Waituna Lagoon Mouth Closure: Summary Report

Report prepared for Environment Southland, March 2013

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Executive Summary

This report summarises the available meteorological and hydrological data prior to Waituna Lagoon closure. It also assesses the likelihood of whether these conditions can be used a predictors for lagoon closure, and what conditions disrupt the closing process. Understanding the processes involved with Lagoon closure is a priority for the Environment Southland, and its partner in the Waituna Lagoon response.

The key findings from this report are:

- The winter months the best chance of Lagoon closure

, due to light to moderate wind speeds from cross-shore directions
No closures have occurred in February, and only three closure have occurred in ummer in the last 40 years

- Wind direction and wind speed highly variable prior to closure, with no closureClosing conditions vary month
- All closures are initiated about 2-4 days prior eap tidehis time period is likely the only closing window over the whole tide cycle
- No closures have been recorded on pring tides
- Only tide can be used as a predictor for closure, as localised weather conditions cannot be accurately forecast outside 3 days
- Catchment rainfall needs to be minimal, and flows in Waituna Creek approaching median
- There is little difference between the conditions prior to Lagoon closure and during prolonged open periods
- For successful closure, there needs to be alignment of tidewind
- The alignment needs to be over the critical period leading up to the tides for a successful Lagoon closure
- The influence of onshore (S/SE) winds on long-shore drift patterns requires further investigation

1.0 Introduction

Since 1908, Waituna Lagoon has been mechanically opened to the sea to drain land and increase farm productivity. The catchment has undergone significant development since then, especially in the last twenty years, transforming into a productive dairying region. Waituna Lagoon, an internationally renowned RAMSAR site, has not fared so well and its current degraded state has been well documented. This report seeks to prevent the lagoon's further degradation into an algae-dominated water body by examining the conditions under which the lagoon closes. By understanding the natural conditions that lead to the lagoon closing to the sea, Environment Southland and its partners may be better able to manage the Lagoon.

desired healthy state for Waituna Lagoonfresh-water lagoon with a short marine phase when open to the sea. However, in more recent times it has been open to the sea for many months, becoming more estuarine in nature than the desired freshwater or brackish state (LWCA opening data 1972-2012). However, seawater flushing is now required because nutrients the lagoon are and may lead to the conditions sustained phytoplankton blooms. But when the lagoon is open to the sea for too long it has the negative effectreducing the desired macropyhte plants necessary for good lagoon health, and instead enhancing nuisance macro-algae.

Modelling work undertaken by Waikato University last year suggests 1 to 3 months is the optimum opening time, to reduce the likelihood of phytoplankton blooms and protect native species, under the current catchment nutrient loads. The problem is the lagoon's closing process is natural, poorly understood and largely unpredictable. Previous work and local observations have highlighted the chaotic nature regarding coastal dynamics and lagoon mouth closures. Narrowing the gaps in understanding the Lagoon closure, including the conditions resulting in prolonged openings, is now a priority for the Waituna Lagoon Technical Group, Environment Southland, the Department of Conservation and Iwi.

1.1 Objectives

As accurate prediction of meteorological conditions beyond three days is not possible, this report's specific purpose was to:

1. Summarise the meteorological conditions prior to Waituna Lagoon closing.
2. Determine if these conditions can be used to assist in highlighting periods when the lagoon is likely to close.
3. Summarise and quantify the conditions which exist in prolonged openings of Waituna Lagoon

4. Assess the meteorological conditions, which disrupt the lagoon closing process, where data exists.
5. Provide information to the Lagoon Technical Group and Environment Southland and its partners, which will aid in managing the lagoon to improve the ecological health of the system.

2.0 Environmental Setting

2.1 Coastline description

Waituna Beach in Toetoes Bay is a steep reflective coastline comprising gravel and mixed sand. The wave environment is slightly sheltered from the larger SW swells of Foveaux Strait. However, wave heights up to 2-3 metres are common, which can result in significant wave run up and overtopping of the Waituna Lagoon barrier. The Toetoes Bay area also has calm sea and wind conditions, especially in Easterly weather patterns.

Waituna Beach is a drift-aligned beach (Figure 1), with no clearly defined wave zone offshore, but with very confined swash zone close to the shore. This means the near shore wave environment is dominated by 'up rush' surges and 'backwash' events. This is instead of rolling lines of broken waves sweeping up the beach, which are more typical of flatter sandier beaches. Often drift-aligned beaches and swash zone coasts are erosive, due to a finite sediment supply after the last glaciation, and where mobilisation of sediment is in a single direction along the coast. Kirk and Lauder (2000) suggest Waituna Beach is rotating around a 'hinge' immediately East of the opening at Walker's Bay. The section of coastline West of this point is aggrading, whereas the section of coast to toward the Matuara River mouth is eroding and rotating Northward. The sediment supply on drift-aligned beaches can also be non-linear, with noticeable 'slugs' or 'pulses' of gravel moving along the coast. Neale (1978) states these under-nourished sections of coast are vulnerable to erosion, overtopping by wave run-up and breaching in storms. These characteristics are consistent with observations on Waituna Beach (Owen 2000-2012, pers obs, Larkin 2007-2012 pers Obs, LWCA members, 1972-2012).

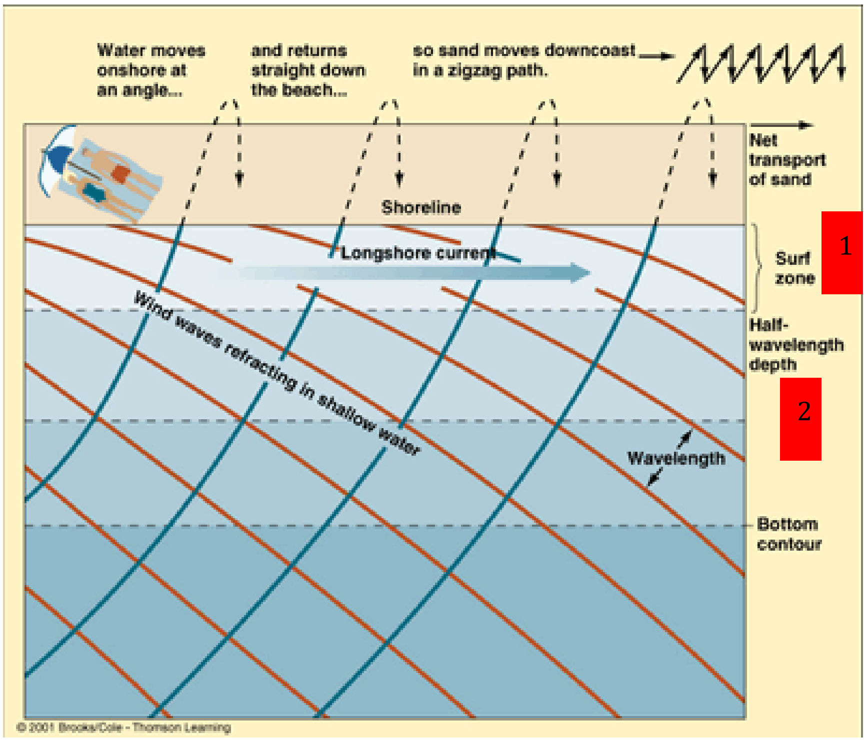

Figure 1 Sediment movement along drift aligned coastlines

2.1 Drift aligned coastlines: description cont'd

The shore environment for drift-aligned coastlines is described below. It is assumed similar coastal processes and features exist on Waituna Beach. However, until accurate surveying of bathymetry, combined with categorising the wave and long-shore drift environment, subtleties may be overlooked and bias may occur.

2.1.1 Coastline morphology

Typically on drift-aligned coastlines the shallow sub-tidal swash zone or 'step' is 0-3 metres deep (No 1 in 1). The swash zone or 'step' doesn't vary over the tidal cycle between high and low tide, but is confined within the 0-3 depth band (Kirk & Lauder, 2000). Wave run-up, however, does differ with the tide, with higher tides resulting in higher wave run-up on the beach face. On steep ($17\text{-}24^0$) beach faces, such as Waituna beach, more coarse and well-sorted gravels are pushed higher on the beach face, whereas small grain sizes such as sand are lower on the beach and often subtidal. Drift-aligned beaches are largely formed by the successive swash and backwash events, and there usually a series of ridge and cusps along the mid to high-tide beach, made up of larger gravels (4-7mm).

Below the swash zone often exists a deeper gravel and sand bank (No 2 in Figure 1), in approximately 3-5 metres water depth. The two distinct zones (gravel banks and swash zone) are morphologically different in both grain size and composition, and have differing rates of sediment movement. Typically, the swash zone mobilses only one-tenth of the sediment, which the deeper gravel bank transports (Kirk and Lauder, 2000).

2.1.2 Long-shore Drift patterns

For drift-aligned coastlines, the direction of the dominant long-shore drift is a function of the angle that waves break on the step, or over the swash zone. For Waituna Beach, the long-shore drift has been noted to travel both Eastward and Westward, depending on wind and sea conditions (Larkin, 2008-2012 pers bs, Hick, 2011,pers obs, Bradley, 2002-2012 per bs, Kirk & Lauder 2000). Therefore, long-shore drift and thus gravel movement appears changeable on a daily time series, due not only to weather and tide in Toetoes Bay, but possibly on larger cycles (5-10 years) related climatic variation.

For the Waituna Beach, interpreting how the dominant swell and wind conditions affects the swash zone, and hence long-shore drift requires considerably more investigation. For example, it is not known if smaller shorter period swell from a cross-shore angle increases the long shore drift and gravel depositions opposed to larger direct onshore swells or winds, which may disrupt the swash zone and possibly slow long shore drift.

2.2 Coastal Lagoon Mouth Dynamics

Coastal Lagoon mouth dynamics have been studied extensively in New Zealand in relation to Hapua type iver mouths, and hydrological variability in the iverine inputs (Hart 2007, Kirk & Lauder 2000). However, there is a paucity of data related to Lagoon mouth dynamics, resulting from artificial breaching, and in particular the behaviour of non-estuarine coastal lagoons, such as Waituna. Hart (2007) states non-estuarine mouths can be categorised into three states; 1) a stable mouth; 2) a mouth which undergoes movement by daily; and 3) a highly unstable mouth which can move many tens of metres daily.

Waituna Lagoon mouth at Walker's Bay has been observed in all three of these states (Owen, 2012, pers obs, LWCA members obs, 1972-2012, Larkin, per obs 2007-2012). After mechanical breaching the mouth reaches a semi-stable state in several days, with an elongated gravel bank extending down-current of the dominant long-shore drift (Figure 2 & 3). Depending on local meteorological conditions this stability may remain until closure, but more often, the mouth becomes unstable and begins a process of daily migration with tide and varying sea state. The mouth can migrate between 10-60 metres in width over the course of a day (Owen, 2012, Larkin, 2007-2012 pers obs).

Figure 2 Walkers Bay opening July 23rd 2005. The lagoon had been open 16 days, Note the elongated gravel spit formed by the dominant astward drift, however, on the day of the photo the long-shore drift was est as evident by the plume dispersal.

Figure 3 Walkers Bay 2011, November 2012. Note the large gravel bank in front of the recent opening. This material was subsequently moved in the following days to form an elongated gravel bank

2.3 Waituna Lagoon Mouth closure: synopsis of observations

The below sub section is a summary of the observations in the days leading up to Lagoon closure. It is not a definitive explanation for all of the processes involved but rather is a generalised account of observations and some of the factors involved prior to mouth closure. The photo sequence is from Walkers Bay (Owen, 2012)

2.3.1 Walker's Bay mouth closures

The process of Waituna Lagoon closure at Walker's Bay is often initiated approximately 2-4 days before its closure, depending on the prevailing and stability of weather conditions in Toetoes Bay (Owen. pers observation, 2000-2012). If conditions are favourable, a 'finger' of gravel extends over the breach hole, enhanced by long-shore drift (Figure 4). Once the opposing bank reached (Figure 5 & Figure 6), a berm is created in the breach. The berm then provides a base for more material to accumulate, and where berm height is increased by successive wave run-up events generated from the swash zone (Figure 6).

Figure 4 Initiation of Walker's Bay mouth closure. Note the gravel finger beginning to migrate over the mouth.

Figure 5 Continuation of gravel across the mouth and formation of the berm

Figure 6 Approaching closure at Walkers Bay. Note the lea state very confined and active swash zone

2.4 Overtopping

If continuation of height gain on the newly formed berm is sufficient water flow is usually cut off at slack tide and the lagoon closes. However, it often requires successive high tides and favourable meteorological conditions to increase the height further to reduce over-topping.

There are examples in the Waghorns Road hydrological record, (Figure 7) where the lagoon partially closed but the berm height was insufficient to stop overtopping. For the example in Figure 7, the lagoon remained closed, but was overtopped for 2 weeks before the berm height was sufficient to stop over-topping.

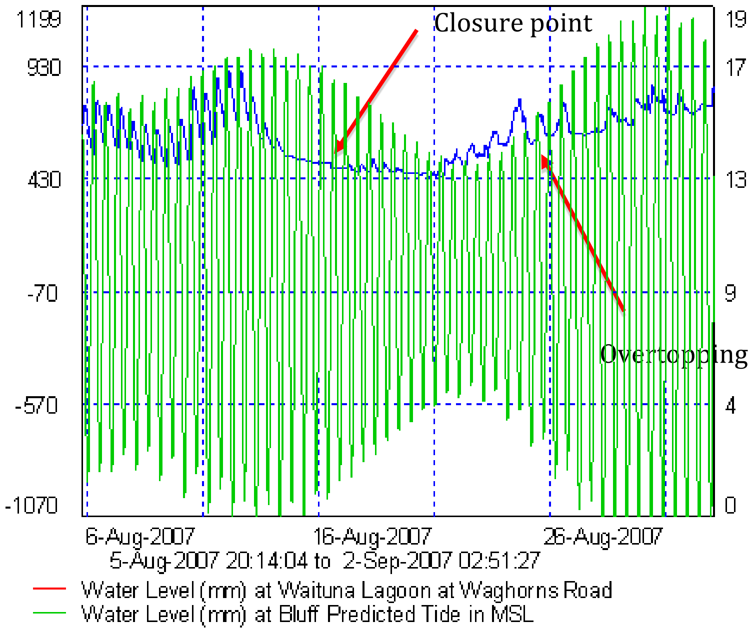

Figure 7 Waituna Lagoon closure August 2007 and subsequent overtopping

3.0 Methods and methodology

3.1 Data Handling and Analysis

3.1.1 Waituna Lagoon Closure

To summarise the spatial and temporal data prior to Waituna Lagoon closure, only the data in the preceding two days of the closure were examined. The time step of two days was utilised after examining the hydrological trace at the Waghorn's Road water level recorder. Approximately, two days before closure, the water level trace became erratic but with noticeable flat spots. These fluctuations were not related to wind and other hydrological interference such as rainfall and/or equipment failure. Furthermore, local observations suggest the mouth is 'prepped' for closure approximately 2-4 days prior to the actual closure point (Owen, 2012 pers).

In this report, all Waituna Lagoon closures over the past 40 years have been at Walker's Bay except on three occasions (in 1972 at the 'Fence', and 1976 and 2011 at Charlie's Bay).

The parameters summarised in this section were wind speed and direction, swell direction, swell height and swell period. All wind data was summarised month, with each parameter average using a equally weighted summary tool developed by Environment Southland (Jenkins, C 2012)

The hydrological inflows from Waituna Creek at Marshall Road (2001-2007, 2011-present day) and total inflows from all inputs to Waituna Lagoon summarised for four days prior to Lagoon closure. The time step of four days, instead of two days was utilised to examine the trend in daily flows to the lagoon.

Total simulated inflows were calculated by adding the flow record from the rated water level recorders at Marshall Road and the Moffat Creek at Moffat Road. Flow relationships between these two sites and Carran Creek (r^2=0.98) and the Carran Creek tributary (r^2=0.91) were then generated. All other inputs were summarised based on land area, rainfall and landuse. For data before Waituna Creek water level recorder, the technique was the same but based on regressions from the Waihopai River flow.

3.1.2 Summary of prolonged openings

To summarise the data during prolonged Waituna Lagoon openings (over 30 days), data at midnight on the day of opening, and the closest known hour after closure was examined. Pre-2000 all Waituna Lagoon opening and closing times were made by personal observations from LWCA and local community members. Post-2000, these observations were corroborated by the Environment Southland Waghorn's Road water level recorder, seven kilometres from Walker's Bay. Therefore, bias may exist where the actual closure time may be several hours different than that reported to Environment Southland.

The parameters summarised in this section were wind speed and direction, swell direction, swell height and swell period, along with Southern Oscillation Index. All wind data was averaged using a tool designed to equally weight wind direction and wind speed (Jenkin, C 2012).

To examine the difference between wind speed during prolonged openings and prior to closure, a comparison of means test and ANOVA analysis was undertaken (SPSS, version 11). The test was deemed significant at $p<0.05$.

3.1.3 Closing Window Summary

To summarise the conditions which disrupt the Lagoon closing process, all closing windows were identified between 2002 and 2012. A closing window was described as the 2- 4 days prior the neap tide, where the Waituna Lagoon water level traces begin to lose tidal amplitude and behave erratically. These fluctuations were not related to equipment malfunctions. Seven openings were examined in the 2002-2012 period and sixteen 'closing windows' were identified. Wind direction and wind speed was then summarised for all the closing windows regardless of month. The 2002 to 2012 data period was used, as it had accurate Waituna Lagoon water level data, Waituna Creek flow and Bluff predicted tides in MASL.

3.2 Wind Data Sources

The three hourly Tiwai Point (agent number 5823) wind direction and wind speed data was extracted from the NIWA clifow website (http://cliflo.niwa.co.nz/). This site was used as it was the closest site to Waituna Lagoon with a significant long-term record. The hourly wind data was used over hourly data so as to reduce computation time over the 40 years of data, and also reduce scatter in the wind data, which occurred in the hourly and ten-minute interval data (Jenkins C pers 2012).

The Tiwai Point meteorological station is 17 kilometres upwind from Waituna Lagoon, therefore localised wind conditions may differ than at Walker's Bay. The Environment Southland meteorological station at Waghorn's Road water level site (7 kilomtres ast, downwind) was not utilsed as it only had two years of data long-term record at Tiwai Point.

All the wind data (direction and speed) was analysed using a wind rose tool in the Hilltop hydro software. This allowed wind direction and speed to be analysed simultaneously, and where the percentage of time within 12 wind vectors was summarised. Wind speed was calculated within four speed ranges, 0-5 km/hr, 5-10 km/hr, 10-20 km/hr and >20 km/hr. The wind speed range of 10-20 km/hr represents a 'gentle breeze' on the Beaufort Scale, whereas wind speeds over 20 km/hr represent a 'moderate breeze'. Obvious whitecaps and chop on the sea surface become visible and prominent at wind speeds over 20km/hr.

Wind run were not used in the analysis, as had the potential to mask smaller wind events over the closure period by more dominant or larger wind events.

3.3 Wave and Tide data

The modelled swell data was supplied by MetOcean Ltd, for the period of 1998 to 2010 (McCombP 2010). Uncertainties in the data may exist where differences between the shore wave environment could create very localised sea state conditions, as opposed to offshore the swell direction, height and wave period values in the data. Therefore, until the actual near shore conditions are quantified, by a current and/or wave meter caution should be exercised in interpreting these values.

The Bluff predicted tide data was supplied by Environment Southland, and was in masl.

4.0 Results

The results section below is split into four sub-sections. The first sub-section summarises Waituna Lagoon closure by month. The second sub-section summarises the conditions prior to closure. The third sub-section summarises conditions during prolonged openings, and the forth sub-section describes the meteorological conditions which disrupt the closing process.

4.1 Lagoon Closure by month

Mouth closure of Waituna Lagoon has been highly seasonal, with the months from March to October having the highest number of closures (Figure 8). The month of June has the most closures with nine, followed by October, May and August, with 7, 6 & 6 closures respectively. Over the last 40 years, there only been three occasions when the lagoon closed between November and January, with no Lagoon closures recorded in February.

Figure 8 Waituna Lagoon closures by month from 1972-2012

4.2 Summary of conditions prior to Waituna Lagoon closure

The sub-section is a summary of the conditions in the two days prior to Waituna Lagoon Closure.

4.2.0 Hydrological and tidal summary

Tidal cycles clearly influence the timing of Waituna Lagoon closures. Eleven of the last twelve Waituna Lagoon closures have occurred on the downward phase from pring tides to eap tides (Figure 9-Figure 13). Approximately, five eight tides from the eap tide, water levels in the begin to behave erratically. There is far reduced tidal amplitude in the Lagoon, in keeping with reduced tidal heights in Toetoes Bay.   Waituna Lagoon closure is initiated at tidal heights between 850 and 650 maslhereas water levels at Waghorns Road are in the range of 700 to 400 masl. The Waghorns Road recorder is 7 km from Walker's Bay, hence there is likely a lag time between the actual closure point and that recorded. With the Monitoring Platform located 1.5 km from Walker's Bay, in the future there is likely to be greater synchronisation between the lagoon and tidal heights at closure (see Figure 13), due to proximity.

Closure of Waituna Lagoon (since 2002) has yet to be recorded on the rising limb of the tidal cycle and/or at the of the pring tides.

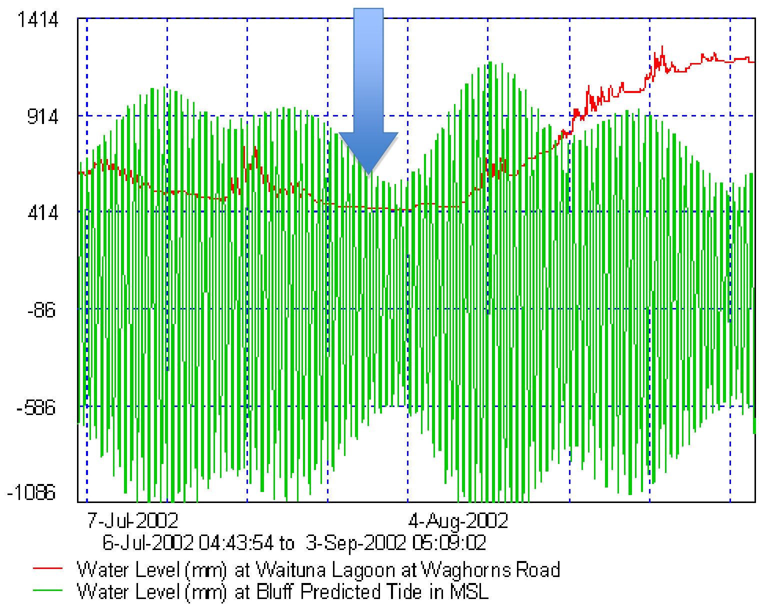

Figure 9 Waituna Lagoon July 2002, arrow denotes closure point

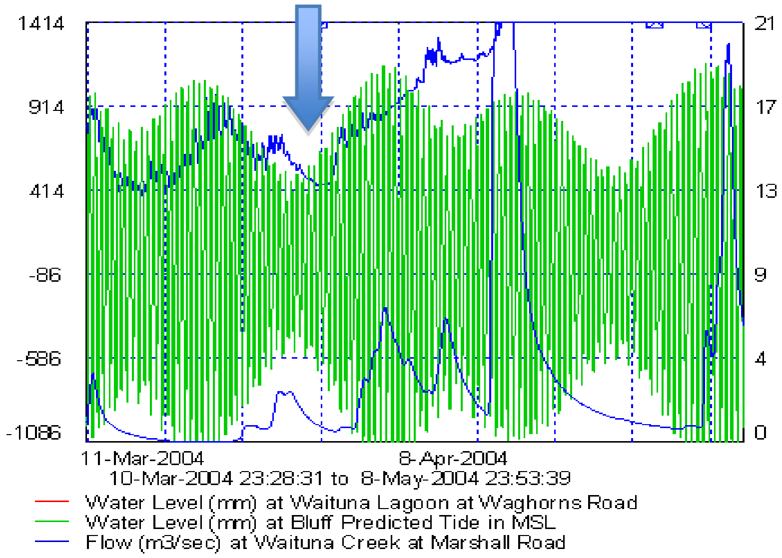

Figure 10 Waituna Lagoon March 2004, arrow denotes closure point

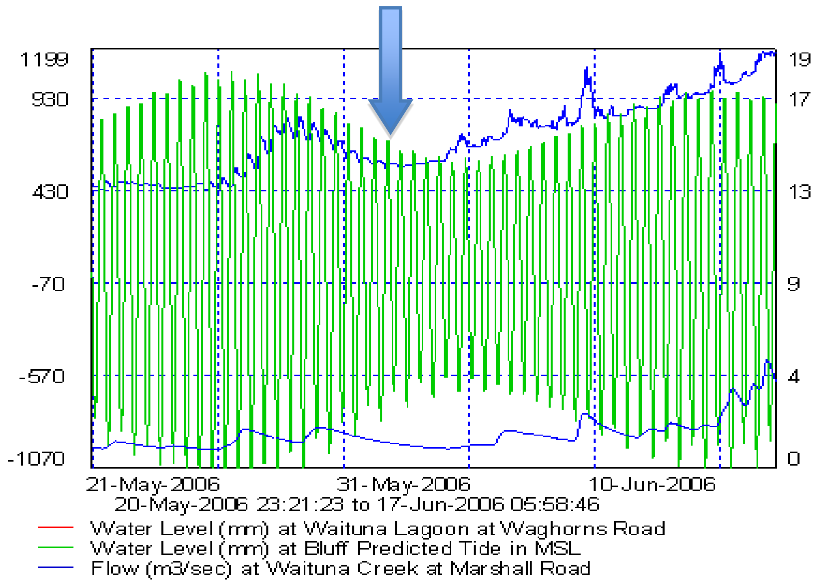

Figure 11 Waituna Lagoon May 2006, arrow denotes closure point

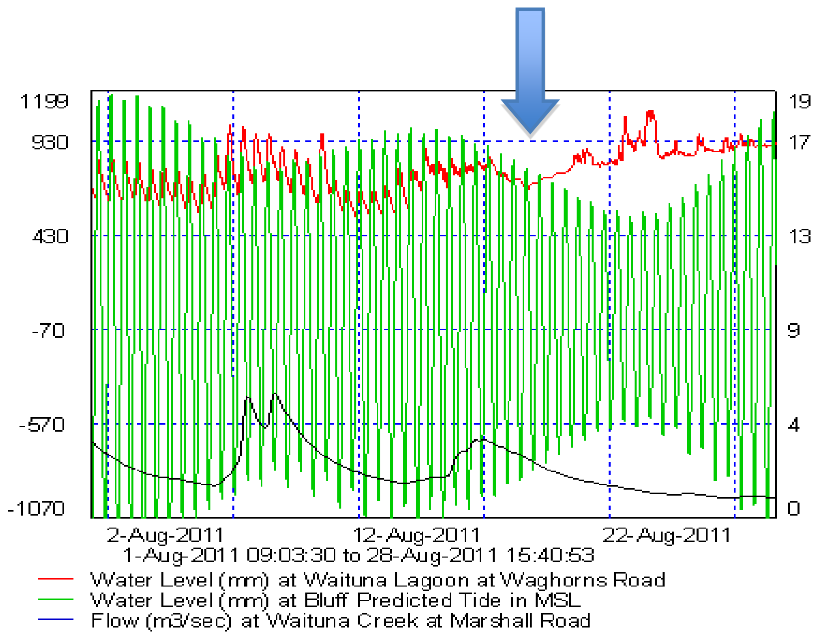

Figure 12 Waituna Lagoon Aug 2011 (Charlie's Bay), arrow denotes closure point

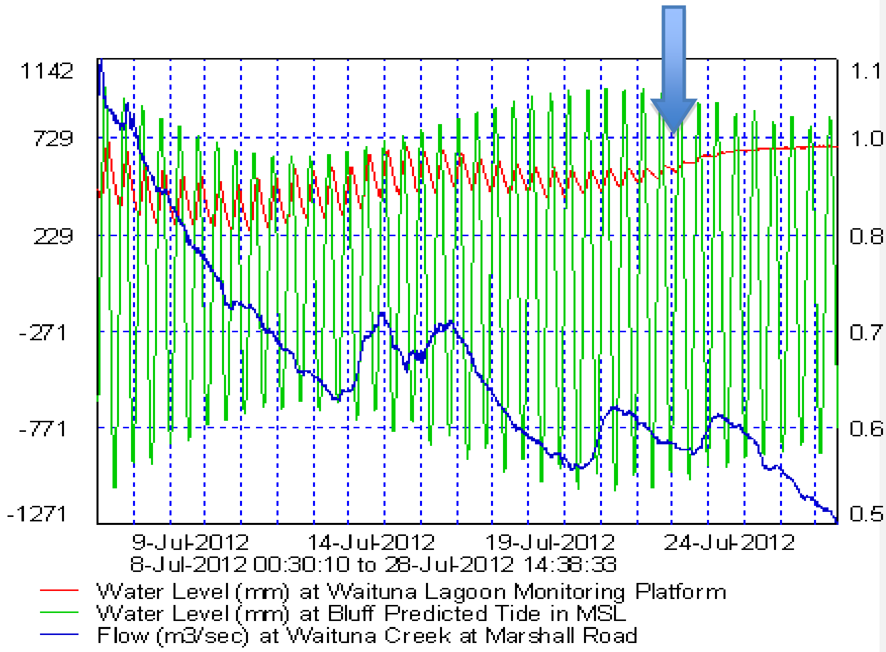

Figure 13 Waituna Lagoon July 2012 closure, arrow denotes closure point

4.2.1 Meteorological Data

The sub-section below is a summary of the wind and modeled swell data in the two days prior to Lagoon closure.

4.2.2 Wind Summary

Wind direction prior to Lagoon closure is highly variable depending on season. Average wind direction prior to closure varies from 14^0 (N/NE) in April, through the Northern and Western vectors to 160^0 (S/SE) in January.   months of May to September have a variety of wind directions prior to lagoon closure. There was no uniform pattern in wind direction between these months in the days prior to closure. equinox months recorded more wind from directions, and the winter months (20/46 closures) recorded winds right around the compass.

Wind speeds are also variable depending on the month, with the closures in the winter months recording reduced wind speeds. Wind speeds in winter ranged between 12-23 km/hr (Gentle to Moderate Breeze).   The equinox months of May, September, and then November recorded the highest wind speeds with 30.9, 39.8 & 32.9 km/hr respectively (resh to trong reeze).

4.2.3 Monthly Wind Rose Synopsis

Below is a monthly synopsis of wind conditions prior to Waituna Lagoon closure.

Note: The percentage of time within each wind vector is represented by the 5% dashed circles around the wind rose. Only the months with more than one closure (March-October) are included in this monthly synopsis.

4.2.3.1 March (5 closures)

an average wind direction of 326^0 N/NW, but the strongest wind prior to closure was from the W (22 % of time) with wind speeds greater than 20 km/hr (Figure 14).

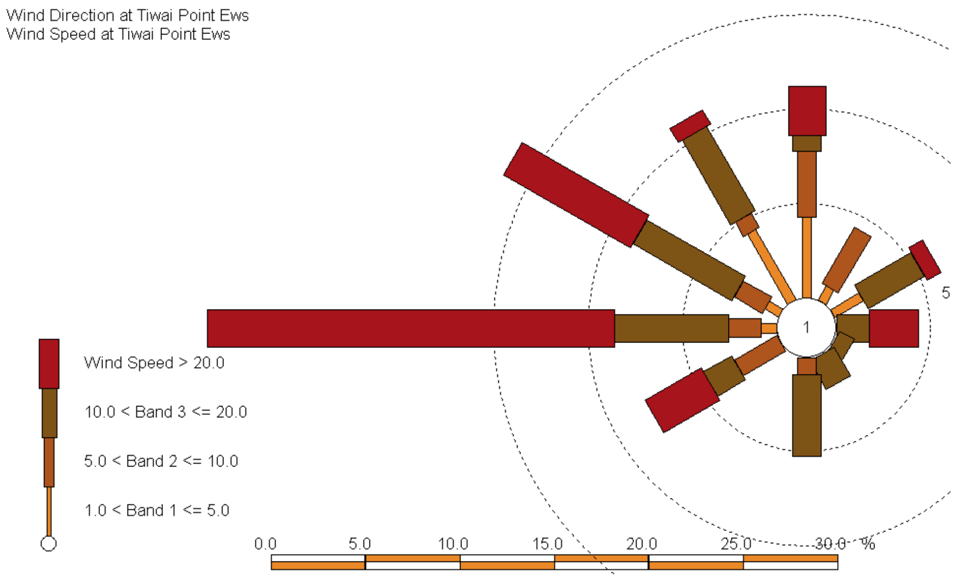

Figure 14 March Wind Summary

4.2.3.2 April (2 closures)

April recorded average wind direction 14^0 N/NE prior to closure, however, the wind was highly variable (Figure 15), with wind from the SE round to the NW prior to closure. No moderate or strong winds from the W to S were recorded with light winds generally dominating. The strongest wind came from the S/SE direction for 10% of the time, whereas the lighter N/NE wind (5-10 km/hr) persisted for 13% of the time, along with a moderate N/NW for the same time period.

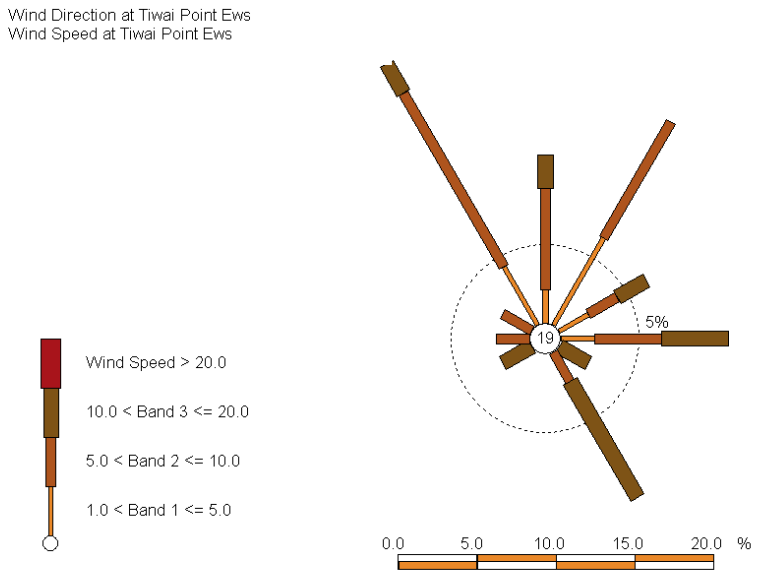

Figure 15 April Wind Summary

4.2.3.3 May (6 closures)

May recorded average wind direction 278^{0} W prior to closure, with the wind during this equinox month very defined (Figure 16). Wind was clustered to vectors from the SW-NW. Wind speeds were very high in the SW vector (20% of time), the Westerly vector (30% of time) and the W/NW vector (12 % of time).

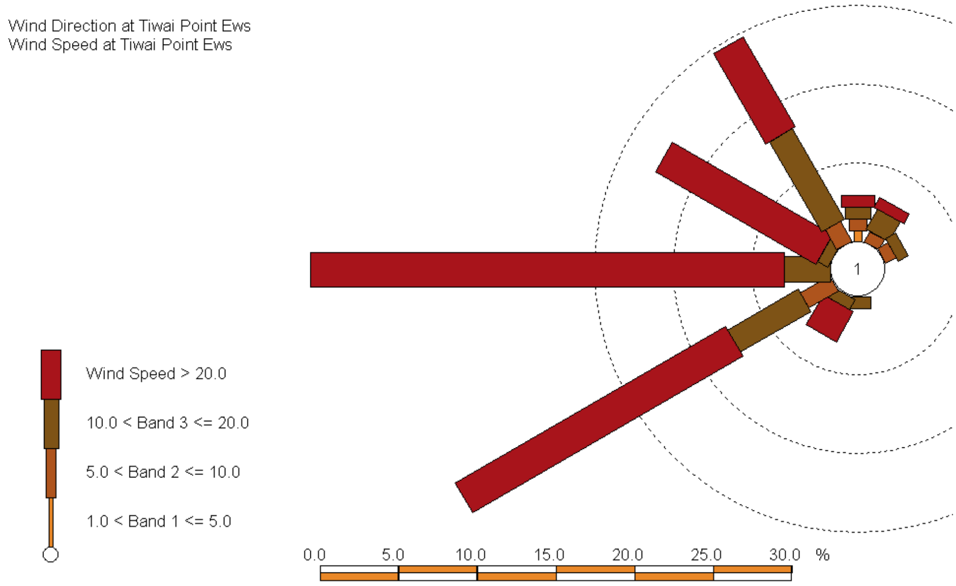

Figure 16 May Wind Summary

4.2.3.4 June (9 closures)

June an average wind direction of 337^0 NW prior to closure, however, wind direction was highly variable with winds from all vectors prior to closure (Figure 17). of time in the orthern vectors, however, wind speeds were generally light to moderate. The strongest winds were esterly, which persisted for 12 % of the time prior to closure. The next dominant wind was due outh and due ast, both for 9% of the time prior to closure.

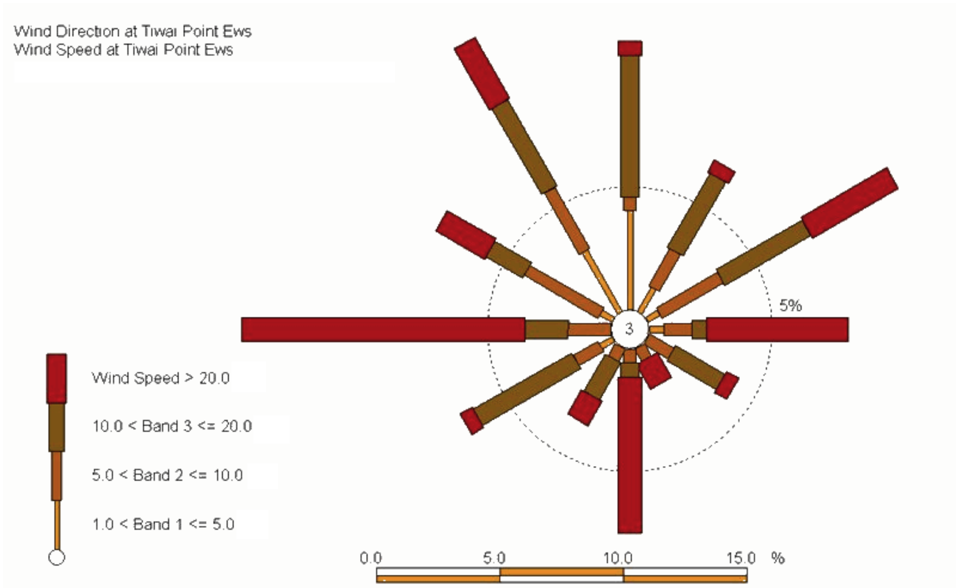

Figure 17 June Wind Summary

4.2.3.5 July (5 closures)

recorded average wind direction 315^0 (W/NW) and similar to June experienced a wide range of winds around the compass from SW through the W to the E (Figure 18). No wind from the E/SE to the S/SE direction was recorded and very little wind in the S/SW direction existed. Strong W winds persisted for 12% prior to closure, along with trong NW and S/SW winds for 11% of the time.

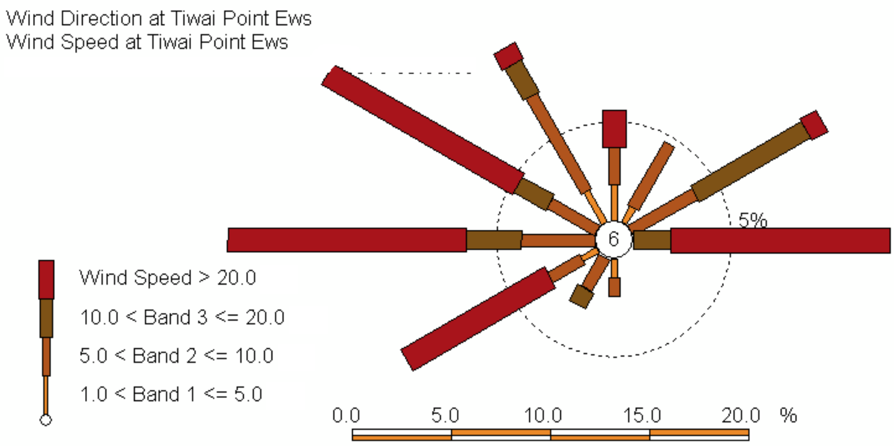

Figure 18 July Wind Summary

4.2.3.6 August (6 closures)

August average wind direction 359^0 N. Again similar to the other winter months, August a wide range of winds, with lighter winds dominating (Figure 19). There was a fairly even distribution from the W to S/SE, however, very little wind was recorded from E/SE. The strongest winds were W for % of the time prior to closure, along with strong S/SE wind, for 6% of the closure period.

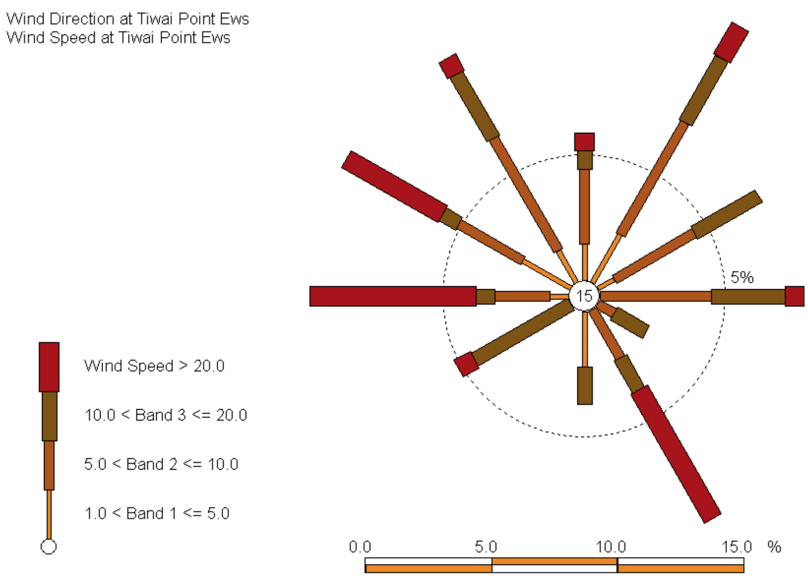

Figure 19 August Wind Summary

4.2.3.6 September (3 closures)

September an average wind direction of 290^0 W/NW prior to closure. No wind was recorded prior to closure from the NE through to the S/SW directions. The wind was strongly skewed to the SW-NW directions, with strong winds dominating. Both strong W and W/NW winds dominated 80% of the time prior to closure (Figure 20). September represented the windiest month prior to closure.

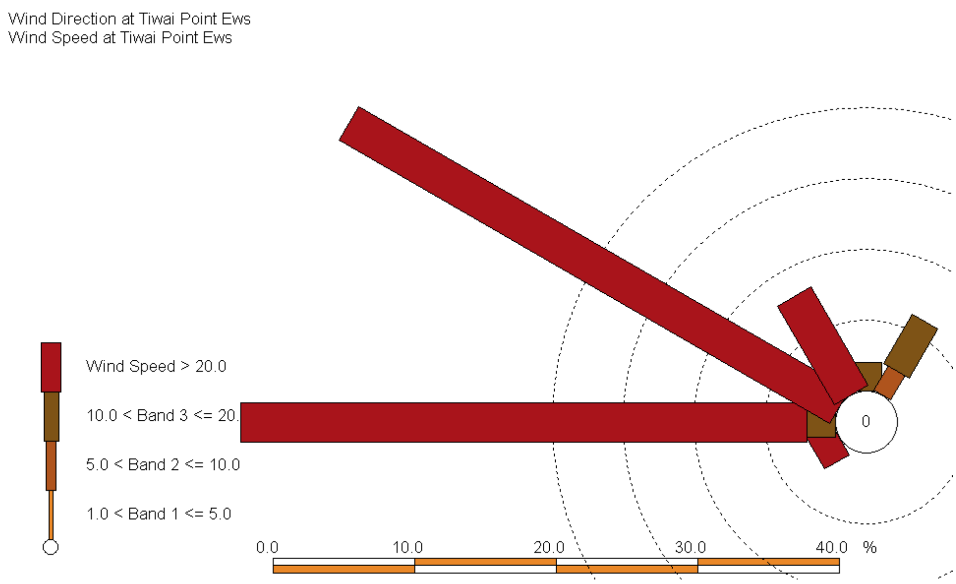

Figure 20 September Wind Summary

4.2.3.7 October (7 closures)

an average wind direction of 268^0 W prior to closure (26% of time), but smaller percentage strong wind right around the compass (Figure 21).

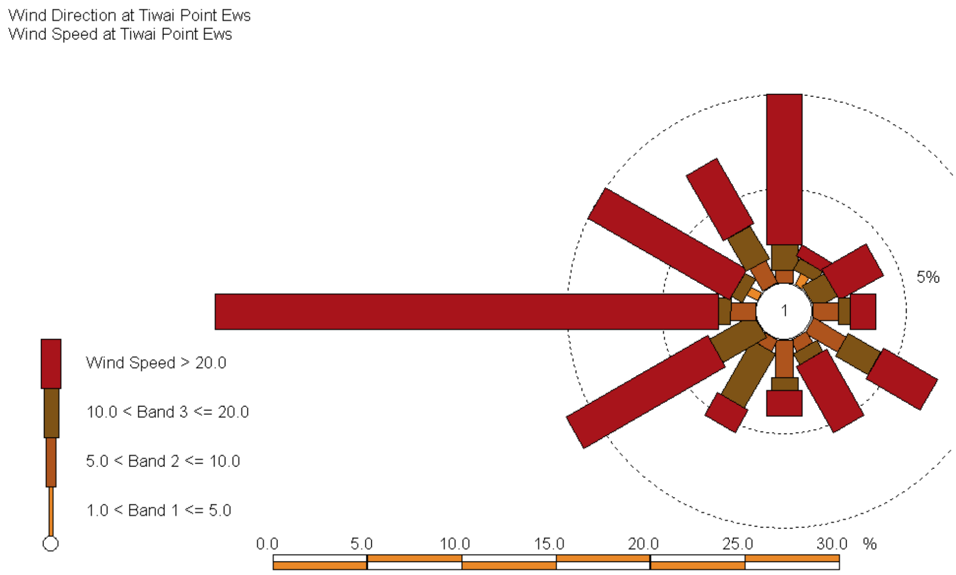

Figure 21 October Wind Summary

4.2.4 Swell Summary

The subsection below contains a summary of the modeled swell conditions prior to closure.

4.2.4.1 Swell direction

Modelled swell direction prior to Waituna Lagoon closure very defined, with swell from 163^{0} to 198^{0}. See monthly synopsis.

4.2.4.2 Swell height

Modelled swell heights prior to Waituna Lagoon closure also highly variable, with the equinox months of October the largest swell heights (1.5 metres). months modeled swell height above 3.0 metres. The smallest swell heights were recorded in July with 0.65 m, followed by June with 0.89 m. These modelled data highlight Toetoes Bay partially sheltered nature, which is out of the way of the larger W/SW swells in Eastern Foveaux Strait.

4.2.7 Swell period

Modelled swell period prior to Waituna Lagoon closure show a consistent trend with swell direction and heightthe winter months period waves compared to the equinox. The month of June has reduced swell period of 10 seconds, which is a wind swell generated locally, as opposed to the 14 second period swells in

October. Typically, higher swell periods are indicative of swell generated further offshore to the SW of New Zealand, as opposed to short period wind swell.

4.2.4.1 Monthly synopsis of Swell Direction and Swell Height

ot all months are represented with closures in the data period of 1998-2010.

March recorded small to moderate (0.3-1.5 m) swells from the S for 49% of the time. Larger S/SE swells were also recorded 23% of the time prior to closure.

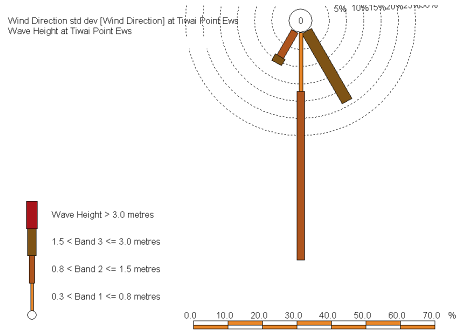

Figure 22 March Wave Summary Rose

May recorded small to large swells from the S/SW direction, with moderate swell dominating 40% of the time, and large swell present 6.4% of the time prior to closure. Small and moderate swells from the S also recorded 29% of the time prior to closure.

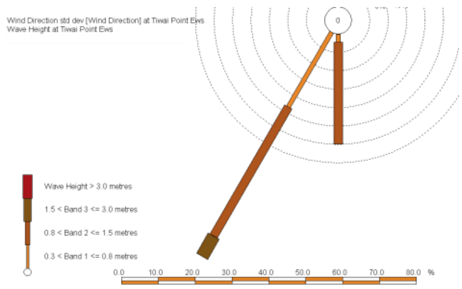

Figure 23 May Wave Summary

Unfortunately data is limited for June, due to only one closure over the analysis period. For the 2006 closure, modeled swell heights are small to moderate, and all from the S direction. June short swell period of only 10 seconds.

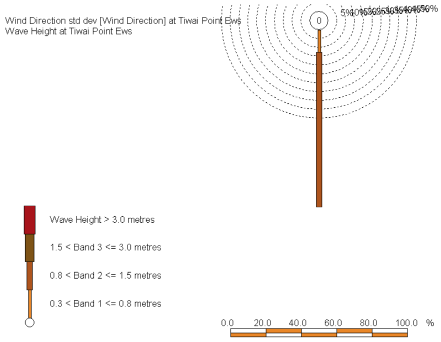

Figure 24 June Wave Summary

Similar to June, data was limited for July, but swell conditions were almost identical. Small S swell dominated along with reduced swell period.

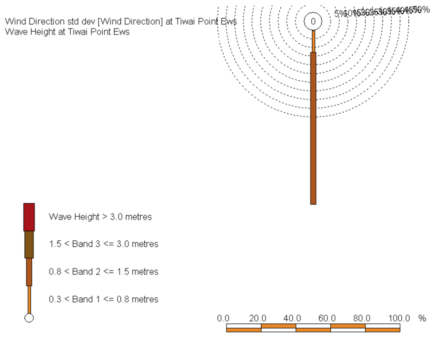

Figure 25 July Wave Summary

August was dominated by small to moderate S swells 82% of the time. Swell period was slightly increased to 12.7 seconds.

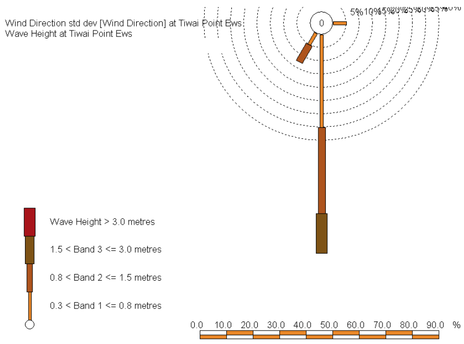

Figure 26 August Wave Summary

Swell conditions in October were very defined. Moderate to large S swells dominated 97 % of the time. Swell period was also increased with sec swell period.

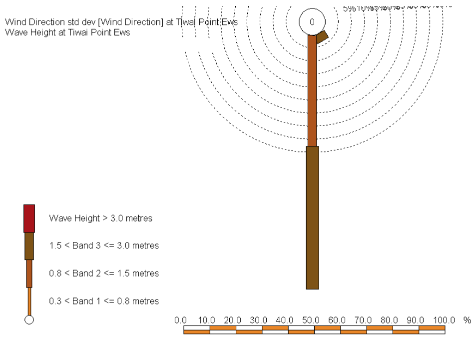

Figure 27 October Wave Summary

4.2.8 Waituna Creek and Total Lagoon Inflows

Waituna Creek inputs and total lagoon inflows prior to Lagoon closure (Table 1 & 2) show a declining trend in flow and inputs. On the day of closure, Waituna Creek flows ranged from 0.137 cumec to 1.276 cumec. Median flows for the Waituna Creek at Marshall Road are 0.898 cumec, which suggests flows approaching or below median are required for Lagoon closure. Total lagoon inflows below 2 appear favourable as not to disrupt the closing process. For a Charlie's Bay opening, Waituna Creek flows can be slightly higher in the order of 3 , and not adversely disrupt the closure process. However, higher flows in Waituna Creek greater than 4 , can result in the mouth at Charlie's Bay being ffected, as in July 2011.

Table 1 Waituna Creek at Marshall Road flows prior Lagoon closure

Closure date	4 days preceding	3 days preceding	2 days preceding	1 day preceding	trend in flow
8/08/02	0.939	0.852	0.808	0.809	down
4/05/03	0.099	0.099	0.101	0.137	stable
1/04/04	2.398	1.571	1.032	0.759	down
15/07/04	1.184	1.186	1.311	1.192	down
1/04/05	1.584	1.449	1.251	1.107	down
2/06/06	1.988	1.684	1.448	1.276	down
24/07/12	0.569	0.627	0.601	0.585	down
18/08/11*	2.326	3.488	3.52	3.015	variable

Note flow record exists in the Waituna Creek at Marshall Road between 2007 and early 2011, hence not all closures are represented
* denotes Charlie's Bay opening.

Table 2 Total inflows to Waituna Lagoon prior to closure

Closure date	4 days preceding	3 days preceding	2 days preceding	1 day preceding
8/8/02	1607	1459	1381	1377
5/4/03	178	178	181	241
4/1/04	4271	2737	1784	1311
7/15/04	2436	2199	2023	2007
4/1/05	2707	2480	2142	1894
6/2/06	3451	2895	2478	2183
*18/8/11	3989	6051	6178	5372

Note simulated flow record ends on Dec 31st 2011
* denotes Charlie's Bay opening

4.3 Summary of meteorological conditions during prolonged openings

verage meteorological conditions during Waituna Lagoon openings over the last forty years listed in Table 3.

There is no relationship between prolonged openings and wind direction (r^2=0.004), between opening duration and wind speed (r=0.003).

4.3.1 Wind and Swell Summary during prolonged openings

Wind direction, wind speed and percentage of time within each vector over the last 40 years of openings show a very uniform pattern (Figure 31 to Figure 34). Westerly winds have dominated in terms of direction, with stronger (>20 km/hr) wind from this direction between 18 and 19% of the time.

Similarly, swell direction and height very defined during all the prolonged openings over the last 10 years (Figure 35).

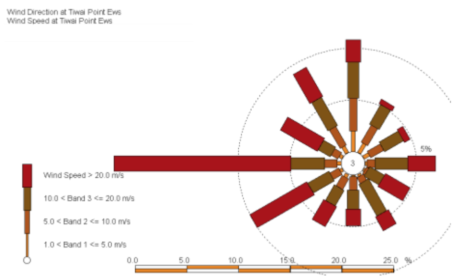

Figure 31 Wind Summary for all Prolonged Openings in 1970s

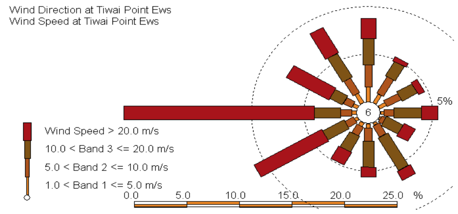

Figure 32 Wind Summary for all Prolonged Openings in 1980s

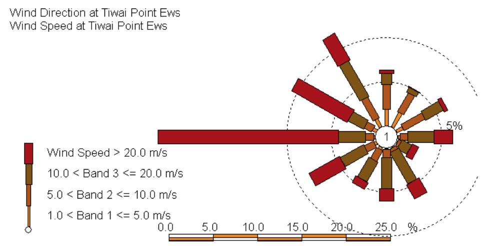

Figure 33 Wind Summary for all Prolonged Openings in 1990s

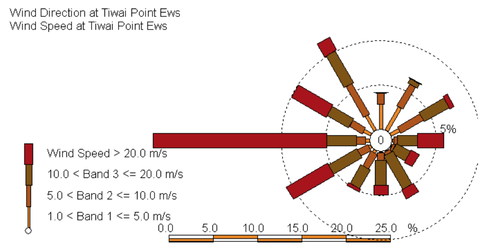

Figure 34 Wind Summary for all Prolonged Openings in 2000s

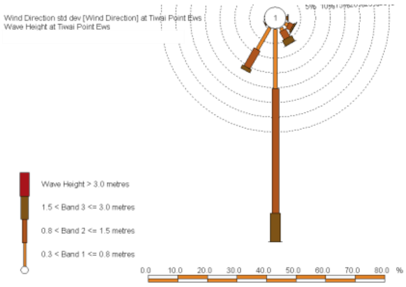

Figure 35 Swell Summary for all Prolonged Openings 1998-2010

a summary of the average meteorological conditions during prolonged openings over the last 40 years. There was no statistical difference between wind speed prior to closure and during prolonged openings.

Table 3 Average meteorological conditions for prolonged openings (1972-2011)

Opening	days open	Wind dir	Wind speed	Swell dir	Swell height	Swell period
pr 72-ay 72	36	269	29.3			
ug 78-ct 78	57	308	17.4			
eb 79-uly 79	127	328	19.7			
ep 79-ar 80	178	275	22.1			
ug 80-ct 80	64	306	23.6			
ul 81-ept 81	46	340	17.3			
ct 81-pril 82	182	270	20.2			
an 83-un 83	178	291	23.2			
ep 83-un 84	270	274	20.0			
ct 84-ay 85	209	285	19.9			
ul 85-ep 85	53	339	19.4			
ug 86-ul 87	263	294	22.8			
ay 88-ul 88	61	306	25.2			
ep 88-ar 89	169	259	23.1			
un 89-un 90	351	294	20.0			
eb 91-un 91	128	287	21.4			
ct 91-ay 92	215	290	23.8			
ug 92-ct 92	75	195	16.2			
ul 94-ep 94	62	309	27.3			
ul 95-ar 96	263	256	19.8			
ul 96-an 97	197	288	19.2			
ec 97-ay 00	863	289	21.6	176	1.0	11.9
un 02-ug 02	59	358	15.1	180	1.0	12.9
ov 02-ay 03	176	259	20.8	177	0.8	11.5
ul 03-pr 04	252	287	21.6	178	0.9	11.5
un 04-ul 04	35	324	14.5	181	0.9	12.3
an 05-pr 05	86	255	19.2	176	0.8	11.3
ul 05-un 06	330	283	19.6	177	0.9	12.0
ul 07-ug 07	39	340	15.5	176	1.0	12.4
ug 08-ct 08	41	316	18.6	173	1.1	14.1
ul 09-ct 09	68	310	17.4	177	1.0	14.1
ep 10-ar 11	185	261	20.5			
ul 11-ug 11	34	275	21.9			
average for all openings	162	292	20.5	177	0.9	12.4

Note data are presented as means

4.4 Closing Window Summary

4.4.1 Disrupted Closures

There are multiple examples since 2002, where the closing process has been disrupted by both hydrological and meteorological fluctuations. The influence of Waituna Creek on the disruption of closure appears straightforward, however, understanding the mechanisms behind meteorological disruptions less so.

The results in the section below summarise the wind conditions present in 17 closing windows, when Waituna Lagoon did not close because of disruption. The 17 closing windows were spread over seven different periods when the lagoon was open to the sea. The closing windows were identified as a likely time period (i.e the eap) when the lagoon water level behaved as though closure was imminent.

4.4.2 Closing Window Wind Rose

Wind direction over the disrupted closing window was highly variable with wind recorded right around the compass (Figure 36). The two strongest winds were a due W (10% of time), due E (7%) of the time. The third prominent wind was a 10-20 km/hr from the S/SE direction for 15% of the time. This straight onshore wind direction, slower wind speed and a higher percentage of time in this S/SE vector, was not recorded in the data prior to Lagoon closure.

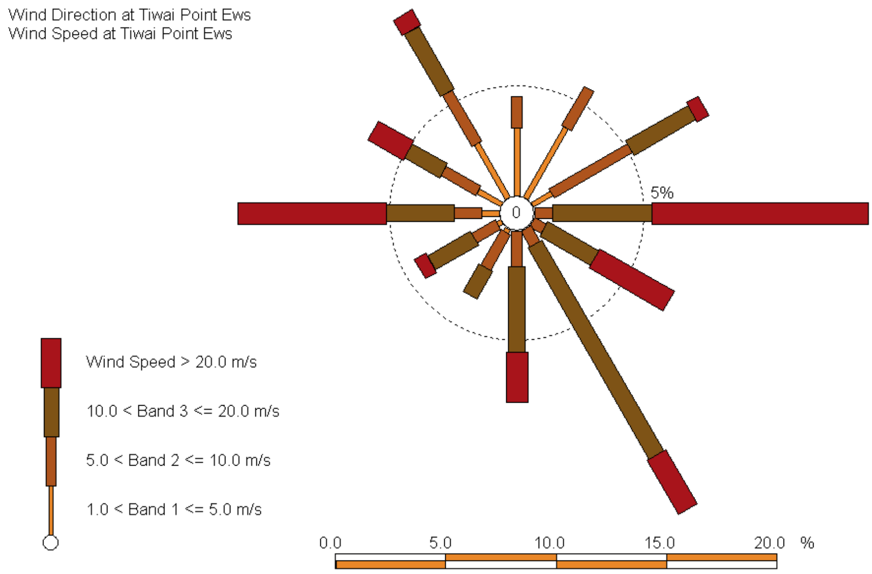

Figure 36 Disrupted 'Closing Window' Wind Summary

4.4.2 Hydrological disruption

As stated previously there are several examples in the lagoon water level record, where increased inflows disrupt the closure process. On two occasions (March 7 2011 and July 25 2011) the mouth was witnessed to almost close(Owen C & Perrin E, 2011). In the Charlie's Bay example in mid-July 2011, (neap tide after opening) 2 cumec of flow from the Waituna Creekdisrupt the closure process. This enabled the mouth to remain open over the bottom of the neap tide cycle. Following this a strong tidal trace returned to the Lagoon, with the increased amplitude toward the upcoming spring tides (Figure 37).

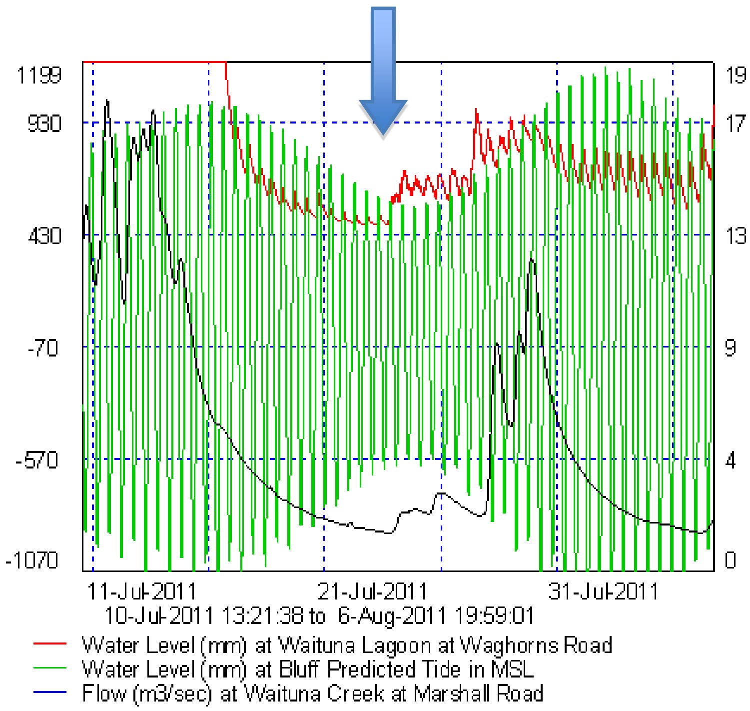

Figure 37 Disrupted Waituna Lagoon closure July 2011 (Charlie's Bay)rrow denote closure was disrupted.

5.0 Discussion

5.1 Summary of closing conditions

The meteorological conditions prior to Waituna Lagoon closure are largely unpredictable and highly variable. Unfortunately, there are no well-defined meteorological condition(s) consistent with Lagoon closure. Meteorological conditions prior to Lagoon closurediffer depending on month, and between each closure. There are, however, three key variables, which influence the process of Lagoon closure. The two most influential conditions are tidal phase and wind, followed by rainfall.

The process of Lagoon closure starts 5-8 tides before closure, or about 2-4 days prior eap tides. No tidal flow measurements have been recorded during eap tidesit is likely a reduction in tidal flow occurs through the mouth associated with the smaller tides. The reduction in tidal flow then allows the continuation of the ‘hapua’ like finger of gravel to extend across the mouth with long-shore drift.

The second and equally important key variable for Lagoon closure is wind. The closure process continues with alignment of favourble wind direction and speed. However, differences exist in both wind speed and direction depending on month. There is no single key direction or speed which is consistent in all Lagoon closures. There are however, general patterns in wind prior to closure.

In the last 40 years, Waituna Lagoon has closed in a range of wind directions and wind speeds. Conditions in the winter months have been dominated by lighter winds from around the compass. The spring and autumn months have stronger W to NW winds. Anecdotal evidence and observations suggest that Waituna Lagoon closure requires low wind speeds (<10 km/hr) prior to closure. These winds were often thought to be from the Easterly quarter (LWCA pers obs, 1972-2011, Owen, 2010-2012 pers obs, Larkin 2007-2012 per obs). onths with the highest number of closures (winter), reduced wind speeds, from many directions. For example, July closure with winds from the E quarter. However, closures do occur in moderately strong winds, as in May and October, where cross-shore NW and W winds dominate. In very strong winds the number of closures reduced, as recorded in September. Conversely, the month of April, which only has two recorded closures, had very light Northern winds dominating, but with no strong cross shore W winds.

Interestingly, wind directions from the E/SE never dominate and are largely absent prior to closure. It is possible wind from this direction does not favour long-shore drift. For Waituna Beach, wind angles from the E/SE are direct onshore. It is feasible this straight perpendicular wind disrupts the swash zone, and drift alignment on the beach. This in turn reduces the wave run up and gravel movement. However, under more cross-shore wind and swell conditions, the wave angle hitting the swash zone enhances wave run-up, and hence gravel mobilsation through the mouth. This would be the case for all closures, where moderate cross-shore esterly or asterly winds prevail.

It is unknown how these variations in wind direction, and wind speed affect the swash zone and/or influence long-shore drift. But the reduced wind speeds in winter obviously assist in the closing process, as evident by the higher number of closures. A short study examining long-shore drift rates, gravel mobilsation and accumulation is recommended, as to corroborate the observed seasonal closure distribution.

The third key condition required for successful Lagoon closure is atchment inflows. There have been several occasions when Lagoon closure appeared imminent, but rainfall (~10mm) in the atchment disrupted the process. For successful lagoon closure at Walker's Bay median flows in Waituna Creek are required. But for a Charlie's Bay opening, Waituna Creek flows can be higher (between 3-4). This is due to the opening further from the primary freshwater input.

5.2 Waituna Lagoon closure prediction

A second aim of this report was to summarise key conditions which may be used as 'predictors' for lagoon closure. However, only tidal phase can be known in advance, therefore prediction of mouth closure largely unreliable. There are, however, windows of timeLagoon closure is more probable. For example, each month has an optimal 'closing window' based on This then represents the 'best' opportunity for a closure event.

Furthermore, time of year can be used as a simple predictor of more 'favourable' closing conditions. inter months are 'best' for an increased chance of lagoon closure. These months typically have reduced wind speeds, more cross-shore wind and swell, and less rainfall. Leading up to eap tides in winter represents the most promising 'closing windows' over the year. Conversely, eap tides during the summer months represent the 'worst' opportunities for closure.

The 'closing window' concept may have implications for Waituna Lagoon water level management in the future. iming of mechanical openingsare based purely on water level management, and not for the protection of environmental and cultural health. For example, if a Lagoon opening is requested to alleviate farm drainage in October, there maybe justification for delaying the opening. This is because there will be a lack of suitable 'closing windows' until autumn the following year.

5.3 Conditions present during prolonged openings and long term

The results how little difference exists between the conditions prior to closure and at other times. This includes prolonged opening periods and long term averages (Appendix A). is not surprising given the wind environment oastal

Southlandover not only daily but hourly time steps. There are, however, subtle differences in the winter conditions prior to closing. Compared to the last 40 years, winter wind direction prior to closure21^0 Winter modeled swell data also deviated from the long-term average prior to closure, with reduced swell heights.

5.4 Disruption of the closing window

For successful Lagoon closure there needs to be sequential alignment of wind, tide and catchment rainfall. These three factors need to stay aligned for up to week prior Lagoon closure, and even subtle changes in the meteorological conditions may disrupt the closure process. pproach of the eap tide the 'closing window'. For example, there are many instances when the lagoon's water level becomes erratic during the lead up to eap tides. This suggests a reduction of tidal flow is occurring but the other meteorological conditions required, such as cross-shore winds are absent. Figure 36 gives some insight to the meteorological conditions present during disruption of the alignment process. In these failed closures, there is a higher percentage of light to moderate S/SE winds. These winds were largely absent during successful Lagoon closures, which have cross-shore winds. As stated previously, it is unknown the impact that direct onshore winds (and swell) have on long-shore drift and gravel movement on Waituna Beach.

6.0 Conclusion

The two most influential conditions required for Waituna Lagoon mouth closure are wind and tidal phase. For a successful Lagoon closure there needs to be a sequential alignment of wind direction, wind speed, swell, tide and finally catchment hydrology. A wide range of wind direction and speeds have been recorded prior to closure, but moderate winds from the cross-shore SW-NW vectors dominate. E/SE winds are largely absent prior closure, but E winds are relatively common. It is unknown influence the moderate cross-shore winds have on enhancing long-shore drift.

Only tidal phase can be used as a predictor of closure. For each month a likely 'closing window' exists on the approach eap tides. The other meteorological conditions, wind and rainfall, cannot be predicted outside three days. The most probable 'closing months' are May to August, with winter representing the 'best' chance of closure. The 'worst' chance of closure is between late-October and early-March. Therefore it is recommended all openings be avoided over the late-spring and summer months.

Acknowledgements

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Appendix A

Differences in average meteorological conditions between closure and all data

Table 4 Average meteorological conditions prior to Waituna Lagoon closures and all for data (1972-2012)

Note data are presented as mean and SD in brackets

Month	wind direction during closure	wind direction (1972-2012)	difference in direction prior to closure	wind speed during closure	wind speed (1972-2012)	difference in wind speed prior to closure
Jan	160(18)	258(92)	98 to S/SE	14.6(3.2)	21.7(14.9)	-7.1
Feb		207(99)			20.8(15.0)	
Mar	326(25)	278(100)	48 to N/NW	20.0(3)	20.9(15.6)	-0.9
Apr	14(138)	298(110)	76 to N	6.2(4.4)	19.6(15.8)	-13.4
May	278(19)	307(111)	29 to W/NW	30.9(5.6)	20.1(16.2)	10.8
Jun	337(29)	315(117)	22 to N/NW	19.3(2.0)	18.0(14.8)	1.3
Jul	315(25)	332(123)	17 to W/NW	23.3(3.5)	16.2(13.5)	7.1
Aug	359(22)	318(117)	41 to N	12.6(4.24)	18.0(13.7)	-5.4
Sep	290(63)	299(107)	9 to W/NW	39.8(12.8)	20.5(14.7)	19.3
Oct	268(22)	277(96)	9 to W	27.8(7.5)	23.2(15.6)	4.5
Nov	298(112)	267(88)	31 to W/NW	32.9(37.4)	24.8(16.2)	8.1
Dec	285(26)	254(93)	31 to W/NW	16.7(3.76)	22.3(14.6)	-5.6
Yearly average	266	284		22.2	20.5	
Winter average	337	318		18.4	17.4	

Comment [jl1]:

Table 5 Average swell conditions prior to Waituna Lagoon closure and for all data (1998-2010)

Month	swell direction during closure	swell direction all data (1998-2010)	swell height during closure	swell height all data (1998-2010)	swell period during closure	swell period all data (1998-2010)
Jan	no data	179(16.5)	no data	0.92(0.40)	no data	11.3(2.2)
Feb	no closes	no closes	no closes	no closes	no closes	no closes
Mar	173(13.8)	178(15.8)	1.3(0.45)	1.0(0.46)	10.1(1.4)	11.6(2.18)
Apr	no data	no data	no data	no data	no data	no data
May	198(13.5)	172(21.6)	1.0(0.3)	1.19(0.54)	11(1.8)	11.9(2.38)
Jun	172(1.5)	175(17.9)	0.9(0.2)	1.27(0.61)	12.6(0.5)	11.9(2.40)
Jul	163(36)	171(20.9)	0.7(0.3)	1.18(0.56)	10.8(2.4)	10.8(2.4)
Aug	179(23.5)	171(22.1)	1.0(0.6)	1.2(0.51)	12.7(2.9)	12.02(2.5)
Sep	no data	177(21.4)	no data	1.08(0.48)	no data	12.07(2.67)
Oct	175.5(7.2)	175(7.2)	1.5(0.4)	1.5(0.4)	14(2.3)	11.9(2.52)
Nov	no data	179(16.1)	no data	1.02(0.46)	no data	11.27(2.14)
Dec	no data	177(22.1)	no data	0.89(0.39)	no data	10.7(2.29)
Yearly Average	177	176	1.07	1.13	11.87	11.55
Winter Average	171	172	0.87	1.22	12.03	11.57

Note data are presented as mean and SD in brackets