REPORT

Tonkin+Taylor

Review of Physical Processes Influencing the 26 June Wairoa Flood

Data summary and analysis

Prepared for
Hawke's Bay Regional Council
Prepared by
Tonkin & Taylor Ltd
Date
August 2024
Job Number
1017353.2406 v3

Together we create and sustain a better world
www.tonkintaylor.co.nz

Document control

Title: Review of Physical Processes Influencing the 26 June Wairoa Flood					
Date	Version	Description	Prepared by:	Reviewed by:	Authorised by:
18/07/2024	0.1	Draft data summary (work in progress) for client review	E Beetham A White	R Reinen-Hamill M Pennington	R Reinen-Hamill
26/07/2024	1.0	Revised draft (work in progress) including analysis	E Beetham A White R Reinen-Hamill M Pennington	R Reinen-Hamill M Pennington	R Reinen-Hamill
06/08/2024	2.0	Revised draft (work in progress) incorporating HBRC comments	E Beetham A White R Reinen-Hamill M Pennington	R Reinen-Hamill M Pennington	R Reinen-Hamill
06/08/2024	3.0	Final issue to client	E Beetham A White R Reinen-Hamill M Pennington	R Reinen-Hamill M Pennington	R Reinen-Hamill

Distribution:

Hawke's Bay Regional Council	1 PDF copy
Tonkin & Taylor Ltd (FILE)	1 electronic copy

Table of contents

Executive summary

Hawke's Bay Regional Council (HBRC) commissioned Tonkin & Taylor Ltd (T+T) to review physical processes that influenced flooding in Wairoa on 26 June 2024.

The scope of this report is to summarise key factual details relating to rainfall, river level, sea level, wave conditions, and the position of Wairoa River mouth bar. It includes an analysis of historical changes to the bar and coast topography to assist understanding of the influence of coastal processes. Key datasets included:

- Rainfall and river level data for the Wairoa Catchment, as measured by HBRC.
- Sea level (tide) measured in Napier (Sourced from LINZ).
- Wave conditions as modelled in 'nowcast' format by MetOcean Solutions Ltd[1].
- Satellite imagery of the bar position before and after the event.
- Beach profile and regional LiDAR terrain surveys from HBRC and LINZ.

This report also presents an analysis of the processes operating through the event. Numerical coastal modelling was used to explore the influence of waves and sea conditions acting on the bar during the event, including wave overtopping and hydraulic gradients within sedimentary bar. A numerical river model was used to represent the observed flooding and test the contribution of different influencing processes, such as the river mouth position and coincidence with tide level and phase.

Setting

The Wairoa River mouth is characterised by a sand and gravel bar typically extends across the river. The dynamic bar is shaped by a combination of coastal and river forces, with the crest elevation of the bar being controlled by wave runup processes. The bar is comprised of permeable sediments (gravels) that allows some water flow through the sediment body. The alignment of the river to the coast and the alongshore transport processes frequently offset the effective river mouth position.

Event summary

Flooding in Wairoa occurred over the early morning of 26 June 2024. Based on the available information, flooding was influenced by multiple factors as summarised below:

- The atmospheric low-pressure system was large and formed rapidly off the East Cape on Tuesday 25 June, less than 24 hours before flooding was impacting Wairoa. Forecast information on the storm and waves underpredicted the significance of the event although the timing of the peak events was reasonably estimated. It is likely that the nowcast data obtained after the event also underpredicts wave and storm conditions based on local observations that the June 2024 waves were the biggest Mahia locals have seen in 30 years. The same nowcast model under-predicted waves at Napier based on a comparison of measured wave data with the nowcast information.
- The nowcast wave model shows a rapid increase in wave height from the evening of Tuesday 25 June, with a peak at midnight. Large waves were therefore influencing the bar and river mouth for approximately 12 hours before the river reached flood levels.
- Individual components of the event did not necessarily reach low probability return periods, but the combination of high rainfall, rising river level, spring tides, large waves, storm surge, as well as the position and size of the river mouth through the bar, all coincided to influence the

---

[1] A nowcast is a computer model that is run live during an event, providing the best simulation of conditions at that point in time. This is similar to a forecast for 0 hours into the future.

flooding experienced. The joint coincidence is therefore likely rarer than the individual elements and makes management of the situation more complex.

- The onset of flooding likely occurred at the start of the rising tide (3:30 am on 26 June), with the peak river level occurring at the next high tide (9:10 am). The incoming tide conditions, combined with large waves and storm surge created elevated water table conditions through the bar and the lower estuary that increased flood levels within the lower river (seepage flow through the bar was reversed due to large waves). Post event imagery indicates that waves were likely over washing sections of the bar during the event, potentially adding volume to the river and changing the crest level of the bar before and during the flooding event.
- A sudden decrease in river level at the turn of the high tide on the morning of 26 June likely indicates the point in time when the bar breached (soon after 9 am). The change from rising to falling tide, in addition to the river water gradient through the bar may influence the timing of the breach, as the outgoing tidal flow combined with river discharge and the steeper gradient through the bar.
- Comparing this event with two previous events, the location of the river mouth and the stage and magnitude of the tide may contribute to natural breaching of the bar. The last two natural breaching events (November 2023 and June 2024) occurred when rising river levels coincided with spring tides, with the breach occurring at the turn of the high tide at the same location adjacent to Pilot Hill, where river flow is constricted though a narrow channel.

River modelling

An existing TUFLOW model was provided by HBRC and adapted to replicate the June 2024 event. The model was adjusted to have a focus in the area of interest, and parameters were ‘tweaked’ to represent the observed water levels and flood extents using expert judgement and the best available information. The model was then applied to explore different influencing features.

The river model represents the measured river flow and tide conditions but does not resolve wave processes that were present during the event. The river model has a ‘fixed bed’ that does not erode or change during the simulation. Therefore, the change in river mouth width and position were represented using a function that allows controlled terrain adjustment during the simulation. This is a simplification of the full environmental complexity at the river mouth but provides a method for systematically assessing the influence of mouth geometry on river outflow.

The river model represented the observed flooding extent and timing, with limited parameter tuning, other than widening the initial river mouth and initialising the breach at Pilot Hill which was informed by observed changes in the bar.

Scenario testing shows that the position of the Wairoa River mouth in relation to Pilot Hill has a significant influence on the lower river system's hydraulic performance. When the mouth is offset to the west of Pilot Hill, the river width becomes constricted between Pilot Hill and the bar, where flow is constrained to a width of about 100 m. River flows need to pass through both the Pilot Hill constriction and the river mouth opening, incurring head losses through each. If the mouth is located east of Pilot Hill, there is less constriction, with water only needing to pass through the river mouth opening.

The timing and existence of a river mouth breach alignment to the main river channel greatly influences the peak flood levels attained. A “no breach” condition results in raised flood levels and extended flood duration, while an earlier breach results in much lower flood levels.

Sensitivity testing of the tide phase and tide level produced similar peak flood levels, indicating that there is limited tidal influence on river flood level. While the flooding on 26 June 2024 can be replicated using only the measured river level, tide conditions, and changes in the river mouth, this does not resolve the influence of waves acting on the bar and to do this coastal modelling was carried out.

Coastal modelling

A numerical model ‘Xbeach-Gravel’ was used to simulate wave and tide processes acting on the bar during the event. This was undertaken to explore the relative balance of sea-state compared to river level on the hydraulic gradient inside the porous gravel bar. Wave overtopping was also modelled for the 24-hour event. Modelling scenarios included:

- The baseline event as measured and nowcast.
- A comparison scenario with the same river level and tide, but small (average) waves.
- A sensitivity test that considered a wave height that is 30% higher than the nowcast wave height, as the nowcast model was potentially under-predicting the actual conditions.

Model results show that the water table dynamics within the bar are strongly controlled by wave and tide conditions, even when the river level is elevated. The baseline model of the event shows that the hydraulic gradient within the bar was dominated by wave action, creating a water slope from the sea, through the bar to the river. This hydraulic gradient facilitates water transfer from the sea to the river and creates an elevated tailwater condition that influences river drainage. In contrast, if the river conditions during the event coincided with typical wave heights, the hydraulic gradient is from the river to the sea, which facilitates drainage and breaching potential.

The crest level of Wairoa bar relative to the river level is an important feature of when and where a breaching event occurs. Analysis of long-term beach profile data suggests that the bar elevation has increased over recent decades. Beach crest levels along the adjacent Wairoa coast are increasing at rates similar to the measured rate of sea level rise. This change is consistent with the predicted changes expected on gravel coasts because of sea level rise. The increasing bar crest elevation increases the risk of flooding events occurring in the future, which may also be compounded by climate change influences on catchment flooding.

Coastal modelling shows that the hydraulic gradient in the bar was dominated by water level transfer from sea to river, which has a significant influence on river outflow and therefore the resulting river level and flooding.

Based on the available data and analysis, the large wave conditions impacting Wairoa were likely to have influenced the flooding, through a combination of elevating the water table condition through the bar, and directly adding volume to the river mouth through wave overtopping.

1 Introduction

1.1 Scope

Hawke's Bay Regional Council (HBRC) commissioned Tonkin & Taylor Ltd (T+T) to review physical processes that were likely to have collectively influenced flooding in Wairoa on 26 June 2024.

The scope of this report is to summarise key factual details relating to rainfall, river level, sea level, wave conditions, and the position of Wairoa River mouth bar. The scope does not include a review of the weather forecast or management activities, nor does it include any recommendations as we understand there to be current engagement with affected stakeholders, from which further recommendations may emerge.

Data sourced for this report is mostly quantitative and includes rain gauges, tide gauges, river level gauges, wave buoys, regional wave forecast models, and satellite images.

All elevations used in the report are in New Zealand Vertical Datum (mRL) and times are in New Zealand Standard Time (NZST).

1.2 Synopsis of flood event

- Flooding occurred in Wairoa on 26 June 2024, with the onset of flooding before dawn.
- Flooding continued over the morning high tide (26 June 2024 8:45 am)
- The flood level reached approximately the 4.2 mRL contour (NZVD)[2].
- Flooding occurred along and landward of Kopu Road on the west side of the river, and around Ngamotu Lagoon on the east of the river.
- Additional flooding was not observed on the evening high tide (26 June 2024 21:09 pm).

HBRC produced a preliminary flood extent map, which is attached in Appendix A. This was compiled using a combination of inspection reports and local observations including a review of social media and news reports that include local photographs and videos of the event.

1.3 Report outline

A description of the geomorphic setting is set out below. Section 2 presents data of the event and recent changes to the coast. Section 3 includes a comparison with other recent near-flood events and an evaluation of the long-term evolution of the bar based on profile surveys and LiDAR. Section 4 presents an analysis of the contribution of different influencing processes, such as the bar position and coastal modelling. Section 5 includes numerical river modelling results that represent the observed flooding.

1.4 Geomorphic setting

Wairoa town is located on the last meander of the Wairoa River before the river flows into Hawke Bay at a 40-degree angle to the coast. The final section of the river is approximately 3.5 km long, from Spooners Point to the river mouth, with Kopu Road extending along the town side riverbank. Elevations along Kopu Road average 3.7 mRL, with some variability as presented in Figure 1.1. Ground levels in the area landward of Kopu Road have similar elevations, as indicated by the contour lines in Figure 1.1.

---

[2] Based on preliminary flood extent mapping by HBRC, Appendix B.

The river mouth position is highly variable in Wairoa. During periods of low river flows, the bar can be substantially closed. When open it can be located towards Ngamotu Lagoon at the eastern side, be aligned with the main river channel, or be offset to the west past Pilot Hill.

The Wairoa coast is characterised by mixed sand and gravel barrier beaches. The Wairoa Bar is an extension of the sand and gravel barrier and is a highly dynamic geomorphic landform that is influenced both by river and coastal forces. Wave processes influence the migration and elevation of the bar through sediment being transported along the shoreline and waves over washing the bar moving sediment from the beach face to the landward side of the bar.

The bar elevation and width are also variable, depending on the river mouth position and recent migration. Sections of the built-up bar can exceed 5 mRL, based on LiDAR surveys (LINZ 2021; 2023). Sections of the bar closer to the active river mouth, or a recent breach location may be lower (2 – 4 mRL).

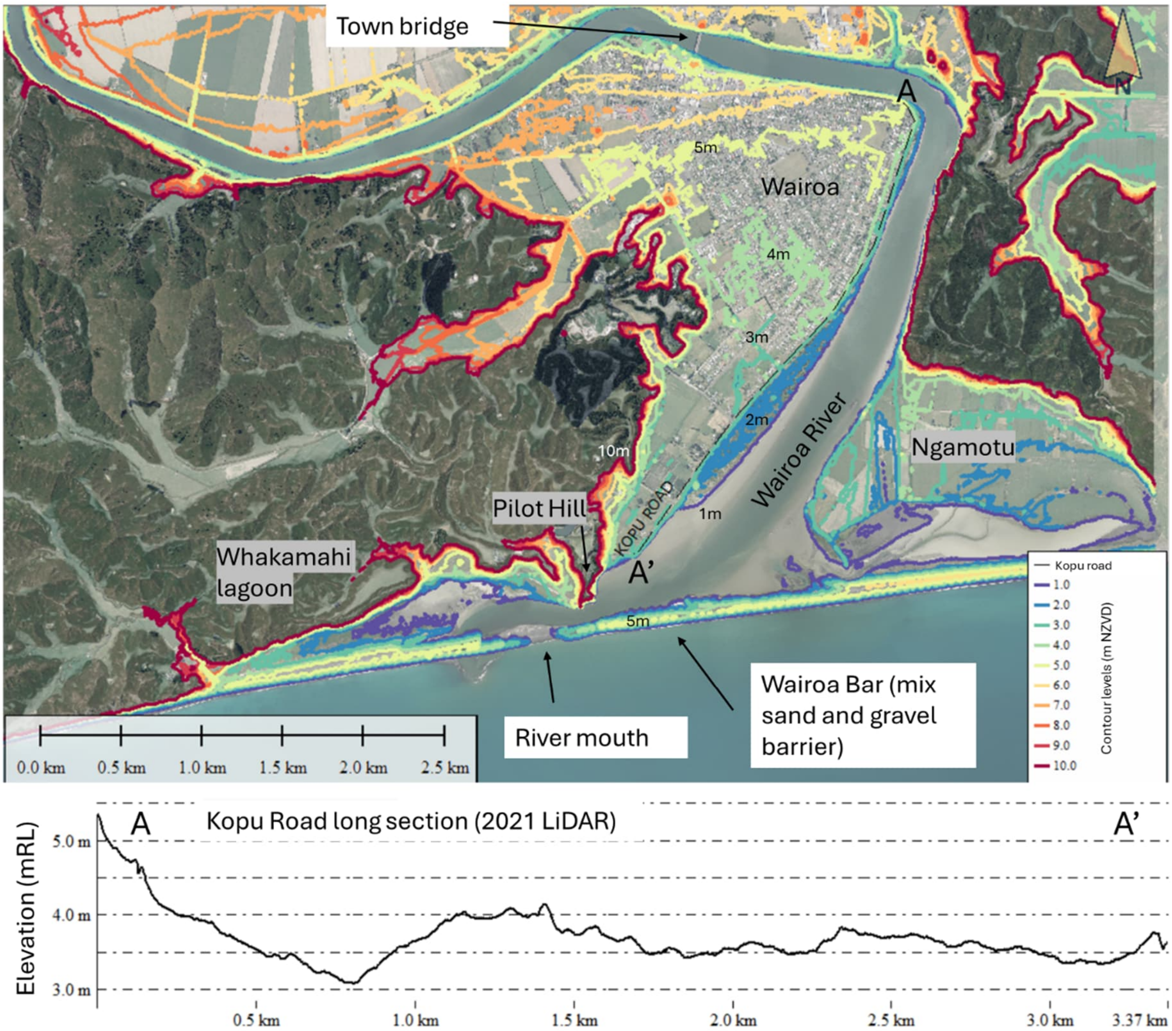


Figure 1.1: Key features and elevations around Wairoa and the river mouth. Elevation contours derived from reigonal LiDAR survey form 2021 (Sourced from LINZ).

2 Baseline data for the 25 - 27 June event

The focus of this section is to understand physical setting and conditions that resulting in the flooding in Wairoa. It covers the weather system and associated rainfall, the river levels as well as tide, storm surge and wave conditions and the position of the bar and how these factors influenced the river levels.

2.1 Weather event

The weather system that caused high rainfall, strong winds and large waves in Hawke Bay and Poverty Bay was a large low-pressure system that rapidly developed offshore of the East Cape on Tuesday 25 June (Figure 2.1)[3].

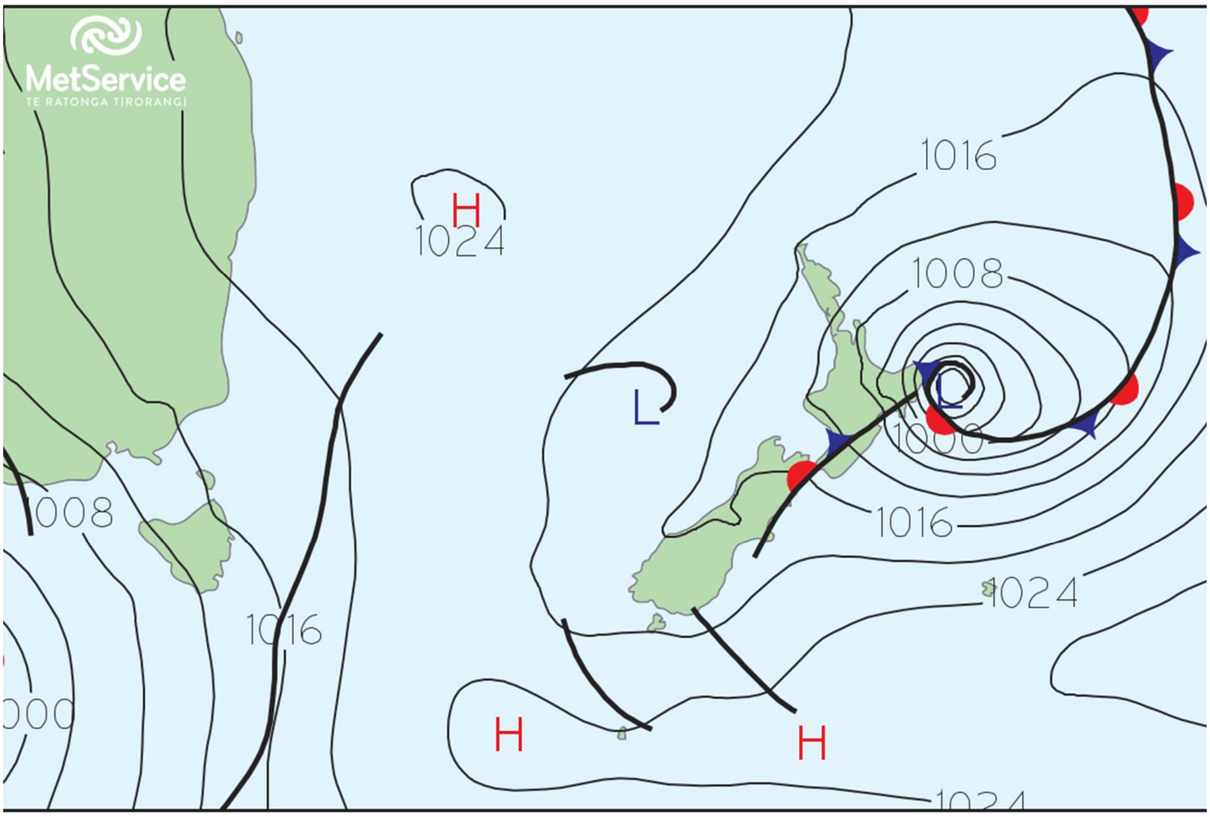


Figure 2.1: MetService weather map for 6:00 pm on 25 June (Source: MetService).

2.2 Rainfall

The focus of this section is to understand the rainfall accumulation that occurred before and during flooding in Wairoa. Rainfall measurements from the 23 locations in the Wairoa catchment were obtained from HBRC for analysis (Figure 2.2).

Rainfall data from HBRC shows that rain started to accumulate from approximately 7:00 am on Tuesday 25 June 2024 and continued to 27 June before the event subsided.

---

[3] Informed by email communication between HBRC and MetService (10 July 2024).

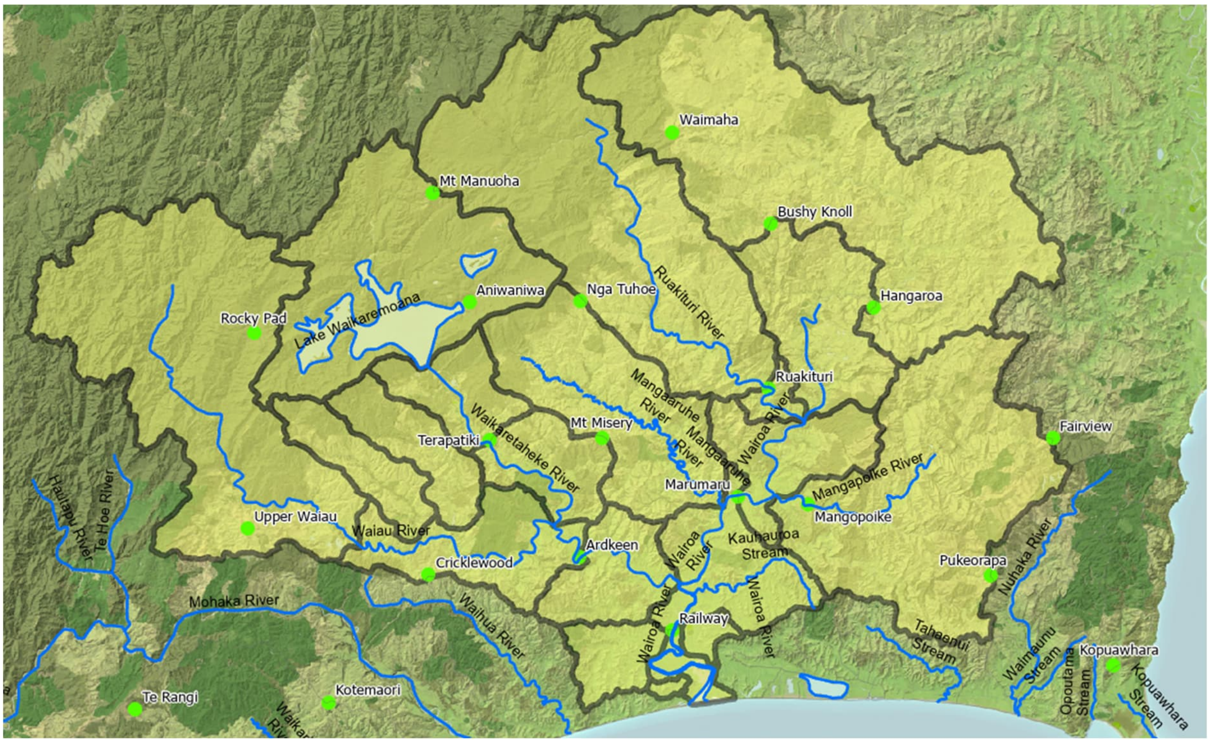


Figure 2.2: Location of rainfall gauges in the Wairoa Catchment (Source: HBRC).

The 24 hour rainfall accumulation in the catchment leading up to the flooding is presented in Figure 2.3. Across the 23 gauges, the rainfall accumulation ranged between 70 mm (Wairoa River Railway Bridge), to a maximum of 180 mm (Fairview). Median 24 hour rainfall across the 23 gauges was 108 mm, leading up to the flooding.

Rainfall at Nga Tuhoe (central catchment) was 126.5 mm in 24 hours, which is close to the 1 year average recurrence interval (ARI) rainfall according to HIRDS (129 mm)[4].

Rainfall at Fairview station (eastern side of catchment) was 180 mm in 24 hours, which is close to the 5 year ARI rainfall according to HIRDS (187 mm)[5].

---

[4] https://hirds.niwa.co.nz/ site ID 877214.

[5] https://hirds.niwa.co.nz/ site ID 878710.

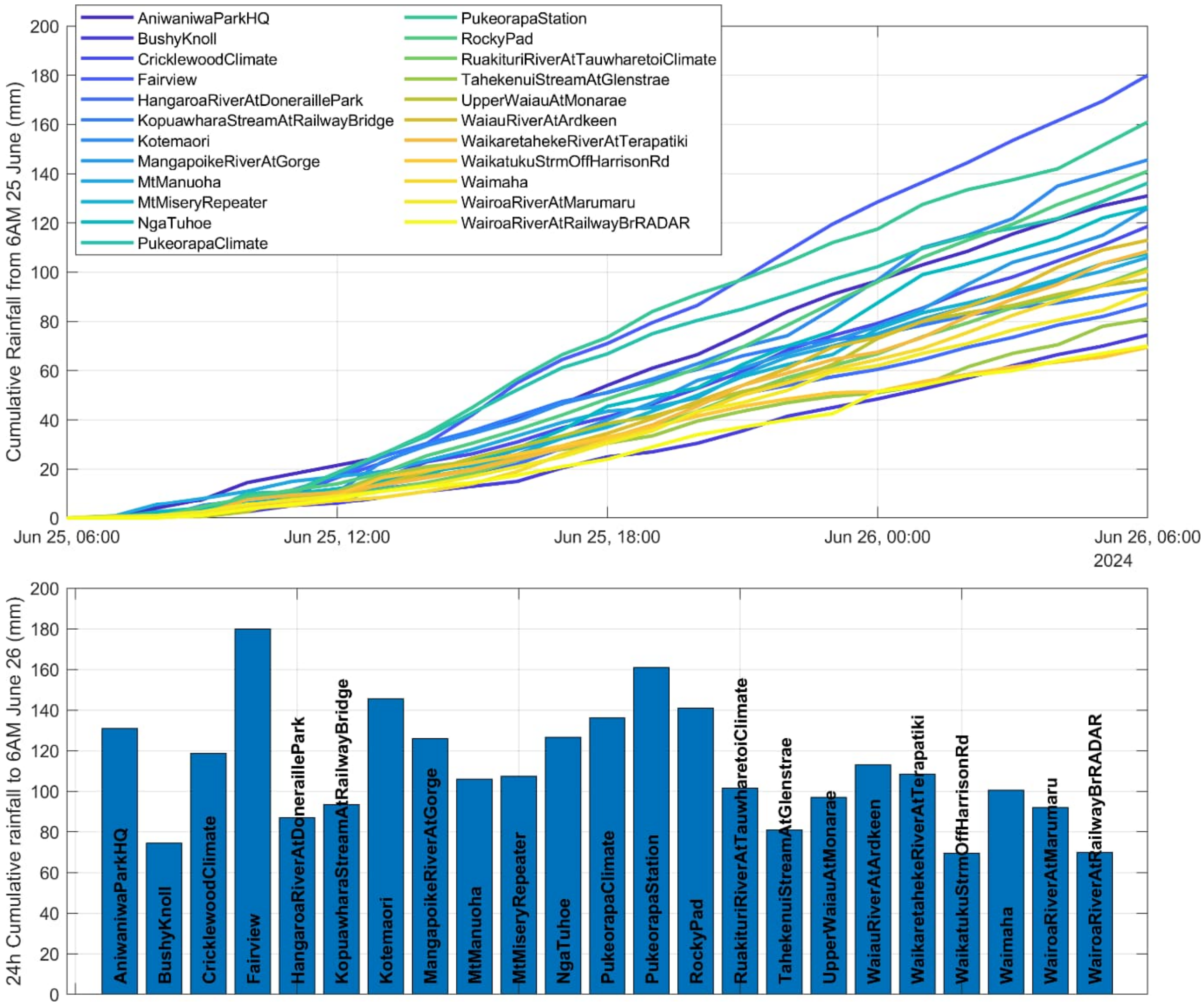


Figure 2.3: Cumulative rainfall for 24 hours between 6AM on Tuesday 2 June and 6AM on Wednesday 26 June (Source: HBRC).

2.3 River levels

2.3.1 Data overview

River levels for the lower reaches of the Wairoa River are recorded at the Railway Bridge, and at the Town Bridge (SH2), as shown in Figure 2.4.

Timeseries for the river level is shown below in Figure 2.5 and shows the river level started to rise above the typical tidal oscillation from 7:00 pm on Tuesday 25 June at both the Town Bridge and the Railway Bridge.

Figure 2.4: Location of River Level measurements on the lower Wairoa River. (Source: Aerial basemap from ESRI).

2.3.2 Railway Bridge

Water level at the Railway Bridge peaked at 11:20 am on Wednesday 26 June at a level of 8.0 mRL before decreasing (Figure 2.5).

2.3.3 Town Bridge

River level at the Town Bridge increased from 7:30 pm (Tuesday 25 June) at an average rate of 0.27 m/hr for 7 hours and the river level exceeded the average elevation of Kopu Road (3.7 mRL) at 3:35 am on Wednesday 26 June (Table 2.1). This occurred soon after low tide, which was predicted for 2:39 am. From this point, the rate of rise decreased to 0.17 m/hr until the peak, as water was likely spilling out of the river channel at the onset of flooding.

Peak water level at the Town Bridge was 4.66 mRL, recorded at 9:10 am on Wednesday 26 June, which coincided around the high tide (peak predicted for 08:40 am). The river level at the Town

Bridge rapidly dropped (-0.5 m/hr) after peaking[6], until the level went below the average level of Kopu Road 1.9 hours later, at 11:05 am (Table 2.1).

The river level at the Town Bridge exceeded the average level of Kopu Road for a total of 7.5 hours. River level continued to gradually decrease over the following two days, with a tidal signal evident from 28 June showing a return of more typical conditions.

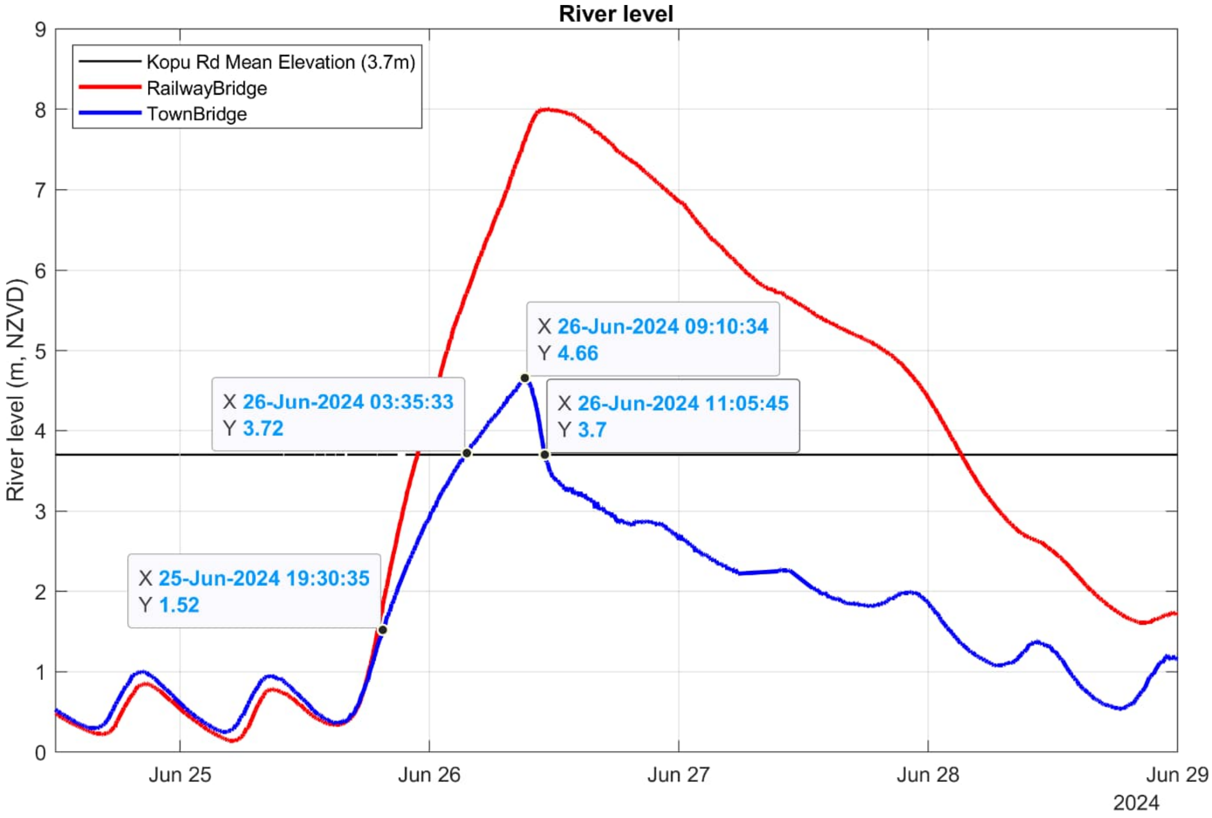


Figure 2.5: River level as measured at the Railway Bridge and at the Town Bridge, with the average elevation of Kopu road shown for reference. Data Source: HBRC.

Table 2.1: Key times from the Town Bridge gauge

Time	Note	River Level (mRL)[1]	change in time (hr)[2]	Change in level (m)	Rate (m/hr)
25/06/2024 19:30	River starts to rise	1.52	0.00	0.00	0.00
26/06/2024 3:35	River level exceeds average level of Kopu Road	3.72	8.08	2.20	0.27
26/06/2024 9:10	Peak river level	4.66	5.58	0.94	0.17
26/06/2024 11:05	River level drops below Kopu Road average level	3.7	1.92	-0.96	-0.50

[1] Town Bridge (m NZVD).

[2] Change in time from previous note.

2.4 Sea levels

There are no measurements of tide or coastal sea levels immediately adjacent to Wairoa. The sea level analysis presents the predicted tide information from the closest available port and is the

---

[6] A decrease in the rate of rise may also be influenced by widening of the river mouth.

information that was available prior to and during the event. Measured data from the closest available measurement station was also sourced post event.

2.4.1 Predicted tides

The predicted high and low tides from LINZ for Napier shown in Table 2.1. This is the closest major port with published tide levels. The flooding event occurred during spring tide conditions with the predicted high tide level of 0.58 mRL which is 0.17 m lower than MHWS. The predicted tides were also obtained from NIWAs tide calculator[7] to compare with measured tides at Napier, which is the closest available sea level monitoring location. The NIWA tide calculator for Wairoa is consistent with the LINZ predictions for Napier.

Table 2.2: Predicted high and low tides for Napier from LINZ

Time	State	Level (CD)	Level (NZVD)
25/06/2024 01:48	Low	0.3	-0.82
25/06/2024 07:53	High	1.6	0.48
25/06/2024 14:00	Low	0.3	-0.82
25/06/2024 20:16	High	1.8	0.68
26/06/2024 02:39	Low	0.2	-0.92
26/06/2024 08:45	High	1.7	0.58
26/06/2024 14:52	Low	0.3	-0.82
26/06/2024 21:09	High	1.8	0.68

2.4.2 Measured water levels

Water level measurements were sourced for Napier using the LINZ sea level monitoring network that was available post event[8]. Data from LINZ were converted to NZVD (mRL) and are plotted in Figure 2.6 below, which also shows the river level and predicted water levels for Wairoa. The raw measurements for the measured tide are sampled in in 1-minute intervals and show an agitated signal which indicates large waves were present[9]. Therefore, the signal was smoothed over a 30-minute moving average to remove high frequency wave effects.

Measured sea level in Napier during the event peaked at 8:56 am on Wednesday 26 June, at a level of 0.89 mRL, when averaged over 30 minutes. This is approximately 0.3 m above the predicted tide level. The peak tide level occurred approximately 30 minutes before the peak of the river level flooding recorded by the Wairoa Town Bridge gauge.

Water level from the river is also presented in Figure 2.6 to show the coincidence of tides and river levels. This shows that prior to the flooding, a tidal signal was evident at the Town Bridge, with a tidal range of 0.62 m, compared to a tidal range in Napier of 1.42 m. This is a ~55% reduction in tidal amplitude under non-flood conditions. High tide at the town bridge occurred approximately 80 minutes after high tide at Napier Port. Note that the dampening of tidal amplitude and the lag in phase is influenced by the river mouth position at the time of measurements, in this case the pre-event mouth location.

---

[7] Sourced from the NIWA tide calculator: https://tides.niwa.co.nz/?_gl=1*1nn274r*_ga*MTk1NzQyODU1OS4xNzEzODQ4MzA3*_ga_4CXN46915J*MTcyMDQ3Njk4Ni41LjAuMTcyMDQ3Njk4Ni4wLjAuMA..&latitude=-39.065658&longitude=177.432917

[8] https://sealevel-data.linz.govt.nz/index.html?tidegauge=NAPT

[9] 1-minute samples are influenced by waves and surf-beat

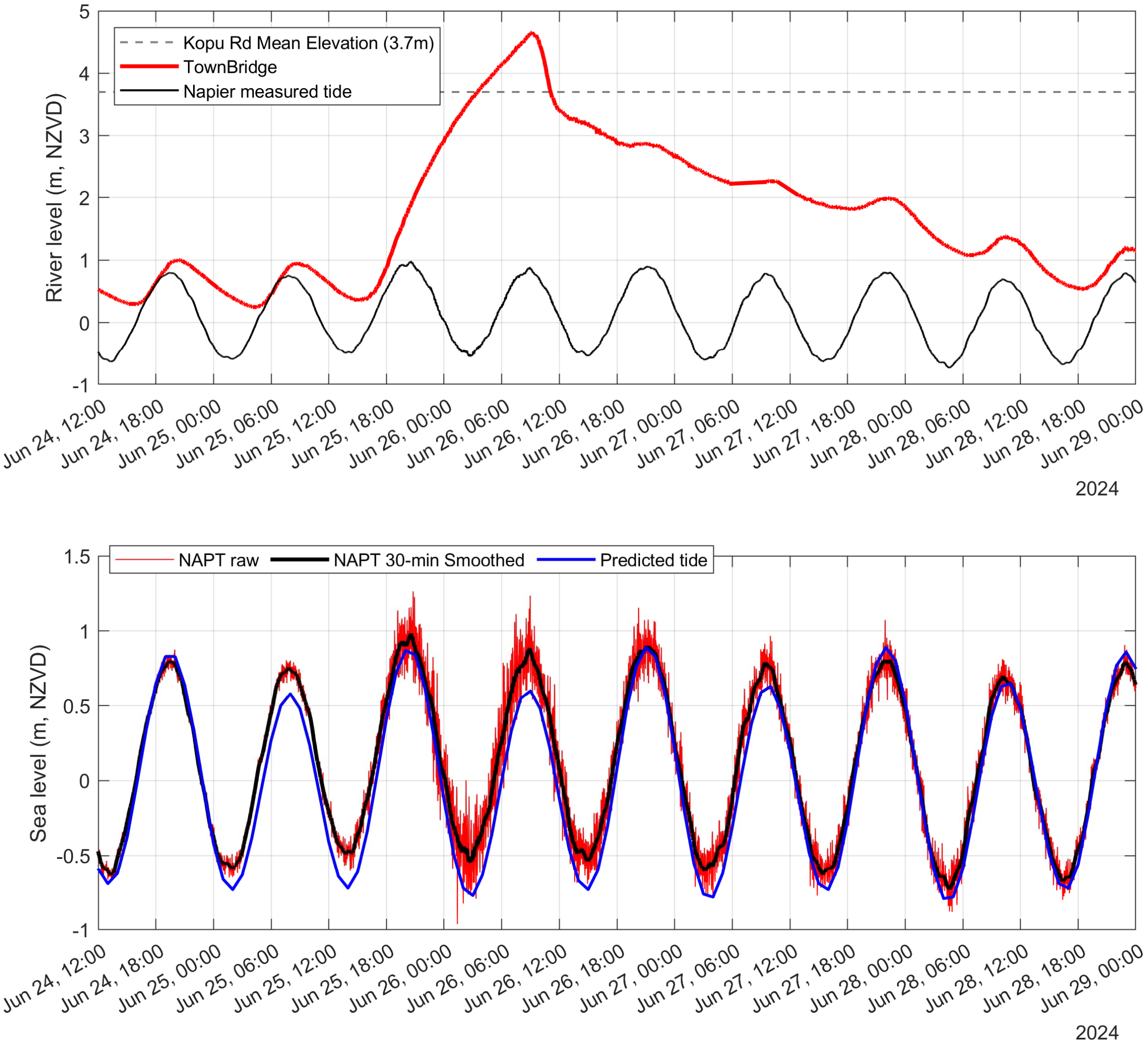


Figure 2.6: Sea level at Napier and rive level at the Town Bridge. Sources: HBRC, LINZ, NIWA.

2.4.3 Storm surge

Storm surge is the increase in coastal sea level at the shoreline and is caused by a combination of strong onshore wind and low atmospheric pressure. No reliable measuring site or storm surge model was available for the event or region to confirm local storm surge levels.

The orientation of the Hawke Bay coast to the wind direction in Figure 2.7 suggests that wind setup could have been higher in Wairoa compared to Napier, as the wind was a true onshore direction for Wairoa and a more cross-shore direction at Napier. The southerly and south-southeasterly wind directions during the storm may have caused elevated storm surge in Wairoa that is not represented in the Napier tide gauge. Wind speed forecasts during the event show wind speeds in the Hawke Bay were in the range of 20 – 30 knots, with gusts 35 - 45 knots, pointing towards Wairoa (MetOcean report issued Midnight on June 26).

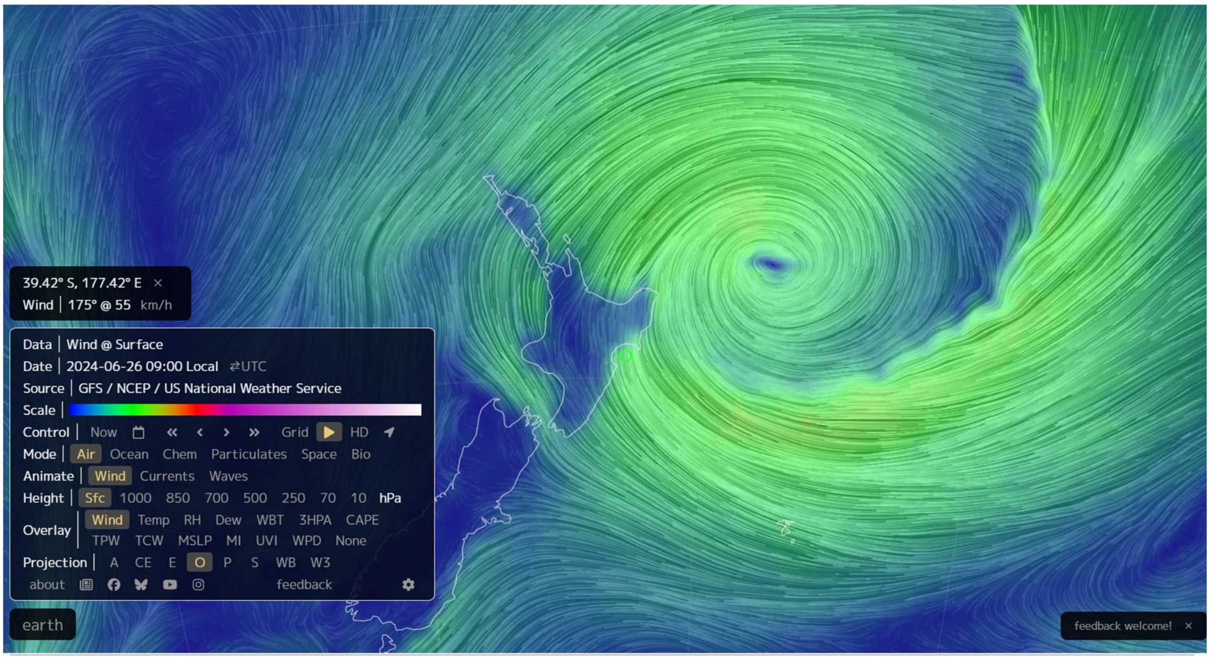
An estimate of wind setup for Wairoa was undertaken using maps of modelled wind speed[10] and empirical calculations from CRESS.nl calculator, considering wind setup in open water[11]. A sustained

---

[10] https://earth.nullschool.net/#2024/06/25/2100Z/wind/surface/level/orthographic=-182.93,-38.73,2614/loc=177.418,-39.416

[11] http://m.cress.tudelft.nl/Regel.aspx

wind speed of 15 m/s (28 knots) was used, with factors for the depth of open and coastal water. The resulting magnitude is sensitive to fetch length, which could be up to 700 km based on Figure 2.7 showing strong winds extending from Chatham Islands to Wairoa. A 700 km fetch with 15 m/s wind speed results in a wind setup level of 0.4 m, which would be considered the upper bound for this event as shorter fetches reduce the setup height.


39.42° S, 177.42° E

Wind | 175° @ 55 km/h

Data | Wind @ Surface

Date | 2024-06-26 09:00 Local ⇄UTC

Source | GFS / NCEP / US National Weather Service

Figure 2.7: Map of wind speed from Nullschool[12] at the time of the storm showing wind stretching from Wairoa to the Chatham Islands (700 km away).

Storm surge from low atmospheric pressure was predicted to be in the order of 0.1 m based on atmospheric pressure during the event of 1005 to 1014 mb (MetOcean Solutions report issued at midnight on 26 June).

Based on the available data and empirical calculations, storm surge levels at Wairoa could have been up to 0.5 m. Our best assessment is that storm surge levels at Wairoa are in the order 0.10 – 0.3 m above measured water level in Napier, but the actual storm surge levels remain unknown.

2.5 Waves

2.5.1 Data overview

Daily forecasting from wave models that provide a seven-day forecast of wind speed, wave height, period and direction at 3 hourly intervals were available prior to and during the event provide an understanding of predicted wave conditions offshore from Wairoa. No local wave buoy is available to understand the actual wave condition at Wairoa during the event.

Post event additional wave data was sourced from HBRC, including the measured wave conditions near Napier Port, and a ‘nowcast’ model from MetOcean Solutions was run to provide more detailed information[13]. The nowcast model provides modelled wave information, including wave height, period and direction at approximately 1 km grid resolution for the entire Hawke Bay. The nowcast is

---

[12] https://earth.nullschool.net/#2024/06/25/2100Z/wind/surface/level/orthographic=-182.93,-38.73,2614/loc=177.418,-39.416

[13] A nowcast is a computer model of waves that is computed live at the time but is not refined afterwards. This is typically more accurate than a forecast, but less accurate than a hindcast.

based on modelled data at the time of the event and is considered more accurate than the forecast that predicts conditions days ahead. However, forecasted wave height is also presented, based on three-day predictions from 24 June 2024, as issued by MetOcean Solutions to HBRC.

Based on a comparison of the forecast and nowcast model output, wave forecast information indicates that the initial wave forecast on the morning and evening of Monday 24 June were likely under-predicting the wave conditions (Figure 2.8). The forecast from the morning of 25 June shows a better match to the conditions represented in the nowcast model. However, visual observation from a long-term resident at Mahunga[14] that the wave conditions were larger than they had seen over the 30 year period they have been in Mahunga by a factor of two, suggest that all the nowcast might also be underpredicting the observed wave events.

2.5.2 Measured wave conditions at Napier

Measured wave conditions are only available for a localised point in Napier, in relatively shallow water (5 m depth) in the lee of Napier Port. Due to the shallow depth and sheltered location this information does not represent conditions in open water, or conditions expected off the Wairoa coast, where the coastline faces a southerly direction. The largest wave heights at the Napier buoy were Hs = 3.47 m, associated with a wave period of Tp = 14.6 s, and direction of Dp = 70˚ (east north-east), recorded at 10:15 pm on Tuesday 25 June (Figure 2.8). This recording represents approximately 30 minutes of higher wave activity. The general peak of the storm recorded waves closer to Hs = 2.9 m from 6:00 pm 25 June until 27 June.

2.5.3 Hawke Bay nowcast model

The MetOcean Solutions nowcast model provides data on wave conditions at 1 km resolution grid points across Hawke Bay, with data output at a 3 hourly timestep. The nowcast model at the Napier wave buoy location shows a reasonable match with the measured conditions with regard to timing (Figure 2.8), but the maximum modelled wave height (Hs = 2.43 m) was 40% below the maximum measured (Hs = 3.47 m), and the general peak in the model (Hs = 2.4 m) under-predicted the general peak in the measured data (Hs = 2.9 m) by a factor of 20%.

Modelled wave period at Napier was slightly lower at 13 s, with modelled wave direction of Dp = 65˚ close to the measured. The shallow water location of the wave buoy at Napier means the comparison of modelled and measured conditions is likely unsuitable for informing the accuracy of modelled conditions at Wairoa.

The nowcast model shows wave height offshore of Wairoa (depth of 23 m) started to increase from midday on 25 June (Hs = 1.6 m) and reached a peak of Hs = 5 m at midnight (Figure 2.8). Following the peak, wave height slowly tapered over the next three days. Wave height modelled at Wairoa at a depth of 10 m shows slightly smaller waves (peak Hs = 4.2 m), following the same trend. Modelled wave periods for Wairoa were consistent during the event, with Tp = 12.5 s. The peak wave height of the storm was associated with a wave direction of Dp = 147˚ (Figure 2.8). This wave direction is at an angle 23 degrees to the coast, which would generate westerly alongshore sediment transport, from Ngamotu to Whakamahi, likely reinforcing the westerly position of the river mouth.

Maps of the wave height and direction at key time intervals of the storm are presented in Figure 2.9.

The nowcast height of 5.0 m offshore of Wairoa, at a depth of 23 m is approximately a 1-year ARI wave height based on previously modelled data from 1979 – 2017 (MetOcean Insights[15]). The 10 and 50 year ARI wave heights are 5.9 m and 6.5 m, respectively. However, the nowcast model indication of a 1 year ARI event is not consistent with local observations that indicate that this event was the

---

[14] Email from Resident of Mahanga to HBRC dated Wed, July 24, at 2:54 pm

[15] https://insights.metservice.com/hindcast/#/ NZ wave Hawke Bay Point 177.4199, -39.1050

largest in 30 years. This further suggests that the nowcast was potentially under-predicting the actual conditions impacting Wairoa during the event, and therefore the return period. For example, if the wave nowcast was under-predicting the actual conditions by 30%, the event would be closer to a 50 year ARI wave event.

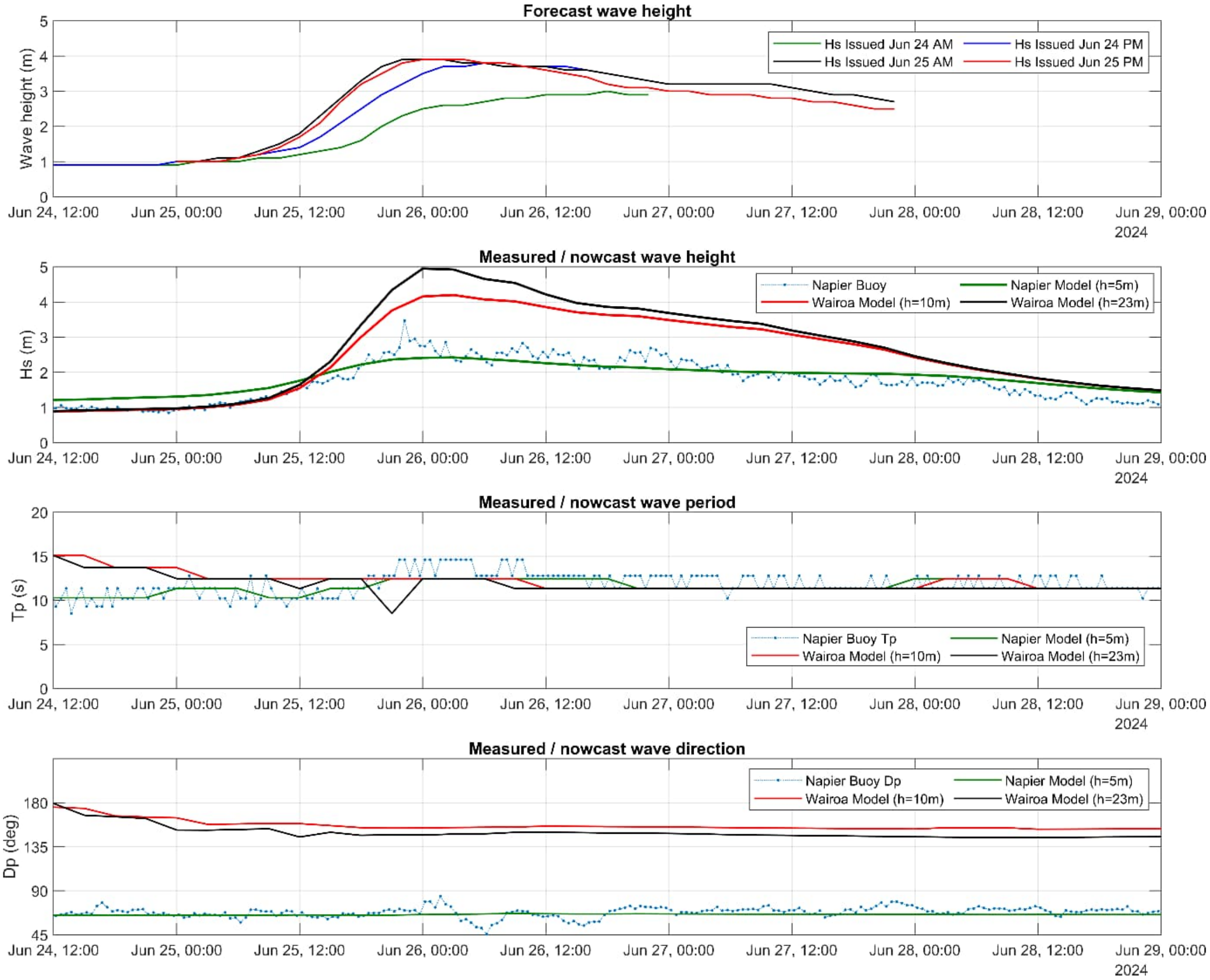


Figure 2.8: Wave conditions for Napier and Wairoa based on the forecast, measured data (Napier buoy provided by HBRC) and a nowcast model (by MetOcean Solutions, provided by HBRC). The h values indicate the water depth at the output points with the 5 m being the closest to the coast and 10 m and 23 m further offshore.

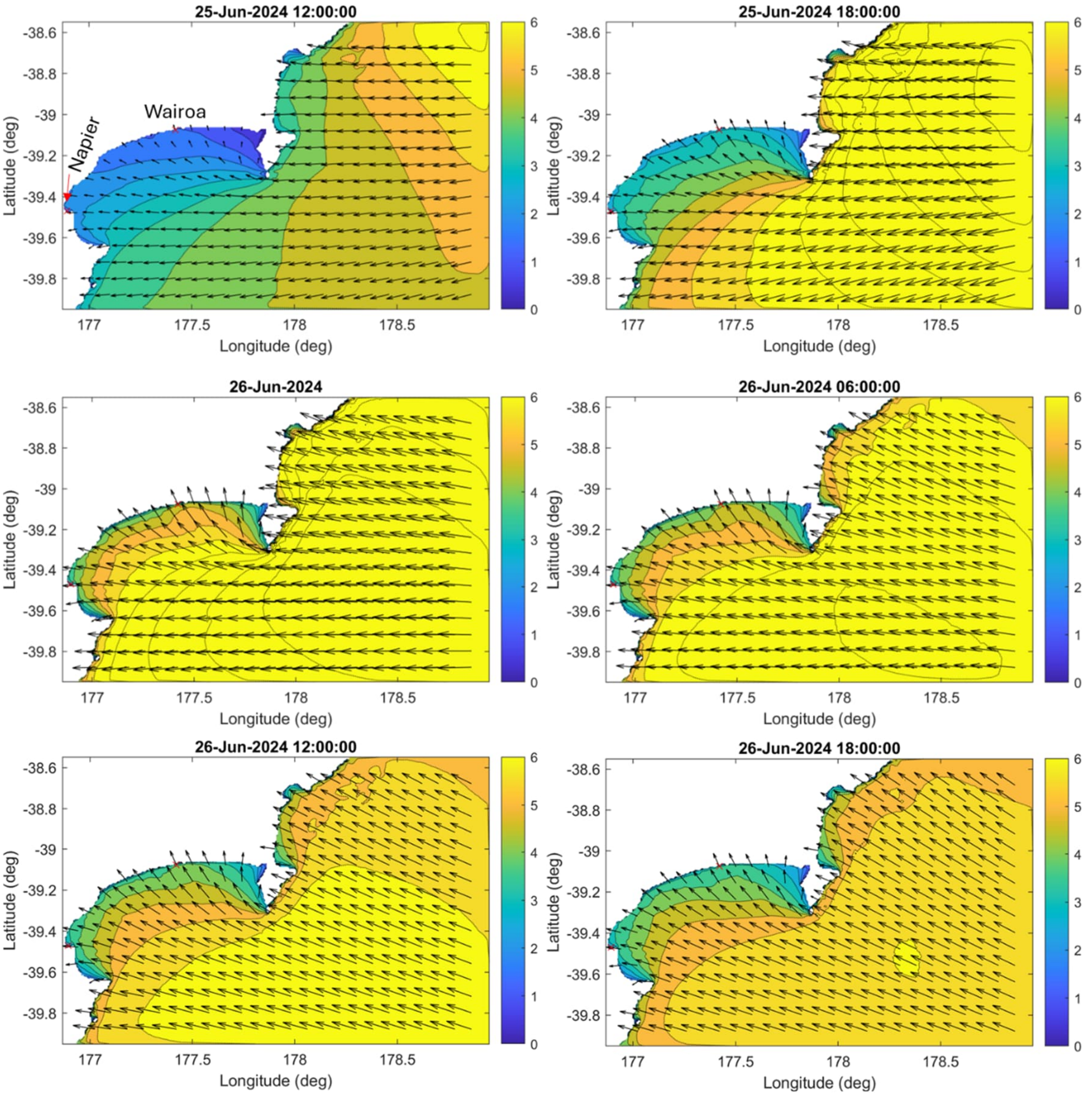


Figure 2.9: MetOcean Solutions Nowcast model for Hawke Bay. Clour shows wave heigth (Hs), with arrows showing wave direction. Small red crosses show the location of point data extracted for Wairoa and Napier.

2.6 Bar position

The position of Wairoa bar and the river mouth was reviewed using satellite images before and after the event and using a combination of satellite images and an aerial drone (UAV) survey by FENZ.

2.6.1 Pre-event

A Sentinel 2 satellite[16] image captured at midday on 24 June 2024 shows the Wairoa Bar extending across the main river and west of Pilot Hill, with the mouth open at Whakamahi. The mouth was located approximately 780 m west of Pilot Hill, where a narrow constriction forms between the bar and the hill (channel is approximately 85 m wide). The river widens again after Pilot Hill, before exiting to the sea through an approximately 70 m wide mouth opening. For context, the main river channel along Kopu Road is approximately 350 m wide.

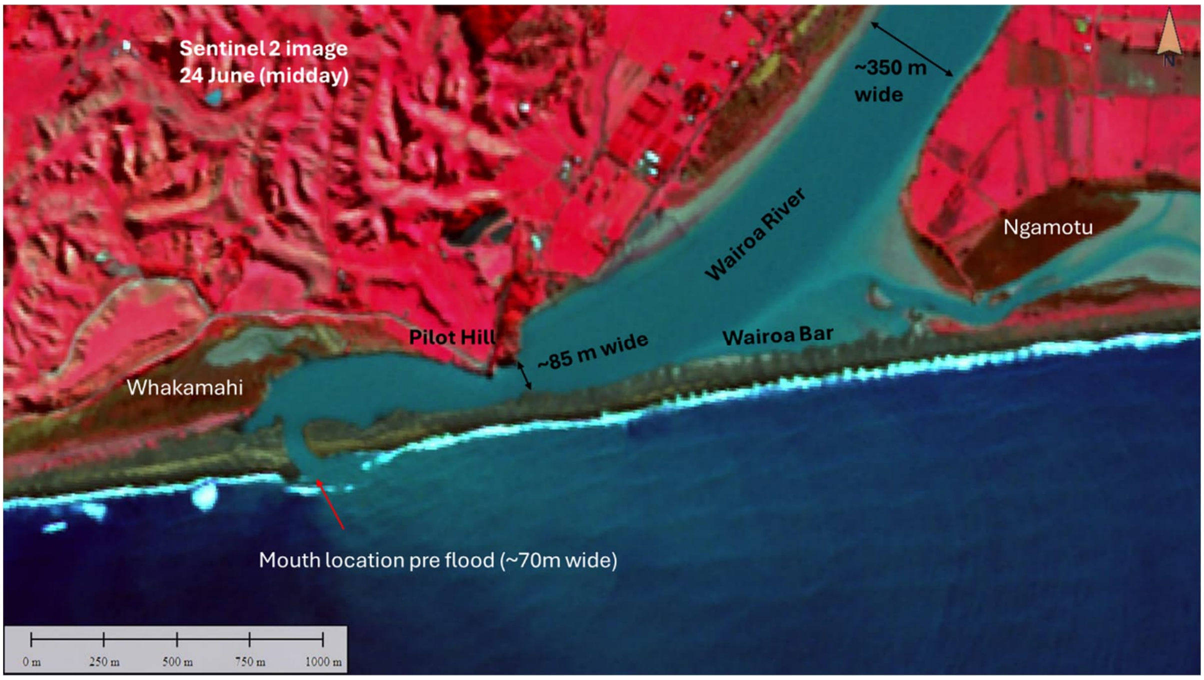


Figure 2.10: Annotated satellite image showing the bar position two days before the flooding event. Source: https://browser.dataspace.copernicus.eu/

2.6.2 Post-event UAV survey

An aerial drone (UAV) survey was conducted by FENZ on the afternoon of 27 June. Images were provided to us by HBRC (Figure 2.11).

The UAV images cover some of the river mouth, where the original mouth was located and where the bar was breached during the flood event, forming a new mouth aligned with Pilot Hill. The exact timing of the breach is unknown. The UAV image also shows the location where excavation works occurred on Tuesday 25 June in an attempt to open a new river mouth in the generally "preferred' central location. A second part breach of the bar is also visible closer to Ngamotu. Survey images and photos appear to show some indication that sections of the bar were being washed over by waves, as indicated by a wave washed smoothing of the sediment texture and over wash lobe patterns visible in the UAV aerial.

---

[16] 10 m pixel resolution, sourced from https://browser.dataspace.copernicus.eu/

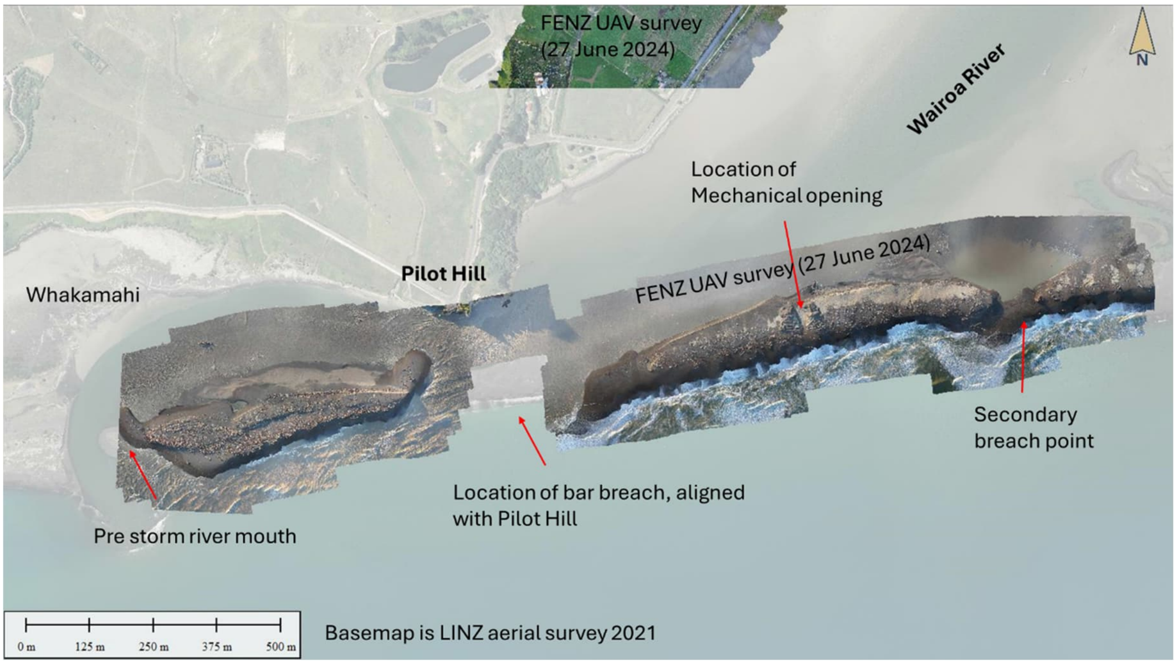


Figure 2.11: Annotated UAV aerial from 27 June (day after flooding) showing the location of the breach near Pilot Hill.

2.6.3 Post event satellite images

The next available satellite image was on 29 June, which is three days after the event and shows a new, second opening aligned with Pilot Hill, where the breach occurred (Figure 2.12). The original mouth is still present and was widened to approximately 150 m. The new river mouth was approximately 250 m wide, and the bar between the two river mouths is starting to merge with Pilot Hill, making the new mouth the most efficient flow path.

On the July 4 (eight days after the event) the bar west of the new mouth has merged with Pilot Hill and the original mouth is nearly closed. The new mouth maintains a width of 250 m (Figure 2.13).

By July 6 (10 days after the event) the original mouth was closed, and Whakamahi Lagoon appears to be closed (Figure 2.14). The bar also appears to be extending across the new mouth, angling seaward.

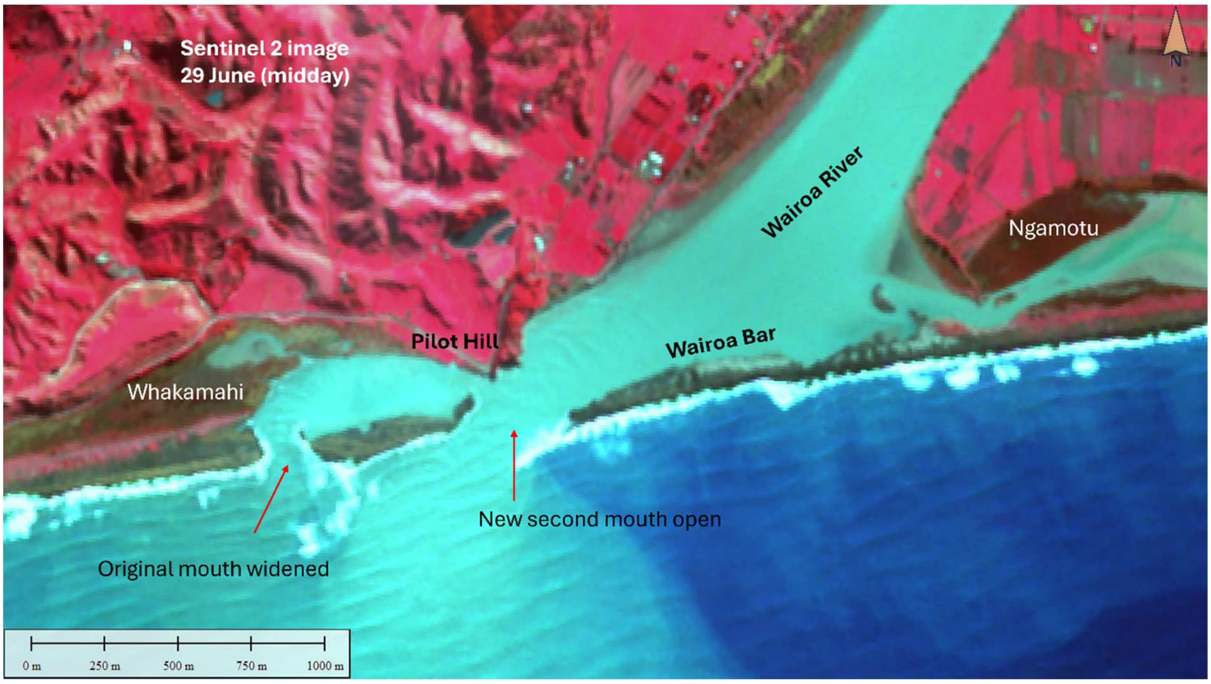


Figure 2.12: Annotated satellite image showing the bar position three days after the flooding event. Source: [*https://browser.dataspace.copernicus.eu/*](https://browser.dataspace.copernicus.eu/)

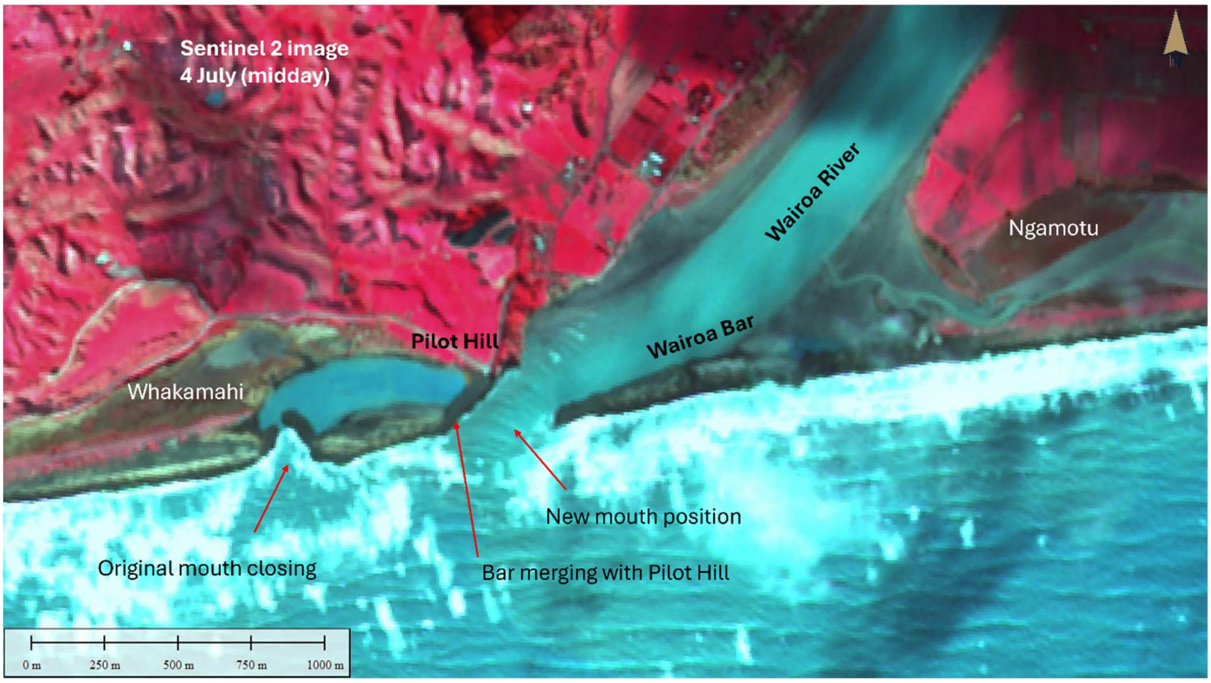


Figure 2.13: Annotated satellite image showing the bar position eight days after the flooding event. Source: [*https://browser.dataspace.copernicus.eu/*](https://browser.dataspace.copernicus.eu/)

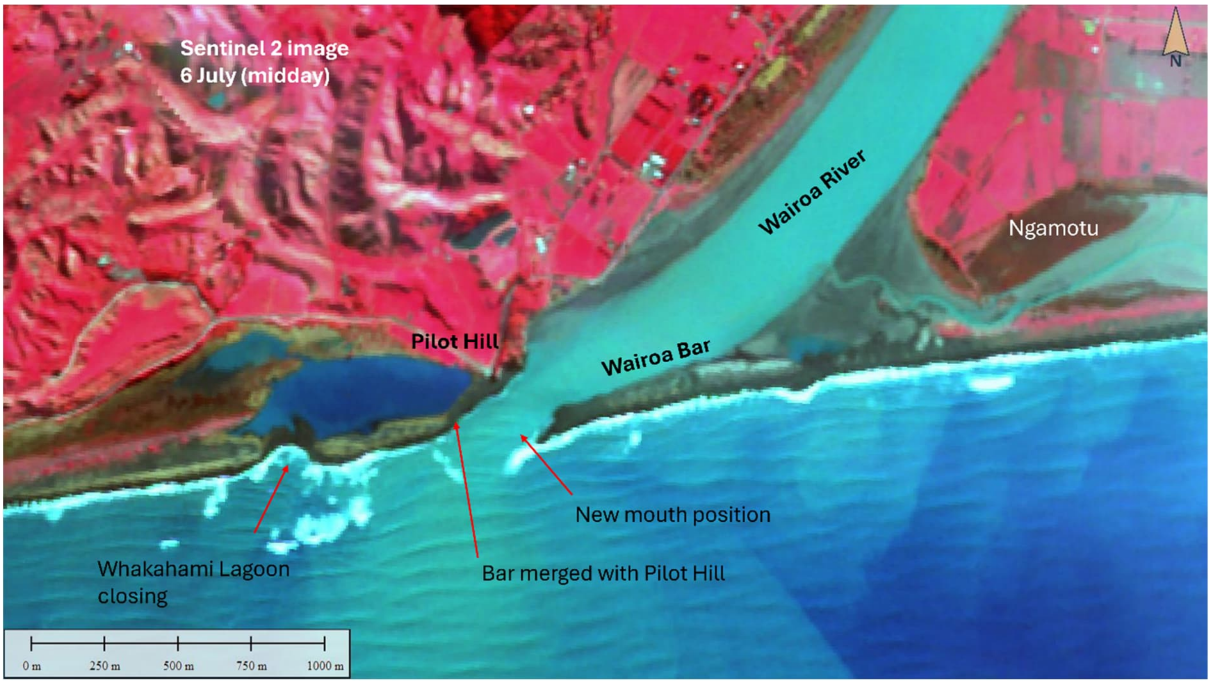


Figure 2.14: Annotated satellite image showing the bar position 10 days after the flooding event. Source: https://browser.dataspace.copernicus.eu/

2.7 Event summary

Flooding in Wairoa occurred over the early morning of 26 June 2024. Based on the available physical data flooding was influenced by multiple factors as summarised below:

- The atmospheric low-pressure system was large and formed rapidly on Tuesday 25 June, less than 24 hours before flooding was impacting Wairoa. Forecast information on the storm and waves underpredicted the significance of the event.
- Individual components of the event did not necessarily reach rare extreme return periods, but the combination of high rainfall, rising river level, spring tides, large waves, and position of the bar, all coincided to influence the flooding experienced. The joint coincidence is therefore likely rarer than the individual elements and makes management of the situation more complex. A summary timeline showing the coincidence of rain, river level, tide and waves is presented in Appendix B.
- The onset of flooding occurred at the start of the rising tide and the peak river level occurred at high tide. The incoming tide conditions, combined with large waves and storm surge may create opposing conditions at the river mouth that could influence flooding in the lower river. It is likely that the bar was breached at the turn of the high tide, as the outgoing tidal flow was assisting river drainage, based on the sudden decrease in river level at this point in the event.
- Waves were potentially over washing sections of the bar during the event.

3 Data on recent bar breach / near flood events and longer-term processes at the bar

This section provides additional context to the 25 - 27 June event by assessing physical condition of two recent bar breach / near flood events. This section also provides information on longer term trends of the bar morphology based on analysing long term trends from topographic surveys.

3.1 Recent bar breach events

3.1.1 Overview

The coastal and catchment data associated with two recent events are outlined below. These include:

- An event on 26 November 2023 when the bar breached at a similar location to the June 2024 event. After the breach in November 2023, the bar migrated again and the temporary second mouth was closed after a few months. By May 2024, the river mouth was again offset at Whakamahi.
- A rainfall event on 23 May 2024 caused elevated river levels that did not breach the bar or cause widespread flooding, although some localised flooding was likely.

Figures showing the data timeline of these events are presented in Appendix C. Summary details for these two prior events, and the 26 June 2024 event are presented in Table 3.1.

Table 3.1: Comparison of recent elevated river level events

Event	26 Nov 2023	23 May 2024	26 Jun 2024
Rainfall (24h before river peak)1	120 mm	90 mm	180 mm
Rainfall (48h before river peak)1	160 mm	168 mm	190 mm
Peak river level (Railway Bridge)	7.3 mRL	5.2 mRL	8.0 mRL
Peak river level (Town Bridge)	4.0 mRL	3.5 mRL	4.7 mRL
Wave height (Hs)	3 m	3 – 3.5 m	5 m
Sea level peak (Napier)	1.0 mRL	0.67 mRL	0.89 mRL
Bar Breach?	Yes	no	Yes
Flooding impact	Localised	Localised	Widespread

[1] Measured at the Fairview gauge.

3.1.2 26 November 2023

River level during the 26 November 2023 event peaked at 5 am, with the Rail Bridge gauge recording a water level maximum of 7.32 mRL, and the Town Bridge gauge recording a maximum of 3.97 mRL. The event coincided with spring tides, and the river level peak was at high tide, with the Napier tide gauge at 1 mRL (Appendix C).

Rainfall accumulation for 48 hours before the peak river level was 160 mm at the Fairview station. This is less than the 24 hour rainfall that occurred prior to the June 2024 flooding.

Modelled wave data (MetOcean Nowcast) shows the sea state was elevated, but not to extreme levels during the event, with waves around 3 m occurring for two days before and during the event.

A breaching of the bar within the main river channel alignment likely occurred at the turn of high tide after 5 am, as indicated by a steep drop in river level (Appendix C). A Hawke's Bay Today article[17] states that the bar breached at approximately 6:30 am, just before water level flooded the road.

Satellite images in Figure 3.1 shows the location of the river mouth before and after the November 2023 event, with the mouth initially offset to Whakamahi, and a new second opening near Pilot Hill after the breach.

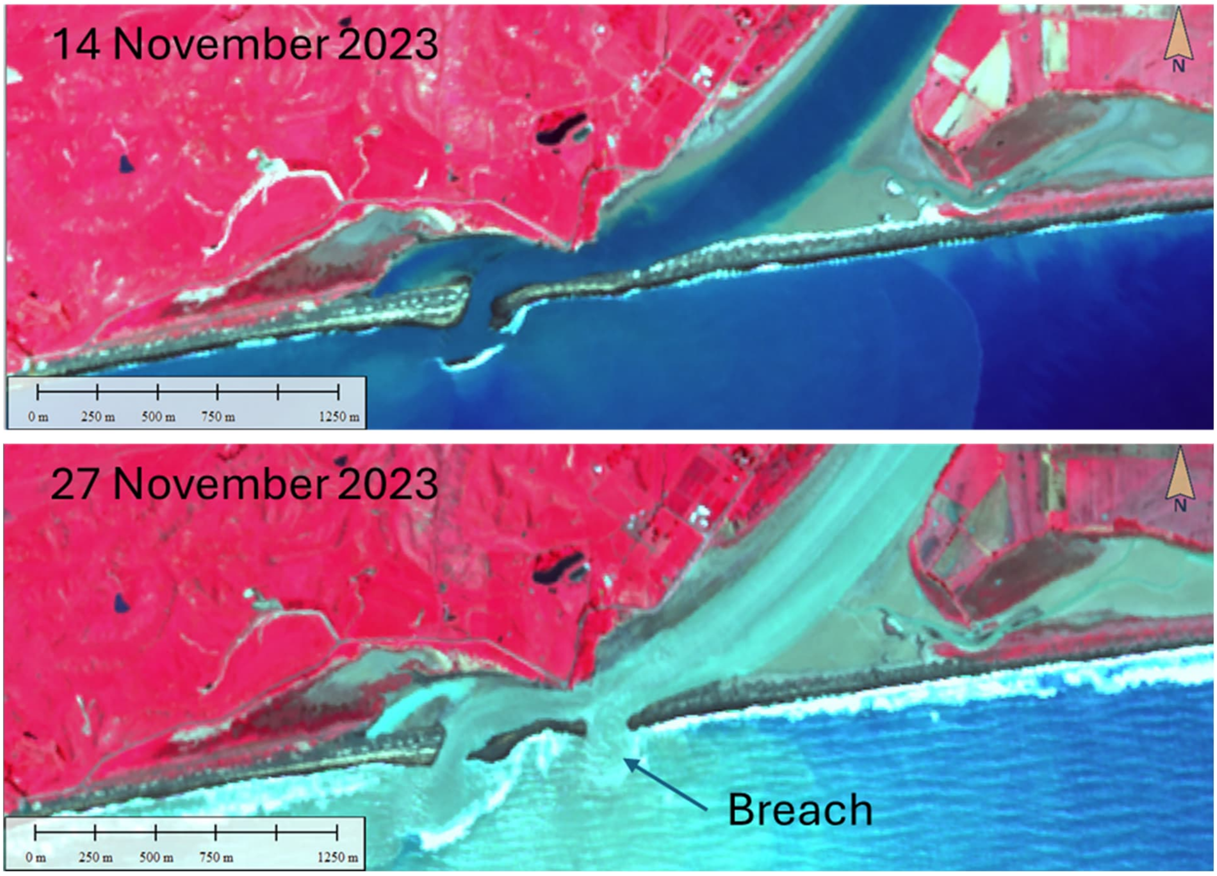


Figure 3.1: Satellite images of a breaching event in November 2023 at the same location as the June 2024 event. Source: browser.dataspace.copernicus.eu/

3.1.3 23 May 2024

River level during the 23 May 2024 event peaked at 2 am, with the Railway Bridge gauge recording a maximum water level of 5.2 mRL, and the Town Bridge gauge recording a maximum wate level of 3.5 mRL. The event coincided with neap tides, and the river level peak was during the mid-rising tide. The high tide occurred at 5 am, measured at 0.67 mRL on the Napier tide gauge.

Rainfall accumulation for 48 hours before the peak river level was 168 mm at the Fairview station. This was less than the 24 hour rainfall that occurred prior to the June 2024 event.

Modelled wave data (MetOcean Nowcast) shows the sea state wave elevated during the event, with waves around 3 – 3.5 m occurring for the day before and during the event. The river mouth before the event was located east of Pilot Hill, towards Whakamahi, with the outlet between the bar being

---

[17] The Wairoa River- when the mouth opened, it all went - NZ Herald

approximately 70 m wide. The event did not cause a breach of the bar, but did widen the outlet to 150 m.

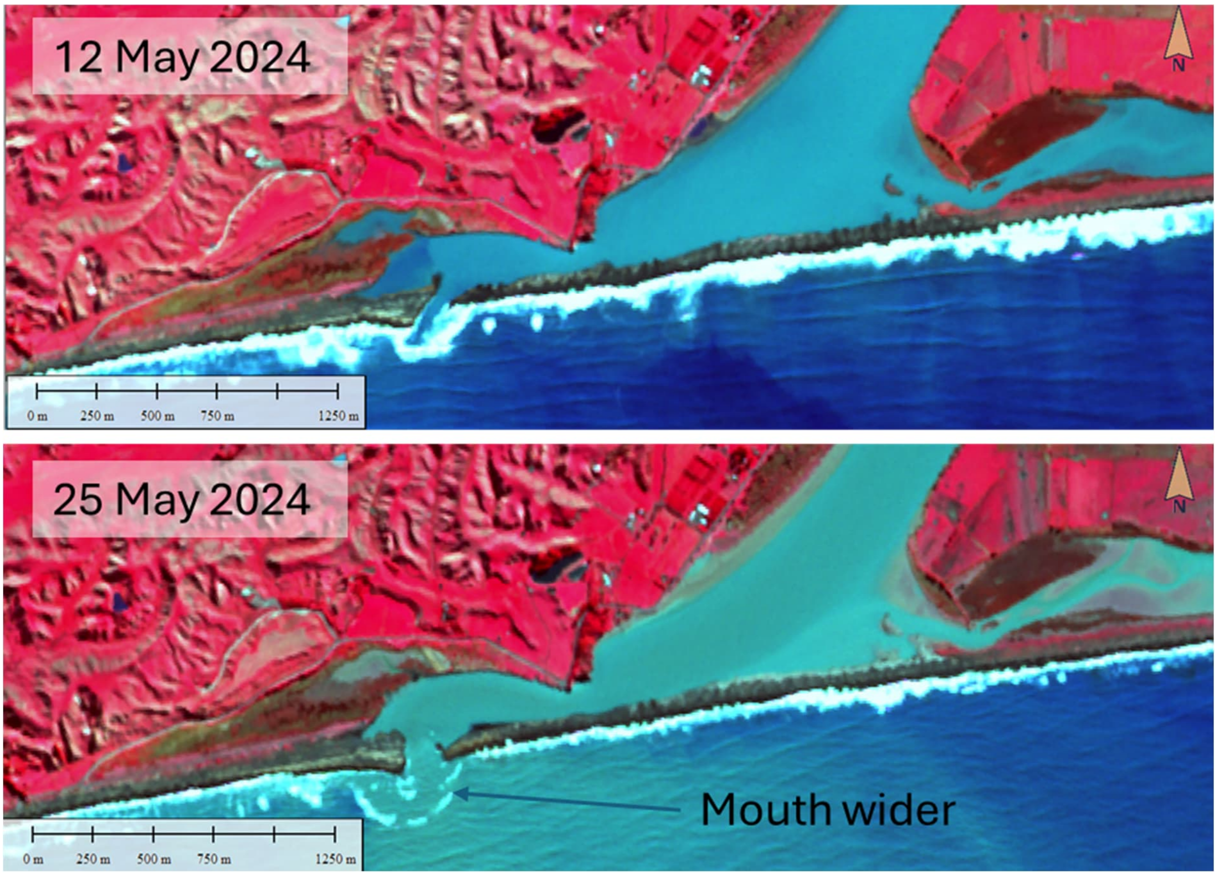


Figure 3.2: Satellite images before and after an elevated river level event in May 2024. Source: browser.dataspace.copernicus.eu/

3.2 Comparison of breaching location

The river mouth breached during the June 2024 flooding event at a location aligned with Pilot Hill. This location is further west of where the mouth is usually opened through mechanical excavation. The location of the breach near Pilot Hill is likely influenced by two factors:

- The river flow is constricted at this point, causing a localised area of high velocity that causes the river level to back-up. The high velocity river flow at this construction point potentially assists scouring of the bar in this location to cause a breach.
- There are similarities between the last two breaching events. The breaching events in November 2023 and June 2024 both occurred at high tide (or just after) and were associated with spring tide conditions. Both breaching events occurred in the same location, aligned with Pilot Hill. It is possible that the bar crest level was lower in this location during the June 2024 event, as the section was still being re-shaped by waves following the November 2023 breach. Photos from Pilot Hill taken in May 2024 show waves overtopping this section of the bar, indicating a lower bar crest elevation at this location (Figure 3.3).

Figure 3.3: Photo of waves washing over the bar at the breach location, taken from Pilot Hill on 28 May 2024.

3.3 Long-term beach profile change

This section also provides information on longer term trends of the bar and adjacent beaches, informed by analysis of long-term topographic survey measurements. This analysis provides context for how the bar has change in recent decades, which helps to inform future changes to coastal erosion and sea level rise. The recent and on-going evolution of the bar is relevant because the bar crest level, relative to the river water level and adjacent land level has an influence on the timing of a natural breach and therefore the potential for flooding.

3.3.1 Available data

Beach profile surveys on and adjacent to the river mouth bar provide a record of environmental change that was analysed to understand trends in coastal change and bar evolution over recent decades of sea level monitoring.

Mean sea level measured at Napier Port has increased at an average rate of 5.4 mm/year between 2000 – 2020, as reported in T+T (2023), and included here in Figure 3.4. Extending this trend to present results in a mean rise in sea level of 0.13 m from 2000 to 2024.

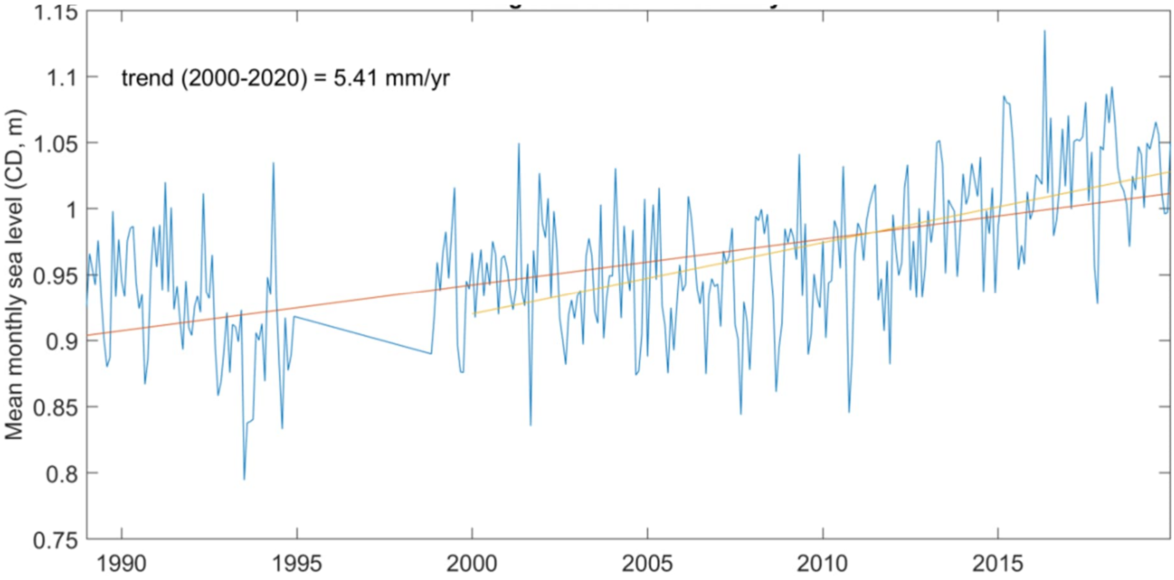


Figure 3.4: Mean monthly sea level measured at Napier Port, as analysed by T+T (2023) with data sourced from University of Hawaii Sea level Centre.

Beach profile cross-sections are monitored by HBRC at 13 transects at the Wairoa River mouth (Figure 3.5). Surveys started in 1997 and continued until approximately 2000, providing three years of historic data. Some of the profiles were re-surveyed in 2021, providing a more recent cross-section.

The historic cross-section surveys were complimented by four LiDAR surveys, with data provided by HBRC or sourced from the LINZ LiDAR database:

- 2003 regional LiDAR survey.
- 2021 regional LiDAR survey (assumed data of January 2021).
- 2023 post Gabrielle LiDAR survey (March 2023 survey by NIWA, University of Canterbury).
- 2023 [preliminary] regional LiDAR survey (14 October 2023 surveyed by NIWE).

Cross-sections were extracted in the same location as the historic surveys for the available LiDAR surveys and a consistent data analysis method was used to understand changes in profile position and elevation.

Figure 3.5: Beach profile locations along the Wairoa River Mouth (WRM).

There is a potential and unquantified error associated with comparing the historic site topographic profile methods with the LiDAR extracted profiles. LiDAR surveys provide high spatial resolution outputs but are subject to post-processing to remove non-ground features (e.g. driftwood, vegetation). In comparison, the historic surveys provide accurate ground measurements but at lower spatial resolution.

A summary of the available profile data is presented in Table 3.2, with profiles having 9 – 12 temporal repeats available over the last 26 years. There is a data gap between 2004 and 2020 which makes trend analysis of changes in the profile less reliable than if the profiles were surveyed regularly with no gaps.

Profile analysis was undertaken to assess changes in profile volume, crest elevation, and beach face position. Analysis is presented for profiles located on the beach at Whakamahi (represented by WRM1 to 3), across the dynamic bar section (WRM4 to 8), and for profile located on the more consistent bar section along Ngamotu (WRM 9 to 13).

Table 3.2: Summary of available beach profile survey including from LiDAR

Name	Northing	Easting	No. Years	No. Surveys	Earliest	Latest
WRM 1	1979614	5666428	26	10	31/10/1997	14/10/2023
WRM 2	1980106	5666528	26	10	31/10/1997	14/10/2023
WRM 3	1980602	5666618	26	10	31/10/1997	14/10/2023
WRM 4	1981094	5666697	26	10	31/10/1997	14/10/2023
WRM 5	1981594	5666739	25	9	31/10/1997	14/10/2023
WRM 6	1982090	5666805	26	11	31/10/1997	14/10/2023
WRM 7	1982582	5666868	26	11	31/10/1997	14/10/2023
WRM 8	1983078	5666940	26	12	31/10/1997	14/10/2023
WRM 9	1983570	5667040	26	11	31/10/1997	14/10/2023
WRM 10	1984073	5667095	26	10	31/10/1997	14/10/2023
WRM 11	1984571	5667146	26	10	31/10/1997	14/10/2023
WRM 12	1985065	5667197	26	10	31/10/1997	14/10/2023
WRM 13	1985670	5667275	25	9	31/10/1997	1/3/2023

3.3.2 Whakamahi Beach profiles (WRM 1 – 3)

Profiles 1 - 3 are located on Whakamahi Beach, to the west of where the river mouth typically migrates. This location is representative of open coast processes with minor influence of the river flows and bar migration processes. The long-term trends in profile change can be used to understand coastal processes that are less influenced by bar migration.

Figures showing the profiles and trends in profile change are presented in Appendix D. A summary of profile change statistics is presented in Table 3.3.

The average profile crest elevation across the three Whakamahi profiles is 5.2 mRL. The change in crest level shows a slight trend of increasing over time, with the linear trend of 8.0 mm/year resulting in an increase of 0.2 m over 26 years. This is consistent with the end point change between the oldest and most recent survey showing a crest increase of 0.18 m. This is also consistent in magnitude with the change in sea level over the monitoring period. The crest position migrated landward on the Whakamahi profiles by an average of 5 m, indicating that barrier roll-over may be occurring on this profile.

The position of the upper beach contour (3 mRL) shows a landward migration (erosion) over the last 26 years. The linear trend in profile recession, accounting for all surveys is -0.43 m/year averaged across the three profiles, which adds to 11 m of recession over 26 years. The change in position between the earliest survey and the most recent survey is more extreme, showing a landward migration of 18 m (end point change).

Profiles 1 and 2 shows a slight reduction in volume over the survey period, with profile 3 showing a slight increase in volume. The volume calculations may be sensitive to the resolution of surveys collected using traditional methods compared to higher resolution LiDAR surveys.

3.3.3 River mouth profiles (WRM 4 – 8)

Profiles 4 – 8 are more dynamic and influenced by the river mouth position and bar migration. The average crest elevation across these five profiles is 4.8 m, with lower crest levels (4.6 m) at profiles 5 – 7, where the river mouth is more frequently located.

Crest level of the bar is dynamic along this section, but the data does show a trend of crest level increasing. Across the 5 profiles, the average trend in crest level is 20 mm/year, which adds to 0.55 m over 26 years. The average crest height in the latest survey is 5.2 mRL, compared to 4.7 mRL in 1997. Therefore, the data does show a trend of bar level increasing, which is consistent with the end point change comparison. The position of the crest along this section also appears to be migrating landward, at a rate of -0.7 m/year, although this is not progressive year to year.

The position of the 3 m contour also shows a landward migration of -0.55 m/year (erosion) across these five profiles. This results in 14 m retreat over the last 26 years, which is consistent with the measured end point change, showing the average contour position in 2023 is 12.2 m landward of the position in 1997.

The trend in profile volume change is small when averaged across the five profiles at 0.55 m^3/year which indicates a general stability in volume, suggesting material is being eroded from the beach and deposited on the crest, in the form of a barrier roll-over adjustment.

3.3.4 Ngamotu profiles (WRM 9 – 13)

Beach profiles along the Ngamotu Lagoon are less influenced by river mouth migration. Profile crests are higher than locations to the west, and the crest level increasing gradually towards the east from WRM 9 – WRM 13. The average crest level is 6.3 mRL across these profiles, with no clear trend in crest level change across these five profiles. The change in crest position is slightly landward, but within 3 m of the initial survey.

The beach face along the Ngamotu section shows a clear trend of erosion, averaging -0.7 m/year. This adds to a change in contour position of -17 m (landward) over the last 26 years, which is consistent with the end point change of -19.6 m from the first survey to the most recent.

The Ngamotu profiles all show a reduction in volume over the survey period, averaged to be -2.4 m^3/year. This is due to the beach eroding, but the crest has maintained a consistent position and level. Therefore, volume is being reduced on the profile (as measured above MHWS).

Table 3.3: Beach profile analysis details

Name	Mean crest level (mRL)	Crest level trend (mm/yr)	Crest position trend (m/yr)	3 m contour trend (m/yr)	End point rate crest level (mm/yr)	End point rate 3 m contour (m/yr)
WRM 1	5.2	2	-0.31	-0.39	5	-0.63
WRM 2	5.3	10	-0.12	-0.44	4	-0.95
WRM 3	5.1	12	-0.16	-0.45	12	-0.56
WRM 4	5.1	0	-0.20	0.11	22	0.29
WRM 5	4.7	40	-1.01	-0.64	47	-0.48
WRM 6	4.6	33	-0.03	-0.09	23	0.59
WRM 7	4.6	35	-1.74	-1.20	16	-2.10
WRM 8	5.1	3	-0.65	-0.91	-7	-0.67
WRM 9	6.1	-1	0.12	-0.50	-1	-0.76
WRM 10	6.3	10	-0.10	-0.95	15	-0.85
WRM 11	6.2	-8	-0.16	-0.67	-11	-0.54
WRM 12	6.4	-8	-0.29	-0.73	-7	-0.83

Name	Mean crest level (mRL)	Crest level trend (mm/yr)	Crest position trend (m/yr)	3 m contour trend (m/yr)	End point rate crest level (mm/yr)	End point rate 3 m contour (m/yr)
WRM 13	6.4	-13	-0.11	-0.59	-12	-0.82

3.3.5 Profile summary

A summary of the breach profile analysis is presented in Table 3.4, based on the three coastal segments. Beach erosion is occurring on all profiles, as measured by the 3 m contour. The most erosion is occurring at Ngamotu, with the lowest rate of change at Whakamahi.

The trend of beach erosion may be influenced by the differences in antecedent crest elevation. The higher profiles at Ngamotu are likely to prevent wave over wash depositing material on the crest during typical conditions. In comparison, some profile translation (roll-over) is likely occurring in the river mouth section, where a trend of crest raising, and landward migration indicates a general volume balance. The crest level at Wahkamahi is lower than at Ngamotu, and the trend in crest level is of accretion and landward migration on these profiles.

The rate of profile accretion and landward roll-over at Whakamahi is consistent with the magnitude of sea level rise measured at Napier. The rate of crest accretion over the river mouth section exceeds the amount of sea level rise and suggests that the recent bar morphology is currently higher than it was in the past.

Table 3.4: Beach profile summary

Location	Average Crest level (mRL)	Crest level / position trend	Beach trend	Volume trend
Whakamahi	5.2	Accretion / landward	Eroding -0.43 m/yr	Dynamically stable
Mouth	4.8	Accreting / landward	Eroding -0.55 m/yr	Dynamically stable
Ngamotu	6.3	Consistent / landward	Eroding -0.7 m/yr	Loss in volume

4 River modelling of the event

4.1 Purpose

This section covers investigations undertaken to simulate the flood mechanisms and physical processes that contributed to the flooding in Wairoa during the June 2024 event.

The purpose of the river modelling covers two specific elements:

- Apply and adapt the model to provide a reasonable hindcast of the flooding and physical processes at play for the June 2024 event. This involves matching the flood extents and levels over time with observations made over the course of the event by varying model inputs within bounds of observation.
- Application of the hindcast model to investigate and understand key drivers of the flood behaviour experienced during that event and provide a synopsis of these.

4.2 Scope

To do this work we used a flood model of the Wairoa River developed by the engineering consultants WSP using the TUFLOW flood modelling package. While other models and modelling approaches are available, our scope was to make the best use of this model in achieving the purposes outlined above. We received a copy of this model on 6 July 2024. Subsequent sections describe the modelling and modifications made to hindcast the June event in the model, and the assumptions and limitations around this.

The flood modelling approach presented here is a robust approach for the purposes on assisting in understanding the drivers of flood behaviour. Morphological modelling would require large amounts of field survey data, collected over time, together with detailed bathymetric data that was not available within the timeframes allowed.

4.3 Model summary

WSP previously undertook hydraulic modelling using the TUFLOW model post Cyclone Gabrielle to assess flood mitigation options for the areas categorised as Category 2A, shown in Figure 4.1. Also shown in this figure is the extent of observed flooding in Wairoa from the June 2024 event.

T+T were provided the WSP TUFLOW model for the Wairoa River on 6 July 2024. Because the focus of our investigations is on the lower reach of the Wairoa River, the model provided was truncated with the upstream boundary being the with upstream edge at the Railway Bridge, covering the model extent shown in Figure 4.2. This was to enable faster run times and to focus on the lower river and mouth processes.

Figure 4.1: Category 2C areas assessed as part of the WSP modelling – not to scale.

4.3.1 Model set-up

The model provided had the following components:

- Provided in TUFLOW version 2023-AB.
- 2D only model, with break lines to describe numerous features not accurately represented in the LiDAR based DEM.
- 16 m model computational grid.
- DEM based on 2023 LiDAR survey post Cyclone Gabrielle.
- River bathymetry understood to have been developed from previous cross section survey.
- Variable roughness derived through calibration.
- Eddy viscosity through calibration.
- Upstream inflow boundary embedded within the model, understood to be based on recorded levels from Cyclone Gabrielle – see Section 4.3.2.
- Steady state sea level tailwater condition.
- Direct rainfall from gauge applied to model domain, noting that model domain does not cover all of the catchment (and would therefore omit some runoff contribution).
- Zero infiltration losses.
- Terrain modifiers to represent mouth configurations.

T+T has retained all of the above model elements, except where specifically noted as having been changed in Section 4.5.

4.3.2 Model checks

Prior to making use of the model, we undertook some high-level model checks to develop confidence in its use. We have made the following review observations:

- The area of interest for the post cyclone modelling was further upstream than the flood extent observed in the June 2024 event. Therefore, we have assumed that no specific model refinements have been done around the area of interest for this work.
- No infiltration losses have been applied to the modelling, therefore any rainfall applied directly to the model extent is likely to be over-estimated as there are no soil infiltration losses accounted for.
- The model is reported to have been calibrated for the roughness and eddy viscosity coefficients. The roughness values are fixed relative to the flood depth, and the eddy viscosity coefficients are in line with expected values. The Smagorinsky approach to eddy viscosity was used.
- The model boundary at the upstream end (Railway Bridge) was provided as a stage-time boundary. After running the model the stage-time relationship was extracted and compared with recorded water level data over the event, with the results being shown in Figure 4.2. This showed good correlation, with the peak inflow at the railway bridge being approximately ~2,800 m^3/s at the peak.

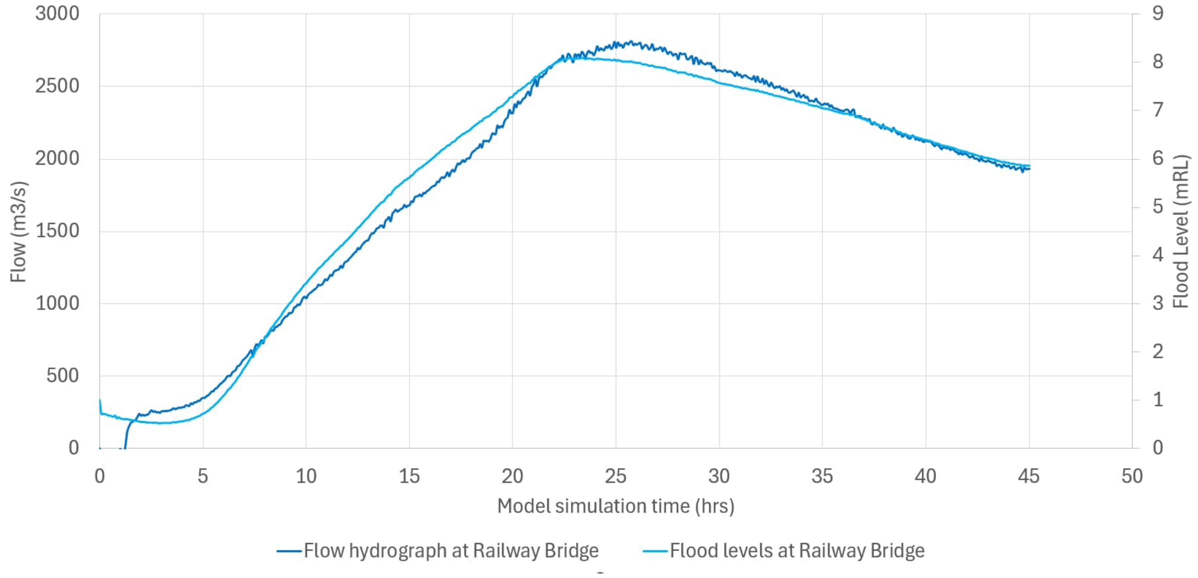


Figure 4.2: Flows and levels at the upstream boundary of the model.

4.4 Time varying adjustments to bathymetry

Even though there is a highly dynamic estuarine environment in the subject area, the model provided is based on a fixed DEM. That is, the model does not allow the bed to deform under the action of flow. It is evident that bed deformation has a notable effect on flood flow conveyance (river mouth was observed to widen during flood conditions) in events that have occurred. Because of this, the fixed bed model was adapted to approximate bed movements by making use of time-varying bathymetry changes.

This time-varying approach does not simulate physical processes of scour and deposition – to do this would require a vastly more complex morphological model that has not been used. Rather, the approach adopted involves consideration of satellite imagery to establish start and end channel widths and locations, with modelling approximations of the time and duration over which these changes occurred being made. This is described in detail in Section 4.7.2.

4.5 Model updates

Modifications to the existing TUFLOW model were made to make it explicitly suit the purpose of this work. T+T have made the following model updates / changes to the base model provided:

- Decreased model cell size downstream of the SH2 bridge: The cell size was decreased from 16 m to 4 m in the lower reaches of the river, and out to the coastal boundary. This was done to better represent the breach conditions, as the original cell size of 16 m was too large to properly assess breach widths of 16 – 120 m. To interface the original 16 m grid with the newly imposed 4 m grid, and area of 8 m grid was developed between these two regions to provide a smooth transition. The revised model cell sizes are shown in Figure 4.3.
- Extended the coastal boundary out 300 m from the shoreline: The coastline bathymetry was extended as per the LINZ hydrographic contours and applied to the model terrain. The coastal boundary was then applied at the seaward edge of this model domain. This was done to remove potential artificial drawdown effects at the river mouth that could come from imposing a tidal boundary close to the mouth, in the area where levels may be affected by river flow in addition to coastal boundary level.
- Extended the model boundary out west of the Whakamahi lagoon: The model extent needed to be extended west past the lagoon in order to include the entire floodplain observed during the June 2024 event. The revised model extent is shown in Figure 4.3.
- Removed the rainfall hyetograph: Rainfall from the June 2024 hindcast event was removed and have only applied river inflows to the upstream boundary of the model at the Railway Bridge. This is because the influence of the rainfall is anticipated to be minor, and there are no calibrated infiltration losses in the model. A sensitivity test was undertaken to demonstrate that removal of rainfall has little impact on the model results and the ability for us to get an adequate hindcast of the June 2024 event. This sensitivity test is reported on in Section 4.9.7.
- Applied a dynamic tide boundary: In previous modelling, the tidal boundary was applied as a static water level for design events, which was adequate for the model's purposes as the areas of interest were remote from tidal influence. For this work, a dynamic tidal boundary was applied derived from what was recorded during the flood event, to best replicate the changing tidal conditions during the event. Note that wave processes are not resolved in this TUFLOW model, and the tailwater is only representing tidal processes.

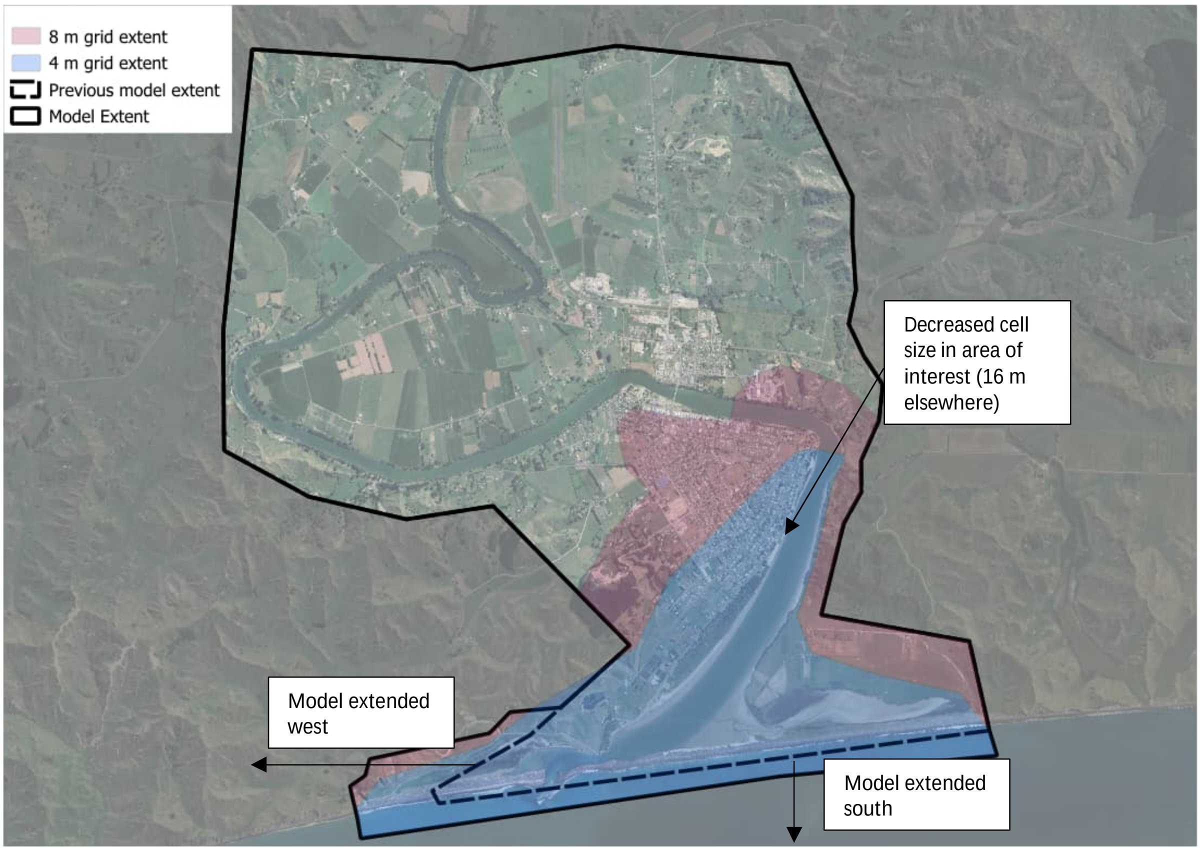


Figure 4.3: Model grid size and extent changes made to original model provided (blue shading indicates 4 m grid, red shading is 8 m grid, elsewhere not shaded is 16 m grid).

4.6 June event observations

Section 2 details the measured data recorded during the June 2024 flood event. In Figure 4.4 the relevant recorded time series covering the event are shown. In the top panel, the water level time series at the railway bridge (upstream end of the model) is shown plotted with the recorded water level time series at the Town Bridge. A notable change of slope in the time series at Town Bridge is evident and has been labelled as “bar breaching”.

In the lower panel in Figure 4.4 some tidal time series are shown, with full descriptions having been provided in the data summaries report. The smoothed tide (black line) was used as the tailwater boundary condition in the model.

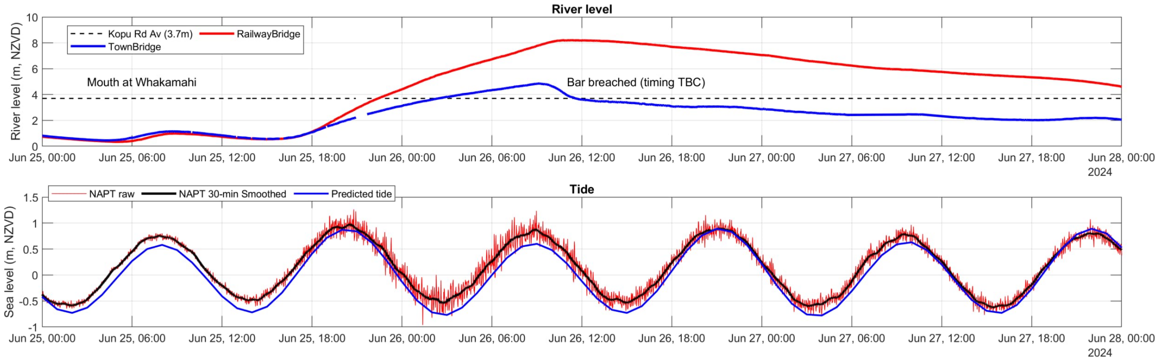


Figure 4.4: June 2024 hydrometric data recorded and used for model hindcast.

The data that was made available that was used to compare the model results, and to quantify the goodness of fit of the model, is as follows:

- Flood level time series recorded at the State Highway 2 or "Town Bridge" during the flood event.
- Flood extents mapped by HBRC after the flood event.
- Spot levels collated by HBRC, sourced from news reports and public observations.

Observed flood extents and locations of available spot flood levels are shown in Figure 4.5.

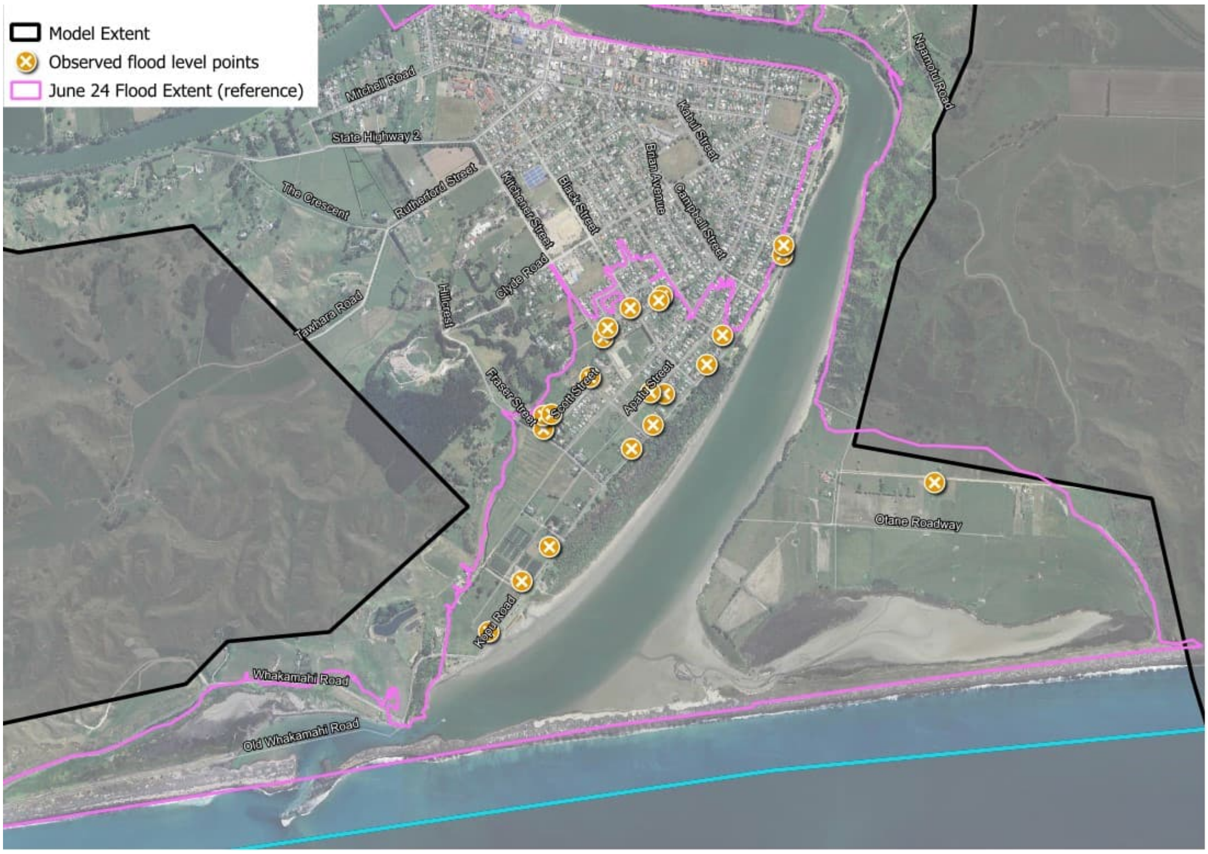


Figure 4.5: June 2024 flood observations.

4.7 Hindcast model of June event

The hindcast model run extended some 45 hours in time, starting at around 11 pm on 25 June, approximately 22.5 hours before the peak of the flood event.

4.7.1 Model boundaries

Two model boundaries were applied, as follows:

- Upstream: The upstream boundary is located at the railway bridge, where a level vs time boundary was applied to the model as recorded during the flood event.
- Downstream: We have applied a time-varying boundary based on observed tide during the event, as described in the data summaries report. This does not include waves or wave effects.

4.7.2 Model terrain

For the model terrain, the post Cyclone Gabrielle LiDAR dataset flown in December 2023 was used as a base. As the river mouth geometry has changed significantly since that LiDAR survey was flown, (mouth has moved towards the west and decreased in width) manual terrain modifications were made based on satellite imagery taken on 23 June (pre storm event) and 28 June (post storm event). Manual terrain modifications to represent pre-event conditions are shown in Figure 4.6 and summarised below:

- Manual enforcement of the gravel bar, with a crest level of 5 mRL across the southern extent of the model, to match pre-event bar configuration indicated in Satellite images.
- River mouth and Whakamahi lagoon set at an invert of -2.5 mRL, and at an initial width of 60 m based on pre storm satellite imagery of the river mouth.

Aerial photography was used to inform the definition of estuary extent in the absence of bathymetric survey. The bed levels set as part of the modelling are based on expert judgement as aerial photography and LiDAR cannot give a representation of bathymetry. As such, the estuary level has been set at -3.5 mRL as per the WSP modelling, and the Whakamahi Lagoon and river mouth level has been set at -2.5 mRL as this provided the best fit in terms of the model calibration. The lack of surveyed bathymetry before the model event is a limitation of this modelling.

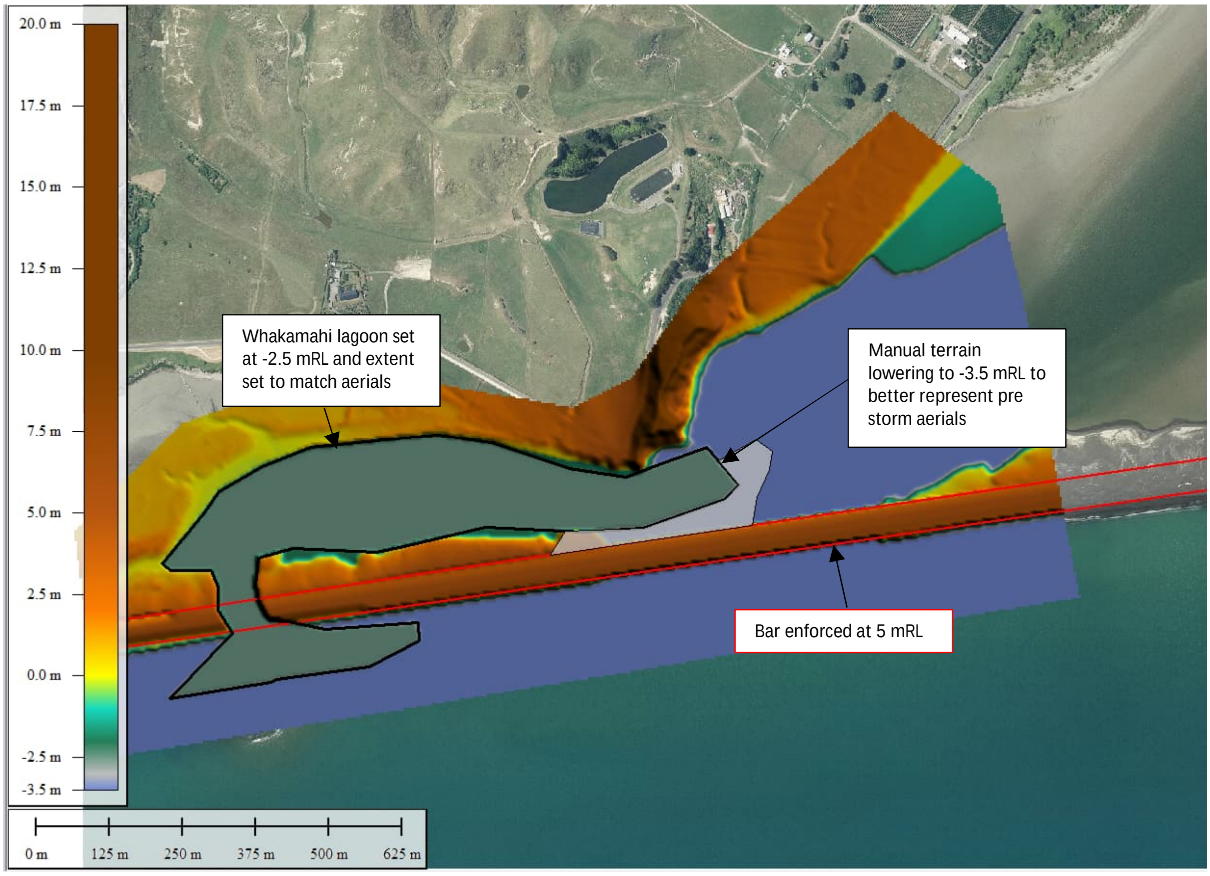


Figure 4.6: Pre-event terrain used in the model.

These modifications form the base terrain which is used at the start of the model simulation. As the differences between the pre and post storm event satellite imagery suggest, the river mouth geometry changed significantly during the storm event, and a breach of the bar was observed approximately 900 m east of the river mouth. Therefore, to get an adequate model hindcast it was necessary to simulate the changes to the terrain during the model simulation. To do this the TUFLOW variable shapefile layers were used to modify terrain over time, the inputs being start and end bathymetry, formation time and, time where the terrain modifications start. The changes to the bathymetry during the model simulation are shown in Figure 4.7.

The breach and mouth deformation in the model is outlined as follows, shown graphically in Figure 4.7:

- T = 0 to t = 12.5 hrs: For the first 12.5 hours in the simulation, the river mouth is kept at 60 m wide and at an invert level of -2.5 mRL as this provided the best match in terms of the flood levels observed.
- T = 12.5 to t = 22.5 hrs: Past 12.5 hours, there is an inflection point in which the rate of rise of the river levels decreases up to the peak observed, despite a relatively consistent rise in river flow from upstream. Through the model calibration it was determined that to replicate the change in the rate of rise between simulation times 12.5 and 22.5 hours, the river mouth needed to widen within this period. This is also supported by aerial imagery pre and post flood event, where the river mouth is shown to widen. Over this period, the mouth was made to widen from 60 m to 120 m in a linear fashion.
- T = 22.5 hours onwards: Past the peak of the storm event, there is a rapid decline in flood levels, which suggests that the breach formation occurred around this time. This breach was replicated in the model, at a width of 120 m with elevation dropping from existing to -2.5 mRL

over 2.5 hours. Past this rapid decline, the rate of decrease in flood levels reduces, and the modelled levels are slightly higher than recorded. This may be due to the fact that the river mouth continued to widen past the peak of the flood event, however this has not been modelled.

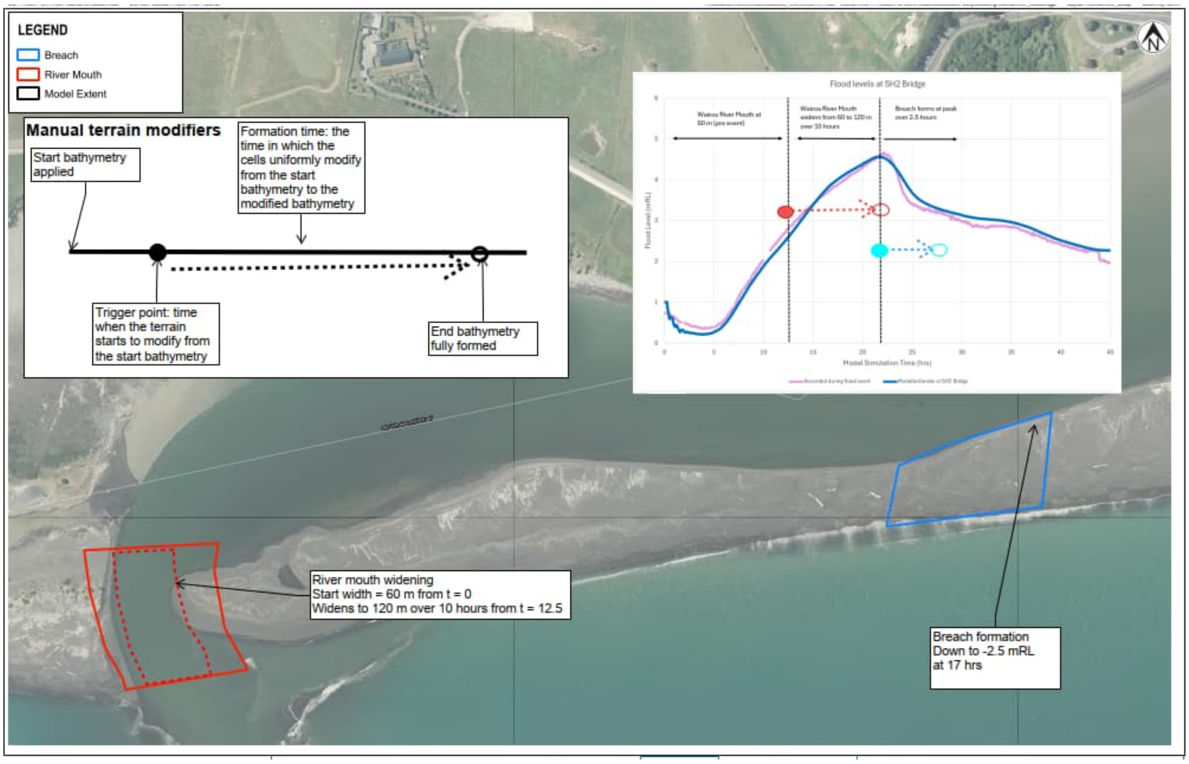


Figure 4.7: Change in bathymetry over time.

The differences between the start and end bathymetry, at the river mouth, are shown in Figure 4.8.

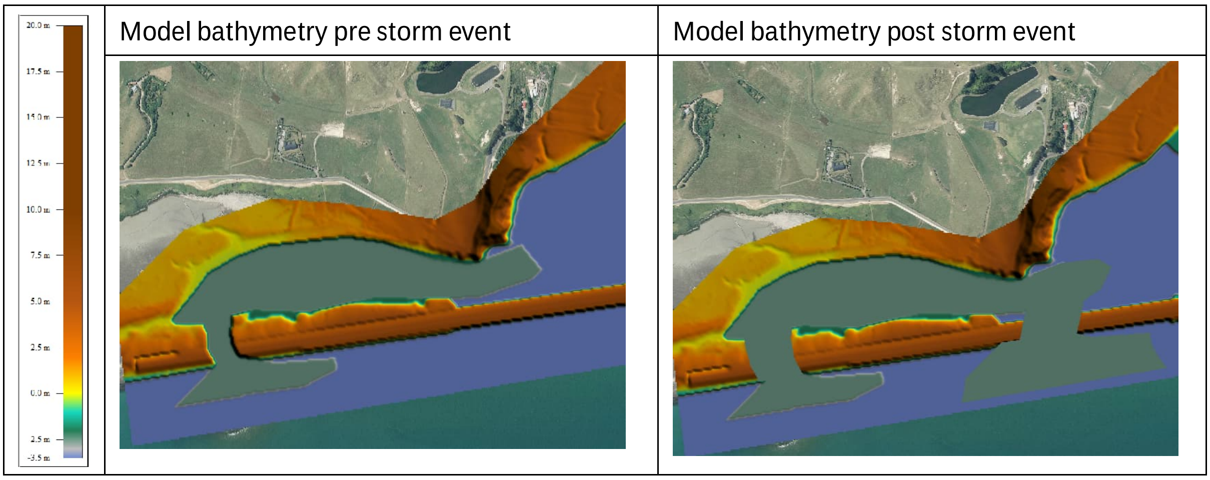


Figure 4.8: Bathymetry over model simulation.

With these terrain modifications applied, both the recorded flood levels at the SH2 bridge, and the flood extents provided by HBRC have been represented in the model. Most of the recorded flood depths captured during the flood event by HBRC matched the modelled depths within a range of +-200 mm.

The modelled versus observed levels at the SH2 bridge are shown in Figure 4.9. There are three key phases separated in this graph, where different mechanisms dictate the flood levels as outlined in the bullet points above.

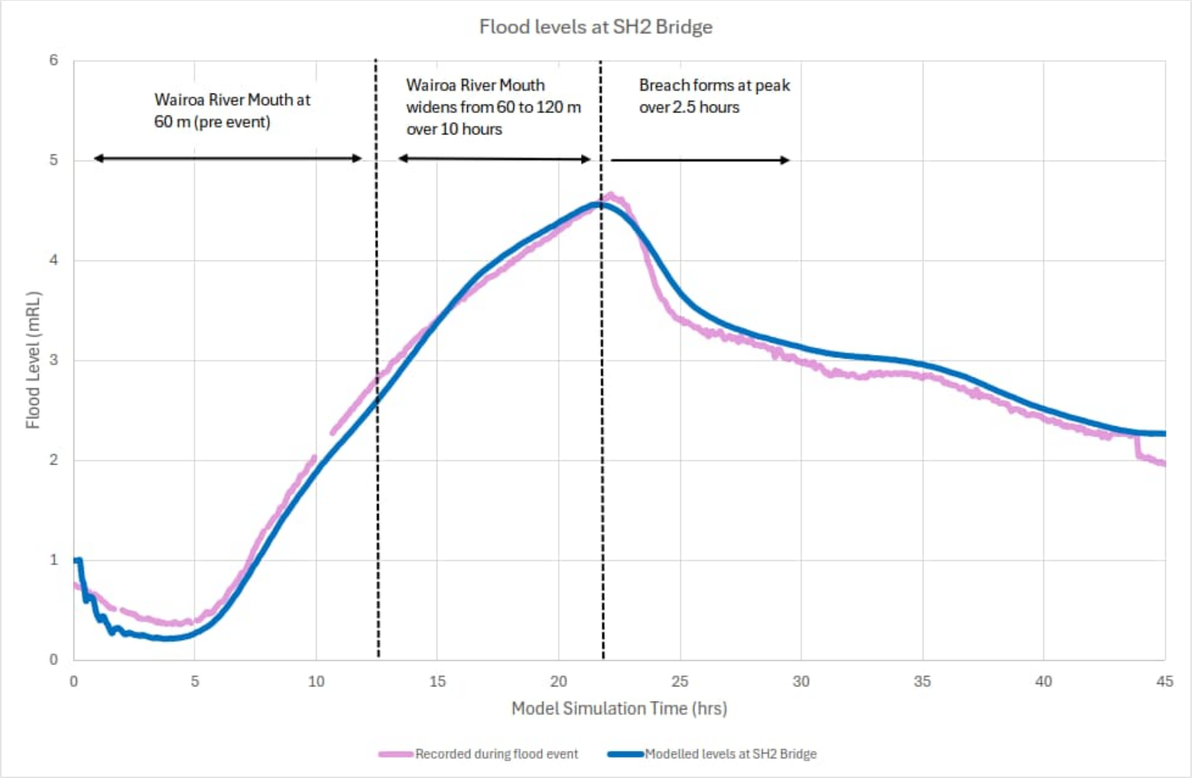


Figure 4.9: Measured and modelled flood level over event simulation.

The flood depths and extents are shown in Figure 4.10. Overall, the flood extents observed and mapped by HBRC match the modelled event results very well. Most of the recorded flood depths match observations within +- 200 mm, however as these were not gauged levels and were largely recorded anecdotally post flood event, we checked these depths for a ‘general match’.

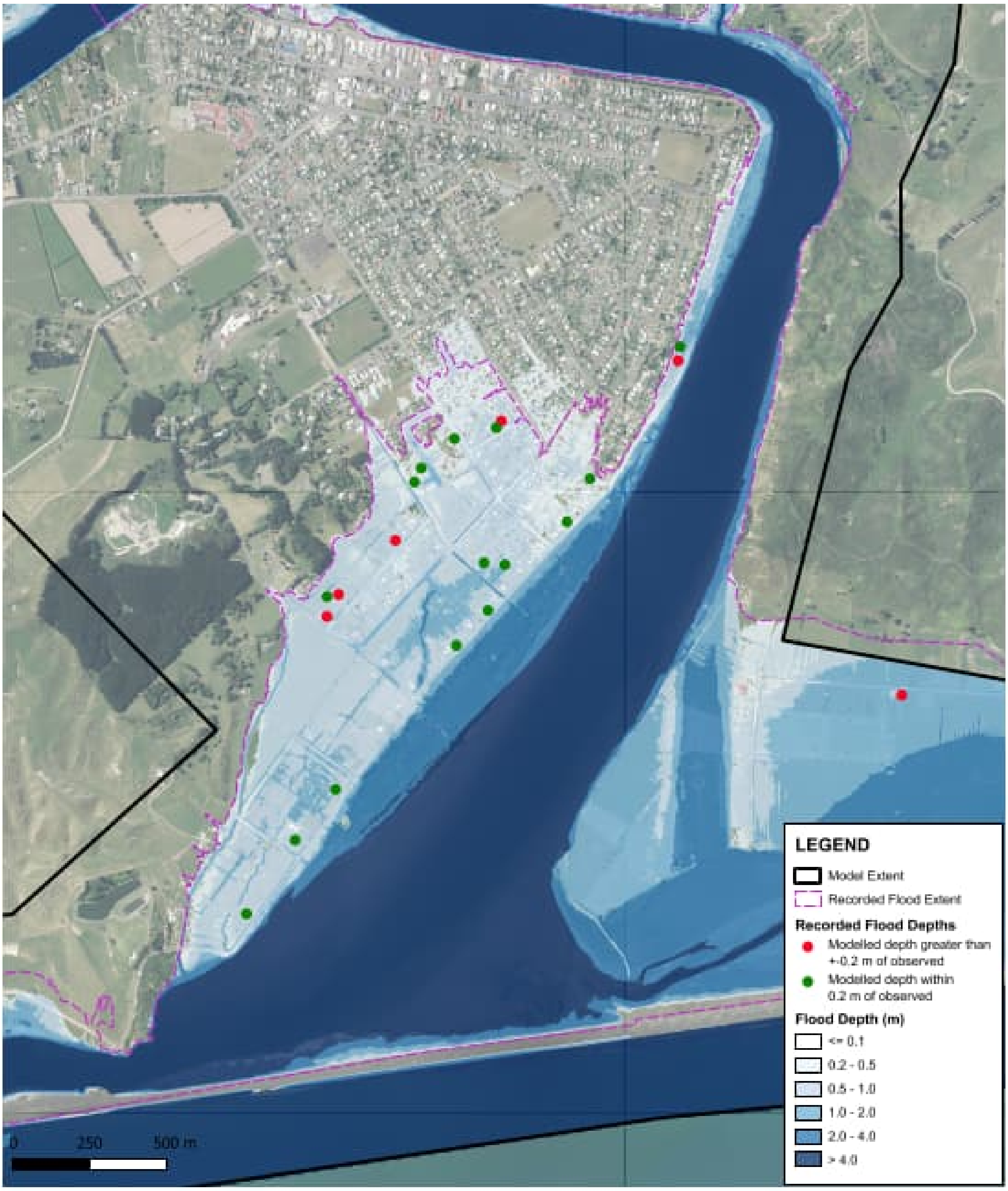


Figure 4.10: Hindcast model flood extents and flood observations.

4.8 Limitations of the hindcast modelling

There are limitations that are important when interpreting these results:

- Due to the many complex physical processes, the modelling we have undertaken to replicate the June 2024 event may not be the only unique simulation of processes that matches the observed flood extents and levels. There will be many processes that affect the final outcome that was observed, such as the influence of wave action and scour which are not explicitly represented in this model.

- For the purposes of this assessment, and in the absence of bathymetric survey, assumptions were made about the bed level in the estuary and lagoon. The WSP modelling assumed that downstream of the last measured cross section in the Wairoa River, the bed level at -3.5 mRL. Through the model hindcast, we found that to match observed flood levels and extents, we needed to set the Whakamahi Lagoon and river mouth at a constant level of -2.5 mRL.
- Variables such as the rate at which the river mouth widens during a flood event, and the rate of breach formation, were manually set in the model. As such, the model cannot 'predict' this behaviour should other variables change, i.e. if the river mouth was moved, or the breach timing was changed. These parameters were set in order match the hindcast the event, and was done reliably, however the model has limitations in terms of its predictive capability. This is because the bathymetry change that was applied was time-varying, rather than being driven by physical processes in the model.

4.9 Physical processes

The outcomes of the model calibration gave a suitable base case to test variables and their effects on the resulting flooding in the June 2024 event. The influence of factors on the resulting flooding with reference to this base case were evaluated, including:

- River mouth dimensions and location.
- Timing of the breach that happened.
- Early formation of the manual breach.
- Tides (amplitude and timing).
- Location of the breach.

In these cases, we have reported on the following:

- Change in flood extent.
- Change in levels over time at the Wairoa Yacht Club during the flood event, which was chosen to represent the flood levels in the area of Wairoa that experienced flooding (shown in Figure 4.11). The flood level that has been chosen as the threshold for "in town flooding" is defined as 3.7 mRL.

Sensitivity of flood extent to wave conditions was not undertaken. This is because the TUFLOW model does not resolve the relevant wave processes that were influencing the event. Rather, the TUFLOW model represents a simplification that focuses on river processes and tides. The effects of wave action on the permeable bar (discussed in Section 4.5) are simplified in this regard, by representing the bar as solid (impermeable) in the TUFLOW model.

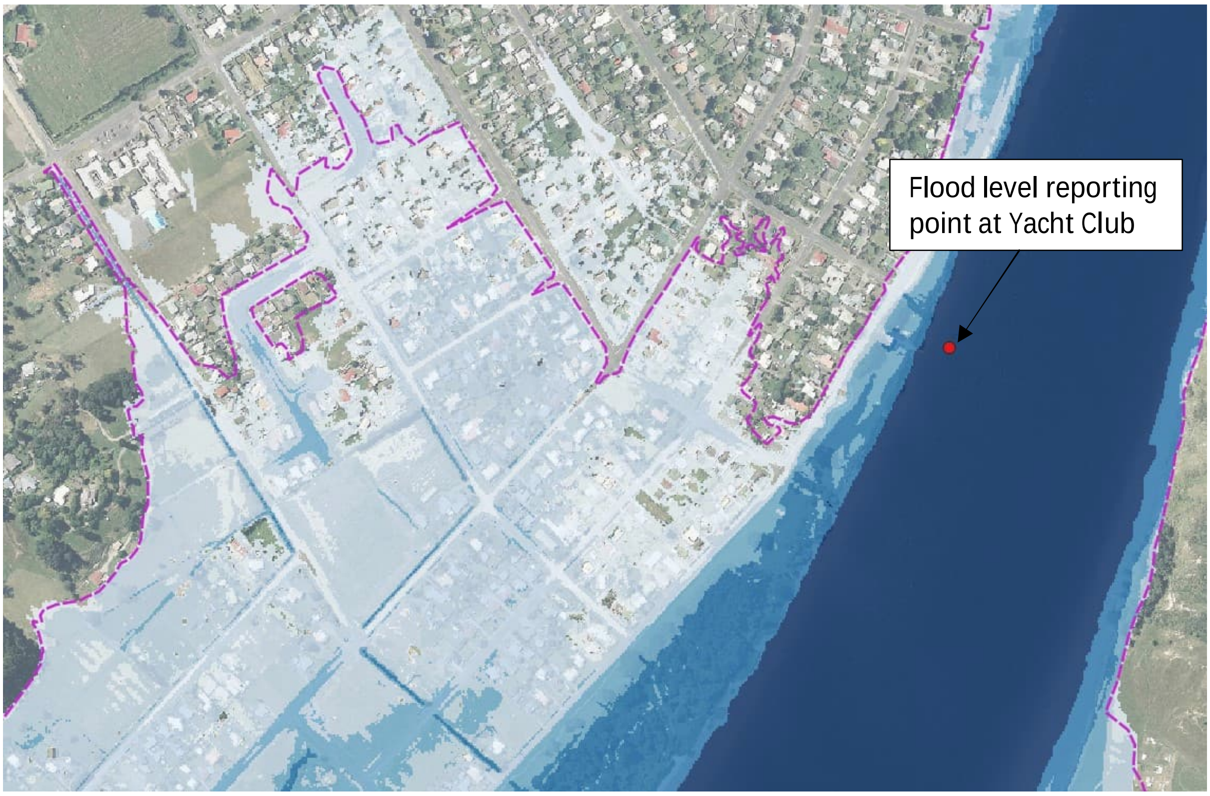


Figure 4.11: Flood level reporting point at Yacht Club.

To do this analysis, the base model was used, and certain parameters adjusted, one-by-one, to test the resulting impact. This assumes that all the factors behave independently of each other, and there is no interdependence between different elements of the model. This will almost certainly not be the case, therefore findings in this section should be treated broadly as 'general trends' and not as definitive in terms of what the result would have been during the June 2024 flood event.

This section is intended to determine a relationship between several physical processes and the resulting impact on flood levels, with respect to the June 2024 event. These findings are intended to inform future decisions related to management of the bar, by better understanding the mechanisms within this system as best as a fixed hydraulic model can.

4.9.1 Location and geometry of the river mouth

The mouth of the Wairoa River moves laterally and had shifted significantly westwards since the Cyclone Gabrielle flood in the time leading up to the June 2024 event. These shifts are understood to have been influenced by prevailing weather conditions, coastal processes and alignment of the lower river to the coast. As such, the width and location of the river mouth are variable and have been found to have significant impact on the conveyance of flood flows to the sea. For this section, the impact of the river mouth location and geometry on the resulting peak flood levels was investigated.

Satellite imagery shows that the position of the river mouth changes relative to Pilot Hill, i.e. the river mouth has, through natural processes, migrated both east and west of Pilot Hill over recorded history. During the June 2024 flood event, the river mouth was located west of Pilot Hill, and was at a width of around 70 m before the flood event.

Through testing using the model, there is sensitivity depending on whether the mouth is located west or east of Pilot Hill. Figure 4.12 shows a plan view of the two ranges of possible river mouth locations relative to Pilot Hill. The location of the river mouth within each of these ranges has minimal effect on resulting flood levels, but there is a notable difference in flooding if the mouth is located in the western area compared to within the east area.

When flood flows need to pass Pilot Hill toward a mouth located to the west there is significantly greater energy loss than when flood flows can exit via a mouth located to the east of Pilot Hill. This is because of the constriction at Pilot Hill and for the longer flow path in taking a western route.

Under flood flow conditions, the Wairoa River is some 350 m wide adjacent to the town. At Pilot Hill the flow is constrained to a width of about 100 m. As mentioned previously the observed pre-flood mouth width is some 70 m. Thus, for flow existing to the west, it needs to pass through both the Pilot Hill constriction and the river mouth constriction, while if the mouth exists east of Pilot Hill it only needs to pass through one constriction (the mouth). These two cases are shown in Figure 4.12.

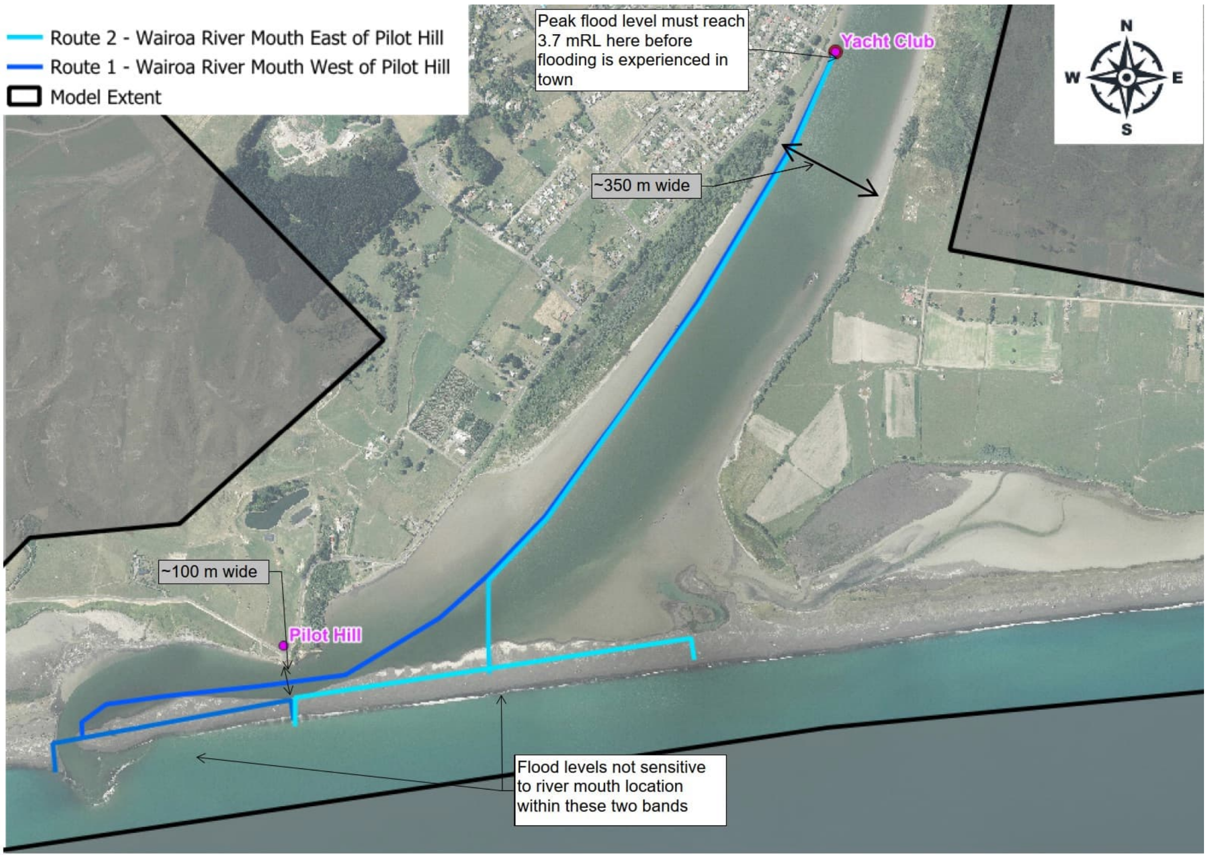


Figure 4.12: Mouth location areas.

The position of the river mouth relative to Pilot Hill is a key contributor to the hydraulic performance of the lower river system. Figure 4.13 shows a long section of the peak flood levels along the Wairoa River mouth, from past the pre-event river mouth location to the SH2 bridge. This long section shows two key hydraulic restrictions along the river for Route 1 – the first being the river mouth, the second being the entry to Whakamahi Lagoon directly south of Pilot Hill. Route 2 has a single hydraulic constriction – which is the river mouth itself. For Route 2 upstream water levels are lower than for Route 1, even if the same mouth dimensions are used.

The hydraulic restriction at the river mouth can be improved by increasing the capacity of the river mouth by deepening or widening.

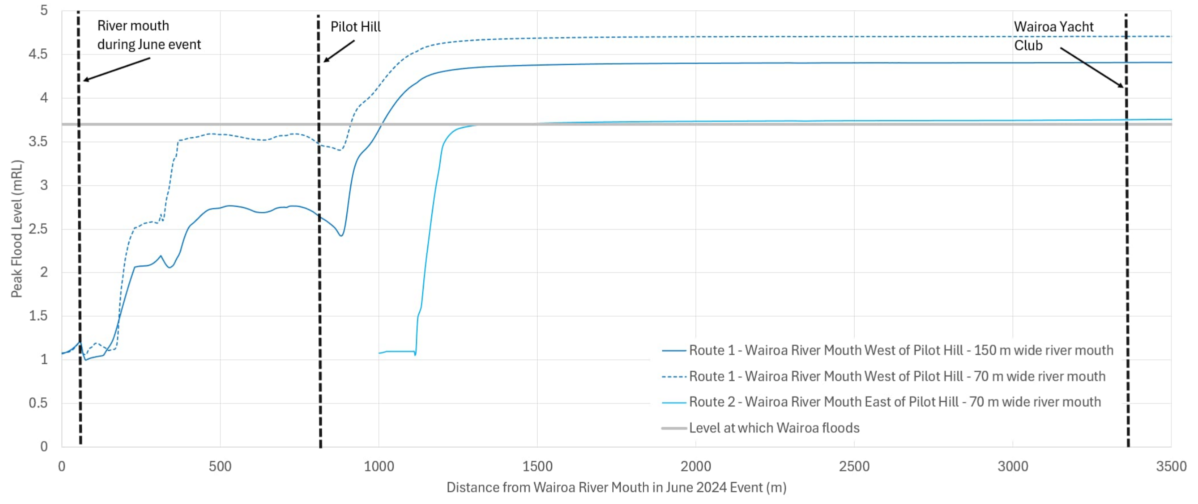


Figure 4.13: Long section.

4.9.2 Breaching of the bar

In the June 2024 event, flood levels rose and there was flooding in town, until such time as a breach formed through the bar. After this had occurred, upstream flood levels were recorded as having dropped rapidly. As shown in Figure 4.9, the model was able to replicate flood conditions that were observed by timing mouth widening and breach formation, together with using dimensions taken from satellite images.

The exact mechanism of breach formation is not fully known for this event, but it appears that upstream flood levels did not rise sufficiently for overtopping to occur. Rather, wave over wash appears to have occurred at some discrete locations where the bar was lower. It is possible that wave overtopping lowered the bar at the breach location, to a point that river outflow could pass over the bar to drive a full breach and new opening.

4.9.2.1 Naturally formed breach

The calibrated model was used to simulate the following cases to determine the relationship between observed flood levels and the natural breach that occurred:

- No breach of the bar and only the river mouth operating (widens from 60 m to 120 m as described above).
- Breach fully formed in advance of the flood event at 150 m in width (without consideration of whether or not this is physically possible to achieve).

The results of these simulations show an envelope of results that might be possible between two likely extremes – no breach and full breach. Time series water level plots (with water level at the Yacht Club being used as the reference) are shown in Figure 4.14 and the flood extents are shown in Table 4.1.

The following observations emerge from these model simulations:

- Without any breach, the model indicates that the June 2024 event could have caused flooding in Wairoa up to 0.5 m higher than what did occur, and the flood duration would have changed from approximately 7 hours to over 20 hours.
- With a fully formed breach in existence before the start of the event (without confirmation that this would have been possible), the model indicates much lower flood levels and no flooding in Wairoa. This scenario does, however, still include the existing mouth and its

widening that was modelled to occur for the June 2024 event. With a fully formed breach in place this mouth may have performed differently. This model also does not account for wave processes that may influence the river mouth and bar dynamically when the mouth is open.

From these results breach timing may be important in determination of peak flood level able to be attained. An early breach could have resulted in levels lower than those at which private property gets flooded, while having no breach form is likely to cause higher flood levels to be attained.

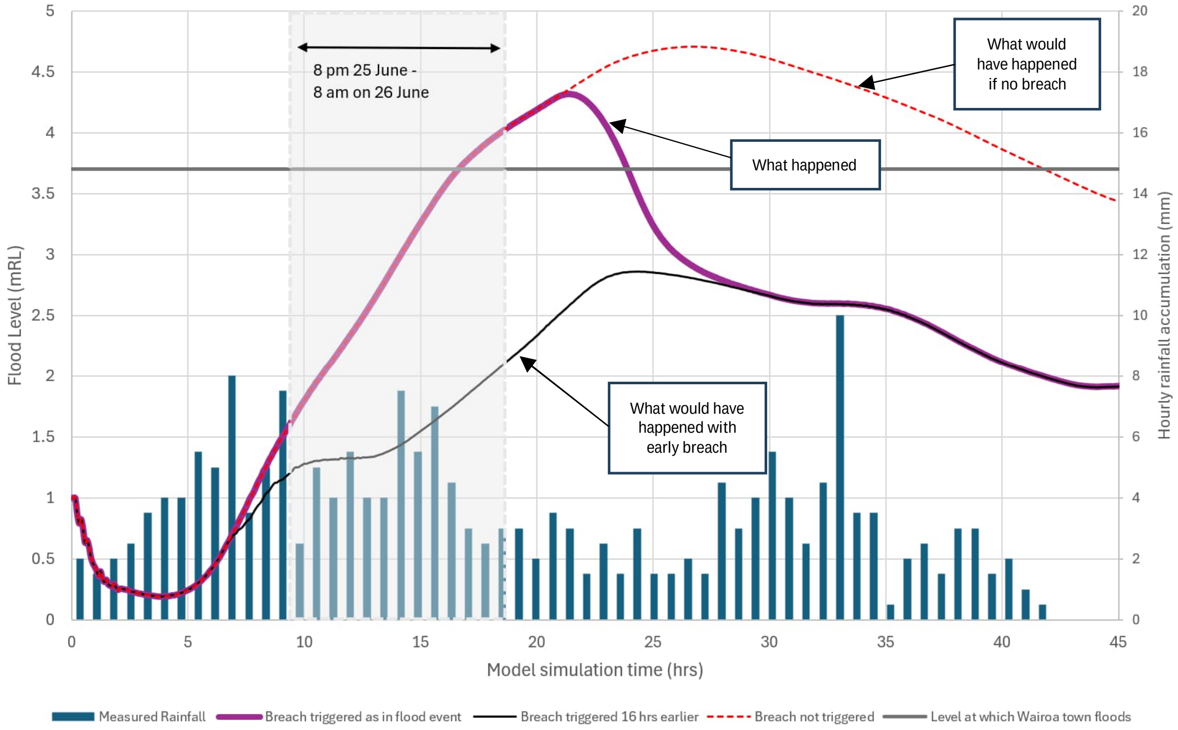
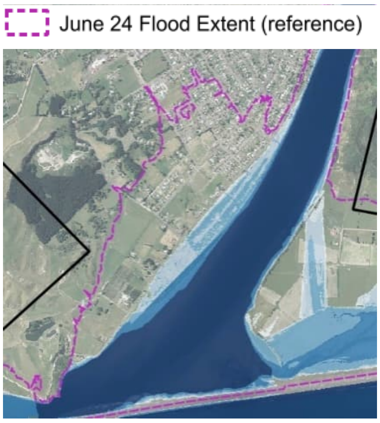
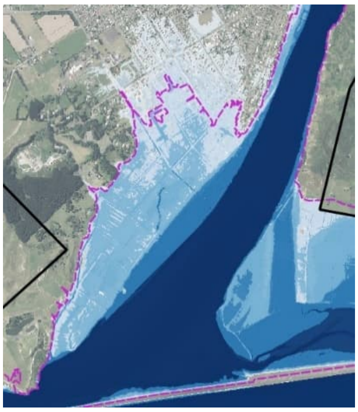


Figure 4.14: Flood levels with different breaches (grey line at 3.7 mRL indicates level at which flooding occurs), assuming no dynamic influence from waves.

Table 4.1: Flood extents for the three different scenarios plotted on Figure 4.14

What could have happened with early natural breach	What happened	What could have happened if no natural breach
		

Note that scenarios do not resolve the influence of waves.

4.9.2.2 Manually formed breach

Based on the aerial and satellite information, an additional manual breach was in the process of being formed prior to the flood event about 1,350 m east of the breach that formed near Pilot Hill. The possible efficiency of this breach was investigated by running two model simulations, as follows:

- Initial width of 16 m (taken from images from a post-event drone capture) at -2.5 mRL as per the satellite imagery, staying the same throughout the flood event.
- Initial width of 16 m at -2.5 mRL as per the satellite imagery, widening to 40 m throughout the flood event. The 40 m width assumed is not based on any observation or calculation. Rather, it is intended to show the type of effect that might occur with this scenario.

For both of the above scenarios the existing mouth at the Whakamahi Lagoon (as shown in Figure 4.6) as simulated in the hindcast model (described in Section 4.7.2) has remained unchanged. The validity of this has not been tested – it may be that having an additional outlet at the manually formed breach would cause different behaviour at the existing mouth.

Modelled flood level time series at the Wairoa Yacht Club are shown in Figure 4.15. In this figure the water level time series that was observed (and hindcast) is shown in solid and heavy line type, together with the two simulations shown as labelled. These results show that with a 16 m wide manual breach established and maintained in place prior to the flood event, peak flood level attained in town could have been reduced from what occurred, although flooding would not have been completely eliminated. If this manual breach could widen with time, the outflow would increase during the event and further reduction in peak flood level could be attained. In using the model to simulate these breaches, no consideration has been given to how the breach could have been established and maintained through the large swell event, to be fully open at the start of elevated river flows. Also evident from Figure 4.15 is that, without the breach forming as did occur, flood duration could have been extended with a narrower opening. That is, flood duration in town is influenced by ultimate breach width able to be achieved.

This model scenario does not account for the influence of waves on moving sediment around and potentially closing the initial bar opening. HBRC note that past opening attempts have been blocked by wave action re-filling channels before the river flow can wash out the bar.

Whether or not the manual breach could be maintained throughout the flood event is not known, especially given the extreme surf that occurred at the coast during the actual event. These results are meant for comparitive purposes only.

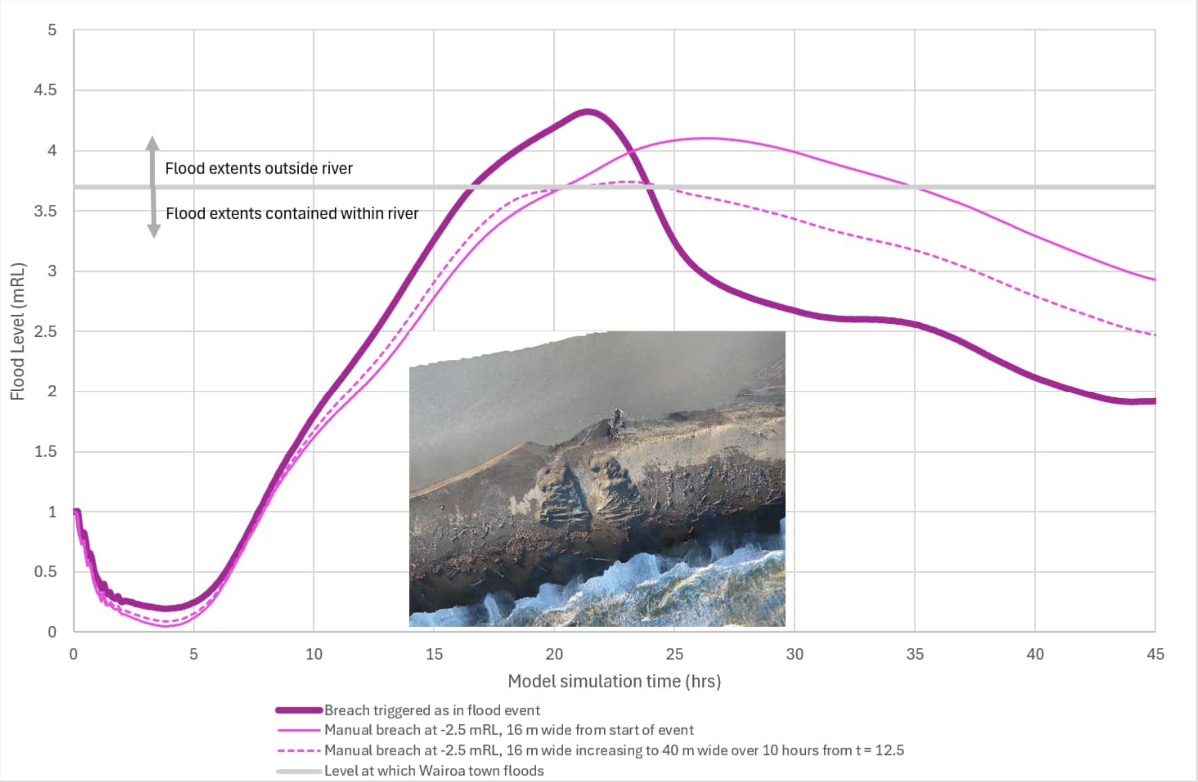


Figure 4.15: Flood level time series from manual breach compared against observed.

4.9.3 Tidal influence

As shown in the data summaries report and in Figure 4.16, peak flood levels during the event (measured at Town Bridge) occurred close to high tide in the ocean (measured at Napier Port). A question that arises immediately is whether the timing of the tide had any influence on flood levels attained, and the hindcast model was used to assess this.

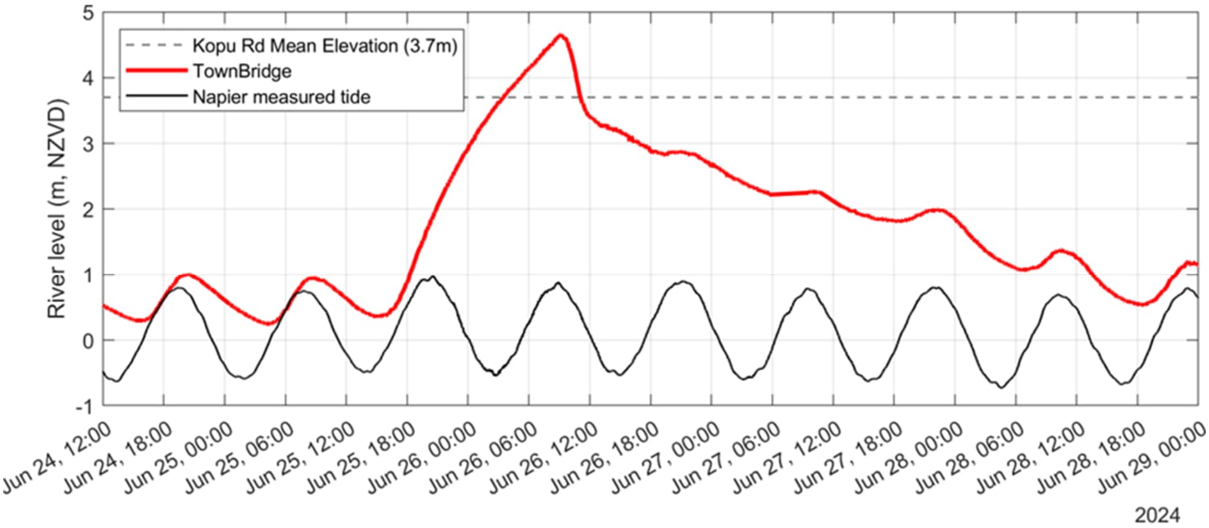


Figure 4.16: River level and sea level time series observed/recorded over the June 2024 event.

Water level time series at the Yacht Club have been plotted for the following tide scenarios, with results shown in Figure 4.17:

- Base scenario (red, bold, solid line) with tide as recorded during the event (black line)
- Red dashed and dotted lines show water levels for tide timing offset with peak of the flood coinciding with low and mid tide respectively
- Orange line shows water modelled level over the event against a tidal time series one metre higher (over the full tide cycle) than what occurred. This could represent wave induced setup, or sea level rise.
- Dotted orange line shows modelled level using the measured tide plus two metres and is intended as a sensitivity test.

Results show that all modelled scenarios result in similar peak flood levels, indicating that there is limited tidal tailwater control and that flood levels attained are more strongly influenced by river hydraulics at the mouth and bar than by tidal water level or timing seaward of the bar. If the tailwater condition is successively raised a situation will be approached where flow through the mouth is drowned and is completely tailwater-controlled.

When sea levels are increased by one metre, there is very little change in peak flood level attained. When increased by two metres, there is an effect on peak flood level of about 200 mm and a stronger tidal signal is observed.

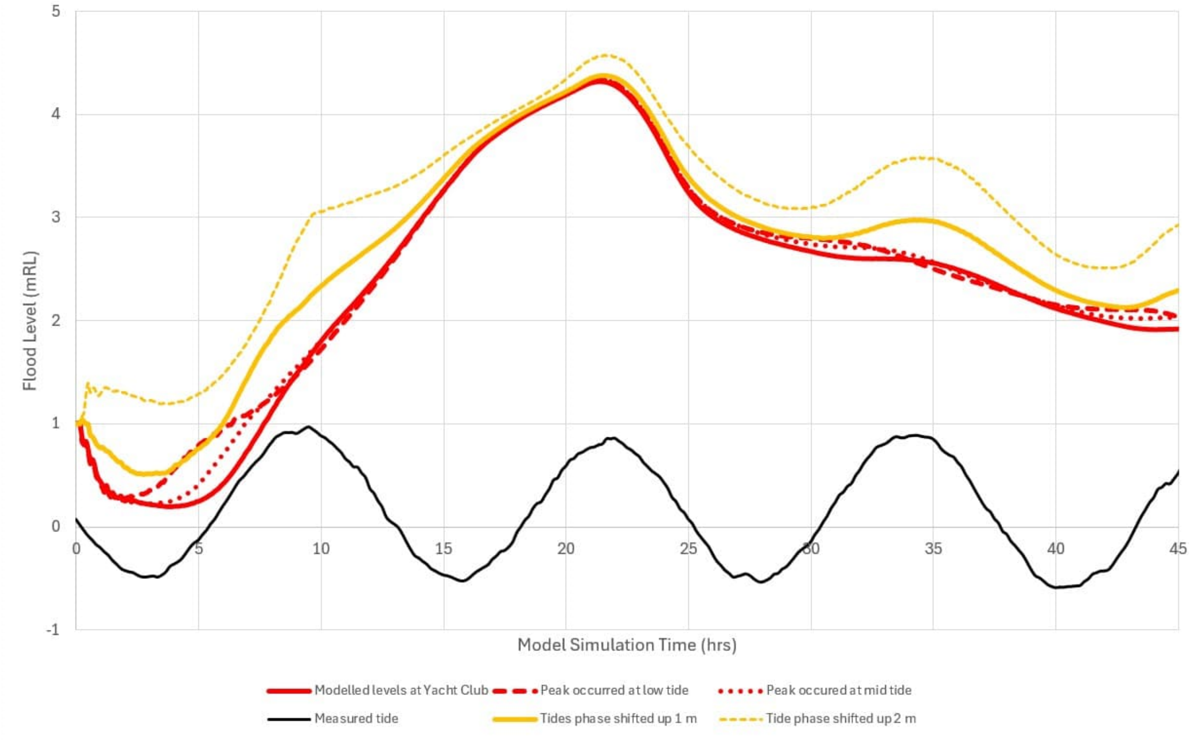


Figure 4.17: Effect of tide on flood levels.

4.9.4 Waves

The effect of the significantly large oceanic swell during the June 2024 event has not been accounted for in the river modelling undertaken using the model provided, as reported on above. This is because the type of model used does not allow for explicit integration of waves on river flows. Separate analysis of this has been undertaken and reported on in Section 5.

4.9.5 Wave over wash

Wave over wash was investigated as a potential additional (in addition to river flow and rainfall) source of flood volume within the estuary of the Wairoa River, which may have contributed to peak flood levels attained. The potential volumes of wave overtopping the bar were assessed in Section 5. These have not been dynamically added as inputs to the river model because the volumes were found to be small relative to river flood volumes.

4.9.6 Breach mechanisms

The breach of the bar south of Pilot Hill was not manually breached and happened as a result of natural processes.

4.9.7 Inclusion of rainfall

As mentioned in Section 4.5 of this report, direct rainfall onto the model domain was not modelled. This applied to the scenarios modelling undertaken as described above. To give confidence in the initial assessment of the lack of relevance of rainfall to the findings, a model run was completed using the hindcast model that includes direct rainfall. The results are summarised in Figure 4.18, which shows that there is minimal effect of rainfall in the lower catchment on the flood levels observed.

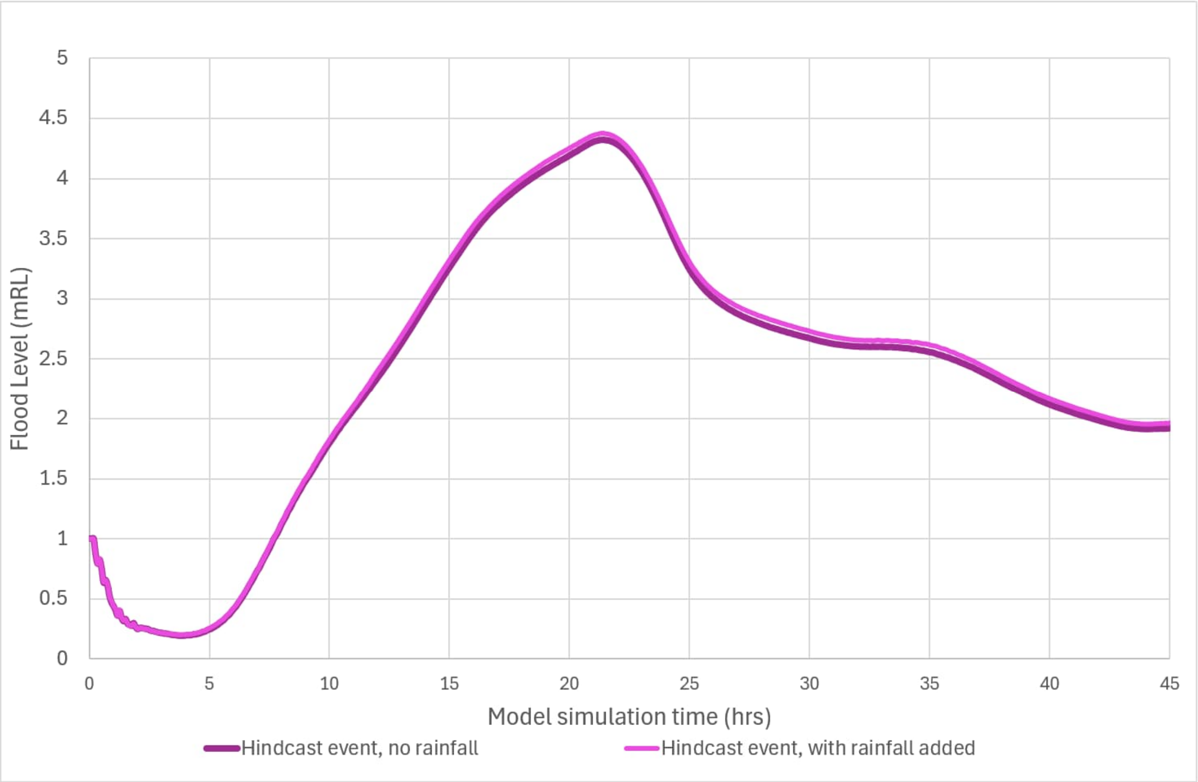


Figure 4.18: Effect of rainfall on flood levels.

4.10 Summary

Table 4.2 and Figure 4.19 summarise the peak flood levels and extents from the model scenarios undertaken as part of this analysis.

Table 4.2: Flood modelling results summary

Model scenario	Peak flood level at Wairoa Yacht Club (threshold for flooding is 3.7 mRL)	Extent
Hindcast of June 2024 event (baseline).	4.2 mRL	🟥
Breach formation		
Natural breach fully formed in advance of the flood event at 150 m in width.	2.8 mRL	⬜
Manually formed breach kept at consistent width of 16 m and widening to 40 m.	3.8 mRL	🟨
Manually formed breach starting at 16 m.	4.1 mRL	🟧
Natural breach not formed at all.	4.7 mRL	🟪
River mouth location relative to Pilot Hill		
River mouth located east of Pilot Hill (no breach).	3.8 mRL	🟨
Tidal effects		
Tide timing offset with peak of the flood coinciding with low tide.	4.2 mRL	🟥
Tide timing offset with peak of the flood coinciding with mid tide.	4.2 mRL	🟥
Tidal time series one metre higher (over the full tide cycle) than what occurred.	4.2 mRL	🟥
Tidal time series two metres higher (over the full tide cycle) than what occurred.	4.6 mRL	🟪

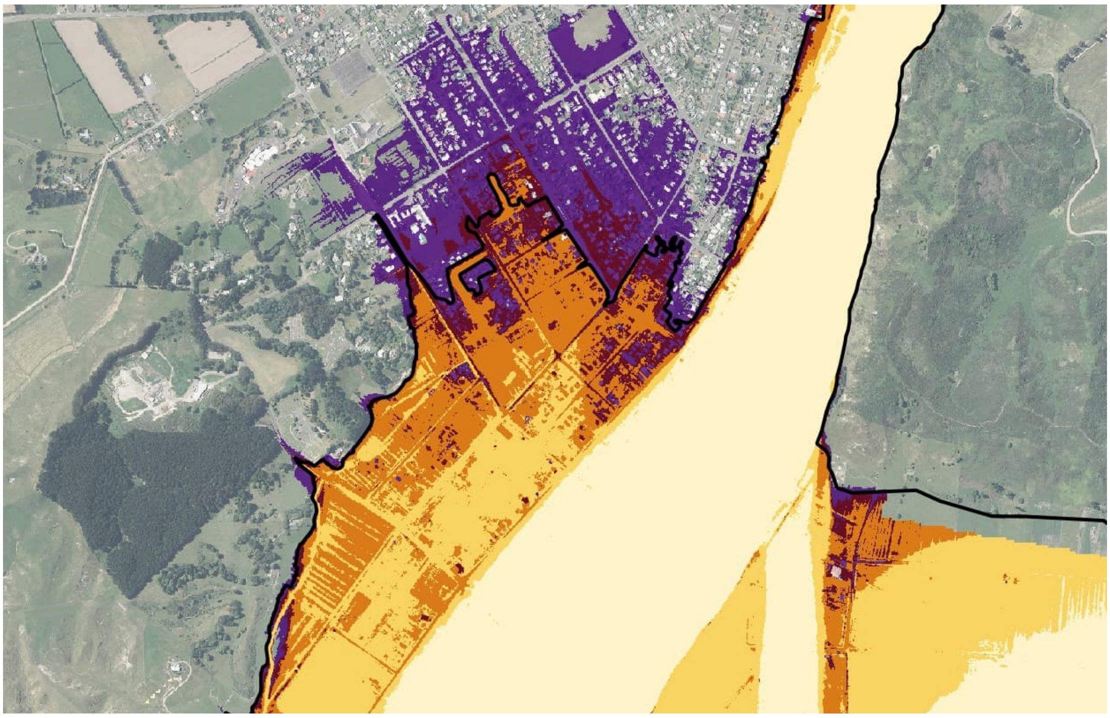


Figure 4.19: Flood extents matched to scenarios in Table 4.2. June 2024 measured flood extent shown as a black outline.

The general conclusions of the analysis are:

- An existing fixed bed TUFLOW model was used to replicate the June 2024 event to hindcast the event in the model with modifications to better inform analysis at this location. The model parameters were 'tweaked' to represent the observed water levels and flood extents.
- The position of the Wairoa River mouth in relation to Pilot Hill plays a significant role in the lower river system's hydraulic performance. At Pilot Hill the flow is constrained to a width of about 100 m. Thus, for flow existing to the west, it needs to pass through both the Pilot Hill constriction and the river mouth constriction, while if the mouth exists east of Pilot Hill it only needs to pass through one constriction (the mouth).
- Timing and existence of the natural breach greatly influences the peak flood levels. Assuming no influence of waves on the bar and river level, a no breach scenario would have resulted in heightened flood levels and extended flood duration, while an earlier breach, if occurred, could have resulted in lower flood levels.
- Changes to the tide levels seaward of the bar result in similar peak flood levels, indicating that there is limited tidal and that flood levels attained are more strongly influenced by river hydraulics at the mouth and through the bar than by tide levels seaward of the bar. This is based on simplified conditions that do not include dynamic wave action influencing the bar and river level.

5 Coastal process influence during the event

5.1 Influence of waves during the event

5.1.1 Introduction

Large waves were impacting the Wairoa coast during the flooding event on 26 June 2024. This section explores the potential contribution of waves in the following mechanisms:

- Wave overtopping of the bar, adding water volume to the lagoon / river level.
- Wave overtopping induced changes to the bar morphology and crest level.
- The relative influence of coastal processes and river level on the hydraulic gradient inside the bar at the river mouth.
- Wave propagation through the river mouth, including infragravity waves and setup.
- Details on the wave conditions influencing Wairoa were summarised in Section 2 and were used to inform his assessment.

5.1.2 XBeach-Gravel model

XBeach-G (gravel) is a physics based coastal model that represents wave processes, sediment transport and morphology change specific to gravel beach and barrier systems (McCall et al. 2014). XBeach-G resolves the water level and velocity of individual ocean waves, the generation and behaviour of infragravity (IG waves) that influence wave runup, the super-elevation of coastal water level through wave setup, and the interaction of these processes with each-other and the coastal terrain. XBeach-G was used to explore how wave runup acting on the bar may have contributed to morphology change, overtopping, and barrier hydraulic gradient within the bar dynamics through the event. The model was run for 24 hours, using a representative coastal profile located near to Pilot Hill with wave conditions, sea levels and river levels informed by data presented in Section 2.

The profile used in the model is based on LiDAR surveyed terrain of the bar from October 2023, combined with offshore contours informed by a historic hydrographic chart (Figure 5.1). The offshore slope transitions to the coastal slope at the -4 m contour, which was informed by historic surveys that extended to that depth (see Appendix D). The gravel barrier in the model has a maximum crest elevation of 4.7 m and is close to the location where a breach occurred a few months after the LiDAR survey was taken captured (WRM profile 6). The bar profile used in the in the model is not as high or wide as it can be in other times and locations.

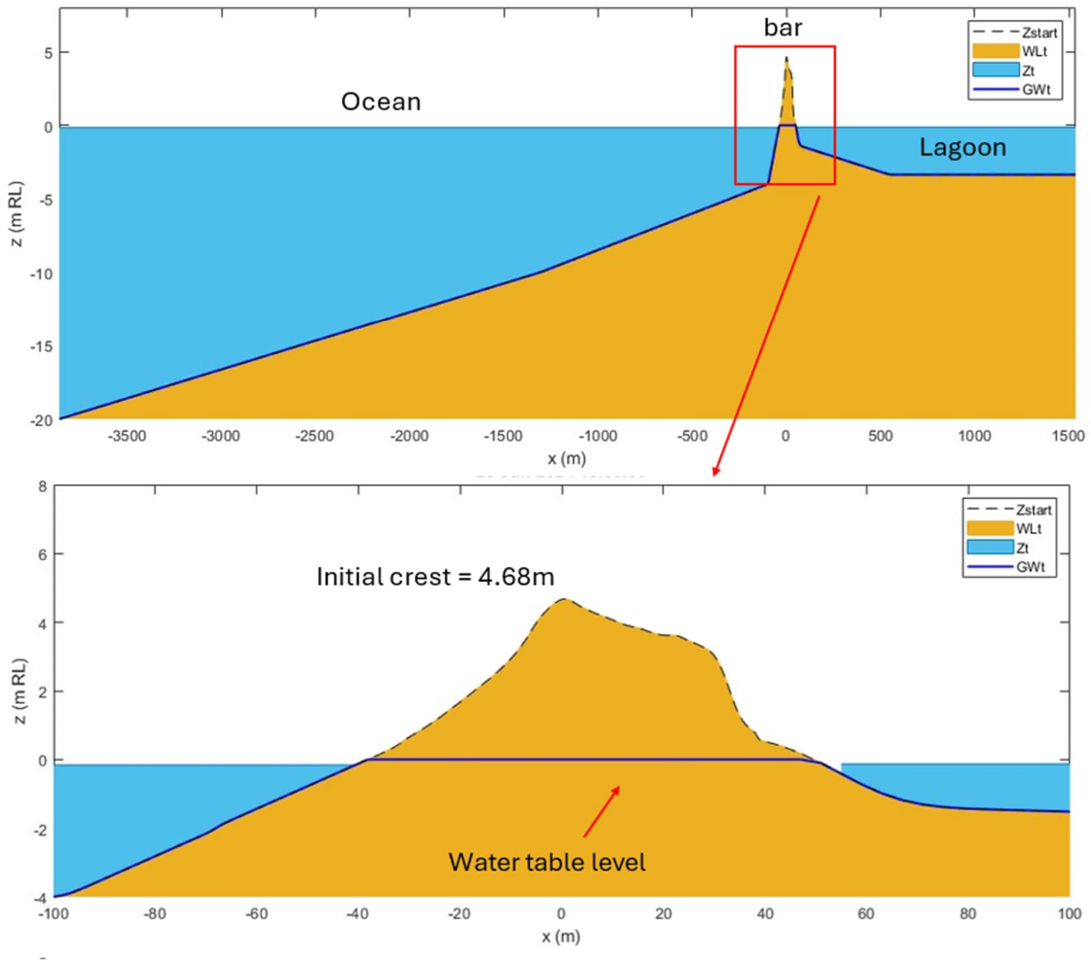


Figure 5.1: Profile used in the XBeach-Gravel model simulations.

Sediment in the model is represented by pebbles, with a median grain size of 2 mm (based on T+T 1999). Mobile sediment was limited to the bar, with sections of the model below -1.5 mRL being immobile and impermeable. The model allows water percolation through the sediment surface to the hydraulic gradient, which is required to represent asymmetric swash zone sediment transport on gravel beaches, where backwash is influenced by water percolation into the porous sediment. Default parameters were used for porosity (0.4) and hydraulic conductivity (0.01 m/s).

Wave conditions were input to the model based on the time-series from the MetOcean nowcast model output at a depth of 23 m (Figure 5.2). Tide level in the model was based on the measured water level at Napier Port, adjusted for additional storm surge of 0.2 m estimated for Wairoa[18]. River level was input as a lagoon boundary based on water level measured at Town Bridge with an offset of -0.5 m so the peak level matched the observed peak inundation flood level (4.2 mRL).

The model therefore represents how waves and tide shape the bar over the first high tide while the river level was still relatively low. The second high tide is characterised by rising river level, where large waves are also influencing the bar.

An initial (baseline) model is presented based on the wave conditions as modelled by the nowcast. Sensitivity tests are then presented for a scenario with small waves, and a scenario with waves 30% larger than the nowcast model, based on the previous discussion that the nowcast model may be an under-prediction of the event.

---

[18] This is an estimate based on the available data, and the actual storm surge may have been higher or lower.

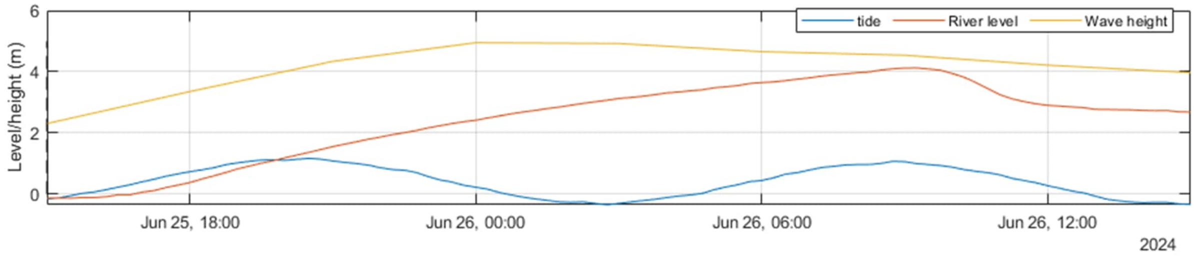


Figure 5.2: Timeseries of wave height, river level, and tide level.

5.1.3 Wave overtopping (baseline model)

The XBeach-G model was used to track overtopping on the representative profile, accounting for waves, tide level, and changes to the crest elevation and position. Overtopping is output for every second in the model (total of 86,400 seconds), which is presented in red to show the peak overtopping flow during individual wave events (Figure 5.3). The more representative value for causing geomorphic change is the mean overtopping (Q_{mean}), which was calculated for 30 minute bins during the simulation, shown in blue Figure 5.3.

Results show that waves were potentially overtopping the bar on the evening of 25 June, on the rising tide and rising wave conditions, with mean overtopping of 1 L/s/m. Wave height peaked during lower tide conditions near midnight and the model shows some wave overtopping could have occurred during this time, with averages between 0 and 1 L/s/m. As the tide increased on the morning of June 26, wave overtopping increased, and averaged around 3 L/s/m, with a Q_{mean} peak of 7 L/s/m. Overtopping results are sensitive to wave heights and crest levels. If the actual waves during the event were larger than the nowcast model, the values could be significantly higher. In areas where the crest is lower, the overtopping volumes could also be higher.

Over the full 24 hour simulation, mean wave overtopping accumulated to be approximately 70 m^3/m for the representative unit length of bar. Upscaling this to the full bar length (assume 3 km) results in approximately 210,000 m^3 of water transfer from ocean to river over the 24h event. This upscaling is sensitive to changes in bar morphology along the bar length and the accuracy of the wave conditions used in the model.

Instantaneous overtopping can be much higher for individual wave crests, in the order of <1,000 L/s/m (e.g. Figure 5.4). Modelled results for overtopping appear reasonable for this type of event but are not calibrated using measured field data for this location and are therefore considered our best representative estimate. Locations with different crest levels and beach slope features could have experienced greater higher or lower or lesser amounts of overtopping volumes.

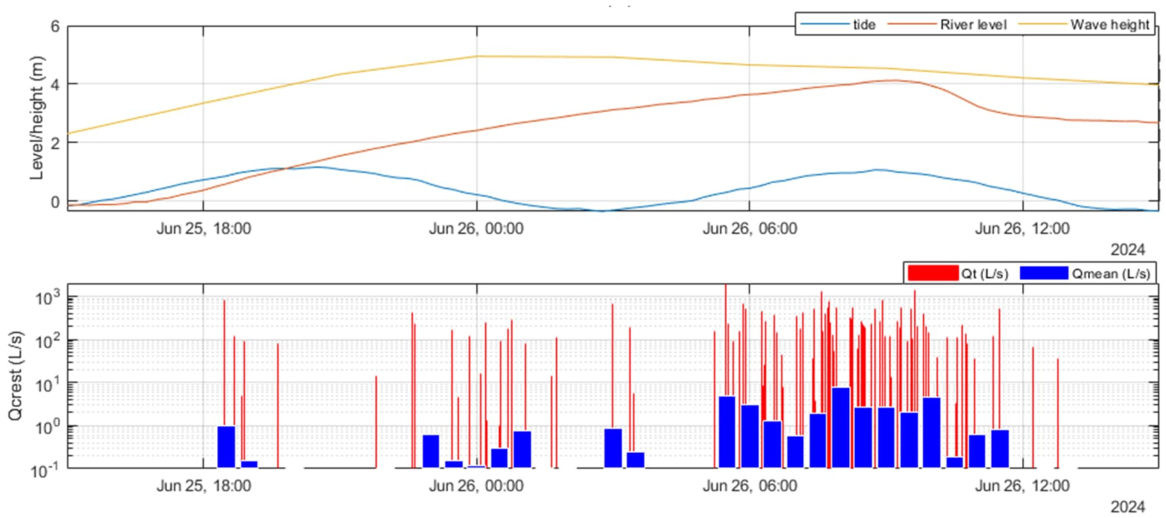


Figure 5.3: Wave overtopping time-series output. Qt is the instantaneous discharge over the crest at each output time. Q_{mean} is averaged over 30 minutes.

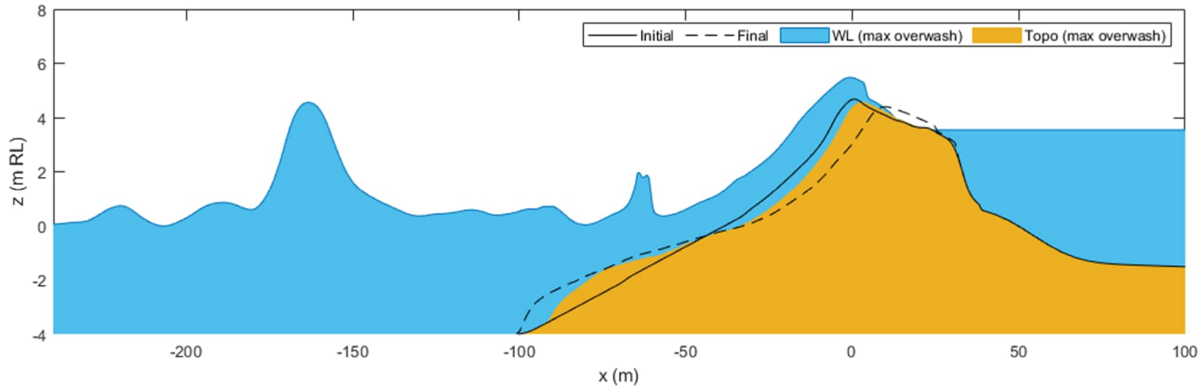


Figure 5.4: Model profile showing a time of maximum overtopping, where a wave crest is washing over the bar.

5.1.4 Changing crest level (baseline model)

The change in crest level of a gravel barrier can be positive (increasing level) or negative (lowering level), depending on the initial crest level relative to the wave and tide conditions. This is a concept called ‘relative freeboard’. If the bar has a low freeboard (height above sea level) relative to the wave height, then wave overtopping can become a destructive force the flattens the crest potentially causing a breach from the coastal side. If relative freeboard is at a balance point (wave height is similar to freeboard), then some overtopping is likely occurring but without major force, then the waves can deposit sediment on the crest and cause an increase in level. This is also sensitive to the grade of sediment on the barrier, with courser grains more likely to be deposited on the crest compared to finer grains.

The actual changes in crest level and position during the event are unknown and would require monitoring in the form of before and after surveys or a time-lapse camera.

The baseline model simulation shows crest lowering of 0.3 m over 24 hours (from 4.7 to 4.4 mRL) and the crest position retreated landward by approximately 10 m (Figure 5.5). It is possible that in some locations wave overtopping caused the crest to build up, assisting in holding back the river level by making breaching more difficult. It is also possible that in some locations wave overtopping caused the crest to lower, which would assist in allowing the river water level to breach the flow over the crest, which could trigger a full breach. The response of the bar crest to overtopping is dependent on the antecedent conditions (e.g. bar crest level and width) prior to the event.

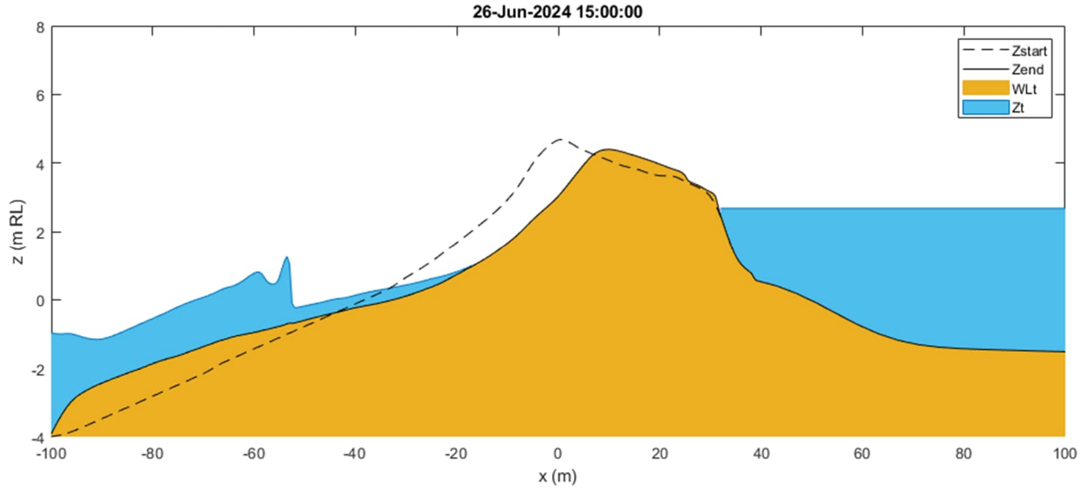


Figure 5.5: Final profile (colour fill) compared to the initial profile (dashed) with water level at the end of the model run in blue.

5.1.5 Hydraulic gradient within the barrier

The difference in water level inside the bar sediments (water table) can generate a level of the hydraulic gradient inside the gravel barrier that facilitates water transfer (seepage) to the sea or to the river, depending on the relative balance of wave action and river level. The hydraulic gradient is sensitive to wave runup and overtopping motions, as the porous material allows relatively efficient percolation of swash when compared to sandy beach environments. The hydraulic gradient level inside the bar was represented in the XBeach-G model and provides insight to how both coastal water levels including wave processes and river levels influence the bar over the event.

The hydraulic gradient slope is presented in Figure 5.6 and Figure 5.7, as the bold blue line that extends through the barrier. Figure 5.6 [A] is on the first incoming tide, when large waves were running up the bar, when the river level was below the sea level. The hydraulic gradient slope is from the coast to the river, at a gradient of -0.04. The next output is at high tide [B], when river level and tide level were equal and shows the influence of waves on the coastal side maintains a hydraulic gradient trend that slopes towards the river. On the falling tide [C], the river keeps rising as the hydraulic gradient level begins to flatten in the early hours of 26 June but still has a slight slope toward the river.

Figure 5.7[D] shows the situation at the base of low tide (2:30 am). River levels were still rising, and the hydraulic gradient starts to slope from the river to the sea. At the peak of the next high tide [E], river level is also at a maximum and the bar becomes fully is nearly saturated, influenced by both elevated waves and river level. On the dropping tide, as the river level starts to lower, the seaward sloping hydraulic gradient trend returns [F].

The hydraulic gradient model is uncalibrated but presents a potentially insightful insight to a phenomenon that may likely have influenced the event. Hydraulic gradient dynamics in the bar show a general dominant trend of sloping from the sea to the river driven by wave processes, this facilitates transfer of water from the coast, through the bar to the river and provides a tailwater control through the bar. The volume of water added to the lagoon through this mechanism is unknown.

A key reason this phenomenon may influence the event is that it creates an opposing force for river level to overwhelm the bar and creates an elevated hydraulic gradient that the river flow is competing with to either flow through or breach the bar.

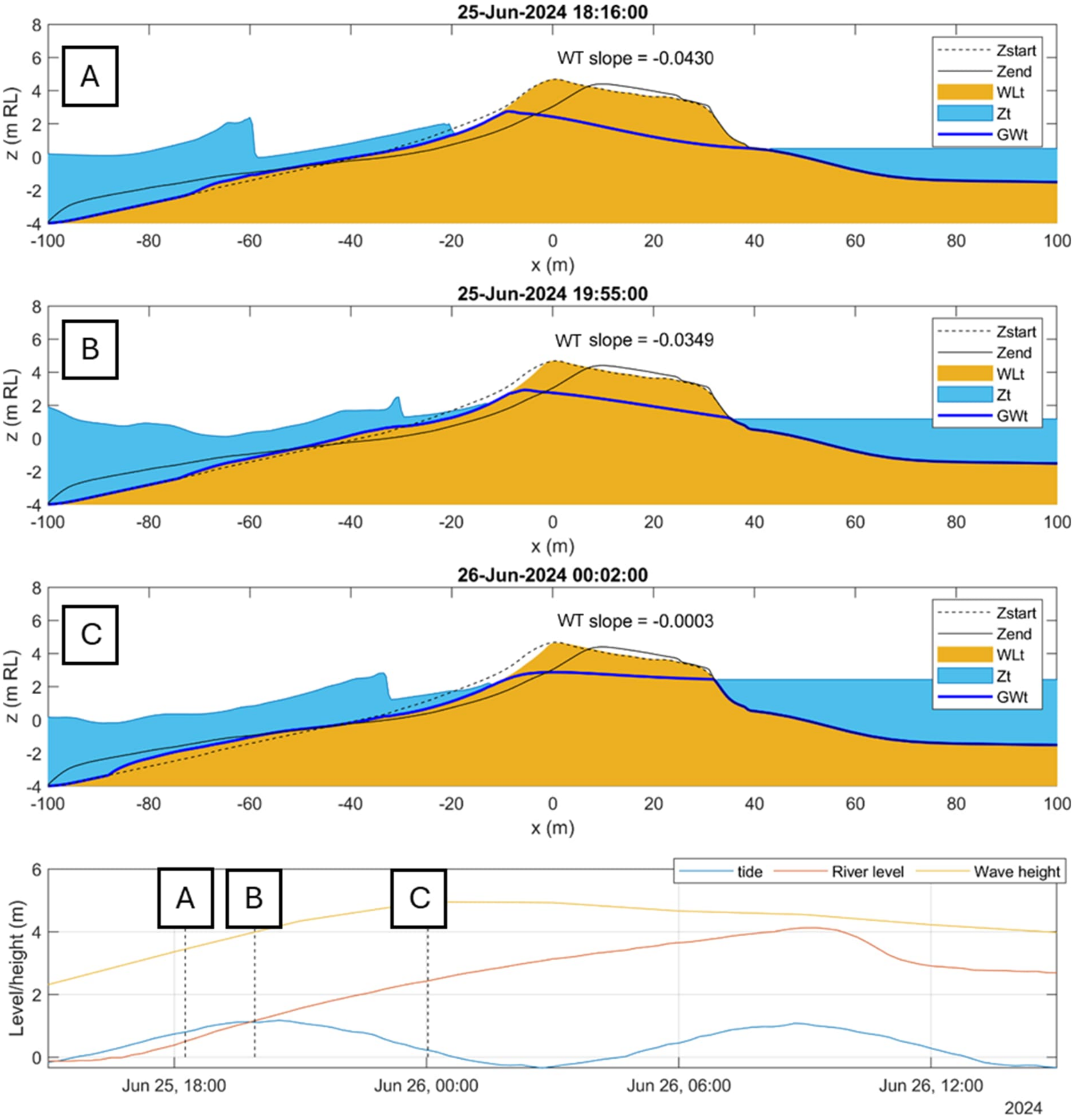


Figure 5.6: Examples of hydraulic gradient dynamics inside the bar at different key points in time during the event, over the first high tide cycle.

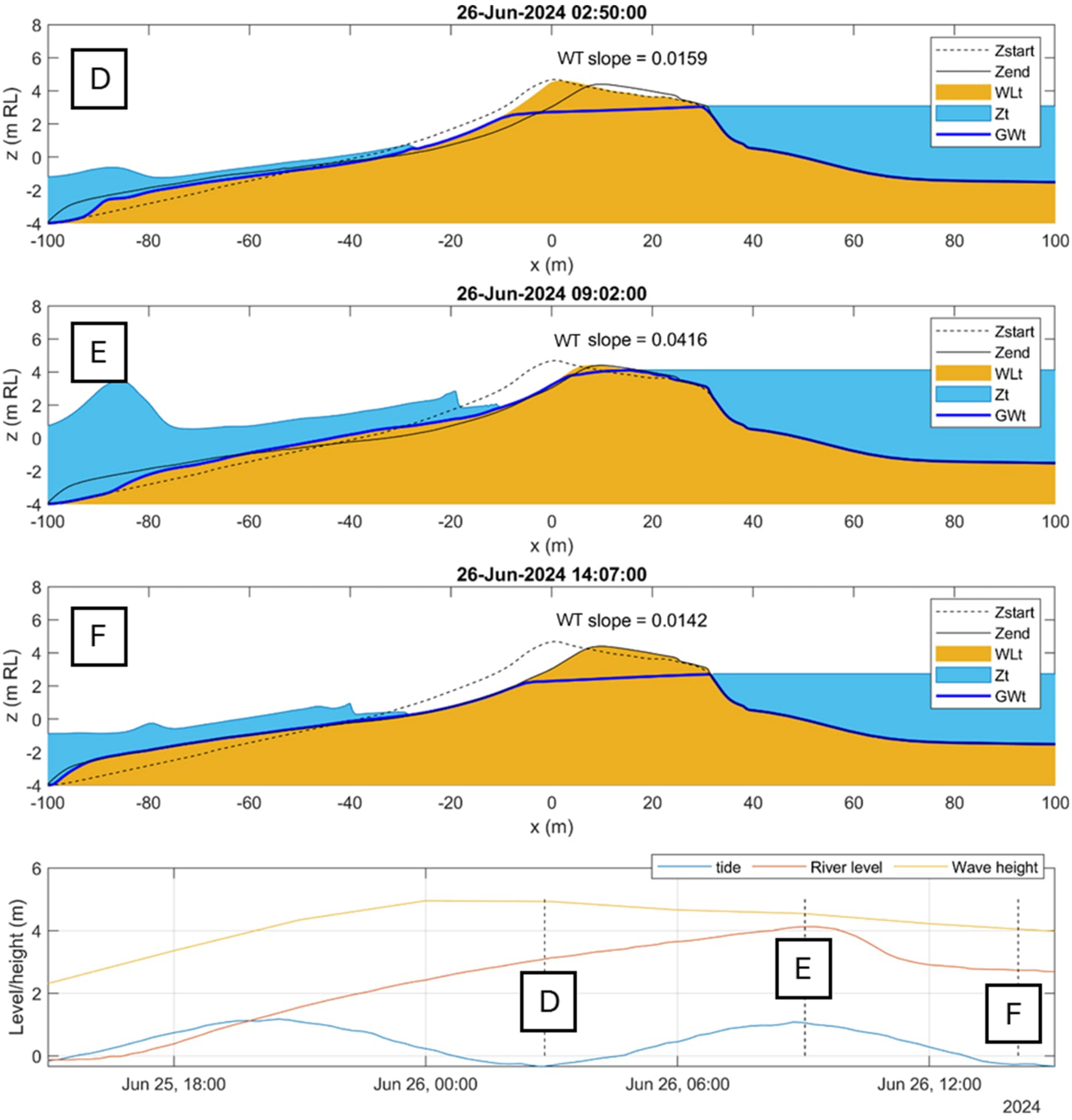


Figure 5.7: Examples of hydraulic gradient dynamics inside the bar at different key points in time during the event, over the second high tide cycle.

5.1.6 Sensitivity to smaller waves

The same model run was repeated using modal wave conditions (Hs =1.5 m) with the river and tide conditions otherwise consistent with the event and baseline model as occurred during the event. The results are presented in Figure 5.8 and Figure 5.9, which show the same snapshots in time as the scenario with waves as modelled during the baseline simulation. The scenario with more typical waves shows that the initial hydraulic gradient slope in the bar is towards the river until the first high tide peak (Figure 5.8 A-B). However, once the river level exceeds 2 mRL (Figure 5.8 C) the hydraulic gradient slope is from the river to the sea, which is sustained for the remainder of the control simulation (Figure 5.9[D, E, F]. Therefore, if the event occurred during low wave conditions, the exchange of water from the river to the sea would likely be more efficient.

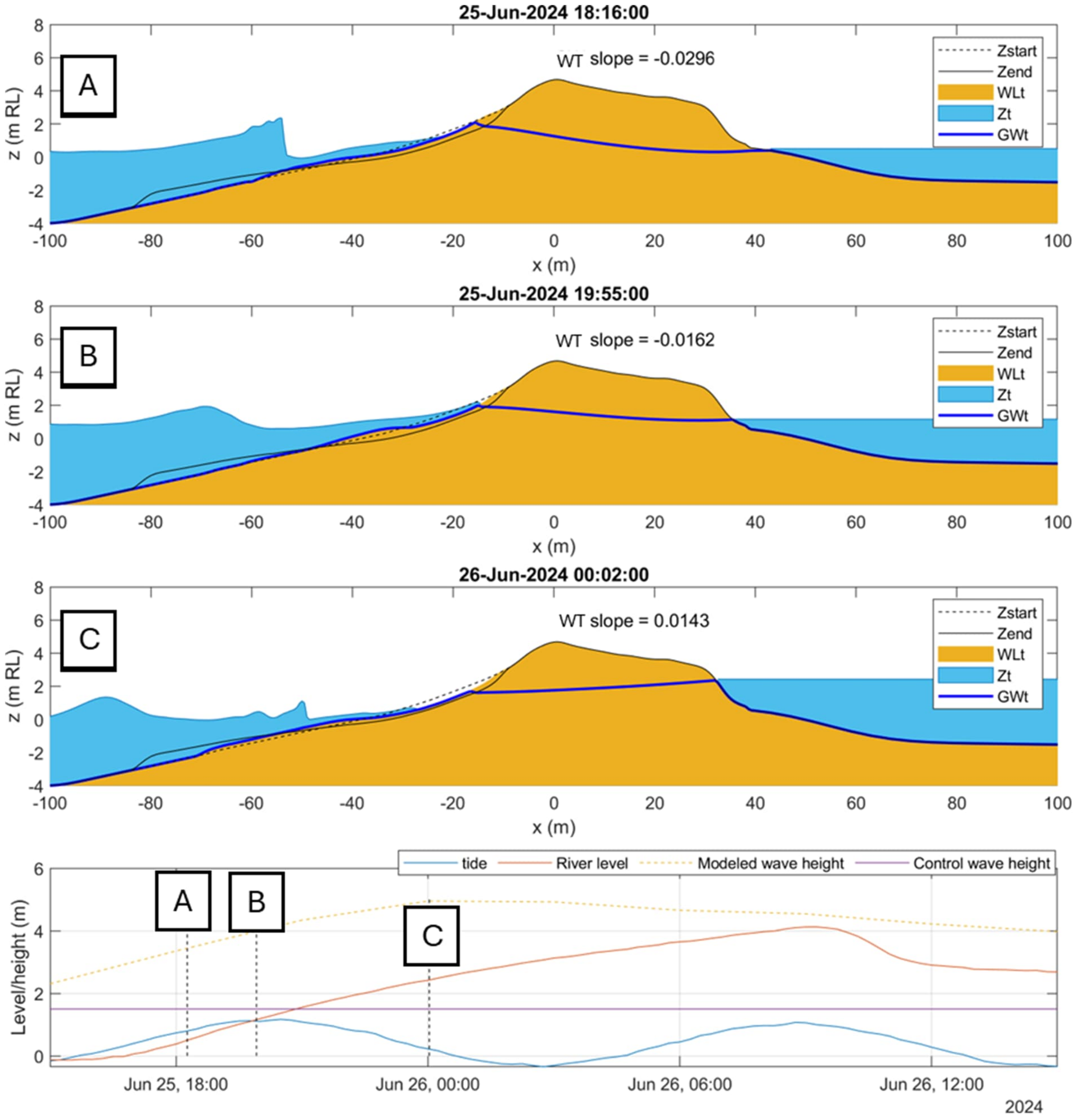


*Figure 5.8: Comparison scenario with typical waves (*Hs = *1.5 m) showing the hydraulic gradient dynamics inside the bar at different key points in time during the event (tide and river level as measured), over the first high tide cycle.*

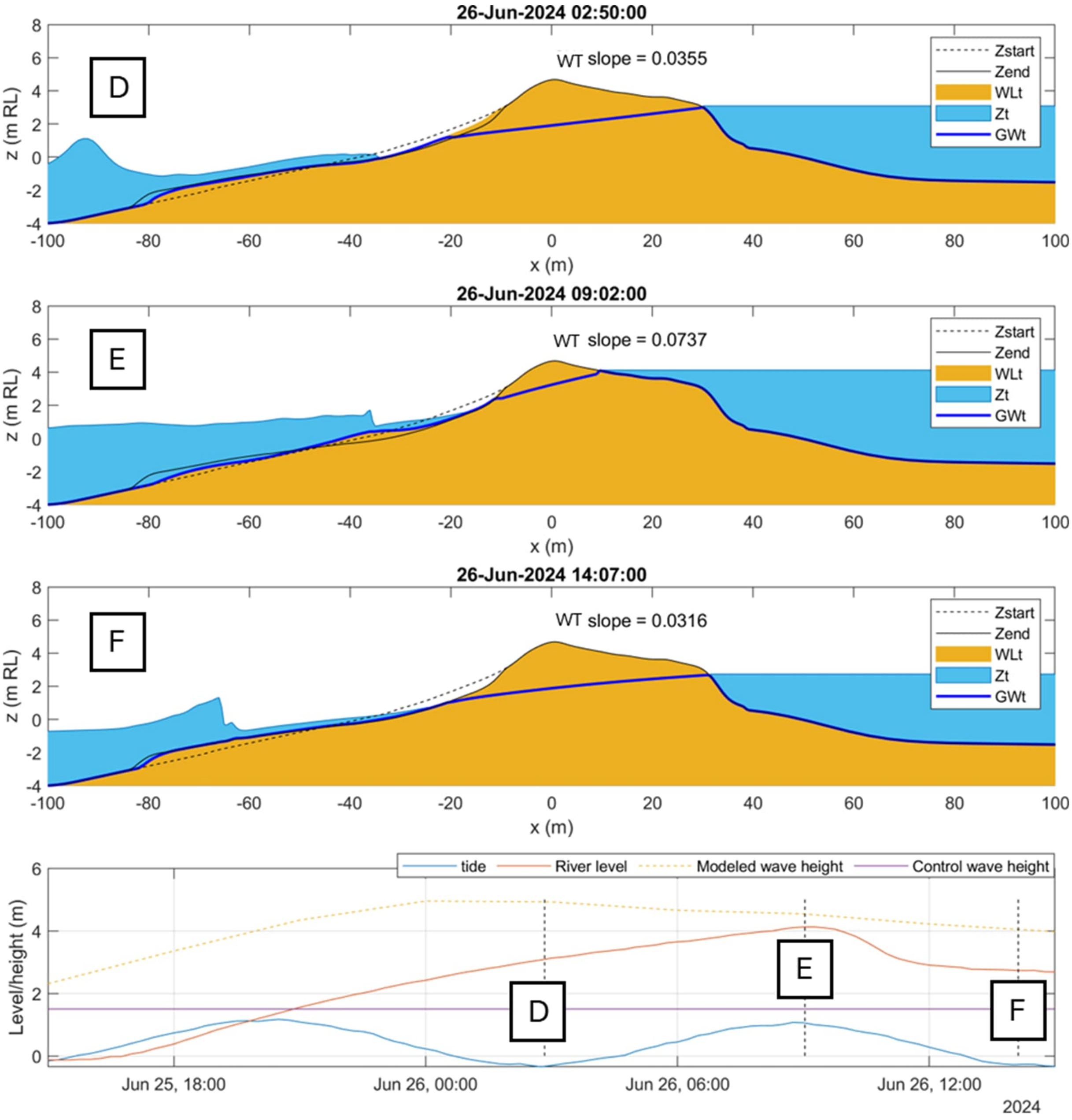


*Figure 5.9: Comparison scenario with typical waves (*Hs *= 1.5 m) showing the hydraulic gradient dynamics inside the bar at different key points in time during the event (tide and river level as measured), over the second high tide cycle.*

5.1.7 Sensitivity to larger waves

There is some uncertainty to the actual wave conditions during the event, as the nowcast model appears inconsistent with local observations, and was underpredicting waves at Napier. Based on observations that wave heights may have been even higher than the Metocean nowcast. Therefore, the same XBeach-G simulation was undertaken but with the nowcast model wave height amplified by 30%.

The larger waves acting on the bar caused more overtopping compared to the baseline scenario. Overtopping averaged around 5 L/s/m during the first high tide and continued over the low tide. Overtopping over the second high tide was much greater that the baseline (10 – 30 L/s/m), as the crest level had been lowered by wave action. Over the 24h simulation, wave action lowered the crest by 0.6 m, causing landward migration of 24 m. The total volume of wave overtopping was 1.5

million m^3 over 24h, when upscaled to the bar length (3 km). Therefore, a 30% increase in wave height resulted in the model predicting a seven-fold increase in overtopping volume, caused by higher wave runup and a greater reduction in barrier crest level.

Modelling a 30% higher wave climate also reinforced the hydraulic gradient from the coast to river, increasing overtopping and elevating the hydraulic gradient through the bar. The influence of higher waves on the bars hydraulic gradient is presented in Figure 5.10 and Figure 5.11. This shows the hydraulic gradient is seaward for the full duration, even at low tide, as waves were the dominant force acting in the bar (Figure 5.10). The bar was completely saturated at the peak of the river level (Figure 5.11).

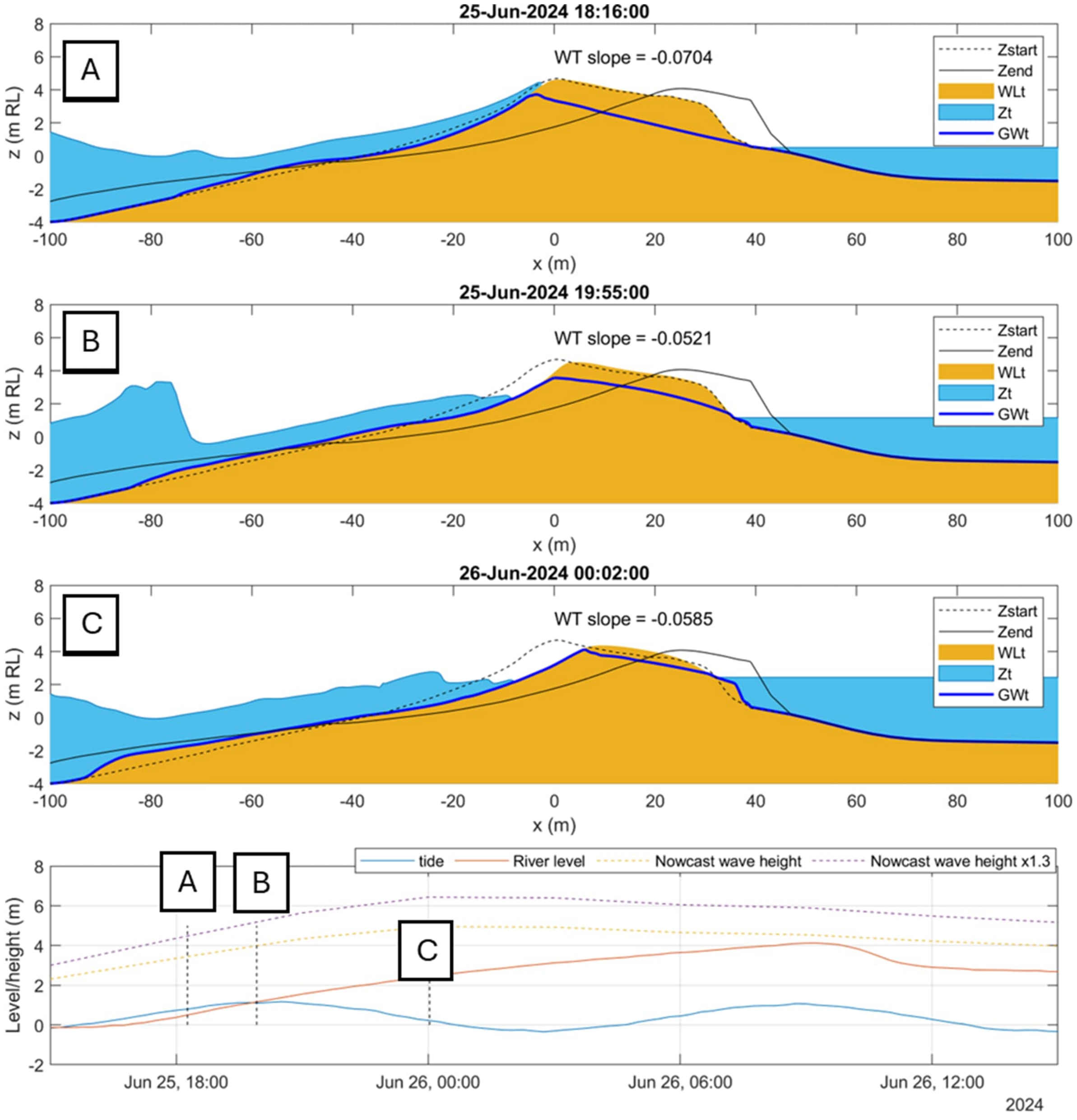


Figure 5.10: Comparison scenario with wave height 30% higher, showing the hydraulic gradient dynamics inside the bar at different key points in time during the event (tide and river level as measured), over the first high tide cycle.

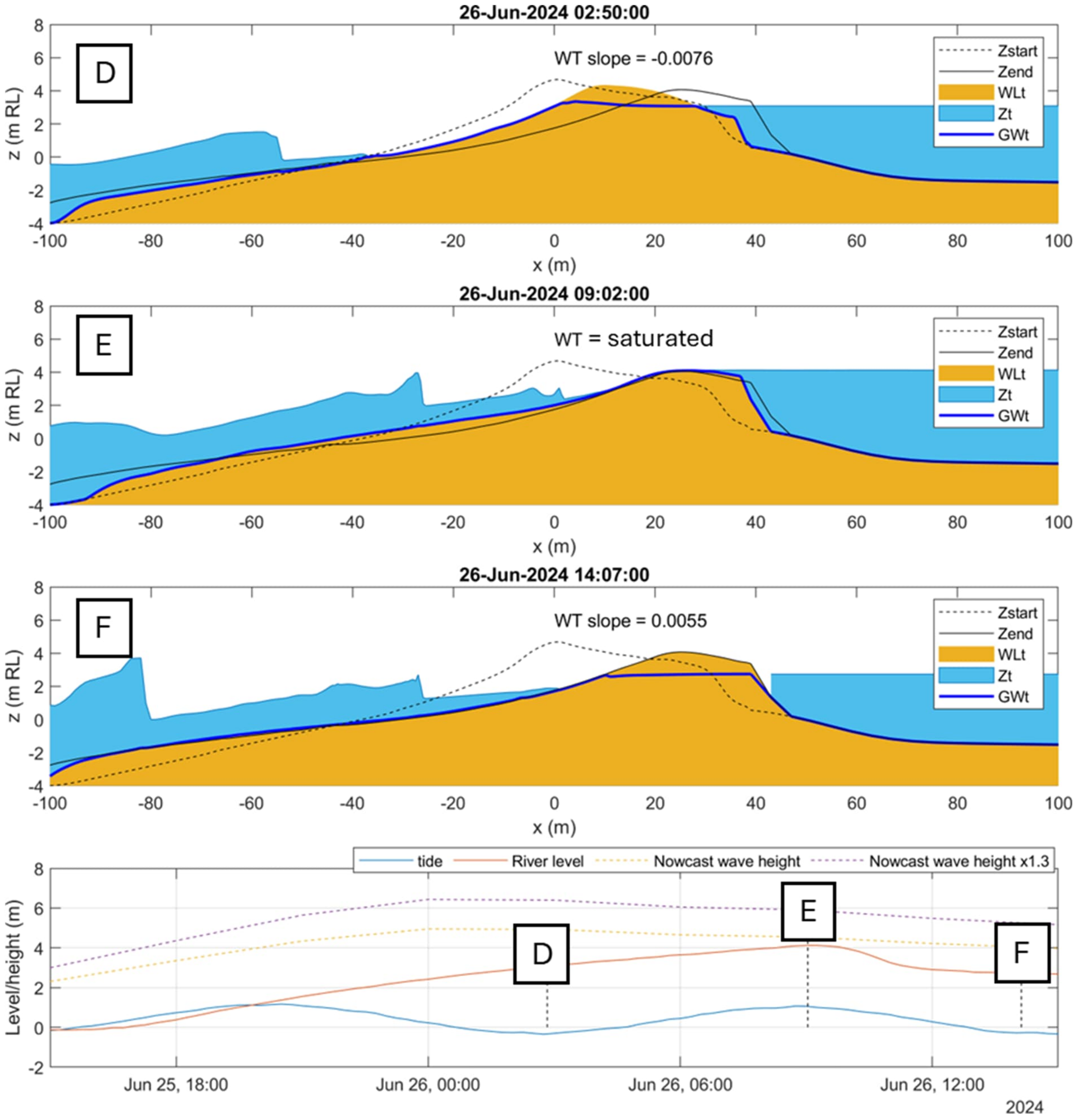


Figure 5.11: Comparison scenario with wave height 30% higher, showing the hydraulic gradient dynamics inside the bar at different key points in time during the event (tide and river level as measured), over the second high tide cycle.

5.1.8 Wave propagation into the river mouth

Waves can propagate into the river mouth at Wairoa. However, the direct propagation of waves into the river mouth during the event is unknown, as wave motions were opposed by strong currents from the outflowing river. During conditions of low or moderate river flow, wave processes can elevate river mouth water level through:

- Direct propagation of swell and wind waves through the river mouth, causing runup on the riverbank.
- Propagation of infragravity (IG) waves through the river mouth. IG waves are surges in water level in the surf zone caused by groups (or sets) of breaking waves. IG wave amplitude can be 10 – 30% of breaking wave height, associated with long periods (30 – 120 seconds) that can

cause inundation to low lying areas. IG waves can propagate into harbours, estuaries and river mouths.

- Wave setup, which is the super-elevation of mean water level caused by wave breaking can increase mean water level in estuaries and river mouth locations.

The influence of wave processes surging through the river mouth is likely sensitive to the river mouth position, mouth width, and the velocity of outflowing river water. For example, a strong outflow river influence by a seaward water level gradient through the river mouth can prevent waves directly flowing into the river (Figure 5.12). This could occur if the river mouth is narrow and when the mean sea level (including storm surge and wave setup is significantly below the river level. For the June 2024 event, mean sea level including storm surge and wave setup was likely below 2 m, and the river level near the bar was closer to 4 m based on the flood level. This water level seaward gradient through the open mouth may prevent wave action directly transferring into the river mouth. However, the opposing force of wave processes and storm surge may still influence the drainage by slowing the outflowing river.

Under conditions where the river level and sea level are the same, wave processes, including IG waves and wave setup can easily pass through the river mouth and elevate river mouth water levels. In the days flowing the flood event, some media images show waves propagating into the river mouth, as the river level settled.

Local observations during the event did mention fast flowing water level surges in areas of town flooding that were interpreted as being from the sea, which suggests some influence from coastal surges flowing either, through the bar, over the bar or through the mouth. The gradient in water level from the river (e.g. 4 mRL) to the sea (< 2 m mRL including storm surge and wave setup) makes it unlikely that waves were able to propagate into the river mouth against the outflowing water level and velocity.

This assessment has not been tested in a numerical model, as the complexity of dynamic wave interaction with outflowing river is not feasible to represent in the timeframes available. An aerial drone video of the river mouth taken the day after the flood (Provided by HBRC) shows an area of no limited wave breaking where the new mouth is outflowing, which could also be influenced by outflowing water and the sea-bed contours. However, the tide, wave and river level conditions the time of the image is unknown.

Wave action is more likely to flow into the river mouth and influence lagoon water level during low river flow conditions and when the river mouth opening is wide.

It was not feasible to develop a suitably accurate two-dimensional numerical model to further test the interaction between waves, the outflowing river, and the bar in the timeframes available.

Figure 5.12: Snapshot from a UAV video provided by HBRC the day after the flood event showing an area of no surf-zone aligned with the outflowing.

5.2 Coastal process discussion

5.2.1 Storm modelling

The XBeach model results showing the hydraulic gradient dynamics, or the hydraulic gradient inside the barrier are generally consistent with results from a physical modelling experiment described in Turner and Masselink (2012). Physical modelling scenarios where with sea level significantly higher than the lagoon level and caused a landward sloping hydraulic gradient through the barrier, which is likely what was occurring for a majority of the June 2024 event in Wairoa. The wave induced gradient significantly increases the flow of water through the barrier as shown in Figure 5.13. This figure shows flows through a gravel barrier with a uniform water level for irregular waves, which is representative of typical conditions as well as with no waves and monochromatic waves which are more representative of larger storm / swell events. The flows through the barrier are more than double for the monochromatic waves.

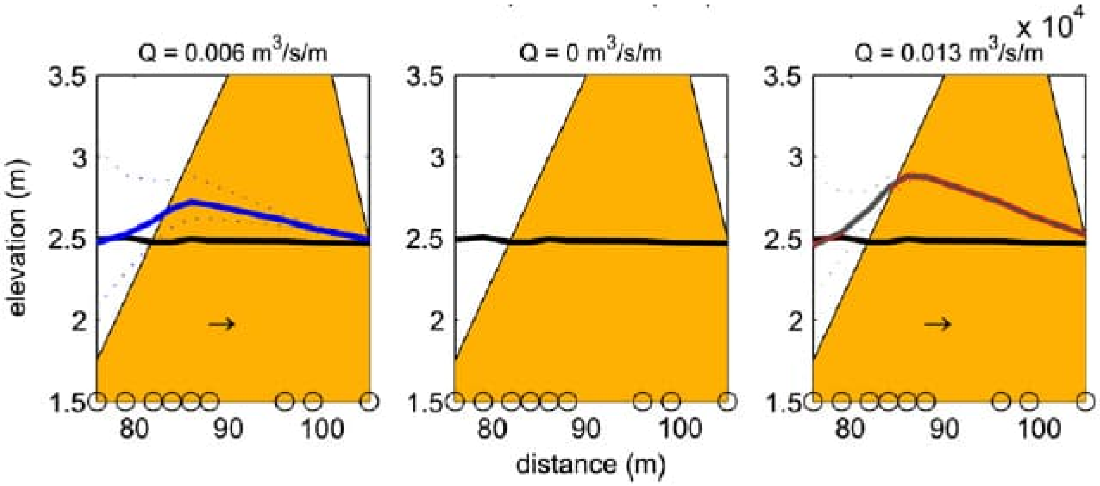


Figure 5.13: Wave induced water table from the sea (LHS) to the lagoon (RHS) for irregular waves (LHS), no waves (middle) and monochromatic waves (RHS). Source Turner & Masselink, 2012).

The response of gravel barrier crest elevation and position has also been investigated with regards to wave overtopping and increasing sea level. Results from physical modelling experiments reported by Matias et al. (2012) show that barrier crest levels can increase. Crest accretion with relative sea level rise was observed in some scenarios. If the lagoon water level was below the ocean level, then accretion was more likely. If the lagoon water level was elevated, less crest accretion was observed. Crest accretion was also sensitive to wave steepness, but at lesser magnitude. Longer wave periods at similar water levels caused crests lowering due to increasing wave overtopping.

The presence of waves during the June 2024 event was significant in terms of influencing hydraulics action on the bar, which influence the management available during the event (e.g. limited access for diggers during overtopping) and the exchange of water between ocean and lagoon. Despite the elevated water level in the river, the action of waves on the bar resulted in hydraulic seepage directed from the coast to the river. a mostly lagoon ward hydraulic gradient which transfers water from the sea to the lagoon. The volume of water transport through the barrier is unknown but is expected to exceed the volume of water transferred through wave overtopping of the barrier crest.

Large waves acting on the bar were approaching the coast from an easterly angle. This generates an alongshore sediment movement on the bar, as waves runup on an angle. Waves washing up the bar on an angle present a significant challenge for digging out a mechanic channel, as waves can bulldoze thought the side-cast[19] material and re-fill the previously dug out channel. For the June 2024 event, it is feasible that wave action on the bar could have closed a channel that was recently cut using mechanical intervention. This is based on large waves impacting the bar on an angle over the first high tide, before the river level increased above the tide level. To sustain a mechanically opened channel, the flow gradient needs to be dominated by seaward moving river water.

5.2.2 Long term trends

Komar (2005) identified the likely long-term trend of gravel barriers to sea level rise is for a landward migration of the gravel barrier ridge and a raising of the crest, with the process initiated by over wash of the barrier (Figure 5.14).

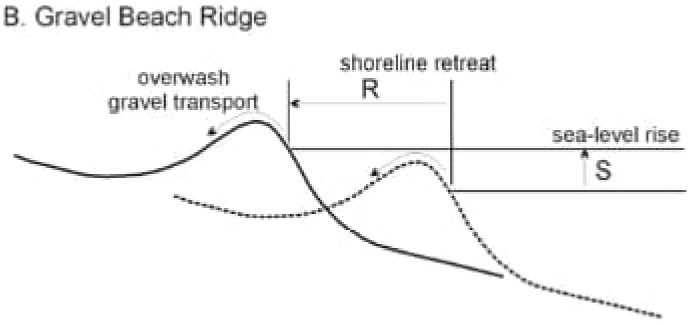


Figure 5.14: Model of gravel beach behaviour with sea level rise (Source: Komar, 2005).

The gravel barrier that extends across Wairoa River mouth is a dynamic coastal landform influenced by river and coastal forces. Available beach profile data, supplemented by LiDAR surveys indicates that the bar across the Wairoa River mouth is accreting in elevation and migrating landward. This is consistent with a barrier roll-over response to wave action and relative sea level rise predicted in literature.

In the longer-term, relative sea level rise is likely to results in more frequent overtopping, of greater volume, unless the crest level maintains a positive freeboard. Trends in beach profile volume

---

[19] Side-cast material the sediment that is dug out to form a new channel, which is typically piled next to the channel.

indicate that there appears to be a general balance in profile volume at Whakamahi and along the bar, indicating either a balance of supply and removal, or a conservation of in-situ volume. There is a net reduction in sediment volume at Ngamotu, which is characterised by a relatively high and stable crest level with landward translation of the beach profile that is not balanced by profile roll-over.

The balance of alongshore transport to the west and east during different wave events and climate patterns is poorly understood at Wairoa. It is unclear of the eroded material is transported south across the bar, which is the main direction of bar migration and expected with easterly swell events such as the July June event. Alternatively, some along shore transport is also expected towards the east during southerly swell events.

Coastal adjustment to sea level rise at Wairoa over the next decades may results in higher bar levels, which may reduce the potential for natural river breaching of the bar.

6 Summary of findings

6.1 Event summary

Flooding in Wairoa occurred over the early morning of 26 June 2024. Based on the available information, flooding was influenced by multiple factors as summarised below:

- The atmospheric low-pressure system was large and formed rapidly off the East Cape on Tuesday 25 June, less than 24 hours before flooding was impacting Wairoa. Forecast information on the storm and waves underpredicted the significance of the event although the timing of the peak events was reasonably estimated. It is likely that the nowcast data obtained after the event also underpredicts wave and storm conditions based on local observations that the June 2024 waves were the biggest Mahia locals have seen in 30 years. The same nowcast model under-predicted waves at Napier based on a comparison of measured wave data with the nowcast information.
- The nowcast wave model shows a rapid increase in wave height from the evening of Tuesday 25 June, with a peak at midnight. Large waves were therefore influencing the bar and river mouth for approximately 12 hours before the river reached flood levels.
- Individual components of the event did not necessarily reach low probability return periods, but the combination of high rainfall, rising river level, spring tides, large waves, storm surge, as well as the position and size of the river mouth through the bar, all coincided to influence the flooding experienced. The joint coincidence is therefore likely rarer than the individual elements and makes management of the situation more complex.
- The onset of flooding likely occurred at the start of the rising tide (3:30 am on 26 June), with the peak river level occurring at the next high tide (9:10 am). The incoming tide conditions, combined with large waves and storm surge to create elevated water table conditions through the bar and the lower estuary that increased flood levels within the lower river. Post event imagery indicates that waves were likely overwashing sections of the bar during the event, potentially adding volume to the river and changing the crest level of the bar before and during the flooding event.
- A sudden decrease in river level at the turn of the high tide on the morning of 26 June likely indicates the point in time when the bar breached (soon after 9 am). The change from rising to falling tide, in addition to the river water gradient through the bar may influence the timing of the breach, as the outgoing tidal flow combined with river discharge and the steeper gradient through the bar.

Comparing this event with two previous events, the location of the river mouth and the stage and magnitude of the tide may contribute to natural breaching of the bar. The last two natural breaching events (November 2023 and June 2024) occurred when rising river levels coincided with spring tides, with the breach occurring at the turn of the high tide at the same location adjacent to Pilot Hill, where river flow is constricted though a narrow channel.

6.2 River modelling

An existing TUFLOW model was provided by HBRC and adapted to replicate the June 2024. The model parameters were 'tweaked' to represent the observed water levels and flood extents using expert judgement and the best available information. The model was then applied to explore different influencing features.

The river model represents the measured river flow and tide conditions but does not resolve wave processes that were present during the event. The river model has a 'fixed bed' that does not erode or change during the simulation. Therefore, the change in river mouth width and position were represented using a function that allows controlled terrain adjustment during the simulation. This is a simplification of the full environmental complexity at the river mouth but provides a method for systematically assessing the influence of mouth position on river outflow.

The river model represented the observed flooding extent and timing, with limited parameter tuning, other than widening the initial river mouth and initialising the breach at Pilot Hill which was informed by observed changes in the bar.

Scenario testing shows that the position of the Wairoa River mouth in relation to Pilot Hill has a significant influence on the lower river system's hydraulic performance. When the bar is offset to the west of Pilot Hill, the river width becomes constricted between Pilot Hill and the bar, where flow is constrained to a width of about 100 m. River flows need to pass through both the Pilot Hill constriction and the river mouth opening. If the mouth is located east of Pilot Hill, there is less constriction, with water only needs to pass through the river mouth opening.

The timing and existence of a river mouth breach aligned to the main river channel greatly influences the peak flood levels. A “no breach” condition results in raised flood levels and extended flood duration, while an earlier breach results in much lower flood levels.

Sensitivity testing of the tide phase and tide level produced similar peak flood levels, indicating that there is limited tidal influence on river flood level. While the flooding on 26 June 2024 can be replicated using only the measured river level, tide conditions, and changes in the river mouth, this does not resolve the influence of waves acting on the bar and to do this coastal modelling was carried out.

6.3 Coastal modelling

A numerical model ‘Xbeach-Gravel’ was used to simulate wave and tide processes acting on the bar during the event. This was undertaken to explore the relative balance of sea-state compared to river level on the hydraulic gradient inside the porous gravel bar. Wave overtopping was also modelled for the 24 hour event. Modelling scenarios included:

- The baseline event as measured and nowcast.
- A comparison scenario with the same river level and tide, but small (average) waves.
- A sensitivity test that considered a wave height that is 30% higher than the nowcast wave height, as the nowcast model was potentially under-predicting the actual conditions.

Model results show that the water table dynamics within the bar are strongly controlled by wave and tide conditions, even when the river level is elevated. The baseline model of the event shows that the hydraulic gradient within the bar was dominated by wave action, creating a water slope from the sea, through the bar to the river. This hydraulic gradient facilitates water transfer from the sea to the river and creates an elevated tailwater condition that influences river drainage. In contrast, if the river conditions during the event coincided with typical wave heights, the hydraulic gradient is from the river to the sea, which facilitates drainage and breaching potential.

The crest level of Wairoa bar relative to the river level is an important feature of when and where a breaching event occurs. Analysis of long-term beach profile data suggests that the bar elevation has increased over recent decades. Beach crest levels along the adjacent Wairoa coast are increasing at rates similar rate to measured sea level rise. This change is consistent with the predicted changes expected on gravel coasts because of sea level rise. The increasing bar crest elevation increases the risk of flooding events occurring in the future, which may also be compounded by climate change influences on catchment flooding.

Coastal modelling shows that the hydraulic gradient in the bar was dominated by water level transfer from sea to river, which has a significant influence on river outflow and therefore the resulting river level and flooding.

Based on the available data and analysis, the large wave conditions impacting Wairoa were likely to have influenced the flooding, through a combination of elevating the water table condition through the bar, and directly adding volume to the river mouth through wave overtopping.

7 Applicability

This report has been prepared for the exclusive use of our client Hawke's Bay Regional Council, with respect to the particular brief given to us and it may not be relied upon in other contexts or for any other purpose, or by any person other than our client, without our prior written agreement.

Tonkin & Taylor Ltd
Environmental and Engineering Consultants

Report prepared by:	Authorised for Tonkin & Taylor Ltd by:
....	....
Dr Eddie Beetham Senior Coastal Geomorphologist	Richard Reinen-Hamill Project Director

Report prepared by:	Reviewed by:
....	....
Alex White Water Engineer	Mark Pennington Technical Director, Water Engineering

EDBE
\\ttgroup.local\files\welprojects\1017353\1017353.2406\issueddocuments\final data analysis report 6 august 2024\wairoajune2024_physicalprocessreportv3.0final.docx

8 References

Komar, P.D. (2007) The coast of Hawke's Bay: processes and erosion problems. HBRC Report No. AM 07/02, January 2007

Matias, A., Williams, J. J., Masselink, G., & Ferreira, Ó. (2012). Overwash threshold for gravel barriers. *Coastal Engineering*, *63*, 48-61.

McCall, R. T., Masselink, G., Poate, T. G., Roelvink, J. A., Almeida, L. P., Davidson, M., & Russell, P. E. (2014). Modelling storm hydrodynamics on gravel beaches with XBeach-G. *Coastal Engineering*, *91*, 231-250.

Pollard, J. A., Christie, E. K., Spencer, T., & Brooks, S. M. (2022). Gravel barrier resilience to future sea level rise and storms. *Marine Geology*, *444*, 106709.

T+T (1999). Wairoa River Mouth Pre-Feasibility design study. Report prepared by Tonkin + Taylor for Hawkes Bay regional Council. January 1999. Reference 16394.

T+T (2023) Coastal Inundation: Tangoio to Clifton. Report prepared by Tonkin + Taylor for Hawkes Bay regional Council, Napier City Council, and Hastings District Council. November 2023. Reference 1019664 v4.

Turner, I. L., & Masselink, G. (2012). Coastal gravel barrier hydrology—Observations from a prototype-scale laboratory experiment (BARDEX). *Coastal Engineering*, *63*, 13-22.

Appendix A HBRC preliminary flood map

Wairoa Flood Extents - June 26, 2024

For internal HBRC use only., Eagle Technology, Land Information New Zealand, GEBCO, Community maps contributors

Note: Flood extents are indicative, and have been derived using aerial photos collected on June 28, 2024, photos sourced from various media, eye-witness accounts of flooding depths, contour information, and water level recordings from HBRC telemetry at the Town Bridge.

0 250 500 Meters

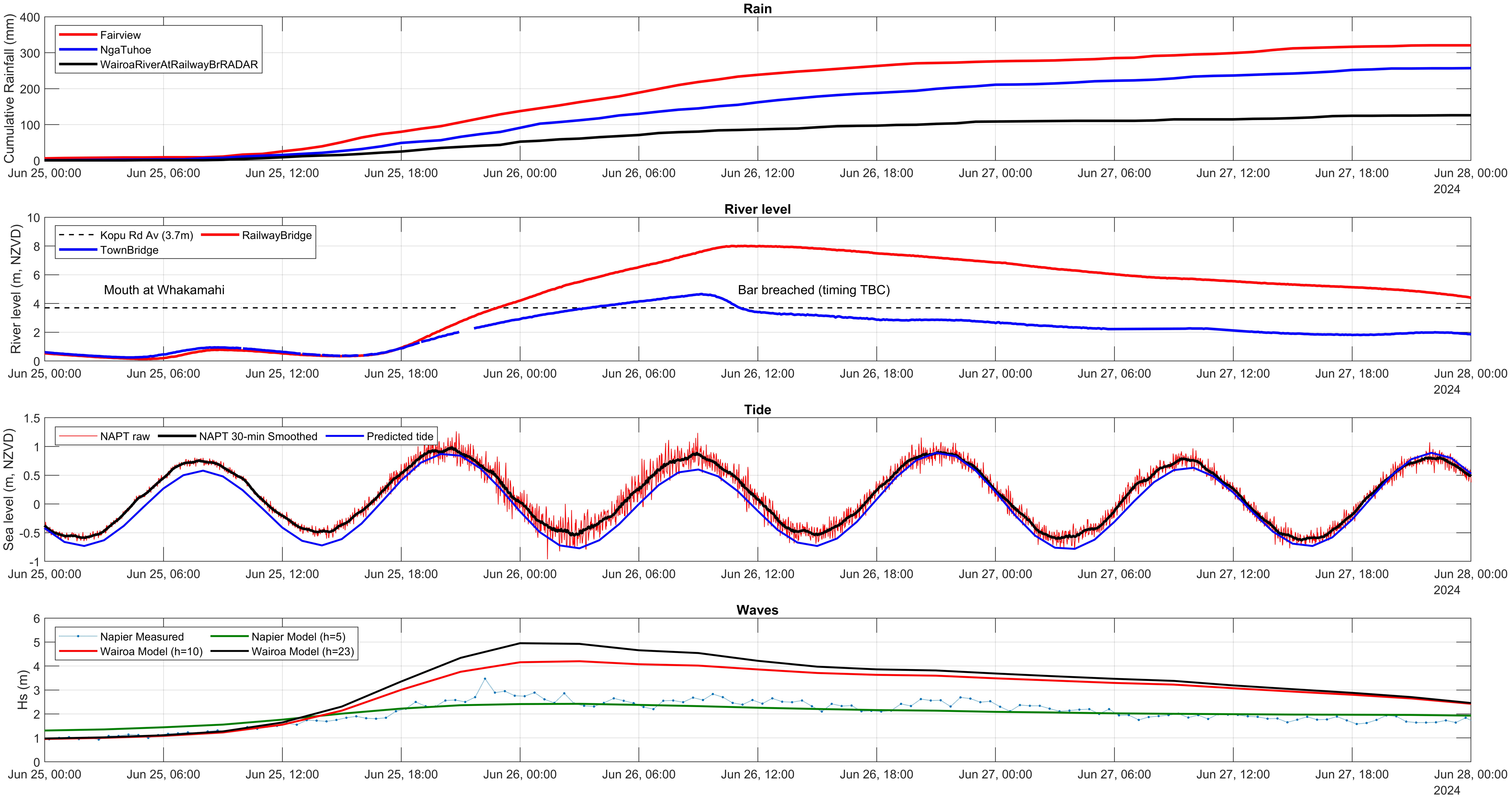
N

HAWKES BAY
REGIONAL COUNCIL
TE KAUNIHERA Ā-ROHE O TE MATAU-A-MĀUI

Map Created on August 02, 2024

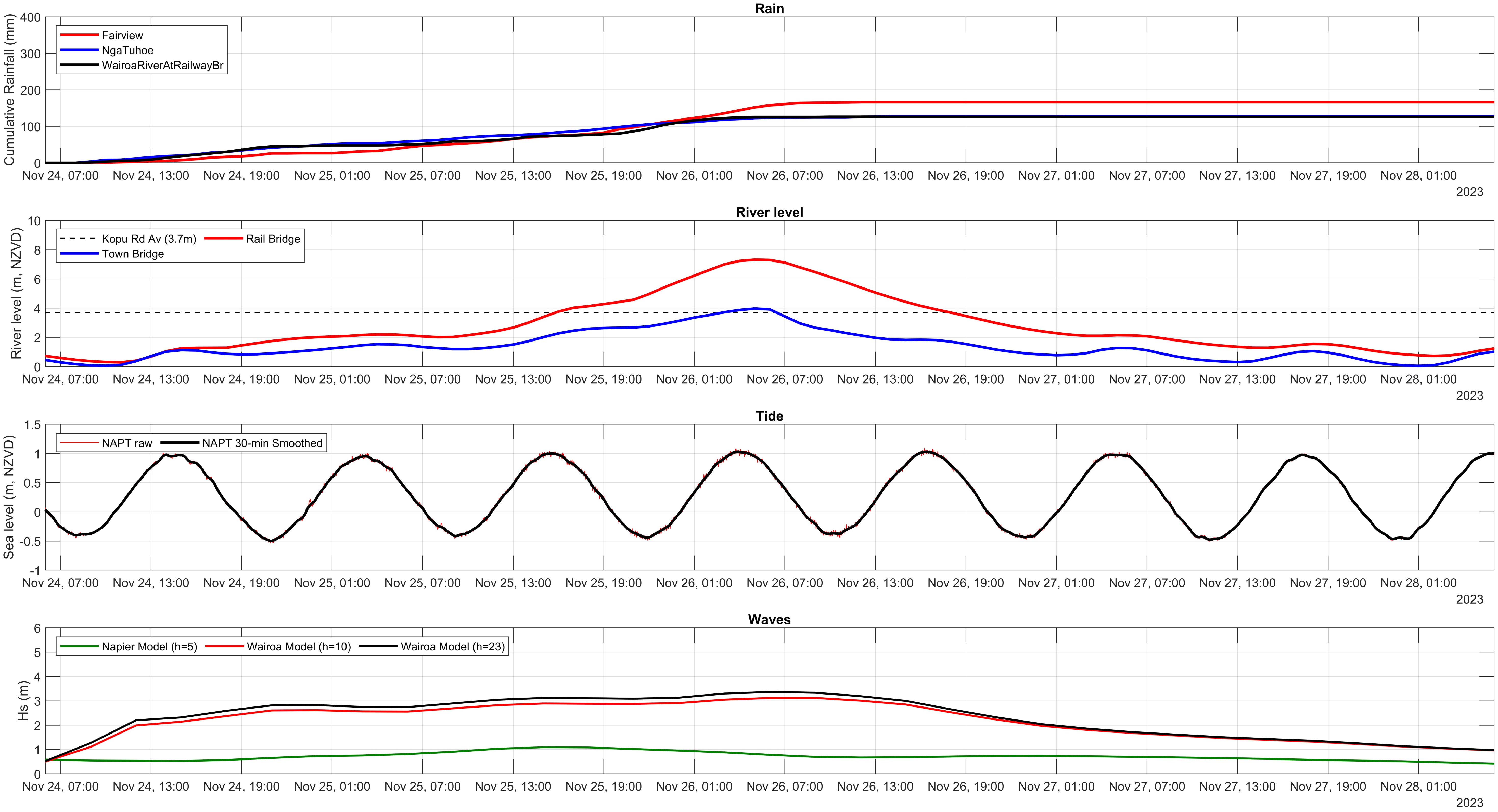
Appendix B Timeline summary figure

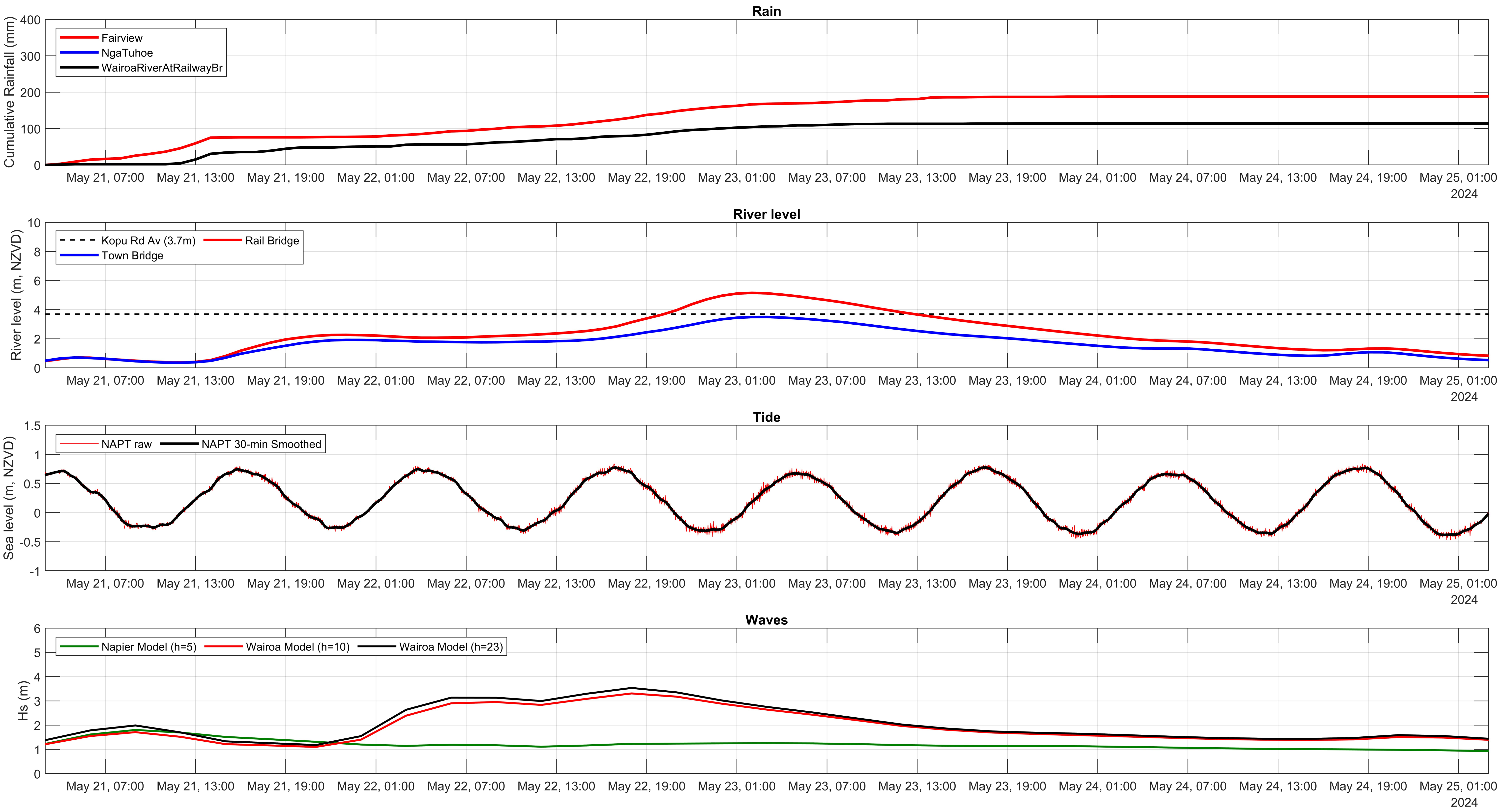
- Figure on the next page shows a summary of the cumulative rainfall (measured by HBRC), river level (measured by HBRC), measured sea level (LINZ, Napier), predicted tide level (NIWA, Wairoa), and the wave conditions for the event as modelled by MetOcean Solutions. Wave data legends of h=5, h=10 and h=23 indicates the output point has a depth of 5, 10, and 23 m respectively.


Rain
Cumulative Rainfall (mm)
400
300
200
100
0
Fairview
NgaTuhoe
WairoaRiverAtRailwayBrRADAR
Jun 25, 00:00
Jun 25, 06:00
Jun 25, 12:00
Jun 25, 18:00
Jun 26, 00:00
Jun 26, 06:00
Jun 26, 12:00
Jun 26, 18:00
Jun 27, 00:00
Jun 27, 06:00
Jun 27, 12:00
Jun 27, 18:00
Jun 28, 00:00
2024
River level
River level (m, NZVD)
10
8
6
4
2
0
Kopu Rd Av (3.7m)
RailwayBridge
TownBridge
Mouth at Whakamahi
Bar breached (timing TBC)
Jun 25, 00:00
Jun 25, 06:00
Jun 25, 12:00
Jun 25, 18:00
Jun 26, 00:00
Jun 26, 06:00
Jun 26, 12:00
Jun 26, 18:00
Jun 27, 00:00
Jun 27, 06:00
Jun 27, 12:00
Jun 27, 18:00
Jun 28, 00:00
2024
Tide
Sea level (m, NZVD)
1.5
1
0.5
0
-0.5
-1
NAPT raw
NAPT 30-min Smoothed
Predicted tide
Jun 25, 00:00
Jun 25, 06:00
Jun 25, 12:00
Jun 25, 18:00
Jun 26, 00:00
Jun 26, 06:00
Jun 26, 12:00
Jun 26, 18:00
Jun 27, 00:00
Jun 27, 06:00
Jun 27, 12:00
Jun 27, 18:00
Jun 28, 00:00
2024
Waves
Hs (m)
6
5
4
3
2
1
0
Napier Measured
Napier Model (h=5)
Wairoa Model (h=10)
Wairoa Model (h=23)
Jun 25, 00:00
Jun 25, 06:00
Jun 25, 12:00
Jun 25, 18:00
Jun 26, 00:00
Jun 26, 06:00
Jun 26, 12:00
Jun 26, 18:00
Jun 27, 00:00
Jun 27, 06:00
Jun 27, 12:00
Jun 27, 18:00
Jun 28, 00:00
2024

Appendix C Timeline summary figures: other events

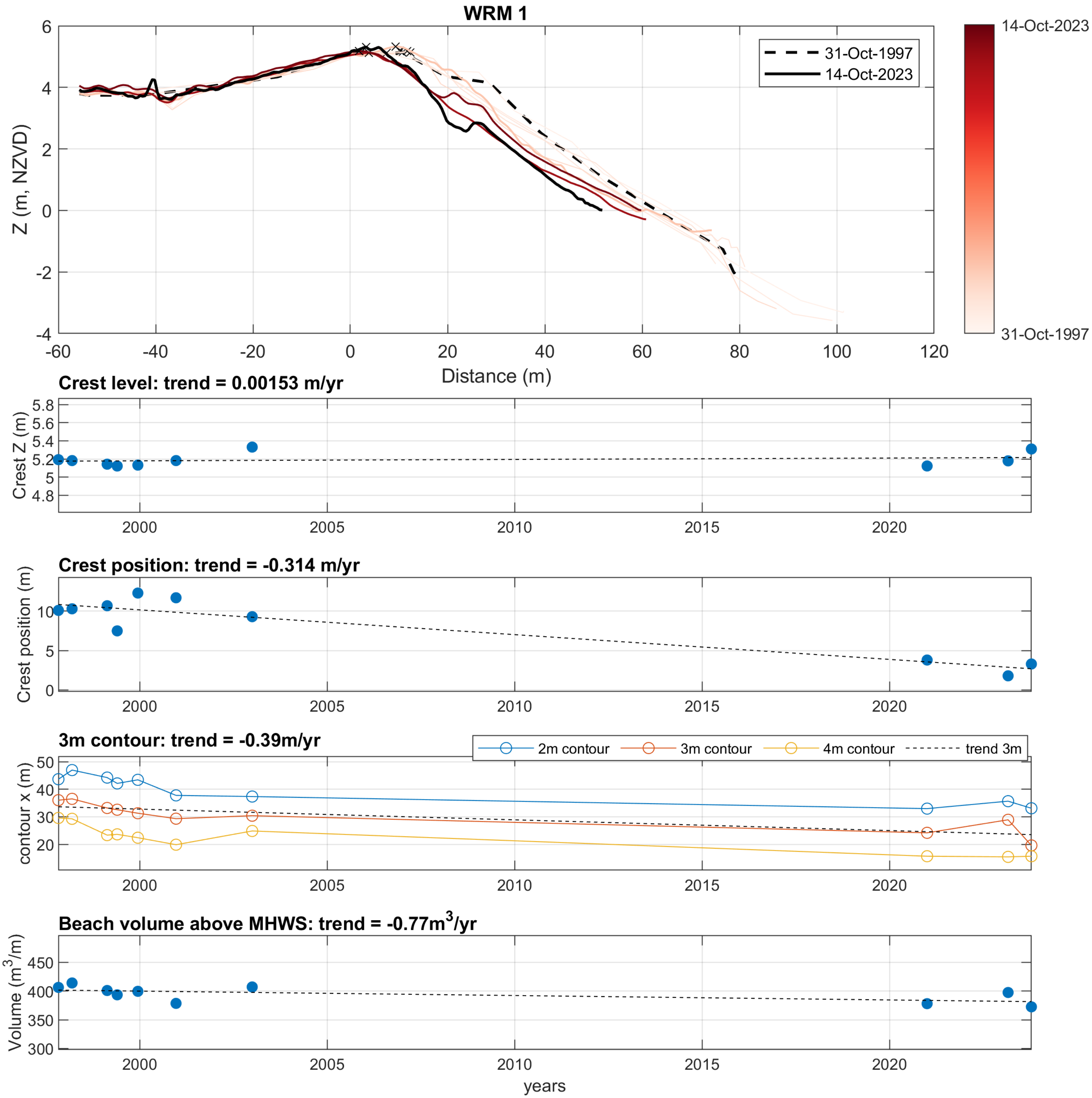
- Figure on the next two page are for the events in November 2023 and May 2024 and show a summary of the cumulative rainfall (measured by HBRC), river level (measured by HBRC), measured sea level (LINZ, Napier), predicted tide level (NIWA, Wairoa), and the wave conditions for the event as modelled by MetOcean Solutions. Wave data legends of h=5, h=10 and h=23 indicates the output point has a depth of 5, 10, and 23 m respectively.


Rain
Cumulative Rainfall (mm)
400
300
200
100
0
Fairview
NgaTuhoe
WairoaRiverAtRailwayBr
Nov 24, 07:00
Nov 24, 13:00
Nov 24, 19:00
Nov 25, 01:00
Nov 25, 07:00
Nov 25, 13:00
Nov 25, 19:00
Nov 26, 01:00
Nov 26, 07:00
Nov 26, 13:00
Nov 26, 19:00
Nov 27, 01:00
Nov 27, 07:00
Nov 27, 13:00
Nov 27, 19:00
Nov 28, 01:00
2023
River level
River level (m, NZVD)
10
8
6
4
2
0
Kopu Rd Av (3.7m)
Rail Bridge
Town Bridge
Tide
Sea level (m, NZVD)
1.5
1
0.5
0
-0.5
-1
NAPT raw
NAPT 30-min Smoothed
Waves
Hs (m)
6
5
4
3
2
1
0
Napier Model (h=5)
Wairoa Model (h=10)
Wairoa Model (h=23)


Rain
Cumulative Rainfall (mm)
Fairview
NgaTuhoe
WairoaRiverAtRailwayBr
0
100
200
300
400
River level
River level (m, NZVD)
Kopu Rd Av (3.7m)
Rail Bridge
Town Bridge
0
2
4
6
8
10
Tide
Sea level (m, NZVD)
NAPT raw
NAPT 30-min Smoothed
-1
-0.5
0
0.5
1
1.5
Waves
Hs (m)
Napier Model (h=5)
Wairoa Model (h=10)
Wairoa Model (h=23)
0
1
2
3
4
5
6
May 21, 07:00
May 21, 13:00
May 21, 19:00
May 22, 01:00
May 22, 07:00
May 22, 13:00
May 22, 19:00
May 23, 01:00
May 23, 07:00
May 23, 13:00
May 23, 19:00
May 24, 01:00
May 24, 07:00
May 24, 13:00
May 24, 19:00
May 25, 01:00
2024

Appendix D Beach profiles


N
WRM1
WRM2
WRM3
WRM4
WRM5
WRM6
WRM7
WRM8
WRM9
WRM10
WRM11
WRM12
WRM13
0.0 km
0.5 km
1.0 km
1.5 km
2.0 km
2.5 km
Unclassified Line Feature



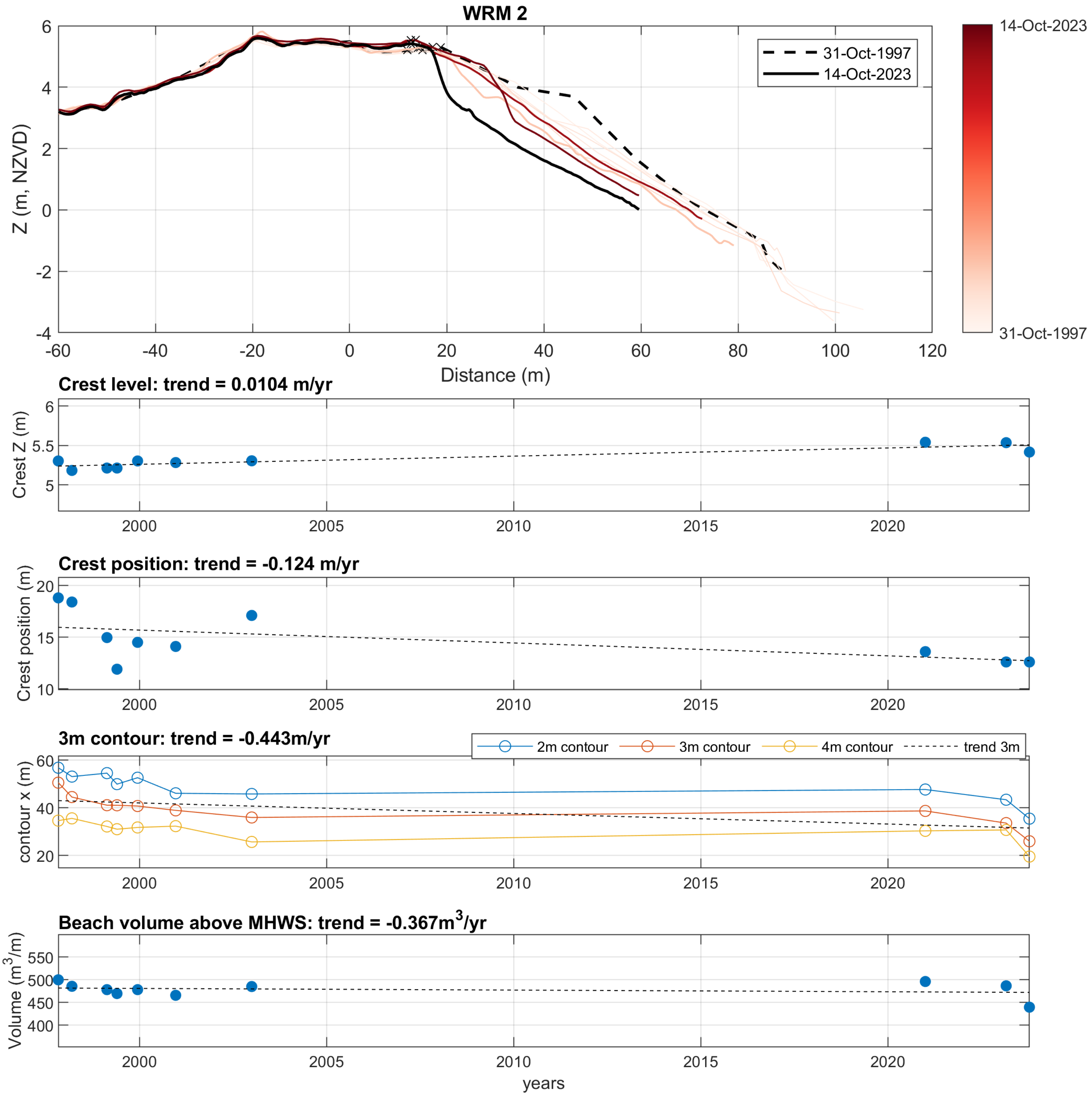
WRM 1

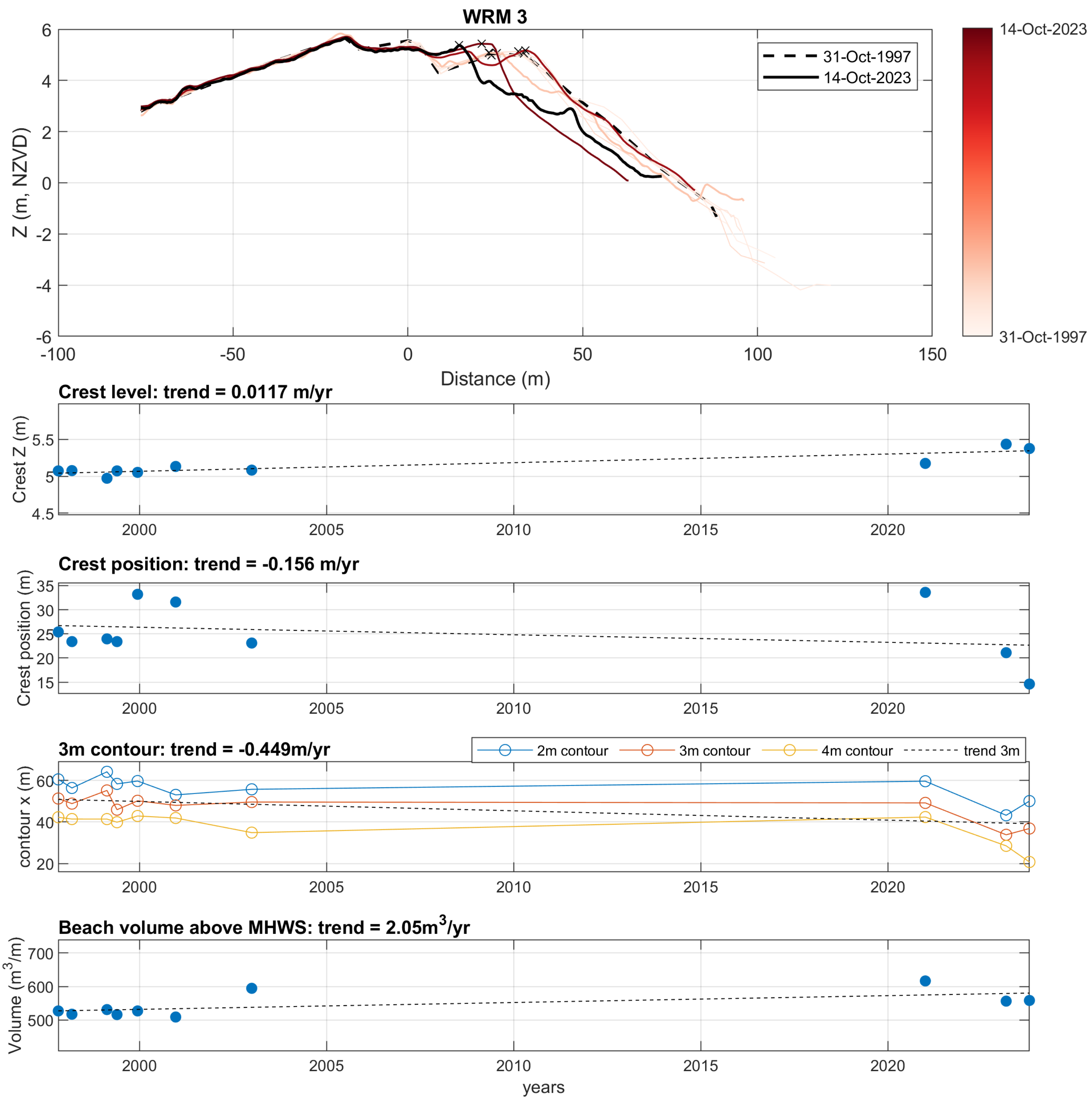
Crest level: trend = 0.00153 m/yr

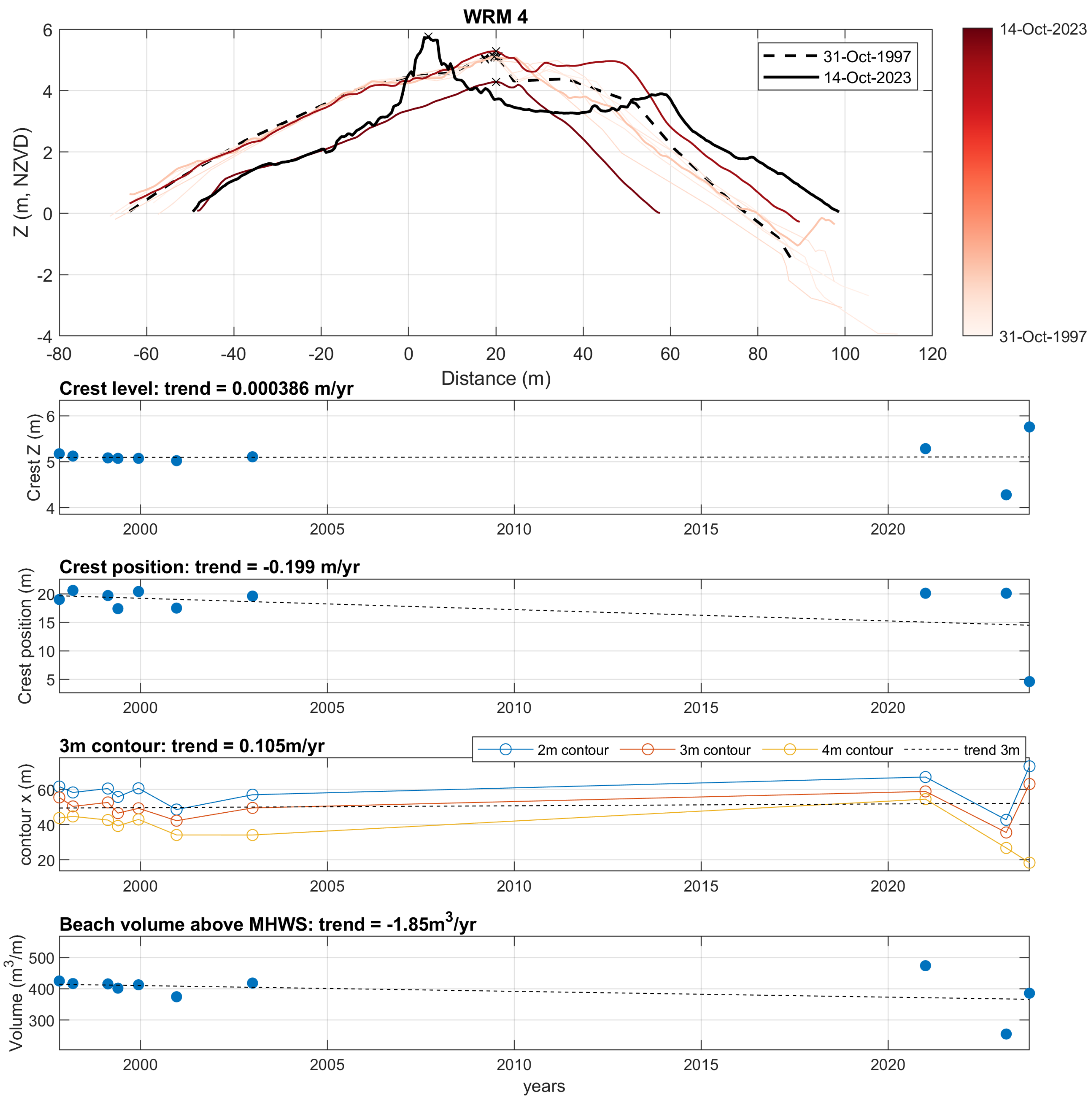
Crest position: trend = -0.314 m/yr

3m contour: trend = -0.39m/yr

Beach volume above MHWS: trend = -0.77m^3/yr


WRM 2
Z (m, NZVD)
6
4
2
0
-2
-4
-60
-40
-20
0
20
40
60
80
100
120
Distance (m)
31-Oct-1997
14-Oct-2023
14-Oct-2023
31-Oct-1997
Crest level: trend = 0.0104 m/yr
Crest Z (m)
6
5.5
5
2000
2005
2010
2015
2020
Crest position: trend = -0.124 m/yr
Crest position (m)
20
15
10
3m contour: trend = -0.443m/yr
2m contour
3m contour
4m contour
trend 3m
contour x (m)
60
40
20
Beach volume above MHWS: trend = -0.367m³/yr
Volume (m³/m)
550
500
450
400
years


WRM 3
Z (m, NZVD)
6
4
2
0
-2
-4
-6
-100
-50
0
50
100
150
Distance (m)
31-Oct-1997
14-Oct-2023
14-Oct-2023
31-Oct-1997
Crest level: trend = 0.0117 m/yr
Crest Z (m)
5.5
5
4.5
2000
2005
2010
2015
2020
Crest position: trend = -0.156 m/yr
Crest position (m)
35
30
25
20
15
2000
2005
2010
2015
2020
3m contour: trend = -0.449m/yr
2m contour
3m contour
4m contour
trend 3m
contour x (m)
60
40
20
2000
2005
2010
2015
2020
Beach volume above MHWS: trend = 2.05m^3/yr
Volume (m^3/m)
700
600
500
2000
2005
2010
2015
2020
years



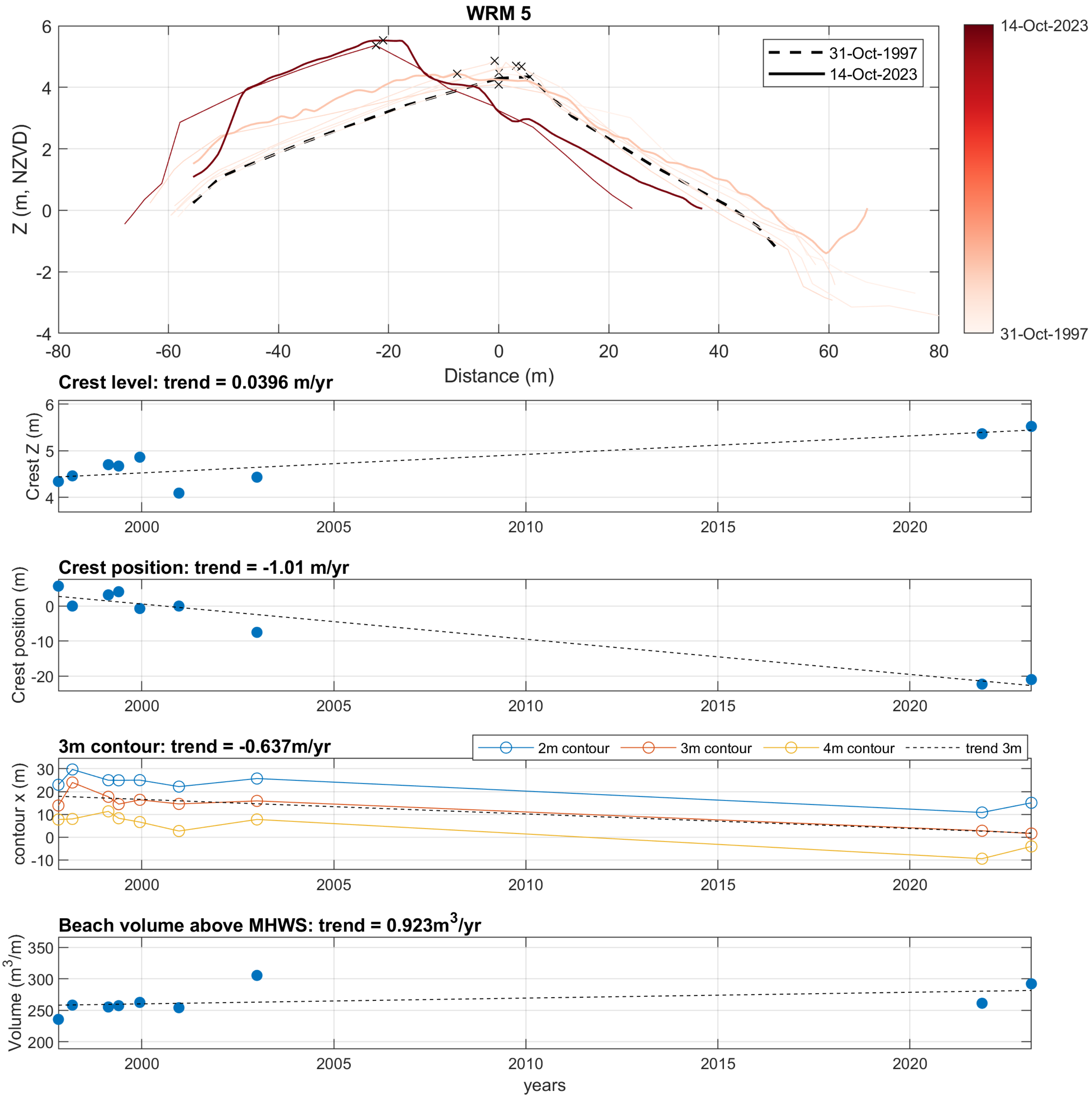
WRM 4

Crest level: trend = 0.000386 m/yr

Crest position: trend = -0.199 m/yr

3m contour: trend = 0.105m/yr

Beach volume above MHWS: trend = $-1.85\text{m}^3/\text{yr}$

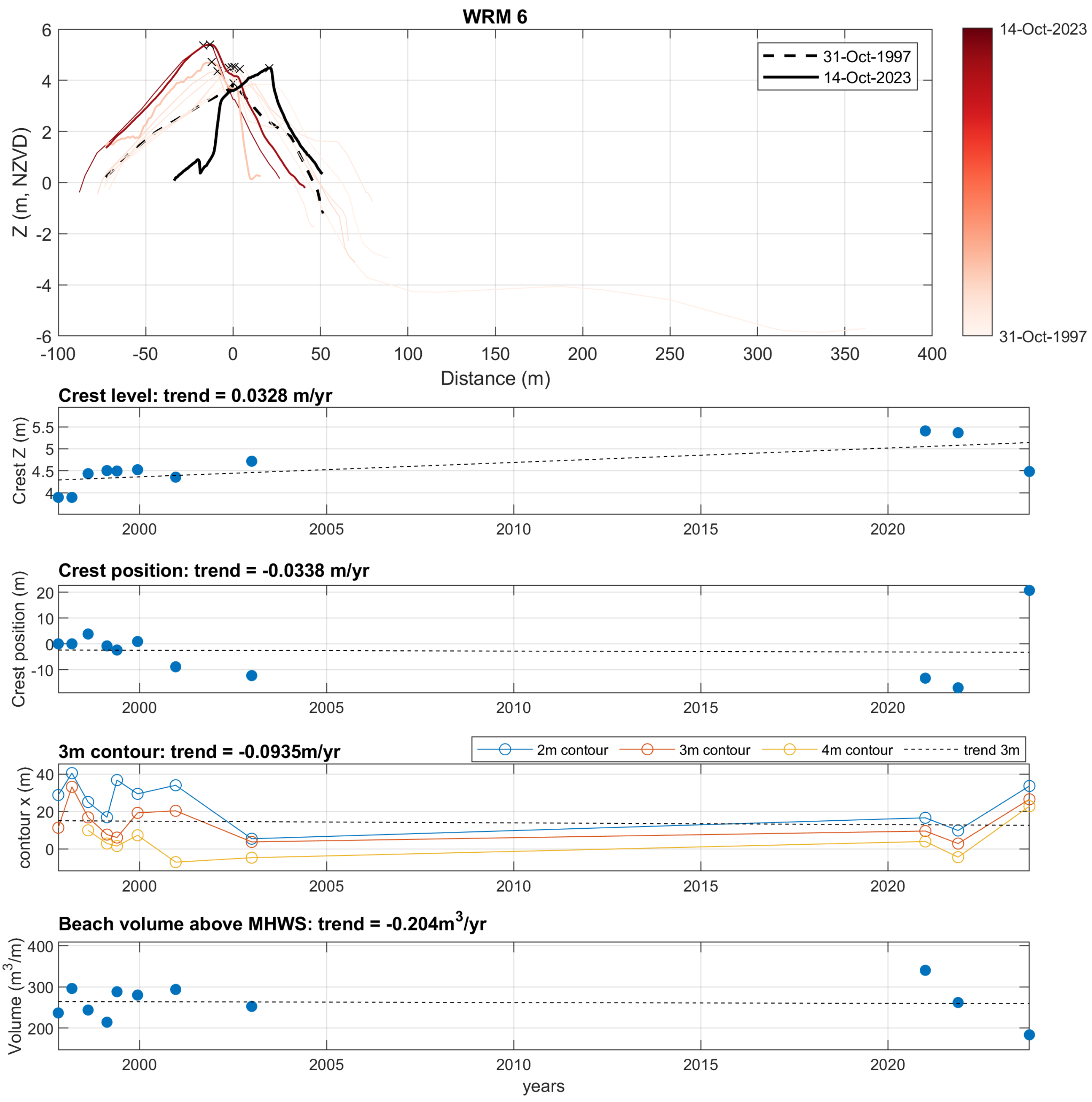

WRM 5

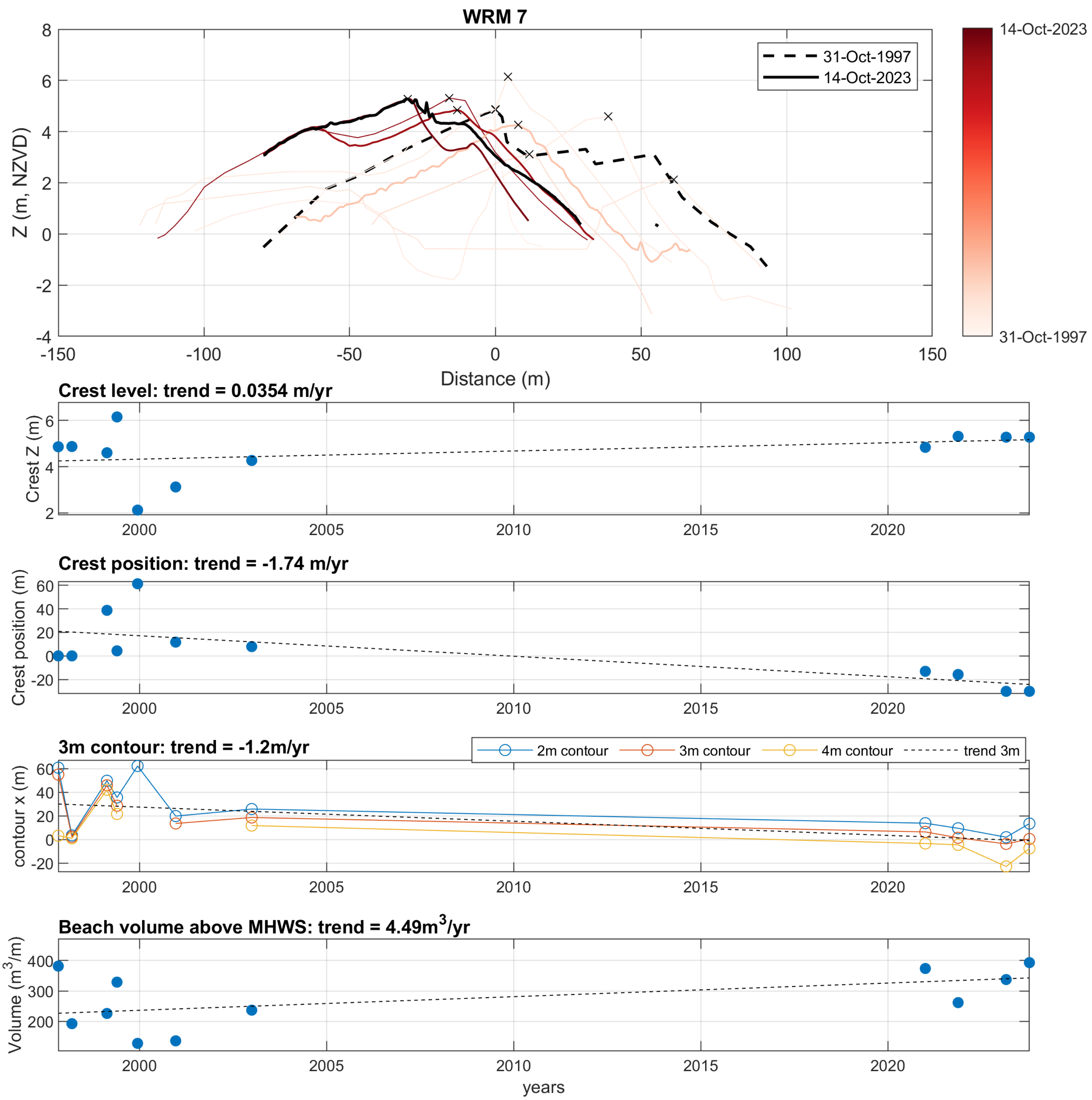
Crest level: trend = 0.0396 m/yr

Crest position: trend = -1.01 m/yr

3m contour: trend = -0.637m/yr

Beach volume above MHWS: trend = 0.923m^3/yr


WRM 6
31-Oct-1997
14-Oct-2023
14-Oct-2023
31-Oct-1997
Z (m, NZVD)
6
4
2
0
-2
-4
-6
-100
-50
0
50
100
150
200
250
300
350
400
Distance (m)
Crest level: trend = 0.0328 m/yr
Crest Z (m)
5.5
5
4.5
4
2000
2005
2010
2015
2020
Crest position: trend = -0.0338 m/yr
Crest position (m)
20
10
0
-10
2000
2005
2010
2015
2020
3m contour: trend = -0.0935m/yr
2m contour
3m contour
4m contour
trend 3m
contour x (m)
40
20
0
2000
2005
2010
2015
2020
Beach volume above MHWS: trend = -0.204m^3/yr
Volume (m^3/m)
400
300
200
2000
2005
2010
2015
2020
years



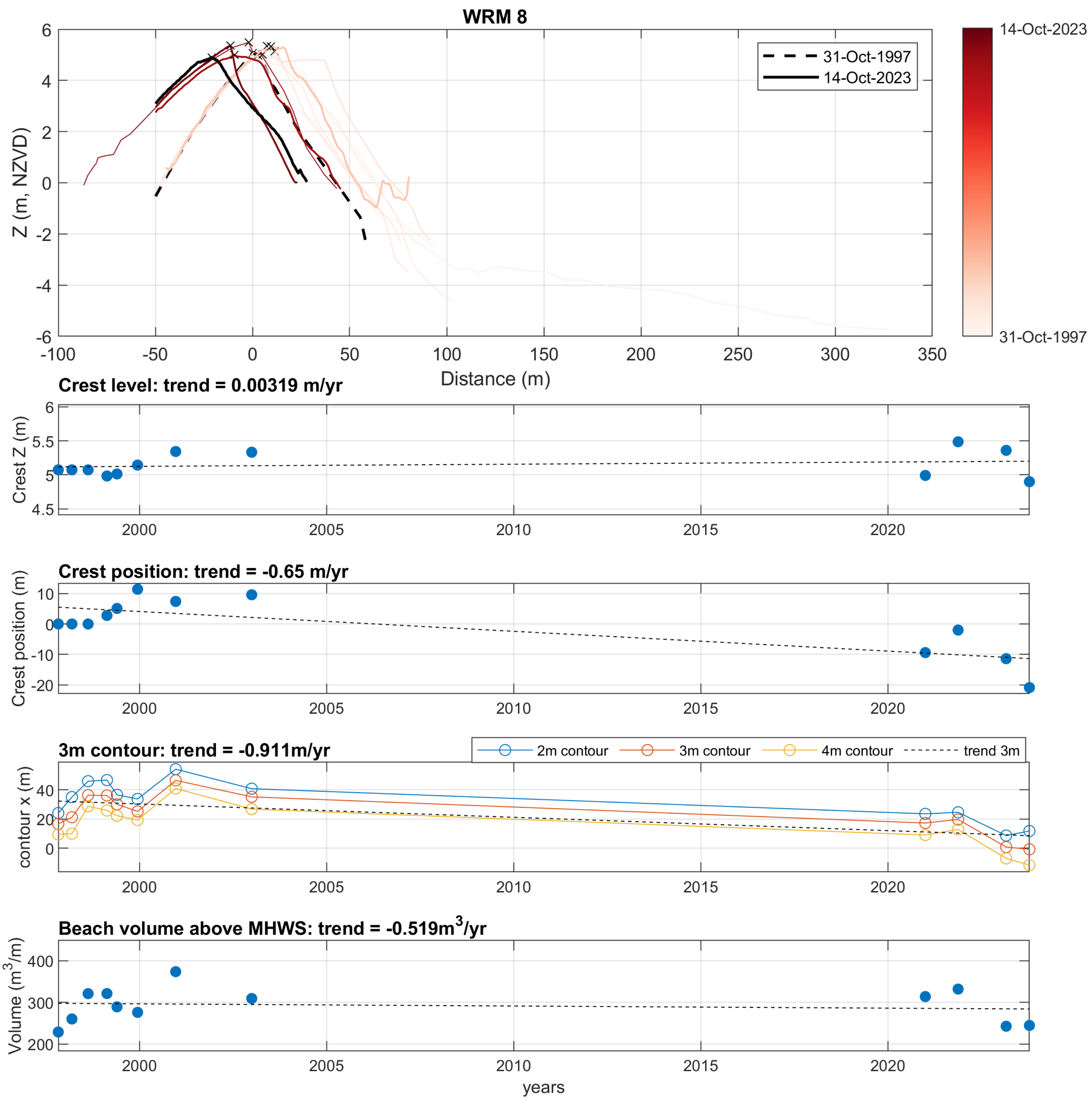
WRM 7

Crest level: trend = 0.0354 m/yr

Crest position: trend = -1.74 m/yr

3m contour: trend = -1.2m/yr

Beach volume above MHWS: trend = 4.49m^3/yr



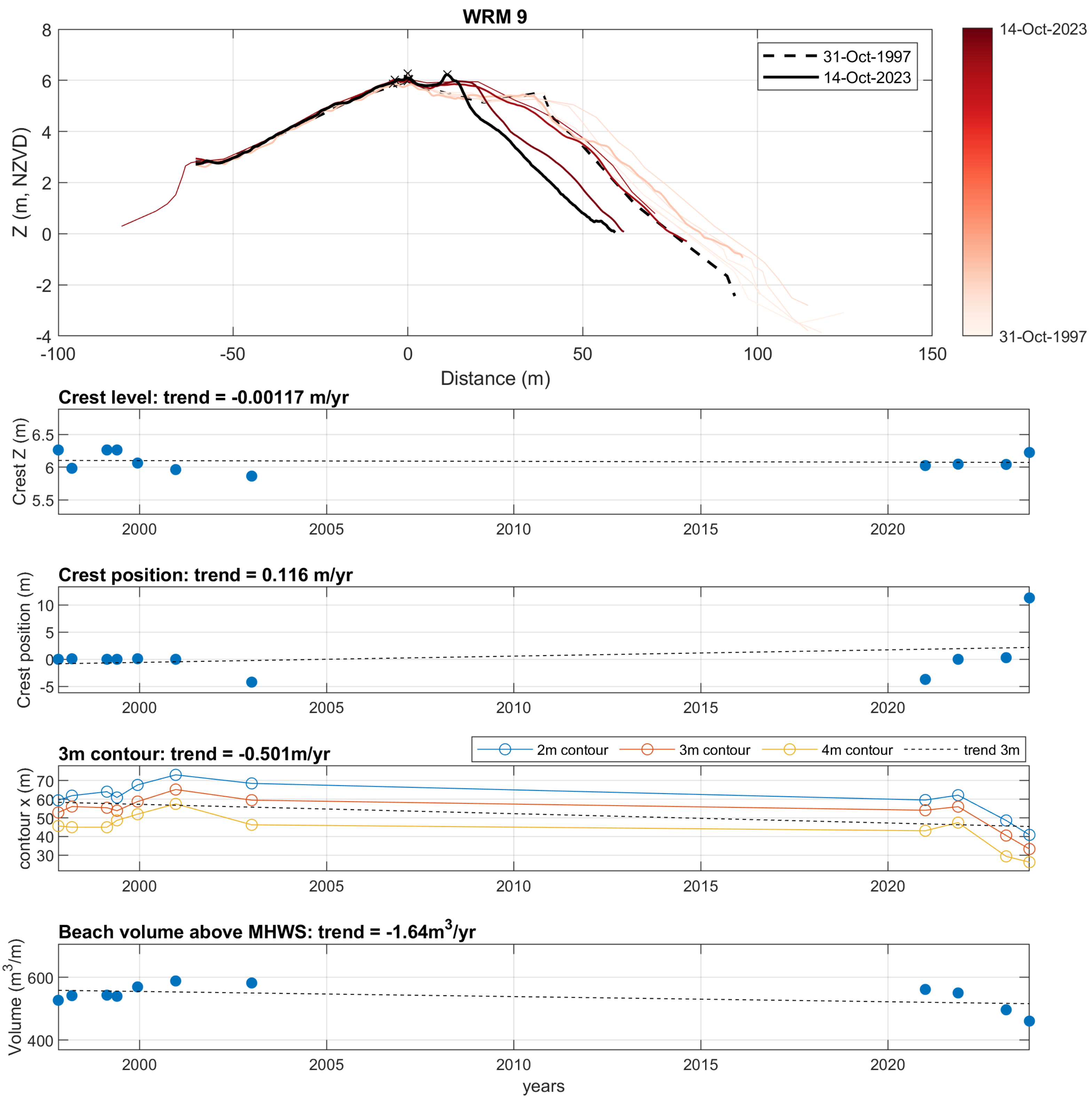
WRM 8

Crest level: trend = 0.00319 m/yr

Crest position: trend = -0.65 m/yr

3m contour: trend = -0.911m/yr

Beach volume above MHWS: trend = -0.519m^3/yr

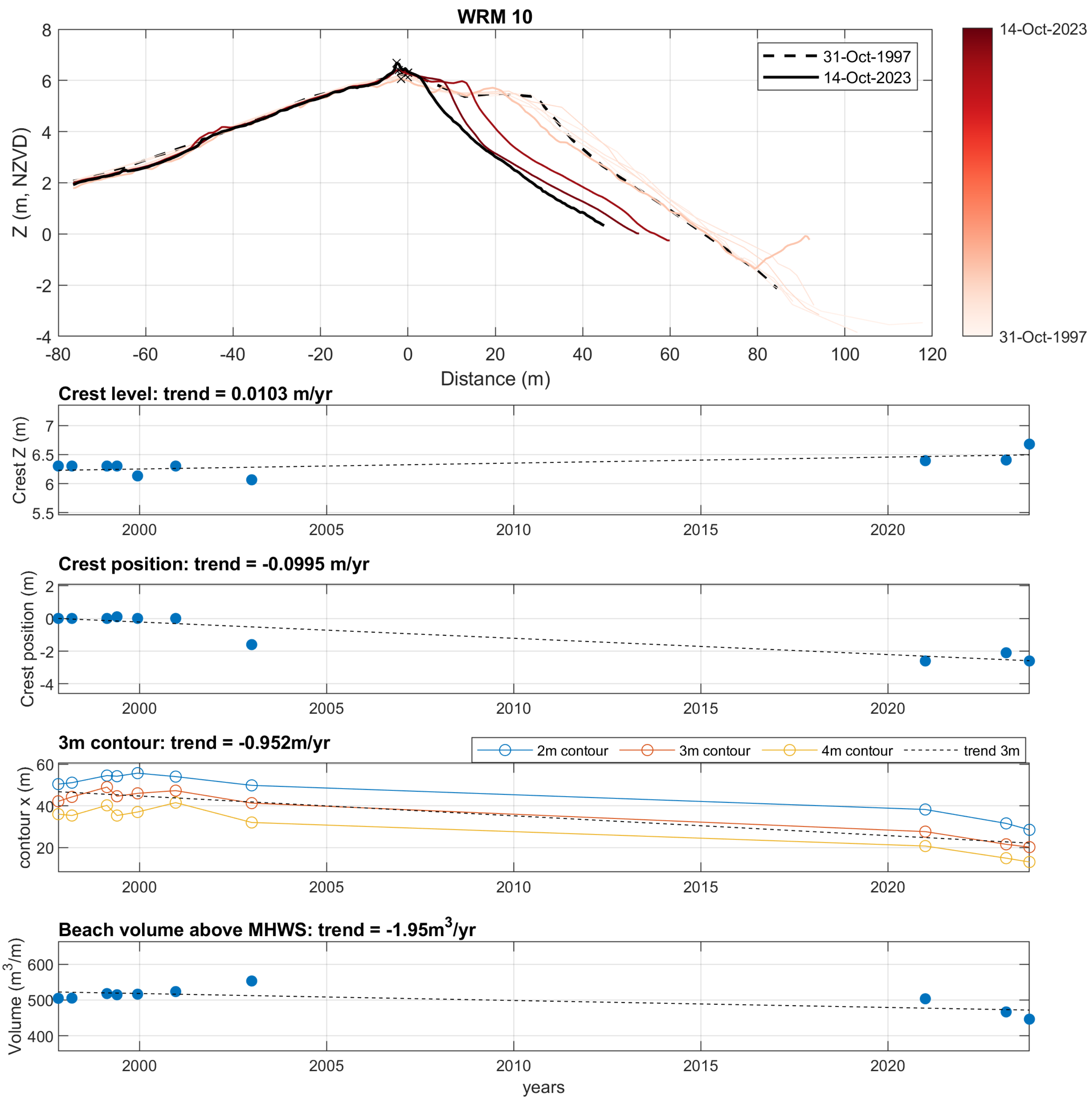

WRM 9

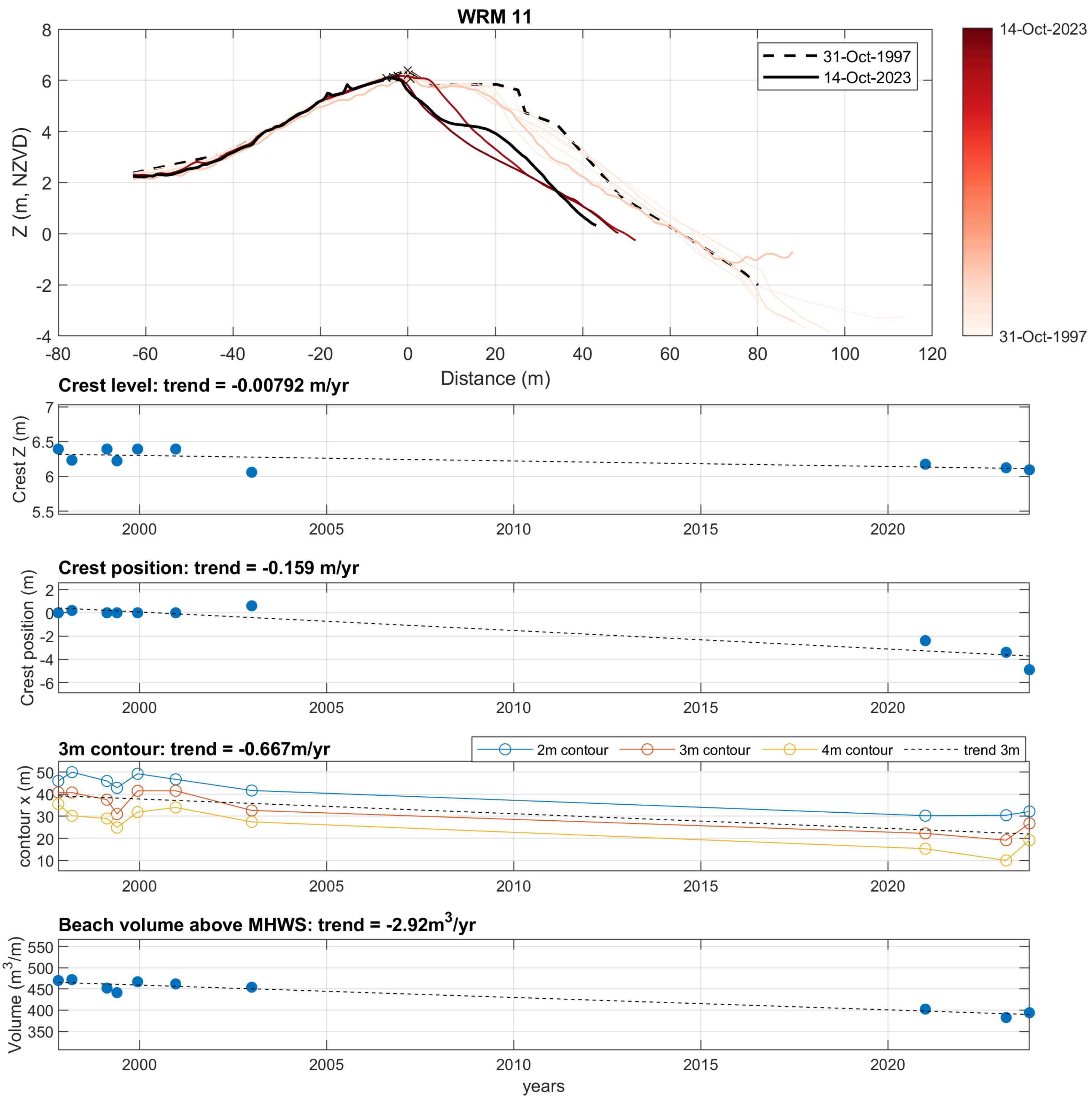
Crest level: trend = -0.00117 m/yr

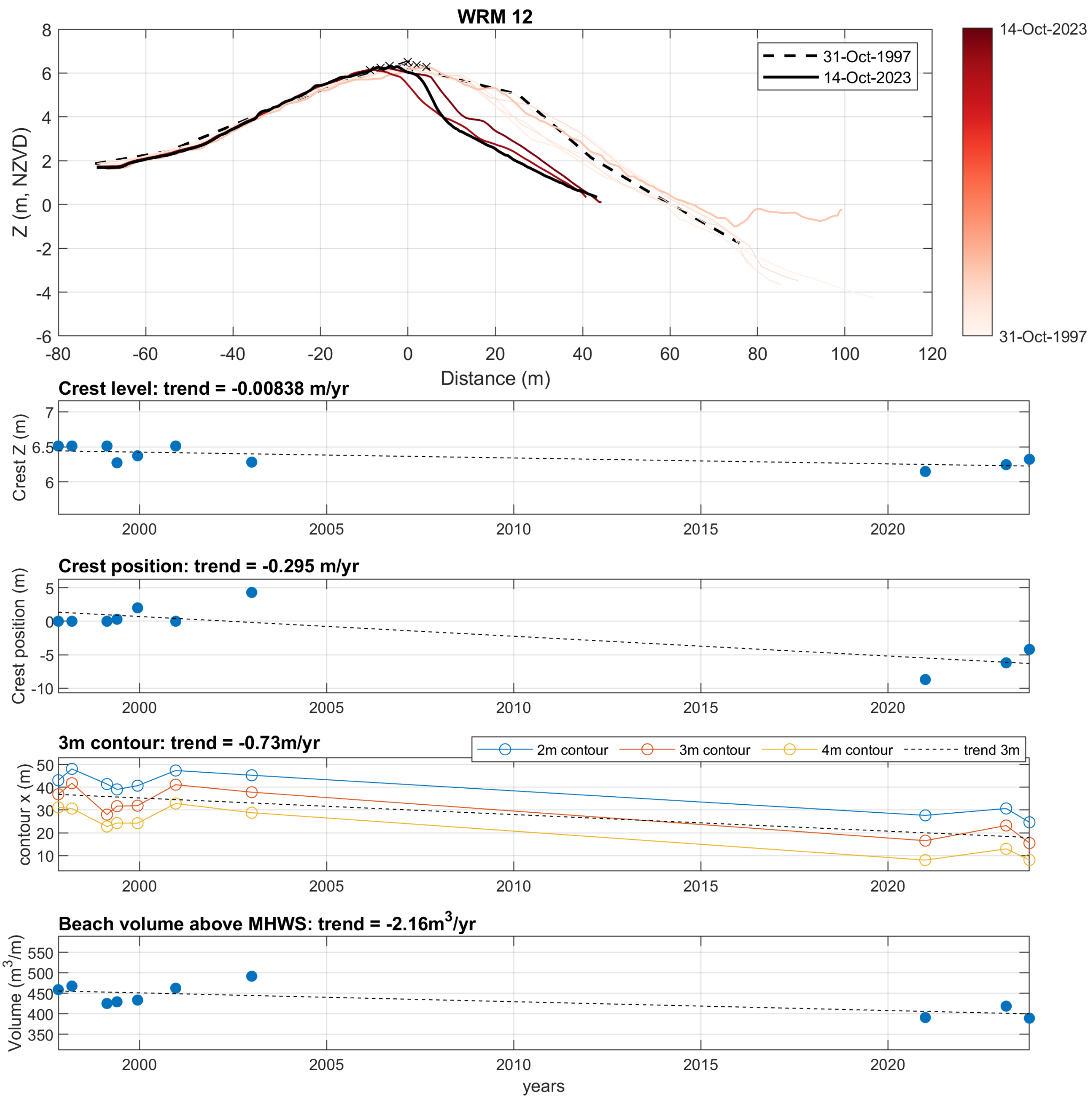
Crest position: trend = 0.116 m/yr

3m contour: trend = -0.501m/yr

Beach volume above MHWS: trend = $-1.64\text{m}^3/\text{yr}$


WRM 10
8
6
4
2
0
-2
-4
Z (m, NZVD)
-80
-60
-40
-20
0
20
40
60
80
100
120
Distance (m)
31-Oct-1997
14-Oct-2023
14-Oct-2023
31-Oct-1997
Crest level: trend = 0.0103 m/yr
Crest Z (m)
7
6.5
6
5.5
2000
2005
2010
2015
2020
Crest position: trend = -0.0995 m/yr
Crest position (m)
2
0
-2
-4
2000
2005
2010
2015
2020
3m contour: trend = -0.952m/yr
2m contour
3m contour
4m contour
trend 3m
contour x (m)
60
40
20
2000
2005
2010
2015
2020
Beach volume above MHWS: trend = -1.95m^3/yr
Volume (m^3/m)
600
500
400
2000
2005
2010
2015
2020
years


WRM 11
31-Oct-1997
14-Oct-2023
Z (m, NZVD)
Distance (m)
8
6
4
2
0
-2
-4
-80
-60
-40
-20
0
20
40
60
80
100
120
14-Oct-2023
31-Oct-1997
Crest level: trend = -0.00792 m/yr
Crest Z (m)
7
6.5
6
5.5
2000
2005
2010
2015
2020
Crest position: trend = -0.159 m/yr
Crest position (m)
2
0
-2
-4
-6
3m contour: trend = -0.667m/yr
2m contour
3m contour
4m contour
trend 3m
contour x (m)
50
40
30
20
10
Beach volume above MHWS: trend = -2.92m³/yr
Volume (m³/m)
550
500
450
400
350
years



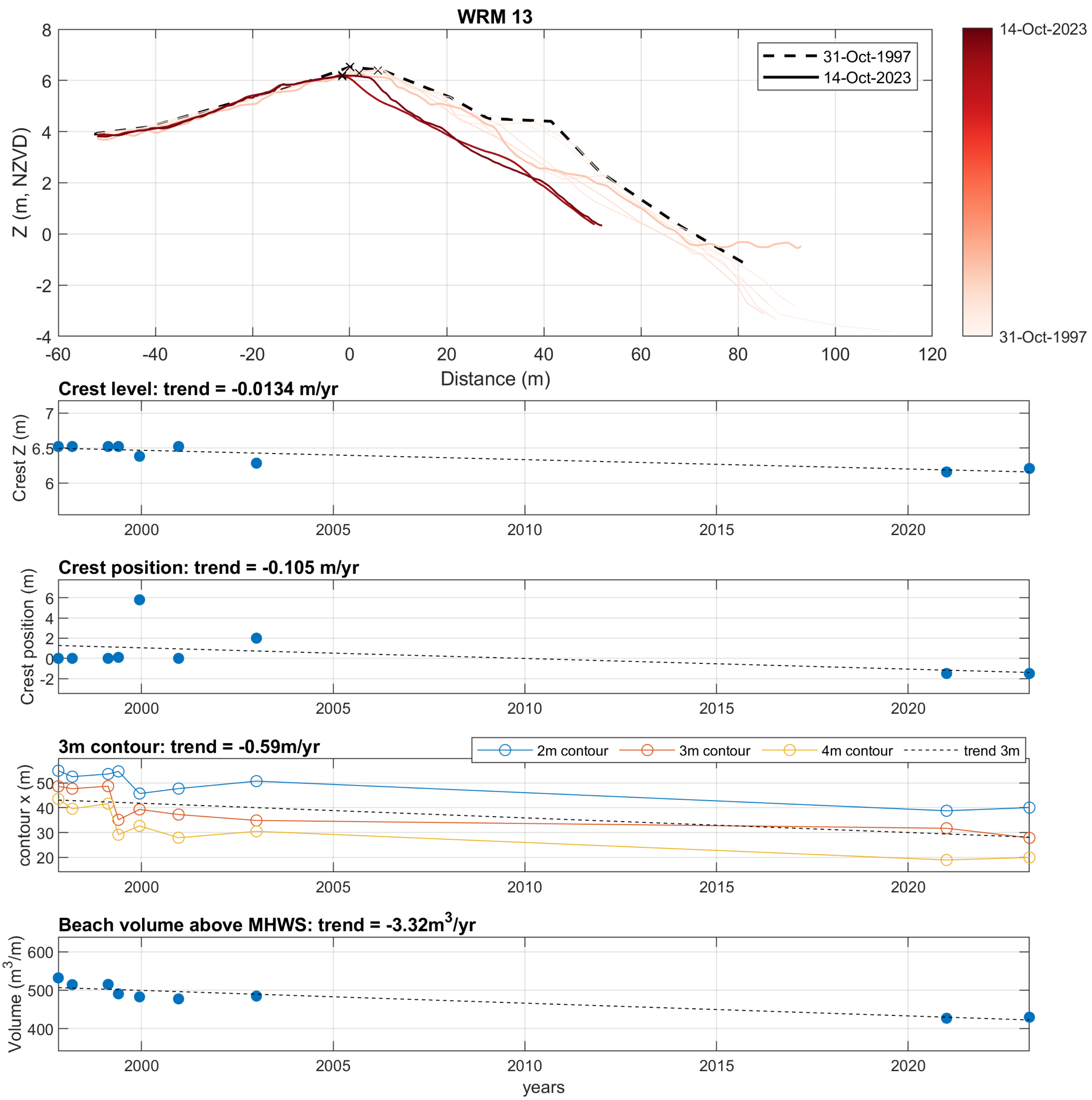
WRM 12

Crest level: trend = -0.00838 m/yr

Crest position: trend = -0.295 m/yr

3m contour: trend = -0.73m/yr

Beach volume above MHWS: trend = -2.16m^3/yr


WRM 13
31-Oct-1997
14-Oct-2023
Z (m, NZVD)
Distance (m)
8
6
4
2
0
-2
-4
-60
-40
-20
0
20
40
60
80
100
120
14-Oct-2023
31-Oct-1997
Crest level: trend = -0.0134 m/yr
Crest Z (m)
7
6.5
6
Crest position: trend = -0.105 m/yr
Crest position (m)
6
4
2
0
-2
3m contour: trend = -0.59m/yr
2m contour
3m contour
4m contour
trend 3m
contour x (m)
50
40
30
20
Beach volume above MHWS: trend = -3.32m^3/yr
Volume (m^3/m)
600
500
400
2000
2005
2010
2015
2020
years

www.tonkintaylor.co.nz