Supplement of Nat. Hazards Earth Syst. Sci., 23, 3125–3146, 2023
https://doi.org/10.5194/nhess-23-3125-2023-supplement

Natural Hazards and Earth System Sciences
Open Access

Supplement of

Modelling extreme water levels using intertidal topography and bathymetry derived from multispectral satellite images

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Supplement S1

The ratio-log method

The logarithm ratio band (Stumpf et al., 2003) is based on the assumption that the light attenuation increases with the water depth. This method estimates the bathymetry using the ratio of the natural logarithm between the reflectance of two different spectral bands. Assuming that these bands are affected similarly by the atmosphere and bottom albedo, the method works because the attenuation rate with depth is dependent on the wavelength. The SDB using the ratio-log method is calculated as follows:

$$Z_{sat} = m1\left(\frac{\ln nR_w(\lambda_i)}{\ln nR_w(\lambda_j)}\right) + m_0 \quad \text{(S1)}$$

Where Z_{sat} is the satellite derived bathymetry, n is a constant used in order to assure that the ratio remains always positive and that the ratio will produce a linear response with depth, m_1 is a tunable constant to scale the ratio to depth, and m_0 is the offset for a depth of 0m (Z=0); $R_w(\lambda_i)$ is the reflectance on the surface of the band i and $R_w(\lambda_j)$ is the reflectance on the surface of the band j. Here we used the green and blue band from Sentinel Copernicus, product type 2A images, respectively. To calculate the derived bathymetry, a single image dated on 2019/04/06 22:16:09 UTC for Tauranga Harbour only, was used when the observed tide was 0.94 m above mean sea-level at the Ōmokoroa tide gauge (at high tide).

The ratio-log-SDB

The ratio-log method was applied for Tauranga Harbour separately for shallow and intertidal areas, and the results can be seen in Figure S1 (which is used in Part A, Figure 1) and S2 (used for the bathymetry in scenario 4 of modelling tests in Part B, Figure 2). The use of this approach generated a high density of estimated points because it provides a value of depth for every image pixel.

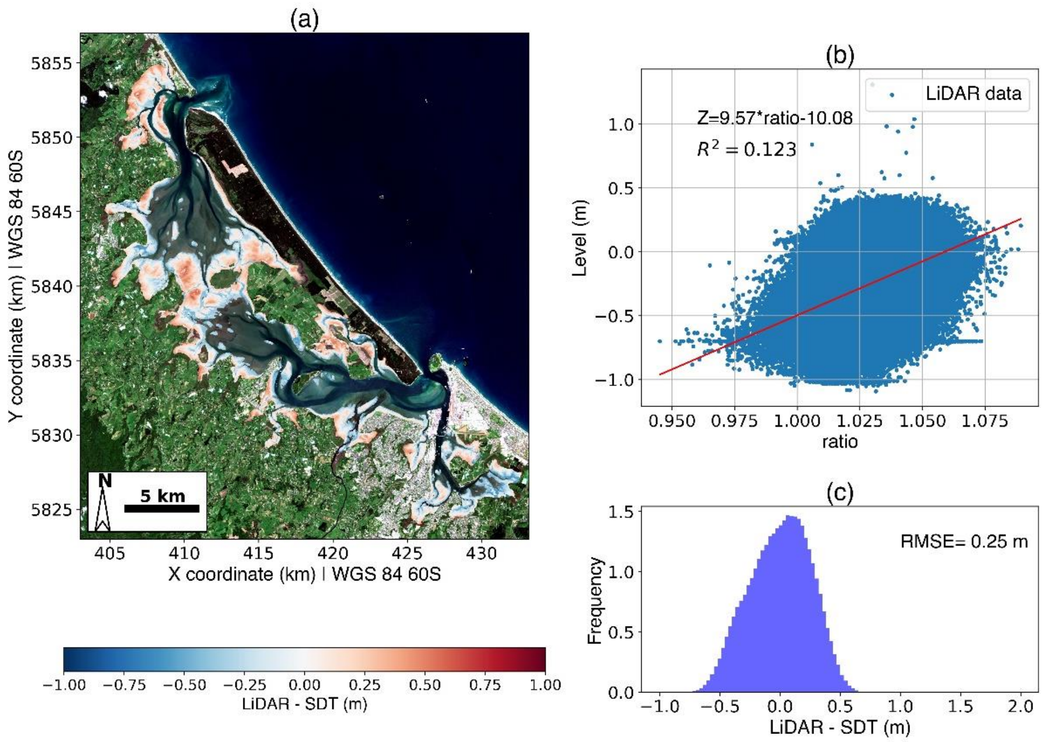

Figure S1. Satellite-derived topography for Tauranga Harbour using the ratio-log method. (a) Map showing the estimated bathymetry samples and the spatial distribution of relative error. (b) Ratio-log method fitted using the LiDAR data ('ratio' is the ratio in Equation S1). (c) Relative error distribution of the SDT using ratio-log method. Background image: ESA Sentinel 2A. Image date and time (UTC+12): 18/12/2018 h. The water level at the moment of image acquisition: -0.41 m at Ōmokoroa tide gauge (MSL)

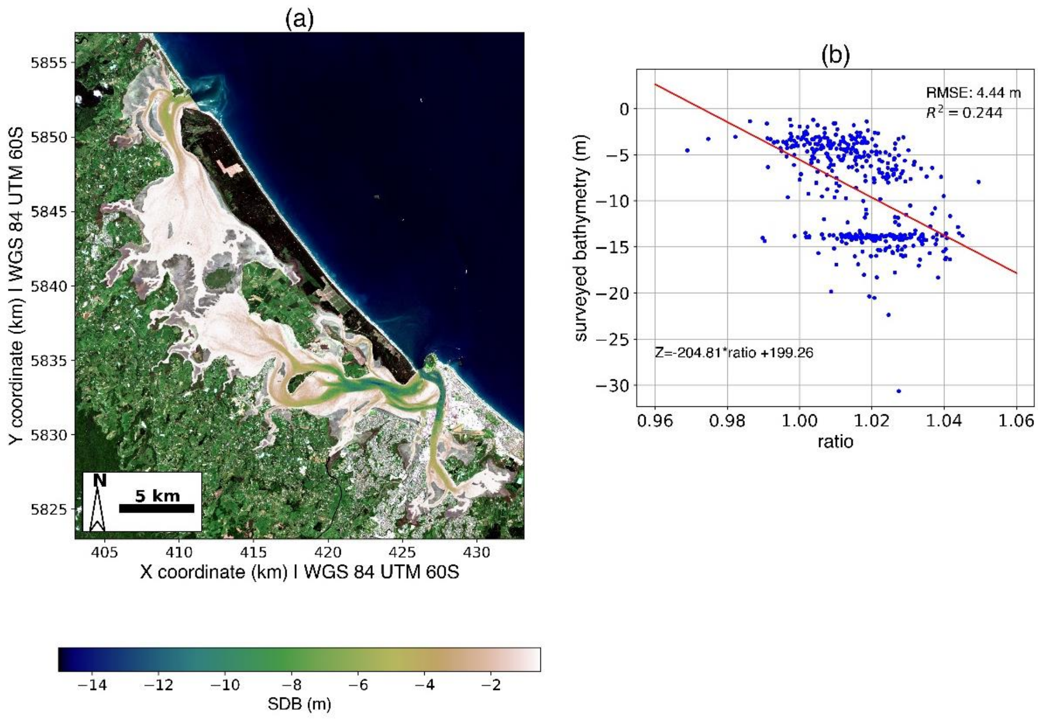

Figure S2. Satellite derived bathymetry for Tauranga Harbour, shallow and channel areas, derived using ratio-log method. (a) Map showing the estimated bathymetry samples. (b) Ratio method fitted using the surveyed bathymetry ('ratio' is the ratio in Equation S1). Note the Harbour is dredged to -14m in some regions around the Port of Tauranga.

Background image: ESA Sentinel 2A. Image date and time (UTC+12): 18/12/2018 h. The water level at the moment of image acquisition: -0.41 m at Ōmokoroa tide gauge (MSL)

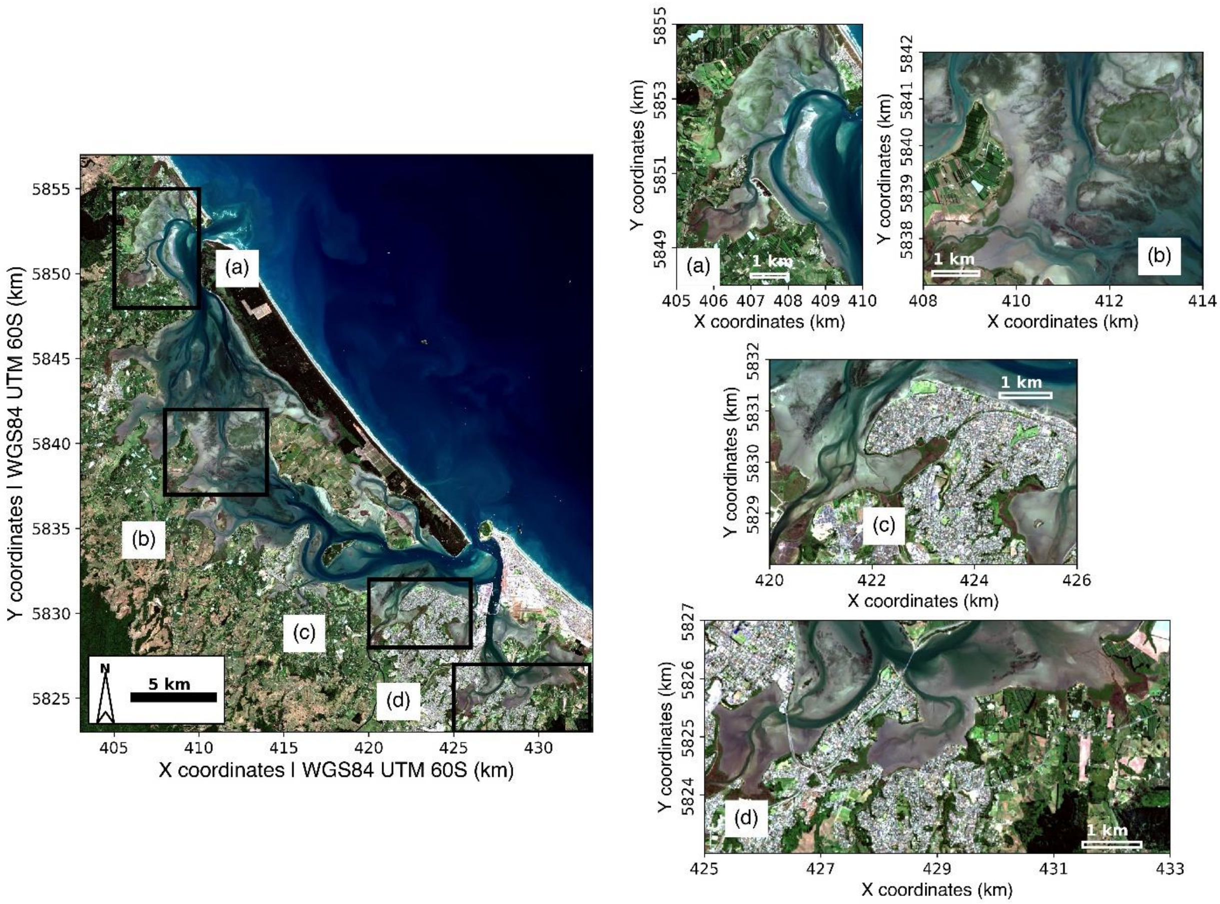

Figure S3. An example of the effect of seagrass and complex morphology in Tauranga Harbour. Background image: ESA Sentinel 2A. Image date and time (UTC+12): 16/02/2019 10:15 h. The water level at the moment of image acquisition: -0.56 m at Ōmokoroa tide gauge (MSL). Note that the round vegetated feature at the top right of panel b is a mangrove 'island' located on the high intertidal.

Supplement S2

Hydrodynamic settings and validation

The bed roughness used in our model was determined by Stewart (Stewart, 2021). The model was run 15 days for calibration to cover a complete spring-neap cycle over the period from 8th – 23rd of March 2017 and compared to the collected field data. The validation period was the following 15 days, which covers a neap-spring cycle between 24th of March – 8th April 2017. The best results were obtained with a variable bed roughness across the model domain, with values of Chézy coefficient of 35 $m^{1/2}/s$ for the tidal flats, 45 and 55 $m^{1/2}/s$ for intermediary-depth areas 65 and 75 $m^{1/2}/s$ for the deepest channels. The model also validated for this study, using the water level for the period that the images where acquired (year of 2019) as described in the main manuscript (Sect. 2.4).

Table S1. Model parameters used in the calibration of the hydrodynamic modelling and determination of bed roughness. Extracted from Stewart (2021).

Parameter	Value	Units (if applicable)
Time step	0.5	minutes
Gravity	9.81	m/s^2
Water density	1000	kg/m^3
Roughness	75 - 35	Chézy ($m^{1/2}/s$). Spatial varying map used
Horizontal eddy viscosity	10	m^2/s
Threshold depth	0.1	m
Advection scheme for momentum	cyclic	-
Depth at grid cell faces	mean	-
Drying and flooding check at	grid cell centres and faces	-
Open boundary type	water level	-
Reflection parameter alpha	50	-
Forcing type	astronomic	-

Table S2. Calibration and validation parameters for the hydrodynamic model of Tauranga Harbour. Extracted form Stewart (2021).

Period	Parameter	Statistics	
		Bias (m)	RMSE (m)
Calibration (08.03.2017 - 23.03.2017)	Water level (m)	0.04	0.15
	Current Velocity (m/s)	0.03	0.11
Validation (24.03.2017 - 08.04.2017)	Water level (m)	0.09	0.16
	Current Velocity (m/s)	0.03	0.13

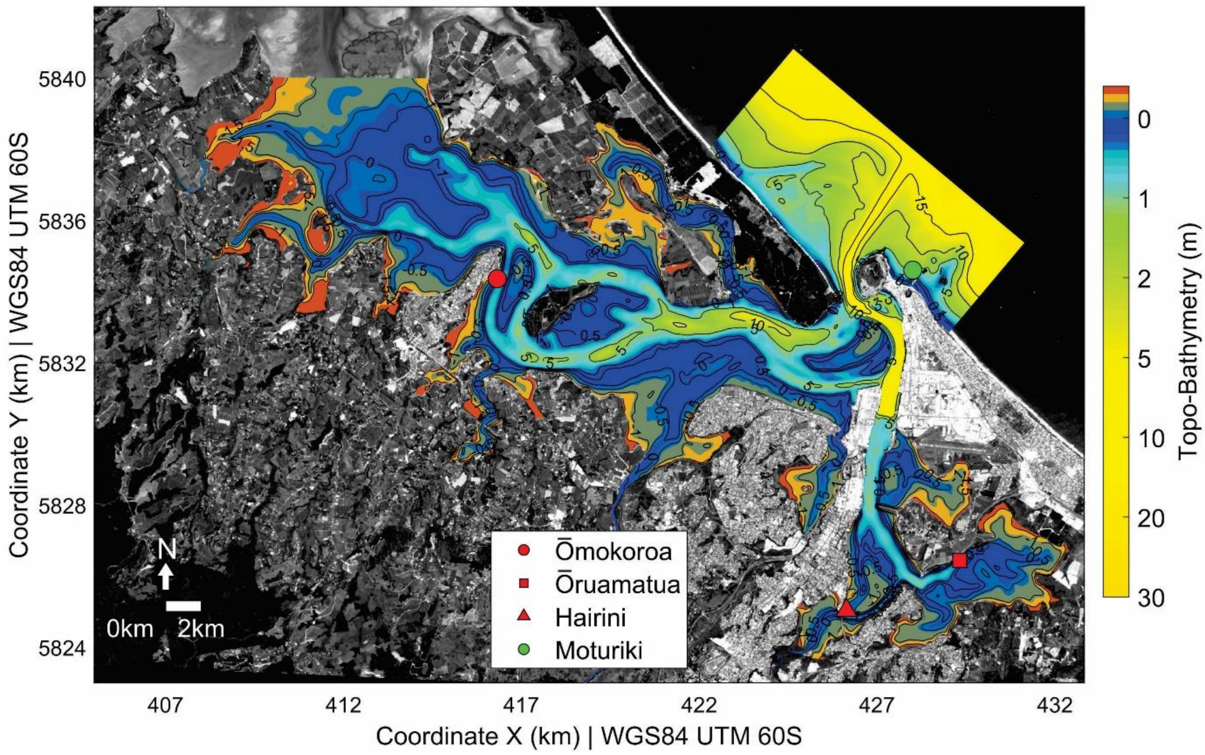

Figure S4 - Tauranga Harbour numerical model. Interpolated bathymetry in the model domain. The triangle, square and circle symbols locate the tide gauges used in the hydrodynamic model. Vertical reference level: MSL. Background image: ESA Sentinel 2A.

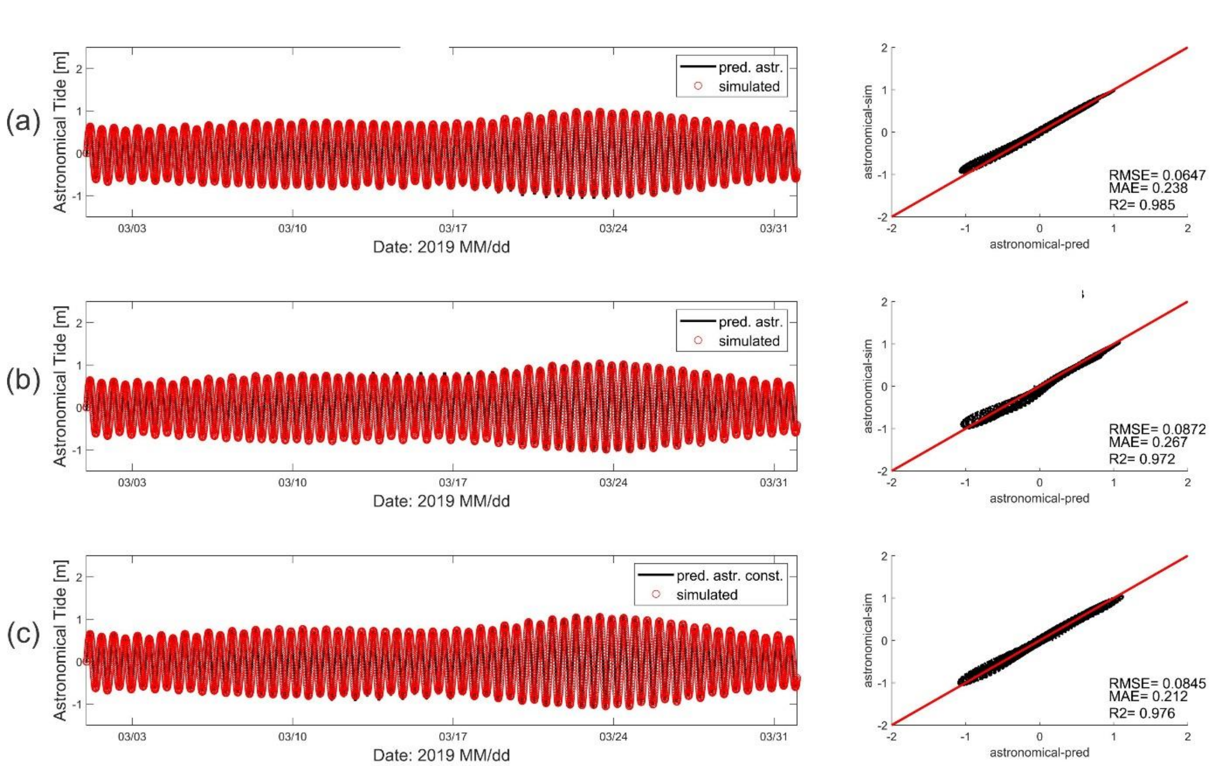

Figure S5 - Hydrodynamic model validation for Tauranga Harbour for an equinoctial tide cycle for the year of 2019 at three different observation points: the Ōmokoroa (a), Hairini (b) and Ōruamatua (c) tide gauges.

Supplement S3

Table S3. Details of each tide gauge used in the study.

Estuary	*Tide gauge name*	*Latitude (WGS 84)*	*Longitude (WGS 84)*	*Easting (m) (UTM WGS 84)*	*Northing(m) (UTM WGS 84)*	*Manager*
Maketū	Moturiki Island	-37°37'48"	176°11'9 "	428172.47 E	5834908.38 S	National Institute for Atmosphere and Water (NIWA)
Ōhiwa	Port Ōhope Wharf	-37° 59′ 2″	177° 6′ 28″	509464.67 E	5795967.06 S	Bay of Plenty Regional Council
Tauranga Harbour	Ōmokoroa	-37° 37′ 58″	176° 3′ 13″	416495.99 E	5834506.66 S	
	Hairini	-37° 42′ 54″	176° 9′ 56″	426454.73 E	5825477.93 S	
	Ōruamatua	-37° 41′ 58″	176° 12′ 13″	429794.21 E	5827233.01 S	
Whitianga	Whitianga Wharf	-36°49'58 "	175°42'32 "	384868.29 E	5922897.54 S	Waikato Regional Council

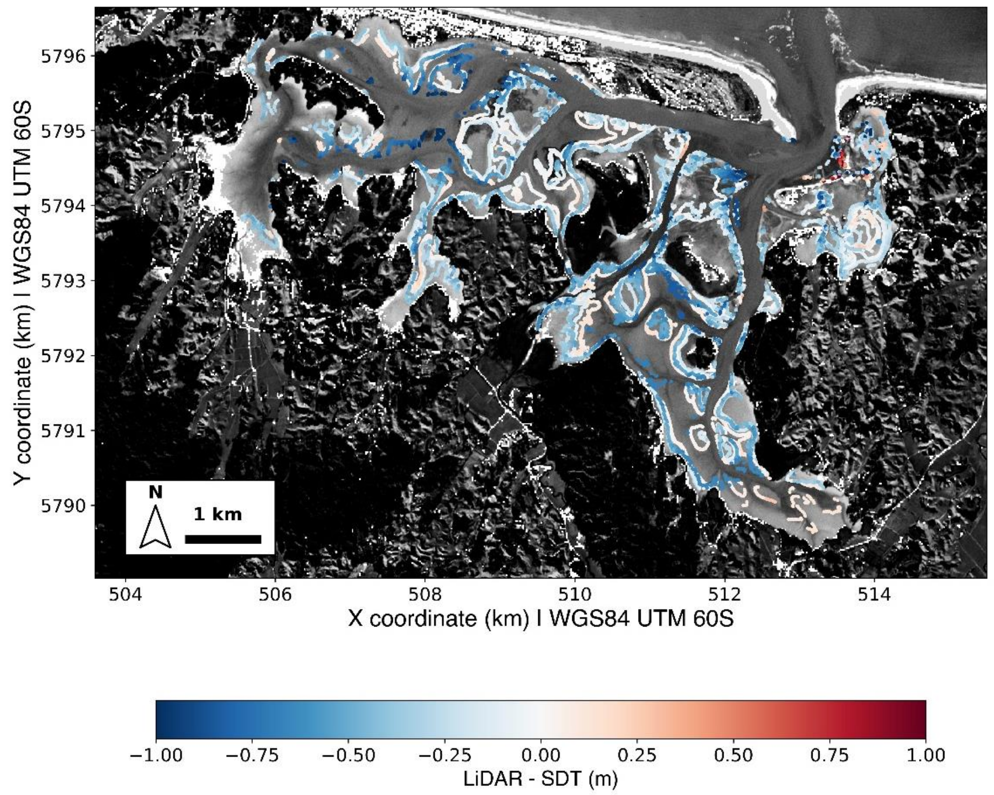

Figure S6. Satellite derived bathymetry for Ōhiwa Harbour using waterline method. Map showing the estimated bathymetry samples and the spatial distribution of relative error. Background image: ESA Sentinel 2A. Image number 3 (see table S4).

Table S4 Ohiwa date, time, and observed water level at Port Ōhope Wharf tide gauge.

Image number	Date and Time (UTC+12h)	Level (m) MSL
1	06/02/2019 10:16	0.656
2	26/02/2019 10:15	0.433
3	16/06/2019 10:16	-0.1
4	27/04/2019 10:16	0.219
5	30/08/2019 10:16	-0.089
6	03/11/2019 10:16	0.62

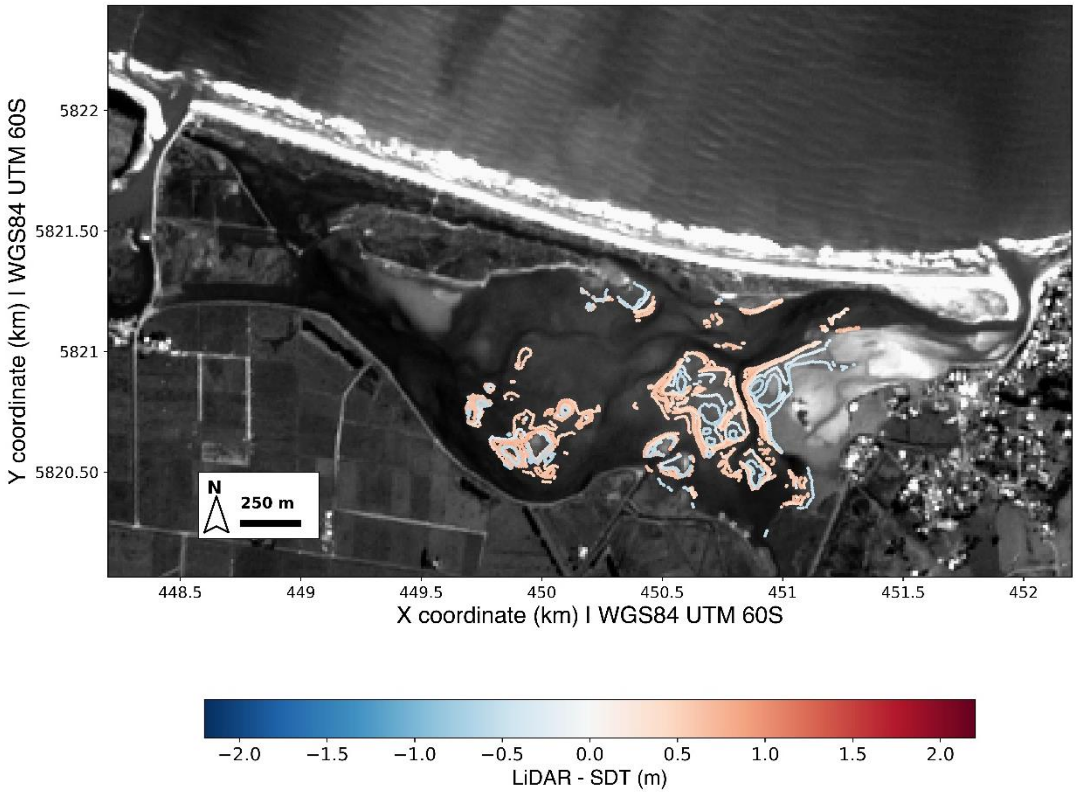

Figure S7. Satellite derived topography for Maketū Harbour using waterline method. Map showing the estimated bathymetry samples and the spatial distribution of relative error. Background image: ESA Sentinel 2A. Image number 8 (see table S5).

Table S5 Maketu date, time, and observed water level at Moturiki Island tide gauge.

Image number	Date and Time (UTC+12h)	Level (m) MSL
1	18/12/2018 10:15	-0.25
2	17/01/2019 10:15	-0.28
3	06/02/2019 10:16	0.41
4	16/02/2019 10:15	-0.4
5	26/02/2019 10:15	0.6
6	03/03/2019 10:15	-0.4
7	02/04/2019 10:16	-0.4
8	07/04/2019 10:16	0.46
9	02/05/2019 10:16	-0.46
10	26/06/2019 10:16	0.11
11	15/08/2019 10:16	-0.19
12	03/11/2019 10:16	0.84

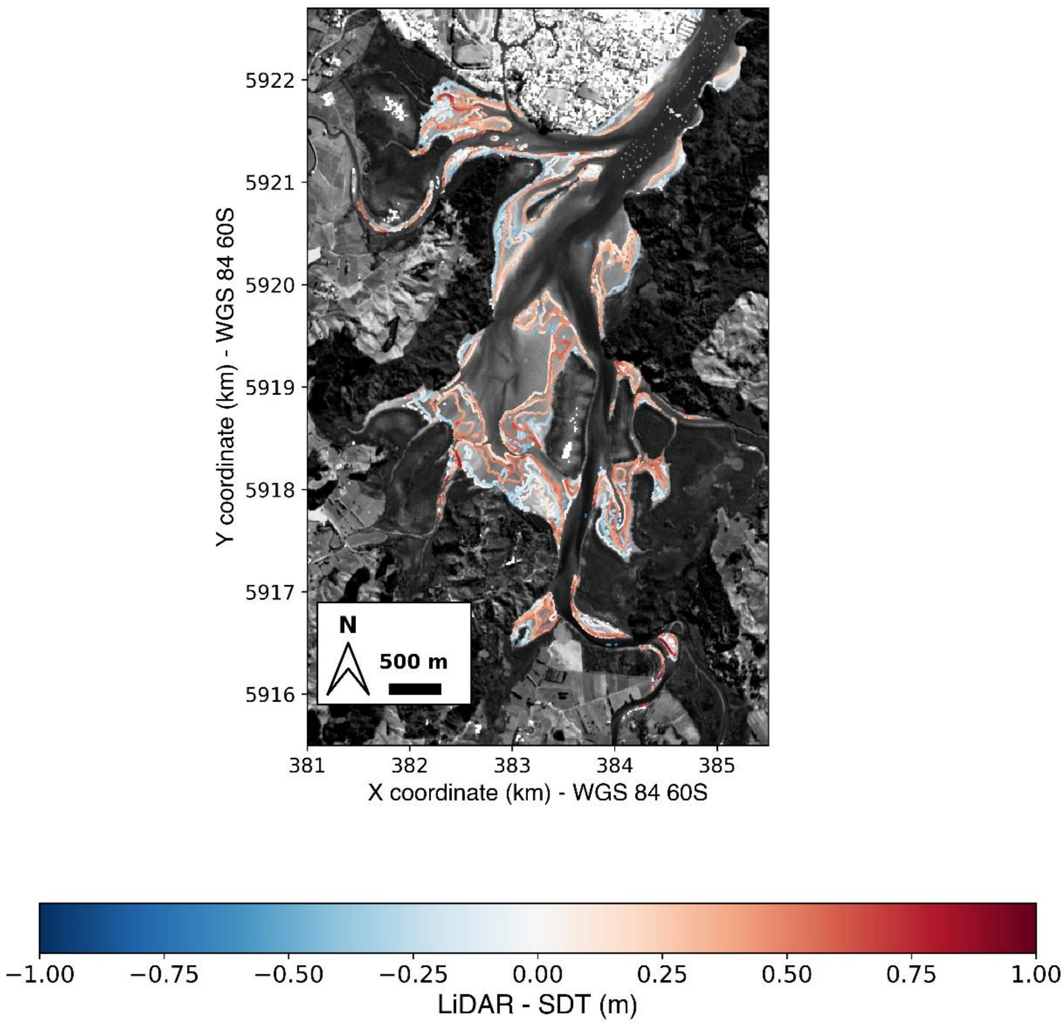

Figure S8. Satellite derived bathymetry for Whitianga Harbour using waterline method. Map showing the estimated bathymetry samples and the spatial distribution of relative error. Background image: ESA Sentinel 2A. Image number 8 (see table S6).

Table S6 Whitianga date, time, and observed water level at Whitianga Wharf tide gauge.

Image number	Date and Time (UTC+12h)	Level (m) MSL
1	18/12/2018 10:15h	-0.243
2	22/01/2019 10:15h	0.365
3	11/02/2019 10:15h	0.816
4	16/02/2019 10:15h	-0.296
5	26/02/2019 10:15h	0.547
6	30/04/2019 10:25h	-0.228
7	16/06/2019 10:16h	-0.312
8	27/10/2019 10:25h	-0.513

Supplement S4

Satellite derived topography and bathymetry use in hydrodynamic modelling assessment.

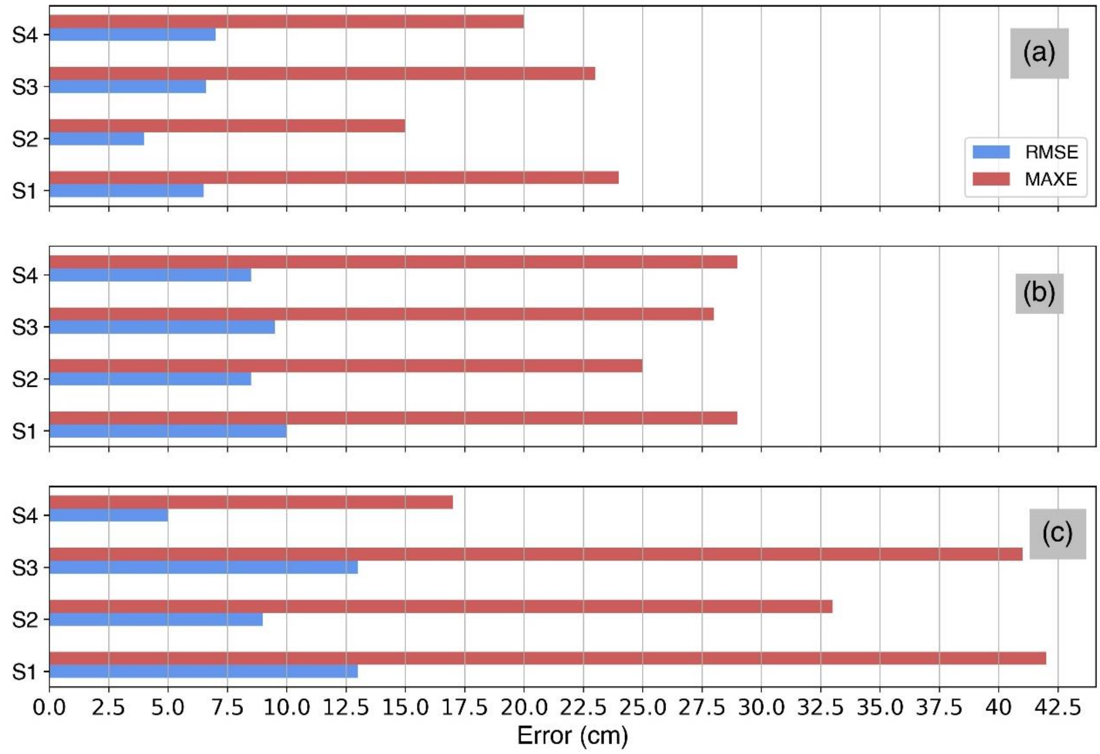

Figure S9 - The parameter errors of the four simulation scenarios (S1, S2, S3, and S4) – RMSE (blue bar), MAE (red bar) –at the 3 tide gauge locations: Ōmokoroa (a), Hairini (b), Oruamatua (c).

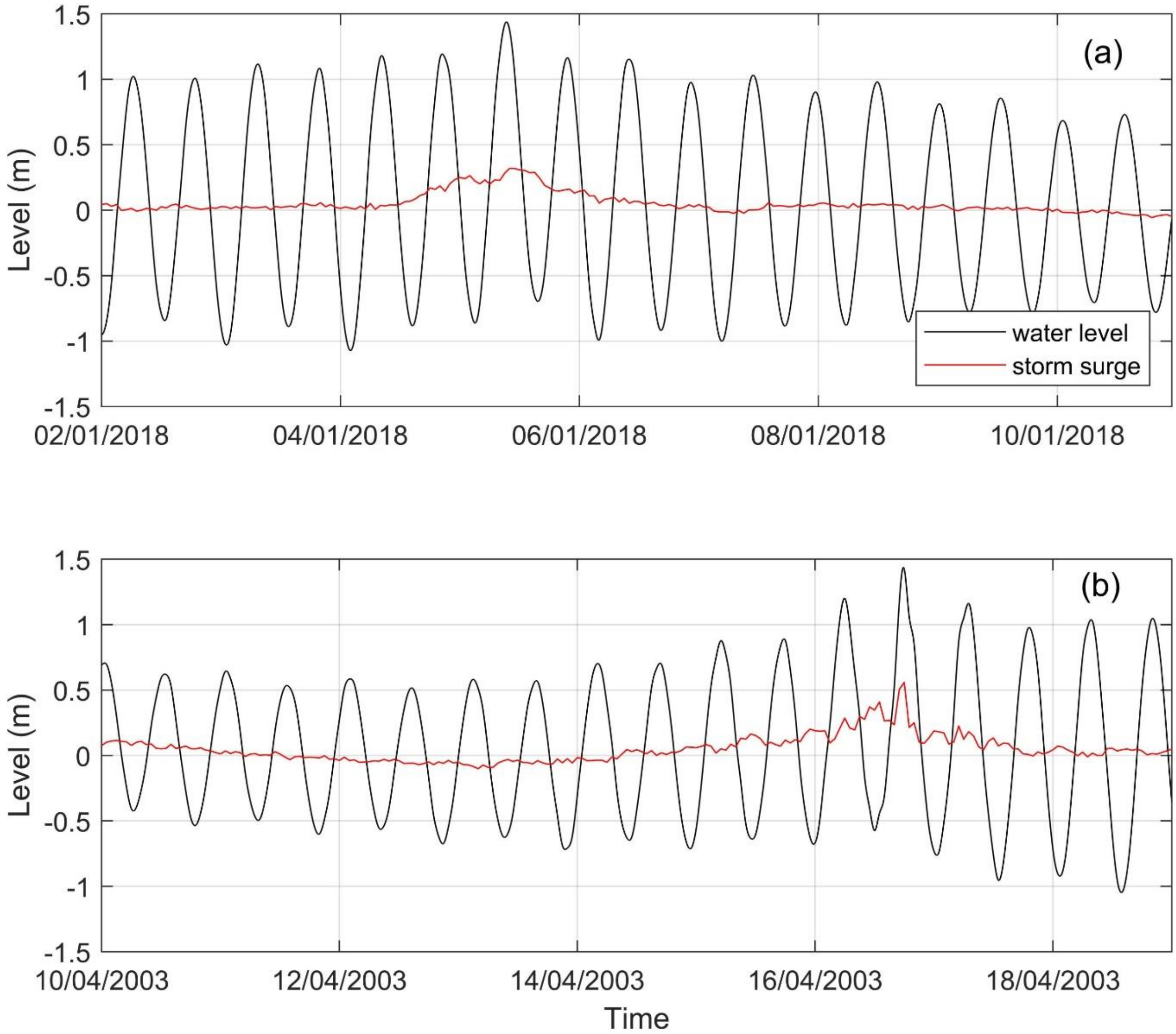

Figure S10. Time series of water level forced in the model boundary of S5 and S6 (a), and S7 and S8 (b). Black line shows the water level record in Moturiki tide gauge at mean sea level. The red line refers to the storm surge contribution to the water level.

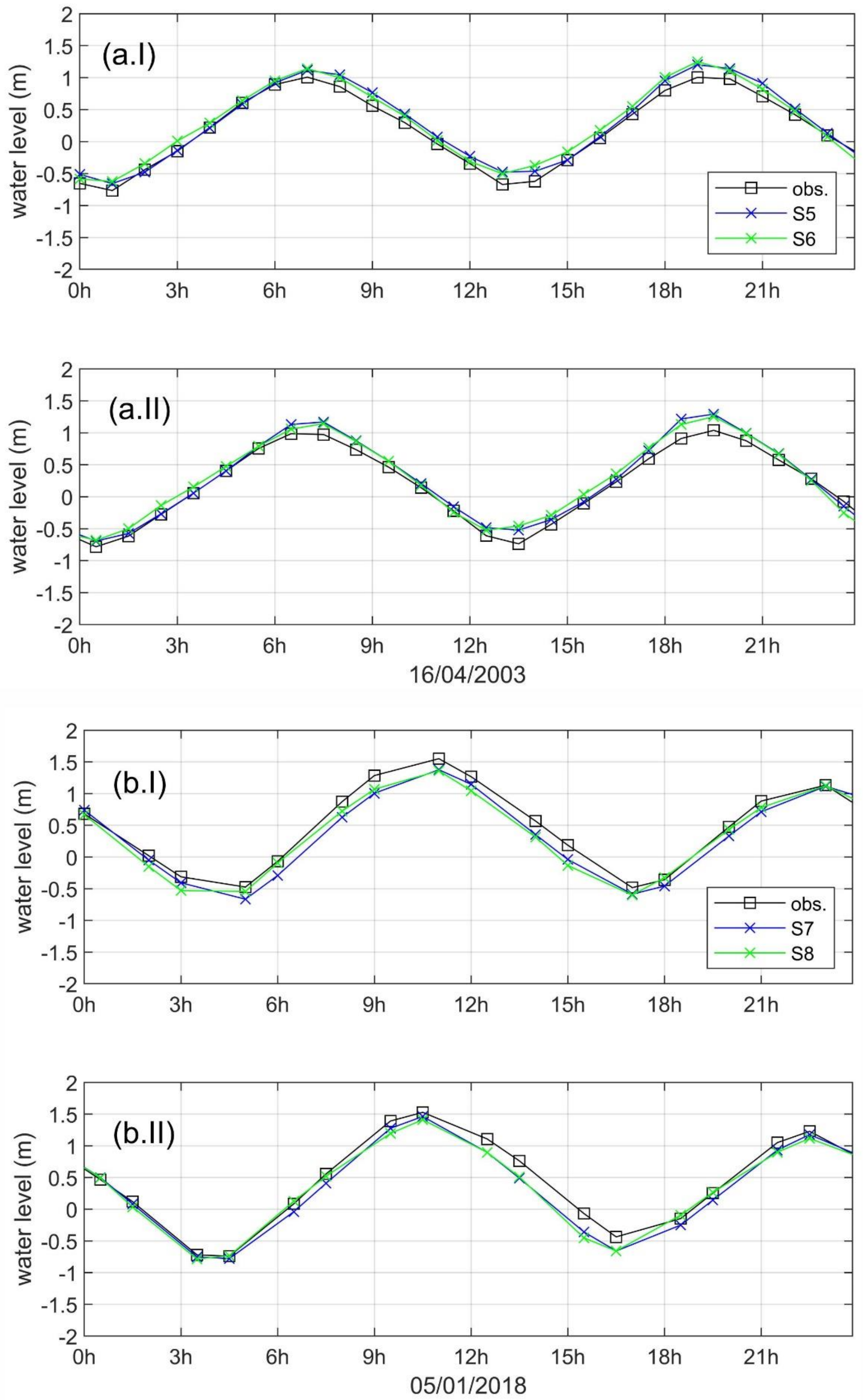

Figure S11. Outputs of S5 and S6 (a), and S7 and S8 (b) for Harini (I) and Oruamatua (II). The observed water level for each time series is shown in black line with square markers.