The Derivation of New Zealand's Monthly and Annual Mean Sea Level Data Sets

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INTRODUCTION

For many decades it was assumed that in the absence of vertical land motion Mean Sea Level (MSL) provided a uniform and stable height datum that could be used as a reference point for topographic mapping and the subsequent development of local and regional infrastructure. Such infrastructure typically included local authority drainage works, road construction, and coastal land development. However, as early anthropogenic related climate change studies began to gather momentum in the 1980s, interest in long-term sea level change also developed. This was in recognition of the fact that any long-term trends in atmospheric temperature should be reflected in changes to the global ice mass balance and in oceanic temperatures – both of which were expected to drive long-term changes to MSL. Such changes in MSL would, in turn, compromise earlier assumptions about the stability of New Zealand's height datums.

In late 1986, with these issues in mind, the Department of Survey and Land Information in conjunction with the Department of Conservation, initiated a project to investigate the records from all 10 of New Zealand's historical tide gauges. While the detailed criteria for the assessment of these gauges are recorded in Hannah (1990), they included issues such as length of record, a well-documented gauge history, the existence of local spirit levelling, and the likelihood of data contamination from local river flows. At a result of this assessment, the tide gauge data from the ports of Auckland, Wellington, Lyttelton, and Dunedin were selected for digitisation and analysis.

While this early project formed the starting point for the development of the monthly and annual MSL data sets used today for the analysis of long term sea level trends, these data sets have been upgraded and augmented over the past three decades. To ensure completeness and provide a definitive document for future use, this report will detail the origins of the data used in both the monthly and annual data sets, the problems that had to be overcome, and the modifications made to the data so as to ensure the construction of a homogeneous and reliable MSL record.

THE ORIGINS OF THE SEA LEVEL DATA

The annual MSL data sets have been derived from a variety of sources, all of which are shown in Table 1. Land Information New Zealand (LINZ) is now the official repository for all hourly sea level data and the source of all post-1998 data. The monthly MSL data set is only available for those time periods for which hourly (or higher frequency) digital data have been able to be collected. In deriving these data sets the following should be noted.

1. Prior to the 1990s, the primary data source for the monthly and annual data sets has been the old graphical tide charts collected by the former Harbour Boards. These tide charts were digitised to give an hourly sea level data set. This hourly data was then processed into daily, monthly and annual means.
2. In many cases and in the earlier years of some of the tide gauges, the original tide charts that showed the hourly sea level data were not available. However, in some of these cases old files kept by the Department of Lands & Survey had records of the calculated annual MSL. Where original tide charts were still available and where the corresponding annual MSL was also found on file (a total of 25 years of data), the two were checked. In every case the

correspondence between the two numbers was within ±5 mm. Given the quality of some of the charts and the accuracy with which they could be read, this was considered to be a satisfactory verification of the calculated annual MSL figures.

3. In Wellington, none of the pre-1945 tide charts had been kept. The only data available were a few derived MSLs and documents showing Mean Tide Levels (MTLs) for all of the years between 1903 and 1970. Whereas a MSL is derived from hourly tidal data (or, as in more recent years, from higher frequency data), a MTL is merely the mean of the daily high and low waters as recorded over a given period of time. It is not only less accurate than a MSL but it may also be biased due to a lack of symmetry in the tides. Using the years for which both MTLs and MSLs were available a mean correction between the two was derived and applied to the earlier MTLs in order to construct an approximate MSL for the missing years.

4. Not all years for which digital hourly data are shown are complete – some records have significant gaps. MSLs have been calculated for every month in which at least one half of the hourly data has been available. Standard deviations for each annual MSL are calculated based using the expression $0.09/\sqrt{n}$ where n = the number of months of data present.

Table 1. The Origins of the MSL Data

	Auckland	Wellington	Lyttelton	Dunedin
Harbour Board mean tide level records held by the local Regional Council.		1891-1893		
Archived annual MSL records (Dept. of Lands & Survey files).		1901, 1909, 1915, 1919, 1921-1924, 1927, 1930, 1933, 1936, 1937, 1939, 1942	1901, 1907, 1908, 1914, 1918, 1919, 1923	1911, 1926, 1927, 1929, 1932, 1935, 1937
Archived mean tide levels (Dept. of Lands & Survey files).	1899-1901	1903-1908, 1910-1914, 1916-1918, 1920, 1925, 1926, 1928, 1929, 1931, 1932, 1934, 1935, 1938, 1940, 1941, 1943, 1944		
Digitised hourly sea levels taken from the original tide gauge charts.	1903-1945, 1947-1998	1945-1998	1903, 1904, 1906, 1913, 1924-1988	1900-1903, 1905-1910, 1912-1915, 1918, 1919, 1921, 1923-1925, 1936, 1938-1942, 1944-1952, 1954-1980, 1983-1990, 1996-1998
Digital hourly data provided by port authorities to LINZ	1998-2013	1998-2013	1989-2013 [see note]	1999-2013

Note: Lyttelton data from Feb.1989-May 1992 supplied by the port authority as monthly means only.

DATA VERIFICATION

The processes used for verifying the quality of the original digitised hourly sea level data files and any editing undertaken, have been outlined in detail in Hannah (2004). Rather than repeat this information it is sufficient to note that the digitized data have all been processed using the Sea Level Data Processing software from the University of Hawaii. Details about this package can be found in Caldwell (1998). During this processing, obvious digitizing errors in the original data were eliminated. Any errors in the data that related to timing (generally the tide gauge clock being in error by up to one hour) were left unchanged on the premise that it would have a negligible effect on monthly MSL averages.

While similar processes have also been used on the digital data more recently produced from the newer digital tide gauges, it is worth noting that with appropriate sound velocity calibration, the quality of the current generation of digital tide gauges is far improved upon the analogue gauges used in earlier decades. Data frequency, if required, is also much improved.

Given appropriate care with internal gauge calibration (so as to ensure a correct reading of the spatial position of the water surface), there remain a variety of other error sources that may contaminate a long term sea level record. These include:

- Unrecorded movements in the gauge zero reference point.
- Vertical movements in the wharf structures to which the gauge is attached.
- Vertical land motion (either of a local or a regional nature).

In the following section the corrections made to the monthly and annual MSL data for each of the tide gauges and for all of these factors are outlined. It is these corrected files that have been supplied to NIWA and that have been used by the author for his analyses of New Zealand's long-term sea level trends. The author continues to hold copies of the uncorrected raw data files.

DATA MODIFICATIONS

1. Auckland

The Auckland data set is by far the most complete and consistent of all the New Zealand MSL data sets. Unfortunately, with the corporatisation of the former Harbour Boards in the 1990s, the quality of the data collected at that time deteriorated. This problem had largely been overcome by 2003.

The most significant datum change applied to the raw monthly data was a shift of 0.5 feet at the start of 1973 to compensate for a change to the tide gauge zero point.

Post-1998 the Auckland data has been sourced from LINZ who applied a +0.0347 m datum correction for the period 1 January 2001- 8 May 2003 prior to data delivery. A new gauge commenced operation on 1 January 2001 but in May 2003 its zero level was found to be incorrectly set. LINZ assumed that this correction was applicable over the entire 2.35yr period. Despite the movement of the gauge in the late 1990s and the installation of this new gauge (with the above correction), a thorough investigation by Beavan (2002) supports the view that the datum zero remains consistent with that used since 1973.

2. Wellington

Correspondence files from the Department of Lands & Survey indicate that a new tide gauge was installed in 1944, beginning operation in November of that year. None of the tide charts prior to that time have been found. Unfortunately, with the installation of the new gauge, there is some evidence to suggest that continuity of datum may have been lost. The correspondence files note a sudden, apparent change in Mean Sea Level between 1944 and 1945 of 0.2 feet. For this reason, the long-term analysis of MSL trends undertaken by

Hannah (1990) and again in Hannah (2004), solve for two datum bias parameters. Given that the monthly MSL data set only begins at the time of the installation of the new (1944) gauge, no adjustment to the gauge zero for this discontinuity has been required.

File notes from the Department of Lands & Survey indicate that the gauge zero was shifted by 1.0 feet at the end of April, 1973. This shift is clearly evidenced in the raw data. The monthly and annual MSL data sets since that date have been adjusted accordingly.

Leveling undertaken by Beavan (2001), when combined with earlier leveling, supports the view that the wharf structure to which the tide gauge is attached subsided at a rate of 0.002 mm/yr from 1945 -2001. The monthly and annual MSL data files from 1946 onwards have been corrected for this effect. Subsequent leveling in 2005 indicated no further subsidence since 2001. The TG system has been assumed to be stable since then.

The data collected from the Wellington gauge since 1944, has been of a high quality. The transition to a digital data collection system that began on 1 January 1998 seems to have been managed very well indeed.

3. Lyttelton

In general terms, the tide gauge record is not clean and continuous. In places the data reflect poor gauge maintenance and have many gaps. These problems are particularly true for the pre–1960 data and again from mid-1988 to mid-1994. Considerable quality assurance work was required to eliminate the obvious problems. Since mid-1994, consistent digital data, although noisy when viewed as 5 min point data, have been giving accurate monthly and annual MSL means. Unfortunately, the earthquake sequences that began in September 2010 have created considerable problems with data reconstruction.

Using archived files from the former Department of Lands & Survey, a complete review of the gauge history was undertaken in 2008. This revealed the following:

(i) The tide pole was moved in 1934 but care apparently taken to ensure that continuity of datum was maintained. However, leveling in 1970 shows the tide pole as being -0.04 ft (0.012 m) lower than in 1940. In the absence of information as to when this change occurred, the period has been split in two segments with no correction being applied to the MSL data from 1940 -1955 inclusive, but -0.012 m being applied to the data from 1956 – 1970. Given the evidence for tide pole stability from 1970 – 1980, this correction has been applied up to and including 1980.

(ii) A new metric tide pole was installed in 1980. Leveling in 1981 showed this pole as being 0.08 ft (0.024 m) too low. In 1987, the local Port company returned the pole to its pre-1981 position. A correction of -0.024 m has thus been applied to all the MSL data from 1981-1987 inclusive. A correction of -0.012 m has continued to be applied to all MSL data thereafter.

(iii) In 2001, the tide pole was moved and a new tide pole installed. At that stage the datum was lowered by 0.96 ft (0.293 m). Thus, all raw MSL data from 2001 onwards must first be corrected by (-0.293 m) and then again corrected again by -0.012 m in order to ensure consistency with the pre-1956 data. These two corrections are ongoing and have been applied through to the end of 2011.

Following the Christchurch earthquake sequence, a number of data changes have been made. The notes below summarise material provided by Glen Rowe, Tidal Officer (LINZ).

a. The Darfield earthquake (4 Sept.2010) caused uplift of an estimated 6 mm at the TG. A decision was made to maintain Chart Datum at its historic height. For this reason all tide gauge readings from 04:35 hr on 4 Sept. 2010 have been increased by 6 mm.

b. Subsequent earthquakes on 22 Feb. 2011 (Christchurch), on 13 June 2011 (Godley Head) and on 23 Dec. 2011 caused uplift of 54 mm, 48 mm and 32 mm respectively at the TG. In the light of the decision to retain Chart Datum at its historic height, the raw TG data for 2011 have been adjusted as follows:

   i. 1 Jan. 2011 – 22 Feb.2011. 6 mm added to all data.
   ii. 22 Feb. 12:51 hr – 13 June 13:00 hr. 60 mm added (6 + 54).
   iii. 13 June 13:00 hr – 23 Dec. 13:58 hr. 108 mm added (6 + 54 + 48)
   iv. 23 Dec. 13:58 hr ongoing. 111 mm added (6 + 54 + 48 + 3)

   Subsequent levelling in 2012 showed that the earthquakes had caused a total uplift at the TG of 111 mm. Thus the raw TG data since 13:58 hr on 23 Dec. 2011 have had 111 mm added. However the data from 2012 onwards show significant and unresolved inconsistencies and for this reason have not yet been added to the monthly and annual MSL data sets.

4. Dunedin

This gauge has also been the object of poor maintenance over the years. There are very significant data gaps, even in the last three decades. There is, for example, a long data gap that runs from mid-1990 until January 1996. A new digital gauge was installed in mid-1999 since which time good data has been produced. At the same time a new gauge was installed at Port Chalmers thus enabling the two gauges to be run in parallel with each other.

Archived file notes and leveling records from the Department of Lands & Survey indicate that the tide-pole was incorrectly positioned by 0.03 ft (0.009 m) between 1964 and 1973. In 1974, when the tide pole was replaced (date uncertain), the zero was found to be 0.027 m too low. Thus all raw monthly and annual MSL figures from 1964-1973 inclusive, have been corrected by -0.009m. The 1974 mean has been corrected by -0.020 m.

1. During the period 1964-1979, the local tide gauge bench mark subsided 0.033 ft (0.00063 m/yr if the movement is considered linear) but the levels from this BM to the 8 ft mark on the TG and to the TG bracket remained unchanged relative to this BM. Thus, in addition to the datum changes noted above, a linear correction of -0.00063 m/yr has been applied at all MSL data from 1963-1979 inclusive.

2. In 1980 the position of the gauge was changed. While the TG BM (beside the old wharf structure) has continued to subside, recent leveling has confirmed the stability of the TG in its new position. No other corrections to the MSL data have thus been necessary.

TECTONIC DEFORMATION

Since 2000, vertical land motion at the Auckland, Wellington, Lyttelton, and Dunedin tide gauges have been monitored using continuous GPS measurement (cGPS) techniques. While this data is currently being prepared for publication (Denys, personal communication), they indicate that general tectonic motion, earthquakes, and slow slip seismic events have had, and are continuing to have a significant impact. At Wellington, for example, there is evidence of a regional subsidence in the order of 3 – 3.5 mm/yr upon which uplift due to slow slip seismic events is superimposed. No corrections have been applied to any of the tide gauge data for these effects.

The Lyttelton site, on the other hand, has been subject to considerable vertical movement as a consequence of the earthquake sequences that began in 2010. As documented earlier, the raw sea level data have been corrected for these events with the monthly and annual sea level means referenced to the pre-2010 datum.

For a number of years the Dunedin region was thought to be stable, although recent cGPS data is bringing this assumption into question. Efforts are presently underway to try to quantify the extent of any vertical land motion (Denys, private communication).

In total, Auckland is the only site that shows overall stability, at least over the monitoring time period. Due to the length of its record and its overall quality, it is vital that every effort is made to ensure good maintenance and monitoring of this tide gauge over the long term. This record is a very important part of global sea level change analyses.

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