# Natural, Physical Characteristics of Te Whaanga, Chatham Island

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Prepared for:
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The photograph on front cover is the Hikurangi Channel at low tide on 7 January 2004, taken from the cockpit of an Air Chathams Convair. The assistance of the aircrew in capturing the shot is gratefully acknowledged.

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# EXECUTIVE SUMMARY

Te Whaanga has two regimes: when the Hikurangi Channel is closed, and when it is open.

## *Mouth Closed*

When the Hikurangi Channel is closed, Te Whaanga behaves like a shallow lake with the following characteristics:

- Water levels vary largely in response to wind. The predominant wind direction is just north of west and this causes levels on the eastern shore to rise by as much as 1.6 m. Winds from the northwest and southwest can push water onto the southern and northern shores respectively by as much as 0.6 m.
- The salinity of the lagoon is fairly uniform at c. 20 ppt, but floods from the Te Awainanga River can drop the salinity to almost zero in the mouth region. The dispersion of the freshwater slug resulting from floods is highly dependent upon winds.
- The water balance of the lagoon is dominated by rainfall, which represents 70% of the inflow, the remainder coming from the Te Awainanga River. Evaporation represents only about 5% of the total inflow (i.e., rainfall + river flow). The result of the imbalance in inflow and outflow is that levels in the lagoon rise until a level is reached that causes the Hikurangi Channel to breach (or the breach is initiated manually).
- The lakes along the eastern side of the lagoon are connected to Te Whaanaga, but the seepage flow is very small. They appear to have no connection to the ocean.

## *Mouth Open*

When the Hikurangi Channel is open, Te Whaanga behaves like a tidal inlet near the mouth, but the northern basin continues to behave like a shallow lake:

- Flows in the Hikurangi Channel reach up to c. 100 cumecs outflow on an ebbing tide and c. 200 cumecs inflow on a flooding tide, depending on the tidal range at sea.
- The extent of tidal influence in the lagoon is limited to the region near the mouth, representing between 5 and 25% of the total lagoon area.
- Little mixing occurs between seawater and lagoon water over a tidal cycle.
- In the northern basin, the level drops when the Hikurangi Channel is first opened, but thereafter the basin behaves as if there were no opening.

# 1. INTRODUCTION

This work was commissioned by Crown Law Office to determine the natural, physical characteristics of Te Whaanga, and its relationship to the ocean.

Te Whaanga is a 185 $km^2$, shallow lagoon that occupies about 20% of the landmass of Chatham Island (Figure 1). It has four compartments: a northern basin that is separated from the remainder of the lagoon by a shallow region that was used as a ford at one time; central and southern basins that are separated by a shallow region; and a mouth region located on the coast between the central and southern basins. There is one major inflow, from the Te Awainanga River, which flows into the southern basin. The outlet is the Hikurangi Channel, which is open for only some of the time. Te Whaanga is generally shallow (a few metres in depth at most), with extensive regions that are dry when the water level is low.

In this report, we first describe the data collection programme, present the data and describe the methods used to analyse them, then we present the results of the analysis and discuss their implications. Finally, we make some conclusions about how Te Whaanga works.

# 2. DATA AND METHODS

In this section, we first describe the sources of the data that were used in the project, then present the data and describe methods used to analyse them.

## *2.1 Data Sources*

Four different types of data were used in this study: meteorological data; hydrological data; tide model data; and data from instruments deployed specifically for this project in a data collection programme. The meteorological and hydrological data are gathered by NIWA as a matter of course for other purposes. The tide model was developed by NIWA as part of a coastal oceanography research programme.

### 2.1.1 Meteorological Data

The meteorological data used in the project came from NIWA's Climate Database for the automatic weather station (AWS) at Airport Chatham Island, located on a promontory between the northern and central basins. Parameters used were: wind, rainfall, atmospheric pressure and air temperature.

### 2.1.2 Hydrological Data

The hydrological data used in this project came from NIWA's Water Resources Archive for Site No. 3446051, the Te Awainanga River at Falls located c. 4km from its mouth, which is at the southern end of the lagoon. The station has been in operation since 1986, and a well-defined, stable rating (that converts water levels into flow) is available. A small creek (Mangahou Creek) flows into the river downstream of Falls.

**Figure 1. Topographic map of Te Whaanga (from LINZ Topographic Map 260 Chatham Islands (Sheet 1)), showing important features and the locations of instruments deployed for this project.**

### 2.1.3 Tide Data

Tide data came from the NIWA Tide Model described in Walters et al. (2001) for the outlet of the Hikurangi Channel at 183.583ºE 43.925ºS. Thirteen tidal constituents were used: $M_2$, $S_2$, $N_2$, $K_2$, $K_1$, $O_1$, $P_1$, $Q_1$, $2N_2$, $\mu_2$, $\nu_2$, $L_2$, and $T_2$. Tidal constituents reflect the influence of the astronomical forces of the Moon and Sun on Earth's waters. Each constituent corresponds to a particular phenomenon. For example, $M_2$ is the twice-daily effect of the Moon's direct gravitational attraction, and $S_2$ is the twice-daily effect of the Sun's direct gravitational attraction. There are c. 600 tidal constituents. The thirteen used here represent the most important of these for the region around New Zealand. With these constituents, we can accurately hindcast the tide for any time in the past or forecast it for any time in the future.

### 2.1.4 Project-Specific Data

Three recording stations were established in the lagoon and one in Lake Kaingarahu (Figure 1) specifically for this project. Each of these stations was equipped with a conductivity and temperature probe; a float-and-counterweight water-level recorder; and a staff gauge. The stations were powered by battery, with a solar panel for charging. A typical site and its equipment are shown in Figures 2a and b.

The first task in processing the water level data from the lagoon was to convert the recorders to a common datum. Unfortunately, the cost of surveying the sites was prohibitive, so we have resorted to using the water level itself during a calm period to level the instruments. The period of record is shown in Figure 3 and the resulting corrections based on the mean levels of each of the recorders during this quiescent period are presented in Table 1. We have chosen Gauge Zero of the Mouth recorder as the datum because this recorder is most likely to be used in the future for management of the mouth. The table lists the quantities that must be added to the levels of each recorder to reduce them to a common datum. Henceforth in this report, all water levels will be relative to this datum. Unfortunately, the tower of the South recorder was knocked askew in a storm on 24 June, but the landowner, Johnny Kamo, kindly righted the tower on 25 July. The resulting offset was different by almost 100 mm, as shown in Table 1.

**Table 1. Corrections required to bring lagoon levels to Mouth Recorder Gauge Zero Datum.**

| Site | Correction mm |
|---|---|
| Mouth | 0 |
| North | 131 |
| South (before 24 June) | -169 |
| South (after 25 July) | -263 |

**Figure 2a. Typical installation (the Mouth recorder) showing PVC tower supported by fence posts driven into the bed, with solar panel and staff gauge.**

**Figure 2b. Equipment installed in the PVC tower.**

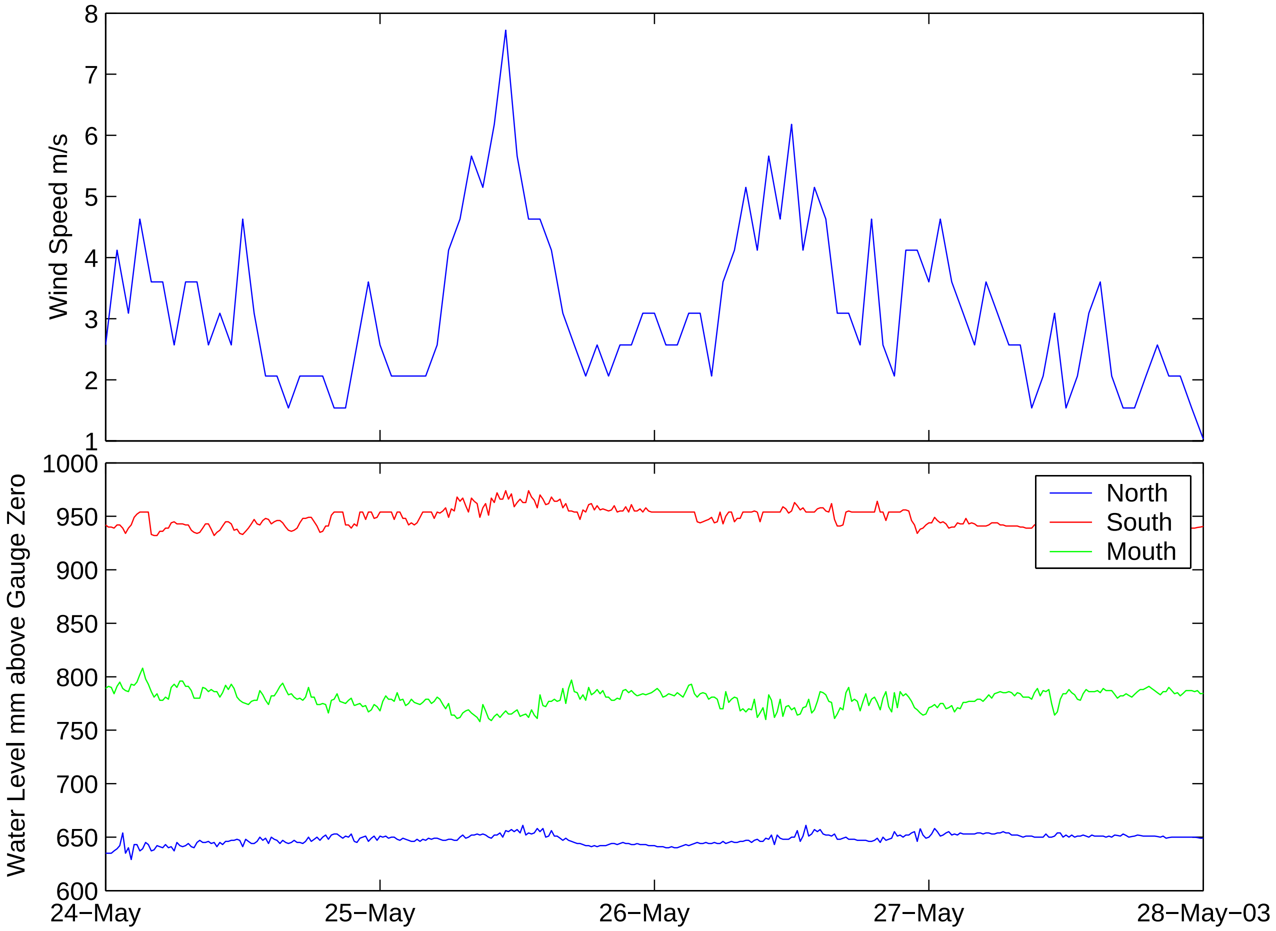

**Figure 3. Comparison of recorder levels (lower plot) for a quiescent period of wind (upper plot).**

## *2.2 Data Presentation*

In this section, we present the data that were used in the project.

### 2.2.1 Water Levels

The complete water level records from the three recorders in the lagoon are presented in Figure 4. Unfortunately, the South recorder was knocked askew by a storm in June and a month of data was lost, then it was drowned by rising lagoon levels on 11 September and ceased to operate. However, the other two recorders operated satisfactorily for the entire period from 27 March 2003 to 4 January 2004.

The three recorders show substantial differences in level, especially between the North recorder and the other two. Indeed, for September and October, when the lagoon was at its maximum level, the North and Mouth recorders exhibit an almost exact inversion of each other. These are wind effects that will be investigated further in Section 3.1. The mouth of the lagoon was opened artificially on 4 November and the nature of the lagoon changed substantially after that. The overall lagoon level dropped by 0.5 m and the Mouth became tidal. This will be investigated in Section 3.3. At the start of the record on 27 March (Figure 4), the lagoon level was 500 mm and by October it had risen to 1270 mm. Indeed, during October the rate of rise slowed and for the latter half of the month, it was constant. This implies that for this period of time there was a balance between inflow and outflow, and this will be investigated further in Section 3.2.

Data from the recorder in Lake Kaingarahu are compared with the data from the North recorder in Figure 5. The purpose of the measurements in the lake was to determine if there was any connection between the lake and the ocean, or between the lake and the lagoon, because this could indicate seepage flows. In the absence of survey information that would establish the levels in the lake relative to the levels in the lagoon, it is difficult to assess the connection between the lagoon and the lake. Suffice it to say, that the lake appears to rise and fall with lagoon level, and there is no evidence of tides. Therefore, we infer that there is a connection between this lake (and therefore the other lakes) and the lagoon, but the connection is not straightforward.

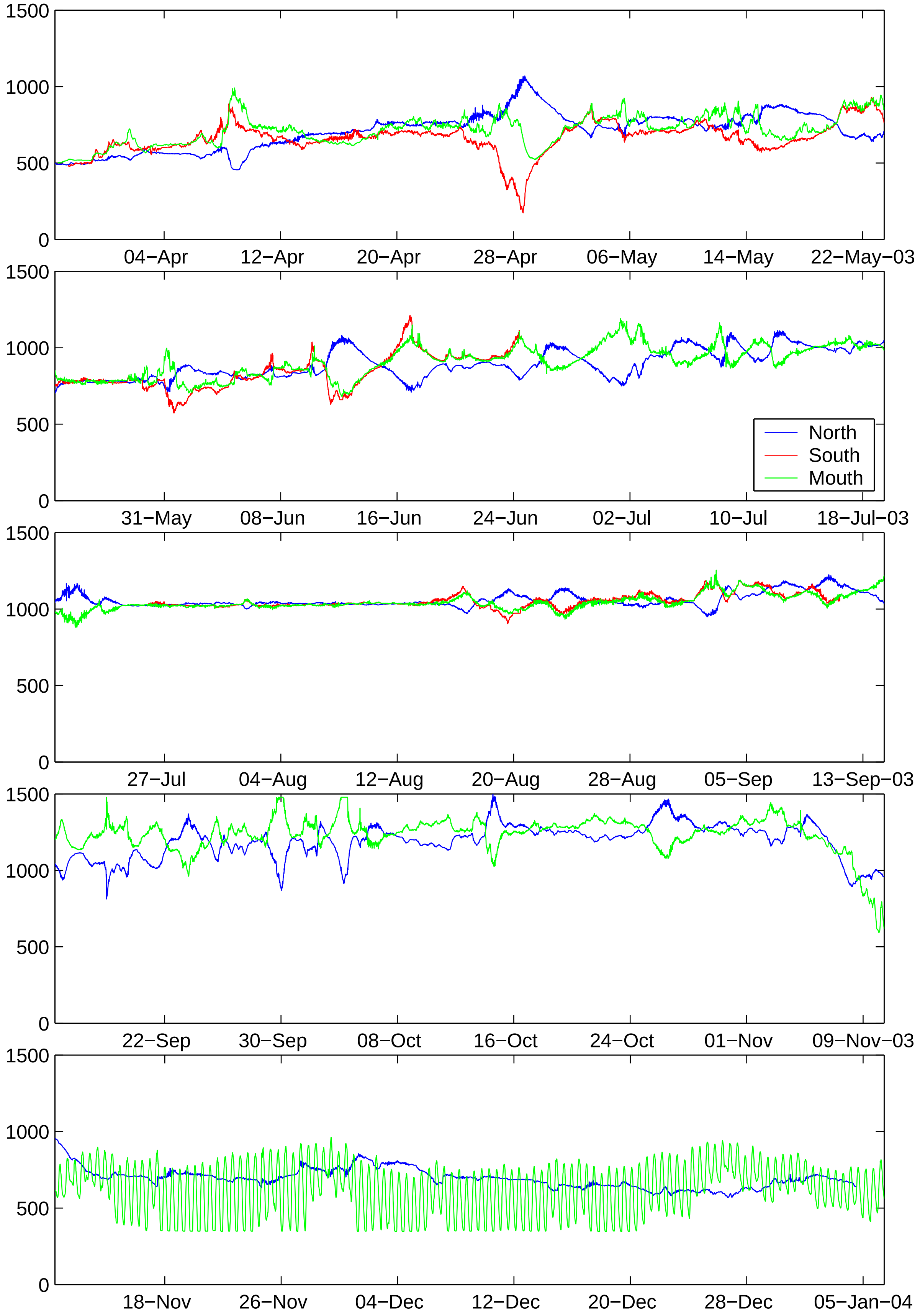

**Figure 4. Water levels in mm above Mouth Recorder Gauge Zero for the entire period of record.**

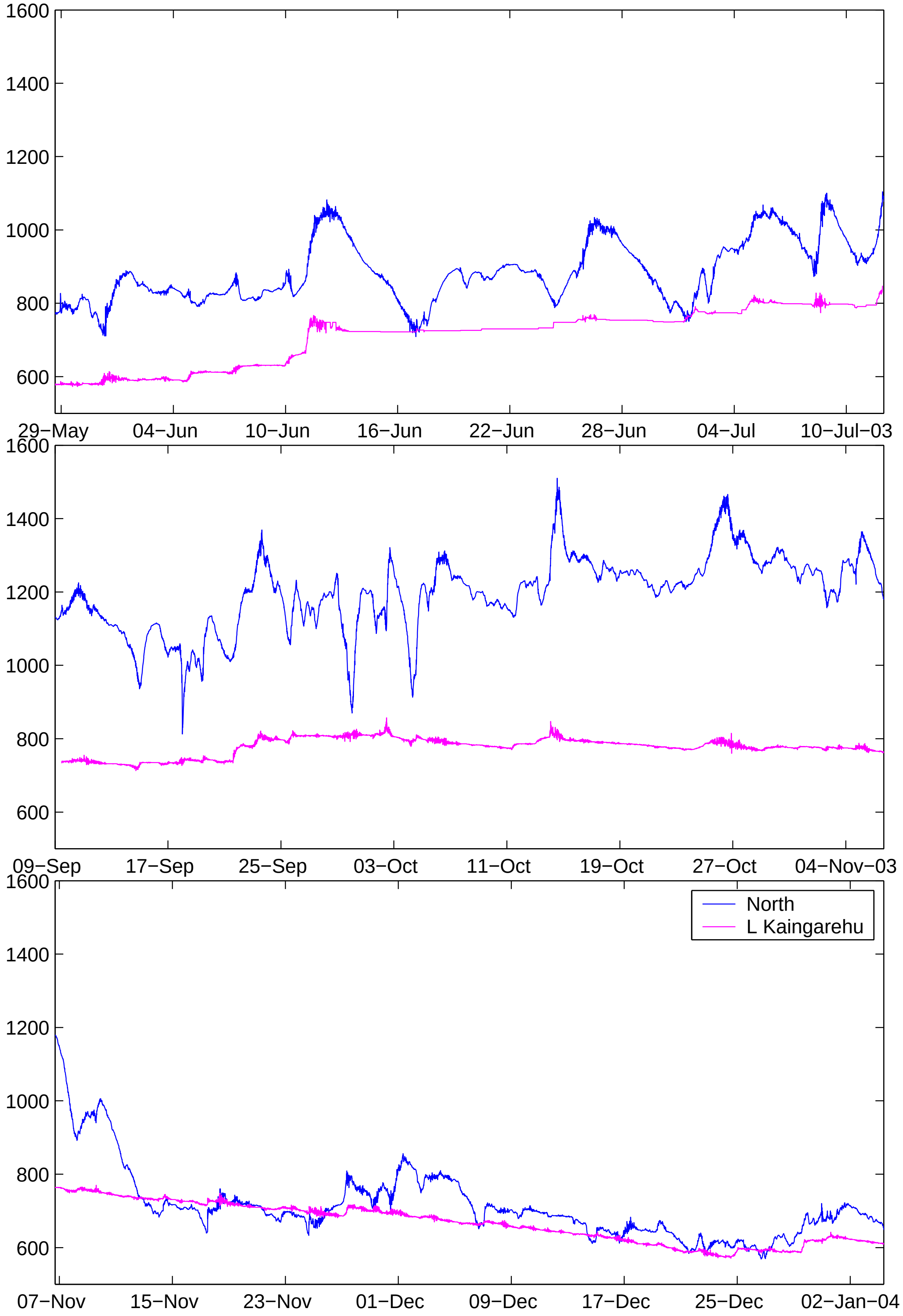

**Figure 5. Comparison of levels in Lake Kaingarahu with those at the North recorder.**

### 2.2.2 Water Temperature

The water temperatures at the three lagoon recorders are presented in Figure 6. For the first few weeks of measurement, the diurnal fluctuations in temperature at the North site were as much as 10ºC, while the diurnal fluctuations at the South and Mouth sites were nearer 5ºC, probably reflecting the deeper water at the latter sites. By mid-April, the diurnal fluctuations at all three sites had dropped to 4ºC, and this continued to fall, along with the mean temperature until 9 Jul when the diurnal fluctuations had decreased to 2ºC, and the mean temperature had reached a minimum of 5ºC for the North and South sites and 3ºC for the Mouth site. Thereafter, the mean temperature and diurnal fluctuations gradually increased. After the mouth was opened on 4 November, the temperature at the Mouth site followed a much more complicated pattern, being primarily influenced by the timing of the daytime low tide. The diurnal fluctuation in temperature at the Mouth site was as much as 15ºC in December.

### 2.2.3 Salinity

The salinity records from the three lagoon recorders are presented in Figure 7. The data have been processed to remove single-point spikes before plotting. The spikes that remain contain two or more points and cannot be distinguished from actual data. The salinity at the South and North sites is reasonably constant at just over 20 ppt, indicating somewhat saline water (freshwater has 0 ppt and seawater has c. 37 ppt). The salinity at the North site does not appear to have changed significantly after the mouth was opened on 4 November, indicating that any seawater entering the lagoon on the flood tide is not penetrating as far as the northern basin of the lagoon. The salinity at the Mouth is quite different to that measured at the South and North sites, fluctuating from just over 20 down to almost zero. This is analysed in more detail in Section 3.4.1. Unfortunately, the conductivity probe at the Mouth became encrusted with vegetation in late September and malfunctioned until it was cleaned just before being removed in January. Two tidal cycles were measured at this time and these are analysed in Section 3.4.2.

### 2.2.4 River Inflow

The flow from the Te Awainanga River at Falls is presented in Figure 8. The record exhibits two long periods of flows less than 1 cumec, one from 18 July to 30 August when the flow fluctuated between 0.5 and 1.5 cumecs, with a mean of 0.8 cumecs, and the other between 8 November and 27 December when the flow fluctuated between 0.2 and 1 cumec, with a mean of 0.5 cumecs. There were a few flood events, with the event of 8 April peaking at 77 cumecs.

### 2.2.5 Rainfall

Daily rainfalls are presented in Figure 9. The peak rainfall of 51 mm occurred on 3 September. The longest period between significant rainfall events was from 23 July to 12 August, though 0.4 mm fell on 3 August. Figure 4 shows that during this period the levels at the three sites were the same and there was a slight rise in the overall lagoon level.

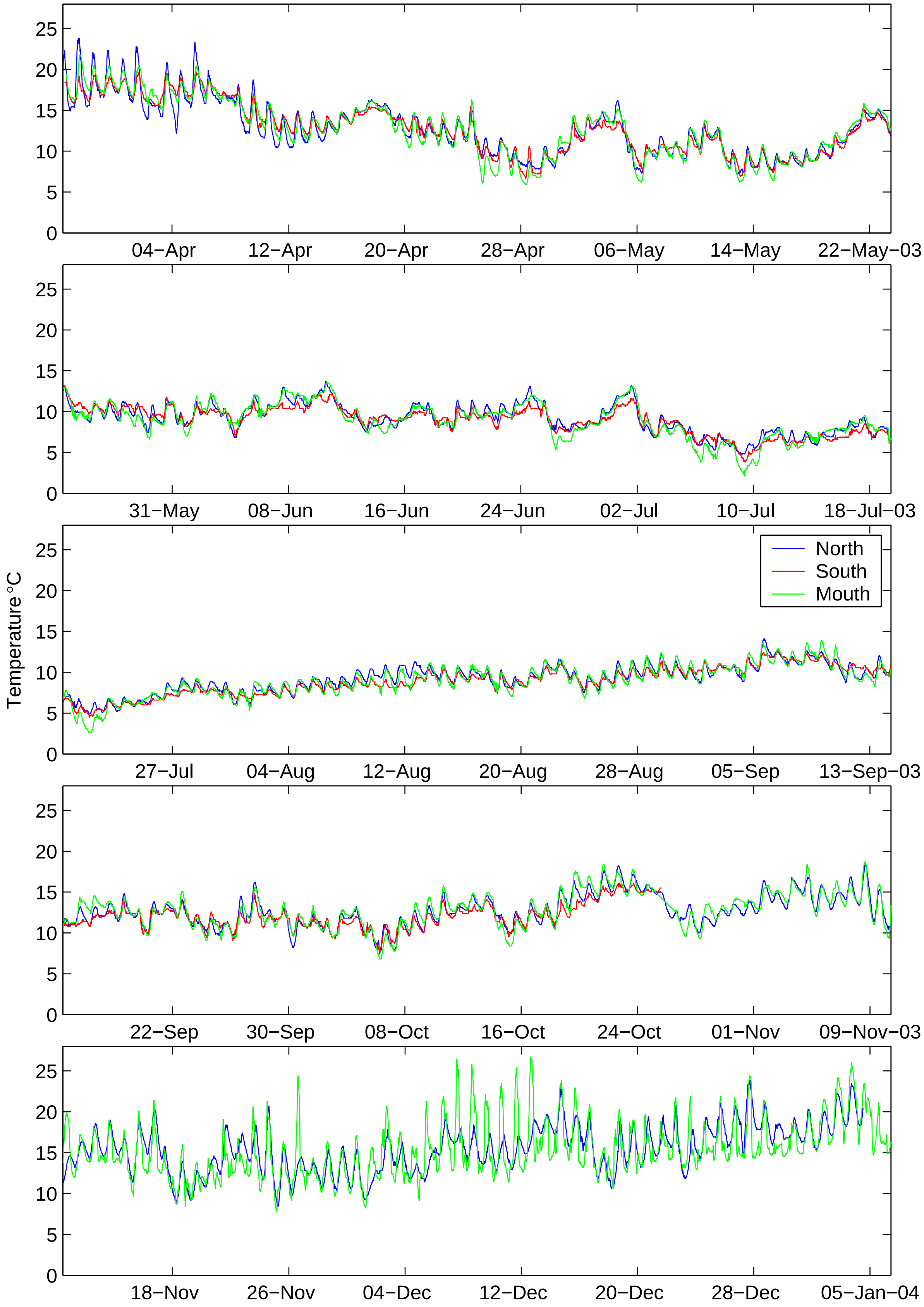

**Figure 6. Water temperatures at the three lagoon sites for the entire period of record.**

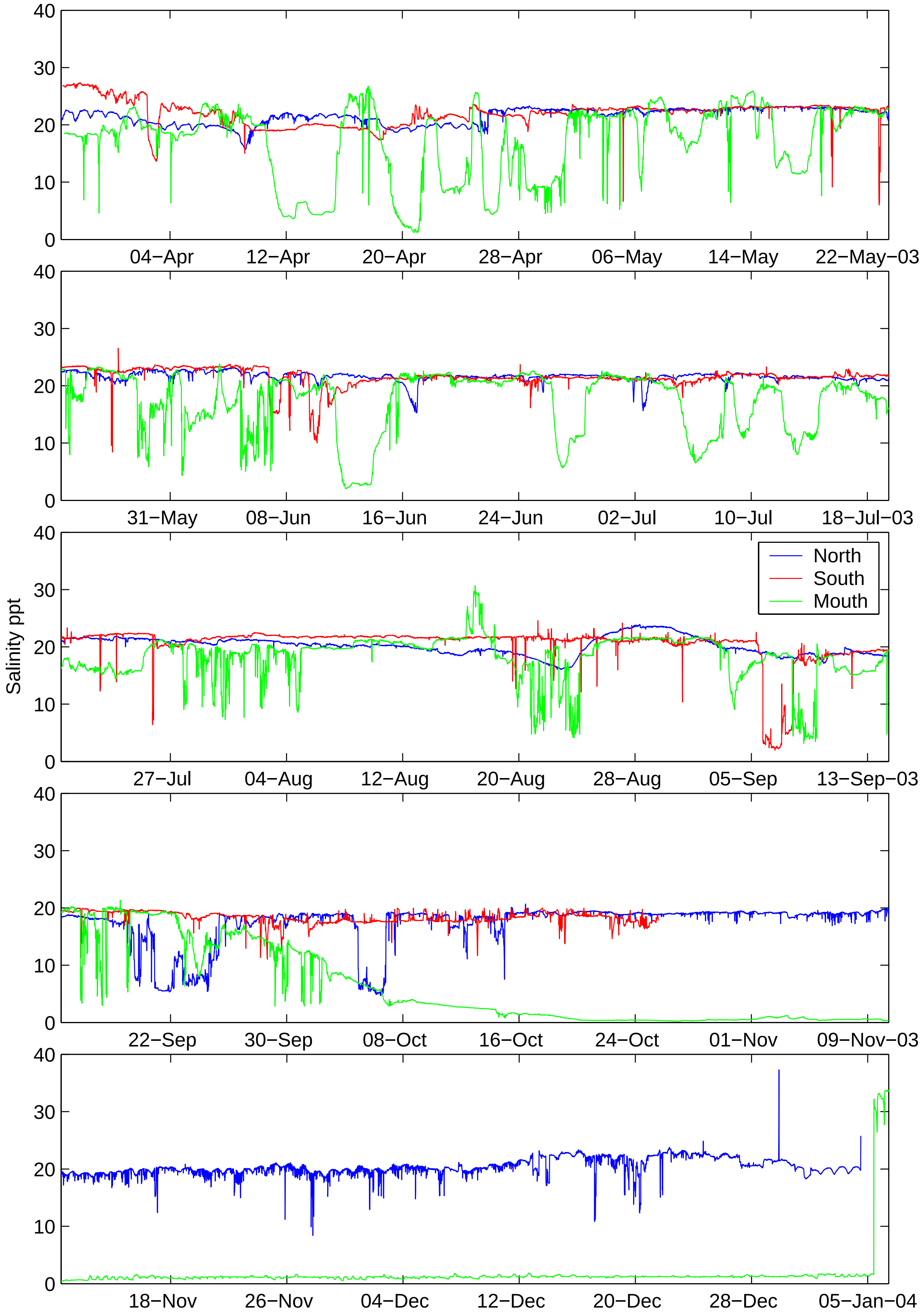

**Figure 7. Salinity at the three lagoon sites for the entire period of record.**

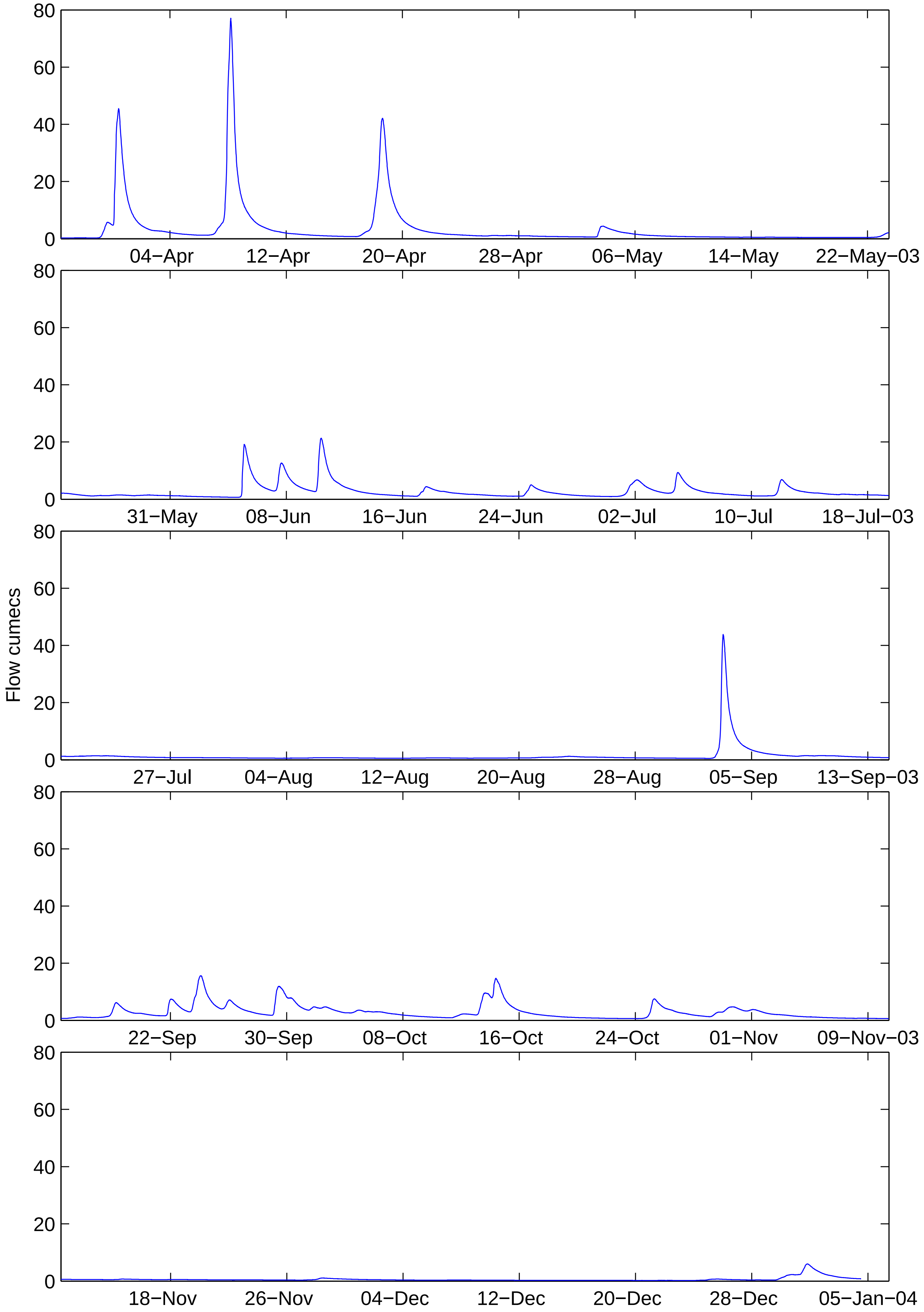

**Figure 8. Inflow to the lagoon from the Te Awainanga River.**

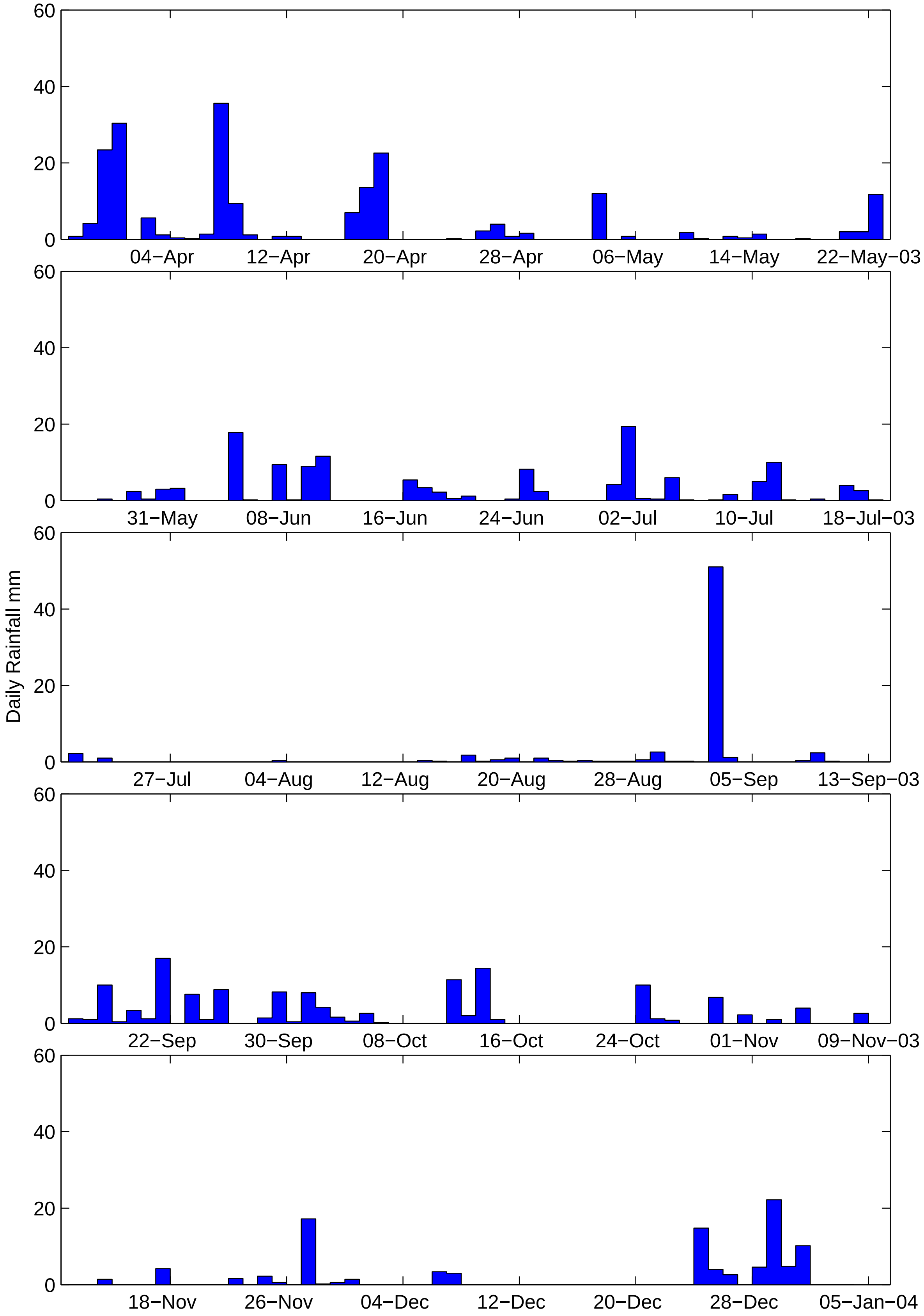

**Figure 9. Daily rainfall recorded at the Airport.**

### 2.2.6 Wind

Wind is important because of its day-to-day effect on lagoon levels. Wind blowing over a water body applies a stress to the surface that causes the water to flow away from the upwind side and to pile up on the downwind side. The longer the distance the wind acts over (called its "fetch"), the more pronounced will be the "set-up" at the downwind side and the "set-down" on the upwind side. The wind rose shown in Figure 10 indicates that for Te Whaanga, wind is mostly from the west, and a principal component analysis confirms this, indicating that the direction of the principal wind is 281° from N (i.e., just north of west). For the lagoon, however, it is wind, or more precisely wind stress (the force of the wind on the water surface), from the north or south that has most effect on levels because they have the longest fetch. Westerly winds are also important, but they have a shorter fetch.

Wind stress is calculated from wind speed using the formula of Wu (1982) for drag coefficient:

$$C_D = (0.8 + 0.065U_{10})/1000$$

where $U_{10}$ is the wind speed in m/s at 10 m above the ground. The stress for a particular direction is calculated from:

$$\tau_i = \rho C_D U_{10} u_i$$

where $\rho = 1.25$ kg/m$^3$ is the density of air, and $u_i$ is the component of wind speed in one direction. Figure 11 shows the daily mean wind stress in the form of a feather plot comprising a set of line vectors, in which the length of the vector indicates the magnitude of the stress and the orientation of the line indicates the direction of application of the stress on the lagoon's surface. Thus, for example, the 45° line below the time axis on 9 April represents a northwest wind of about 0.35 N/m$^2$ stress. The total force on the lagoon's surface can be obtained by multiplying the stress by the area (185 km$^2$). This reveals that the force can be as large as 90 megaNewtons (equivalent to approximately 9,000 tonnes of weight).

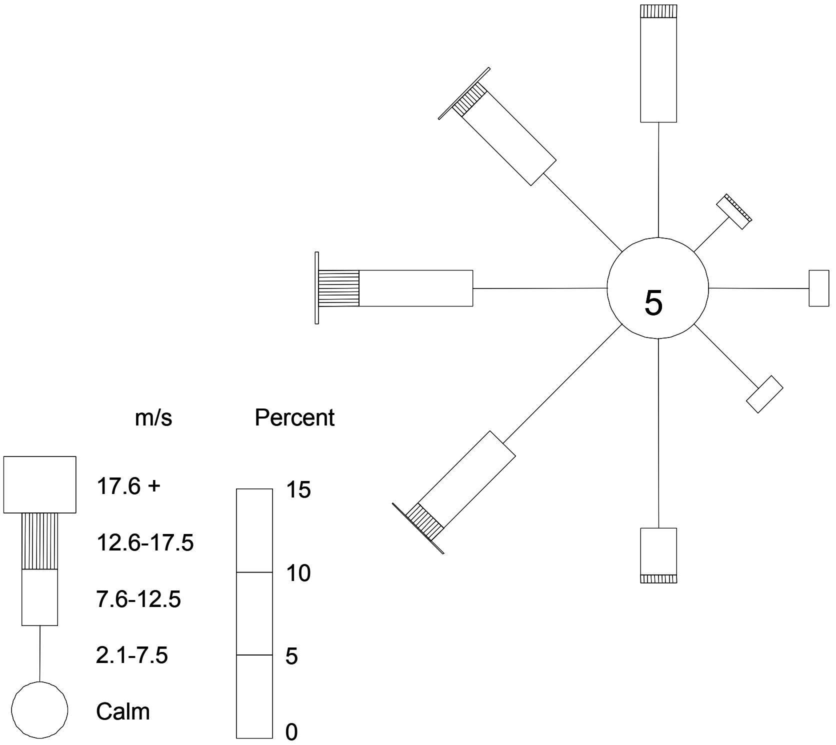

**Figure 10. Wind rose from Chatham Island Airport for 28 March 2003 to 4 January 2004.**

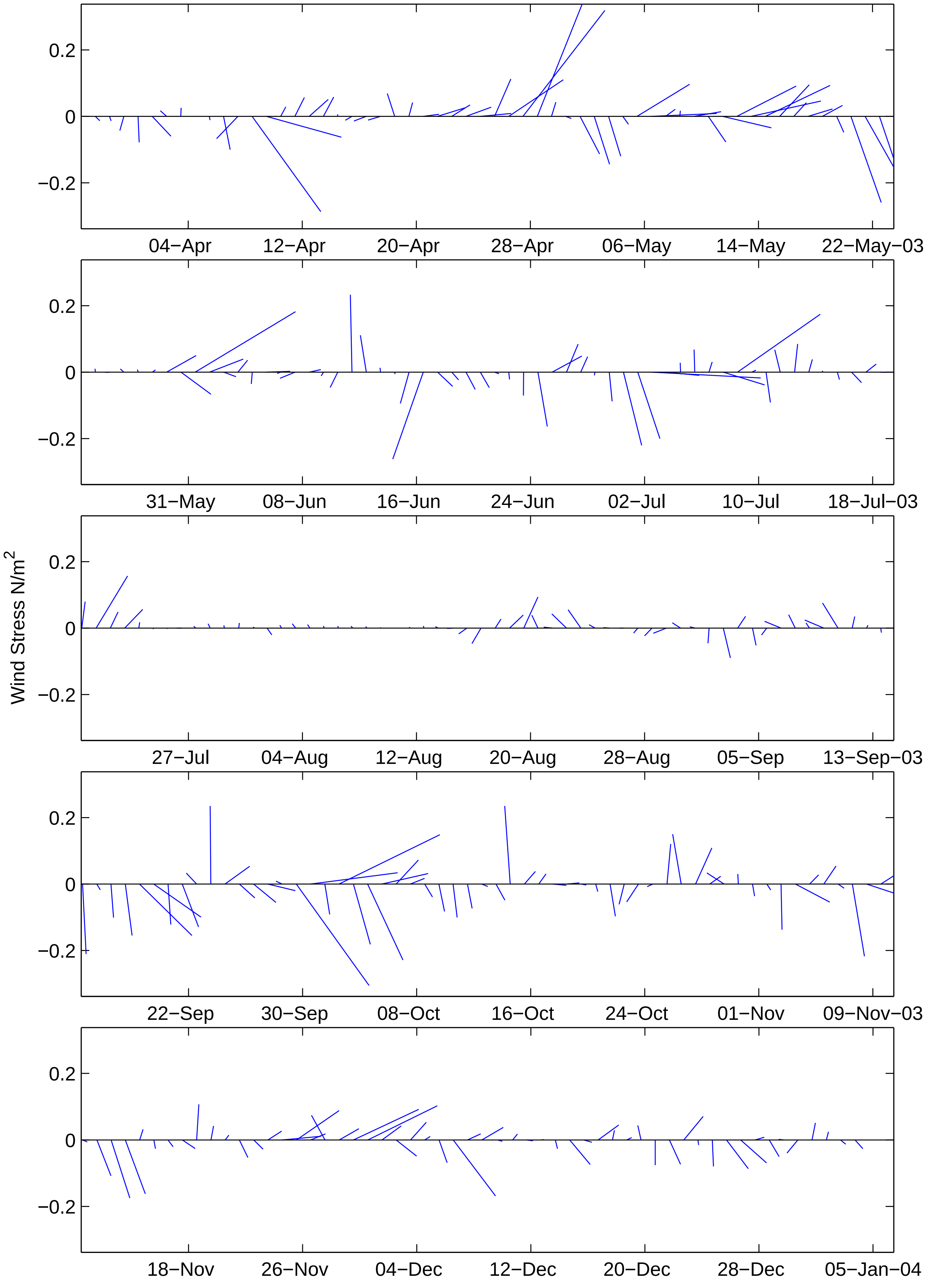

**Figure 11. Daily mean wind stress on the lagoon for the entire period of record.**

### 2.2.7 Evaporation

Applying the methods for calculating evaporation described in Appendix I, resulted in the estimates of evaporation presented in Figure 12. Hargreaves' method, which is based solely on the air temperature and a semi-empirical estimate of solar radiation, gives zero evaporation over the winter months, then a rapid increase during spring to a peak evaporation of 1.08 mm/day at the start of the year. Brutsaert's method, which is based on lagoon area, wind and the difference in vapour pressure between water and air, gives evaporation rates of c. 0.1 mm/day in winter, rising to a maximum of c. 0.6 mm/day in November. Converting these rates to an equivalent flow yields 2.3 cumecs for the maximum rate using Hargreaves equation and between 0.2 and 1.3 cumecs for Brutsaert's equation.

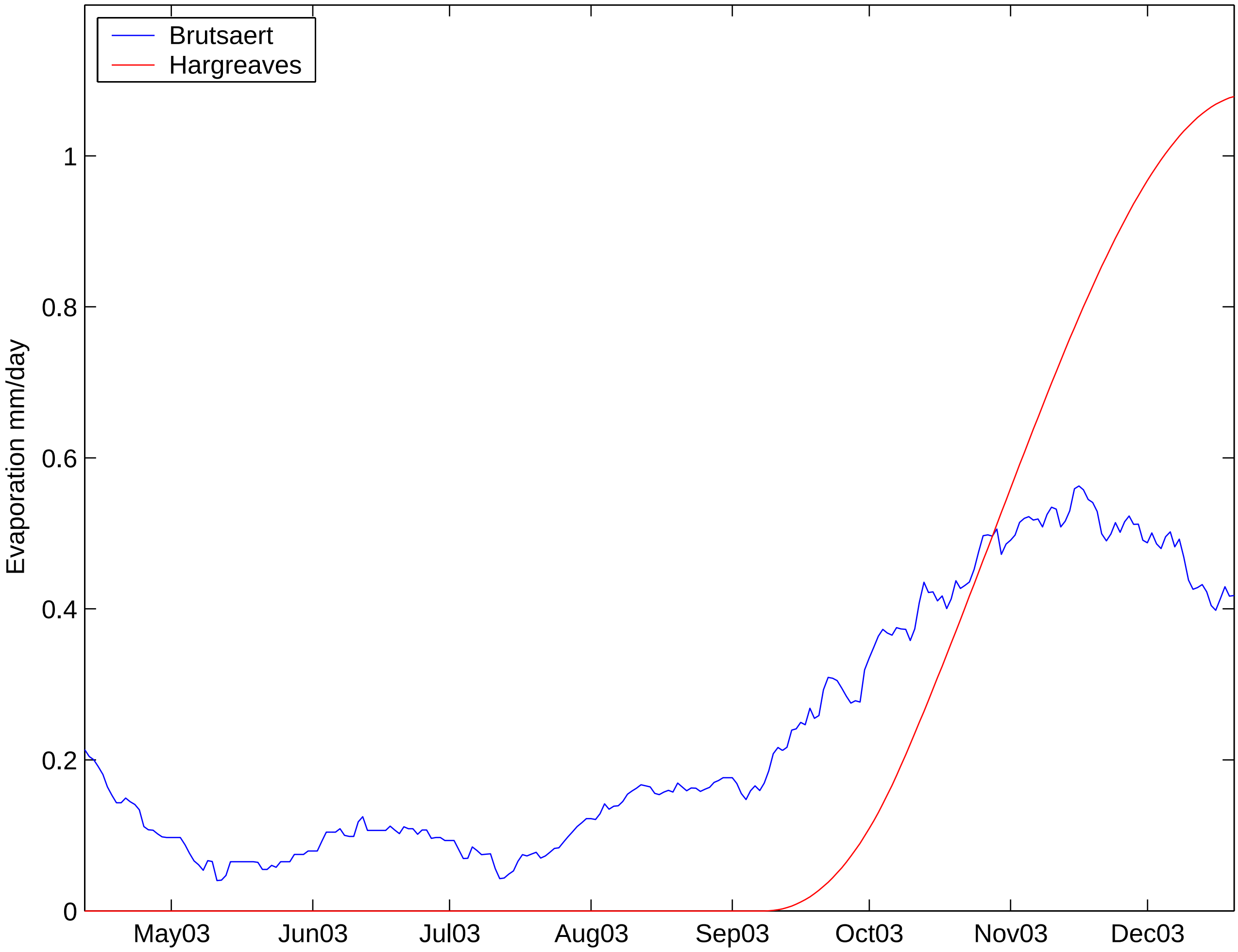

**Figure 12. Estimated evaporation from Te Whaanga calculated using two different methods.**

### 2.2.8 Sea Level

The tide just offshore from the Hikurangi Channel is presented in Figure 13, along with inverted barometer and the tidal portion of the record from the Mouth recorder for comparison. Inverted barometer is an estimate of how sea level varies in response to changing weather. It is calculated by subtracting atmospheric pressure from its mean, using the theoretical isostatic relationship that a 1 hPa change in pressure produces a 1 cm change (in the opposite direction) in sea level. Both tide and inverted barometer fluctuate about the mean level of the sea (MLOS), and MLOS in turn fluctuates with large timescale climate effects like El Niño-Southern Oscillation (ENSO) and long-term sea-level change, though MLOS could be reasonably assumed to be constant over the period of record shown in Figure 13. However, we have no information on how MLOS is related to the datum of the Mouth recorder. Therefore, we cannot directly relate the levels at the Mouth recorder to tide and inverted barometer.

The Mouth levels fluctuate in response to changing inverted barometer (as well as the tide), with the most obvious portion being on 7 December when inverted barometer rose from –100 to +50 mm above MLOS, and the Mouth levels rose by the same amount. Of course, the Mouth levels are responding not only to tide and inverted barometer, but also to changing levels in the lagoon as a result of increased inflow from the Te Awainanga and from rainfall, such as in the period towards the end of the record. Notice that when the Mouth levels are elevated like this, the tide height (i.e., the difference in elevation between high tide and low tide) reduces, indicating that the tide has less influence. At the other extreme, for the period from the 19 to 25 November, the tide height is a maximum and the levels at the Mouth bottomed out before low tide.

The tide is mainly semidiurnal (twice-daily), but it has some diurnal components as well. These manifest themselves by making each alternate tide larger or smaller than the previous one. The effect is most pronounced around 13 December when there is a 150 mm difference in adjacent high tide heights. This effect is reflected in the Mouth record also, though much reduced.

The figure shows there is a lag between high tide at sea and high tide at the Mouth recorder. The lag is quantified in the histogram in Figure 14, which shows that it is mostly between 0.5 and 0.75 h. This reflects the time it takes for the effects of an ebbing tide at sea to propagate through the mouth to the recorder site.

Figure 15 shows an oblique photograph of the mouth at 1.75 h before low tide and we see the channel from the Mouth recorder to the main stream is still reasonably deep. At low tide this channel becomes only a few cm deep. At low tide on 6 January, a flow gauging was done across the Hikurangi Channel. Only the first 115 m from the right bank could be gauged before the channel became too deep and swift to continue, leaving ungauged a 30 m wide channel that was more than 1 m deep, with currents greater than 1 m/s. This can be seen in Figure 15 at the left bank of the gauging section. Allowing for this channel, the calculated flow was 60 cumecs ±6 cumecs error.

Clearly, the mechanics of a tidal mouth like the Hikurangi Channel are complicated and difficult to understand. For this reason, a mathematical model has been developed that simulates the physics, and this is presented in Section 3.3.

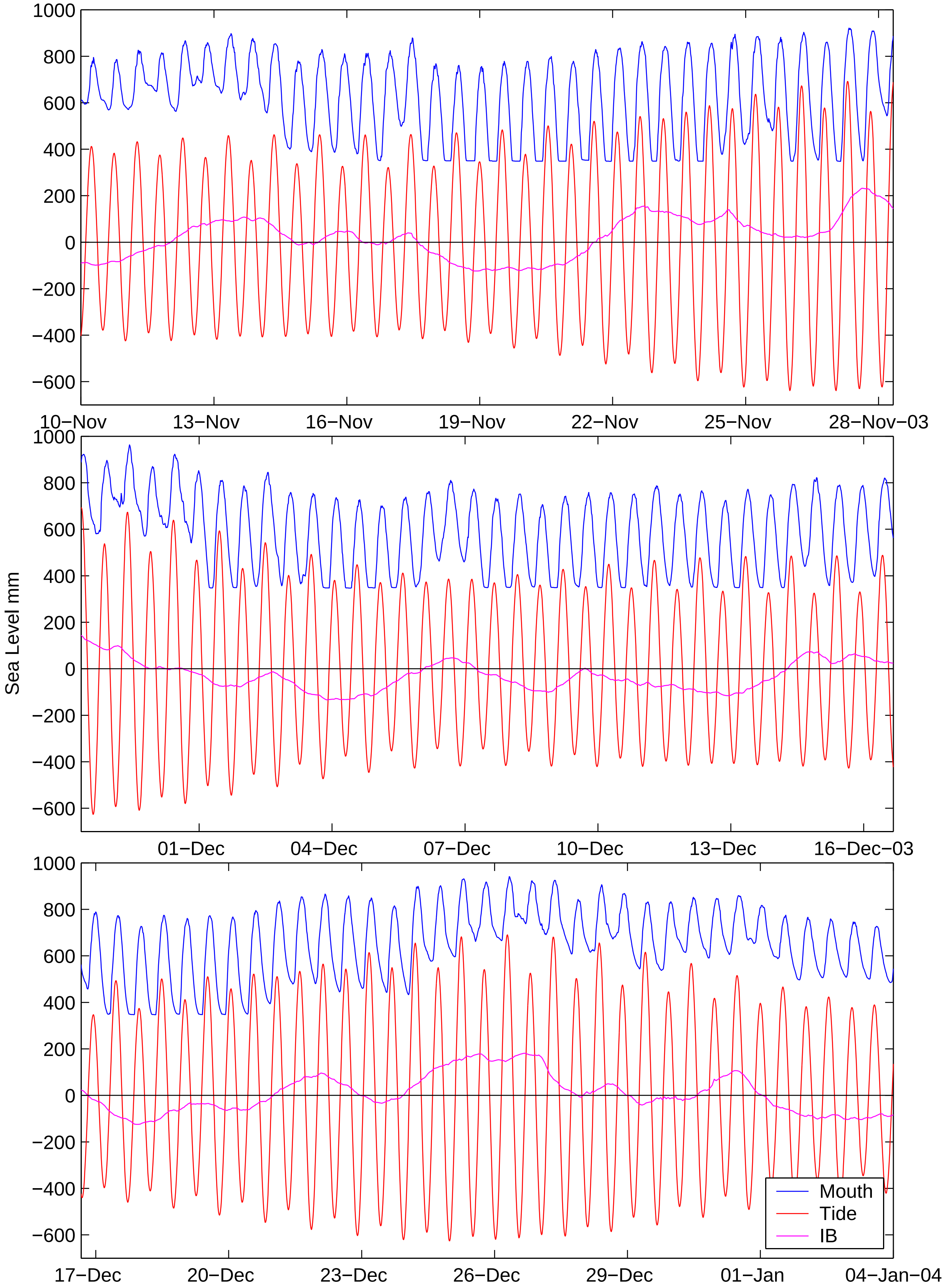

**Figure 13. Comparison of levels at the Mouth recorder (to Gauge Zero datum) with tide and inverted barometer (IB) (to MLOS datum) for the period when the mouth was open.**

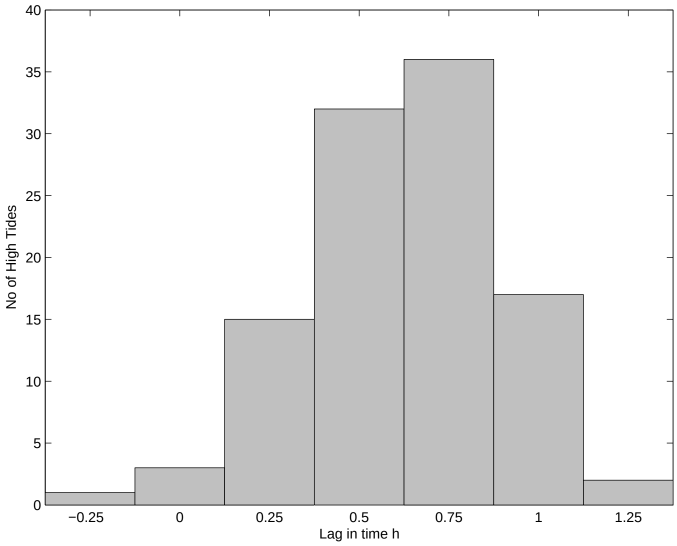

**Figure 14. Distribution of lags in the time of high tide at sea and high tide at the Mouth recorder.**

**Figure 15. Aerial photograph of the Hikurangi Channel at 0945 CIST on 7 January 2004, 1.75 hours before low tide at sea. (Assistance of Air Chathams in capturing this shot is gratefully acknowledged.)**

# 3 ANALYSIS

In this section, we analyse the data presented in the previous section to obtain an appreciation of how Te Whaanga behaves from a physical point of view.

The data show quite clearly that the mouth region of the lagoon has a completely different regime when the mouth is closed to when it is open. When it is closed, the mouth region behaves like a lake (as does the whole lagoon), with water levels being influenced on a day-to-day basis by the wind and on a week-to-week basis by the hydrological cycle (i.e., inflow from rain and river flow and outflow by evaporation), but when the mouth is open, ocean effects dominate.

We start this section with an analysis of how wind affects water levels and follow that with an assessment of the water balance when the mouth is closed. We then consider the hydraulics of the lagoon when the mouth is open. Finally, we look at salinity both when the mouth is open and when it is closed.

## *3.1 Effect of wind on water levels*

A comparison of Figure 4 (showing water levels) with Figure 11 (showing wind stress) reveals that for the period before the mouth opened, each significant fluctuation of the water surface coincided with a moderate to large wind stress. We have chosen three events in this period to study in more detail: 5 - 13 April (a northerly event); 23 April – 1 May (a southerly event); and 10-18 June (a southerly followed by a northerly). The data are presented in Figures 16 a, b, and c.

### 3.1.1 Northerly Event: 5 – 13 April

When the event started, the South and Mouth sites were already elevated by 50 mm over the North site, then a small north-westerly event on 6 April increased the southern levels, but these dropped again until a strong ENE wind struck in the afternoon of 7 April, pushing water away from the Mouth towards the South site. On 8 April a very strong NW wind pushed the water back towards the Mouth site and levels to the north dropped until the recorder at the North site bottomed out. The westerly component of the wind kept the level at the Mouth site higher than the level at the South site. As the wind tended more westerly on 9 April, the level at the North site quickly rose and the levels at the southern sites fell as the wind stress died.

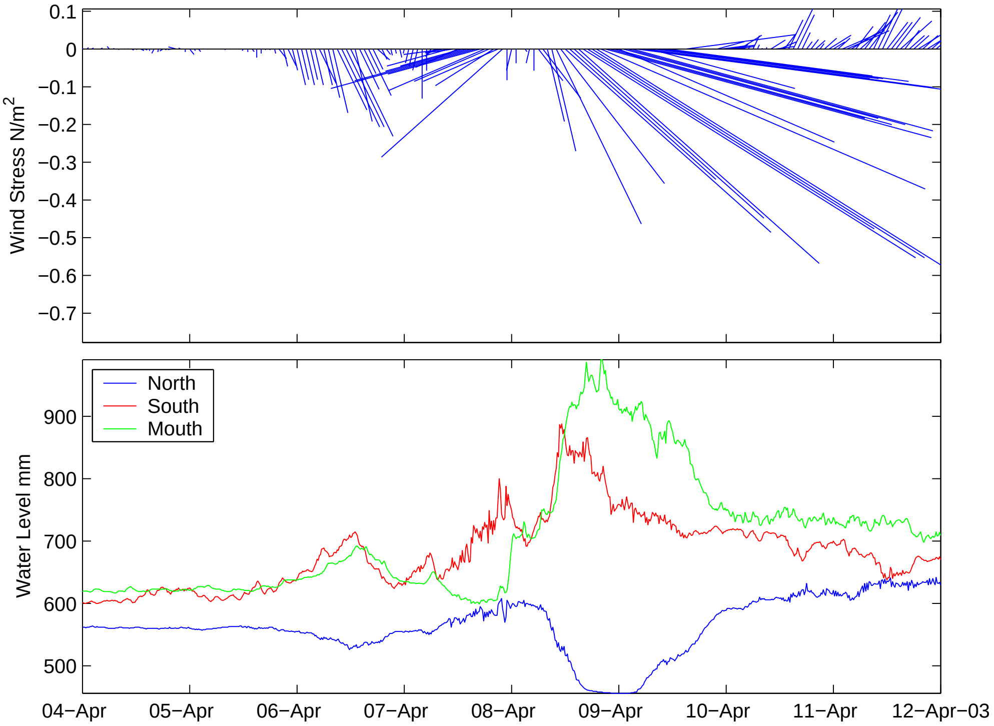

**Figure 16 a. Northerly wind event: hourly wind stress (upper plot) and lagoon levels in mm above Mouth Gauge Zero datum (lower plot).**

### 3.1.2 Southerly Event: 23 April – 1 May

At the start of the event, westerly winds elevated levels at the Mouth site over those at the South site, and as the wind turned southerly on 25 April and strengthened, levels at the North site increased. A short period of WSW winds on 26 April elevated the Mouth site enough to actually exceed levels at the North site briefly, then the southerly component strengthened and the levels at the North site rose, while those at the South site fell. The westerly component in the wind kept the Mouth site elevations well above those at the South site.

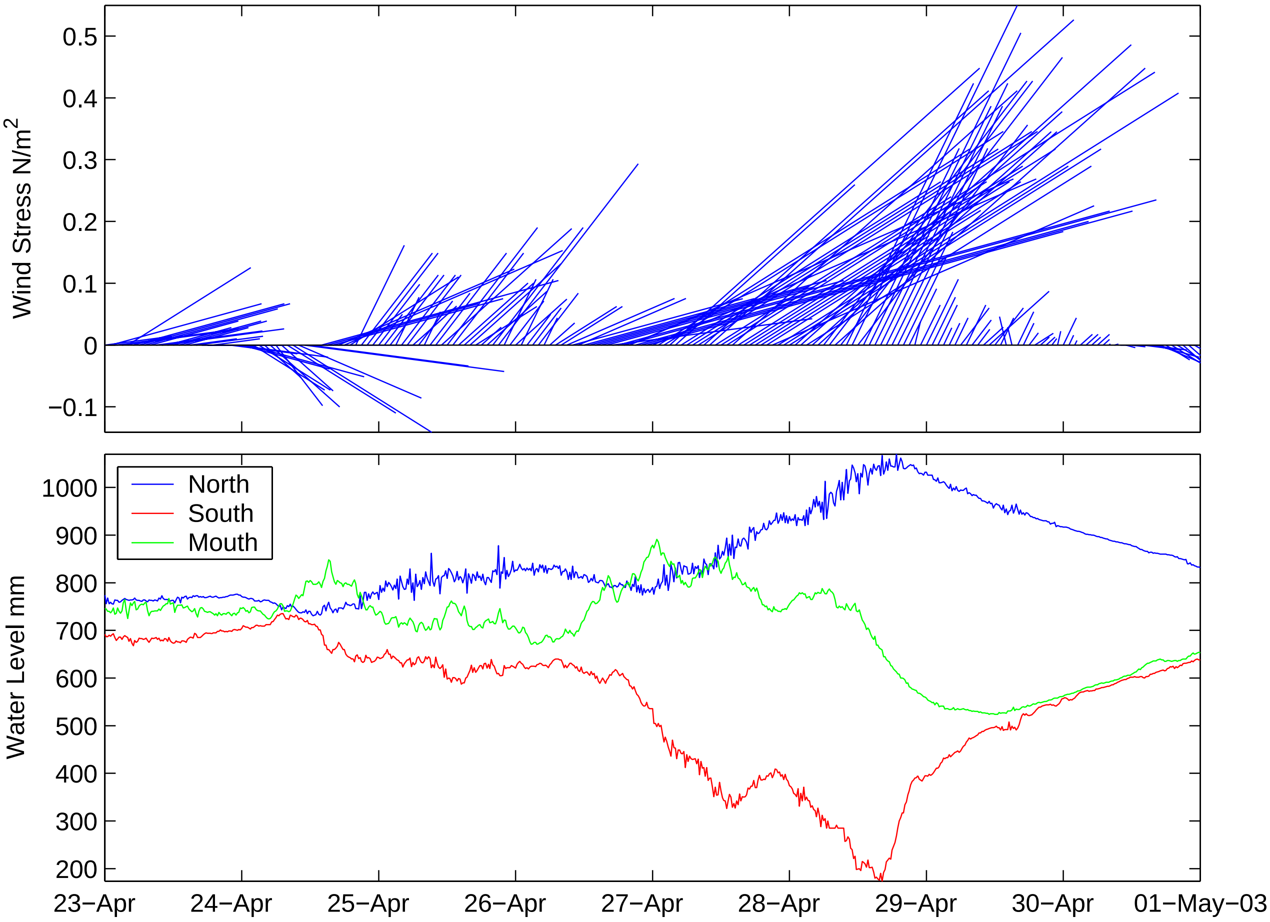

**Figure 16 b. Southerly wind event: hourly wind stress (upper plot) and lagoon levels in mm above Mouth Gauge Zero datum (lower plot).**

### 3.1.3 Southerly followed by a Northerly: 10 – 18 June

A southerly storm elevated levels at the North site and dropped levels at the southern sites, then after a couple of days of calm weather as the lagoon levels recovered, a north-easterly storm hit and caused the opposite effect. The result was that the water levels at the South site increased from 650 to 1210 mm in 5 days.

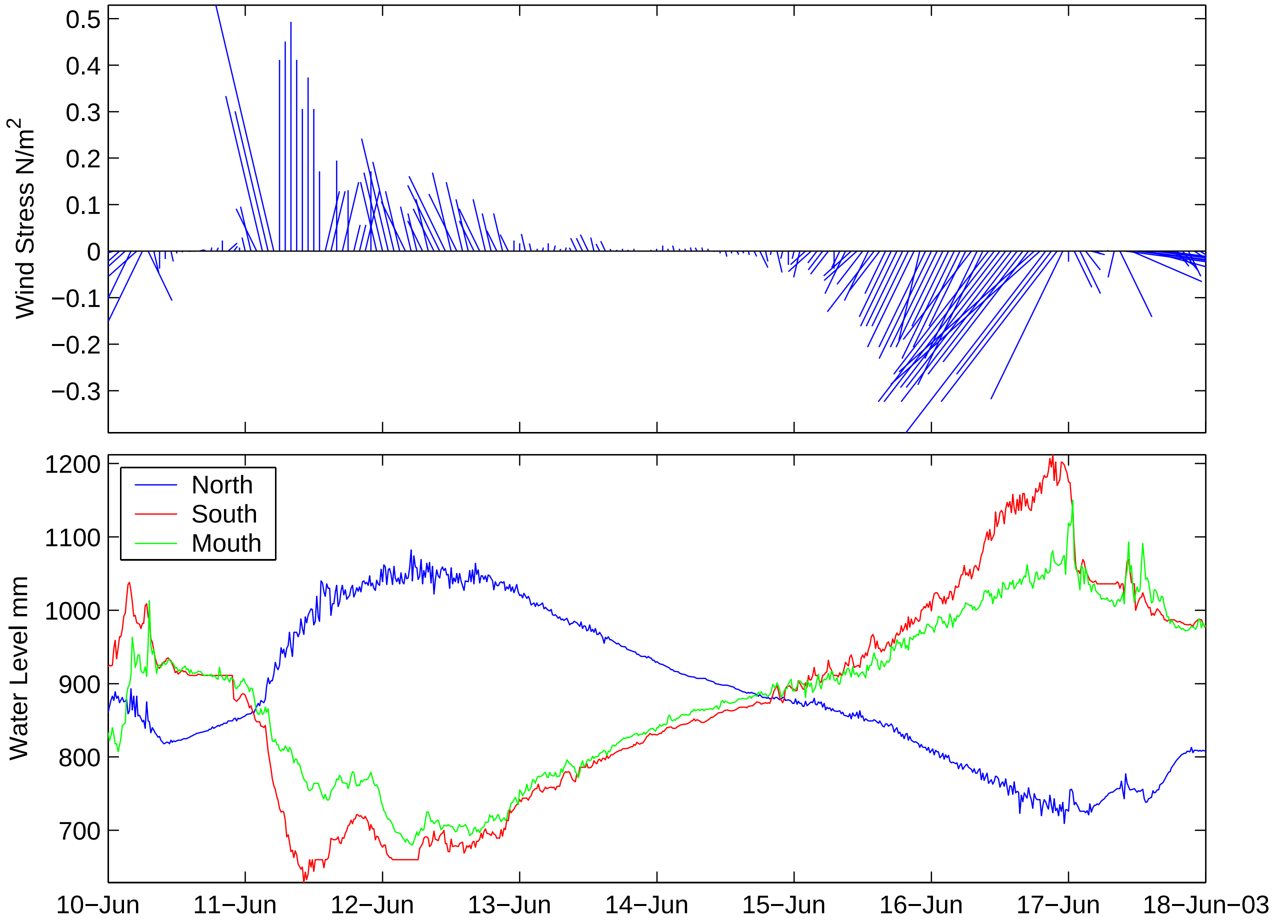

**Figure 16 c. Southerly followed by a northerly: hourly wind stress (upper plot) and lagoon levels in mm above Mouth Gauge Zero datum (lower plot).**

Analysis of these three events has shown that the lagoon responds very quickly to changes in the wind's strength and direction, but unlike a normal deep lake (L. Wakatipu, for example), there is no sieche[1]. Both of these effects (i.e., quick response and lack of ongoing oscillations) can be attributed to the very shallow water of the lagoon. The small inertia of shallow water means that the water body responds quickly and the high friction attendant with shallow water means that the oscillations dissipate quickly when the force is removed.

The water elevations at the three measurement sites are unique to those sites and do not necessarily represent the levels that other locations would experience. For example, somewhere in the centre of the lagoon, we would expect that water levels would change only slightly in response to wind. To examine this further, we digitised the lagoon boundary as shown in Figure 17 and modelled the

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[1] Seiche is a Swiss word of unknown origin that has been used for hundreds of years to refer to the tide-like fluctuations of Lake Geneva after winds have dropped. Nowadays it is used to refer to oscillations in any lake or embayment that persist after the driving force has died away.

water surface of the lake by assuming that a plane passes through the three measuring sites and extends to the lake boundaries. Then, by applying the water-level time series for each measurement site, we could simulate the water surface of all parts of the lagoon for the period of record. The resulting range of levels (i.e., the difference between the maximum and minimum levels) is presented as a contour plot in Figure 18. Of course, this model is an approximation that has some serious limitations such as: (i) the surface may not be planar; and (ii) some areas will become completely dry. Nevertheless, in the absence of more measurements, it provides an estimate of how the entire lagoon responds to wind.

Figure 18 shows the North and Mouth sites, along with the Airport, are actually in locations of low wind effects (c. 600 mm range), whereas the South site is in a region of moderate wind effects (c. 1000 mm range). This probably explains why the North and Mouth sites survived the entire period of deployment, but the South site was drowned. The largest wind effects occur in the easternmost corner of the lagoon where the range is more than 1.5 m, but this is the area of least certainty in the calculations (there is considerable extrapolation from the plane through the measurement points). Reference to the topographic map in Figure 1 reveals that this area has an extensive marsh area, and it is directly aligned to the prevailing wind (just north of west) with a large fetch.

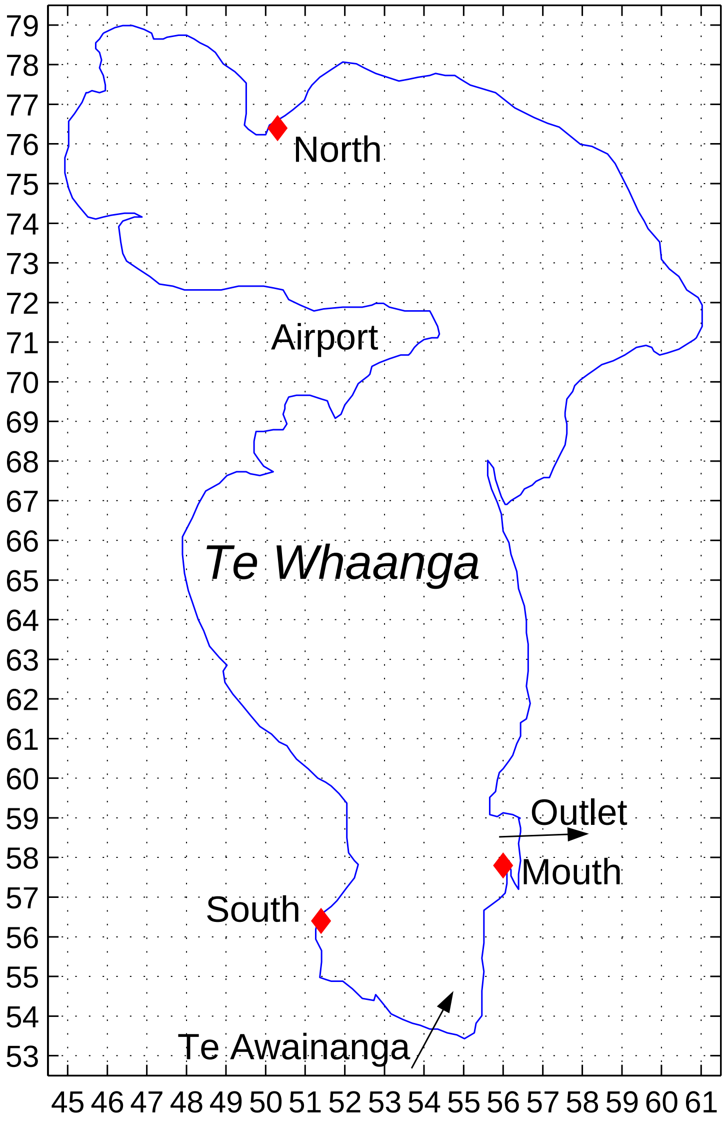

**Figure 17. Diagrammatic layout of Te Whaanga.**

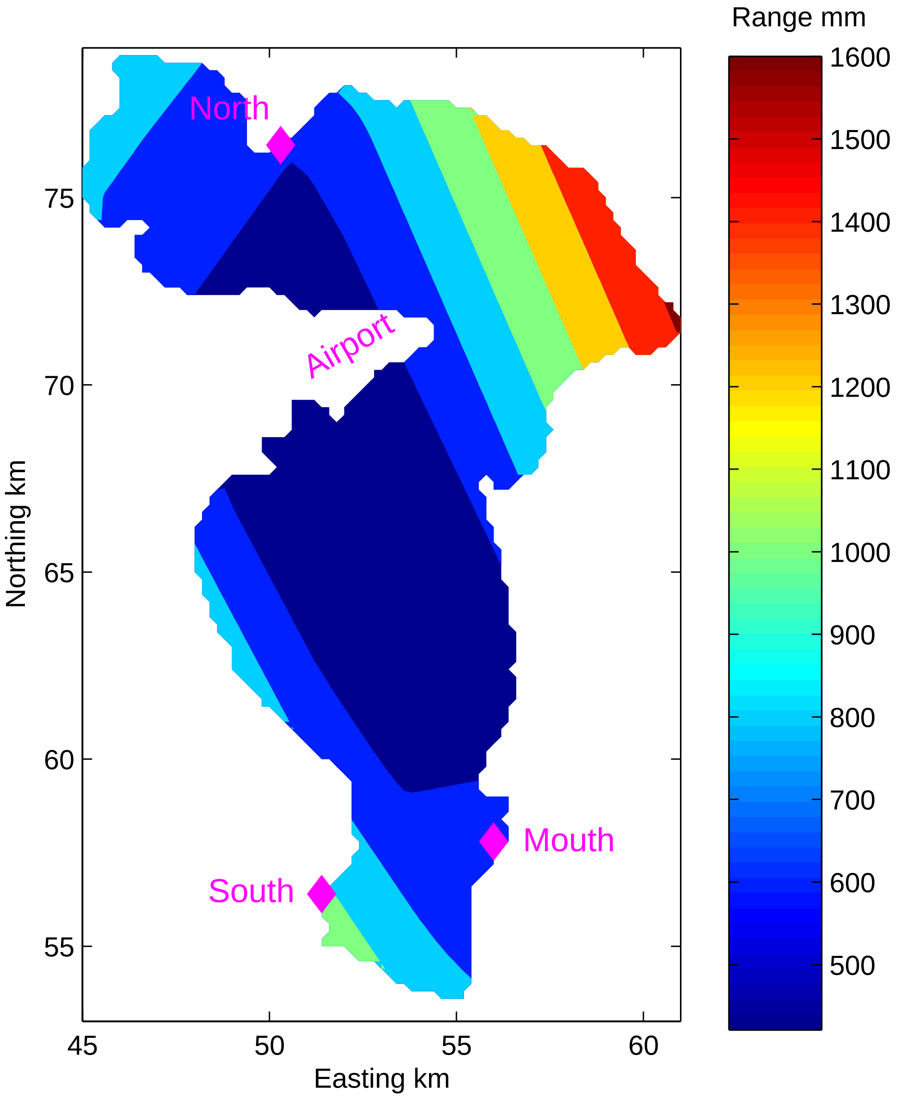

**Figure 18. Range (i.e. maximum – minimum) of wind effects on water levels from a model that assumes a planar surface.**

## *3.2 Mouth-Closed Water Balance*

When the mouth is closed, we have a relatively simple water balance model with the following inflows and outflows, listed with their source of information:

**Inflows:**

- River inflow – Te Awainanga River, Section 2.2.4, converted to mm/day by integrating over each day and dividing by the lagoon area.
- Rainfall – Airport rain gauge, Section 2.2.5, in mm/day.
- Groundwater – unknown.

**Outflows:**

- Evaporation – calculated, Section 2.2.7, in mm/day.
- Seepage – unknown.

In response to the inputs and outputs, the lagoon's water level will fluctuate over its 185 km$^2$ surface area. There is an unknown degree of inaccuracy in this surface area because we have no information about how it varies with lagoon level. A bathymetric survey was planned that would provide this information, but funding was cut before it could be undertaken. We understand that others have done such a survey, but to date, we have not been able to gain access to the data.

The results of the water balance are presented in Figure 19a. The upper plot shows the individual inflows (river flow and rainfall) and outflow (evaporation from the Brutsaert model). All quantities have been smoothed using a 30-day running mean. We see that rainfall falling on the lagoon is by far the most important, followed by river inflow. Evaporation has a minor contribution in comparison. The lower plot shows the actual daily rate of change in lagoon level compared to the rate calculated from the net inflow (i.e., river inflow + rainfall – evaporation). The lagoon level used for the actual rate is the mean of the North and Mouth levels, smoothed using a 30-day running mean. Considering the approximations that have been made in arriving at these two curves, there is remarkable agreement between them. Indeed, integrating the various quantities over the length of record gives the total volumes in Table 2, showing that in the long term the match is within 1%. However, this agreement must be used with caution because we have omitted some parameters and made some gross assumptions about others. For example, we have:

- completely neglected groundwater inflows and seepage outflows;
- assumed the rainfall is uniform across the lagoon;
- assumed no rain falling outside the shoreline of the lagoon affects the lagoon;
- assumed the lagoon area is constant with water level;
- neglected any river inflow other than the Te Awainanga.

Clearly, for the match to be within 1%, the effects of these assumptions and omissions must cancel out, or be of minor importance compared to the factors considered.

**Table 2. Water balance over 187 days, where the net inflow is rainfall + river flow – evaporation.**

| **Contribution** | **Volume millions of m$^3$** |
|---|---|
| Rainfall | 73 |
| River flow | 37 |
| Evaporation | 5 |
| Net inflow | 105 |
| Change in lagoon volume | 104 |

The data presented in Figure 19a are plotted only until the mouth was opened on 4 November, when the nature of the lagoon near the mouth changed substantially. At that time, the curves for rainfall and flow in the upper plot were trending downwards, while evaporation was trending upwards. It is interesting to speculate on what would have happened if the mouth had not been opened, as shown in Figure 19b. The figure shows that on about 10 November, river flow fell below evaporation and the rate of rise of lagoon level started to drop sharply. Only the small rainfall event towards the end of November and then two events towards the end of December arrested the decline. Without these events, it is likely that the net rate of rise in lagoon level would have been negative by Christmas (i.e., the lagoon level would have started dropping naturally).

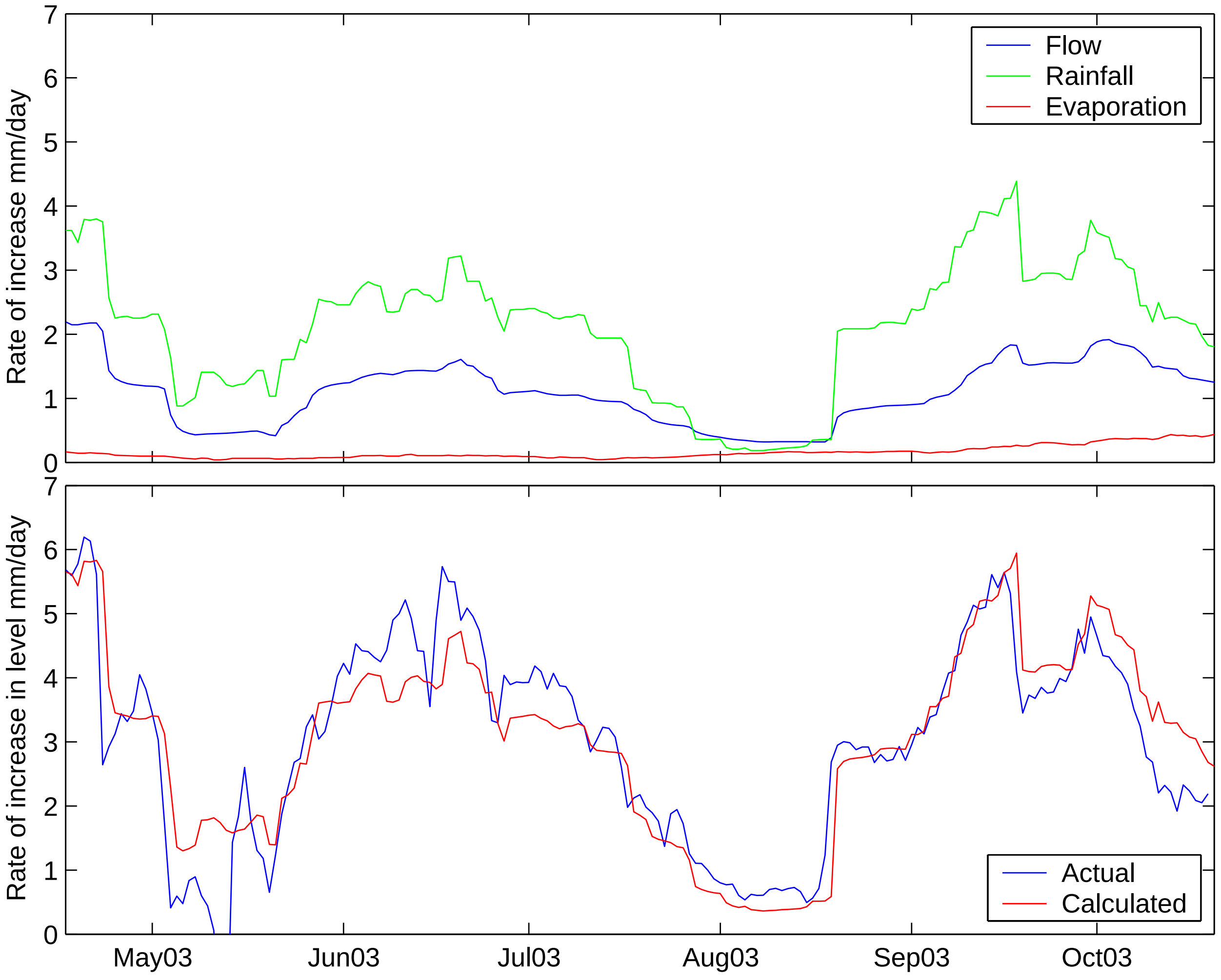

**Figure 19a. Water balance inflows and outflow (upper), and overall rates of change of level (lower).**

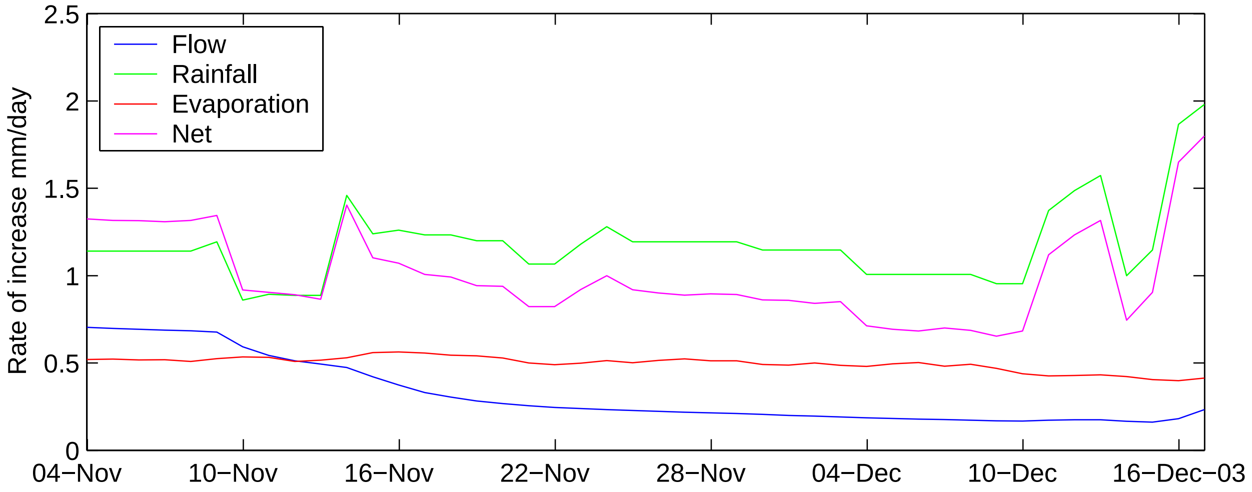

**Figure 19b. Water balance components for the period after the mouth was opened, and the net change of level in the lagoon that would have occurred if the mouth had not been opened.**

## 3.3 Mouth Open Hydraulics

When the mouth of Te Whaanga is open, the behaviour of the lagoon in the vicinity of the mouth changes substantially from that with the mouth closed. Instead of rainfall having the most influence, ocean forces dominate. However, Figure 7 showing salinity indicates that there is no increase in salinity at the North site when the mouth is open. Hence, seawater does not penetrate the lagoon far enough to reach the North site, at least in the two months of measurement that the mouth was open. Furthermore, Figure 4 showing water levels indicates there is no tidal component to the levels at the North site. This implies energy penetrating the lagoon from the ocean in the form of the twice-daily tidal wave is dissipated by friction before it reaches the North recorder.

If we had a bathymetry map of the lagoon, we could model the propagation of the tidal wave into and out of the lagoon and establish quite accurately the extent of the tidal influence. In the absence of such data, we can only approximate the physics with the very simple model of Bruun (1978) developed for tidal inlets. The mathematics is described in detail in Appendix II. Briefly, the model assumes the ocean is connected to the lagoon by a straight channel. An energy balance is formulated between the energy in the ocean (i.e., its elevation), the energy in the lagoon (i.e., its elevation - velocities are assumed zero), the inertia in the channel, and the energy lost in the channel from entrance and exit losses and friction. The flow in the outlet channel is matched with the river inflow and the rate of rise of lagoon level.

The gauging of the flow through the mouth at low tide on 6 January, along with the tide at sea, and the levels at the Mouth site give us enough information to calibrate the model, and thereby determine the flow rate over a tide cycle, as well as an approximation of the zone of influence of the ocean in the lagoon.

The results of this modelling are that the tide affects between 10 and 50 $km^2$ of the lagoon's area (i.e., between 5 and 25%), and flows in the Hikurangi Channel oscillate between -200 cumecs (at high tide) and 120 cumecs (at low tide) as shown in Figure 20. Compared to the usual flows from the Te Awainanga of around 1 cumec and even the peak flow of 77 cumecs, these tidal flows are huge, and they occur twice a day.

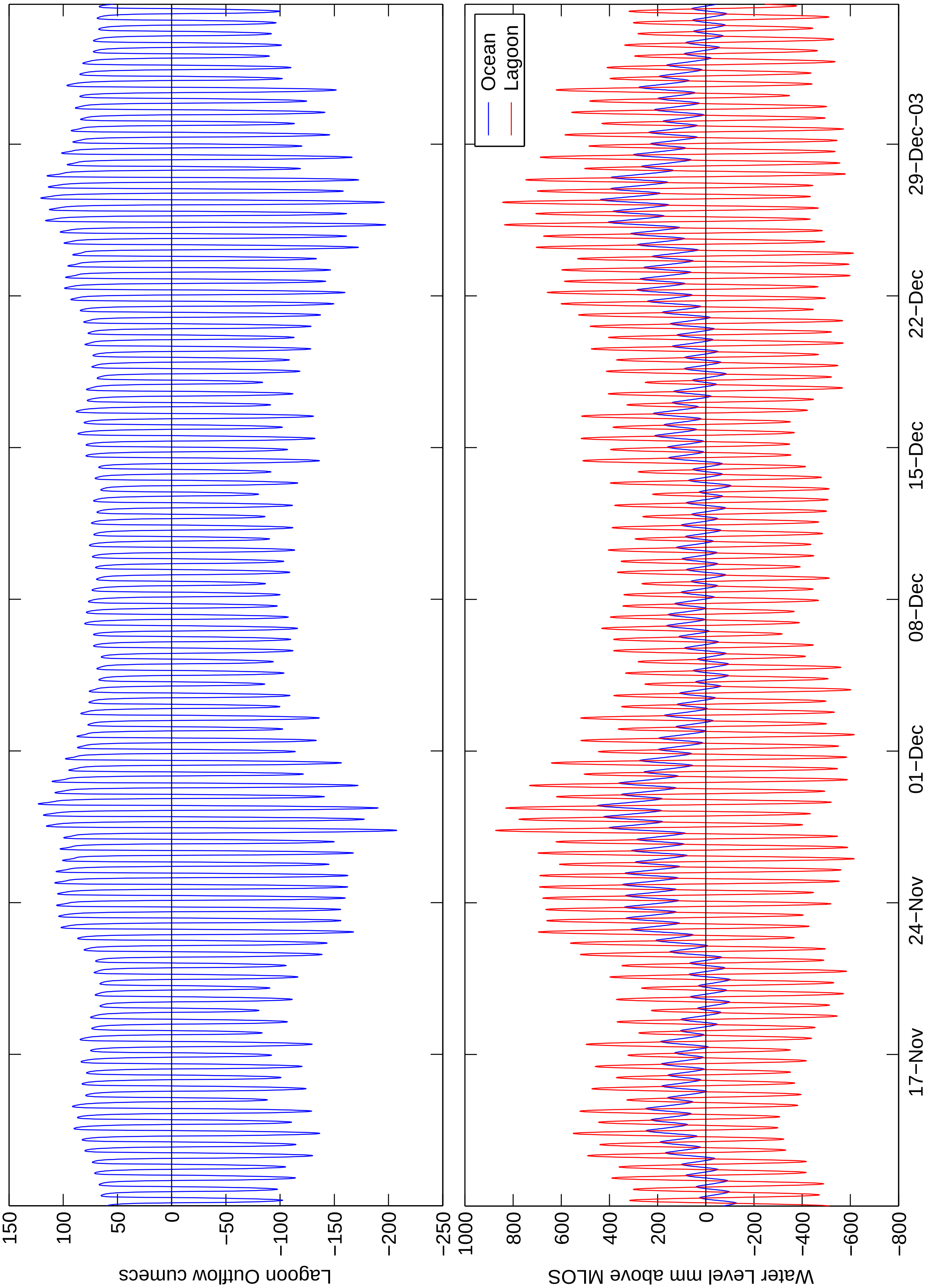

**Figure 20. Results of modelling Te Whaanga as a tidal inlet showing (upper) outflow in the Hikurangi Channel and (lower) water levels in the ocean and the lagoon.**

## *3.4 Salinity at the Mouth*

When the salinity data for all three sites were presented in Section 2.2.3, we noted that the salinity at the Mouth site was different from the others, having several large events when the salinity dropped to almost zero. In this section, we analyse some of those events and also consider the last two tidal cycles of the record.

### 3.4.1 Salinity Events

Figure 7 shows that several salinity events occurred at the Mouth site in April. We consider two of the largest in Figure 21, where we compare salinity, flow from the Te Awainanga, daily rainfall, and wind stress. There was a rainfall event on 8 April that delivered 35.6 mm at the Airport. It was followed by a flood in the Te Awainanga that peaked in the early morning of 9 April at 77 cumecs. Yet, the salinity at the Mouth site did not change until two days later. The reason can be seen in the wind stress plot showing strong northwest winds. Soon after they stopped, the salinity at the Mouth site started to drop, indicating freshwater from the Te Awainanga had reached the Mouth recorder c. 4 km from the mouth of the river. The salinity stayed low for 5 days before returning to normal levels over one day.

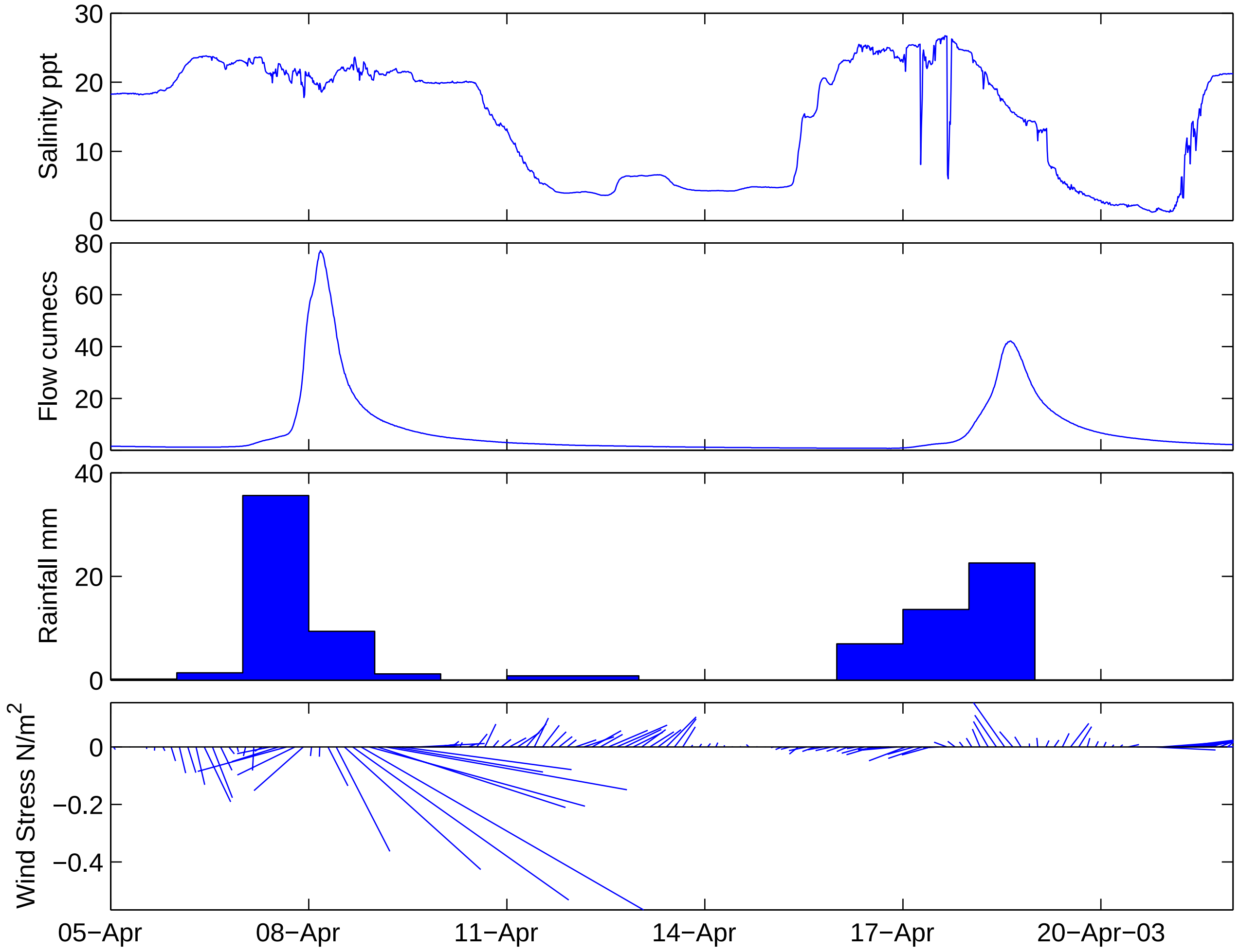

**Figure 21. Comparison of salinity at the Mouth site, river inflow, rainfall, and wind stress for two salinity events in April.**

Another rainfall event started on 16 April and on 17 April there were two sharp drops in salinity. These may be data errors, but on the other hand they could be slugs of freshwater that reached the conductivity probe from rain falling on or near the recorder. In this event there was little wind and what occurred was from the south, so the salinity at the Mouth site responded much faster to the increase in freshwater flow than the earlier event.

These two events have shown that the variation in salinity in the lagoon is highly dependent on the wind. In a shallow lagoon such as Te Whaanga, we would expect that vertical mixing would be very efficient and there would be no stratification. However, horizontal (i.e., plan view) mixing clearly is not as efficient, and slugs of freshwater are washed around by the wind, perhaps staying intact for days.

### 3.4.2 Salinity in the Mouth-Open Regime

When we arrived at the Mouth recorder on 5 January with the intention of removing it, we found that the conductivity probe was not operational, having become completely encrusted with vegetation. Examination of the record on-site revealed that we had missed all of the period when the mouth was opened, so we decided to clean the probe and leave it running for two tidal cycles so that we could obtain at least a small amount of data in the mouth-open regime. Next day, we came back and recovered the instrument. The resulting salinity data are presented in Figure 22, along with calculated outflow from the lagoon and water levels from the Mouth recorder.

The salinity is high, but not as high as seawater (37 ppt). In fact, the salinity hardly changes on the ebbing tide (when the outflow is positive). This indicates that the water flowing out of the lagoon is likely to be the same water that flowed in during the flood tide. Thus, there has been little if any exchange between the seawater flowing in and the resident lagoon water. There are two dips in salinity just before high tide when the salinity drops below 30 ppt. At this time the outflow shows large negative values (which is actually an inflow, of course) of almost -100 cumecs. We interpret the dips to be a mixture of lagoon and seawater sweeping up the channel where the recorder was located, but their origin is not clear.

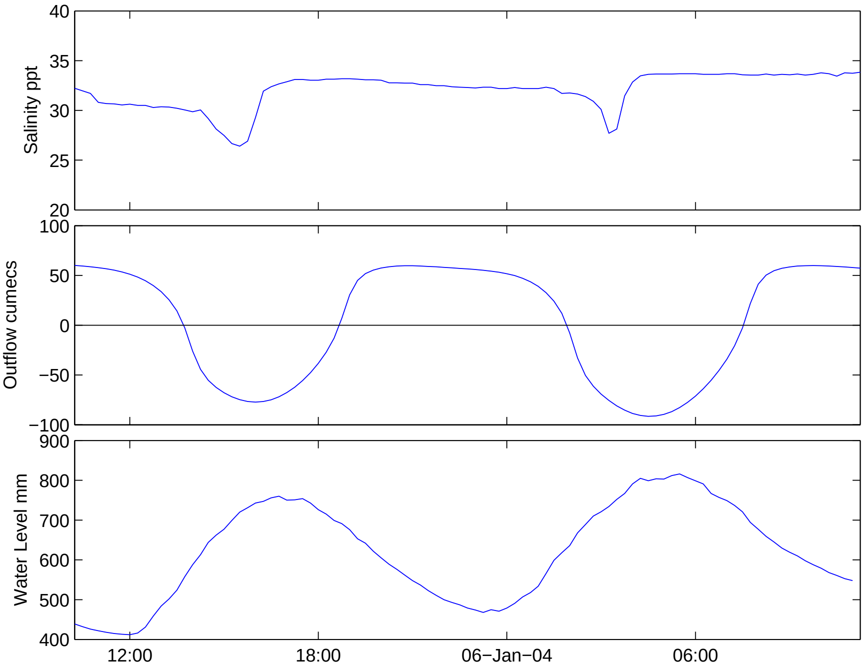

**Figure 22. Comparison of salinity and water levels from the Mouth recorder (upper and lower) and outflow from the model (centre) over a day when the mouth was open.**

# 4. DISCUSSION

In the previous two sections, a large quantity of data has been presented and analysed. Nevertheless, there are some missing pieces of data that would have helped in gaining an understanding of how Te Whaanga works. The important missing items are:

- a map of the bathymetry of the lagoon; and
- salinity and water level data from the South site when the mouth was open.

Both of these would have enabled us to establish with more certainty the extent of the influence of the ocean when the mouth is open.

A question that could not be addressed in our study was: how and why does the mouth close? Indeed, looking at the outflows fluctuating between –200 and 100 cumecs twice a day in the Hikurangi Channel in Figure 20, and having gauged the channel by wading through it, it is difficult to imagine the channel ever closing. Nevertheless, it does close and it must do so as a result of ocean effects, not lagoon effects, because the flow rates in the closed lagoon are two orders of magnitude less than the tidal flows. However, the ocean forces required to close the mouth are large. The power in the flow in the channel reaches as much as 80 KW and the daily energy is as high as 600 KWh. However, there are some days when the daily energy drops to 150 KWh because the tides are small. If large ocean waves occur during such a period, particularly waves at an oblique angle to the coastline (i.e., from either the northeast or the southeast), the energy in the waves could far exceed the energy in the channel, thus pushing sediment across the entrance and gradually over a few days blocking it.

A question that has been posed about Te Whaanga is: what was the lagoon like in the 1840s?
In terms of the physics that has been the subject of this study, we can answer this question quite clearly: it was like it is today (except of course for manmade intervention in opening the mouth). There would have been times when the mouth was open and times when it was closed. When it was open, the mouth area and the southern basin would have been like a tidal inlet. A tidal inlet is not an "arm of the sea", but a water body that is connected to the sea by a narrow channel and whose level fluctuates in response to the tide. When the Hikurangi Channel was closed, Te Whaanga would have been like a salty lagoon, responding to winds, rainfall, river inflow, and evaporation, with no relationship to the sea. Indeed, the northern basin appears to have these characteristics always, even when the mouth is open. These days, the mouth can be opened in a few hours with a hydraulic excavator, and if the level in the lagoon is large enough and the winds are offshore, the channel will establish itself and tides will keep it open. In times before such methods were available, there are other natural mechanisms that could have initiated an opening. One scenario is for the water level in the lagoon to build up to such a level that a natural breaching occurs. This could be assisted by large waves during elevated sea levels (at high tide and with storm surge) breaking onto or over the sandy berm. However, in view of the broad, gently sloping berm (shown in Figure 15) it is unlikely that waves would cause breaching from the ocean side on their backwash, as occurs at locations in New Zealand such as the Wainono Lagoon in South Canterbury where the gravel berm has been known to lose more than 1 m of height in a storm.

# 5. CONCLUSIONS

After analysing a large quantity of information from Te Whaanga, we can draw some conclusions about how the lagoon works from a physical point of view. We separate into two categories: mouth closed and mouth open.

## *5.1 Mouth Closed*

When the Hikurangi Channel is closed, Te Whaanga behaves like a shallow lake with the following characteristics:

- Water levels vary largely in response to wind. The predominant wind direction is just north of west and this causes levels on the eastern shore to rise by as much as 1.6 m. Winds from the northwest and southwest can push water onto the southern and northern shores respectively by as much as 0.6 m.

- The salinity of the lagoon is fairly uniform at c. 20 ppt, but floods from the Te Awainanga River can drop the salinity to almost zero in the mouth region. The dispersion of the freshwater slug resulting from floods is highly dependent upon winds.

- The water balance of the lagoon is dominated by rainfall, which represents 70% of the inflow, the remainder coming from the Te Awainanga River. Evaporation represents only about 5% of the total inflow (i.e., rainfall + river flow). The result of the imbalance in inflow and outflow is that levels in the lagoon rise until a level is reached that causes the Hikurangi Channel to breach (or the breach is initiated manually).

- The lakes along the eastern side of the lagoon are connected to Te Whaanaga, but the seepage flow is very small. They appear to have no connection to the ocean.

## *5.2 Mouth Open*

When the Hikurangi Channel is open, Te Whaanga behaves like a tidal inlet near the mouth, but the northern basin continues to behave like a shallow lake:

- Flows in the Hikurangi Channel reach up to c. 100 cumecs outflow on an ebbing tide and c. 200 cumecs inflow on a flooding tide, depending on the tidal range at sea.

- The extent of tidal influence in the lagoon is limited to the region near the mouth, representing between 5 and 25% of the total lagoon area.

- Little mixing occurs between seawater and lagoon water over a tidal cycle.

- In the northern basin, the level drops when the Hikurangi Channel is first opened, but thereafter the basin behaves as if there were no opening.

## 6. ACKNOWLEDGMENTS

The assistance of many Chatham Islanders is gratefully acknowledged. Without their help, this project could never have proceeded. My particular thanks go to Pete Mason, NIWA Field Party Leader, Christchurch who attacked this project with his usual combination of gusto and professionalism. He carried out all of my requests, no matter how unreasonable, with a positive, responsible attitude. His staff Dave Paull and Marty Flanagan also contributed. Working in a remote, muddy, unfamiliar environment like Te Whaanga is not easy, and successfully acquiring all those excellent data represents an outstanding effort. Well done guys! My thanks also go to Derek Todd of DTec Consulting Ltd for a thorough and insightful review.

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## APPENDIX I: Calculating Evaporation

Evaporation was estimated using two different relationships given by Shuttleworth (1993). The first is Hargreaves equation that uses air temperature and an estimation of the extraterrestrial radiation as it affects the water body:

$$E = 0.0023 S_0 (T + 17.8)\sqrt{\delta_T}$$

where:
$E$ = an average monthly potential evaporation in mm/day.
$T$ = temperature in ºC.
$\delta_T$ = difference between mean monthly maximum temperature and mean monthly minimum temperature.
$S_0$ = the water equivalent of extraterrestrial radiation for the location, given by:

$$S_0 = 15.392 d_r (\omega_s \sin\phi \sin\delta + \cos\phi \cos\delta \sin\omega_s)$$

$\phi$ = latitude in ºN.
$\omega_s$ = the sunset hour angle in radians:

$$\omega_s = \arccos(-\tan\phi \tan\delta)$$

$\delta$ = solar declination on day J (Julian day) of the year in radians:

$$\delta = 0.4093 \sin\left(\frac{2\pi}{365} J - 1.405\right)$$

$d_r$ = relative distance of Earth from Sun on day J:

$$d_r = 1 + 0.033 \cos\left(\frac{2\pi}{365} J\right)$$

The second relation is attributed by Shuttleworth(1993) to Brutsaert. It uses the concept that evaporation over a water body is governed by the area of the water body, along with the wind speed at 2 m over the water, and the difference in saturated vapour pressure between the water and the air:

$$E = 2.909 A^{-0.05} (e_w - e) U_2$$

where:
$A$ = area of the water body in $m^2$.
$e_w$ and $e$ = saturated water vapour pressures (in kPa) calculated from the water temperature and the air temperature respectively using:

$$e = 0.6108\left(\frac{17.27T}{237.2 + T}\right)$$

$U_2$ = wind speed in m/s at 2 m above the surface. $U_2 \approx 0.75 U_{10}$, where $U_{10}$ is the wind speed at 10 m (where winds are usually measured).

# APPENDIX II: Bruun's tidal inlet model

The simple Bruun(1978) model is based on two concepts. First, the lagoon water level, $h_L$, varies according to continuity:

$$A(h_L)\frac{dh_L}{dt} = Q_{in} - Q_{out} \qquad \text{(AII.1)}$$

where $A$ is the wetted surface area that varies with water level, $Q_{in}$ is the river inflow that is prescribed, and $Q_{out}$ is the outflow into the ocean, which is determined by the second concept which is that there is an energy balance between the lagoon and the ocean:

$$h_L = h_O + (k_{en} + k_{ex} + \frac{LC_f}{d})\frac{V|V|}{2g} + \frac{L}{g}\frac{dV}{dt} \qquad \text{(AII.2)}$$

where $h_O$ is the ocean level, $k_{en}$ and $k_{ex}$ are entrance and exit losses respectively, $L$ is the length of the channel, $C_f$ is a friction coefficient, d is the depth at the mid-length of the outlet channel $d = \frac{1}{2}(h_L + h_O) - z_c$, where $z_c$ is the level of the bed of the outlet channel at mid-length, and $V = Q_{out} / Bd$ is the mean velocity in the outlet channel and $B$ is the width.

The assumption is made with this model that the velocities in the lagoon and the ocean are negligible.

Equations (AII.1) and (AII.2) form a set of nonlinear, ordinary differential equations that can be solved in routine manner using a form of the Runge Kutta method.