Modelling of the 2 February 1936 storm tide in Wellington Harbour

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Executive Summary

This project builds on a previous project undertaken by NIWA in 2002 for Greater Wellington Regional Council (GWRC) on assessing weather-related hazards and the impacts of climate change. This previous report highlighted the need for some specific components of work to quantify the storm tide hazard for Wellington Harbour (in terms of return period) and to address the lack of information on the hazard around the remainder of the region's coastline.

GWRC contracted NIWA to undertake modelling of the 2 February 1936 storm tide in Wellington Harbour, which anecdotal evidence suggests was the highest storm tide in Wellington Harbour over the last century. If previous estimates this storm tide were accurate, inclusion of this event in extreme-value analyses would make a large difference to calculated extreme value storm tide probabilities within Wellington Harbour. Further investigation was of considerable relevance to coastal hazard planning. Sea levels during the 1936 storm were simulated using a numerical hydrodynamic model using physically realistic forcing by tides, external surge and local winds, to derive a credible storm tide level and its various sea level components. The storm was then re-simulated for the 2090s taking account of potential climate change impacts.

Measured sea level data from 1975–2008 at Queens Wharf were analysed and decomposed into its constituent components of astronomical tide, mean level of the sea and storm surge. In Wellington Harbour the tides are relatively small compared to many areas around New Zealand with high perigean-spring tide heights of 0.83 m relative to Wellington Vertical Datum 1953 (WVD53). This means that storm surges are a relatively important component of storm tide. Examination of all annual maxima sea levels showed that in every case the storm surge was an important contributor to the high sea levels. Extreme-value analysis of measured storm surges at Queens Wharf shows that a storm surge with a 1% Annual Exceedance Probability (AEP), or 1-in-100-year Average Reccurrence Interval (ARI), has a value of about 0.43 m at Queens Wharf.

The numerical re-creation of the 2 February 1936 storm in Wellington Harbour indicates that the storm tide level reached about 1.33 m WVD53 at Queens Wharf, including an astronomical tidal component of 0.89 m WVD53 and a storm-surge component of ~0.43 m. This is larger than any sea level measured at Queens Wharf since 1975, but is in keeping with the extreme value analysis using modern digital sea level records and is much lower than a previous estimate based on anecdotal evidence from the 1936 event. Storm tide levels for a southerly storm like the 1936 event would be around 0.05 m higher at the Petone foreshore than Queens Wharf, due to slightly higher tides and wind setup in the Harbour. The other finding from the numerical modelling study is there is virtually no amplification of storm-surge height within the Harbour relative to the Cook Strait storm-surge height.

The estimated 1.33 m WVD53 1936 storm tide height was based on an assumed storm surge of 0.5 m at the entrance to Wellington Harbour. Any further refinement to this estimate would necessitate the simulation of the 1936 cyclone using New Zealand-scale weather, tide and storm-surge models to isolate the regional storm tide response in greater Cook Strait.

An extreme value analysis was used to calculate the probabilities associated with extreme sea levels, using the measured annual maxima total sea levels. The estimated 1% AEP (or 1-in-100-year ARI) sea level was 1.29 m based on the measured annual maxima since 1975. Inclusion of the 1936 storm into the analysis raised the 1% AEP estimate to 1.32 m, a difference of only 0.03 m. Thus the inclusion of the simulated 1936 storm tide has not made much difference to the extreme value estimates. The extreme value analysis shows that annual exceedance probability of the simulated 1936 storm tide (1.33 m) was 0.6% (170-year ARI). Note: these storm tide levels don't include any wave run-up or wave overtopping.

Simulations with the same model, but for climate-change scenarios, show that a storm event similar in magnitude to the 1936 storm could result in a storm tide height of 1.93 m or 2.22 m WVD53 by the 2090s, assuming sea level rise of 0.5 or 0.8 m respectively. Again these estimates exclude any wave runup and overtopping.

1. Introduction

This project builds on a previous project undertaken by NIWA in 2002 for Greater Wellington Regional Council (GWRC) on assessing weather-related hazards and the impacts of climate change in the Wellington Region (Tait et al. 2002). This previous report highlighted the need for further work to quantify the storm tide hazard for Wellington Harbour (in terms of return period) and to address the lack of information on the hazard around the remainder of the region's coastline, including Porirua Harbour. Further work was undertaken by NIWA in 2005 for Wellington City Council (Gorman et al. 2005) on quantifying the joint-probability of wave height and water levels within Wellington Harbour, including the effect of climate change. This provided guidance for engineering design or maintenance of coastal margin infrastructure where extreme water levels and waves are a consideration.

Historic events such as the February 1936 Great Cyclone have previously caused coastal flooding in Lambton Quay and at other locations in the Wellington region. For example Castlepoint (see Tait et al. 2002 for more details). In the future, climate-change will also increase the risk of storm tide inundation through sea-level rise and potentially through increased intensity of storms (higher wind speeds and lower central storm pressures). If previous estimates of a very large storm tide of ~1.7 m WVD53 for the 1936 storm were accurate (Tait et al. 2002), then inclusion of this event in extreme-value analyses would make a substantial difference to calculated extreme storm tide probabilities in Wellington Harbour. Hence further investigation is of considerable relevance to coastal hazards and planning.

After preliminary discussions with the Hazard Analyst at GWRC (Iain Dawe), NIWA proposed a two-stage approach to addressing gaps in the information and regional understanding of storm tide hazards based on robust analysis of return periods and potential inundation zones for the present climate and projected climate change.

The two proposed stages were:

- **Phase I—Wellington Harbour**: perform modelling of anecdotally the highest historic storm tide event on 2 February 1936 (Brenstrum 2000) to determine the magnitude of the contributing factors e.g., tide, storm surge, local wind set-up. Repeat this storm for 2090s, accounting for climate-change. Re-evaluate the current return-period analysis of storm tide levels in the Harbour by including the results from the modelling for a present-day climate and two climate-change projections.

- **Phase II—Wellington region**: perform storm tide modelling of the entire coastline of the Wellington region (west, south and east coasts), including Porirua and Wellington Harbours for a number of historic storms. This will provide the spatial variability of projected climate-change effects of storm tide levels around the coast, and by also including wave set-up and run-up modelling, can be used to produce coastal storm inundation zones.

GWRC contracted NIWA to undertake the Phase 1 component to model the 2 February 1936 storm tide in Wellington Harbour. Modelling of this storm tide event was performed to determine the magnitude of the contributing astronomical tide plus storm surge (storm tide) and then re-evaluated the current return period analysis of storm tide levels in the Harbour. This storm was then re-simulated in a 2090s climate-change context.

2. The 2 February 1936 storm

The "Cyclone of 1936", as it is known, occurred on 2nd February 1936, generated by a deep depression reaching 970 hPa that passed over the North Island (Brenstrum 2000). The storm generated strong easterly and south-easterly winds that slammed into the Wairarapa and South Wellington coasts respectively, with similar strength to those experienced during the later *Wahine* storm in 1968. Large tides coincided with the storm. Hindcast tide prediction for Queens Wharf show that high tides of 0.86 m and 0.75 m WVD53 occurred at 00:15 and 12:30 respectively on 2 February 1936, both being higher than mean-high-water-springs Scientific[1], and the earlier tide being in the top 6 percent experienced (Figure 1). It is the combined effect of the high tides and storm surge, the "storm tide", that is the focus of the numerical modelling component of the study.

For storm surge an approximate rule of thumb is that inverted barometer (air pressure effect) contributes half the set-up in ocean storm surge (above the predicted tide level), while the other half comes from wind set-up and other coastal-trapped-waves that propagate out from the storm centre (Bell et al. 2000). This rule is only approximate, as the two contributory processes can vary considerably.

Meteorological conditions associated with the 2 February 1936 cyclone are summarised by Barnett (1938). The 9 a.m. daily weather synopsis charts from 28 January to 3 February 1936 (e.g., Figure 2) indicate that the cyclone moved rapidly across New Zealand on 2 February 1936. The lowest pressure reliably recorded was 974 hPa in Auckland, but it is estimated that the pressure at the cyclone centre while crossing New Zealand was about 970 hPa. Wellington experienced a southerly gale throughout Sunday 2 February 1936, and a maximum gust of 126 km/hr was recorded. The 9 a.m. synopsis suggests that the wind at Wellington blew from SSE at Force 8 on the Beaufort scale, equivalent to a 10-minute mean speed of 19 m s^{-1}.

[1] There are several ways to calculate mean high water springs (MHWS). The Scientific definition is the sum of the M2 + S2 tidal harmonic constituents = 0.71 m WVD53, a pragmatical approach is the level exceeded by 12% of all tides = 0.79 m WVD53, while LINZ defines it as the average of the levels of each pair of successive high waters, and of each pair of successive low waters, during that period of about 24 hours in each semi-lunation (approximately every 14 days), when the range of the tide is greatest (Spring Range).

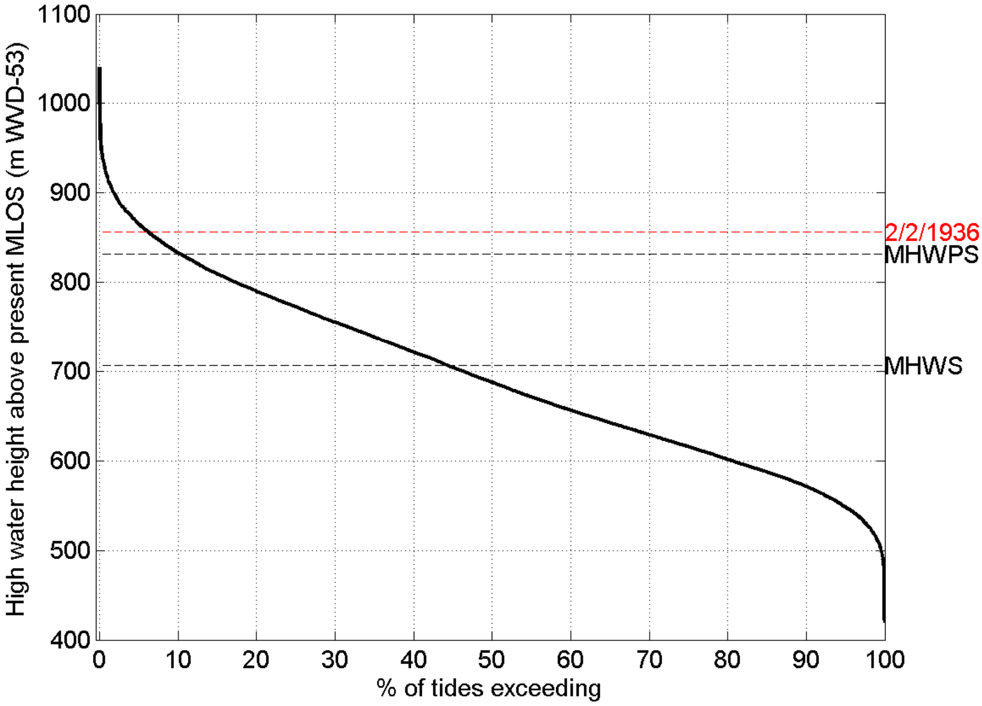

Figure 1: High tide exceedance curve based on the tidal component of the Wellington sea level record (see Figure 6). Also shown are MHWS = Mean high water springs Scientific (when $M_2 + S_2$ combine over a fortnight) and MHWPS = mean high water perigean springs (when $M_2 + S_2 + N_2$ combine over 6–7 months) levels, along with the back-predicted high tide level at 00:15 on 2 Feb 1936. MLOS = mean level of the sea.

Tait et al. (2002) calculated an inverted barometer sea level rise of 0.45 m based on the 970 hPa pressure estimate from Barnett (1938), and doubled that using the aforementioned rule of thumb to estimate a storm surge of 0.9 m. This, combined with high tide peaks of 0.86 and 0.75 m above WVD53 gave an estimated storm tide height of 1.7 m above WVD53. As is shown later in this report (Table 1), this is much larger than modern measured storm tide maxima.

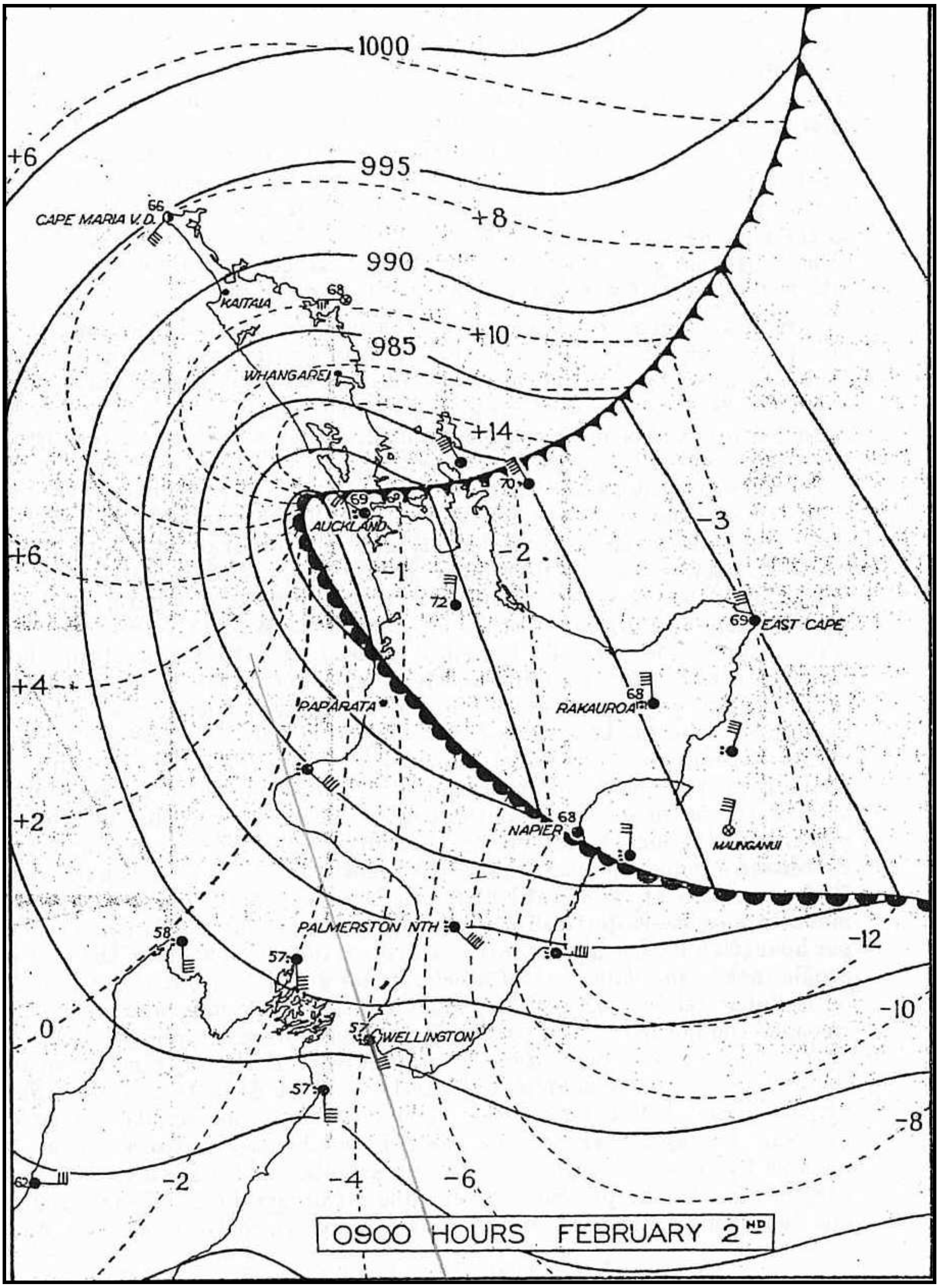

Figure 2: Weather chart illustrating pressure system and wind vectors during the 2nd February 1936 storm, reproduced from Barnett (1938).

3. Sea level

3.1 Introduction

There are a number of meteorological and astronomical phenomena involved in the development of an extreme sea level event. These processes can combine in a number of ways to create inundation of low-lying coastal margins. The processes involved are:

- Mean level of the sea (MLOS)
- Astronomical tides
- Wind set-up
- Inverse-barometer (IB) effect
- Wave set-up
- Wave run-up

Storm surge = wind set-up + IB

The mean level of the sea describes the variation of the non-tidal sea level on longer time scales ranging from a monthly basis to decades due to such things as sea temperature and variability in El Niño Southern Oscillation (ENSO) and Interdecadal Pacific Oscillation (IPO) patterns. In this report, all analyses and sea level heights are relative to present-day (2008) MLOS.

The astronomical tides are caused by the gravitational attraction of solar bodies, primarily the sun and the Earth's moon. In New Zealand the astronomical tides have by far the largest influence on sea level, followed by storm surge, which is caused by a combination of wind set-up and the inverse barometer effect.

Wind set-up describes the "piling up" of water against the coast by an onshore (or alongshore if the coast is to the left of the wind) prevailing wind. The effect of wind stress on the sea surface increases inversely with depth and therefore is most important in shallow water (Pugh, 2004). The inverse-barometer effect describes the change in sea-surface elevation as a response to changes in atmospheric pressure: more specifically sea level temporarily rises in a response to decreasing atmospheric pressure and decreases as atmospheric pressures increase. The combined effect of wind set-up and inverse barometer produce "storm surge" events. Storm surges generally only have consequential effects when they coincide with high tides.

In the open oceans, there is a direct isostatic[2] relationship between sea level and barometric pressure, known as the inverted barometer (IB) response: 1 hPa decrease in pressure results in a 10 mm increase in sea level (and vice versa). However, isostatic conditions rarely apply (particularly around islands such as New Zealand) and the relative importance of the IB-induced pressure wave interactions with the coastal landmass determines how applicable the IB response is. An analysis of tide gauge records at 15 locations around New Zealand showed that Wellington had a relatively strong IB response, explaining 69% of sea level change associated with weather systems (Goring 1995). This shows that on average, up to 30% of sea level variation in Wellington Harbour is explained by non-IB effects, such as wind setup for example. The barometric factor at Wellington was 0.97 (Goring 1995), which means that the average IB response is 0.97 of the isostatic response, i.e., 1 hPa decrease in pressure results in a 9.7 mm increase in sea level (and vice versa). Thus an air pressure of 975 hPa would be expected result in a 0.37[3] m storm-surge height relative to the average air pressure of 1013 hPa. Thus, based on the analysis of Goring (1995), we might expect up to 0.11 m of non-IB related storm surge, caused by such things as wind setup, leading to a total storm surge of about 0.48 m. This is considerably lower than the potential storm surge of 0.9 m postulated by Tait et al. (2002). Later in the report we have shown results of simulated surge values of 0.5 m and 0.6 m in the hydrodynamic model, and undertaken sensitivity analyses by using surge values of 0.5, 0.6, 0.7 and 0.8 m in the extreme-value analyses.

Waves also raise the effective sea level at the coastline by two mechanisms. Wave set-up is the increase in mean sea level through the transfer of excess momentum from organised wave motion in the surf zone (Longuet-Higgins and Stewart 1962). Set-up due to waves is the result of a constant raised elevation of sea level when breaking waves are present. Wave run-up is the maximum vertical extent of wave "up-rush" on a beach or structure above the still water level, and thus constitutes only a short-term fluctuation in water level relative to set-up and storm surge time scales (Komar 1998).

In this report we do not consider the effects of waves, which are localised within the surfzone or adjacent to seawalls at the shoreline. We focus on the "storm tide" that results from a combination of MLOS, tide and storm surge, and which can be resolved

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[2] An isostatic sea level response to changing atmospheric pressure occurs when an atmospheric pressure change results in an exactly equal pressure adjustment in the water column, thus 1 hPa change in pressure results in a 10 mm inverse response in sea level.
[3] IB response = (1013-975 hPa) $\times$ 10 mm $\times$ 9.7 = 369 mm.

from the sea-level record at Queens Wharf, or re-created for the 1936 storm using a numerical model.

3.2 Sea-level data

Sea-level data from Wellington Harbour were obtained from Greater Wellington Regional Council (GWRC) and from Land Information New Zealand (LINZ). The GWRC data was sourced from three sea level gauges: Somes Island, Waterloo Wharf, and Queens Wharf (Table 1, Figure 3). The extreme value analyses presented here have been based on data from the wharves, since these provide the most consistent dataset spanning the longest time period. The Somes Island record was not employed as the storm surge characteristics are different due to its location in the centre of the Harbour. The raw Somes Island, Waterloo Wharf and Queen's Wharf datasets all have offsets in their gauge zeros, and the Waterloo Wharf record has a negative sea level trend that is inconsistent with the other datasets.

Following an analysis of the datasets it became apparent that the LINZ data is a compilation of three gauge records, 1970–1984, 1984–1990 and 1990–1999. The data from 1991 onward in the LINZ record is consistent with the raw Queens Wharf data supplied by GWRC. The LINZ data from 1984–1990 is consistent with the Waterloo Wharf data where it overlaps, but the data seamlessly matches the 1991-onward block with no bias, and without the negative trend seen in the raw Waterloo data. It is apparent that the three blocks that make up the LINZ data have been corrected to a consistent datum. For this study, we adopted the LINZ data from 1970–1994 and joined it to the modern Queens Wharf record. The datum of the LINZ data was adjusted to match the datum of the modern Queens Wharf record.

Table 1: Sea-level datasets used in this study.

Dataset	Start	Finish
Somes Island (LINZ)	28-Jan-1969 14:30:00	22-May-1996 12:30:00
LINZ	01-Jan-1975 00:00:00	31-Dec-1999 23:00:00
Waterloo Wharf (GWRC)	13-Aug-1990 16:00:00	31-Aug-1994 11:10:00
Queens Wharf (LINZ, GWRC)	31-Aug-1994 13:55:00	01-Nov-2008 10:00:00

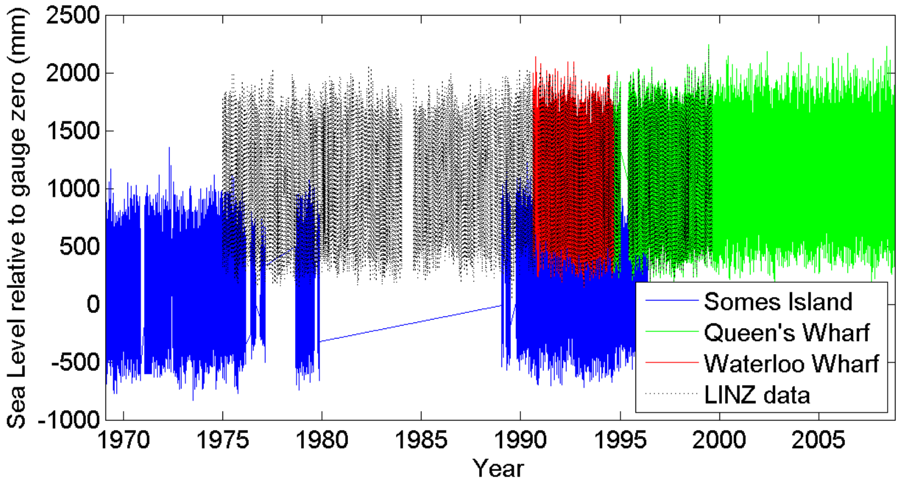

Figure 3: Raw sea-level data used in this study.

The datum of the combined sea level record was converted from Queen's Wharf tide gauge zero to Wellington Vertical Datum 1953 (WVD53) using the survey information provided by Beavan (2001). Chart Datum is 3.002 m below B.M. K80/1, a stainless steel pin set in concrete under iron cover, in Featherston Street at the intersection with Lambton Quay (Figure 4). A detailed assessment of the stability of the Queens Wharf tide gauge was carried out by Beavan (2001). This showed some slight subsidence of around 0.2 mm/yr of the gauge site, which has been corrected for in the analysis and plotting of data in this report.

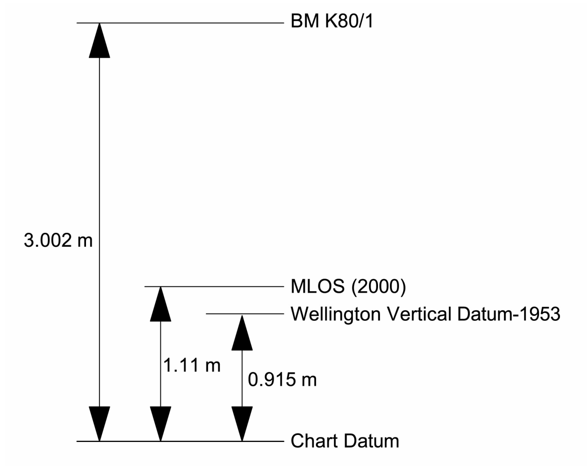

Figure 4: Relationship between datum levels at the Queens Wharf site. MLOS (2000) is the mean level of the sea reported by LINZ in 2000. Another longer-period estimate of MLOS by LINZ is 1.08 m averaged over the 18-year period 1989-2007.[4]

[4] http://www.linz.govt.nz/hydro/tidal-info/tide-tables/tidal-levels/index.aspx

The sea-level record is plotted relative to WVD53 in Figure 5. Tidal harmonic analysis was undertaken on an annual basis following (Pawlowicz et al. 2002). The predicted water-level variation due to tides was then subtracted from the total sea levels to give the residual non-tidal component of water-level variation. Wavelet filters were then used to calculate the mean level of the sea (MLOS = the component of sea level variation with a period of greater then 1-month), and the storm surge (SS = the component of sea level variation having energy in the 1–16 day band). The tidal, MLOS and SS components of sea level are plotted in Figure 6. MLOS for the year 2000 was calculated as being 1.10 m above WVD53, which is consistent with the longer 18-year average of 1.08 m given on the LINZ website[5]. The sea levels show a linear rise of 1.5 mm per year over the 33.8-years of record. Note: the long-term rise in relative sea level at Wellington is at a rate of 1.78 ±0.21 mm/yr from 1891 up to 2001 (Hannah, 2004).

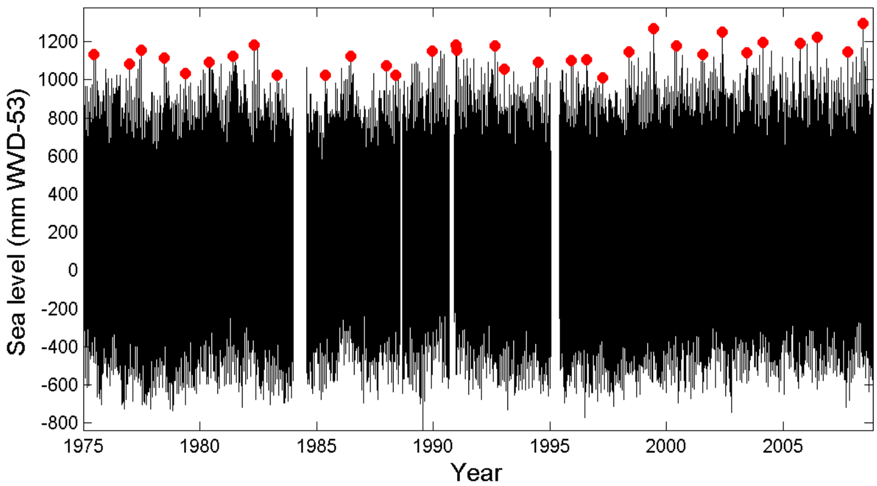

Figure 5: Wellington sea level measured at Port of Wellington, relative to WVD53. The Annual Maxima (largest sea levels for each calendar year) are marked by the red dots.

[5] http://www.linz.govt.nz/hydro/tidal-info/tide-tables/tidal-levels/index.aspx

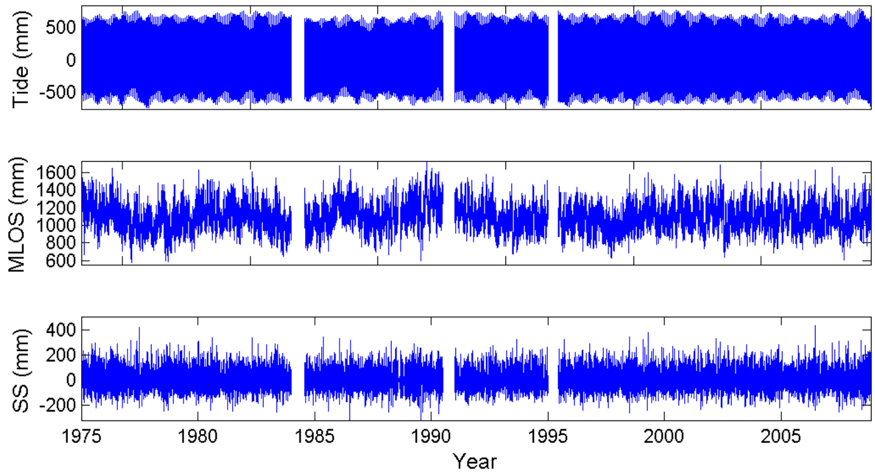

Figure 6: Components of the Wellington sea level record (mm relative to WVD53). MLOS = Mean level of the sea, SS = storm surge.

In Wellington Harbour the tides are relatively small compared to many areas around New Zealand. This means that the storm surges are a relatively important component of the storm tide. This is illustrated in Figure 7 for the 1975 annual maximum. Examination of all 33 annual maxima sea levels showed that in every case the occurrence of a significant storm surge was an important contributor (e.g., Table 1).

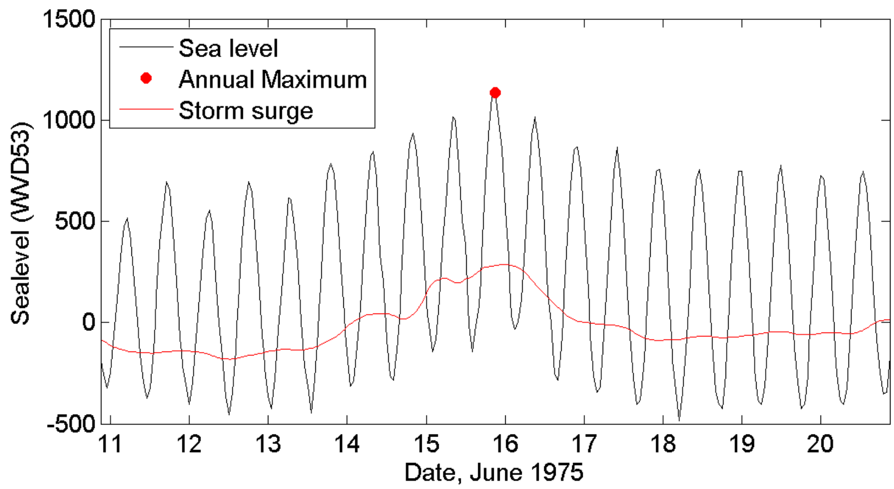

Figure 7: Measured sea level, with the 1975 annual maximum sea level marked, and filtered storm surge component of sea level (that starts with set-down due to a high-pressure system and culminates in a storm-surge set-up of ~0.3 m on the 15 June for this particular event).

Table 1: Annual maxima storm tide levels and storm surge height (both m) from the Queens Wharf record (Figure 5). Storm tide levels are relative to Wellington Vertical Datum 1953 whereas storm surge is a relative height for that component.

Year	Storm tide	Storm surge	Year	Storm tide	Storm surge	Year	Storm tide	Storm surge
1975	1.14	0.30	1987	1.07	0.23	1998	1.15	0.34
1976	1.09	0.29	1988	1.02	0.31	1999	1.27	0.38
1977	1.16	0.42	1989	1.15	0.29	2000	1.18	0.27
1978	1.12	0.30	1990	1.18	0.23	2001	1.13	0.27
1979	1.03	0.28	1991	1.16	0.26	2002	1.25	0.33
1980	1.09	0.34	1992	1.18	0.28	2003	1.14	0.28
1981	1.12	0.22	1993	1.06	0.32	2004	1.20	0.28
1982	1.18	0.34	1994	1.09	0.26	2005	1.19	0.28
1983	1.02	0.29	1995	1.10	0.32	2006	1.23	0.43
1985	1.02	0.35	1996	1.11	0.29	2007	1.15	0.31
1986	1.12	0.33	1997	1.01	0.26	2008	1.30	0.32

4. Numerical modelling of the 2 February 1936 storm

4.1 The model

The DHI MIKE 21 numerical model is a finite difference two-dimensional model that numerically solves solutions for the Navier-Stokes equations for momentum whist conserving mass through the principle of continuity (DHI, 2002). The hydrodynamic model in MIKE 21 is a numerical modelling system for the simulation of water levels and flows in Wellington Harbour. It simulates unsteady two-dimensional flows in one-layer (vertically homogeneous) fluids. MIKE 21 Flow Model is applicable to the simulation of hydraulic and environmental phenomena in lakes, estuaries, bays, coastal areas and seas. The model is suitable for simulating the still-water level that includes the components of mean level of the sea (MLOS) astronomical tide and storm surge, but it does not include waves or wave setup and runup. The MIKE 21 modelling system (DHI, 2001) has been set-up to simulate water levels in Wellington Harbour for the period from 31 January 1936 to 3 February 1936. This 4-day period covers the period during the storm where both winds and changing atmospheric pressures were recorded.

4.2 Bathymetry

An existing model bathymetry created from current LINZ fair sheet soundings was used for this project. The grid resolution is 100×100 m^2 with an overall grid size of 110×137 cells oriented at 30°anticlockwise from a north-south alignment. The grid origin (cell (1, 1)) was at NZMG (2657608.30E, 5986589.26N), and vertical datum was Chart Datum. The area of interest consists of the greater Wellington Harbour with the forcing boundary located at the entrance to the Harbour (Figure 8).

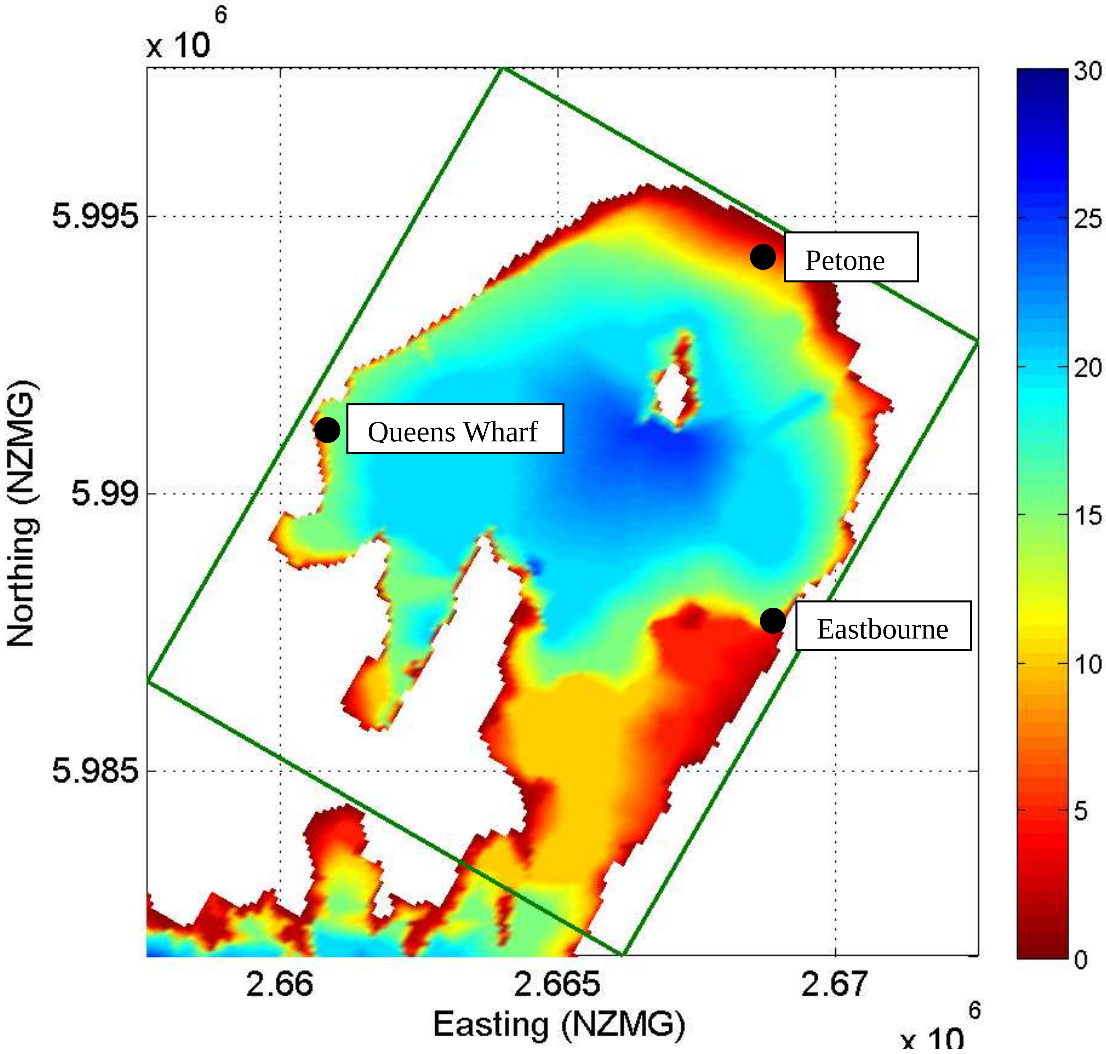

Figure 8: Bathymetry of Wellington Harbour illustrating the model grid area, which was subsequently orientated 30° relative to True North. Model output sites at Queens Wharf, Petone and Eastbourne are marked.

4.3 Boundary conditions and scenarios modelled

NIWA has built a computer tidal model to simulate 16 of the most important tides across the Exclusive Economic Zone (EEZ) around New Zealand. The model has been calibrated with measurements from a national sea-level network and is the basis of the NIWA Tide Forecaster service[6]. For most coastal locations the forecasts of high and low tides will be accurate within 0.1 m in height and 5-10 minutes in time. Tidal information from the NIWA EEZ tide model (Walters et al. 2001) was used to derive the fluctuations in water levels due to tides along the open-sea boundary of the

[6] http://www.niwa.co.nz/services/free/tides

Wellington Harbour model. Hourly tide levels were extracted for the period around the 1936 storm (Figure 9).

The scale of weather pressure systems is considerably larger than our model domain, which means that it was not possible to directly simulate atmospheric-pressure-induced water level changes in the model. This necessitated an alternative approach being taken to simulate the storm-surge component of sea level during the 2 February 1936 storm, by using a water level increase at the open boundary at the Harbour entrance to create a corresponding "surge" within the Harbour.

The storm surge for input at the Harbour entrance was calculated by fitting a cubic spline to daily atmospheric pressure readings (Barnett, 1938), converting this to an inverse-barometer sea-level rise and then adjusting the curve to reach 0.5 m at its peak (Figure 9). For climate change scenarios the peak surge height was nominally increased to 0.6 m to allow for possible increases in wind speed or more intense storms (besides sea-level rise).

Local winds within Wellington Harbour were also included in the simulations. The daily weather charts presented by Barnett (1938) show that the 2nd February 1936 cyclone moved rapidly across New Zealand. A cubic spline was used to interpolate the daily wind speed and direction and atmospheric readings at Wellington from the 9 a.m. synopsis weather map in Figure 2 into an hourly-spaced time series. The lowest pressure reliably recorded in Wellington was 974 hPa (Barnett, 1938). Wind speeds during the storm were recorded as turning southerly and rising to a speed of 125 km hr^{-1}. To drive the tide-surge model, hourly-spaced values of pressure at mean sea level and the horizontal wind components were extracted for each of the simulations. These forcing data were interpolated linearly to match with the space-time grid of the hydrodynamic model domain of the Harbour.

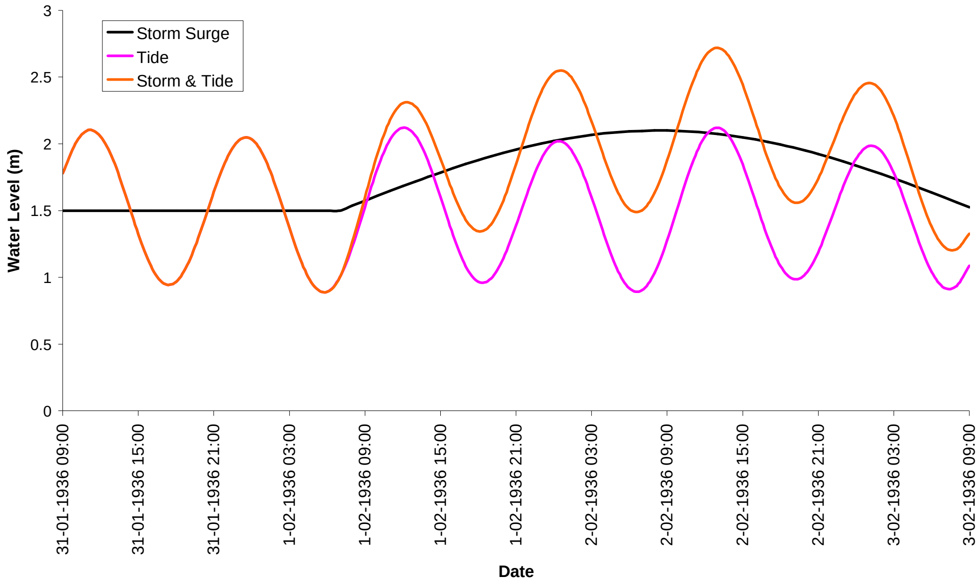

Figure 9: Boundary conditions used to force the MIKE 21 storm surge model. The vertical datum for the plot is Chart Datum.

Simulations were also run to predict the height that storm tides might reach if a similar cyclone occurred in the 2090s, but with the added factor of climate change. The 2008 Ministry for the Environment Coastal Hazards and Climate Change Report (Ministry for the Environment 2008) recommends for planning and decision timeframes out to the 2090s (2090–2099):

1. a base value sea-level rise of 0.5 m relative to the 1980–1999 average should be used; along with

2. an assessment of the potential consequences from a range of possible higher sea-level rises (particularly where impacts are likely to have high consequence or where additional future adaptation options are limited). At the very least, all assessments should consider the consequences of a mean sea-level rise of at least 0.8 m relative to the 1980–1999 average.

Climate change sea level rise scenarios of 0.5 and 0.8 m were used in this general Harbour study. But where the potential consequences of sea-level rise are substantial in specific coastal areas or for high-value or long-term assets, even higher sea-level rise values need to be considered.

To investigate the individual and combined effect of the various “drivers” of extreme sea levels in Wellington Harbour (tide, surge, local wind and sea-level rise), six simulations were run. For all the simulations MLOS was assumed to be at present-day (2008) level, i.e., how high the 1936 storm tide would be if it occurred today. The six simulations were:

1. Tide Only: The astronomical tide levels were back-predicted using NIWA's tide forecaster for the period around the 1936 storm. The tide was applied as a varying water level at the open boundary at the Harbour entrance. The simulated high tide at the Harbour entrance peaked at 0.66 m at 00:15 and again at 0.53 m at 12:30 on 2 February 1936, relative to MLOS.

2. Surge only: A rising and falling storm surge peaking at a height of 0.5 m was applied as a time-varying water level at the open boundary at the Harbour entrance (e.g., Figure 9). The surge was set to peak at 09:00 2 February 1936, increasing from 0 m two tidal cycles (25-hours) earlier and diminishing after the peak to reach zero again two tidal cycles later. Thus at 00:15 and 12:30 on 2 February 1936, the simulated surge levels at the Harbour entrance were 0.44 m and 0.48 m respectively relative to MLOS.

3. Wind only: The local wind in the model was set to peak at 18 m s^{-1} at 09:00 2 February 1936, increasing from 0 m s^{-1} two tidal cycles (25-hours) earlier and diminishing after the peak to reach zero again two tidal cycles later. The direction of approach was from 160°. In this sense the wind is a "local" wind; any setup induced by it comes from wind stress over the limited fetch of the model domain, which is mainly in the Harbour. An open-coast wind setup effect of 0.1 m outside the Harbour was judged to have been allowed for in the 0.5 m surge boundary.

4. Tide + storm-surge + local wind: The combination of simulations 1–3: tidal and storm-surge boundaries were summed and applied at the Harbour entrance, while local wind was also included. This combination of tide and surge led to simulated water levels at the Harbour entrance of 1.1 m (0.66 m tide + 0.44 m surge) and 1.01 m (0.53 m tide + 0.48 m surge) at 00:15 and 12:30 respectively, relative to present-day MLOS.

5. Climate change scenario of 0.5 m sea level rise by the 2090s: tide + larger 0.6 m surge + faster 25 m s^{-1} local wind (this was the fastest mean wind speed measured across New Zealand during the storm, (Barnett, 1938)). The 0.5 m sea-level rise is the least value to be considered for the 2090s (Ministry for the Environment 2008), and is modelled assuming a more intense storm, with additional surge 0.1 m component at the Harbour entrance and more severe wind speed.

6. Climate change scenario of 0.8 m sea level rise by the 2090s: tide + larger 0.6 m surge + faster 30 m s^{-1} local wind. The 0.8 m sea level rise is the least upper-range sea-level rise that should be considered by the 2090s (Ministry for the Environment 2008).

Table 2 summarises the scenarios that were simulated using the numerical model.

Table 2: Summary of storm tide scenarios for Wellington simulated using the numerical model (where SS= storm surge and SL=sea level). MLOS was assumed to be at present-day level for all the simulations.

Scenario	Components ("drivers")	Description
1	Tide only	Astronomical tide from the EEZ tide model.
2	SS of 0.5 m only	Peak storm surge height of 0.5 m at 09:00 2 Feb 1936 at Harbour entrance
3	Wind only	Wind speed peak of 18 m s^{-1} at 09:00 2 Feb 1936
4	Tide + SS of 0.5 m + wind	Peak storm surge height of 0.5 m at 09:00 2 Feb 1936, wind speed peak at 18 m s^{-1} at 09:00 2 Feb 1936
5	Tide + SS of 0.6 m + wind + SL rise of 0.5 m	Sea-level rise of 0.5 m, peak storm surge height of 0.6 m and wind speed peak at 25 m s^{-1}
6	Tide + SS of 0.6 m+ wind + SL rise of 0.8 m	Sea-level rise of 0.8 m, peak storm surge height of 0.6 m and wind speed peak at 30 m s^{-1}

5. Results

5.1 The 1936 Event

Table 3 shows the numerical model predictions of the magnitude of the various components of storm tide caused by the various forcing mechanisms (tide, surge, local wind), simulated separately (Model scenarios 1–3, Table 2), and combined (Scenario 4, Table 2). Note that because of non-linear interactions between the various forcing mechanisms the total predicted storm tide level when including all the "drivers" in the simulation is not exactly the sum of the various sea-level components when simulated separately.

Table 3: Water-level elevations (in metres) at three sites in Wellington Harbour, from a reconstruction of the 2nd February 1936 storm using present-day climate and a storm surge of 0.5 m. Elevations are given for times coinciding with the high tide peaks at 00:15 and 12:30, the former being larger. Elevations are given relative to present-day mean level of the sea (MLOS), and the total elevations are also given relative to Wellington Vertical Datum 1953 (WVD53).

	Model scenario (Table 2)	Queens Wharf (00:15)	Queens Wharf (12:30)	Petone (00:15)	Petone (12:30)	Eastbourne (00:15)	Eastbourne (12:30)
Tide	1	0.70[ϒ]	0.57	0.75	0.63	0.73	0.61
Surge	2	0.43	0.48	0.43	0.48	0.43	0.48
Wind	3	0.01	0.02	0.05	0.07	0.04	0.05
Total ($MLOS_{2008}$)	4	1.14	1.06	1.18	1.11	1.17	1.09
Total (WVD-53)	4	**1.33**	1.25	**1.38**	1.30	**1.36**	1.28

Note that the 1936 storm was simulated in a present-day context, assuming present-day $MLOS_{2008}$, without allowing for differences in mean sea level between 1936 and the present day. Using the long-term average rate of sea level rise of 1.78 mm/yr between 1891 to 2001 (Hannah, 2004), mean level of the sea would have been about 0.13 m lower than present in Wellington Harbour. However, the aim of this study was

[ϒ] Note that the if an offset of 0.19 m is added to convert from MLOS to WVD53, then the simulated high tide peaks at Queens Wharf are similar to those hindcast using tidal harmonic constituents derived from the Queens Wharf tide gauge (0.86 m (00:15) and 0.75 m (12:30) WVD53).

to re-create the storm tide height above MLOS to enable comparison with more recent storm conditions. This issue does become important when the 1936 storm tide is used to extend the extreme-value analyses. Technically, this means that the simulated 1936 storm tide is conservatively large (by about 0.13 m) when used to extend the extreme-value analyses that are presented later in this report. However, as is also discussed in detail later in this report, there is some uncertainty as to the magnitude of the storm surge applied at the Harbour entrance, which also affects the extreme-value analyses. In light of this uncertainty, it was decided to use the simulated 1936 storm tide level relative to present-day mean level of the sea ($MLOS_{2008}$) in the extreme-value analyses.

For this storm event it is seen that the astronomical tide is the largest component of sea level. However, the storm-surge component is also significant, translating to a storm surge of 0.43 m within the Harbour coincident with the first and highest tide, and to a storm surge of 0.48 m coincident with the second tide, which are equivalent in heights to about 60% and 80% of the two high tide heights above MLOS on that day respectively. The model predicts the storm surge at the three output sites (Figure 8) to be the same as that input at the open-sea boundary, i.e., the model does not predict any significant amplification or damping of the external storm surge as it propagates into Wellington Harbour. We use this outcome later to explore the sensitivity of extreme-value estimates to surges up to 0.8 m. The simulated local winds from the south set the water level up higher at Petone, where the fetch was largest, but were almost negligible at Queens Wharf. Local wind set-up is a relatively minor component of the total storm tide, reaching only 0.05–0.07 m at Petone for the scenarios modelled. Finally, the high-tide heights are slightly higher at Petone (another 0.05–0.06 m relative to Queens Wharf). Overall, combining all the driving factors (Scenario 4), the storm tide levels for a southerly storm like the 1936 event would be around 0.05 m higher at Petone than Queens Wharf.

The numerical re-creation of the 2 February 1936 storm tide (applying a 0.5 m storm surge to the model boundary in Cook Strait) suggests that storm tide reached 1.33 m above WVD53 at Queens Wharf and 1.38 m at Petone (Table 3). The Queens Wharf prediction is considerably smaller than the potential storm tide of ~1.7 m postulated by (Tait et al. 2002) based on the estimated 0.9 m storm surge assuming a simple doubling of the 0.45 m inverted barometer effect. There are several lines of evidence to suggest that the Tait et al. (2002) estimate is probably too high.

Recent evidence collected from storm surge modelling within NIWA's real-time forecasting system EcoConnect (Lane et al. 2009) over the past 3 years suggests that storm surges in Cook Strait are more constrained than other regions, with the highest being ~0.35 m. Looking at the spatial patterns from the storm-surge forecasts, surges around NZ tend to be larger in some of the wide open bays e.g., Pegasus Bay and South Taranaki Bight but there is insufficient geographical constriction in Cook Strait for the wind-induced component of storm surge to build in response to the wind forcing (Philip Gillibrand, NIWA, pers. comm.).

The cyclone of 2 February 1936 moved rapidly over the country which would reduce the magnitude of regional wind setup. As noted earlier, an analysis by Goring (1995) suggests that inverted barometer (IB) is responsible for 70% of sea-level variation in the "weather band" at Wellington, with ≤ 30% due to other causes including wind setup and coastal-trapped waves propagating in from other regions. This advice would suggest that a doubling of the IB setup, i.e., assuming the wind-induced component of storm surge will match the IB component, is probably not reasonable for Wellington Harbour, and further with the speed of the cyclone centre, the wind-induced component is likely to have been proportionately less. Extreme-value analysis of measured storm surges 1975–2008 (Table 7) shows that a 1-in-100-year Average Reccurrence Interval (ARI) storm surge has a value of about 0.43 m at Queens Wharf and that a 0.5 m storm surge has an ARI of ~1500 years. Despite the above indications that storm surges in Wellington are unlikely to be as high as 0.9 m (Tait et al. 2002), we also explored the impact that surges > 0.5 m would have on the extreme-value results, below.

5.2 Future storm tide events arising from climate change

The combined effects of sea-level rise and potential increases in storm intensity (higher wind speeds and lower atmospheric pressure) could result in a storm tide of 1.93–2.22 m WVD53 by the 2090s (Table 4).

Table 4: Storm tide elevations (m) at three sites in Wellington Harbour, from a reconstruction of the 2nd February 1936 storm using climate-change scenarios for the 2090s. Elevations are given for times coinciding with the high tide peaks at 00:15 and 12:30, the former being larger. Elevations are given relative to both present-day mean level of the sea (MLOS) and to Wellington Vertical Datum 1953 (WVD-53).

	Model scenario (Table 2)	Queens Wharf (00:15)	Queens Wharf (12:30)	Petone (00:15)	Petone (12:30)	Eastbourne (00:15)	Eastbourne (12:30)
0.5 m sea level rise (MLOS)	5	1.73	1.65	1.78	1.71	1.76	1.71
0.5 m sea level rise (WVD53)	5	**1.93**	1.85	**1.97**	1.91	**1.95**	1.91
0.8 m sea level rise (MLOS)	6	2.02	1.95	2.08	2.01	2.07	1.99
0.8 m sea level rise (WVD53)	6	**2.22**	2.15	**2.28**	2.21	**2.26**	2.18

6. Extreme sea levels in Wellington Harbour

6.1 Extreme storm tide analysis

The simulated 2 February 1936 storm tide elevations can now be included in an extreme-value analysis to characterise the storm in terms of its probability of re-occurring and to calculate expected probabilities of occurrence of other high storm tide levels.

Based on the assumption of a 0.5 m storm surge at the entrance to Wellington Harbour, the simulated storm tide on 2 February 1936 of 1.33 m above WVD53 at Queens Wharf is larger than any other storm tide on record since 1975 (Table 1).

A Generalised Extreme Value (GEV) analysis was used to calculate the probabilities associated with extreme sea levels, using the measured annual maxima total sea levels (Table 1, Figure 5) and storm surges, following Coles (2001). The results are presented in Tables 5–7 and Figures 11–17. The sea level associated with a given ARI is defined as the sea level that would be expected to be equalled or exceeded in elevation, once, on average, every "ARI" years. The Annual Exceedance Probability is the probability of a given sea level being equalled or exceeded in any given calendar year. For example, the 1% or 0.01 AEP (or 1-in-100-year ARI) sea level is calculated to be 1.29 m WVD-53 using a GEV fit to the modern (1975–2008) annual maxima (Table 5). In other words, based on our analysis of the sea-level data measured since 1975, we expect the total storm tide level to equal or exceed 1.29 m WVD53 only once every 100-years, on average. Expressed in terms of AEP this means that there is a 1% chance on average of the sea level equalling or exceeding 1.29 m WVD53 in any given year.[7] Note that 1.29 m WVD53 is the median value of the GEV fit, but that there is some uncertainty in the exactness of this "best-guess" estimate due to uncertainty in the GEV model fit. The 95% confidence intervals indicate the range within which we are confident that the extreme values will lie. Table 5 shows that we expect the "true" 1% AEP storm tide to lie in the range 1.24–1.35 m WVD53.

[7] Note: some years have higher tides than other years within the 18.6 year nodal-tide cycle, which means this won't be exactly the case in any particular year.

Table 5: Results of GEV model fit to measured annual maxima sea levels. Results are in m WVD53 relative to the MLOS over the analysis period (1975–2008). ARI = average reccurrence interval. AEP = annual exceedance probability. C.I. = confidence intervals of GEV fit.

ARI (years)	2	5	10	20	50	100	200
AEP	0.5	0.2	0.1	0.05	0.02	0.01	0.005
Median	1.13	1.19	1.22	1.25	1.27	1.29	1.30
5% C.I.	1.11	1.17	1.20	1.21	1.23	1.24	1.24
95% C.I.	1.16	1.22	1.25	1.28	1.32	1.35	1.38

The fit of the GEV model to the storm tide annual maxima can be visually assessed by plotting the GEV model alongside the data. The annual data are plotted using their Gringorten plotting positions (Gringorten 1963), which are obtained by plotting the cumulative probability of the sample distribution against the sample value. If the GEV model is a good fit to the data, then the plotted data should lie within the 95% confidence intervals. We see that this does happen when the GEV model is fitted to the modern measured annual maxima (Figure 11), and also when the 1936 storm tide is estimated at 1.33 m WVD53 based on a 0.50 m storm surge at the entrance to Wellington Harbour and included in the extreme analysis (Figure 12).

If we adopt the assumption of potentially higher storm surges at the entrance to Wellington Harbour during the 1936 storm, i.e., 0.6, 0.7 and 0.8 m respectively, we see that if the 1936 storm tide level is estimated at successively larger values of 1.43 m (Figure 13), 1.53 m (Figure 14) and 1.63 m (Figure 15), that the plotted position for the estimated 1936 storm tide (and also some of the larger measured annual maxima) does not fall within the GEV confidence intervals (Figure 14 and Figure 15). This indicates that these larger estimates of the 1936 storm tide level come from a different storm population than the rest of the (measured) data. In other words, it suggests that for the time period from 1936–2008, the simulated storm tide estimates of 1.43 m and upward are so large that they are fundamentally different in nature from the measured storms, being either a) fictitiously large because of unrealistic surge input to the hydrodynamic model, or b) caused by a Harbour and Cook Strait response to a weather event that was fundamentally different from those that occurred in the period 1975–2008. A GEV extreme-value analysis of the storm-surge component of storm tides provides similar information. Figure 16 shows the GEV fit to storm surge annual maxima, while Figure 17 shows a GEV fit assuming a 0.7 m surge associated with the 1936 storm. A 0.7 m surge appears to be from a different population to the

1975–2008 measurements (Figure 17). Conversely, using a 0.5 m surge at the Harbour entrance, a 1936 storm tide estimate of 1.33 m is in keeping with the extreme-value fit to the modern measured annual maxima (Figure 12). Also the distributions of extreme storm tide levels at other sites around New Zealand that we have investigated (e.g., Mt. Maunganui, New Plymouth) also show a more gradual increase with longer ARI that align closely to the relevant GEV fit.

Incidentally, a 0.5 m storm surge at Queens Wharf (and therefore also at the Harbour entrance in the hydrodynamic model) has an ARI of ~1500-years suggesting that storm surges in excess of 0.5 m are extremely rare based on the 1975–2008 dataset. Along with the lines of reasoning presented in section 5.1, the extreme-value sensitivity analyses suggest that storm-surge heights in excess of 0.5 m would seldom occur in Wellington Harbour, and that the 0.6 m storm surge used in the climate change scenarios is also conservative. Nevertheless, the only way to quantitatively reconstruct the storm tide from the 1936 storm, would be to apply New Zealand-scale weather, storm-surge and tide models that attempt to re-create the event in the wider Wellington and Greater Cook Strait region. However, due to limited weather observations and no regular mean-sea-level pressure analyses throughout the 1936 event, there would still be a degree of uncertainty about the actual storm tide level (excluding wave runup). There is merit though, in assessing the spatial distribution of storm tide levels around the entire Wellington region's coastline using such an approach with modern storms.

The empirical ARI of the 1936 storm tide is 130 years. For the GEV fit using a storm tide of 1.33 m for the 1936 event, the estimated ARI was 170 years (0.6% AEP) (Table 6, Figure 12).

Climate change simulations show that the combined effects of sea-level rise and potential increases in storm intensity (higher wind speeds and lower atmospheric pressure) could result in storm tide levels of 1.93–2.22 m WVD53 from a 200 year ARI storm by the 2090s (Table 4).

The extreme-value analyses are based on real data and so cannot be produced for climate-change scenarios without simulation of multiple storms in a climate change context, i.e., with sea level and storm intensity change included (we have simulated only one such storm here).

Table 6: Results of GEV model fit to measured annual maxima sea levels and also including the simulated storm tide of 1.33 m on 2 February 1936 for Queens Wharf (Table 3). Results are in m WVD53 relative to the MLOS over the 1975–2008 period. ARI = average reccurrence interval. AEP = annual exceedance probability. C.I. = confidence intervals of GEV fit.

ARI (years)	2	5	10	20	50	100	200
AEP	0.5	0.2	0.1	0.05	0.02	0.01	0.005
Median	1.13	1.20	1.23	1.26	1.30	1.32	1.33
5% C.I.	1.12	1.18	1.22	1.25	1.28	1.30	1.31
95% C.I.	1.15	1.21	1.25	1.28	1.32	1.35	1.38

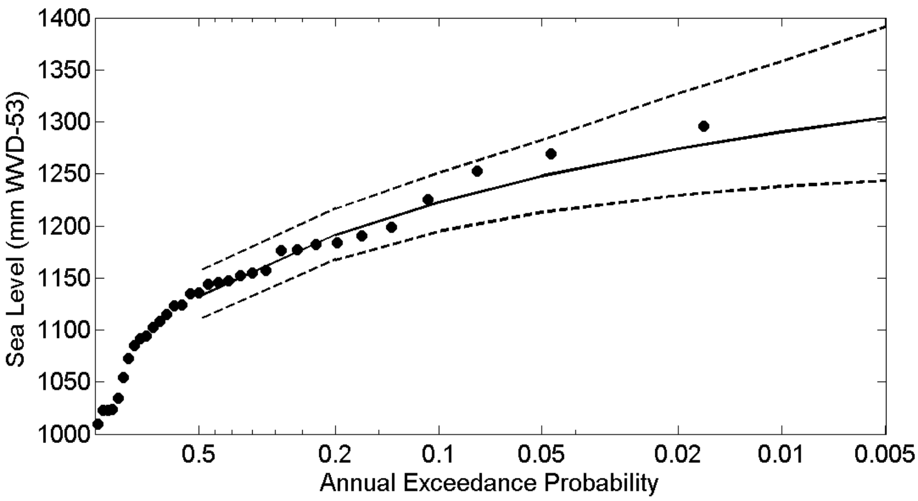

Figure 11: GEV fit to measured annual maxima sea levels (Table 3). The dots mark the annual maxima plotted in their Gringorten plotting positions. The solid line marks the best-fit of the GEV model to the data. The dashed lines show the 95% confidence intervals for the GEV model. The GEV fit parameters are ξ = shape parameter = -0.25, σ = location parameter = 66, μ = location parameter = 1107.

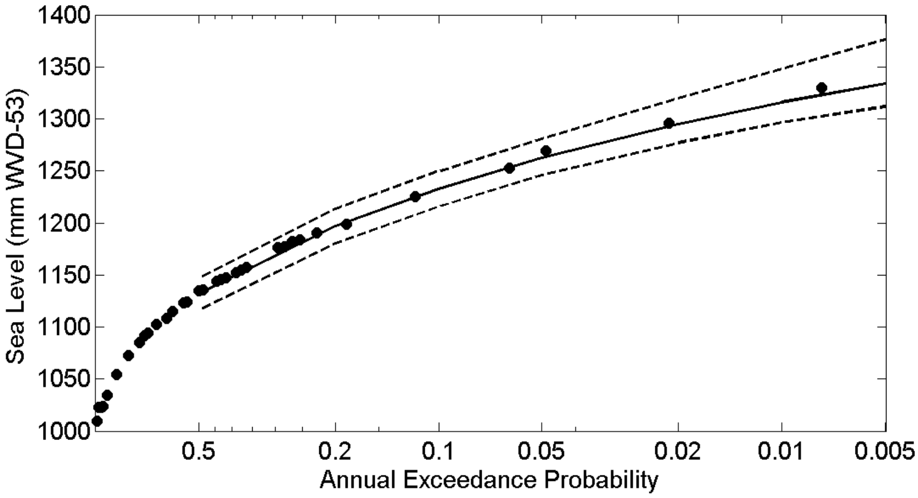

Figure 12: GEV fit to measured annual maxima sea levels (Table 3) and also including a simulated storm tide of 1.33 m for Queens Wharf on 2 February 1936. The dots mark the annual maxima plotted in their Gringorten plotting positions. The solid line marks the best-fit of the GEV model to the data. The dashed lines show the 95% confidence intervals for the GEV model. The GEV fit parameters are ξ = shape parameter = -0.19, σ = location parameter = 68, μ = location parameter = 1108.

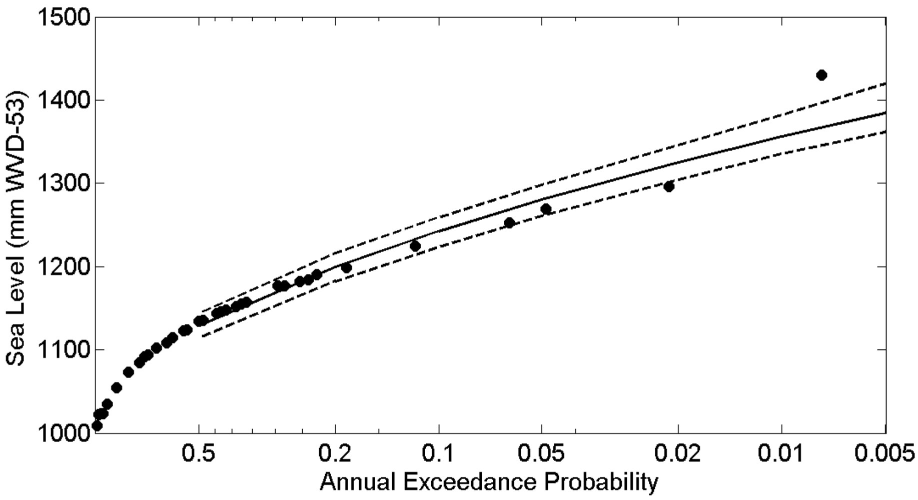

Figure 13: GEV fit to measured annual maxima sea levels (Table 3) and also including a simulated storm tide of 1.43 m on 2 February 1936. The dots mark the annual maxima plotted in their Gringorten plotting positions. The solid line marks the best-fit of the GEV model to the data. The dashed lines show the 95% confidence intervals for the GEV model.

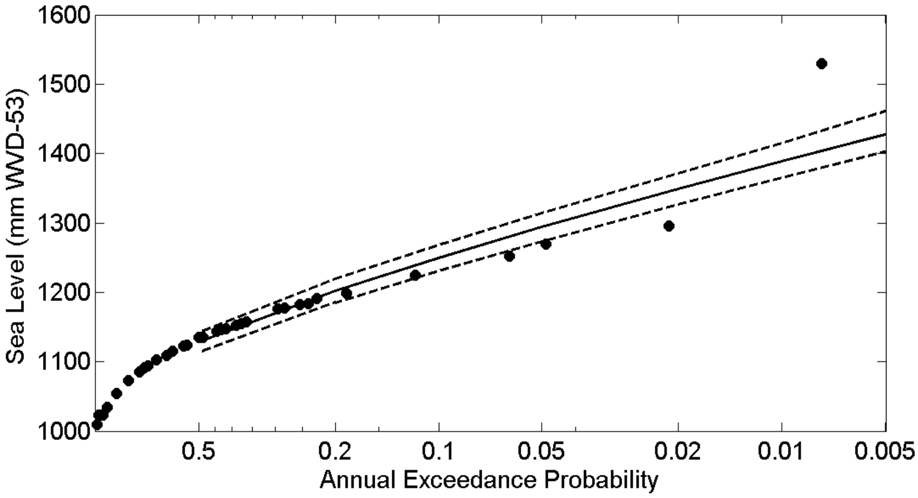

Figure 14: GEV fit to measured annual maxima sea levels (Table 3) and also including a simulated storm tide of 1.53 m on 2 February 1936. The dots mark the annual maxima plotted in their Gringorten plotting positions. The solid line marks the best-fit of the GEV model to the data. The dashed lines show the 95% confidence intervals for the GEV model.

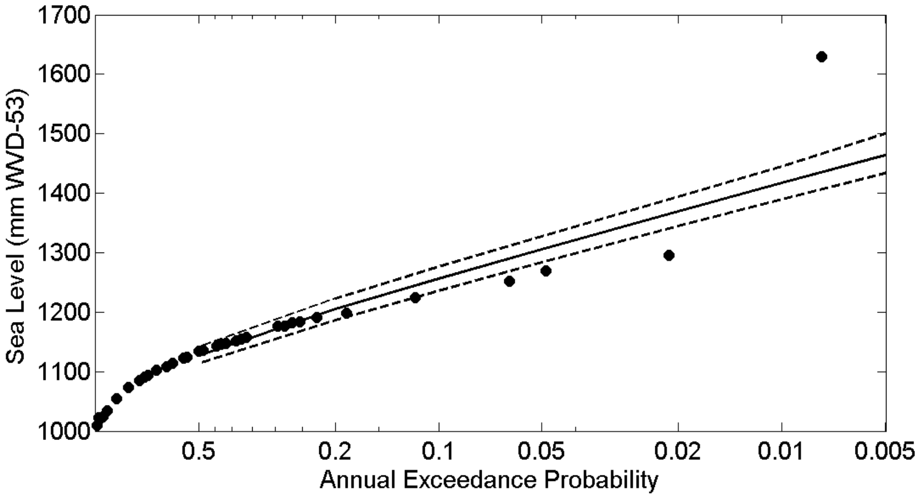

Figure 15: GEV fit to measured annual maxima sea levels and (Table 3) also including a simulated storm tide of 1.63 m on 2 February 1936. The dots mark the annual maxima plotted in their Gringorten plotting positions. The solid line marks the best-fit of the GEV model to the data. The dashed lines show the 95% confidence intervals for the GEV model.

Table 7: Results of GEV model fit to measured annual maxima storm surges. Results are in m. ARI = average reccurrence interval. AEP = annual exceedance probability. C.I. = confidence intervals of GEV fit.

ARI (years)	2	5	10	20	50	100	200
AEP	0.5	0.2	0.1	0.05	0.02	0.01	0.005
Median	0.30	0.34	0.36	0.38	0.41	0.43	0.45
5% C.I.	0.28	0.32	0.34	0.35	0.37	0.38	0.38
95% C.I.	0.31	0.36	0.39	0.42	0.47	0.52	0.57

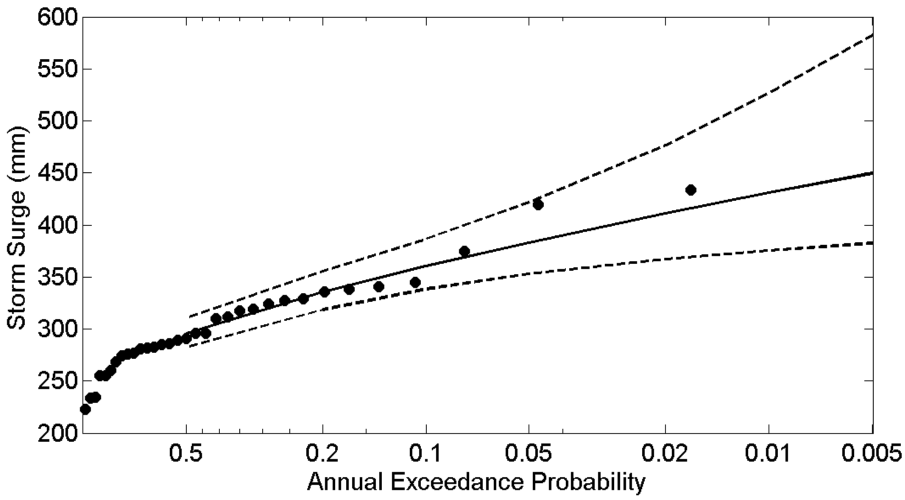

Figure 16: GEV fit to annual maxima storm surge data. The dots mark the annual maxima plotted in their Gringorten plotting positions. The solid line marks the best-fit of the GEV model to the data. The dashed lines show the 95% confidence intervals for the GEV model. The GEV fit parameters are ξ = shape parameter = -0.0651, σ = location parameter = 37, μ = location parameter = 283.

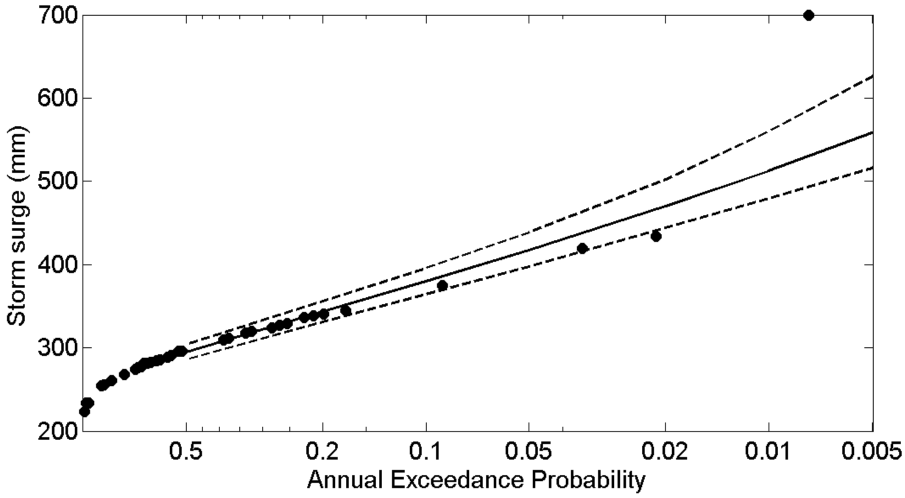

Figure 17: GEV fit to annual maxima storm surge data, and also including an arbitrary storm tide estimate of 0.7 m on 2 February 1936. The dots mark the annual maxima plotted in their Gringorten plotting positions. The solid line marks the best-fit of the GEV model to the data. The dashed lines show the 95% confidence intervals for the GEV model.

6.2 Comparison with previous work

The observations of previous damaging storms in Wellington Harbour (Tait et al. 2002) were reviewed in the context of this report. It was interesting to observe that several storms with reported inundation from the sea and associated wave erosion and damage did not always have particularly large estimated storm tides. Many storm tides have been measured since 1975 at Queens Wharf (Table 1) that are as large or larger than back-calculated storm tides for historically damaging storms prior to 1975 (Tait et al. 2002).

This raises an important point. While storm tides by themselves are hazardous and can cause inundation of low-lying areas, they also set a higher base sea level for wave attack or overtopping on the coastline. Thus it is the joint occurrence of high storm tide levels and waves that can be of most concern, and this is supported by much of the anecdotal evidence of historically damaging storms (Tait et al. 2002). A joint probability analysis of wave height and storm tide for Wellington Harbour was previously undertaken by (Gorman et al. 2005). The 14-year water level record used by Gorman et al. (2005) was considerably shorter than the 33-year record used here, and the estimated return storm tide levels were lower than those from the present study by 0.01–0.09 m depending on the method used, at the 1% AEP level.

7. References

Barnett, M.A.F. (1938). The cyclonic storms in northern New Zealand on the 2nd February and the 26th March 1936. Department of scientific and industrial research.

Beavan, R.J. (2001). Long-term stability of Wellington tide gauge, 1911-2001, incorporating May 2001 levelling survey to Wellington fundamental benchmark K80. Institute of Geological and Nuclear Sciences Ltd. Institute of Geological and Nuclear Sciences science report 2001/9.

Bell, R.G.; Goring, G.D.; de Lange, W.P. (2000). Sea level change and storm surges in the context of climate change. *IPENZ Transactions (General) 27*: 1-10.

Brenstrum, E. (2000). The cyclone of 1936: the most destructive storm of the Twentieth Century? *Weather and Climate 20*: 23-27.

Coles, S. (2001). An introduction to statistical modeling of extreme values. Springer. London; New York.

Goring, D.G. (1995). Short level variations in sea level (2-15 days) in the New Zealand region. *New Zealand Journal of Marine and Freshwater Research 29*: 69-82.

Gorman, R.M.; Mullan, B.; Ramsay, D.; Reid, S.; Stephens, S.; Thompson, J.; Walsh, J.; Walters, K.; Wild, M. (2005). Impacts of long term climate change on weather and coastal hazards for Wellington City. NIWA Client Report HAM2005-036.

Gringorten, I.I. (1963). A plotting rule for extreme probability paper. *Journal of Geophysical Research 68*: 813-814.

Hannah, J. (2004). An updated analysis of long-term sea level change in New Zealand. *Geophysical Research Letters, Vol. 31*, L03307.

Komar, P.D. (1998). Beach processes and sedimentation. 2. Prentice-Hall. New Jersey.

Lane, E.M.; Walters, R.A.; Gillibrand, P.A.; Uddstrom, M., 2009. Operational forecasting of sea level height using an unstructured grid ocean model, Ocean Modelling, doi:10.1016/j.ocemod.2008.11.004.

Longuet-Higgins, M.S.; Stewart, R.W. (1962). Radiation stress and mass transport in gravity waves, with application to 'surf-beats'. *Journal of Fluid Mechanics 13*: 481-504.

Ministry for the Environment 2008: Coastal Hazards and Climate Change: A Guidance Manual for Local Government in New Zealand. 2nd Edition. Revised by Ramsay, D. & Bell, R. (NIWA). Ministry for the Environment Report ME892. Wellington.

Pawlowicz, R.; Beardsley, B.; Lentz, S. (2002). Classical tidal harmonic analysis including error estimates in MATLAB using T_TIDE. *Computers and Geosciences 28*: 929-937.

Pugh, D. T. 2004: Changing sea levels. Effects of Tides, Weather and Climate. Cambrdge University Press. New York.

Tait, A.; Bell, Rob; Burgess, S.; Gorman, Richard M.; Gray, W.; Larsen, H.; Mullan, B.; Reid, Steve; Sansom, J.; Thompson, C.; Wratt, D.; Harkness, M. (2002). Meteorological hazards and the potential impacts of climate change in Wellington Region. NIWA Client Report prepared for Wellington Regional Council WLG2002/19 (WRC Pub. No. WRC/RP-T-02/16).

Walters, R. A.; Goring, D. G.; Bell, R. G. 2001: Ocean tides around New Zealand. *New Zealand Journal of Marine and Freshwater Research 35*: 567-579.