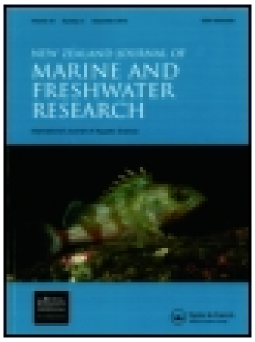

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Jonathan C. Allan & Robert M. Kirk

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Wind wave characteristics at Lake Dunstan, South Island, New Zealand

JONATHAN C. ALLAN*
ROBERT M. KIRK
Department of Geography
University of Canterbury
Private Bag 4800
Christchurch, New Zealand
email: r.kirk@regy.canterbury.ac.nz

*Present address: Oregon Department of Geology and Mineral Industries, Coastal Field Office, 313 SW 2nd, Suite D, Newport, OR 97365, United States. email: jonathan.allan@dogami.state.or.us

Abstract Information on wave statistics, seasonal characteristics, and their distribution about lacustrine shorelines is virtually non-existent. The absence of such data limits the effective management of lake shores where issues of shoreline erosion are no less significant than on open ocean coasts. Results from instrumentally measured waves during seven storm events in 1995 are presented for the Clutha Arm of Lake Dunstan, South Island, New Zealand. The significant wave height ranged from 0.07 to 0.57 m with a mean of 0.28 m, whereas the maximum wave reached 1.05 m. Peak spectral wave periods ranged from 1.7 to 3.6 s with a mean of 2.46 s. The largest and most destructive waves are observed along the southern shore of the Clutha arm where fetch lengths are at their maximum. These waves exhibit the longest and widest range of periods and are generally the steepest waves, making them highly erosional at the shore. Correlations of waves with those predicted by NARFET, a deepwater wave-hindcasting computer model, revealed reasonable predictions of the wave height ($R = 0.77$–0.81), particularly for sites exposed to longer fetches, while the correlations with the wave period were lower ($R = 0.56$–0.69). Wave hindcasting indicates that the wave regime in the Clutha Arm is bi-directional, with most waves arriving from the north or south. Findings from Lake Dunstan have important implications for larger lakes located throughout New Zealand, where considerably larger waves can be expected to occur during severe storm events.

Keywords Lake Dunstan; high-frequency waves; wave measurements; wave statistics; wave climate; hindcasting

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INTRODUCTION

Waves are a fundamental process that determines the geometry and composition of beaches. They are the principal source of energy into the littoral zone, contributing to the redistribution of beach sediments both along and across a shore, and the initiation of shoreline change (Komar 1998). This is true of both ocean shores, and the more restricted waters of lacustrine environments. In New Zealand many lake shores present significant management problems as a result of shoreline change (Pickrill 1985; Kirk & Henriques 1986; Mark & Kirk 1987; Kirk et al. in press). Given their importance, it is surprising to note that there is a dearth of information about the characteristics of waves that form on the inland waters of New Zealand, their distribution about lake shores, seasonal variability, and wave statistics (heights and periods).

To our knowledge there is no published description of the characteristics of lake waves in New Zealand. Instead, New Zealand lake wave studies have been confined to a few unpublished theses and reports associated with specific management problems. The pioneering study of Lakes Manapouri and Te Anau by Pickrill (1976) provided the first attempt at wave measurement in New Zealand, made with a capacitance wave staff. Much later, Macky (1991) used a Waverider buoy and two pressure transducers at Lake Waikaremoana. However, the study by Macky is largely qualitative with limited wave analysis provided. Elsewhere, the specification of waves

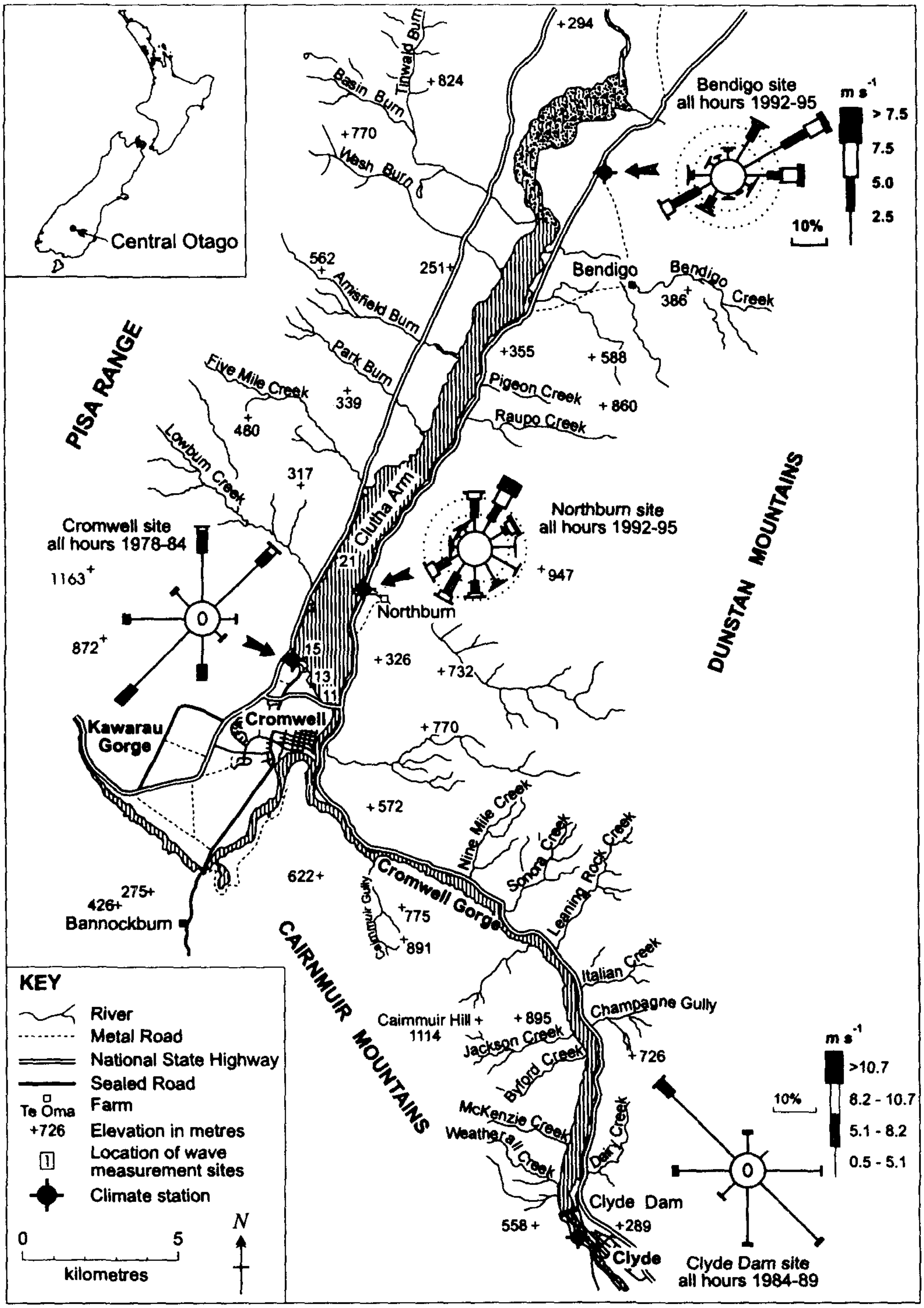

Fig. 1 Map of Lake Dunstan, South Island, New Zealand, showing the wave measurement sites, important place names, and summary wind roses. Wind roses presented for Cromwell and Clyde are from Fitzharris & Reid (1993).

has relied on the use of hindcasting techniques. In particular, such studies have been done for Lake Manapouri (Pickrill 1976), Lake Pukaki (Kirk 1988; Allan 1991), Lake Coleridge (MacBeth 1988), and Lake Dunstan (Croad 1980; Allan 1998), while Allan (1991) provided visual observations of waves at Lake Pukaki. Despite extensive use of wave hindcasting models, no attempt has been made to verify these models for South Island lake environments.

The paucity of wave statistics for lakes in New Zealand is surprising since one would expect that knowledge of them would be integral to effective management of lake shores. This is particularly true for hydro-electric power generating lakes, which experience seasonal variations in their water levels. For example, the Alpine lakes of southern New Zealand typically experience their highest water levels during spring and summer (Pickrill 1976; Kirk 1988; MacBeth 1988). These are periods that also have strong winds, so that large waves are created when water levels are high. The potential for shore erosion is thus maximised during these periods. Kirk et al. (2000) examined one such episode of strong erosion at Lake Hawea in the South Island. Considerable shoreline erosion occurred adjacent to the community of Hawea in December 1995/January 1996. Eventually storm waves undermined and destroyed a rock revetment structure established to mitigate the effects of shore erosion along the township foreshore. Information on wave statistics is thus also important for effective engineering design of shore-protection structures. Similar problems concerning high water levels in lakes, coincident with storm waves can be readily found in North America (e.g., Hands 1983; Davidson-Arnott 1989; Lorang et al. 1993).

This paper has two objectives: first, to provide an examination of wave characteristics on one lake located in the South Island of New Zealand, and; second, to test a simple wave prediction model against measured wave data. The study area is Lake Dunstan, a 26.4 km^2 recently established hydro-electric power generating lake located in Central Otago (Fig. 1). Lake Dunstan was formed behind the 60 m high Clyde Dam (New Zealand's largest concrete gravity dam). The lake was filled over a period of 17 months beginning in April 1992, and became fully operational on 2 September 1993. This paper presents results from wave measurements in the Clutha Arm of Lake Dunstan and describes their distribution about the lake shore using a simple wave hindcasting model. The paper is drawn from the doctoral thesis of Allan (1998), which examined the temporal morphological development of beaches about the lake.

STUDY AREA

Lake Dunstan occupies the Cromwell Basin, a broad fault-angle inter-montane basin, in-filled with a variety of deposits including ancient lacustrine sediments (Douglas 1985), and glacio-fluvial outwash gravels associated with previous Pleistocene glaciations (Turnbull 1987). The basin is bounded by four uplifted schist mountain ranges that rise to over 1000 m a.s.l (Fig. 1). The ranges cause topographical channelling of airflow along the valley and play an important role in the generation of steep wind waves on the lake. Lake Dunstan has three distinctive arms: the Clutha Arm; Kawarau Arm; and Cromwell Gorge, and it has 152 km of shoreline. Fig. 1 shows that much of the lake is dominated by short fetch (F) lengths, whereas the maximum fetch, $F_{MAX.}$, (and hence potentially the largest waves) occurs in the Clutha Arm (14.5 km). The widest part of the lake is also located in the Clutha Arm and is less than 2.0 km.

Much of the lake basin can be characterised as deep, with the deepest point occurring near the dam (~60 m). Hydrographic surveying by the writers over much of the Clutha arm has revealed that water depths are typically between 10 and 30 m, with depths decreasing to several metres at the northern end of the Clutha Arm. Further, because the beaches are typically narrow (average width = 10.9 m) and steep (average = 9.2°), high frequency waves are little modified by the subaqueous bed so that wave breaking occurs very close to the shore, producing narrow surf zones with minimal losses of energy in shoaling. Qualitative observations made by Pickrill (1976) and Kirk (1988) at other South Island lakes reveal that this is typical for South Island alpine lakes.

Water levels on Lake Dunstan fluctuate between Relative Level (RL) 193.5 and 194.5 m (Dunedin Mean Sea Level Datum); a 1.0 m range. During times of flood, water levels may be extended a further 0.6 m to RL 195.1 m. Since lakefill in September 1993, water levels have rarely fallen below RL 194.0 m (<10% of the time), and have exceeded the maximum operating level (RL 194.5 m) for 12.3% of the time (Allan 1998). These have occurred principally during the spring/summer period in 1993–94 and in 1994–95.

WIND CHARACTERISTICS IN THE CROMWELL BASIN

Previous investigations of winds in inter-montane basins of the South Island have highlighted the complexities associated with the development and passage of airflow along valleys bounded by steep topography (Sturman et al. 1985; McGowan et al. 1996). It follows that these complexities should also be manifested in the generation of wind waves on lakes bounded by steep terrain such as at Lake Dunstan. An understanding of lake waves thus requires a comprehensive understanding of the wind regime over the entire study area.

General descriptions of winds in the Cromwell Basin can be found in Blair & McDonald (1979), Fitzharris & Reid (1993), and Butler (1996). However, for the purposes of understanding and hindcasting waves on Lake Dunstan, a more detailed analysis of wind characteristics was prepared. Wind data were obtained from the National Institute of Water and Atmospheric Research (NIWA) for two climate stations, Northburn and Bendigo (Fig. 1). Wind data for these sites span the period 15 June 1992–31 December 1995. A longer wind record (1976–84) was also examined for Cromwell. Wind roses were plotted using "WNDROSE", a "QUICKBASIC" computer program. Results are presented in Fig. 1, along with wind roses determined by Fitzharris & Reid (1993) for Cromwell and Clyde.

Blair & McDonald (1979) noted that 50% of winds in the Central Otago region occur from the north (N) and north-west (NW) directions. Because of the presence and orientation of the Dunstan mountains to the north-east (NE) of the lake, these winds are deflected off the Range and are channelled down the Cromwell Basin, initially as a strong NE wind (Bendigo), becoming more NNE by the time they reach Northburn and Cromwell (Fig. 1). It can be seen from Fig. 1 that winds from the south-west (SW) are also important, though less significant than winds from NNE. Thus, the wind regime in the Cromwell Basin is predominantly bi-directional and is strongly influenced by the local topography. Further evidence for this can be seen from the wind rose for Clyde, where NW and south-east (SE) winds predominate (Fig. 1).

Summary data for each of the climate stations reveal a small incidence of calm conditions (<0.3%), whereas near gale wind conditions (13.9–17.1 m s^{-1}) are also found to have a low occurrence (<0.08%). Mean wind speeds are c. 3.0 m s^{-1}. Strongest winds

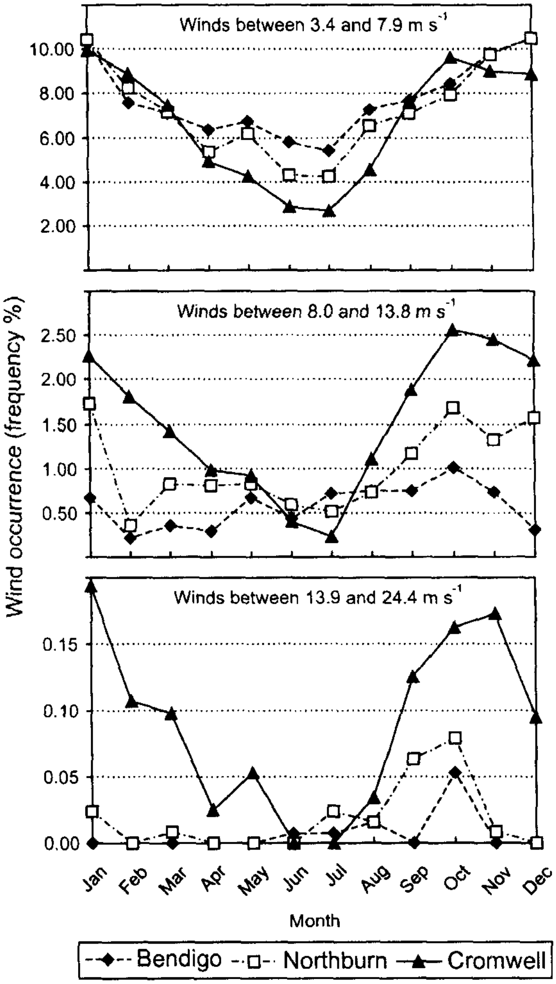

Fig. 2 Frequency of wind incidence at Lake Dunstan, New Zealand: 3.4–7.9, 8.0–13.8, and 13.9–24.4 m s^{-1}.

blow from NNE (along the direction of F_{MAX}), which results in a concentration of large waves along the southern shore of the Clutha Arm. The strongest wind speed recorded was 21.6 m s^{-1} for an event in Spring 1981 at the Cromwell station, whereas the strongest wind measured since the lake was filled was 17.0 m s^{-1} at Bendigo. Both wind events were from the N and NE respectively. It is also interesting to note that this latter event produced lower wind speeds (~10.0 m s^{-1}) at the Northburn site. Such differences in wind speeds along the Cromwell Basin were also noted for other strong wind events, and serve to further highlight the complexities associated with wind development in mountainous terrain.

Nevertheless, a comparison of the wind records along the Cromwell Basin (Fig. 2), suggests that the wind velocity increases along the lake. This is probably produced by the convergence of winds in the basin. These differences are most apparent as the wind velocity increases.

Figure 2 also describes the seasonality of winds at Lake Dunstan. In general, it can be seen that the frequency of stronger winds tends to be higher during spring and summer, decreasing toward winter. At the lower wind speeds (<8.0 m s^{-1}), winter winds tend to show a higher incidence at Bendigo compared with Northburn, whereas in summer the pattern is reversed. As can be seen from Fig. 2, strongest winds predominate during spring (September and October) and in summer (particularly January). It follows that the incidence of large waves should reflect this pattern, so that larger waves will tend to be more frequent in spring and summer, decreasing toward winter. In addition, extreme high lake levels have tended to occur during periods when wind speeds and incidence are greatest, and this has resulted in increased shore erosion during these periods (Allan 1998). It is this combination of large waves and high lake levels that presents the most significant management problems for lakeshore managers in New Zealand.

METHODS

Wave measurement and analysis

Wave measurement can be achieved with either a pressure sensor or capacitance wave staff. Since wave periods on small lakes (F < 50 km) typically occur at higher frequencies (Pickrill 1976, 1983), problems arise when using bottom-mounted pressure recorders to sample waves. This is because with increasing depth, the wave-induced pressures generated by a moving wave are rapidly attenuated (Kinsman 1965). As a result, a pressure sensor must be located at a sufficiently shallow depth to detect the pressure signal from the shortest wave length (shortest period) of interest. In contrast, a wave staff directly measures the elevation of the water surface so that many of the problems associated with a pressure sensor are avoided.

An InterOcean S4ADW directional wave and current recorder and a Brancker Research WG-30 capacitance wave staff were used to measure waves at Lake Dunstan. The latter instrument was used to provide a test of the wave data measured by the S4ADW. Unfortunately, because the lake receives heavy recreational use (particularly in the summer), it was not possible to deploy the instruments long term. Instead, deployment was confined to seven storm events in 1995 at four sites in the Clutha Arm. Although this approach yielded a small data set, the measured data still provide a useful insight into the characteristics of wind waves at Lake Dunstan, and permits a testing of the wave prediction model.

The two instruments were deployed c. 5 m apart, in water depths ranging from 1.0 to 1.4 m, and programmed to sample at 2 Hz, on the hour, for a period of 18 min. Earle et al. (1995) have indicated that a standard of 17 min is now considered to be sufficient for most ocean wave measurements. The S4ADW was mounted on a stainless steel shaft, so that it was located 0.4 m above the lake bed, and bolted to a 50 × 50 × 15 cm concrete pad. In contrast, the wave staff was attached to a steel Waratah embedded in the lake bed and further supported by three guywires. The wave staff was connected to a Campbell 21-X data-logger and a computer laptop, while the S4ADW logged all information internally. Table 1 describes the general characteristics

Table 1 General characteristics associated with each site and measured storm event.

Study site	Fetch length (km)	Date of event	Duration of event (h)	Average wind speed (m s^{-1})	Maximum wind speed (m s^{-1})	Average direction (deg)	Average water depth (m)	Instrument
DU11	6.4	21 Jan 1995	18	9.8	11.9	39.8	1.20	S4
		30 Oct 1995	15	8.1	10.0	51.3	1.03	S4 and WG-30
		07 Dec 1995	14	8.6	11.0	32.6	1.13	S4 and WG-30
DU13	14.5	10 Dec 1995	30	8.4	12.7	37.7	1.03	S4 and WG-30
DU15	13.5	04 Dec 1995	15	6.5	9.3	24.9	1.32	
DU21	6.8	29 Nov 1995	10	5.9	6.8	48.4	1.33	S4 and WG-30
		30 Nov 1995	9	7.6	8.9	35.2	1.35	S4 and WG-30
Mean			13.7	7.8	10.1	38.6	1.20	

associated with each deployment. As can be seen from the table, three of the sites (DU11, DU13, and DU15) are located along the southern Clutha Arm shore (F = 6.4, 14.5, and 13.5 km respectively), while the fourth site (DU21) is located just north of Lowburn on the western shore (Fig. 1) and has a maximum fetch of 6.8 km. Average wind speeds for the seven events was 7.8 m s^{-1} while the range of wind speeds varied from 0.9 to 12.7 m s^{-1} and were mainly from the NE. As noted earlier, strong wind events have reached 21.6 m s^{-1} in the Cromwell Basin, so that the six events can be regarded as "moderate" storms as opposed to more "extreme" events.

Wave data measured by the S4ADW were analysed using "WAVE", an interactive wave analysis package written specifically for the S4ADW. The WAVE program uses spectral analysis (FFT) to examine the data and follows well established principles described in Harris (1971, 1974) and InterOcean (1990). A variety of variables are required by the program for data analysis, including instrument height, number of data points for the FFT, choice of a cosine taper window, and the frequency range. Estimates of the significant wave height by the WAVE program is derived as 4 times the standard deviation of the water elevation (4σ) determined from FFT. In terms of an appropriate spectrum "window", InterOcean (1990) recommend a cut-off frequency of 0.3 Hz for ocean waves. However, using such a window ignores the concentration of lake wave energy located at the high frequency end of the spectrum, producing extremely low estimates of wave height (when compared with those visually observed at the time of the event, and those measured by the WG-30). It was found that by increasing the cut-off frequency to 0.6 Hz, representative wave heights could be obtained. These data were further verified by correlating results from the S4ADW with those obtained from the WG-30 wave staff, described below.

Since the WAVE program cannot import wave data measured by other types of instruments, an alternative approach was used to examine the wave staff data. The approach used is the zero-up-crossing method described by Tucker (1963) and Draper (1967). The WG-30 data were first de-trended for variations in water levels (a function of seiching, wind stress, or lake level changes) using linear regression analysis, and then analysed using the zero-up-crossing method in an "EXCEL" spreadsheet. The WG-30 data were also subjected to spectral analysis using a program written in "MATLAB". The data were transformed to the frequency domain using an FFT over 2160 samples and a boxcar window of length 40. The peak spectral periods (Tp) and the significant wave height (4σ) were determined for each sampling interval. Further, spectral analysis permitted evaluation of the proportions of energy spectra associated with the main frequency bands. This last step is important for assessing the effects of wave frequencies beyond the record length or extremely high frequency "noise" beyond the nyquist frequency ($1/(2\Delta t)$ where Δt is the sampling interval) that may be "folded" back into the sample

Table 2 Various wave statistical nomenclature (Sargeant & Timme 1974; CERC 1984).

Nomenclature	Name	Description
H_M	Mean wave height	Average height of all waves in a given record (m)
H_S	Significant wave height	Average height of the one-third highest waves of a given wave group (m)
H_{RMS}	Root mean square wave height	Square root of the average squared height of all waves in the record (m)
H_{10}	No name	Average height of the highest one-tenth waves (m)
$H_{MAX.}$	Maximum wave height	Maximum wave height for a specified period of time (m)
T_P	Peak spectral wave period	Peak spectral period. Inverse of the dominant frequency of a wave energy spectrum (s)
T_S	Significant wave period	Average period of the one-third highest waves of a given wave group (s)
T_Z	Zero-crossing period	Average period of the zero-up-crossing waves of a given wave group (s)
T_C	Wave crest period	Average period of all wave crests of a given wave group (s)
ε (ETA)	Spectral band-width	Measure of the range of frequencies present in a wave record relative to the average wave frequency

$$\varepsilon = \left(1 - \left(\frac{T_Z}{T_C}\right)^2\right)^{0.5}$$

record thereby contaminating the data. Table 2 lists the summary wave parameters obtained from both forms of analysis.

To increase confidence in the wave data measured by the two instruments, regression analyses was performed on the output heights (H) and periods (T). The results of the regression analyses, Table 3, reveal the existence of strong correlations between the two measures of the significant wave height (Pearsons $R = +0.99$, $P = 0.000$, and $R = +0.98$, $P = 0.000$) between the instruments. A similarly strong correlation ($R = +0.97$, $P = 0.000$) is found between the zero-up-crossing period (T_Z) and the significant wave period (T_S), while correlations between the zero-up-crossing period (T_Z) and the peak period (T_P), and between the significant wave period (T_S) and the peak period (T_P) were slightly lower (+0.90 and +0.88 respectively) (Table 3). These results demonstrate that a pressure sensor such as the S4ADW, provides reliable measurements of high frequency lake waves, provided the instrument is located in sufficiently shallow water depths, whereas calibration against an instrument such as a wave staff provides a check on the measured data.

Figure 3 is a plot of the frequency spectrum derived from two sampling intervals measured at DU13 by the wave staff on 11 December 1995. Fig. 3 clearly indicates a dominant spectral peak period c. 0.31 Hz (3.2 s), with a secondary peak c. 0.6 Hz (1.7 s). Two other frequencies apparent in Fig. 3 are worth mentioning; one located at 0.14 Hz (7.1 s) may be associated with wave groupiness, while the smaller peak at 0.048 Hz (20.8 s) could reflect infragravity waves. Since the area under the spectral density curve is a measure of the energy for that frequency, the integral of the spectral density across the entire bandwidth is a measure of the total energy of the signal. This approach enables the proportion of energy contained within specific frequency bands to be determined. The analysis reveals that c. 70% of the energy in Fig. 3 is concentrated between 0.2 (5.0 s) and 0.5 Hz (2.0 s). However, as the wind strength decreases, there is a progressive shift in the peak frequency to c. 0.5 Hz (2.0 s) (Fig. 3) and a concentration of energy (72%) between 0.35 (2.9 s) and 0.65 Hz (1.5 s). It is possible at these higher frequencies that some loss of energy may occur because of the 2 Hz sampling frequency used, so that part of the high frequency tail becomes truncated. However, given the prominence of the spectral peaks observed in both plots, it is unlikely that the loss is substantial.

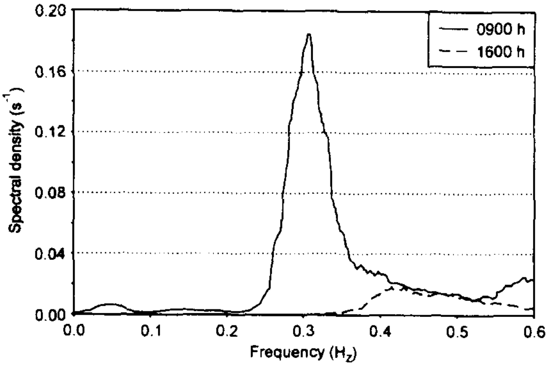

Fig. 3 Sample frequency spectrum plot measured at DU13 on 11 December 1995, at 0900 and 1600 h.

Table 3 Correlation matrix of wave height and wave period variables ($N = 49$). R values determined using the Pearson product moment correlation and are significant at the 0.01% level (see Table 2 for nomenclature).

Wave staff	S4ADW	R	Intercept	Slope
$H_{1/3}$	H_S	0.99	−0.03	1.09
H_S	H_S	0.98	−0.05	1.02
T_Z	T_S	0.97	+0.53	0.85
T_P	T_P	0.95	−0.10	1.02
T_Z	T_P	0.90	−0.03	1.20
T_S	T_P	0.88	−0.53	0.95

Wave hindcasting

Since it was not possible to measure waves at a large range of sites at Lake Dunstan, the distribution of waves at the shore and their seasonality was determined from wave hindcasting using the computer model NARFET developed by the Coastal Engineering Research Center of the U.S. Army Corps of Engineers (Smith 1991). This model was formulated specifically for wave generation on small bodies of water similar to Lake Dunstan, where fetches are short and vary with direction due to the complicated nature of the shoreline. Wave heights hindcast by NARFET were verified by correlating them against measured waves to assess the ability of the model to estimate waves at Lake Dunstan. This section provides a brief description of the NARFET model, while a more complete discussion of the model and its application can be found in Allan & Kirk (unpubl. data).

Development of the NARFET model was based on detailed analysis of the performance of four wave hindcasting models in use at the time (Smith 1991). These included the effective fetch (EF) and simple fetch (SF) methods described in CERC (1984), the Donolan (1980) model, which used a reduced wind forcing component for off-wind directions, and the Walsh et al. (*in*: Smith 1991) model. Smith (1991) used linear regression analysis to assess each of the models against measured wave data. Her results revealed that the EF method performed poorly, tending to underestimate the wave parameters, so that this model was not considered further. The SF model was found to provide reasonable agreement between the hindcast and measured waves, though it did tend to underestimate the wave height (by as much as 40% for larger wave conditions), while the wave period was over-estimated. The Donolan model was found to provide the best estimate of wave period, whereas the Walsh et al. model estimated wave height best. This last finding is not surprising since the Donolan model uses a lower power function (to the 0.38 power) compared with the Walsh et al. model which maximises both the wave height and period to the 0.5 power. Based on these results, Smith (1991) retained the Donolan concept of wave development in off-wind directions, but modified the equations for predicting wave height and period. The equations used in the NARFET model are:

$$H = 0.0015\, g^{-0.5}\, F^{0.5}\, (U \cos \varnothing) \quad (1)$$

and

$$f_p = 2.6\, g^{0.72}\, F^{-0.28}\, (U \cos \varnothing)^{-0.44} \quad (2)$$

where H is the significant wave height, g is acceleration due to gravity (9.81 m s^{-1}), F is the straight-line fetch in the direction of the wind, U is the wind speed, f_p is the peak frequency and Ø is the angle between the wind and off-wind direction. Smith (1991) found good agreement between her measured wave data and those hindcast by the NARFET model. As a result, it is concluded that NARFET is currently the best available method for hindcasting waves in narrow fetch environments.

NARFET requires various input data including radial fetch lengths at the point of interest, a stability correction factor (R_T) derived from the air-water temperature differential ($\Delta T_{AW} = \Delta T_A - \Delta T_W$), and wind data (wind speed, direction, and duration). The model adjusts the wind speed for wind measurement elevation, instrument location (whether the winds are measured over water or on land) and ΔT_{AW}, and outputs values of H_S, T_P, and wave direction. The stability correction factor (R_T) adjusts the wind speed for variations in the stability or instability of the boundary layer and is important for the growth of waves (CERC 1984). In general, when ΔT_{AW} is negative, the boundary layer is unstable and wave growth is maximised. The converse applies when ΔT_{AW} is positive, while neutral conditions exist when $\Delta T_{AW} = 0$ so that no correction is required. CERC (1984) note that the R_T correction factor can be substantial at times and may also vary seasonally, while use of the wrong correction factor can result in either considerable over-estimation or under-prediction of wave conditions.

Hourly wind and air temperature data for the period 1 September 1992–30 June 1996 were obtained from the NIWA climate station located at Northburn, while water temperatures were measured at the Clyde Dam. These data have been used to evaluate ΔT_{AW} for Lake Dunstan (Table 4), and for modelling waves for the seven storm events measured, as well as for modelling the long-term wave climate about the lake. As can be seen from Table 4, a distinct seasonal cycle in ΔT_{AW} exists at Lake Dunstan. In terms of wave hindcasting, the values shown in Table 4 result in wind speeds being maximised in autumn and winter (up to 11%) and reduced (by c. 10%) in spring and summer. One would therefore expect such effects to be reflected in the wave data. However, given the limited data available, these variations cannot be properly assessed. Further, as indicated earlier the preponderance of strong wind events tends to be confined to a few months in spring and summer, whereas autumn and winter are dominated by few strong wind events. For the purposes of comparing the measured and hindcast wave data, we have used the ΔT_{AW} observed on the day in which wave measurements occurred, while the long-term wave climate has been modelled using the seasonal values shown in Table 4.

Smith (1991) limited her comparison of measured and predicted waves to a data set of 54 cases. These

Table 4 Seasonal air-water temperature differentials ($\Delta T_{AW} = \Delta T_A - \Delta T_W$) determined for Lake Dunstan, New Zealand.

Season	ΔT_{AW} (°C)
Summer	2.21
Autumn	−1.82
Winter	−2.51
Spring	1.01

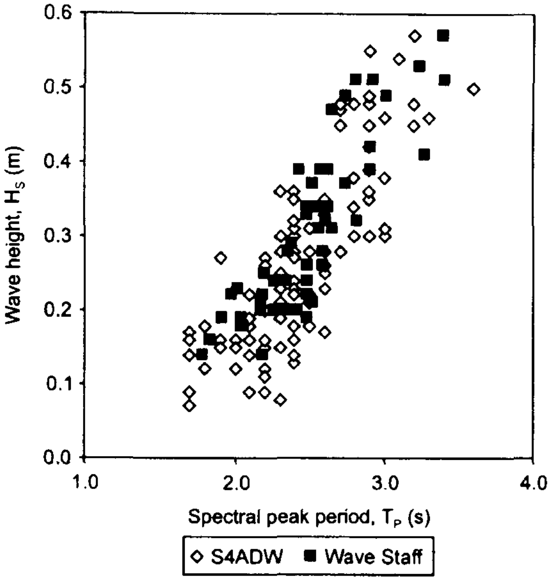

Fig. 4 Relationship between the significant wave height (H_S) and spectral peak period (T_P) for both instruments.

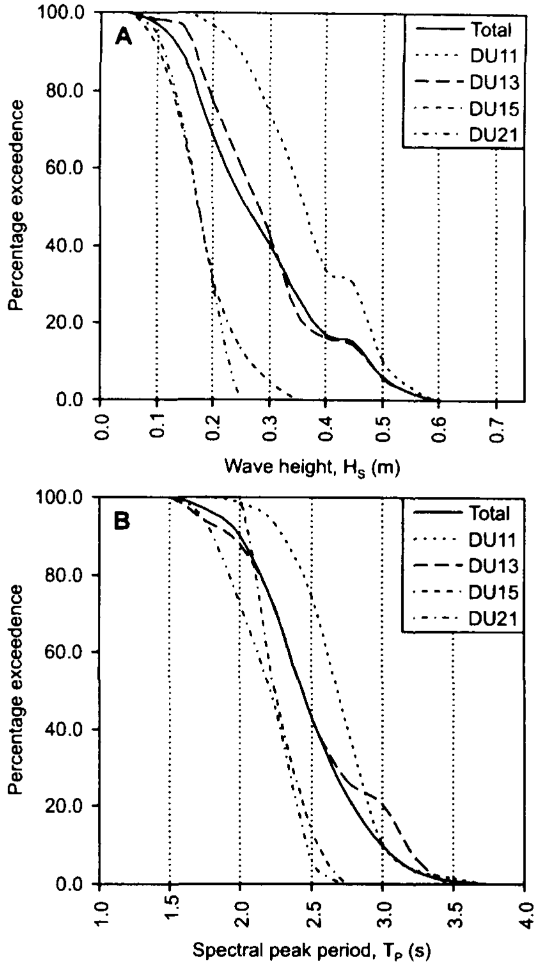

Fig. 5 **A**, Percentage exceedence curves of the significant wave height (H_S) for four sites and expressed as a total. **B**, Percentage exceedence curves of the spectral peak period (T_P).

cases were chosen according to the following criteria: wave conditions were not fully developed; each case was subject to steady wind speeds and direction; and wave conditions were not duration limited. To maintain a degree of comparability, the same criteria were adopted for modelling the waves at Lake Dunstan. Further, because NARFET provides an estimate of the deepwater wave height (H_0), waves measured at Lake Dunstan were converted to their deepwater equivalent using tables provided in CERC (1984). Since the largest number of records were measured by the S4ADW, these data were used in the comparison. The number of cases ranged from 36 at DU11 to 12 at DU21. Hence, an immediate limitation of the comparison is the small number of cases.

RESULTS

Wave height and period (H_S and T_Z)

In total, 163 eighteen-min sample records were measured at Lake Dunstan (110 from the S4ADW and 53 from the wave staff). The range of wave heights and peak periods measured is shown in Fig. 4. As can be seen from the figure, an overall positive correlation occurs between the significant wave height and spectral peak periods, consistent with

Table 5 Wave statistics for Lake Dunstan, New Zealand, for seven storm events measured at Lake Dunstan (*N* = 163, See Table 2 for nomenclature).

Parameter	Mean	Max.	SD
H_S (m)	0.28	0.57	0.12
H_{10} (m)	0.34	0.73	0.15
$H_{MAX.}$ (m)	0.49	1.05	0.21
T_P (s)	2.46	3.60	0.39
T_Z (s)	2.18	2.90	0.28
T_S (s)	2.54	4.04	0.47

observations by Goda (1990) and Tillotson & Komar (1997). Fig. 4 also highlights the strong correlation noted previously in the wave statistics produced by the two instruments. Table 5 provides a summary of the wave statistics for the seven storm events measured. Fig. 5 shows percentage exceedence graphs of H_S and T_P for each of the study sites and expressed as a total. However, Fig. 5 should be viewed with some caution given the small data set obtained.

The significant wave height ranged from as little as 0.07 m to a maximum of 0.57 m for the combined storm wave data, while the mean H_S was 0.28 m (Table 5). It can be seen from the total exceedence curve (Fig. 5A) that for 85% of the time waves exceeded 0.16 m and for 50% of the time they exceeded 0.26 m. H_S exceeded 0.51 m for only 5% of the time and exceeded 0.57 m for only 1% of the time. As a result, despite mainly focusing on the measurement of waves arising from stronger wind events, waves at Lake Dunstan are predominantly small. The maximum wave measured during the study was 1.05 m (Table 5) during an event early in January 1995 at DU11, while another event in December produced an $H_{MAX.}$ of 0.9 m (measured at DU13). Thus, although the bulk of the waves measured are small, it is quite clear that large waves can be experienced on small lakes such as Lake Dunstan.

The largest H_S was measured at sites DU11 and DU13 (0.57 and 0.53 m respectively). Both sites are located at the downwind end of the Clutha Arm and have long fetches (Fig. 1). In contrast, waves measured along the axial shore at DU21 are consistently small (90% being less than 0.23 m). A feature of Fig. 5A is the very small waves measured at DU15, despite the long fetch (comparable to DU13) (Table 1). Although wind conditions at the time of measurement were slightly lower when compared with the other sites (Table 1), it is unlikely that this influenced the waves measurements so significantly. The most likely explanation is that the S4ADW may have been located in too deep of water (~1.3 m) for the wave conditions at the time. For example, it was found that the S4ADW wave data were up to 40% smaller than those identified from the wave staff. This finding highlights the importance of locating a pressure recorder in very shallow water to obtain reliable wave measurements of high frequency lake waves. A slight plateauing can also be seen in Fig. 5A c. 0.4–0.45 m. It is not immediately clear from the data why this should occur. Two likely explanations are offered. First, it may reflect truncation of the energy spectra caused by the 2 Hz sampling rate used; second, it may simply be a function of insufficient wave data. Wave sampling at a much higher frequency is likely to be the only means by which this pattern can be properly assessed, while a much longer wave record is required to properly describe the wave climate on the lake.

Peak wave periods (T_P) ranged from 1.7 to 3.6 s, while the mean T_P was 2.46 s. For 85% of the time, T_P at Lake Dunstan was less than 2.9 s (Fig. 5B). In contrast to the wide range of measured H_S values (Fig. 4), it is apparent from Fig. 4 and 5B that the range of T_P is narrower with the bulk of the wave periods located in a 1 s band, between 2 and 3 s. This occurs despite significant variations in the fetch length. Nevertheless, a general pattern can be discerned such that sites exposed to the longest fetches (DU11 and DU13) tend to experience the longest and greatest range of wave periods (Fig. 5B). For the largest wave measured (H_S = 0.57 m), T_P was 3.2 s. In contrast, sites exposed to shorter fetch lengths (such as at DU21) experience higher frequency waves and a narrower range of frequencies.

Table 6 Wave statistical ratios derived from the present study and those from other investigations (See Table 2 for nomenclature).

Description	$H_{MAX.}/H_S$	H_{10}/H_S	H_{RMS}/H_S	H_M/H_S
Theoretical prediction identified by Longuet-Higgins (1952) for a narrow spectrum	1.53 –1.85	1.27	0.71	0.64
25 records, 20-min interval (Putz 1952)	1.87	1.29	–	0.62
Wave staff, Pickrill (1976)	1.41	–	–	–
3728 records, 10-min interval, every 2 h, pressure sensor (Hastie 1985)	1.56	1.22	0.70	0.62
57 records, 18-min interval, hourly wave data, wave staff—**this study**	**1.84**	**1.27**	**0.58**	**0.61**

Statistical ratios of wave height

Table 6 presents statistical ratios among H_M, $H_{1/3}$, H_{RMS}, H_{10}, and H_{MAX} from this study along with theoretical estimates derived by Longuet-Higgins (1962), and results from empirical data measured by Putz (1952), Pickrill (1976), and Hastie (1985). The ratios identified for this study have been derived solely from the wave staff data (Table 2) since the S4ADW wave data are already based on statistical manipulations.

It can be seen from Table 6 that the wave statistic ratios are comparable between small lakes (Pickrill 1976, results from this study) and oceanic environments (Putz 1952, Hastie 1985) and with the theoretical values of Longuet-Higgins (1962). The higher H_{MAX}/H_S ratio identified by this study compared with Pickrill (1976) probably reflects the significantly shorter wave records obtained by Pickrill; the average number of zero crossings from wave data samples measured by Pickrill was 44.4 compared with 532.2 in the present study. Using the theoretical tables presented in Longuet-Higgins (1962), the theoretical relation for 50 waves is 1.42 and is close to the 1.41 value identified by Pickrill. For 500 waves, the theoretical relation is 1.77. Although this value is lower than the value of 1.84 identified in this study, Longuet-Higgins notes that there is a slight error, generally less than 8% and often considerably less than this, between theory and observed values. It can be concluded from Table 6, that the theoretical relationships identified by Longuet-Higgins (1962) are extremely useful for identifying wave height statistics from a known height value such as the significant wave height. In addition, the above results provide a simple means of identifying extreme conditions that may occur during large events. Findings here are important for specifying the range of elevations at which waves are able to cause change to the shore and for engineering design of structures.

Wave steepness (H/L)

The steepness of waves, the ratio of wave height to length (H/L), is recognised as important to the type of beach response, that is whether the beach erodes or accretes (Battjes 1974; Kraus 1990; Komar 1998). In general, steeper waves cause erosion of beaches while flatter waves result in accretion. Since waves measured at Lake Dunstan fall in the region between $0.00155 > d/gT_P^2 < 0.0792$, where d is the water depth, g is acceleration due to gravity, and T_P is the peak wave period, they are classified as "transitional" and the wave length may be determined from:

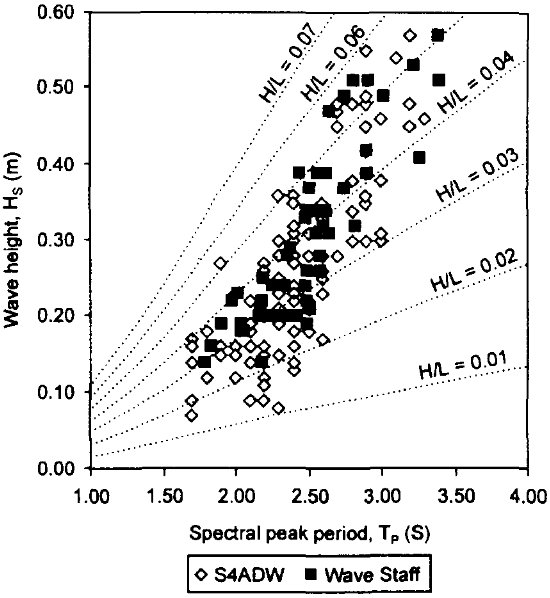

Fig. 6 Joint plot of wave steepness isolines, significant wave heights and spectral peak periods.

$$L = \frac{gT_P^2}{2\pi}\tanh\left(\frac{2\pi d}{L}\right) \tag{3}$$

However, use of Equation 3 is made somewhat difficult since the unknown L is located on both sides of the equation (CERC 1984). Eckart (1952) presents an alternative solution that is correct to within c. 5%, and is satisfactory for describing the wave steepness at Lake Dunstan. This is given by:

$$L = \frac{gT_P^2}{2\pi}\sqrt{\tanh\left(\frac{4\pi^2}{T_P^2}\frac{d}{g}\right)} \tag{4}$$

Figure 6 presents wave steepness isolines calculated for a range of wave heights and periods. These data have been overlaid on a plot of the measured wave heights and peak periods identified at Lake Dunstan. A fixed depth (d) of 1.2 m was used in all calculations of the wave length and represents the average water depth where wave measurements were taken (Table 1). As a result, because we have used a fixed depth in calculating the wave length, there is a slight difference between the estimated wave steepness isolines and the actual wave steepness values determined for the Lake Dunstan wave data.

Steepness values ranged from 0.012 (associated with the smallest wave measured) to 0.066, while the mean steepness was 0.039. As can be seen from Fig. 6, waves measured at Lake Dunstan are concentrated between the 0.03 and 0.05 isolines, with fewer waves (<5.5%) found below the 0.02 isoline. As the wave height or period increases, there is a corresponding increase in the wave steepness (Fig. 6). Steepest waves, and hence potentially the most erosive waves, are associated with longer spectral peak periods coincident with the larger wave heights. These waves dominate sites exposed to the longest fetch lengths such as at DU11 and DU13. In addition, these sites are also influenced by the greatest range of wave steepnesses, a function of the wide range of wave heights and periods observed along such shores. Less steep waves were identified along the western shore of the Clutha Arm at DU21 and at DU15. These data suggest that during storms, lake waves grow in height and period to become highly erosional at the shore, particularly at the downwind ends of lakes where larger waves may be experienced. It is these latter sites that can present significant management problems as a result of shore erosion (e.g., at Lakes Pukaki (Kirk 1988), and Hawea (Kirk et al. 2000)).

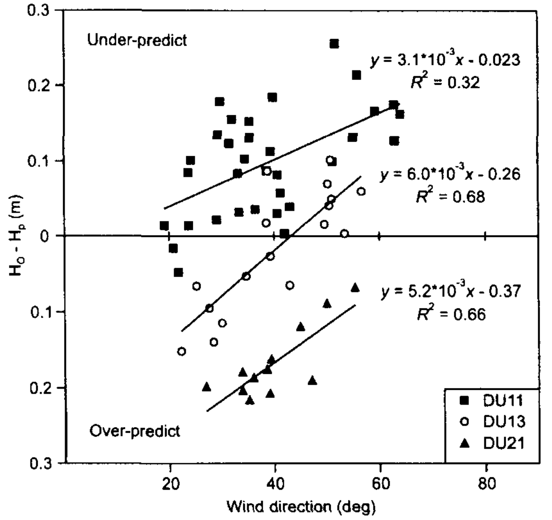

Fig. 7 Regression of the differential measured deepwater wave height and the predicted wave height (H_o–H_p) against wind direction.

TEST OF THE NARFET HINDCASTING MODEL

Table 7 presents results from the correlation analysis of NARFET wave predictions versus those measured at Lake Dunstan. Since the wave data measured at DU15 is considered to be less reliable, this site has been ignored in the regression analysis. As can be seen from Table 7, reasonable correlations are achieved for estimates of the wave height (R = 0.77–0.81), whereas lower correlations were achieved for the wave period (R = 0.56–0.69). At DU11, NARFET was found to under-predict the wave height by on average 26%, while at DU13 there is an even split between over-prediction (23%) and under-prediction (15%) by the model. In contrast, the model was found to over-estimate the wave height at DU21 by about half. The surprising feature of Table 7 is the lower correlations identified for the wave period. Further, NARFET consistently under-estimated the wave period by c. 1 s. This was unexpected since Smith (1991) had identified strong correlations with the wave period when developing NARFET. Use of other variables such as the zero-crossing period and the significant wave period did not result in any improvement in the regression analysis.

The smaller waves predicted at DU11 is likely to be related to the shorter radial fetch lengths caused

Table 7 Correlation analysis of the measured wave height and period with those predicted by NARFET (See Table 2 for nomenclature). Note: H_0 denotes the deepwater significant wave height.

Site	Variable	R	a	b
DU11	H_0	0.80 P<0.01	0.88	+0.13
(N = 35)	T_P	0.56 P<0.01	0.47	+1.78
DU13	H_0	0.77 P<0.01	0.62	+0.10
(N = 17)	T_P	0.69 P<0.01	0.92	+0.57
DU21	H_0	0.81 P<0.01	0.53	–0.01
(N = 12)	T_P	0.66 P<0.05	0.79	+0.51

by the geometry of the eastern Clutha Arm shore, particularly in the vicinity of Northburn (Fig. 1). Because of the shape of this section of shore, the longest fetch toward the north is only 6.3 km (as opposed to 14.5 km at DU13 just to the west of DU11). The model therefore assumes that waves can only form along the lower half of the Clutha Arm. In reality this is not the case, so that wave development is occurring along the full length of the Clutha Arm and the waves simply propagate around the Northburn prominentary (Allan & Kirk unpubl. data). As a result, DU11 experiences waves of a similar size to those measured at DU13 as indicated by the wave measurements.

The cause of the NARFET over-prediction at DU21 is less clear. One possibility is that it reflects a limitation of the model. This is highlighted when the difference between the measured and predicted heights are correlated with wind direction (Fig. 7). As can be seen from the figure, the model appears to increasingly over-predict the wave height as the wind swings from ENE to N (Fig. 7). At DU21, greatest over-prediction occurs when winds are blowing from NNE (20–40°), with the margin of difference decreasing as winds become increasingly more ENE (~60°). It can be seen from the map of Lake Dunstan (Fig. 1), that when the wind is blowing from ENE it would be oriented directly at DU21, whereas when the wind is blowing from NNE, any wave development would be increasingly influenced by the north-western shore of the Clutha Arm, so that smaller waves would be expected to predominate (Allan & Kirk unpubl. data). A similar trend can also be identified for DU13, though differences there are much less than at DU21. In contrast, the reverse appears to occur at DU11, so that the model predicts wave height best when winds are from the N, while poorer predictions occur as the wind swings to the E (Fig. 7). Such a pattern suggests a problem with either NARFET's ability to account for the lake geometry or its ability to specify waves for off-wind directions. Further work is required to clarify this pattern. It is also likely that some of the differences noted between the sites may simply be a function of changes in the wind field. Wave hindcasting models rely on constant wind speeds and directions along the entire fetch (Smith 1991). However, winds are rarely constant in mountainous terrains so that gusts may rise and fall along a water body, and may be substantial at times (Dr H. McGowan, University of Canterbury, 1997 pers. comm.). As an example, maximum wind gusts measured at Northburn can be as much as 80% greater than the average hourly wind speeds. One would expect such variations to be manifested in the waves.

WAVE CLIMATE ALONG THE CLUTHA ARM

Despite some uncertainty with the NARFET model, it appears to provide reasonable estimates of wave heights along the southern shore of Lake Dunstan. As a result, we have used it to provide an insight into the distribution of waves at the shore for a range of sites along the southern half of the Clutha Arm (Fig. 8). Wave rose plots were created using a modified "QUICKBASIC" wind-rose program called "TEKROSE". Calm conditions (when no waves were present) have been removed from the plotted data and are presented as percentages alongside the appropriate site. The wave-roses indicate wave approach angles, while the frequency of occurrence of a particular wave height is represented as a percentage distance from the innermost ring.

As can be seen from Fig. 8, the Clutha Arm shoreline is influenced by waves from a wide range of directions. Nonetheless, it is possible to distinguish a bi-directional nature to the wave regime. The dominant direction of wave approach is from the northerly quarter (between NE and NW directions) (Fig. 8). These waves show a greater frequency of heights that exceed 0.4 m (up to 13%) and have occurred more frequently than similar sized waves from other directions. The second important direction is from the southerly quarter (between SE and SW directions). Wave heights exceeding 0.4 m occur for only a small proportion of the time (generally below 3%) for the southerly quarter.

From the percentage exceedence curves for three sites (DU13, DU21, and DU26) (Fig. 8), it can be seen that in general the eastern shore (DU26) has a higher incidence of smaller wave heights when compared with sites on the western (DU21) and southern shores (DU13) of the Clutha Arm. This pattern is primarily a function of a particular site's fetch length and orientation (exposure) toward the predominant wind directions. In addition, it can be seen from Fig. 8 that the bulk of the waves hindcast for the Clutha Arm are small (≤0.2 m), a finding that is consistent with the wave measurements. For example, at DU13 c. 70% of waves are less than 0.25 m in height (Fig. 8). Since this site is exposed to the longest fetch, one might expect sites located further up the Clutha Arm to experience a greater proportion of waves that are less than 0.25 m in height. This

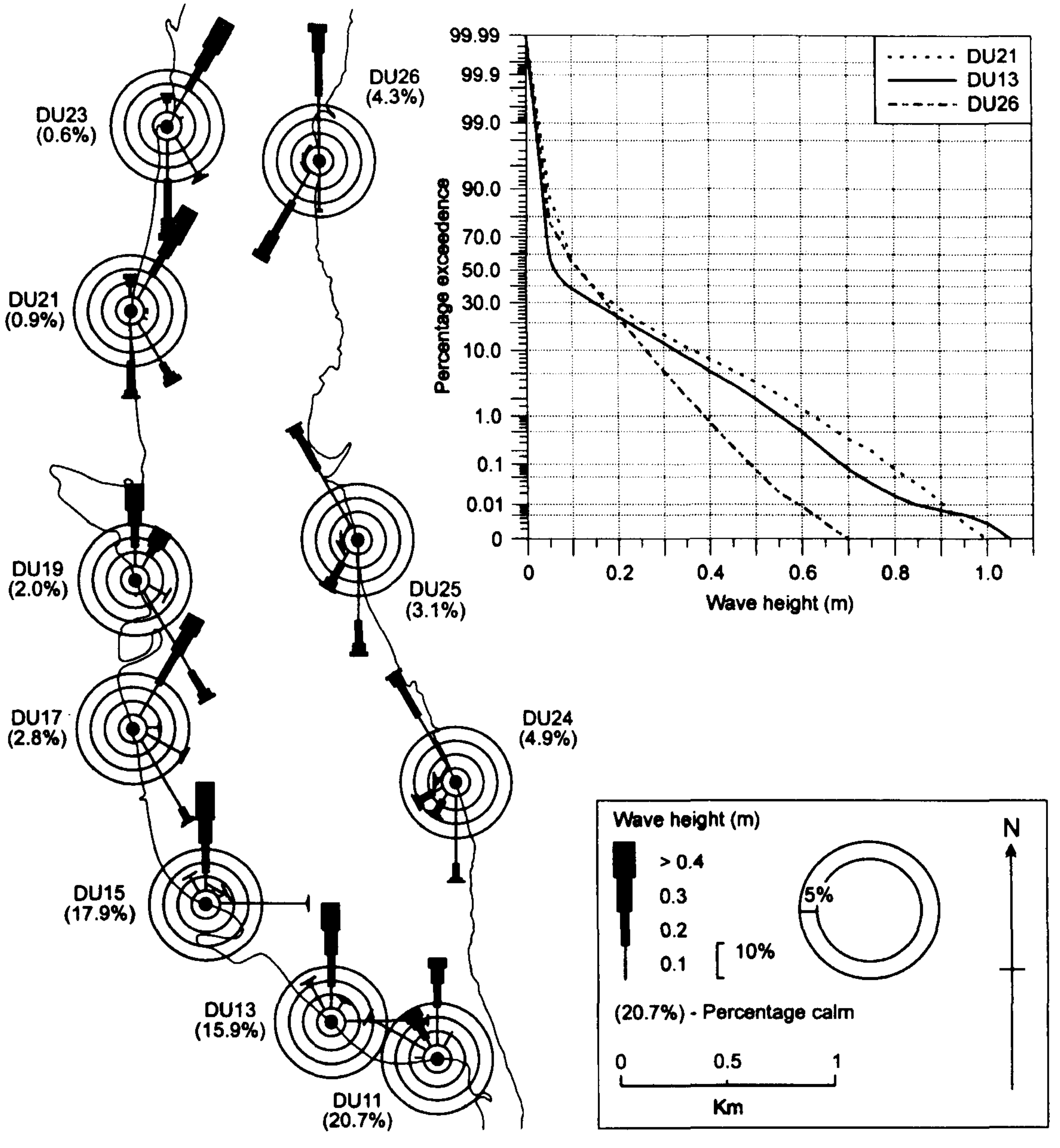

Fig. 8 Hindcast wave frequency and directions of wave-approach in the Clutha Arm, New Zealand.

certainly appears to be the case for DU26, whereas DU21 appears to experience slightly fewer waves below 0.25 m. Differences here are probably related to this sites exposure to winds from both the N and S. In contrast, DU13 is mainly influenced by winds from the N.

The degree of calm (when no waves are present) is also shown in Fig. 8. In general, sites located further up the Clutha Arm (e.g., sites DU21 and DU23) tend to experience fewer calms (<1.0%). This is because these shores are increasingly exposed to a greater range of wind directions and hence wave

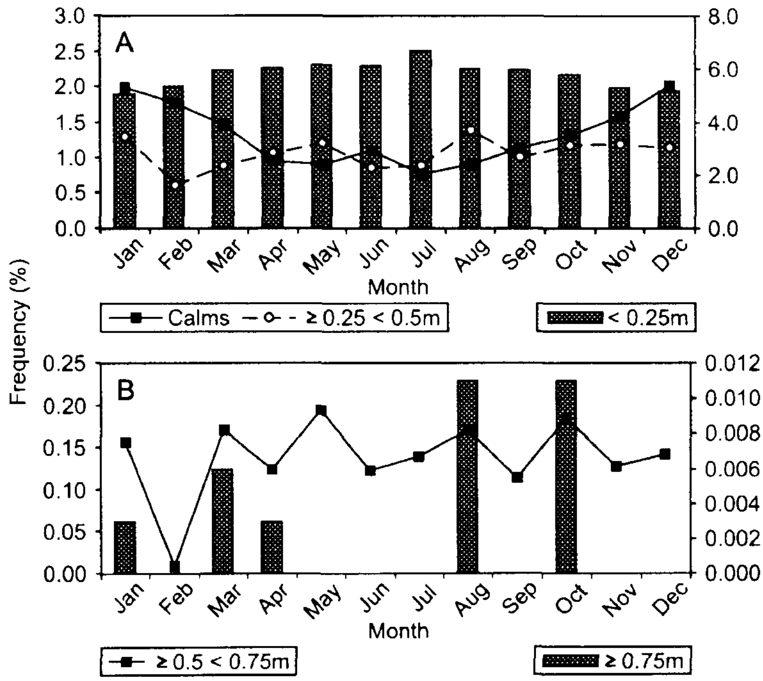

Fig. 9 Seasonal variations of hindcast wave heights for DU13 in the Clutha Arm, New Zealand.

approach. Alternatively, sites located at the downwind end of the Clutha Arm (DU15–DU11) experience a higher incidence of calms (up to 21% of the time at DU11) since they are influenced by winds from predominantly the N and NW directions. Although not shown in Fig. 8, one would expect to find the incidence of calms increasing to the N, since these shores will be mainly influenced by winds from the S.

Seasonal variation of waves

The seasonal variation in wave height is shown in Fig. 9 for one site (DU13) located at the downwind end of the Clutha Arm. As noted earlier, wind strength at Lake Dunstan tends to be highest during spring and summer and is at its lowest in autumn and winter. Intuitively, one might expect a similar pattern to be reflected in the hindcast wave data. As noted previously, the southern Clutha Arm shore experiences a reasonably high amount of calm conditions; at DU13, this equates to c. 16% of the time (Fig. 8). As shown in Fig. 9A, the incidence of calms along this shore is highest during the summer period, particularly January and December, and decreases toward winter. This finding can be explained in terms of a higher incidence of southerly winds that takes place in spring and summer and which decreases over autumn and winter (Fitzharris & Reid 1993; Allan 1998). As a result, the pattern of calms shown in Fig. 9A, mirrors the seasonal characteristics of southerly winds in the Cromwell Basin.

Apparent from Fig. 9A is that smaller waves (<0.25 m) occur more frequently during autumn and winter and are less frequent in the spring/summer months. In contrast, waves between 0.25 and 0.5 m show a slightly higher incidence in summer and spring (Fig. 9A). With increasing wave height (Fig. 9B), there appears to be greater variability in the seasonal component of waves on Lake Dunstan. Waves between 0.5 and 0.75 m occur most frequently in May, followed by the spring period, particularly October. Of note also is the near absence of larger wave conditions during the month of February. This finding is consistent with a "dip" in the wind frequency noted for February (Fig. 3). Waves greater than 0.75 m are particularly prevalent in spring, mid summer, and early autumn (Fig. 9B), a pattern that is reasonably consistent with observations of winds in the area. Thus, although there does appear to be a seasonal component to waves at Lake Dunstan (particularly for the smaller waves), the findings suggest that larger waves (particularly those between 0.5 and 0.75 m) can occur during any time of the year.

DISCUSSION

The strong correlations identified between the different measures of H_S as determined by the S4ADW pressure transducer and wave staff is in agreement with previous work undertaken by Harris (1971). Harris compared four different techniques of ocean wave heights and found that all of the measures for H_S are highly correlated. Therefore, based on these results it appears to make little difference which method is used to identify H_S from a wave record. While strong correlations were found to exist between the different measures of H_S, Harris (1971) found that correlations between different measures of wave period (such as T_Z and T_S) were less consistent. Results from the present study show that both these measures and the spectral peak period are highly correlated (Table 3). Sargeant & Timme (1974) suggest that T_Z and T_S may be said to be equal if the spectral band width (ε) (Table 2) falls between certain limits (though they offer no indication of what these limits might be) and the wave spectrum is relatively simple. This is likely to be correct since the spectral band width at Lake Dunstan ranged from 0.16 to 0.6 (mean was 0.34 ± 0.09). This suggests that wave frequencies at Lake Dunstan may be regarded as narrow-banded. Such a finding is primarily a function of the short fetch lengths present on the lake whereby limited sorting of the wave frequencies occurs and is consistent with the findings of Pickrill (1976).

In terms of the significant wave heights (H_S) on lakes, Pickrill (1976) indicated that they ranged from 0.05 to 0.35 m, whereas $H_{MAX.}$ reached 0.48 m at Lake Manapouri. Macky (1991) measured H_S from 0.1 to 0.58 m at Lake Waikaremoana (where $F_{MAX.}$ is similar to Lake Dunstan). It is apparent from the present study that although the bulk of the waves observed at Lake Dunstan are small, 95% of the waves being less than 0.51 m, they are significantly larger than those measured by Pickrill (1976), and are comparable to those measured by Macky (1991). It is likely that differences between this study and the results of Pickrill (1976) reflect simply limitations of the instrument used by him and the small samples measured. These findings have important implications for the larger lakes located throughout New Zealand where considerably higher waves, and hence greater potential erosion, can be expected to occur during severe storm events. A greater appreciation of the magnitude and frequency of these waves is required for the effective management of their lake shores. Presently, such data are not available. However, in the absence of measured wave data, this study has shown that $H_{MAX.}$, or H_{10} can be simply derived, providing there is at the very least visual estimates of H_S.

Wave periods measured at Lake Manapouri ranged from 1.3 to 3.6 s (Pickrill 1976), and are predominantly less than 4.0 s at Lake Waikaremoana (Macky 1991). Peak wave periods determined for Lake Dunstan ranged from 1.7 to 3.6 s and exhibit a slightly narrower range of frequencies when compared with those measured by Pickrill (1976) and Macky (1991). This is likely to be mainly a function of variations in the fetch lengths and also the different instruments used. Nevertheless, findings from Lake Dunstan are reasonably consistent with field measurements made by Pickrill and Macky. These findings reinforce claims made by Pickrill (1976) and Kirk (1988) that the dominance of high frequency waves in small lakes will limit the range of morphological forms that can develop. Accordingly, accretion of beaches will tend to be confined to areas experiencing longshore sediment transport and swash processes because of the absence of longer period waves. Furthermore, the concentration of the peak spectral periods at the high frequency end of the spectrum limits the morphological change done lakeward of the breaker zone, particularly for those lakes that contain coarse sediments, and concentrates the wave energy to a narrow band landward of this zone. As a result, greatest changes to the alpine lake beaches occur in the swash zone, a conclusion that is supported by field measurements obtained at Lake Dunstan (Allan 1998).

Examination of the distribution of waves about the Clutha Arm has indicated considerable variability along the shore, although a predominant bi-directional nature to the wave regime can be broadly identified. From the wave hindcasting, it is clear that the southern end of the Clutha Arm receives the largest and most destructive waves. For example, the present study identified an $H_{MAX.}$ of 1.05 m at DU11 for a moderate wind event. Along the axial shores of the Clutha Arm, wave approach is strongly oblique while the waves tend to be smaller in height. Nevertheless, a strong southward directed longshore component is generated during storms, which results in a predominant drift of sediments toward the southern end of the lake. This finding is consistent with observations made elsewhere, in particular, Lake Ohau (Kirk & Henriques 1986) and at Lake Pukaki (Kirk 1988). However, the present findings suggest a greater complexity in the wave regime, their distribution about the lake shore, and the seasonality of lake waves than has previously been identified.

CONCLUSIONS

Several important characteristics concerning the measurement of waves and the wave regime at Lake Dunstan have been identified in this study. (1) A pressure transducer such as that in an S4ADW can be used in a small lake environment to measure high frequency waves, provided it is located in shallow water depths. Our study has indicated that water depths of c. 1.0 m provide reasonable estimates of the wave statistics. Further, since high frequency lake waves are rapidly attenuated with depth, we recommend that pressure transducer devices be calibrated against a capacitance wave staff to increase confidence in the wave statistics. (2) The measurement of wave statistics over seven moderate storm events during 1995 at Lake Dunstan indicated significant wave heights that ranged from 0.07 to 0.57 m with a mean value of 0.28 m. For 95% of the time, significant wave heights were less than 0.51 m for the combined storm wave data. The maximum wave height identified for this study was 1.05 m. Thus, although most of the waves measured on the lake are small, this study has shown that large waves can be experienced in small lake environments. It is these larger waves, coincident with high water levels, which can lead to significant shoreline hazards and problems for lakeshore managers. (3) Peak spectral wave periods ranged from 1.7 to 3.6 s with a mean value of 2.46 s. For 85% of the time the peak wave period was less than 2.9 s. (4) The largest waves occur along the southern end of the Clutha Arm. These waves exhibit the longest and widest range of wave periods, and are generally the steepest waves, making them highly erosional at the shore. (5) Comparisons between NARFET predicted and measured wave statistics indicate reasonable agreement for the wave height, particularly for sites exposed to the longest fetches, whereas correlations of the peak wave period were lower. In general, NARFET was found to over-predict the wave height and under-predict the wave period. Since there appears to be some discrepancy between the predictions made by NARFET, particularly for sites located along the axial shore of the lake, we recommend further work be undertaken to examine the NARFET model using a much longer time series of wave data. (6) The wave climate at Lake Dunstan was described using the computer wave hindcasting model, NARFET, for a 3.5-year period. The wave regime in the Clutha Arm is bi-directional. Dominant directions of wave approach are from the north and south. A seasonal regime was identified in the hindcast wave data that approximates the wind regime at Lake Dunstan. In general, smaller waves (<0.25 m) occur more frequently during autumn and winter, while waves between 0.25 and 0.5 m show a slightly higher frequency in summer and spring. Larger waves (>0.5 m) are particularly prevalent in spring, mid summer, and early autumn.

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