MHWS level for the Bay of Plenty

NIWA Client Report: HAM2006-133
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Prepared for

Environment Bay of Plenty

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Executive Summary

NIWA was commissioned by Environment Bay of Plenty in August 2006 to prepare a brief report on definitions on Mean High Water Spring (MHWS) levels on the open coast for the Bay of Plenty.

Defining MHWS can be a complex issue, especially if stricter requirements for its accuracy and appropriateness are required. The strategic importance of a sound definition of MHWS level arises from its use in defining the landward limit of coastal marine area (CMA) on the open coast under the Resource Management Act–RMA (1991) and the landward limit for the foreshore under the Foreshore and Seabed Act (2004).

The report canvasses different approaches to defining MHWS that can be categorised as: mathematical, algorithms and practical application of "natural indicators" of the upper tide level. Case law also upholds a flexible approach which inevitably requires a judgement of what constitutes the MHWS boundary. For example, the Environment Court decision in 2000 on Ann's Creek of Mangere Inlet (Hastings *vs.* Auckland Regional Council, Decision A130/2000) stated:

"*We accept that a practical solution is required. From the surveying evidence there is in no definitive answer. Neither a strictly mathematical surveying approach, nor any other approach, will produce a solid irrefutable result. A judgment is needed, and whatever decision is reached will not be universally acceptable.*" [Section 35].

In this report, we have coalesced alternative definitions of MHWS for the open coast of Bay of Plenty onto a high-tide exceedance curve, which then provides the context for judging how often any defined MHWS level is exceeded. The exceedance curves provide the frequency at which a given high tide is exceeded based on high-tide predictions for the next 100 years (2007–2107). Tide predictions were based on NIWA's New Zealand tidal model, and ground-truthed using a 19-year tidal analysis of measurements from the Moturiki sea-level gauge.

These exceedance curves are provided for six sites (five on the open coast and one at the Port of Tauranga) in terms of high-tide <u>height</u> above the Mean Level of the Sea (MLOS). This means the exceedance curves can be used for several decades; with the only requirement to update the MLOS level (above Moturiki Vertical Datum–1953) when there has been sufficient change in MLOS due to long-term climate cycles or sea-level rise.

The high-tide exceedance curves for the open-coast areas of the Bay of Plenty are similar (within 1 cm) for the reach from Waihi Beach to Torere (east of Opotiki), but the high-tide level steadily reduces towards Lottin Point (near East Cape). High-tide levels are even lower in the Port of Tauranga. Consequently, on the open coast, the interpolated MHWS surface could be set to the same value from Waihi Beach to Torere, thereafter reducing linearly eastwards toward Lottin Point.

Finally, a judgement is required to select the most appropriate MHWS definition for the Bay of Plenty. This could be one of those listed in Table 1, combined with an MLOS from Table 2 of this report. Some example definitions of MHWS levels are shown in Table 4 of this report, covering MHWS–10, MHWS–12 (10% and 12% exceedance levels), and Mean High Water Perigean Spring (MHWPS) levels.

Further refinement may be necessary at a particular locality in the Bay of Plenty in transferring the MHWS level to a natural shoreline boundary, taking into account “natural” indicators of a MHWS mark, such as edge of “terrestrial” vegetation, toe of dunes, tide marks on fence posts or rocks etc.

1. Introduction & brief

NIWA was commissioned by Environment Bay of Plenty in August 2006 to prepare a brief report on definitions on Mean High Water Spring (MHWS) levels on the open coast for the Bay of Plenty.

Defining MHWS can be a complex issue, especially if stricter requirements for its accuracy and appropriateness are required. The strategic importance of a sound definition of MHWS level arises from its use in defining the landward limit of coastal marine area (CMA) on the open coast[1] under the Resource Management Act–RMA (1991) and the landward limit for the foreshore under the Foreshore and Seabed Act (2004).

In this report, we present various alternative definitions of MHWS for the open coast of Bay of Plenty based around a high-tide exceedance curve which provides the context for how often any defined MHWS level is exceeded. Further refinement may be necessary at a particular locality taking into account "natural" indicators of a MHWS mark, such as edge of "terrestrial" vegetation, toe of dunes, tide marks on fence posts or rocks etc.

1.1. Brief

The Brief from Environment Bay of Plenty (EBOP) was as follows:

- Develop high-tide exceedance curves (annotated with typical tidal levels e.g., MHWS etc.) for four locations along the Bay of Plenty coastline in order to generate an interpolated tidal plane (representing an elevation of interest (e.g., MHWS or MHWS–12%). [EBOP could then intersect this onto their LIDAR topography model.]

- The four locations for which exceedance curves are required are: a) Waihi Beach; b) Maketu Headland; c) Opotiki; and d) Lottin Point. The vertical datum should be Moturiki MSL datum.

- Validation should be done with existing open-coast tide gauges, particularly Moturiki and Kohi Point recorder time-series would be made available by EBOP for this validation.

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[1] The RMA (1991) has additional definitions of the landward limit of the CMA for river mouths, harbours and estuaries.

- Output in the form of a short technical report outlining: a) methodology used; b) sea level rise effects; c) discussion on the accuracy of the supplied curves; d) data points for each curve in an electronic spreadsheet. For sea-level rise, use the most-likely mid-range values of 0.2 m (by 2050) and 0.5 m (by 2100) projections recommended by MfE Guidance Manual. For the exceedance curves, base on tide predictions for the next 100 years (2007–2107).

1.2. Datum’s

There are three datum’s referred to in this report, defined as follows:

Gauge Zero	is the zero datum of the instrument. Any data retrieved from the instrument are to this datum;
MLOS	is the present actual Mean Level Of the Sea. The high-tide exceedance curves are all calculated relative to MLOS to enable them to be used into the future (as long as MLOS is known relative to Moturiki MSL datum–see below). MLOS itself is not fixed, but varies with long period (1 year or longer) fluctuations in sea level. These include El Niño-Southern Oscillation (ENSO) effects through to long-term sea-level rise. Tides are essentially very long waves that ride on back of the MLOS they encounter;
MSL	is Mean Sea Level Vertical datum for the region. This is a fixed survey datum set by Land Information NZ (LINZ). Around New Zealand, it has been derived from calculating the MLOS from tide measurements over several years during the 1920s to 1940s. For the Bay of Plenty, MSL Datum (called Moturiki Vertical Datum–1953 or MVD–53 for short) was determined from tide gauge measurements from Feb 1949 to Dec 1952. MVD–53 is 1.487 m above Gauge Zero of the Moturiki tide gauge (also referenced to BM–LINZ Code AB4Q). MVD–53 is also 0.9622 m above Chart Datum at the Tug Berth, Port of Tauranga (referenced to BM–LINZ Code B309). Because of sea-level rise, the present MLOS is now several cm higher than MVD–53.

2. Definitions of MHWS

There are a variety of quantitative and qualitative definitions of what constitutes a MHWS level, depending on its intended usage.

The RMA (1991) defines the landward boundary of the CMA in Section 2 as "….*the line of mean high water springs, except that where that line crosses a river, ….*".

Several variations of the definition of MHWS were found in a small sample of planning/policy documents on web sites:

- **MHWS** is Mean High Water Springs which is generally the line of the average of the highest tides (known as spring tides). [*Westland District Council*].

- **MHWS:** The average line of spring high tide. [*Regional Coastal Environment Plan, Environment BoP*].

- **Mean High Water Springs** means the average line of spring high tide. [*Dunedin City Council*].

- **MHWS** means the average of each pair of successive high waters during that period of about 24 hours in each semi-lunation (approximately every 14 days), when the range of tides is the greatest. The times predicted for high water can be affected by changes in the force and direction of the wind and by changes in barometric pressure. It will generally be found that heights are increased with onshore winds and decreased with offshore winds. Sea level rises as the barometer falls and vice versa. [*Marlborough Sounds Resource Management Plan, also 1st sentence same for Nelson City Council Resource Management Plan*].

- **Mean High Water Springs (MHWS)**–excluding the effects of wind and storms the average of each pair of successive high waters during the period of about 24 hours in each semi-lunation (approximately every 14 days), when the range of the tides is the greatest. [*Environment Southland*].

In the context of defining the landward boundary of the CMA, it would seem pragmatic that the marine area (foreshore) should encompass an area that is swept by a high proportion of the high tides (leaving aside storm and meteorological effects).

The following sub-sections discuss various approaches to defining an open-coast MHWS level, covering mathematical definitions, algorithms and practical local determinations.

2.1. Mathematical definitions

In the past, heavy reliance was placed on using the quantitative "tidal harmonic" definition of MHWS. It is defined as:

$$MHWS = MLOS + A(M_2) + A(S_2) \qquad (1)$$

where $MLOS$ is described above in Section 1.2, and $A(M_2)$ and $A(S_2)$ are the amplitudes (half-range) of the twice-daily lunar ("M") and solar ("S") tidal constituents (with subscript "2" for twice-daily). The reasoning is that this gives the average additive (combined) effect of the sun and the moon at spring tides when they coincide (pull together) at New and Full Moons. $A(M_2)$ and $A(S_2)$ are determined by least-squares fitting of sine curves to tidal measurements to find the optimum amplitudes of the sine curves (referred to as a harmonic analysis). The "tidal harmonic" definition of MHWS was universally used by the Royal NZ Navy (Hydrographic Office) and Land Information NZ (LINZ) until recently.

However, extensive observations for the New Zealand region over the past decade and recent tidal modelling (e.g., Walters et al. 2001) have shown that the "tidal harmonic" definition is not a consistent[2] measure of MHWS around New Zealand. This is because the twice-daily solar tide (S_2) is very small between central-eastern coasts and Chatham Islands due to an amphidrome (null region) produced by the way the solar tide propagates through the Pacific and interacts with the New Zealand landmass. Instead, along eastern coasts (from Bluff to Marsden Point), the largest high tides each month are usually perigean tides (rather than the more well-known spring tides). The Moon orbits the Earth in a non-centric elliptical path every 27.5 days, and when it is closest to the Earth in that orbit, it is called the perigee. The tidal constituent amplitude representing this perigean tidal effect is denoted $A(N_2)$. The perigean versus spring-tide difference is greatest in the Kaikoura area, where MHWS defined by Equation 1 is exceeded by 54% of all tides. The higher perigean-tide differential reduces slowly north and south of Kaikoura, but is still present in the Bay of Plenty where 26–27% of high tides exceed this definition, as described in Section 3.

An alternative combined perigean-spring harmonic definition (denoted MHWPS) that could be used for an upper-level MHWS is:

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[2] Consistent, in terms of the % of high tides that exceed the so-defined MHWS height.

$$MHWS = MLOS + A(M_2) + A(S_2) + A(N_2) \qquad (2)$$

where the amplitude of the perigean tidal component $A(N_2)$ is added to Equation 1. Higher perigean-spring tides occur in clusters for a few months, peaking at approximately 7-month periods when Full or New Moon coincide closely with the Moon's perigee (sometimes called "king tides"). Generally around New Zealand, the MHWPS level (Equation 2) is exceeded by 3% to 12% of all high tides, depending on the regional tidal regime.

2.2. Algorithms

2.2.1. LINZ algorithm

LINZ has recently (2006) changed the method of calculating MHWS levels at Standard Ports (e.g., Port of Tauranga). Previously, separate tables were produced that used Equation 1 (to be used for mariners and hydrographic charts) and Equation 2 (recommended for engineering design and surveying boundaries). LINZ now produce two tables for each of those end-user groups, but use a "search and average" algorithm for two different periods (1 year and 19 years respectively) that is based on a traditional definition of MHWS:[3]

The average of pairs of successive high waters during that period of about 24 hours in each semi-lunation (approximately every 14 days), when the range of tides is the greatest. [Underlining by authors]

Traditionally, for a twice-daily tidal regime like New Zealand, this averaging has been done on spring tides around New and Full Moon, and usually based on limited past measurements. But for reasons outlined in the previous sub-section on New Zealand's complex tidal regime, the change has been made by LINZ to use an amended algorithm on future tide predictions to search for the highest pairs of successive high tides at approximately 2-week intervals. The LINZ algorithm is now more flexible, finding the highest tides in each semi-lunation irrespective of whether it is around New/Full Moon, or Moon's perigee or any other local complexity. Essentially the algorithm returns four of the highest tides in approximately each 4-week period and does one average of all the returned high tides over a specified period of future tide predictions. The LINZ Table of MHWS and other levels in Section 2 of their web page[3] is recommended by LINZ for use by mariners and hydrographic surveyors, and is based on tide predictions (using all relevant harmonic constituents) for each Standard port for the coming year only (1 July 2006 to 30 June 2007). Consequently, this table will need to be updated every year. For cadastral purposes, LINZ have

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[3] http://www.hydro.linz.govt.nz/tides/info/tideinfo5/index.asp

produced a second table[4] which uses the same algorithm, but averages all the high tides that are returned from tide height predictions for the next 19 years (1 January 2000—31 December 2018). The longest-period tide is the 18.6 year nodal tide, so a 19-year period is seen by LINZ as representative of most of the tide height distribution. These new MHWS (and other) levels are referenced to the Chart Datum (CD) applying at the particular Standard Port. For example, 1.88 m above CD is given as the MHWS level to use for cadastral purposes for Tauranga (which is equivalent to 0.918 m above MVD–53). The current MLOS derived by LINZ (they use the acronym MSL) is 1.03 m above CD.[3] An advisory note from the Surveyor-General on the determination of MHWS and use of this table can be found on the LINZ web site.[5]

2.2.2. Percentile-exceedance algorithm

NIWA has developed an approach (e.g., Bell et al. 1999) that involves the combination of an algorithm, using high-tide predictions (for either the next 50 or 100 years) and a degree of judgement in selecting an appropriate percentile of the high tides that would exceed a MHWS level. The approach is based around summarising the high-tide distribution in a continuous percent-exceedance curve, along with other mathematical or algorithmic definitions of MHWS, and then selecting the most applicable percentile-exceedance level to define MHWS for a particular region. This is the approach used in this report. The need for a judgement on the final MHWS level chosen for the jurisdictional boundary, in the context of mathematical information, is echoed in case law (see next section).

2.3. Practical local determinations

LINZ and the Environment Court both re-iterate that there is no single definitive method that can be used to establish a natural boundary like MHWS. LINZ state[5] that the approach taken by the surveyor needs to be customised to the individual location and take into account, amongst other things, the hydraulic gradient, the type and value of land concerned and the survey accuracy required.

The Environment Court decision in 2000 on Ann’s Creek of Mangere Inlet (Hastings *vs.* Auckland Regional Council, Decision A130/2000) stated:

“*We accept that a practical solution is required. From the surveying evidence there is in no definitive answer. Neither a strictly mathematical surveying approach, nor any other approach, will produce a solid irrefutable result. A judgment is needed, and whatever decision is reached will not be universally acceptable.*” [Section 35].

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[4] http://www.linz.govt.nz/core/surveysystem/geodeticinfo/geodeticdatums/tidalinfo/index.html
[5] http://www.linz.govt.nz/core/surveysystem/meanhighwater/index.html

Similarly, in a previous case (Falkner *vs.* Gisborne District Council, Decision A82/94, p. 35), the Planning Tribunal (predecessor to Environment Court) stated:

"Not establishing mathematically the precise geographic location of the line of mean high water springs, but of taking a practical approach in applying our specialist skills to understand the evidence and finding a line of mean high water springs as "an administrative boundary which is conveniently ascertainable, so that people can tell without difficulty which set of rules governs their activities"

Baker and Watkins (1991)[6] give a number of different options for establishing MHWS boundaries that depend on the accuracy of the survey required, basically the higher the accuracy the more work that is required by the surveyor. They range from using natural indicators of the upper-tide level (e.g., toe of dune, toe of cliff, edge of vegetation, highest line of driftwood, tide marks on fence posts, and for estuaries, the seaward edge of glasswort (*Salicornia australis)* or other salt-marsh plants) through to accurate transfers of the selected MHWS level from a Standard Port (e.g., Port of Tauranga) or reference gauge (e.g., Moturiki gauge).

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[6] http://www.surveyors.org.nz/Documents/MeanHighWaterMark-LandTitleSurveys(1).PDF

3. Methodology

The methodology adopted for this report (based on the Brief; Section 1) involves encapsulating mathematical and algorithmic definitions of MHWS on a high-tide exceedance (probability) plot, which can then be used to make a judgement on an appropriate percentile (of time) for which a MHWS level would be exceeded.

Only the open coast portion of the Bay of Plenty shoreline is considered. Definition of MHWS in estuaries, harbours, and river mouths is more complex.

Steps used to develop the summary high-tide exceedance curves are as follows:

a) Extract the main 16 tidal constituents[7] from the NIWA's tide model of New Zealand (Walters et al. 2001) for the 4 selected sites (Waihi Beach, Maketu Headland, Opotiki, Lottin Point), and also for Moturiki and Kohi Point, where tide datasets can be used to ground-truth and verify respectively the model results to the Bay of Plenty shoreline.

b) Compare the tide-model constituents for Moturiki with those tidal constituents obtained from long-term measurements (19 years) from NIWA's Moturiki Island sea-level gauge. The same difference (bias) between the measured and modelled Moturiki tidal constituents was then applied to the relevant amplitudes and phases for all the Bay of Plenty sites extracted from the model. The assumption here is that the tide model is a good spatial-integrator for a contiguous coastline like Bay of Plenty (i.e., the results for each site are consistent relative to each other), but the model has an overall bias that can be corrected for by comparing with measurements.

c) Without changing anything else, the ground-truth step above was verified by comparing the un-biased (corrected) tidal constituents from the tide model for Kohi Point with tidal constituents derived from the Environment BoP sea-level gauge off the headland at Kohi Point. The difference between the two datasets can then be used as an indication of the uncertainty in the determination of mathematical definitions of MHWS. Note: less than 1 year of continuous measurements was available from Kohi Point, so the uncertainty values will also contain a contribution from variability in tidal constituents that can occur over a 19-year period.

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[7] A tidal constituent is defined by an amplitude (half-range) of a sine curve representing that particular tide (e.g., lunar, solar, elliptical orbit) and a phase, which is the timing relative to NZST of the peak height of that particular tide (e.g., high tide).

d) Use the un-biased sets of 16 tidal constituents from each of the four sites plus Moturiki to predict all the high tides in the next 100 years from 2007 to 2107 using a harmonic tidal-prediction system. These high tides do not include meteorological or climate effects, nor sea-level rise. All the high-tide values for each site were then sorted in descending order of height and a high-tide exceedance curve produced. The “datum” for the exceedance curves is given in terms of the mean level of the sea (MLOS). This means the high-tide exceedance plots can be used well into the future without having to be updated, other than updating the MLOS level, relative to Moturiki Vertical Datum, to which the MHWS height is added to as MLOS changes substantially. Changes in MLOS will occur as sea-level rises or as a result of climate cycles such as the 2–4 year El Niño–Southern Oscillation and the 20–30 year Interdecadal Pacific Oscillation.

e) Sea-level rise values for 2050 and 2100 to add to the exceedance curves via MLOS use the recommendations of the MfE Coastal Hazards Guidance Manual (MfE, 2004).

f) Various mathematical and algorithmic definitions of MHWS are annotated on the high-tide exceedance curves for comparison.

g) A high-tide exceedance curve was also produced for the Tug Berth (Salisbury Wharf) in Tauranga Harbour for comparison with open-coast sites; given it is a Standard Port where the MHWS level is determined by LINZ. Because of shallow-water effects of the tide as it enters the harbour entrance and propagates up various channels, we have used all 39 derived tidal constituents from port measurements at the Tug Berth. This means there is a more consistent comparison of high-tide exceedance with the latest MHWS level promulgated by LINZ using the new algorithm approach (see Section 2).

4. Results for appraising MHWS

Based on the un-biased corrections to the sixteen main tidal constituents from the NIWA tidal model, high tide exceedance curves relative to MLOS are produced for the following sites: in order from west to east plus a Tauranga Harbour site (Standard Port) for comparison:

- Waihi Beach (Figure 4.1).
- Moturiki–Mt. Maunganui (Figure 4.2).
- Maketu Headland (Figure 4.3).
- Opotiki (open coast) (Figure 4.4).
- Lottin Point (Figure 4.5).
- Tug Berth (Salisbury Wharf, Port of Tauranga) (Figure 4.6).

The following features are annotated on the plots:

a) Site Nos. were allocated based on the tide model cell number.

b) Max HW—the maximum high-tide height in the next 100 years.

c) MHWPS—Mean High Water Perigean Spring tide height derived by summing the A values in Eqn. 2.

d) MHWS-12—an example of a percentile-based judgement on a MHWS height; in this case a level that is only exceeded by 12% of all high tides. It could equally be judged that a 10-perecentile height is appropriate or some other chosen percentile value.

e) MHWS—Mean High Water Spring height derived by summing the A values in Eqn. 1.

f) Min HW—the minimum high water height in the next 100 years.

g) LINZ—the latest (2006) definition of MHWS by LINZ for surveyors (taking the 1.88 m above Chart Datum minus a MLOS of 1.03 m (Sec. 2.2.1).

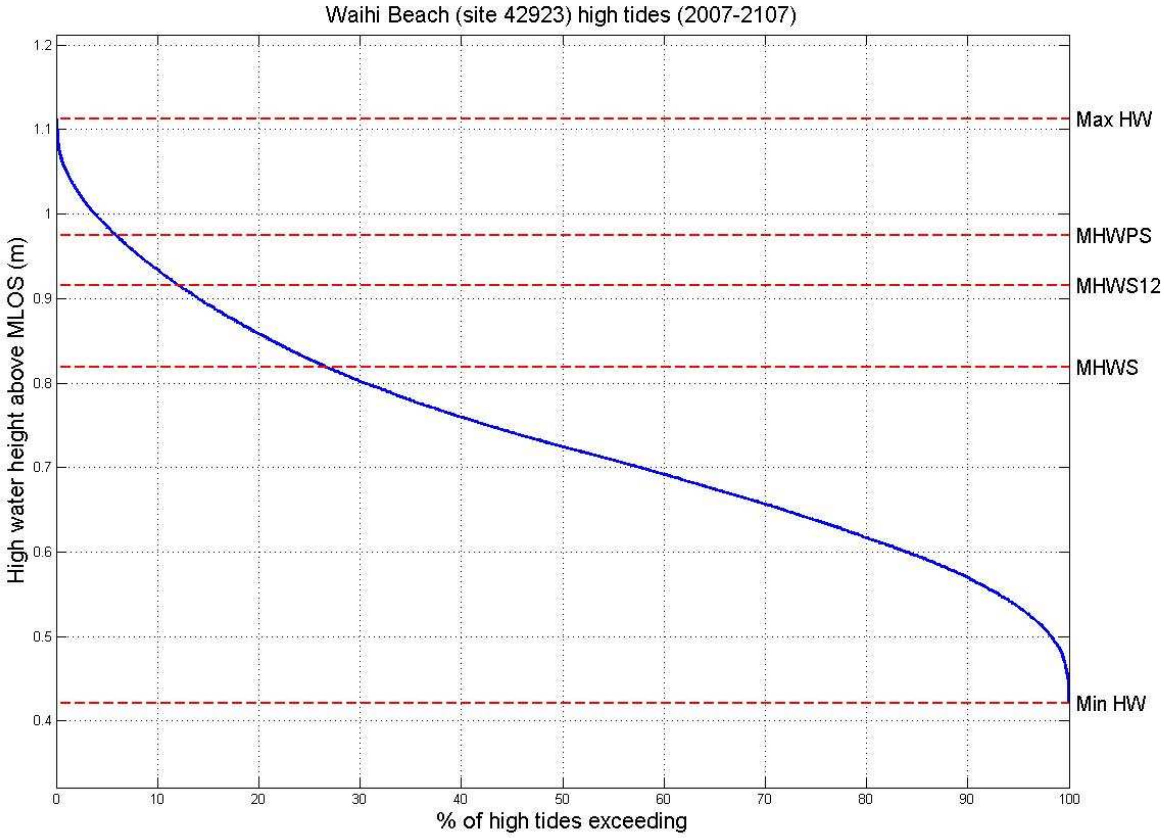

Figure 4.1: High-tide exceedance curve for **Waihi Beach** relative to MLOS (which will vary). Annotation descriptors are given in the text above.

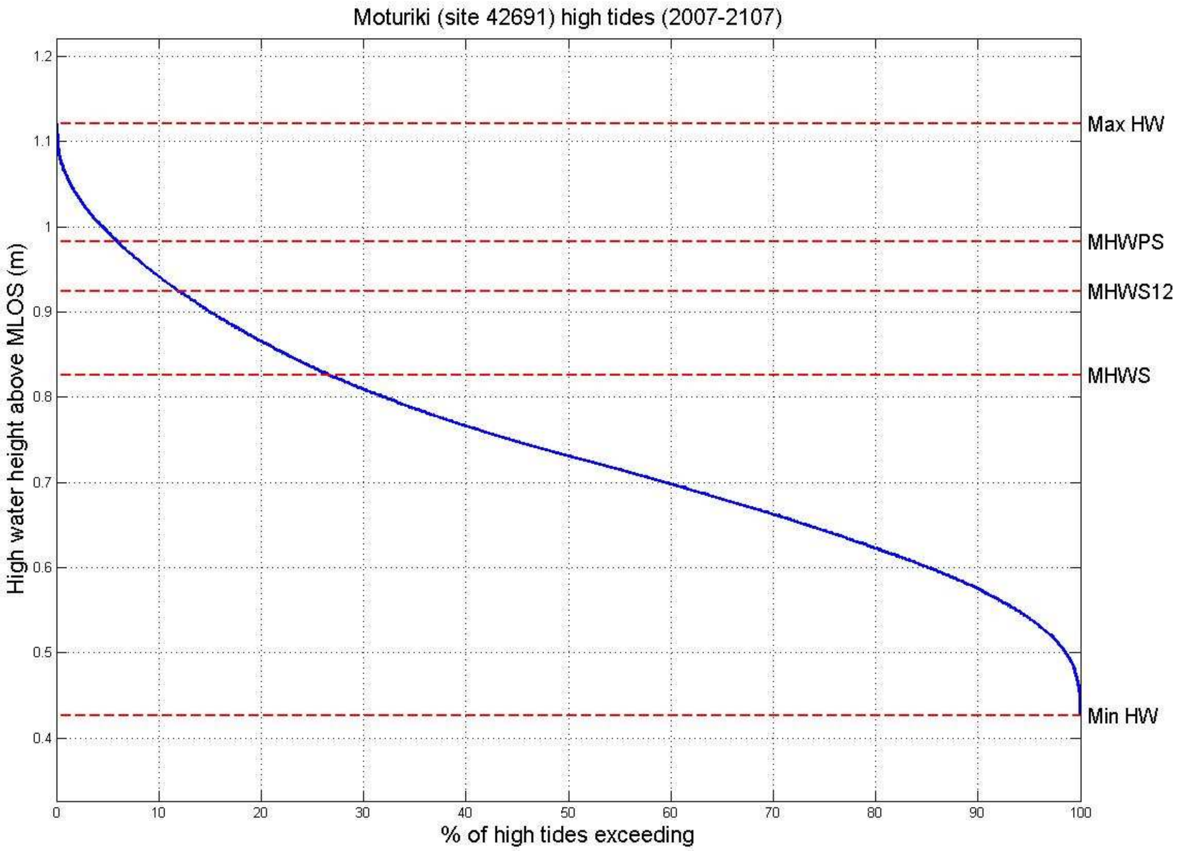

Figure 4.2: High-tide exceedance curve for **Moturiki** relative to MLOS (which will vary). Annotation descriptors are given in the text above.

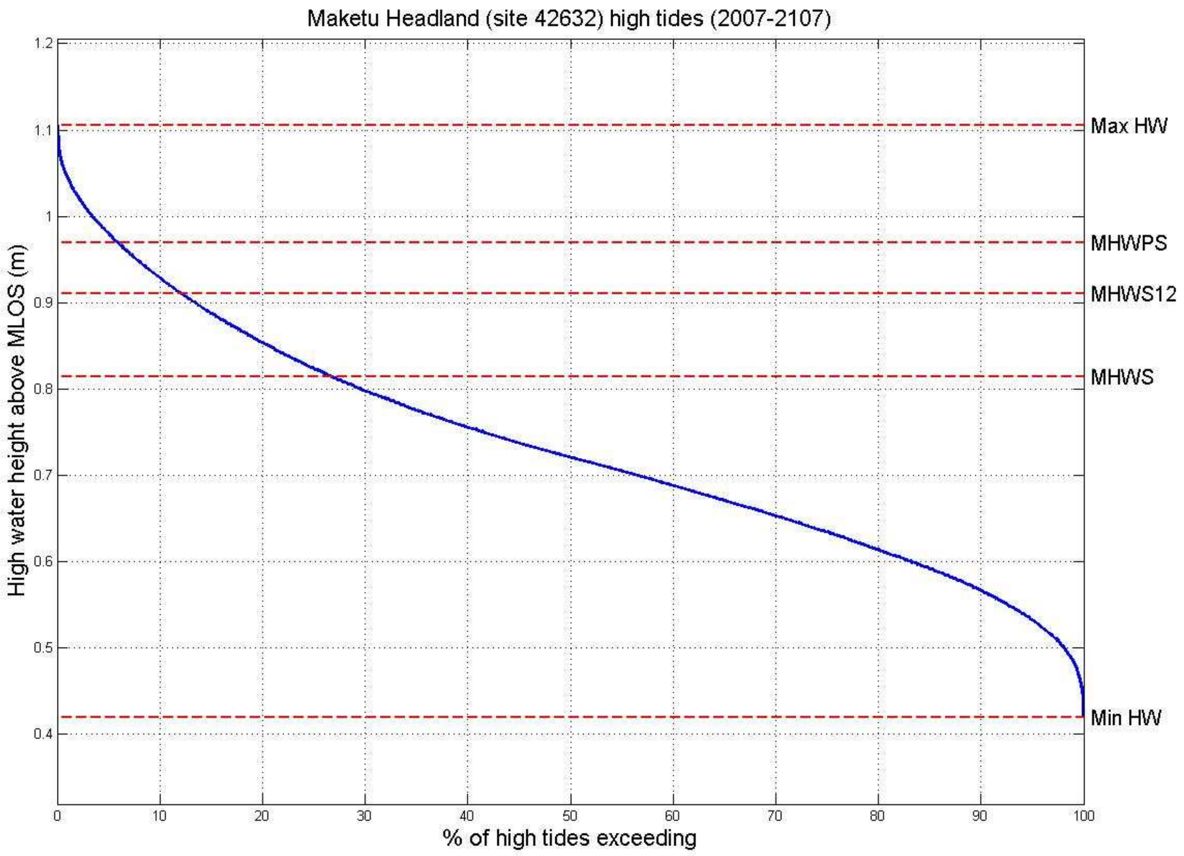

Figure 4.3: High-tide exceedance curve for **Maketu Headland** relative to MLOS (which will vary). Annotation descriptors are given in the text above.

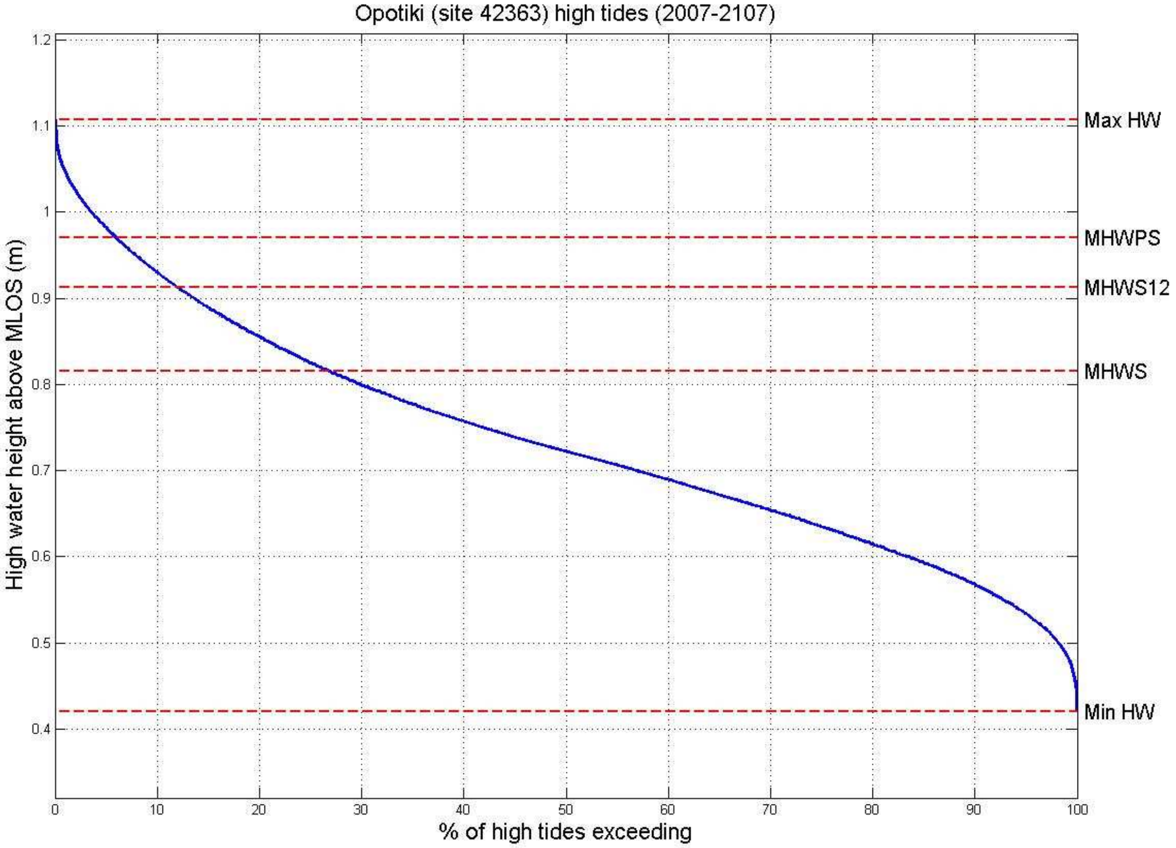

Figure 4.4: High-tide exceedance curve for **Opotiki (open-coast)** relative to MLOS (which will vary). Annotation descriptors are given in the text above.

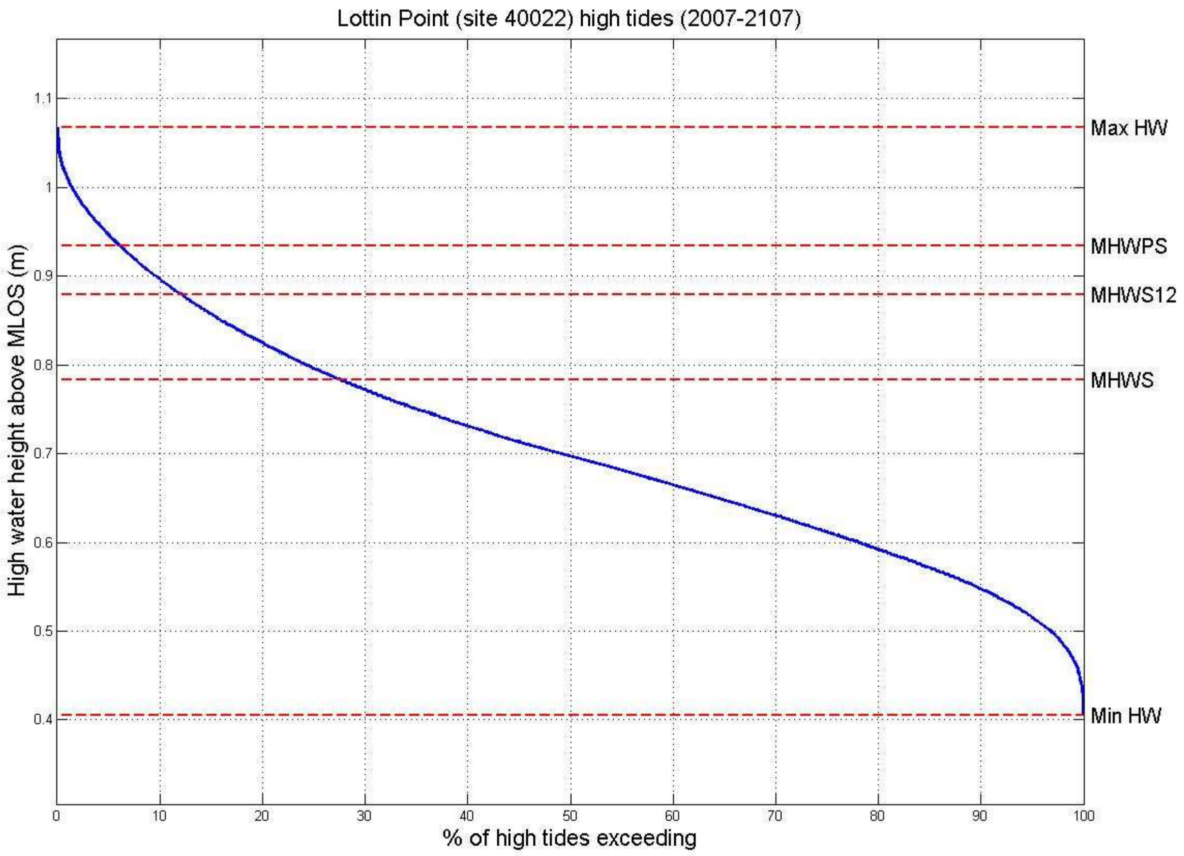

Figure 4.5: High-tide exceedance curve for **Lottin Point** relative to MLOS (which will vary). Annotation descriptors are given in the text above.

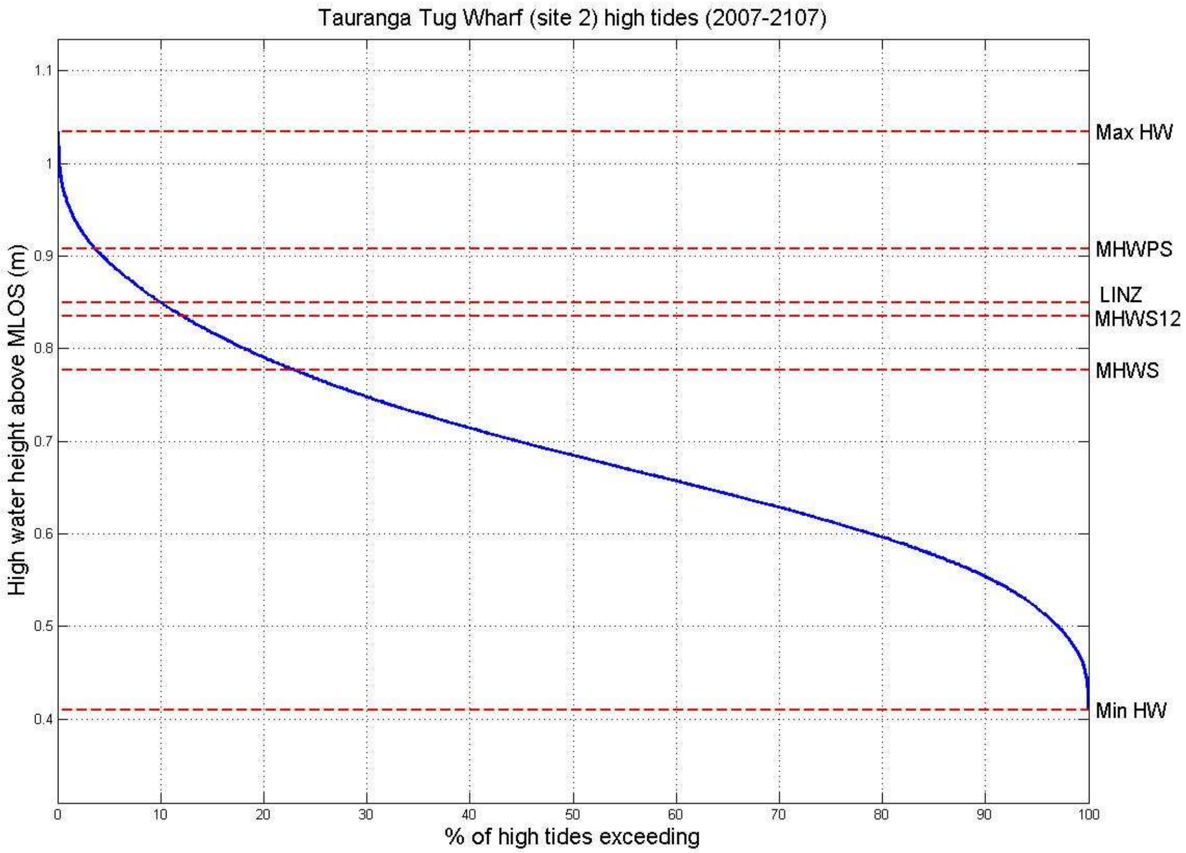

Figure 4.6: High-tide exceedance curve for **Tug Wharf (Port)** relative to MLOS (which will vary). Annotation descriptors are given in the text above.

The summarised results of high-tide exceedance heights for the four selected sites plus Moturiki and Tug Wharf are listed in Table 1.

Table 1: Comparison of various MHWS height definitions and the maximum and minimum high waters from the high-tide exceedance curves in Figures 4.1–4.6, relative to MLOS).

MHWS Definition **Location:**	**Tide-mark height above MLOS [m]**	**% of high tides exceeding this height**
Max HW		
Waihi Beach	1.112	0.0
Moturiki Island	1.121	0.0
Maketu Headland	1.106	0.0
Opotiki (open coast)	1.107	0.0
Lottin Point	1.068	0.0
Tug Wharf (Port)	1.035	0.0
MHWPS		
Waihi Beach	0.974	5.90
Moturiki Island	0.983	5.91
Maketu Headland	0.969	5.90
Opotiki (open coast)	0.970	5.93
Lottin Point	0.934	6.07
Tug Wharf (Port)	0.908	3.64
MHWPS-12 (example)		
Waihi Beach	0.916	12.0
Moturiki Island	0.924	12.0
Maketu Headland	0.911	12.0
Opotiki (open coast)	0.912	12.0
Lottin Point	0.880	12.0
Tug Wharf (Port)	0.836	12.0
MHWS		
Waihi Beach	0.819	26.5
Moturiki Island	0.826	26.5
Maketu Headland	0.815	26.6
Opotiki (open coast)	0.815	26.7
Lottin Point	0.783	27.5
Tug Wharf (Port)	0.777	22.9
Min HW		
Waihi Beach	0.421	100.0
Moturiki Island	0.426	100.0
Maketu Headland	0.419	100.0
Opotiki (open coast)	0.420	100.0
Lottin Point	0.405	100.0
Tug Wharf (Port)	0.410	100.0

To get MHWS levels relative to Moturiki Vertical Datum–1953, you will need to ADD the appropriate MLOS values from Table 2 to the heights in Table 1 above.

We have assumed that MLOS throughout the Bay of Plenty in open-coast locations is going to be the same everywhere as that measured at the Moturiki sea-level gauge. This is a reasonable assumption given that year-by-year variability in MLOS at Moturiki also matches closely with variability at the Port of Auckland, meaning most of the north-east coast is responding similarly to climate cycles (Bell et al. 2006). It is also confirmed by the closeness of the 19-year average MLOS for 1987 to 2005 obtained independently by LINZ for the Port of Tauranga (Table 2). However, there could be some small differences in the Lottin Point area, approaching the East Cape headland, where MLOS could also be influenced by coastal currents to the east and south of the Cape. There are no sea-level measurements in the East Cape area to confirm this or otherwise.

Table 2: MLOS values relative to Moturiki Vertical Datum–1953 (MVD–53) to ADD to any of the high-tide heights in Table 1. The latter MLOS values for 2050 and 2100 have had 0.2 and 0.5 m added to estimates of the 1987–2005 average MLOS, being the most likely mid-range projections for sea-level rise in the Third Assessment Report by the IPCC (see Bell et al. 2006).

MLOS (Location & years)	**MLOS relative to MVD–53 [m]**
MLOS (open-coast/NIWA)—1987 to 2005	0.069
MLOS (Port of Tauranga/LINZ)—1987 to 2005[8]	0.068
MLOS (open coast/NIWA)—2002 to 2005	0.090
MLOS (Port of Tauranga)—2002 to 2005 [*estimate*]	0.090
MLOS (open coast)—2050 [*projection*]	0.27
MLOS (Port of Tauranga)—2050 [*projection*]	0.27
MLOS (open coast)—2100 [*projection*]	0.57
MLOS (Port of Tauranga)—2100 [*projection*]	0.57

The most recent open-coast MLOS for the Bay of Plenty coastline was obtained by averaging the last 4 years (2002 to 2005) of annual MLOS from the Moturiki sea-level gauge measurements as shown in Figure 4.7 (from Bell, et al. 2006).

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[8] http://www.hydro.linz.govt.nz/tides/info/tideinfo5/index.asp

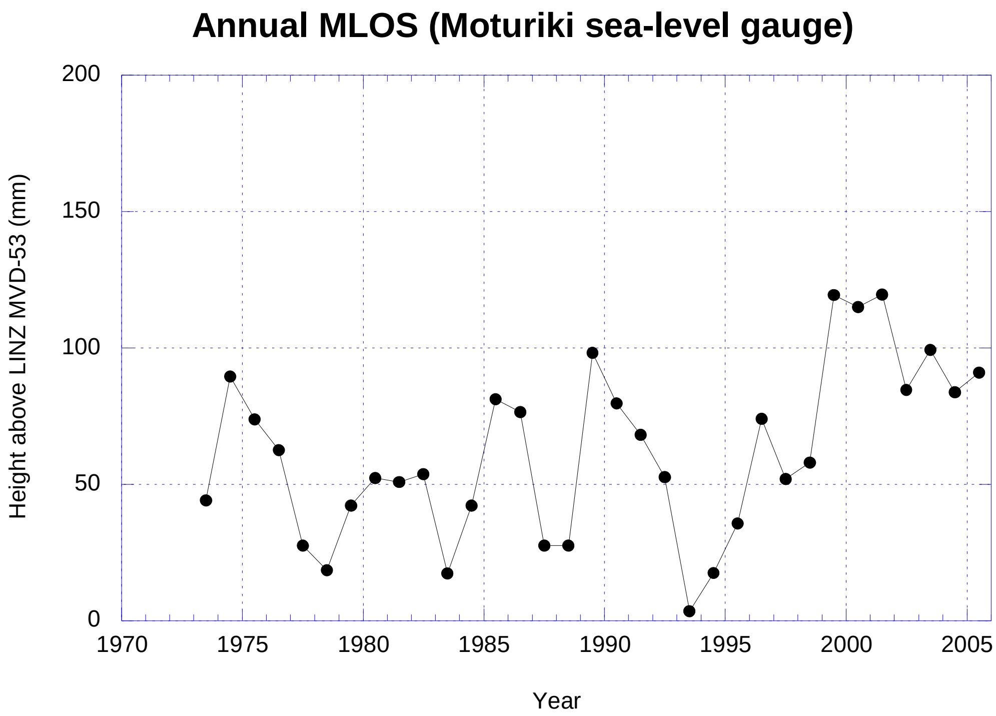

Figure 4.7: Annual MLOS (mm) based on sea-level measurements from the Moturiki Island gauge reduced to Moturiki Vertical Datum–1953.

All the high-tide exceedance curves are plotted together in Figure 4.8 to compare the spatial variability along the coast and include the curves computed from tidal measurements at the Tug Wharf (Port of Tauranga) and Kohi Point. It shows that the is only slight differences in the high-tide exceedance distribution in the wide sweep of the Bay of Plenty from Waihi Beach to Opotiki, but the high tides begin to diminish somewhat towards Lottin Point. The high-tide levels are lowest in Tauranga Harbour, where the tide range is reduced as the tide propagates into the Harbour Entrance and throughout the Harbour channels.

Overall, there is little spatial change in the height (and hence level) of MHWS definitions in the western Bay of Plenty, with local heights peaking in the Tauranga/Waihi and Ohope/Opotiki areas. The largest gradient in MHWS heights (Figure 4.9) occurs in the eastern Bay of Plenty in the stretch of coastline from about Torere (T) around to Lottin Point (LP) near East Cape where a drop of ~3 cm occurs. The contour plot shows that an approximate linear decrease in MHWS height with distance along the coast could be applied to this eastern section of coast. Otherwise, one could argue that a constant MHWS value (using whatever definition is adopted) is applicable to the rest of the Bay of Plenty coast west of Torere.

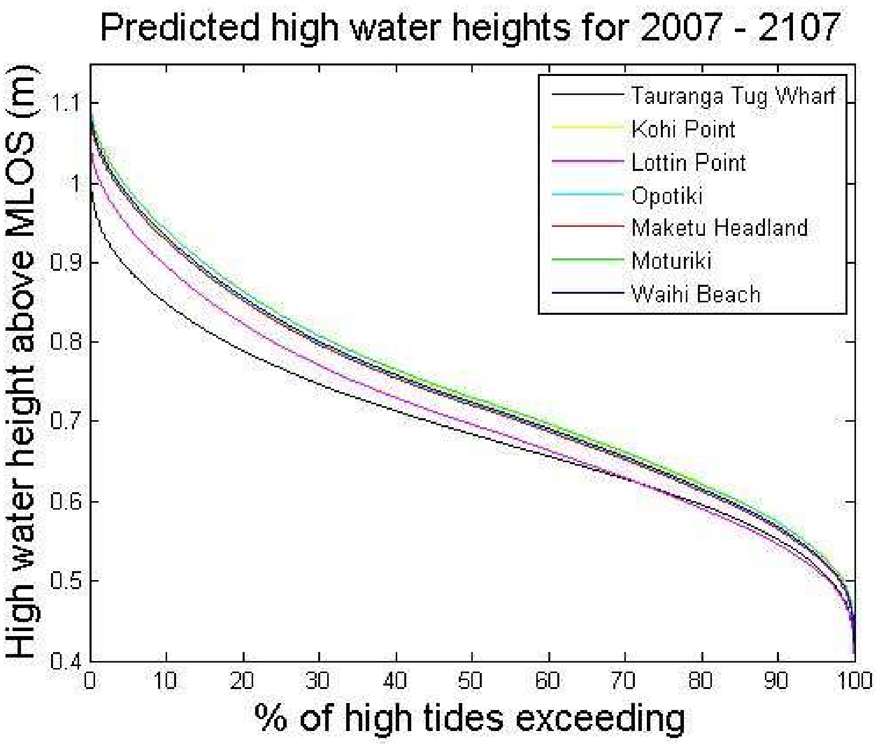

Figure 4.8: Summary of ALL the high-tide height exceedance curves to compare locations.

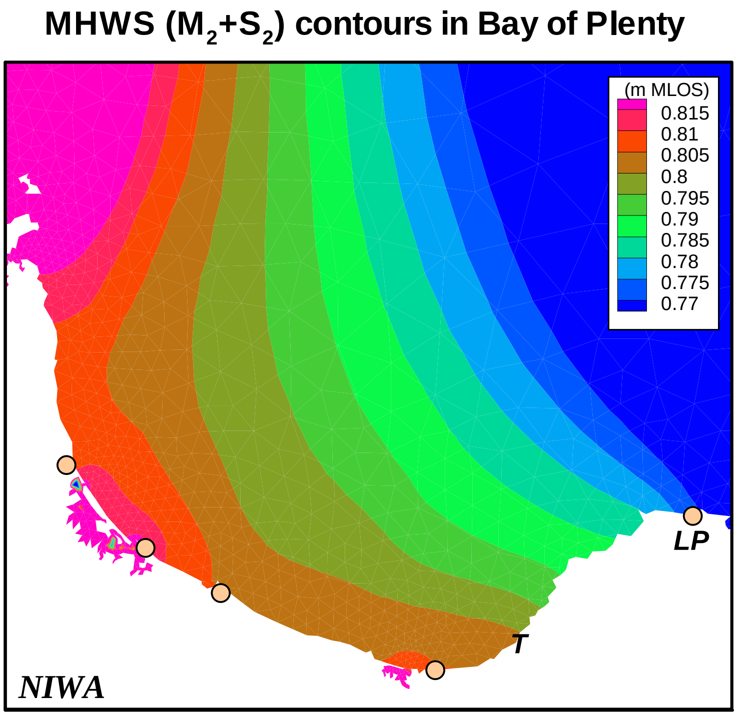

Figure 4.9: Contours of MHWS (based on M_2+S_2 height definition) marked with sites from which constituents were extracted from the NIWA tide model. [T= Torere; LP= Lottin Pt.]

4.1. LINZ definition

The recent change by LINZ in the way they define MHWS at Standard Ports was outlined in Section 3. For the Bay of Plenty, the only location where LINZ has officially defined MHWS is at the Tug Wharf at the Port of Tauranga. The MHWS level of 0.85 m above a 19-year MLOS of 1.03 m (or 1.88 m above Chart Datum) is also plotted on Figure 4.6 along with the other MHWS definitions. The MHWS–LINZ mark is exceeded by 10% of all high tides at the Tug Wharf. This then offers another "definition" of MHWS i.e., the 10-percentile exceedance level for the case of Tauranga Harbour. By extrapolation, the "10-percentile exceedance" concept could also be applied to the open coast of the Bay of Plenty. Because the tide range is different inside the Harbour than on the open coast, the MHWS level at the Tug Wharf will not be the same level (relative to MVD-53) as a 10-percentile exceedance level on the open coast. But MHWS could be transferred from the Port to a locality using hydrographic survey datum techniques e.g., observing MHWS at a locality when the high-tide level at the Port is at the MHWS–LINZ mark (Baker and Watkins, 1991).

4.2. Uncertainty in MHWS levels

An estimate of the uncertainties in calculating typical MHWS heights using the methodology outlined in Section 3 and based on the present-day MLOS, are given in Table 3. This verification indicates that MHWS levels, spanning between the two definitions, using the NIWA tide-model datasets (corrected for bias) are likely to be accurate to the nearest 1 cm compared to the same methods using sea-level measurements that span at least 1 year. This uncertainty by be somewhat higher in the Lottin Point region, given the somewhat different high-tide exceedance curve (Figure 4.8) and the larger distance from the Moturiki reference gauge used to correct the bias in the tide model.

The uncertainty, without correcting for the bias in the NZ tidal model, would have been about 1.9–2.4 cm at Kohi Point, so correction for the bias via Moturiki data has improved the accuracy of determining MHWS heights by just over 1 cm.

There will also be uncertainty in the value of MLOS because of natural variability (see Figure 4.7) which will flow through to the estimates of MHWS level.

Finally there will be uncertainty associated with the measurement or survey technique for establishing the selected MHWS level "on the ground" at any particular locality.

Table 3: Verification of uncertainties in two "mathematical" MHWS heights relative to MLOS comparing the tidal model (corrected for bias) and Kohi Point gauge measurements.

MHWS level	From tidal model (corrected for bias) [m]	From field data (Kohi Point) [m]	Difference [m]
MHWS (Harmonic)	0.8145	0.8234	–0.009
MHWPS (Harmonic)	0.9692	0.9779	–0.009

5. Summary of findings

Defining MHWS can be a complex issue, especially if stricter requirements for its accuracy and appropriateness are required. The strategic importance of a sound definition of MHWS level arises from its use in defining the landward limit of coastal marine area (CMA) on the open coast under the Resource Management Act–RMA (1991) and the landward limit for the foreshore under the Foreshore and Seabed Act (2004).

The report canvasses different approaches to defining MHWS that can be categorised as: mathematical, numerical algorithms and practical application of “natural indicators” of the upper tide level. Case law also upholds a flexible approach which inevitably requires a judgement of what constitutes the MHWS boundary.

In this report, we have coalesced alternative definitions of MHWS for the open coast of Bay of Plenty onto a high-tide exceedance curve, which then provides the context for judging how often any defined MHWS level is exceeded. The exceedance curves provide the frequency at which a given high tide is exceeded based on high-tide predictions for the next 100 years (2007–2107). Tide predictions were based on NIWA’s New Zealand tidal model, and ground-truthed using a 19-year tidal analysis of measurements from the Moturiki sea-level gauge.

These exceedance curves are provided for six sites (five on the open coast and one at the Port of Tauranga) in terms of high-tide height above the Mean Level of the Sea (MLOS). This means the exceedance curves can be used for several decades; with the only requirement to update the MLOS level (above Moturiki Vertical Datum–1953) when there has been sufficient change in MLOS due to long-term climate cycles or sea-level rise.

The high-tide exceedance curves for the open-coast areas of the Bay of Plenty are similar (within 1 cm) for the reach from Waihi Beach to Torere (east of Opotiki), but the high-tide level reduces towards Lottin Point (near East Cape). High-tide levels are even lower in the Port of Tauranga. Consequently, on the open coast, the interpolated MHWS surface could be the same from Waihi Beach to Torere, thereafter reducing linearly eastwards toward Lottin Point.

Finally, a judgement is required to select the most appropriate MHWS definition for the Bay of Plenty. This could be one of those listed in Table 1, combined with an MLOS from Table 2 of this report. Some example definitions of MHWS levels are shown in Table 4, covering MHWS–10, MHWS–12 (10% and 12% exceedance levels), and Mean High Water Perigean Spring (MHWPS) levels. The levels are expressed relative to Moturiki Vertical Datum–1953 assuming an MLOS of 0.09 m (see Table 2).

Further refinement may be necessary at a particular locality in the Bay of Plenty in transferring the MHWS level to a natural shoreline boundary, taking into account "natural" indicators of a MHWS mark, such as edge of "terrestrial" vegetation, toe of dunes, tide marks on fence posts or rocks etc.

Table 4: Examples of a few MHWS level definitions for the open coast of the Bay of Plenty, relative to Moturiki Vertical Datum–1953 (based on the MLOS averaged from 2002 to 2005) and expressed to the nearest cm recognising the uncertainty of the estimates.

MHWS Definition (examples) Location:	Tide-mark level above MVD–53 [m]	% of high tides exceeding this height
MHWPS		
Waihi Beach	1.06	5.90
Moturiki Island	1.07	5.91
Maketu Headland	1.06	5.90
Opotiki (open coast)	1.06	5.93
Lottin Point	1.02	6.07
MHWS–10		
Waihi Beach	1.02	10.0
Moturiki Island	1.03	10.0
Maketu Headland	1.02	10.0
Opotiki (open coast)	1.02	10.0
Lottin Point	0.99	10.0
MHWPS–12		
Waihi Beach	1.01	12.0
Moturiki Island	1.01	12.0
Maketu Headland	1.00	12.0
Opotiki (open coast)	1.00	12.0
Lottin Point	0.97	12.0

6. References

Baker, R.F.; Watkins, M. (1991). Guidance notes for the determination of mean high water mark for land title surveys. Report published by the Professional Development Committee of the NZ Institute of Surveyors. 12 p. + Appendices. http://www.surveyors.org.nz/Documents/MeanHighWaterMark-LandTitleSurveys(1).PDF

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