.70	2.91	3.12	3.58	3.92	2.85	4.01	4.35
38	1.04	1.30	1.51	1.71	2.17	2.54	2.32	3.49	2.52	2.60	2.80	3.01	3.22	3.67	4.00	3.07	4.19	4.52
39	1.04	1.30	1.51	1.71	2.17	2.54	2.48	3.62	2.69	2.77	2.96	3.16	3.37	3.80	4.13	3.28	4.36	4.68
40	1.06	1.32	1.52	1.73	2.19	2.56	2.42	3.66	2.69	2.90	3.07	3.27	3.45	3.86	4.18	3.52	4.57	4.86
41	1.03	1.30	1.51	1.71	2.17	2.54	2.47	3.60	2.67	2.74	2.93	3.13	3.34	3.77	4.10	3.24	4.32	4.64
42	1.03	1.30	1.50	1.71	2.18	2.54	2.34	3.51	2.52	2.59	2.80	3.01	3.23	3.67	4.01	3.02	4.17	4.50
43	1.03	1.30	1.51	1.71	2.18	2.55	2.34	3.53	2.53	2.59	2.81	3.02	3.24	3.70	4.04	2.99	4.17	4.51
44	1.04	1.30	1.51	1.72	2.19	2.56	2.35	3.49	2.55	2.61	2.81	3.02	3.23	3.67	4.00	3.12	4.23	4.55
45	1.04	1.30	1.52	1.72	2.19	2.56	2.40	3.57	2.61	2.66	2.88	3.09	3.30	3.75	4.09	3.12	4.27	4.60

Location	MHWS−7 + 0.13 m SLR	MHWS−7 + 0.4 m SLR	MHWS−7 + 0.6 m SLR	MHWS−7 + 0.8 m SLR	MHWS−7 + 1.25 m SLR	MHWS−7 + 1.6 m SLR	2% AEP + 0.13 m SLR	2% AEP + 1.25 m SLR	1% AEP + 0.13 m SLR	1% AEP + 0.2 m SLR	1% AEP + 0.4 m SLR	1% AEP + 0.6 m SLR	1% AEP + 0.8 m SLR	1% AEP + 1.25 m SLR	1% AEP + 1.6 m SLR	0.2% AEP + 0.13 m SLR	0.2% AEP + 1.25 m SLR	0.2% AEP + 1.6 m SLR
46	1.05	1.32	1.53	1.74	2.20	2.57	2.40	3.56	2.64	2.68	2.89	3.10	3.30	3.74	4.07	3.21	4.32	4.63
47	0.92	1.29	1.52	1.73	2.19	2.56	2.43	3.56	2.65	2.70	2.90	3.10	3.31	3.75	4.08	3.24	4.34	4.65
48	1.01	1.30	1.51	1.73	2.20	2.56	2.52	3.61	2.73	2.79	2.98	3.18	3.38	3.81	4.13	3.37	4.42	4.73
49	1.01	1.31	1.51	1.72	2.19	2.56	2.46	3.62	2.66	2.72	2.93	3.14	3.35	3.79	4.13	3.17	4.31	4.63
50	1.03	1.30	1.51	1.72	2.19	2.56	2.24	3.41	2.40	2.47	2.69	2.90	3.11	3.56	3.91	2.79	3.96	4.30
51	1.04	1.31	1.52	1.73	2.21	2.58	2.32	3.49	2.48	2.56	2.77	2.99	3.19	3.64	3.98	2.90	4.04	4.38
52	1.05	1.32	1.53	1.74	2.22	2.59	2.50	3.61	2.68	2.75	2.96	3.16	3.36	3.78	4.12	3.21	4.29	4.62
53	1.07	1.27	1.53	1.75	2.23	2.60	2.58	3.59	2.77	2.82	3.02	3.21	3.39	3.79	4.11	3.43	4.43	4.73
54	1.05	1.32	1.53	1.74	2.22	2.59	2.48	3.59	2.67	2.73	2.95	3.15	3.34	3.77	4.10	3.20	4.28	4.60
55	1.07	1.34	1.55	1.76	2.23	2.61	2.57	3.64	2.74	2.83	3.03	3.22	3.40	3.82	4.15	3.35	4.40	4.71
56	1.07	1.34	1.53	1.76	2.23	2.61	2.75	3.77	2.92	3.00	3.20	3.38	3.56	3.96	4.29	3.58	4.60	4.90
57	1.07	1.32	1.53	1.76	2.24	2.61	2.58	3.67	2.77	2.87	3.06	3.25	3.44	3.85	4.18	3.38	4.41	4.73
58	1.06	1.30	1.48	1.70	2.26	2.61	2.57	3.73	2.86	2.96	3.14	3.33	3.51	3.92	4.24	3.51	4.51	4.82
59	1.07	1.34	1.55	1.76	2.23	2.61	2.47	3.57	2.62	2.73	2.93	3.11	3.31	3.74	4.08	3.16	4.21	4.54
60	1.07	1.29	1.54	1.74	2.24	2.61	2.47	3.56	2.59	2.77	2.95	3.13	3.32	3.73	4.07	3.26	4.25	4.57
61	1.06	1.31	1.55	1.75	2.24	2.61	2.44	3.55	2.58	2.69	2.89	3.09	3.27	3.71	4.06	3.09	4.16	4.49
62	1.06	1.33	1.54	1.76	2.23	2.60	2.33	3.47	2.46	2.56	2.77	2.97	3.17	3.62	3.97	2.89	4.00	4.35
63	1.02	1.30	1.52	1.73	2.21	2.59	2.23	3.34	2.37	2.43	2.62	2.82	3.02	3.47	3.83	2.70	3.77	4.12
64	1.02	1.30	1.52	1.74	2.21	2.59	2.42	3.47	2.57	2.63	2.81	3.00	3.18	3.62	3.97	3.05	4.00	4.34
65	1.03	1.31	1.52	1.74	2.21	2.59	2.52	3.54	2.70	2.74	2.91	3.09	3.27	3.70	4.05	3.25	4.13	4.45
66	1.02	1.31	1.52	1.74	2.21	2.59	2.41	3.45	2.57	2.62	2.80	2.99	3.17	3.61	3.96	3.04	3.99	4.32
67	1.02	1.30	1.52	1.73	2.21	2.59	2.28	3.38	2.43	2.49	2.68	2.88	3.07	3.52	3.88	2.80	3.84	4.19
68	1.03	1.31	1.53	1.74	2.21	2.60	2.43	3.45	2.60	2.65	2.82	3.01	3.19	3.61	3.96	3.16	4.04	4.36
69	1.03	1.31	1.52	1.74	2.21	2.60	2.21	3.30	2.37	2.42	2.61	2.81	3.00	3.45	3.80	2.76	3.77	4.12
70	1.02	1.31	1.52	1.74	2.21	2.59	2.23	3.41	2.37	2.43	2.64	2.85	3.07	3.54	3.90	2.71	3.82	4.19
71	1.02	1.30	1.52	1.73	2.21	2.59	2.12	3.33	2.25	2.31	2.53	2.75	2.97	3.45	3.82	2.53	3.69	4.06

Location	MHWS–7 + 0.13 m SLR	MHWS–7 + 0.4 m SLR	MHWS–7 + 0.6 m SLR	MHWS–7 + 0.8 m SLR	MHWS–7 + 1.25 m SLR	MHWS–7 + 1.6 m SLR	2% AEP + 0.13 m SLR	2% AEP + 1.25 m SLR	1% AEP + 0.13 m SLR	1% AEP + 0.2 m SLR	1% AEP + 0.4 m SLR	1% AEP + 0.6 m SLR	1% AEP + 0.8 m SLR	1% AEP + 1.25 m SLR	1% AEP + 1.6 m SLR	0.2% AEP + 0.13 m SLR	0.2% AEP + 1.25 m SLR	0.2% AEP + 1.6 m SLR
72	1.00	1.29	1.50	1.72	2.20	2.58	2.08	3.28	2.20	2.27	2.47	2.67	2.89	3.39	3.76	2.46	3.57	3.96
73	0.99	1.28	1.50	1.71	2.19	2.57	2.13	3.37	2.26	2.33	2.55	2.78	3.00	3.49	3.86	2.48	3.73	4.11
74	1.00	1.28	1.50	1.72	2.20	2.58	2.27	3.45	2.41	2.47	2.68	2.90	3.11	3.59	3.96	2.74	3.93	4.29
75	0.99	1.28	1.51	1.72	2.20	2.58	2.26	3.42	2.41	2.46	2.68	2.89	3.10	3.57	3.94	2.79	3.95	4.30
76	0.99	1.27	1.51	1.73	2.20	2.58	2.20	3.38	2.36	2.40	2.63	2.85	3.05	3.52	3.89	2.73	3.89	4.25
77	0.94	1.29	1.51	1.72	2.20	2.58	2.45	3.58	2.61	2.66	2.87	3.07	3.28	3.73	4.09	3.06	4.16	4.50
78	0.99	1.27	1.49	1.71	2.19	2.57	2.22	3.41	2.36	2.42	2.63	2.85	3.07	3.55	3.91	2.66	3.85	4.22
79	0.97	1.26	1.47	1.69	2.18	2.56	2.16	3.39	2.29	2.36	2.58	2.80	3.02	3.51	3.89	2.56	3.79	4.17
80	0.94	1.23	1.45	1.66	2.14	2.52	2.04	3.29	2.15	2.23	2.45	2.68	2.91	3.41	3.78	2.34	3.61	3.99
81	0.93	1.21	1.42	1.63	2.11	2.49	2.05	3.29	2.18	2.25	2.48	2.70	2.92	3.41	3.79	2.41	3.65	4.04
82	0.93	1.20	1.41	1.63	2.10	2.47	2.01	3.23	2.13	2.21	2.42	2.64	2.86	3.35	3.73	2.38	3.61	3.99
83	0.89	1.21	1.43	1.65	2.11	2.47	2.07	3.20	2.20	2.27	2.42	2.61	2.83	3.33	3.70	2.58	3.62	4.01
84	0.90	1.22	1.43	1.66	2.11	2.47	2.15	3.32	2.31	2.38	2.59	2.80	3.00	3.46	3.82	2.74	3.86	4.22
85	0.96	1.22	1.42	1.63	2.10	2.47	2.13	3.32	2.29	2.36	2.57	2.78	2.99	3.47	3.83	2.65	3.82	4.19
86	0.96	1.22	1.43	1.64	2.11	2.47	2.22	3.38	2.38	2.44	2.65	2.85	3.06	3.53	3.88	2.79	3.91	4.27
87	0.95	1.22	1.43	1.64	2.11	2.47	2.42	3.51	2.59	2.65	2.84	3.03	3.23	3.68	4.02	3.09	4.14	4.48
88	0.98	1.23	1.43	1.64	2.11	2.47	2.45	3.56	2.62	2.69	2.88	3.07	3.27	3.72	4.07	3.13	4.18	4.53
89	0.98	1.23	1.43	1.64	2.10	2.46	2.25	3.40	2.41	2.48	2.68	2.88	3.08	3.55	3.91	2.82	3.95	4.31
90	0.98	1.23	1.43	1.64	2.10	2.46	2.23	3.35	2.39	2.46	2.66	2.85	3.05	3.51	3.86	2.86	3.94	4.30
91	0.98	1.23	1.43	1.63	2.10	2.45	2.27	3.34	2.44	2.50	2.69	2.87	3.06	3.50	3.85	2.94	3.96	4.30
92	0.90	1.12	1.27	1.45	1.89	2.22	1.91	3.15	1.96	2.00	2.18	2.43	2.69	3.33	3.73	2.44	3.80	4.19
93	0.88	1.11	1.26	1.45	1.88	2.22	1.94	3.16	1.99	2.02	2.21	2.46	2.71	3.35	3.75	2.49	3.83	4.21
94	0.97	1.22	1.41	1.61	2.06	2.39	2.25	3.26	2.40	2.46	2.64	2.80	2.98	3.42	3.78	2.88	3.87	4.24
95	0.98	1.23	1.43	1.64	2.10	2.46	2.12	3.32	2.26	2.34	2.56	2.76	2.98	3.46	3.83	2.59	3.79	4.17
96	0.94	1.20	1.40	1.61	2.07	2.44	2.04	3.26	2.16	2.24	2.46	2.67	2.89	3.39	3.76	2.40	3.63	4.01
97	0.94	1.23	1.44	1.66	2.14	2.52	1.97	3.24	2.08	2.15	2.38	2.61	2.84	3.35	3.73	2.22	3.53	3.93

Location	MHWS–7 + 0.13 m SLR	MHWS–7 + 0.4 m SLR	MHWS–7 + 0.6 m SLR	MHWS–7 + 0.8 m SLR	MHWS–7 + 1.25 m SLR	MHWS–7 + 1.6 m SLR	2% AEP + 0.13 m SLR	2% AEP + 1.25 m SLR	1% AEP + 0.13 m SLR	1% AEP + 0.2 m SLR	1% AEP + 0.4 m SLR	1% AEP + 0.6 m SLR	1% AEP + 0.8 m SLR	1% AEP + 1.25 m SLR	1% AEP + 1.6 m SLR	0.2% AEP + 0.13 m SLR	0.2% AEP + 1.25 m SLR	0.2% AEP + 1.6 m SLR
98	1.01	1.30	1.51	1.72	2.21	2.59	1.80	3.02	1.88	1.96	2.18	2.40	2.63	3.12	3.50	1.97	3.20	3.59
99	1.04	1.34	1.54	1.74	2.24	2.60	2.04	3.21	2.14	2.21	2.40	2.63	2.85	3.32	3.69	2.33	3.50	3.87
100	1.01	1.31	1.52	1.73	2.21	2.59	2.06	3.21	2.16	2.23	2.43	2.64	2.85	3.32	3.69	2.37	3.51	3.88
101	1.06	1.33	1.53	1.74	2.22	2.59	2.19	3.38	2.32	2.41	2.64	2.85	3.05	3.51	3.87	2.65	3.81	4.16
102	1.03	1.30	1.51	1.71	2.19	2.56	2.16	3.35	2.30	2.37	2.60	2.82	3.03	3.49	3.84	2.64	3.84	4.19
103	1.02	1.32	1.52	1.71	2.18	2.55	2.40	3.23	2.55	2.59	2.72	2.86	3.00	3.35	3.64	3.00	3.67	3.91
104	1.00	1.31	1.51	1.71	2.17	2.54	2.10	3.00	2.22	2.27	2.42	2.57	2.72	3.10	3.48	2.51	3.28	3.64
105	1.02	1.28	1.49	1.69	2.15	2.51	2.07	3.28	2.21	2.28	2.50	2.72	2.94	3.41	3.76	2.52	3.73	4.08
106	1.01	1.27	1.46	1.66	2.12	2.47	1.93	3.12	2.05	2.12	2.33	2.54	2.76	3.25	3.61	2.32	3.54	3.90

Appendix G Figure 8-4 and Tables 8-5 and 8-6 from Stephens (2017)

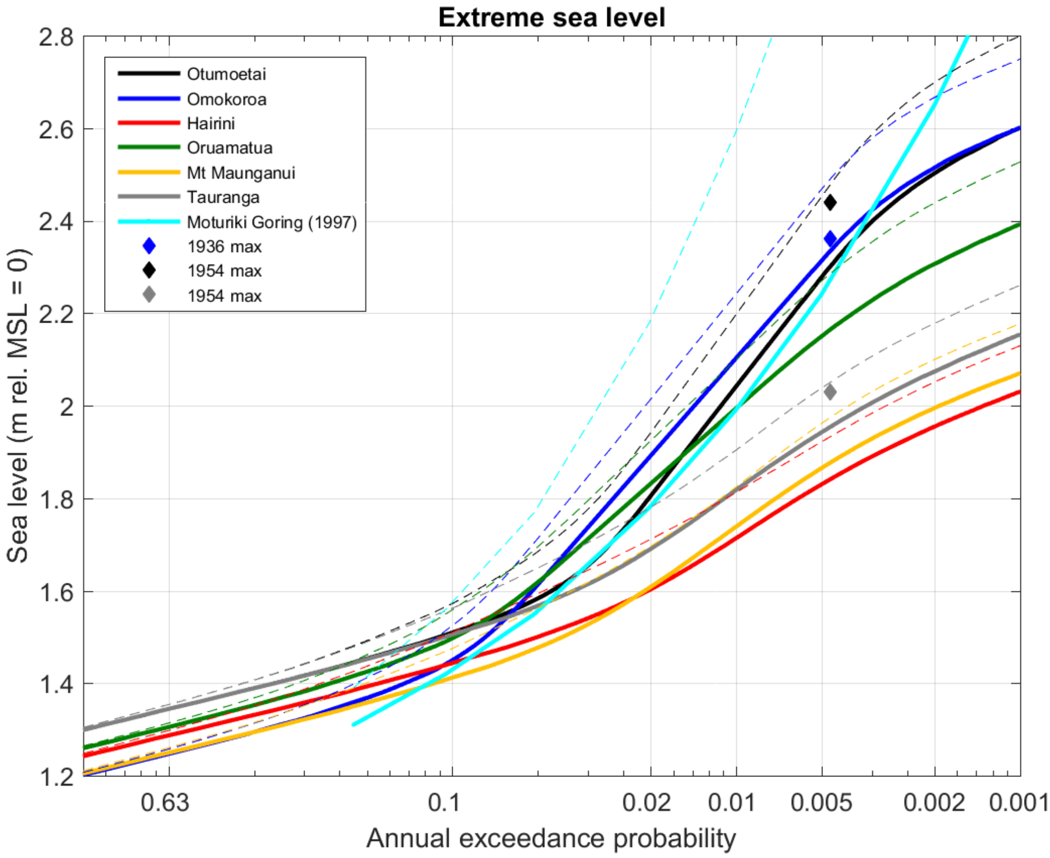

Figure 8-4: Extreme sea levels in Tauranga Harbour. Sea levels require the addition of MSL to make them relative to MVD–53. Dashed lines represent upper 95% confidence intervals. Extreme sea levels were calculated using the SSJPM method, except at Moturiki where the Goring et al. (1997) RJPM results are used. Historic maxima are plotted using Gringorten (1963) plotting position for the annual maximum in a 120-year sequence.

Table 8-5: Maximum potential sea levels in Tauranga Harbour using a "building block" approach for maximal values of the components. Sea levels require the further addition of MSL to make them relative to MVD–53. Only measured maxima are included – the potential for larger surges is not considered.

Site	MSLA	Tide	Measured surge	Maximum (measured) potential TWL	Historical surge	Maximum (historical) potential TWL
Mount Maunganui	0.17	1.07	0.88	2.12	0.88	2.12
Tauranga	0.17	1.21	0.75	2.13	0.75	2.13
Omokoroa	0.14	1.06	0.55	1.75	1.68	2.88
Oruamatua	0.40	1.12	0.51	2.03	1.07	2.59
Hairini	0.24	1.12	0.38	1.74	0.83	2.19
Moturiki	0.15	1.14	0.53	1.82		

Table 8-6: Extreme sea levels in Tauranga Harbour relative to MVD–53, including 2020 MSL (projected).

	AEP	0.1	0.02	0.01	0.005	0.002
	ARI	**10**	**50**	**100**	**200**	**500**
Mount Maunganui	Lower	1.51	1.67	1.79	1.90	2.02
	Median	**1.54**	**1.74**	**1.87**	**2.00**	**2.12**
	Upper	1.61	1.83	1.95	2.09	2.23
Tauranga	Lower	1.58	1.72	1.84	1.95	2.07
	Median	**1.61**	**1.79**	**1.92**	**2.04**	**2.17**
	Upper	1.66	1.88	2.00	2.14	2.28
Otumoetai	Lower	1.58	1.78	2.00	2.21	2.42
	Median	**1.61**	**1.90**	**2.14**	**2.38**	**2.60**
	Upper	1.67	2.04	2.30	2.55	2.80
Omokoroa	Lower	1.57	1.94	2.13	2.33	2.51
	Median	**1.61**	**2.05**	**2.26**	**2.47**	**2.67**
	Upper	1.68	2.17	2.40	2.63	2.83
Oruamatua	Lower	1.64	1.92	2.08	2.22	2.37
	Median	**1.68**	**2.01**	**2.17**	**2.33**	**2.49**
	Upper	1.74	2.10	2.28	2.45	2.62
Hairini	Lower	1.59	1.71	1.81	1.92	2.03
	Median	**1.61**	**1.77**	**1.88**	**2.00**	**2.12**
	Upper	1.68	1.88	1.98	2.09	2.22

Appendix H Inundation map metadata

Identification information

Name: Tauranga Harbour storm-tide inundation raw model files.

Abstract: Inundation maps were produced for the total inundation level based on both the storm-tide and wave setup for a set of annual exceedance probability likelihoods of 2%, 1% and 0.2% (50, 100 and 500-year average recurrence intervals). The inundation levels and maps were calculated relative to Moturiki Vertical Datum 1953 (MVD–53) and include a present day mean sea level of 0.13 m to the year 2020. Further inundation maps were produced for additional sea-level rise scenarios of 0.2, 0.4, 0.6, 0.8, 1.25 and 1.6 m MVD–53.

Purpose: Map the overland extent of coastal inundation for the Tauranga Harbour coastline. These inundation hazard map outputs can be used for RMA planning and climate change adaptation planning. The mapped inundation scenarios were designed to meet the requirements of the New Zealand Coastal Policy Statement, the Bay of Plenty Regional Policy Statement and the recently updated MfE (2017) guidance for local government on climate change and coastal hazards.

Access constraints: Permission for use required from Bay of Plenty Regional Council, Tauranga City Council and western Bay of Plenty District Council.

Use constraints: Use in conjunction with report Reeve G, Stephens SA, Wadhwa S 2018. Tauranga Harbour inundation modelling. NIWA Client Report 2018269HN to Bay of Plenty Regional Council, June 2019. 107 p.

Credit: Glen Reeve, Scott Stephens, Sanjay Wadhwa, National institute of Water and Atmospheric Research, New Zealand.

Originator: Glen Reeve, Scott Stephens, Sanjay Wadhwa, National institute of Water and Atmospheric Research, New Zealand.

Publication Date: 20190601, 1 June 2019.

Progress: Complete.

Update frequency: None planned.

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Quality

Completeness report: Inundation maps cover the entire Tauranga Harbour, except upstream of the Wairoa River Rail Bridge.

Data acquisition methods: Storm-tides were simulated using Delft2d–FM hydrodynamic model. The model bathymetry was built from surveyed depths and LiDAR. Storm-tide elevations from the model were exported to GIS and then overland depths were calculated from the elevation difference between the simulated storm-tide height and the underlying a 1 × 1 m bathymetry to determine the inundation depths at 1 × 1 m resolution. The results are presented as GIS files. A complete description is provided in Reeve G, Stephens SA, Wadhwa S 2018. Tauranga Harbour inundation modelling. NIWA Client Report 2018269HN to Bay of Plenty Regional Council, June 2019. 107 p.

Attribute field descriptions

Data were supplied as a GIS geodatabase where each layer has associated metadata inserted into the GIS file. The following tables summarise the metadata.

Table H-1: Delft2D-FM, GIS raw model output attribute field names and description of the data in each field. MHWS–7 occurs approximately once every fortnight. SLR = sea-level rise. wl_max and max_eta both describe maximum water level, but max_eta was created by merging simulations of two wind directions.

Scenario	Name of processed GIS layer (raw)	Description	Hazard layer exceedance probability (%)	MSL above MVD-53	Layer type	Attribute name
1	sc01_mhws7_slr013	MHWS–7 + 0.13 m SLR	MHWS–7	0.13	Polygon	wl_max
2	sc02_mhws7_slr040	MHWS–7 + 0.4 m SLR	MHWS–7	0.4	Polygon	wl_max
3	sc03_mhws7_slr060	MHWS–7 + 0.6 m SLR	MHWS–7	0.6	Polygon	wl_max
4	sc04_mhws7_slr080	MHWS–7 + 0.8 m SLR	MHWS–7	0.8	Polygon	wl_max
5	sc05_mhws7_slr125	MHWS–7 + 1.25 m SLR	MHWS–7	1.25	Polygon	wl_max
6	sc06_mhws7_slr160	MHWS–7 + 1.6 m SLR	MHWS–7	1.6	Polygon	wl_max
7	sc07_2AEP_slr013	2% AEP + 0.13 m SLR	2% AEP	0.13	Polygon	max_eta
8	sc08_2AEP_slr125	2% AEP + 1.25 m SLR	2% AEP	1.25	Polygon	max_eta
9	sc09_1AEP_slr013	1% AEP + 0.13 m SLR	1% AEP	0.13	Polygon	max_eta

Scenario	Name of processed GIS layer (raw)	Description	Hazard layer exceedance probability (%)	MSL above MVD-53	Layer type	Attribute name
10	sc10_1AEP_slr020	1% AEP + 0.2 m SLR	1% AEP	0.2	Polygon	max_eta
11	sc11_1AEP_slr040	1% AEP + 0.4 m SLR	1% AEP	0.4	Polygon	max_eta
12	sc12_1AEP_slr060	1% AEP + 0.6 m SLR	1% AEP	0.6	Polygon	max_eta
13	sc13_1AEP_slr080	1% AEP + 0.8 m SLR	1% AEP	0.8	Polygon	max_eta
14	sc14_1AEP_slr125	1% AEP + 1.25 m SLR	1% AEP	1.25	Polygon	max_eta
15	sc15_1AEP_slr160	1% AEP + 1.6 m SLR	1% AEP	1.6	Polygon	max_eta
16	sc16_02AEP_slr013	0.2% AEP + 0.13 m SLR	0.2% AEP	0.13	Polygon	max_eta
17	sc17_02AEP_slr125	0.2% AEP + 1.25 m SLR	0.2% AEP	1.25	Polygon	max_eta
18	sc18_02AEP_slr160	0.2% AEP + 1.6 m SLR	0.2% AEP	1.6	Polygon	max_eta

Table H-2: GIS polygons of inundation extent.

Name of geodatabase—tauranga_harbour_ inundation_polygons_May2019.gdb. This geodatabase includes direct inundation polygons for all model scenario layers, direct meaning that all isolated polygons ("ponds") from each scenario layer have been removed.

Scenario	Name of processed GIS layer (raw)	Description	Hazard layer exceedance probability (%)	MSL above MVD-53	Layer type
1	sc01_mhws7_slr013	MHWS–7 + 0.13 m SLR	MHWS–7	0.13	Polygon
2	sc02_mhws7_slr040	MHWS–7 + 0.4 m SLR	MHWS–7	0.4	Polygon
3	sc03_mhws7_slr060	MHWS–7 + 0.6 m SLR	MHWS–7	0.6	Polygon
4	sc04_mhws7_slr080	MHWS–7 + 0.8 m SLR	MHWS–7	0.8	Polygon
5	sc05_mhws7_slr125	MHWS–7 + 1.25 m SLR	MHWS–7	1.25	Polygon
6	sc06_mhws7_slr160	MHWS–7 + 1.6 m SLR	MHWS–7	1.6	Polygon
7	sc07_2AEP_slr013	2% AEP + 0.13 m SLR	2% AEP	0.13	Polygon
8	sc08_2AEP_slr125	2% AEP + 1.25 m SLR	2% AEP	1.25	Polygon
9	sc09_1AEP_slr013	1% AEP + 0.13 m SLR	1% AEP	0.13	Polygon
10	sc10_1AEP_slr020	1% AEP + 0.2 m SLR	1% AEP	0.2	Polygon
11	sc11_1AEP_slr040	1% AEP + 0.4 m SLR	1% AEP	0.4	Polygon
12	sc12_1AEP_slr060	1% AEP + 0.6 m SLR	1% AEP	0.6	Polygon
13	sc13_1AEP_slr080	1% AEP + 0.8 m SLR	1% AEP	0.8	Polygon
14	sc14_1AEP_slr125	1% AEP + 1.25 m SLR	1% AEP	1.25	Polygon
15	sc15_1AEP_slr160	1% AEP + 1.6 m SLR	1% AEP	1.6	Polygon
16	sc16_02AEP_slr013	0.2% AEP + 0.13 m SLR	0.2% AEP	0.13	Polygon
17	sc17_02AEP_slr125	0.2% AEP + 1.25 m SLR	0.2% AEP	1.25	Polygon
18	sc18_02AEP_slr160	0.2% AEP + 1.6 m SLR	0.2% AEP	1.6	Polygon

Table H-3: GIS rasters of inundation depths.

Name of geodatabase—tauranga_harbour_ inundation_depth_rasters_May2019.gdb. This geodatabase has direct inundation rasters for all model scenario layers, direct meaning that all isolated 'ponds" from each scenario layer have been removed. The depth of inundation in metres is available as negative raster values.

Scenario	Name of processed GIS layer (raw)	Description	Hazard layer exceedance probability (%)	MSL above MVD-53	Layer type	Attribute name
1	sc01_mhws7_slr013	MHWS–7 + 0.13 m SLR	MHWS–7	0.13	Raster	Value
2	sc02_mhws7_slr040	MHWS–7 + 0.4 m SLR	MHWS–7	0.4	Raster	Value
3	sc03_mhws7_slr060	MHWS–7 + 0.6 m SLR	MHWS–7	0.6	Raster	Value
4	sc04_mhws7_slr080	MHWS–7 + 0.8 m SLR	MHWS–7	0.8	Raster	Value
5	sc05_mhws7_slr125	MHWS–7 + 1.25 m SLR	MHWS–7	1.25	Raster	Value
6	sc06_mhws7_slr160	MHWS–7 + 1.6 m SLR	MHWS–7	1.6	Raster	Value
7	sc07_2AEP_slr013	2% AEP + 0.13 m SLR	2% AEP	0.13	Raster	Value
8	sc08_2AEP_slr125	2% AEP + 1.25 m SLR	2% AEP	1.25	Raster	Value
9	sc09_1AEP_slr013	1% AEP + 0.13 m SLR	1% AEP	0.13	Raster	Value
10	sc10_1AEP_slr020	1% AEP + 0.2 m SLR	1% AEP	0.2	Raster	Value
11	sc11_1AEP_slr040	1% AEP + 0.4 m SLR	1% AEP	0.4	Raster	Value
12	sc12_1AEP_slr060	1% AEP + 0.6 m SLR	1% AEP	0.6	Raster	Value
13	sc13_1AEP_slr080	1% AEP + 0.8 m SLR	1% AEP	0.8	Raster	Value
14	sc14_1AEP_slr125	1% AEP + 1.25 m SLR	1% AEP	1.25	Raster	Value
15	sc15_1AEP_slr160	1% AEP + 1.6 m SLR	1% AEP	1.6	Raster	Value
16	sc16_02AEP_slr013	0.2% AEP + 0.13 m SLR	0.2% AEP	0.13	Raster	Value
17	sc17_02AEP_slr125	0.2% AEP + 1.25 m SLR	0.2% AEP	1.25	Raster	Value
18	sc18_02AEP_slr160	0.2% AEP + 1.6 m SLR	0.2% AEP	1.6	Raster	Value

Appendix I Variation-07: 2, 10 and 20-year ARI elevations

28 February 2019

Kathy Thiel-Lardon
Bay of Plenty Regional Council
PO Box 364
Whakatāne 3158

Dear Kathy

Estimation of 2, 10 and 20-year average recurrence interval storm-tide + wave-setup elevations within Tauranga Harbour.

This letter report contains estimates of 2, 10 and 20-year average recurrence interval storm-tide + wave setup elevations within Tauranga Harbour, and explains the methods used.

The work was undertaken under variation order V07 of the BOPRC Tauranga Harbour Coastal Hazard Study. The scope was to estimate 2, 10 and 20-year average recurrence interval (ARI) storm-tide elevations, at 33 sites within the harbour. 2, 10 and 20-year ARI are equivalent to 39%, 10% and 5% annual exceedance probability (AEP). These scenarios were not modelled in the previous study. Rather than limit the analysis to 33 sites, we have instead produced results for all 106 sites shown in Figure 6-1 and Table E-1 in the 2018 NIWA report Tauranga Harbour Inundation Modelling 2018269HN (Reeve et al. 2018).

The results are presented in tables below and these have also been supplied to Bay of Plenty Regional Council in an excel spreadsheet. The tables include the storm-tide + wave setup elevations already produced in the previous study (Reeve et al. 2018), so the tables below contain elevations for MHWS–7 and 39, 10, 5, 2, 1 and 0.1% AEP scenarios.

Results were produced for present-day mean sea level (MSL) and for sea-level rise (SLR) scenarios of 1.25 m and 1.6 m relative to Moturiki vertical datum 1953 (MVD–53). “Present-day” MSL is considered to be 0.13 m MVD–53, which is the projected MSL in 2020 (Stephens 2017). The 0.13, 1.25 and 1.9 m MSL scenarios are provided in separate tables.

We used Table F-1 and the continuous storm-tide distributions derived from sea-level gauges in NIWA report Tauranga Harbour Extreme Sea Level Analysis 2017035HN (Stephens 2017) to estimate 2, 10 and 20-year ARI storm-tide elevations. Since the previous studies produced MHWS–7 and 2%, 1% and 0.2% AEP scenarios, we used these to interpolate the 39%, 10% and 5% AEP scenarios. A full description of the methods is provided below, followed by the result tables.

Yours sincerely

Reviewed by

Dr Scott Stephens
Group Manager—Coastal and Estuarine Physical Processes

Glen Reeve

Methods

Storm-tide + wave setup elevations were produced by Reeve et al. (2018) for 2, 1 and 0.2% AEP, along with mean high-water springs (MHWS–7) elevations.

Extreme sea-level frequency–magnitude curves produced by Stephens (2017) are shown in Figure 12-1. To estimate 39, 10 and 5% AEP elevations, a cubic polynomial was fitted to each extreme sea-level curve and the polynomial was evaluated at the required output probabilities—these are marked by the black crosses in Figure 12-2. The median of the polynomials was used to model the shape of the extreme sea-level curves and the transition from common MHWS–7 elevations to large and rare 2% AEP elevations and above—the median values are marked by the purple diamonds in Figure 12-2.

At each of the 106 output sites the median polynomial was scaled to match the modelled MHWS–7 at the low-elevation end, and to match the 2% AEP at the high-elevation end. The 39, 10 and 5% AEP elevations were then interpolated using the scaled polynomial. This is illustrated in Figure 12-3 for the Wairoa River, site 40. The process was repeated for each of the 106 sites, and for each scenario of 0.13 (Table 12-1), 1.25 (Table 12-2) and 1.6 m (Table 12-3) MVD–53 MSL. The results are included in Table 12-1 – Table 12-3.

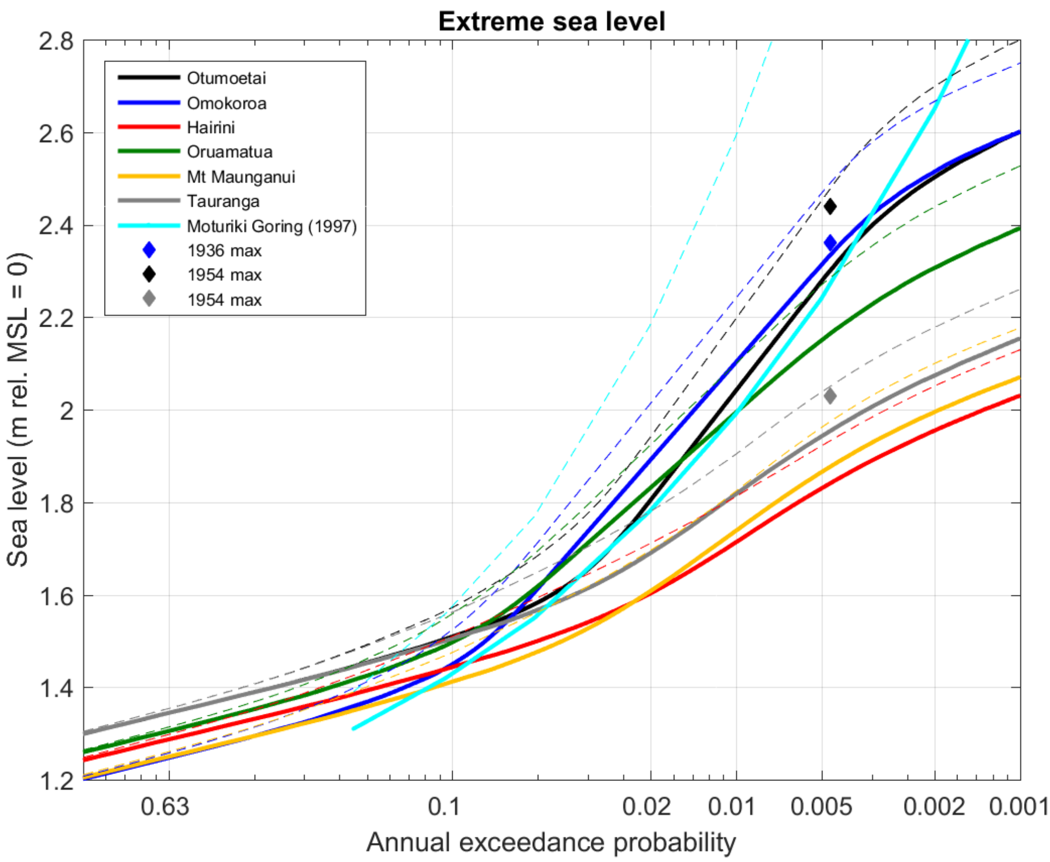

Figure 12-1: Extreme sea levels in Tauranga Harbour from Stephens (2017). Sea levels require the addition of MSL to make them relative to MVD–53. Dashed lines represent upper 95% confidence intervals.

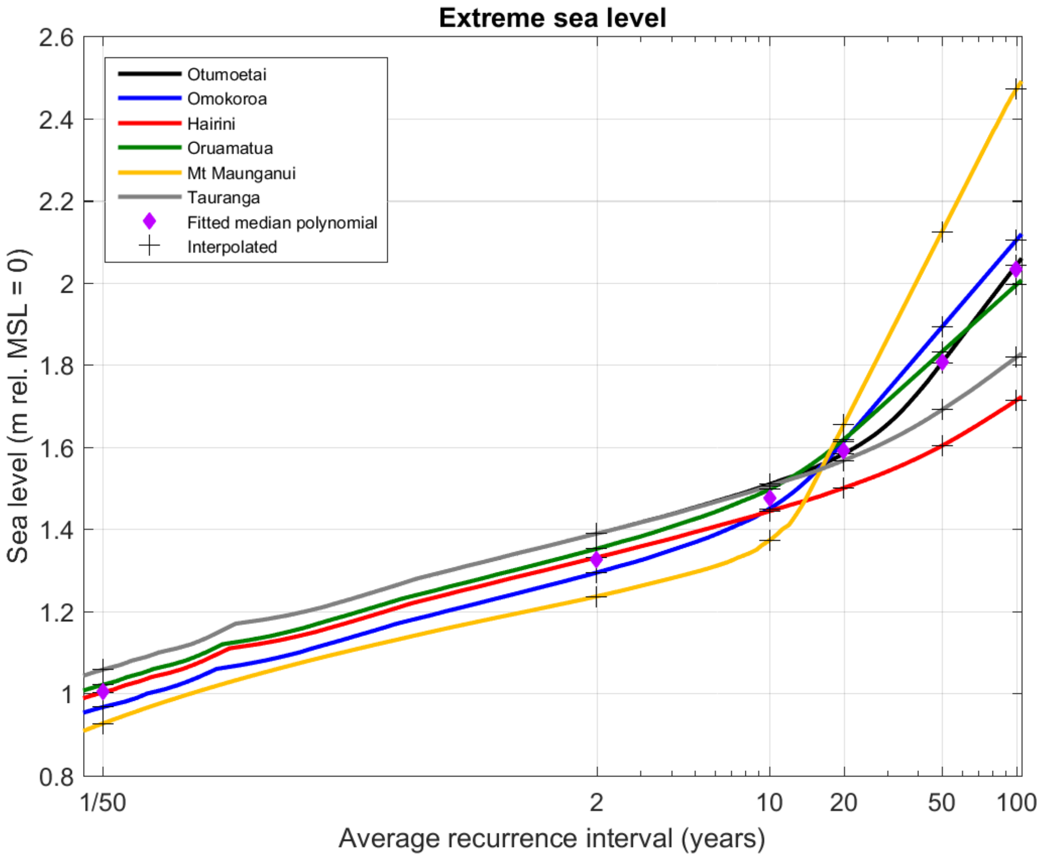

Figure 12-2: Extreme sea levels in Tauranga Harbour with fitted polynomial. Black crosses mark the polynomials fitted to each extreme sea-level curve. The purple diamonds mark the median polynomial from the fits to the individual sea-level curves at the points marked by the black crosses.

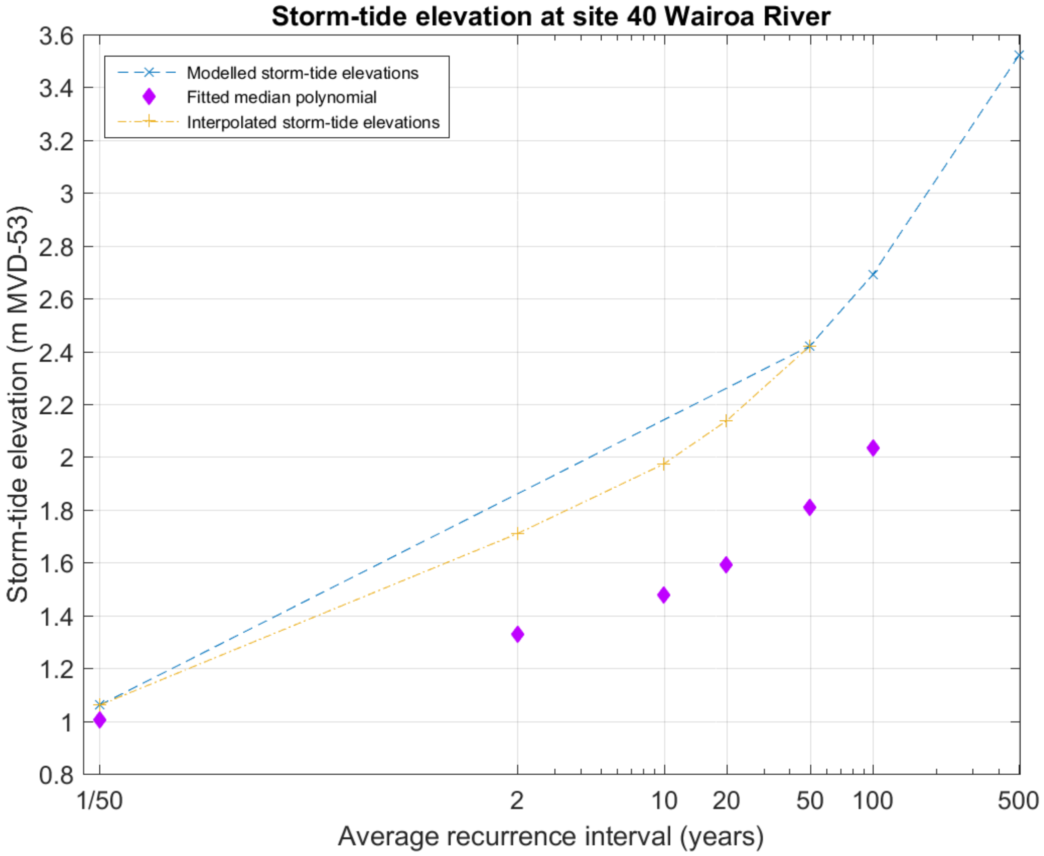

Figure 12-3: Demonstration of interpolation method. The blue crosses mark the model results from Reeve et al. (2018). The yellow crosses mark the interpolated elevations at 39, 10 and 5% AEP, obtained by scaling the median fitted polynomial to match the model results at ARI of 1/50 and 50 years. Purple diamonds mark the median extreme sea-level polynomial fit.

References

Reeve, G., Stephens, S.A., Wadhwa, S. (2018) Tauranga Harbour inundation modelling. *NIWA Client Report* 2018269HN, to Bay of Plenty Regional Council, December 2018: 107.

Stephens, S.A. (2017) Tauranga Harbour extreme sea level analysis. *NIWA Client Report* to Bay of Plenty Regional Council, March 2017, 2017035HN: 47.

Results

Table 12-1: Modelled storm-tide + wave setup sea levels at sites throughout Tauranga Harbour, for present-day mean sea level (MSL) scenario 0.13 m MVD–53.

Location	MHWS–7+ 0.13 m SLR	39% AEP + 0.13 m SLR	10% AEP + 0.13 m SLR	5% AEP + 0.13 m SLR	2% AEP + 0.13 m SLR	1% AEP + 0.13 m SLR	0.2% AEP + 0.13 m SLR
1	1.04	1.33	1.47	1.58	1.79	1.89	2.12
2	1.04	1.35	1.50	1.61	1.83	1.94	2.21
3	1.06	1.42	1.58	1.70	1.92	2.03	2.37
4	1.06	1.38	1.53	1.64	1.86	1.98	2.28
5	1.06	1.43	1.59	1.71	1.94	2.07	2.43
6	1.06	1.54	1.74	1.88	2.13	2.28	2.74
7	1.07	1.51	1.71	1.84	2.08	2.22	2.65
8	1.08	1.52	1.71	1.84	2.08	2.22	2.65
9	1.09	1.52	1.71	1.84	2.08	2.21	2.63
10	1.10	1.52	1.70	1.83	2.07	2.21	2.62
11	1.09	1.53	1.72	1.85	2.09	2.24	2.66
12	1.09	1.53	1.73	1.86	2.10	2.24	2.68
13	1.08	1.53	1.72	1.86	2.10	2.24	2.68
14	1.08	1.54	1.73	1.87	2.11	2.25	2.70
15	1.08	1.55	1.75	1.88	2.13	2.27	2.73
16	1.08	1.53	1.72	1.86	2.10	2.25	2.69
17	1.07	1.51	1.71	1.84	2.08	2.23	2.66
18	1.07	1.54	1.74	1.87	2.12	2.27	2.72
19	1.08	1.56	1.76	1.90	2.15	2.29	2.76
20	1.09	1.58	1.79	1.93	2.18	2.33	2.81
21	1.07	1.54	1.74	1.87	2.12	2.27	2.72
22	1.07	1.53	1.73	1.86	2.11	2.25	2.70
23	1.06	1.50	1.70	1.83	2.07	2.22	2.65
24	1.05	1.48	1.67	1.80	2.04	2.19	2.62
25	1.06	1.44	1.61	1.73	1.96	2.09	2.45
26	1.05	1.41	1.57	1.69	1.92	2.04	2.39
27	1.03	1.47	1.67	1.80	2.04	2.18	2.61
28	1.05	1.52	1.72	1.86	2.11	2.25	2.72
29	1.05	1.54	1.74	1.88	2.13	2.27	2.74
30	1.05	1.53	1.73	1.87	2.12	2.26	2.73
31	1.04	1.52	1.72	1.86	2.11	2.25	2.71
32	1.04	1.49	1.68	1.82	2.06	2.20	2.64
33	1.04	1.47	1.66	1.79	2.03	2.16	2.58
34	1.04	1.46	1.64	1.77	2.01	2.14	2.56
35	1.04	1.45	1.63	1.76	1.99	2.13	2.54

Location	MHWS−7+ 0.13 m SLR	39% AEP + 0.13 m SLR	10% AEP + 0.13 m SLR	5% AEP + 0.13 m SLR	2% AEP + 0.13 m SLR	1% AEP + 0.13 m SLR	0.2% AEP + 0.13 m SLR
36	1.02	1.45	1.63	1.76	2.00	2.16	2.58
37	1.03	1.46	1.65	1.78	2.02	2.19	2.62
38	1.04	1.57	1.79	1.93	2.19	2.39	2.94
39	1.04	1.62	1.86	2.01	2.28	2.49	3.08
40	1.06	1.69	1.95	2.11	2.39	2.72	3.53
41	1.03	1.61	1.85	2.00	2.27	2.47	3.04
42	1.03	1.53	1.74	1.89	2.14	2.32	2.82
43	1.03	1.51	1.71	1.85	2.10	2.28	2.75
44	1.04	1.63	1.87	2.02	2.29	2.48	3.06
45	1.04	1.56	1.78	1.92	2.18	2.40	2.92
46	1.05	1.64	1.88	2.03	2.30	2.55	3.12
47	0.92	1.61	1.88	2.05	2.34	2.56	3.15
48	1.01	1.70	1.97	2.14	2.43	2.65	3.28
49	1.01	1.57	1.80	1.95	2.22	2.42	2.94
50	1.03	1.48	1.67	1.81	2.05	2.21	2.61
51	1.04	1.50	1.69	1.83	2.07	2.23	2.65
52	1.05	1.62	1.86	2.01	2.28	2.47	2.99
53	1.07	1.80	2.09	2.27	2.57	2.76	3.42
54	1.05	1.63	1.87	2.02	2.29	2.48	3.01
55	1.07	1.72	1.98	2.15	2.43	2.60	3.22
56	1.07	1.84	2.15	2.33	2.64	2.81	3.50
57	1.07	1.71	1.97	2.13	2.41	2.60	3.20
58	1.06	1.70	1.96	2.12	2.40	2.69	3.34
59	1.07	1.64	1.87	2.02	2.29	2.44	2.97
60	1.07	1.68	1.94	2.09	2.37	2.50	3.17
61	1.06	1.60	1.82	1.97	2.23	2.37	2.88
62	1.06	1.53	1.73	1.86	2.11	2.24	2.67
63	1.02	1.46	1.66	1.79	2.03	2.16	2.50
64	1.02	1.56	1.79	1.94	2.20	2.36	2.83
65	1.03	1.69	1.95	2.12	2.40	2.57	3.17
66	1.02	1.59	1.83	1.98	2.25	2.41	2.91
67	1.02	1.49	1.69	1.83	2.08	2.22	2.59
68	1.03	1.63	1.88	2.04	2.31	2.49	3.04
69	1.03	1.52	1.72	1.86	2.11	2.26	2.66
70	1.02	1.47	1.66	1.80	2.04	2.17	2.50
71	1.02	1.42	1.59	1.72	1.95	2.07	2.36
72	1.00	1.37	1.54	1.66	1.89	2.01	2.27
73	0.99	1.38	1.55	1.67	1.90	2.03	2.25

Location	MHWS–7+ 0.13 m SLR	39% AEP + 0.13 m SLR	10% AEP + 0.13 m SLR	5% AEP + 0.13 m SLR	2% AEP + 0.13 m SLR	1% AEP + 0.13 m SLR	0.2% AEP + 0.13 m SLR
74	1.00	1.48	1.68	1.82	2.07	2.21	2.54
75	0.99	1.52	1.74	1.88	2.14	2.29	2.67
76	0.99	1.50	1.71	1.86	2.11	2.27	2.64
77	0.94	1.56	1.81	1.97	2.25	2.41	2.86
78	0.99	1.45	1.64	1.78	2.02	2.16	2.46
79	0.97	1.39	1.57	1.70	1.94	2.07	2.34
80	0.94	1.30	1.46	1.58	1.80	1.92	2.10
81	0.93	1.31	1.48	1.60	1.83	1.95	2.18
82	0.93	1.31	1.48	1.60	1.83	1.95	2.20
83	0.89	1.37	1.57	1.71	1.96	2.09	2.46
84	0.90	1.43	1.65	1.80	2.06	2.22	2.65
85	0.96	1.40	1.60	1.73	1.97	2.12	2.49
86	0.96	1.45	1.66	1.80	2.05	2.21	2.63
87	0.95	1.55	1.79	1.95	2.22	2.39	2.90
88	0.98	1.55	1.78	1.93	2.20	2.37	2.87
89	0.98	1.46	1.66	1.80	2.05	2.20	2.62
90	0.98	1.51	1.73	1.87	2.13	2.30	2.76
91	0.98	1.55	1.78	1.93	2.20	2.37	2.87
92	0.90	1.30	1.47	1.60	1.83	1.88	2.35
93	0.88	1.32	1.51	1.64	1.88	1.94	2.44
94	0.97	1.50	1.72	1.87	2.13	2.29	2.77
95	0.98	1.38	1.55	1.68	1.91	2.05	2.38
96	0.94	1.28	1.44	1.56	1.78	1.90	2.14
97	0.94	1.27	1.42	1.53	1.75	1.85	1.99
98	1.01	1.20	1.30	1.40	1.59	1.67	1.76
99	1.04	1.35	1.49	1.61	1.82	1.91	2.10
100	1.01	1.35	1.50	1.62	1.84	1.95	2.16
101	1.06	1.43	1.60	1.72	1.95	2.08	2.40
102	1.03	1.42	1.59	1.71	1.94	2.09	2.42
103	1.02	1.58	1.81	1.96	2.22	2.37	2.82
104	1.00	1.43	1.61	1.74	1.98	2.10	2.39
105	1.02	1.36	1.51	1.63	1.85	2.00	2.30
106	1.01	1.30	1.44	1.55	1.76	1.89	2.16

Table 12-2: Modelled storm-tide + wave setup sea levels at sites throughout Tauranga Harbour, for SLR scenario 1.25 m MVD–53.

Location	MHWS–7+ 1.25 m SLR	39% AEP + 1.25 m SLR	10% AEP + 1.25 m SLR	5% AEP + 1.25 m SLR	2% AEP + 1.25 m SLR	1% AEP + 1.25 m SLR	0.2% AEP + 1.25 m SLR
1	2.15	2.46	2.61	2.72	2.94	3.06	3.32
2	2.14	2.48	2.64	2.76	2.98	3.11	3.40
3	2.18	2.56	2.73	2.85	3.08	3.21	3.57
4	2.18	2.55	2.71	2.83	3.06	3.20	3.55
5	2.19	2.59	2.76	2.89	3.12	3.26	3.66
6	2.19	2.66	2.86	2.99	3.24	3.40	3.87
7	2.21	2.68	2.88	3.01	3.26	3.42	3.90
8	2.22	2.68	2.88	3.01	3.26	3.42	3.91
9	2.23	2.69	2.88	3.02	3.26	3.43	3.90
10	2.24	2.69	2.88	3.02	3.26	3.42	3.89
11	2.23	2.69	2.89	3.02	3.27	3.44	3.91
12	2.23	2.70	2.90	3.03	3.28	3.44	3.92
13	2.22	2.69	2.89	3.02	3.27	3.44	3.93
14	2.23	2.70	2.90	3.03	3.28	3.45	3.95
15	2.23	2.70	2.90	3.04	3.29	3.47	3.96
16	2.22	2.69	2.89	3.03	3.28	3.45	3.94
17	2.21	2.68	2.88	3.01	3.26	3.43	3.92
18	2.21	2.70	2.90	3.04	3.29	3.46	3.96
19	2.21	2.71	2.92	3.06	3.31	3.48	3.99
20	2.22	2.72	2.93	3.08	3.33	3.51	4.03
21	2.21	2.70	2.90	3.04	3.29	3.46	3.96
22	2.21	2.69	2.89	3.03	3.28	3.45	3.94
23	2.20	2.67	2.87	3.00	3.25	3.41	3.89
24	2.19	2.65	2.84	2.98	3.22	3.38	3.84
25	2.18	2.58	2.76	2.89	3.12	3.26	3.65
26	2.16	2.55	2.72	2.84	3.07	3.21	3.57
27	2.16	2.60	2.80	2.93	3.17	3.32	3.75
28	2.17	2.64	2.84	2.97	3.22	3.38	3.84
29	2.17	2.64	2.84	2.98	3.23	3.39	3.85
30	2.17	2.64	2.84	2.98	3.23	3.39	3.85
31	2.17	2.64	2.84	2.97	3.22	3.38	3.84
32	2.16	2.62	2.81	2.95	3.19	3.35	3.79
33	2.16	2.60	2.79	2.92	3.16	3.31	3.72
34	2.15	2.59	2.78	2.91	3.15	3.30	3.71
35	2.15	2.59	2.78	2.91	3.15	3.29	3.70
36	2.15	2.60	2.79	2.93	3.17	3.32	3.73

Location	MHWS−7+ 1.25 m SLR	39% AEP + 1.25 m SLR	10% AEP + 1.25 m SLR	5% AEP + 1.25 m SLR	2% AEP + 1.25 m SLR	1% AEP + 1.25 m SLR	0.2% AEP + 1.25 m SLR
37	2.16	2.62	2.82	2.95	3.20	3.35	3.78
38	2.17	2.72	2.95	3.10	3.36	3.53	4.06
39	2.17	2.76	3.00	3.15	3.42	3.60	4.16
40	2.19	2.90	3.19	3.36	3.66	3.87	4.57
41	2.17	2.74	2.98	3.13	3.40	3.57	4.12
42	2.18	2.69	2.91	3.05	3.31	3.47	3.97
43	2.18	2.68	2.89	3.04	3.29	3.46	3.93
44	2.19	2.76	3.00	3.15	3.42	3.60	4.17
45	2.19	2.73	2.96	3.11	3.37	3.55	4.07
46	2.20	2.80	3.04	3.20	3.47	3.65	4.23
47	2.19	2.79	3.04	3.20	3.47	3.66	4.25
48	2.20	2.83	3.09	3.25	3.53	3.72	4.33
49	2.19	2.73	2.96	3.11	3.37	3.55	4.07
50	2.19	2.65	2.84	2.98	3.22	3.37	3.77
51	2.21	2.67	2.86	3.00	3.24	3.39	3.80
52	2.22	2.76	2.99	3.14	3.40	3.57	4.08
53	2.23	2.88	3.14	3.31	3.59	3.79	4.42
54	2.22	2.76	2.99	3.14	3.40	3.58	4.09
55	2.23	2.83	3.07	3.23	3.50	3.69	4.26
56	2.23	2.90	3.17	3.34	3.63	3.83	4.49
57	2.24	2.83	3.07	3.23	3.50	3.68	4.24
58	2.26	2.87	3.13	3.28	3.56	3.75	4.35
59	2.23	2.76	2.98	3.12	3.38	3.55	4.01
60	2.24	2.81	3.04	3.19	3.46	3.64	4.16
61	2.24	2.74	2.95	3.09	3.34	3.50	3.95
62	2.23	2.68	2.87	3.01	3.25	3.40	3.78
63	2.21	2.60	2.77	2.90	3.13	3.27	3.56
64	2.21	2.67	2.87	3.00	3.25	3.40	3.79
65	2.21	2.74	2.96	3.11	3.37	3.54	3.99
66	2.21	2.69	2.89	3.03	3.28	3.44	3.83
67	2.21	2.62	2.81	2.93	3.17	3.31	3.63
68	2.21	2.72	2.93	3.08	3.33	3.50	3.92
69	2.21	2.64	2.82	2.95	3.19	3.34	3.67
70	2.21	2.65	2.85	2.98	3.22	3.35	3.63
71	2.21	2.62	2.80	2.93	3.16	3.28	3.51
72	2.20	2.57	2.73	2.85	3.08	3.19	3.38
73	2.19	2.59	2.77	2.90	3.13	3.25	3.49
74	2.20	2.67	2.87	3.00	3.25	3.39	3.73

Location	MHWS–7+ 1.25 m SLR	39% AEP + 1.25 m SLR	10% AEP + 1.25 m SLR	5% AEP + 1.25 m SLR	2% AEP + 1.25 m SLR	1% AEP + 1.25 m SLR	0.2% AEP + 1.25 m SLR
75	2.20	2.70	2.91	3.05	3.30	3.45	3.82
76	2.20	2.70	2.91	3.05	3.30	3.44	3.81
77	2.20	2.74	2.97	3.12	3.38	3.53	3.96
78	2.19	2.64	2.83	2.97	3.21	3.34	3.65
79	2.18	2.61	2.79	2.92	3.16	3.29	3.57
80	2.14	2.53	2.70	2.82	3.05	3.17	3.37
81	2.11	2.52	2.70	2.83	3.06	3.19	3.43
82	2.10	2.51	2.69	2.82	3.05	3.17	3.43
83	2.11	2.53	2.71	2.84	3.08	3.22	3.51
84	2.11	2.62	2.83	2.98	3.23	3.38	3.77
85	2.10	2.57	2.77	2.91	3.16	3.30	3.66
86	2.11	2.61	2.82	2.96	3.21	3.36	3.75
87	2.11	2.67	2.90	3.05	3.31	3.48	3.94
88	2.11	2.67	2.90	3.05	3.31	3.47	3.93
89	2.10	2.60	2.81	2.95	3.20	3.35	3.75
90	2.10	2.63	2.85	2.99	3.25	3.41	3.85
91	2.10	2.64	2.86	3.01	3.27	3.44	3.89
92	1.89	2.43	2.65	2.80	3.06	3.24	3.71
93	1.88	2.45	2.68	2.83	3.10	3.28	3.77
94	2.06	2.56	2.77	2.91	3.16	3.32	3.77
95	2.10	2.54	2.74	2.87	3.11	3.25	3.58
96	2.07	2.47	2.65	2.78	3.01	3.13	3.37
97	2.14	2.50	2.66	2.78	3.01	3.12	3.31
98	2.21	2.42	2.53	2.62	2.82	2.91	2.99
99	2.24	2.53	2.67	2.78	2.99	3.09	3.27
100	2.21	2.52	2.66	2.78	2.99	3.10	3.30
101	2.22	2.61	2.78	2.90	3.13	3.26	3.56
102	2.19	2.59	2.77	2.90	3.13	3.27	3.62
103	2.18	2.54	2.70	2.82	3.05	3.17	3.49
104	2.17	2.44	2.57	2.67	2.88	2.98	3.15
105	2.15	2.54	2.71	2.83	3.06	3.19	3.51
106	2.12	2.46	2.62	2.74	2.96	3.08	3.38

Table 12-3: Modelled storm-tide + wave setup sea levels at sites throughout Tauranga Harbour, for present-day mean sea level (MSL) scenario 1.6 m MVD–53.

Location	MHWS–7+ 1.6 m SLR	39% AEP + 1.6 m SLR	10% AEP + 1.6 m SLR	5% AEP + 1.6 m SLR	2% AEP + 1.6 m SLR	1% AEP + 1.6 m SLR	0.2% AEP + 1.6 m SLR
1	2.50	2.76	2.89	3.00	3.20	3.42	3.68

Location	MHWS–7+ 1.6 m SLR	39% AEP + 1.6 m SLR	10% AEP + 1.6 m SLR	5% AEP + 1.6 m SLR	2% AEP + 1.6 m SLR	1% AEP + 1.6 m SLR	0.2% AEP + 1.6 m SLR
2	2.50	2.79	2.92	3.03	3.24	3.46	3.75
3	2.53	2.86	3.02	3.13	3.35	3.58	3.94
4	2.54	2.87	3.02	3.13	3.35	3.58	3.94
5	2.54	2.90	3.06	3.18	3.41	3.64	4.04
6	2.54	2.97	3.15	3.28	3.52	3.76	4.24
7	2.57	3.00	3.18	3.31	3.55	3.79	4.28
8	2.58	3.01	3.20	3.33	3.57	3.81	4.30
9	2.60	3.02	3.20	3.33	3.57	3.81	4.29
10	2.60	3.02	3.20	3.32	3.56	3.80	4.28
11	2.60	3.02	3.20	3.33	3.57	3.81	4.30
12	2.59	3.02	3.21	3.34	3.58	3.82	4.31
13	2.59	3.02	3.21	3.34	3.58	3.82	4.32
14	2.59	3.03	3.22	3.35	3.59	3.83	4.33
15	2.59	3.03	3.22	3.36	3.60	3.84	4.35
16	2.58	3.02	3.21	3.34	3.58	3.82	4.32
17	2.57	3.00	3.19	3.32	3.56	3.80	4.30
18	2.57	3.01	3.20	3.34	3.58	3.82	4.32
19	2.57	3.02	3.22	3.35	3.60	3.84	4.35
20	2.58	3.04	3.24	3.38	3.62	3.87	4.39
21	2.57	3.02	3.21	3.34	3.59	3.83	4.33
22	2.57	3.01	3.20	3.34	3.58	3.82	4.31
23	2.56	2.99	3.17	3.30	3.54	3.78	4.26
24	2.55	2.96	3.14	3.27	3.50	3.74	4.21
25	2.53	2.89	3.05	3.17	3.40	3.63	4.03
26	2.51	2.85	3.00	3.12	3.34	3.57	3.93
27	2.51	2.91	3.08	3.21	3.44	3.68	4.09
28	2.52	2.94	3.12	3.25	3.49	3.73	4.18
29	2.52	2.95	3.13	3.26	3.50	3.74	4.19
30	2.52	2.94	3.12	3.25	3.49	3.73	4.19
31	2.52	2.94	3.12	3.25	3.49	3.73	4.17
32	2.52	2.92	3.10	3.23	3.46	3.70	4.12
33	2.51	2.90	3.07	3.19	3.42	3.66	4.07
34	2.51	2.89	3.06	3.19	3.42	3.65	4.05
35	2.51	2.89	3.06	3.19	3.42	3.65	4.05
36	2.51	2.90	3.08	3.20	3.43	3.67	4.08
37	2.52	2.92	3.10	3.23	3.46	3.70	4.12
38	2.54	3.03	3.23	3.37	3.62	3.87	4.39
39	2.54	3.06	3.27	3.42	3.68	3.93	4.48

Location	MHWS–7+ 1.6 m SLR	39% AEP + 1.6 m SLR	10% AEP + 1.6 m SLR	5% AEP + 1.6 m SLR	2% AEP + 1.6 m SLR	1% AEP + 1.6 m SLR	0.2% AEP + 1.6 m SLR
40	2.56	3.20	3.46	3.63	3.91	4.18	4.86
41	2.54	3.04	3.25	3.39	3.65	3.90	4.44
42	2.54	2.99	3.19	3.32	3.57	3.81	4.30
43	2.55	2.99	3.18	3.32	3.56	3.80	4.27
44	2.56	3.07	3.29	3.43	3.69	3.94	4.48
45	2.56	3.04	3.24	3.38	3.63	3.88	4.40
46	2.57	3.10	3.32	3.46	3.72	3.98	4.54
47	2.56	3.10	3.32	3.47	3.73	3.99	4.56
48	2.56	3.13	3.36	3.51	3.78	4.04	4.64
49	2.56	3.04	3.24	3.38	3.63	3.88	4.39
50	2.56	2.95	3.13	3.25	3.48	3.72	4.11
51	2.58	2.97	3.15	3.27	3.50	3.74	4.13
52	2.59	3.06	3.27	3.40	3.65	3.90	4.40
53	2.60	3.18	3.42	3.58	3.85	4.11	4.72
54	2.59	3.07	3.27	3.41	3.66	3.91	4.41
55	2.61	3.14	3.36	3.50	3.76	4.02	4.57
56	2.61	3.21	3.45	3.61	3.88	4.15	4.78
57	2.61	3.13	3.35	3.50	3.75	4.01	4.55
58	2.61	3.17	3.40	3.55	3.81	4.07	4.65
59	2.61	3.07	3.26	3.40	3.64	3.89	4.34
60	2.61	3.11	3.32	3.46	3.72	3.97	4.48
61	2.61	3.05	3.24	3.37	3.61	3.85	4.29
62	2.60	2.99	3.16	3.28	3.51	3.75	4.13
63	2.59	2.92	3.07	3.18	3.40	3.63	3.92
64	2.59	2.98	3.16	3.28	3.51	3.75	4.12
65	2.59	3.05	3.25	3.39	3.63	3.88	4.31
66	2.59	3.00	3.18	3.31	3.54	3.78	4.16
67	2.59	2.94	3.10	3.22	3.44	3.67	3.98
68	2.60	3.04	3.23	3.36	3.60	3.84	4.25
69	2.60	2.96	3.12	3.24	3.47	3.70	4.01
70	2.59	2.96	3.13	3.25	3.48	3.71	4.00
71	2.59	2.93	3.08	3.20	3.42	3.65	3.88
72	2.58	2.88	3.02	3.13	3.35	3.57	3.76
73	2.57	2.91	3.06	3.18	3.40	3.63	3.88
74	2.58	2.98	3.16	3.29	3.52	3.76	4.09
75	2.58	3.01	3.20	3.33	3.57	3.81	4.18
76	2.58	3.01	3.19	3.32	3.56	3.80	4.17
77	2.58	3.05	3.26	3.39	3.64	3.89	4.30

Location	MHWS−7+ 1.6 m SLR	39% AEP + 1.6 m SLR	10% AEP + 1.6 m SLR	5% AEP + 1.6 m SLR	2% AEP + 1.6 m SLR	1% AEP + 1.6 m SLR	0.2% AEP + 1.6 m SLR
78	2.57	2.95	3.12	3.25	3.48	3.71	4.02
79	2.56	2.93	3.09	3.21	3.44	3.67	3.95
80	2.52	2.84	2.98	3.10	3.32	3.54	3.76
81	2.49	2.83	2.99	3.11	3.33	3.56	3.81
82	2.47	2.82	2.98	3.10	3.32	3.55	3.81
83	2.47	2.84	3.01	3.13	3.36	3.59	3.89
84	2.47	2.92	3.11	3.24	3.49	3.73	4.13
85	2.47	2.88	3.06	3.19	3.42	3.66	4.03
86	2.47	2.91	3.10	3.24	3.48	3.72	4.11
87	2.47	2.97	3.18	3.32	3.58	3.83	4.29
88	2.47	2.97	3.18	3.32	3.57	3.82	4.28
89	2.46	2.90	3.09	3.23	3.47	3.71	4.11
90	2.46	2.93	3.13	3.27	3.51	3.76	4.20
91	2.45	2.94	3.14	3.28	3.53	3.78	4.24
92	2.22	2.76	2.98	3.13	3.39	3.65	4.10
93	2.22	2.78	3.01	3.16	3.42	3.68	4.15
94	2.39	2.85	3.05	3.19	3.43	3.68	4.15
95	2.46	2.85	3.03	3.15	3.38	3.62	3.95
96	2.44	2.78	2.93	3.05	3.27	3.50	3.75
97	2.52	2.82	2.96	3.07	3.29	3.51	3.71
98	2.59	2.73	2.82	2.91	3.09	3.29	3.38
99	2.60	2.83	2.95	3.05	3.25	3.46	3.64
100	2.59	2.84	2.96	3.06	3.27	3.48	3.66
101	2.59	2.91	3.06	3.18	3.39	3.62	3.92
102	2.56	2.90	3.06	3.18	3.40	3.63	3.97
103	2.55	2.81	2.93	3.04	3.24	3.46	3.72
104	2.54	2.75	2.86	2.96	3.15	3.36	3.52
105	2.51	2.84	2.99	3.10	3.32	3.55	3.87
106	2.47	2.77	2.91	3.02	3.23	3.45	3.74