Hydraulics Research
Wallingford

WAVE PREDICTION IN RESERVOIRS:
A Literature Review

Report No EX 1527
February 1987

Registered Office: Hydraulics Research Limited,
Wallingford, Oxfordshire OX10 8BA.
Telephone: 0491 35381. Telex: 848552

Wave prediction in reservoirs: a literature review,
Report EX 1527,
Hydraulics Research Ltd, Wallingford,
February 1987

ABSTRACT

This report describes a review of the available literature referring to wind waves in lakes and reservoirs. Published information on wave measurements is examined, concentrating particularly on those articles which contain sufficient detail for the data to be compared with wave prediction techniques. Since almost all wave prediction methods for reservoirs are based on modifications to open ocean techniques, these methods are briefly reviewed and compared, confining attention to those relatively simple formulae which can be presented graphically or programmed on a desk-top computer. The report then considers the various ways in which these formulae have been adapted for application in reservoirs, and examines the data to support these modifications. The literature review indicates that there is still considerable uncertainty about wave prediction in reservoirs, and makes suggestions for further research to improve the reliability of predictions.

The work described in this report was funded by the Department of the Environment under research contract PECD 7/7/187, and formed a part of the research on reservoir safety recommended by the Department's Reservoir Safety Committee. The review was carried out by Mr M W Owen, Research Manager of the Coastal Engineering Group within the Maritime Engineering Department.

NOTATION

E	Wave energy
$E_i(f)$	Component of the wave energy/frequency spectrum
F	Fetch length
$\hat{F}$	Dimensionless fetch length (gF/U^2)
F_e	Effective fetch length
F_i	Fetch length measured along a direction Θ_i
F_φ	Fetch length measured along the predominant wave direction
f	Wave frequency (1/period)
f_m	Wave frequency at the peak of the energy/frequency spectrum
$\hat{f}_m$	Dimensionless peak frequency $f_m U/g$
g	Acceleration due to gravity
H_s	Significant wave height
$\hat{H}$	Dimensionless wave height gH_s/U^2
n	Directional spreading exponent
n_p	Directional spreading exponent at the peak frequency
T_p	Wave period at the peak of the wave energy/frequency spectrum
T_z	Mean zero-crossing wave period
$\hat{T}$	Dimensionless wave period, gT_z/U
U	Wind speed (usually at a height of 10m above water level)
X_i	Component of fetch length parallel to wind direction ($F_i \cos\Theta$)
α	Phillips 'constant' in wave energy/frequency spectrum
γ	Peak enhancement factor in wave energy/frequency spectrum
η	Factor in wave energy/frequency spectrum
Θ	Angle between wind direction and fetch direction
Θ_i	Fetch direction
Θ_w	Wind direction
σ	Factor in JONSWAP energy/frequency spectrum
φ	Predominant wave direction

CONTENTS

1 INTRODUCTION

The generation of waves on any body of water depends on the strength of the wind, the length of time for which it has been blowing (duration), and the distance over the water for which it has been acting (fetch). Most of the research effort on the measurement and prediction of waves has been devoted to oceanic and coastal waters, with long wide fetches and typical durations of several hours or even days. Inland reservoirs are however very different: fetch lengths are typically only a few kilometres, the width of the reservoir is frequently small compared to its length, and wave conditions can often be governed by high wind speeds acting for very short durations, typically less than 1 hour. In addition, reservoirs are frequently constructed in deep valleys in upland areas, where the local topography can significantly affect both the wind speed and direction over the reservoir. Bearing all these factors in mind, it would be very surprising if wave prediction methods developed for coastal and oceanic waters could be applied without modification to the estimation of waves in reservoirs. A limited amount of work has therefore been undertaken by various researchers to measure waves in reservoirs, and/or to derive methods of modifying the wave prediction techniques used for open waters.

This report reviews published information on wave measurement studies in reservoirs and lakes, and also on methods of predicting such waves. The report starts by examining references to wave measurements (Section 2), concentrating particularly on those reports and papers which contain sufficient detail to enable later researchers to re-analyse the data in the light of recent developments in wave prediction techniques. Since almost all wave prediction methods for reservoirs and lakes are based on modifications to open-water wave prediction techniques, these open water techniques are described next (Section 3). This section concentrates on methods which rely on simple formulae, or on procedures which can be programmed onto a desk-top computer. The much more complex finite-difference mathematical models which are increasingly being used for ocean wave prediction are unlikely to be relevant to wave prediction in reservoirs. In Section 4, the report goes on to consider the ways in which various researchers have sought to modify open-water techniques to make them applicable to reservoirs and other enclosed bodies of water. Finally the report contains suggestions for further research to improve the reliability of wave prediction in reservoirs.

2 WAVE MEASUREMENTS IN RESERVOIRS AND LAKES

There are numerous references in the literature to the results of wave measurements in oceans and coastal waters, but relatively few to measurements in reservoirs or inland lakes. Reservoirs typically have a length of only a few kilometres, whereas lakes can have lengths up to several hundred kilometres. For this reason, references to measurements in reservoirs and lakes will be discussed separately.

2.1 Waves in reservoirs

The most extensive set of wave data ever obtained in reservoirs resulted from a study conducted by the US Army Corps of Engineers between 1950 and 1954, although not fully reported until 1962 (Ref 1). The measurements were carried out in two deep water reservoirs, having surface areas of 50 and 130 square km respectively. The reservoirs were of rather complex shape, with several arms and creeks. At a total of 5 locations in these reservoirs, measurements of wave heights and periods, wind speed and direction were taken at purpose-built towers. All measurements were taken at 10 minute intervals, but since all the analysis in those days had to be performed manually, only those records showing wind speeds greater than 9m/s (20mph) or wave heights greater than 0.6m (2ft) were analysed in detail. During the period of measurement, wind speeds up to 20m/s (45mph) were recorded, with significant wave heights up to 1.5m. In Fort Peck Reservoir, (2 locations) 17 major storms were recorded, and in Denison Reservoir (3 locations) 14 major storms occurred. For each of these storms, Reference 1 gives the measured values of wind speed, wind direction, significant wave height, and significant wave period at 10 minute intervals. The values of effective fetch (see Section 4.1) and corrected wind speed are also tabulated. The wind speed correction was judged to be necessary because the wind speed measured at the recording towers located in the middle of the reservoirs was consistently higher than that measured at nearby land-based anemometers. From the measurement at the 5 sites, it was found that the ratio of overwater to overland wind speeds varied with fetch length when that length was less than about 10km, and a figure relating wind speed ratio to fetch length was included in the report. However, the report points out that this figure relates specifically to the two reservoirs studied, and is not necessarily applicable to other sites.

The whole purpose of this extensive study was to determine methods of predicting waves in reservoirs, and the results obtained were compared with the most widely adopted prediction method available at that time for predicting waves in oceanic and coastal waters. The results of this comparison are discussed later (Section 4.1), but the study report contains almost all the data necessary for comparison with more modern wave prediction techniques, if so required. The only information missing is an accurate map of each reservoir, which would presumably be fairly easy to obtain.

Apart from these early measurements in the USA, the only other reference to systematic wind and wave measurements in reservoirs is a recent HR report detailing studies at Megget Reservoir, Scotland (Ref 2). The reservoir is about 3.7km long and 0.6km wide, with a fairly straightforward rectangular shape in plan. Measurements of wave height and period were obtained from a waverider buoy located about 250m from the dam, with wind speed and direction measured at the draw off tower, about 100m from the dam. Measurements were made only when 15 minute average wind speeds exceeded 10m/s, which occurred for about 16% of the time at the site during the 12 months for which the equipment was deployed. During strong winds, records were obtained every 15 minutes: the highest recorded mean-hourly wind speed was 29m/s, with a maximum value of significant wave height of 1.5m. The report contains time-series graphs of significant wave heights for the full 12 months of recording, but similar information on wave periods, and wind speeds and direction is given only for sample periods.

The main purpose of these measurements was to provide information for the designer and owner of the reservoir, because visual observations since completion of the reservoir a few years earlier had suggested that higher waves than expected were occurring. The main analysis of the wind and wave data was therefore on a statistical basis, to enable estimates to be made of extreme wave heights. Analysis of the wind data showed very much higher wind speeds than expected, with severe funnelling effects between the hills rising steeply on either side of the reservoir. Detailed analysis of the wave spectra and steepness indicated the presence of significant wave reflections off the dam face, which consisted of rock riprap at a slope of 1 in 1.5. Because of this, between 20 and 30% of the measured wave height was deducted before carrying out the statistical analysis of wave heights, this percentage being based on theoretical considerations of expected reflection coefficient, expected wave steepness, and expected spectral shape.

Although not strictly necessary for the purposes of the study, the measured wave data was compared with wave predictions using the HINDWAVE numerical model, to assist the designers in any future reservoir project. This comparison, and the HINDWAVE model, are discussed later (Section 4.2.2).

Apart from these two references, no further data on wave measurements in reservoirs could be found. It seems difficult to believe that such measurements have not been carried out elsewhere, and it is possible that additional information exists in confidential or in-house reports which are not generally available.

2.2 Waves in lakes

Most of the systematic measurements of winds and waves in inland waters have been obtained in the Great Lakes of North America. These lakes vary in length from about 300km (Lake Ontario) to about 600km (Lake Superior), with widths varying from 60 to 200km. The earliest reported measurements were by Brebner and Le Mehauté in 1961 (Ref 3). They deployed a pressure cell at a depth of 21ft (6.4m) in a water depth of 46ft (14m) at a location about 1km offshore from the city of Cobourg, approximately midway along the north shore of Lake Ontario. Waves were recorded for 7 minutes every 3 hours, unless wave heights were less than 2ft (0.6m) in which case no further measurements were taken for 12 hours. The recorded pressure variations were converted to wave heights by manual calculations based on linear wave theory, and applied on a wave-by-wave basis, a very time consuming task. The average wave height for each 7 minute record was obtained, and the significant wave height was taken to be a constant 1.6 times the average. Wind speeds and directions were recorded continuously at a weather station located on an exposed part of the nearby coastline. Measurements were taken during the period February 1959 to October 1960, during which time significant wave heights up to 6.7ft (2m) were recorded. Detailed information on 46 storms is included in the report, including wind speed, direction and duration; fetch length; average and significant wave height. Based on a statistical analysis of this data estimates were made of the design wave height for a proposed breakwater at Cobourg, and also of the rate of alongshore transport of beach sediments. The data was also compared with 3 simple empirical formulae for wave prediction, and gave reasonably good agreement with all three, especially for the larger waves.

The Great Lakes Environmental Research Laboratory, Michigan have apparently carried out many studies of winds and waves, but the results of many of these are not available in the general literature. Information published by Liu (Ref 4) relates briefly to measurements made at one site in Lake Michigan (just off the city of Muskegon), and at another in Lake Ontario (in mid-lake opposite the city of Oswego). Lin refers only to two storms, one in October 1981, the other October 1982, and gives details of wind speed and direction, and wave height and period during those storms. Clearly additional data for different storms was gathered at each site, but was not utilised by Lin in his paper. Later, Schwaub et al (Ref 5) described further measurements at the same site in Lake Michigan, on this occasion using four wave gauges arranged at the centre and vertices of an equilateral triangle of side 3.05m in order to measure wave directions. The measurements were made between July and October 1977, when the mast supporting all the gauges collapsed. Wind speeds up to 49mph (21.8m/s) were recorded, with significant wave heights up to 3.2m (just before collapse). The data in this report was presented in the form of histograms of wind direction, wave height/direction, wave period/direction etc. This form of presentation, while interesting in itself, precludes a detailed re-analysis on a storm-by-storm basis, although Liu (Ref 6) published details of the directional wave spectra for two particular storms.

Resio and Vincent (Ref 7) have carried out extensive studies to develop and calibrate mathematical models to hindcast wave action at any selected location in any of the Great Lakes. The mathematical models were fairly complex, requiring wind conditions to be input at up to 340 grid points covering the lake area. This type of model is very unlikely to be justified for wave prediction in reservoirs. However, Ref 7 used wave data collected at 4 sites in Lake Ontario, 4 in Lake Superior, and 3 in Lake Erie for calibration of the model. Some of this measured data is included in Ref 7, mainly in the form of graphs comparing measured and calculated wave heights. No information on wind conditions is given. The data in Lakes Ontario and Superior was collected by Canadian researchers, and references are given where further information may be found (Refs 8 and 9). These publications have not been examined during the present study. The source of the American measurements in Lake Erie is not given.

Apart from the Great Lakes, the only other measurements in lakes which have been discovered in the literature were obtained over a period of 3 years in Lake Geneva, Switzerland (Ref 10). Wind and wave measurements were obtained from a tower located in 5 metres of water off the beach at Geneva, at the south-western end of the lake. The wind records were tied-in with records from other meteorological stations bordering the lake. Lake Geneva is kidney-shaped, with a total length of about 70km, and a width of about 8km. The wind records showed quite clearly that the wind direction changes significantly along the lake, tending always towards its centre-line. During 3 years of recording, wind speeds up to 17m/s and significant wave heights up to 1.45m were obtained. The reference includes details of 10 major storms, giving information on storm duration, mean and standard deviation of wind speed and direction, mean wave period, and the root-mean-square, significant, and maximum wave heights.

The various wind and wave measurements obtained were used in a comparison with the SMB wave prediction method (see Section 3.1). Because the wind direction was changing along the lake, Bruschin and Schneiter argued that a straight-line fetch drawn on a map was meaningless. Best agreement between measured and predicted waves was obtained with a fetch length of about 20km, compared with a straight-line fetch at the site of about 65km.

3 WAVE PREDICTION IN OPEN WATERS

As in many other subjects, the rapid advances in computer power and availability since the late 1960's have enabled complex numerical models of wave prediction to be developed, where previously only relatively simple manual methods were practicable.

The biggest change to occur was the ability to consider the full wave energy spectrum as a function of both wave frequency (the inverse of wave period) and direction. Previously only characteristic parameters such as the significant wave height, mean wave period and dominant wave direction could be derived. Depending on their complexity, these spectral models can consider such effects as spatially varying windfields, time-varying wind speeds and directions, the co-existence and interaction of wind seas and swell seas, refraction due to varying water depths, etc. Most of these effects are insignificant in reservoirs, especially during those periods of strong winds which are of most interest to the reservoir engineer. This report therefore concentrates on methods which are likely to be used by practising engineers, ie those methods which rely on simple formulae and/or can be programmed onto a desk-top computer.

3.1 SMB method

Simple formulae for the prediction of wind waves in oceanic and coastal waters have been in existence for over 100 years (Ref 11), but the formulae which gained the most widespread acceptance were published in 1947 by Sverdrup and Munk (Ref 12). Simple curves were produced, relating significant wave height and wave period to the wind speed, fetch length, and wind duration. These curves were based partly on theoretical considerations, but mostly on empirical data obtained from the oceans. These curves were revised by Bretschneider in 1952 (Ref 13), using rather more data, to produce what became commonly known as the "SMB method". The curves themselves have been reproduced in many different papers and reference books, including the influential Shore Protection Manual, published by US Army Corps of Engineers (Ref 14). The curves cover fetch lengths varying from

1 to 10,000 nautical miles (2 to 18,000km), durations between 1 hour and 10 days, and wind speeds between 10 and 100 knots (5 to 51m/s). For waves which are governed entirely by the fetch length, which is likely to be the case in most reservoirs, the curves can be represented by the equations:

$$\hat{H} = 0.283 \tanh [0.0125\ \hat{F}^{0.42}] \quad (1)$$

and $$\hat{T}_z = 7.54 \tanh [0.077\ \hat{F}^{0.25}] \quad (2)$$

where the dimensionless wave height $\hat{H}$, dimensionless period $\hat{T}_z$, and dimensionless fetch length $\hat{F}$ are defined as:

$$\hat{H} = gH_s/U^2$$
$$\hat{T}_z = gT_z/U$$
$$\hat{F} = gF/U^2$$

(see Notation for list of symbols).

For typical reservoirs with lengths varying between 1 and 10km, and with wind speeds between 10 and 30m/s, F lies in the range of approximately 10 to 1,000. Within this range, the formulae for wave height and period can be written approximately as:

$$\hat{H} = 0.00354\ \hat{F}^{0.42} \quad (1a)$$

and $$\hat{T}_z = 0.581\ \hat{F}^{0.25} \quad (2a)$$

With these simpler formulae, and within the range specified, the error in wave height will be less than 2% and in wave period less than 6% compared with

Equations (1) and (2), with the simpler formulae giving a slight over-prediction in each case.

3.2 JONSWAP formulae

The SMB method of wave prediction was in almost universal use until about the mid 1970's. At that time a series of fundamental experiments were made in the southern North Sea, as part of the Joint North Sea Wave Project (JONSWAP) (Ref 15). Measurements were made of wind and wave conditions at several locations, and the results provided valuable insight into the mechanisms of wave growth. By combining these results with those from other sites, ranging from laboratory wind/wave flumes to deep ocean, a new series of equations were proposed (Ref 16) to describe the wave energy-frequency spectrum, as a function of wind speed, fetch length, or duration. The basic shape of the wave energy spectrum was defined by the equation:

$$E_i(f) = \alpha\, g^2\, (2\pi)^{-4}\, f^{-5} \exp\{-1.25(f_m/f)^4\}\, \gamma^{\eta} \qquad (3)$$

where $\alpha = 0.032\,(f_m U/g)^{2/3}$

$\gamma = 3.3$

$$\eta = \exp\left\{\frac{-(f-f_m)^2}{2 f_m^2\, \sigma^2}\right\}$$

$\sigma = 0.07$ for $f \le f_m$

$\sigma = 0.09$ for $f \ge f_m$.

The peak frequency, f_m, is related to the wind speed and fetch length by the equation:

$$\hat{f}_m = \frac{f_m U}{g} = 2.84\, \hat{F}^{-0.3} \qquad (4)$$

Equation (4) can be re-written to obtain the dimensionless peak period:

$$\hat{T}_p = 0.352\ \hat{F}^{0.3} \tag{5}$$

With a typical JONSWAP spectrum of wave energy the mean zero-crossing wave and the peak wave periods are related approximately by the expression $T_z = 0.87\ T_p$. The equation for the dimensionless mean wave period therefore becomes

$$\hat{T}_z = 0.306\ \hat{F}^{0.3}$$

The significant wave height can be obtained from Equation (3) by observing that:

$$H_s = 4\sqrt{E} \quad \text{where} \quad E = \int E_i\ df.$$

Unfortunately, Equation (3) is so complex that integration has to be carried out by a numerical rather than an analytical method. Also, as far as can be discovered, the results of the necessary numerical integration have never been published by the original JONSWAP collaborators. Results published by other authors suggest an equation of the type:

$$\hat{H} = k\ \hat{F}^{0.5} \tag{6}$$

with values of k varying between 0.0016 (Ref 17) and 0.00178 (Ref 18), a range of about ±5%. The higher of these two values was derived in personal communication with Hasselmann, and is the value used at Hydraulics Research. Frequently however the complete wave spectrum (Equation 3) is predicted for given conditions, and numerical integration is only carried out at the very end of any calculations.

3.3 Donelan's formulae

In 1980 Donelan published a paper (Ref 19) presenting new formulae for the prediction of wave heights and periods. The formulae were based on extensive measurements carried out in Lake Ontario, Canada, in which the full wave energy/frequency/direction spectra were obtained. Using the same basic reasoning as Hasselmann et al (Ref 16), but working with different data, he obtained the following equations for wave height and period:

$$T_p \; (1.85 \; g^{0.77} \; U^{-0.54}) = F^{0.23}$$

and $H_s = 0.00366 \; g^{-0.62} \; U^{1.24} \; F^{0.38}$

These may be re-written in non-dimensional terms as:

$$\hat{H} = 0.00366 \; \hat{F}^{0.38} \quad (7)$$

and $\hat{T}_p = 0.541 \; \hat{F}^{0.23}$ (8)

or $\hat{T}_z = 0.471 \; \hat{F}^{0.23}$

Donelan also suggested that the wave energy/frequency spectrum was better described by the expression:

$$E_i(f) = \alpha \; g^2 \; (2\pi)^{-4} \; f^{-4} \; f_m^{-1} \exp \left[\frac{-5}{4} \left(\frac{f_m}{f}\right)^4\right] \gamma^{\eta} \quad (9)$$

where α (Donelan) $= 0.0165 \; (f_m U/g)^{0.55}$

γ (Donelan) $= 2.2$ when $2\pi \; f_m U/g \leq 1$

$= 2.2 + 7.7 \log_{10} (2\pi \; f_m U/g)$ when $2\pi \; f_m U/g \geq 1$

η (Donelan) $= \exp \left[-22 \left(\frac{f}{f_m} - 1\right)^2\right]$

$f_m = 1/T_p$

As far as is known, Donelan's wave prediction formulae have not gained much acceptance, but they are included here because Donelan went on to develop the formulae for application in enclosed bodies of water with irregular shoreline geometry (see Section 4.3).

3.4 Other methods

The three methods described earlier have all been modified in various ways by different authors to make them more applicable for wave prediction in areas where the fetch width is relatively small compared to the fetch length. There are however numerous other formulae which are available for wave prediction in open waters, including those of Derbyshire and Draper (Ref 20), Mitsuyasu (Ref 21), Lin (Ref 22) etc. Occasionally modifications suggested for the three main methods (SMB, JONSWAP or Donelan) have been used with some of these other methods, without any real justification. In addition to these formulae, various complex numerical models have also been used for wave prediction in open waters, including those of Barnett (Ref 23), Resio and Vincent (Ref 7), Meteorological Office (Ref 22), and NORSWAM (Ref 25). In each of these models the fetch area is divided by a rectangular grid. Within each grid square the basic equations of wave growth, wave energy transfer, etc are solved for discrete wave frequencies and directions to build up a description of the complete wave energy spectrum at each location. The input conditions are the values of surface wind speed and direction at each grid point. Some of these methods, particularly those of Barnett and Resio and Vincent, have been adapted for use in the Great Lakes of North America. In these lakes fetches are not as open as in coastal or oceanic waters, but on the other hand are not as restricted as on most reservoirs. Furthermore, the Great Lakes are about two orders of magnitude larger than most reservoirs. It is very unlikely that complex numerical models are necessary for wave prediction in typical reservoirs.

3.5 Comparison of SMB, JONSWAP and Donelan's methods

In the three main methods of wave prediction discussed so far, the formulae for wave height and wave period can be expressed in the dimensionless forms:

$\hat{H} = f_1(\hat{F})$, and
$\hat{T} = f_2(\hat{F})$.

It is therefore instructive to compare the results obtained from the three methods for a given range of dimensionless fetch F.

Typical reservoirs in the UK have lengths varying between about 1 and 10km, and the wind speeds of interest vary from about 10m/s (22mph) to about 35m/s (78mph). The table below gives the corresponding dimensionless fetch values.

Fetch length km	Wind speed m/s	Dimensionless fetch
1	10	98
1	35	8
10	10	981
10	35	80

Figure 1 shows the dimensionless wave height and dimensionless wave period plotted from the different formulae over a range of dimensionless fetch from 10 to 1,000. From this figure it can be seen that within the range typical of reservoirs, the SMB method predicts larger wave heights and periods than JONSWAP, especially at low values of $\hat{F}$ (short reservoirs, high wind speed). The two methods give equal wave heights and periods when $\hat{F}$ is about 3,000 (long reservoir, low wind speed). Within the range of interest, the Donelan method lies between SMB and JONSWAP, being close to SMB at low values of $\hat{F}$, and close to JONSWAP at higher values of $\hat{F}$. The most noticeable feature of Donelan's method is the relatively low power of dimensionless fetch $\hat{F}$ in the expressions for both dimensionless wave height and period. In the JONSWAP method, and in those of Lin (Ref 22) and Mitsuyasu (Ref 21) the dimensionless wave height is given by an expression of the type:

$$\hat{H} = k\ \hat{F}^{0.5}$$

the only differences being in the values of the 'constant' k. Donelan alone among modern researchers arrives at the expression $\hat{H} = k\ \hat{F}^{0.38}$.

Similarly, Donelan arrives at $\hat{F}^{0.23}$ in the expression for dimensionless wave period, compared to $\hat{F}^{0.33}$ in most other recent papers. Similarly, the equation for the wave energy/frequency spectrum derived by Donelan contains a term proportional to f^{-4} where all other workers quote f^{-5}. On the other hand, Donelan's expression (Equation 9) does have the advantage that the peak enhancement factor γ changes smoothly between a developing sea and a fully-developed situation, where in the JONSWAP formulation it changes abruptly from fixed values of 3.3 to 1.0. However in reservoirs the conditions which are of most interest, ie severe storms, are rarely sustained for long enough for the waves to become fully developed.

4 WAVE PREDICTION IN RESTRICTED FETCHES

Various adaptations have been made to the SMB, JONSWAP and Donelan methods by different authors at different times, to make them more applicable to restricted-fetch situations, such as lakes, reservoirs, estuaries or deeply indented coastal bays. For convenience, discussion on the adaptations will be grouped according to the original open-water method used as the source for the modified expression.

4.1 SMB modifications - Saville

At about the same time as the SMB method was being derived for predicting wave conditions in open waters, the US Army Corps of Engineers recognised that relationships derived from ocean studies might not be directly applicable in inland lakes and reservoirs. A program of studies was therefore begun in 1948, with wind and wave measurements being undertaken in a shallow lake, and in two deep water reservoirs. The results obtained from the shallow lake (Ref 26) are of little relevance to the present review, since conditions were hardly typical of reservoirs. The lake was approximately circular in plan, with a diameter of about 50km and an average depth of about 4 metres. The lake was subject to winds up to hurricane strength, which at times caused so much change in water level across the lake that the bed was exposed at the upwind end.

The measurements carried out in the two deep water reservoirs between 1950 and 1954 still form the most extensive set of wave data ever obtained in reservoirs, and are described in Section 2.1 of this report. Since the SMB method was by then widely used for wave prediction in open waters, the measured wave conditions were compared with those which would have been predicted from the measured winds using this method. Although the full report of the measurements and of the analysis was not produced until several years later (Ref 1), the most significant result was published soon after the measurements had been completed (Ref 27). During the preliminary analysis of the data, the fetch lengths had been selected as the greatest straight-line distance over open water in the direction of the wind. However, it soon became apparent that where the width of the fetch area was small compared with its length, measured waves were much lower than predicted. In contrast, measured waves were higher than expected when the wind was blowing over short, wide fetches.

To overcome these problems, several different methods of re-defining the fetch length were considered. Saville (Ref 27) described five of those methods, and compared the results obtained for idealised rectangular fetch areas having different length/width ratios. Without giving details, he stated that the analysis of the wave measurements in the two deep water reservoirs had shown which was the most accurate method. This method, as applied to irregular fetch areas, was then described in detail in the final project report (Ref 1), and also in a paper published in the same year (Ref 28). By redefining the fetch lengths using this method good agreement was reached between measured waves and those predicted using the SMB formula applied to the measured winds.

The method of determining the 'effective fetch' as recommended by Saville is illustrated in Figure 2. Briefly it consists of constructing 15 radials from the wave prediction point at intervals of 6°, out to an angle of 45° on either side of the wind direction. These radials are extended until they first intersect the shoreline. The component of length of each radial in a direction parallel to the wind direction is measured, and multiplied by the cosine of the angle between the radial and the wind direction. The effective fetch is then given by the formula:

$$F_e = \frac{\sum X_i \cos(\Theta_i - \Theta_w)}{\sum \cos(\Theta_i - \Theta_w)} \qquad (10)$$

$$\text{or } F_e = \frac{\sum F_i \cos^2(\Theta_i - \Theta_w)}{\sum \cos(\Theta_i - \Theta_w)}$$

where F_i is the fetch length along the radial, and X_i is the component of the fetch length parallel to the wind direction.

This method is based on the following assumptions:

(a) Wind moving over a water surface transfers energy to the water surface in the direction of the wind and in all directions within 45° on either side of the wind direction;

(b) The wind transfers a unit amount of energy to the water along the central radial in the direction of the wind, and along any other radial an amount modified by the cosine of the angle between the radial and the wind direction;

(c) Waves are completely absorbed at shorelines.

The main advantage of this method is its simplicity; once the calculations have been repeated for selected wind directions, the effective fetches obtained can be used for obtaining wave heights and periods for any combination of wind speed and direction. It is also worth noting that because the effective fetch calculation assumes no contribution to wave energy beyond ±45° from the wind direction, the method is clearly unnecessary when the ratio fetch width/fetch length is greater than about 2 for the given wind direction.

Saville's method of determining the effective fetch soon gained general acceptance, being based on extensive data analysis. During the next 20 years or so it was quoted in many papers and reference books related both to the design of dams (Refs 29 & 30), and to the design of coastal works in areas of restricted fetch (Ref 14).

In recent years there has been considerable discussion about Saville's concept of 'effective fetch'. It is worth recalling that Saville's method was derived to obtain better agreement between measured wave heights in reservoirs, and those predicted from measured winds using the SMB formulae or charts. In most reference books the two methods (SMB and Saville) are quoted together. However, as new wave prediction formulae were developed, particularly JONSWAP, it became clear that for fetch lengths typical of reservoirs the SMB method predicted larger wave heights than any other method (see Fig 1). It has therefore been argued that the only reason why Saville had to develop the concept of effective fetch was to compensate for the inadequacy of the SMB method at short fetches. While the argument may be partly true, it overlooks the fact noted by Saville that under some conditions the measured wave heights were actually greater than predicted. These situations arose when the wind direction was such that the direct fetch length was quite short, but a much longer fetch existed within ±45° of the wind direction. In these situations the discrepancy between the measured and predicted waves could not be resolved without some form of effective fetch concept, whatever wave prediction formula is used.

Bearing these comments in mind, it would be a worthwhile project to re-analyse Saville's data, comparing measured waves with those predicted by modern formulae to see what form any effective fetch concept should take. In the meantime however, it is recommended that the SMB method of wave prediction, and Saville's concept of effective fetch, should always be used together.

4.2 JONSWAP modification

4.2.1 Seymour

Soon after the publication of the results of the JONSWAP experiments (Ref 15) Seymour proposed an alternative to Saville's method for dealing with wave prediction on restricted fetches. Seymour pointed out that in Saville's method the wave energy was in effect assumed to be distributed according to cos Θ (Θ is the angle relative to the wind direction), whereas later information suggested distributions varying from $\cos^2\Theta$ (Ref 31) to $\cos^n\Theta$ (Ref 32), where n is frequency dependent, having a very high value near the peak frequency, reducing to about one at frequencies well away from the peak. Saville's method of obtaining a weighted average also implicitly assumes that wave energy is linearly dependent on fetch length, which is not precisely the case (see Equation 1 for example where $E \propto H^2 \propto F^{0.84}$). For situations in which the waves are fetch-limited, and where the fetch width is also restricted, Seymour therefore proposed a method whereby the wave energy is distributed according to $\cos^2\Theta$, and where the weighted average is based directly on the wave energy along each fetch, rather than on the fetch length. With these assumptions, the total wave energy generated by a given wind speed in an area of restricted fetch is therefore given by:

$$E = \frac{2}{\pi} \sum E_i \cos^2 (\Theta_i - \Theta_w) \, \Delta \Theta \qquad (11)$$

where E_i is the wave energy generated along a direction Θ_i by a wind speed U acting over the fetch length F_i, and $\Delta \Theta$ is the directional increment. Seymour suggested that the summation should be over the logical range $/\Theta_i - \Theta_w/ \leq 90°$, rather than the somewhat arbitrary 45° adopted by Saville.

The wave energy E_i could be calculated by any open sea prediction method if only the resulting wave height is required, but for the prediction of the accompanying wave period, or of the predominant wave direction, it is necessary to use a method which gives the wave energy/frequency spectrum. Seymour used the JONSWAP method.

The JONSWAP-Seymour (JONSEY) and SMB-Saville (SMB-S) methods were then compared with the straightforward SMB method at four sites where wind and wave conditions had been recorded. All were coastal sites with differing degrees of fetch restriction, and the results showed:

(a) When fetch widths are much greater than fetch lengths, all methods give approximately equal results;

(b) When fetch widths are approximately equal to fetch lengths, the JONSEY and SMB-S methods give similar results, with much better agreement with the data than the straightforward SMB method;

(c) For fetch widths appreciably less than the fetch length, the JONSEY method gave the best agreement with the measured data.

Reservoirs are frequently long and narrow, and the JONSEY method would therefore be expected to give better results than the SMB-Saville method, although it has to be recalled that the latter was derived specifically for use in reservoirs. The JONSEY method is rather more cumbersome to use, since the calculations have to be repeated not only for different wind directions (as SMB-S), but also for different wind strengths. However, such calculations are easily performed by a desk-top computer.

4.2.2 Higher order spreading functions

As mentioned previously, Seymour's modification to the JONSWAP equation includes the assumption that wave energy is spread over direction according to $\cos^2\Theta$. For one of the measurement sites, he also examined the effects of introducing a $\cos^n\Theta$ distribution, where n was defined by the function due to Mitsuyasu (Ref 33). However, Mitsuyasu's function was derived from measurements in the open ocean, with dimensionless fetch lengths varying over the comparatively narrow range 3,000 to 6,500. Within this range he found the expression:

$$n_p = 0.00345\ \hat{F}^{0.825} \qquad (12)$$

where n_p is the value of n at the peak frequency of the spectrum. At frequencies either higher or lower than the peak, the value of n decreases. Mitsuyasu himself commented that the form of this expression is very unexpected, because it implies that the angular distribution of wave energy becomes very narrow for long dimensionless fetches, and very broad for short fetches. For example, if the expression is extrapolated down to the dimensionless fetch of about 660 applicable at Seymour's site, the value of n_p is about 0.7. With a distribution $(\cos \Theta)^{0.7}$, about 10% of the wave energy would exist at directions greater than 65° from the wind direction, which seems very unlikely. Not surprisingly therefore, Seymour found poor agreement between the measured wave heights and predictions using a $(\cos \Theta)^n$ distribution, when n was defined by Equation (12).

Recent studies carried out at Hydraulics Research have also examined the effect of different angular distributions. Using the HINDWAVE numerical model (Ref 34), the long term wave climate has been predicted at very many sites. At a few sites, short term wave measurements were available for comparison and calibration. The HINDWAVE model is based principally on the JONSEY method, and at each site the value of n was initially set at 2. For most sites this gives very good agreement with measured data, but at some sites a very much higher power has been found to be necessary. These sites are usually those having either a very short fetch length, or a narrow fetch width, or both. Typical values used range from 6 in the narrows of the Dover Strait (Ref 35) (long narrow fetch) to 30 in the Megget Reservoir (Ref 2) (short very narrow fetch). With a power of 6, 90% of the energy would exist within ±33° of the wind direction, and with power 30 within about ±15°. However, no method has yet been found of predicting accurately the value of n which is likely to be required at any particular site.

4.2.3 Resio and Vincent

Resio and Vincent and their colleagues have been engaged for many years on a program of research on wave measurement and prediction in the Great Lakes of North America. Much of their work has been devoted to setting up and comparing different numerical models. However, the simpler SMB and JONSWAP wave prediction methods have also been compared. Since the lakes are enclosed bodies of water with an irregular shoreline (although very much larger than any reservoir), part of the research has been concerned with the exact definition of fetch length. In 1979 they published a paper (Ref 36) which contained a brief comparison between observed wave heights at three locations, and predictions based on either straight-line fetch, or Saville's effective fetch. Although Seymour's method was also mentioned in the paper, this was not included in the comparison. The results showed that much better agreement between measured and predicted waves was obtained when the straight-line fetch was used. On the strength of these results, the latest edition of the influential Shore Protection Manual (Ref 37) recommends the abandonment of both Saville and Seymour's methods of dealing with narrow fetches, and instead relying simply on the straight-line fetch measured along the wind direction.

Since this recommendation is a direct reversal of the advice contained in earlier editions, it would be worthwhile examining the comparison in more detail. Unfortunately, the only information available in the paper is that contained in a table, reproduced here as Table 1, and no reference is given where more details may be obtained. The table does not contain any information on the shape of the fetch area, on the wind direction, or on the wave prediction method employed, although it is probably JONSWAP rather than SMB. In the Shore Protection Manual (1984 edition) it is also stated that wave measurements in reservoirs agree with theoretical wave growth curves (such as Equations 5 and 6) when the straight-line fetch is used. In this case the only information given is a graph showing dimensionless wave energy plotted against dimensionless fetch for 34 data sets. No information is given on the particular definitions used for the dimensionless parameters, nor are any details given of the reservoir(s) (length, width etc), or of the wind speeds and wave heights included. For this reservoir data, no comparison is made for different methods of determining the fetch.

Because of this lack of detail, it is not possible to check the validity of the recommendation made in the Shore Protection Manual that in future only the straight-line fetch should be used for wave prediction. In practical terms, the SPM recommends that the straight-line fetch should be taken as the arithmetic mean of the fetch lengths measured over an angular range ±12° from the wind direction. If this is equated with angular wave energy distribution $(\cos \Theta)^n$, it represents a value of 'n' of about 45, a very high value indeed. Although it has been mentioned earlier (Section 4.1), it should be repeated here that the use of a straight-line fetch does not explain the fact that when winds were blowing across rather than along a narrow reservoir wave heights measured by Saville were greater than expected.

4.3 Donelan's method

Although Donelan's method of wave prediction was developed originally for open water, it was later modified by the author to enable its use on bodies of water with an irregular shoreline (Ref 19). The most important difference between this and other methods is the recognition from the outset that the wind direction and the wave direction may be quite different in situations of unequal fetch. For example, if winds are blowing along a short fetch, but there exists a relatively long fetch at a modest angle to the wind direction, then it seems reasonable to assume that the predominant wave direction will be biassed towards the longer fetch direction. Donelan then argued that the fetch length should be measured along the wave direction, not the wind direction. On the other hand, the wind speed along this fetch was assumed to be $U\cos\Theta$, where Θ is the angle between the wind direction and wave direction. With these modifications the Donelan wave prediction formulae became:

$$\frac{gH_s}{(U\cos\Theta)^2} = 0.00366 \left(\frac{gF_\varphi}{U^2\cos^2\Theta}\right)^{0.38} \qquad (13)$$

and
$$\frac{gT_p}{U\cos\Theta} = 0.54 \left(\frac{gF_\varphi}{U^2\cos^2\Theta}\right)^{0.23} \qquad (14)$$

where F_φ is the straight-line fetch length along the wave direction φ. To apply these formulae, it is however necessary to know the value of φ, the wave direction. To derive φ, Donelan argued that the predominant wave direction was that which produced the maximum value of T_p, the wave period at the peak of the energy spectrum. By re-arranging Equation (14), it can be seen that this condition is achieved when the product $\cos(\Theta_w-\varphi)^{0.54} F_\varphi^{0.23}$ reaches a maximum within the range $|\Theta_w-\varphi| \le 90°$. For an irregular shoreline, and a given wind direction, the value of φ satisfying this condition can only be determined by trial and error. However, since the product is independent of the wind speed, the calculations have to be performed once only for each wind direction, and could easily be programmed onto a desk-top computer.

In many respects, Donelan's method for restricted fetches combines some of the concepts of both Seymour's and Resio and Vincent's methods. Like Resio and Vincent, Donelan takes a straight-line fetch, rather than a weighted average obtained over a large range of directions, as used by Seymour. When the wind is blowing centrally down a long narrow fetch, Donelan's methods therefore makes no allowance for fetch width. On the other hand, in both Seymour's and Donelan's method the wave direction is allowed to differ from the wind direction, although in Seymour's case no prior assumptions are necessary and the angle between wind and wave directions can vary depending on wind speed and duration. Because the wave and wind directions are allowed to differ, both Donelan's and Seymour's methods help to explain the fact that in Saville's original wave measurements in reservoirs (Ref 1) some measured wave heights were larger than predicted, mainly when the wind was blowing from a short-fetch direction, but a long-fetch direction existed within ±4 [illegible] of the wind direction.

The biggest difference between Donelan's method, and those of Seymour or Resio and Vincent lies in the basic wave prediction formula used, which differs considerably from the JONSWAP formula (see Section 3.5). It would be very interesting to combine the basic concept of Donelan's method of treating irregular fetches with a more widely accepted wave prediction formula, such as JONSWAP.

At a practical level, Bishop (Ref 17) published a comparison of 3 methods of wave prediction with waves measured in Lake Ontario for fetch-limited, steady state waves. The three methods used were SMB, JONSWAP and Donelan, in each case taking a nominal straight-line fetch, measured along the wind direction for SMB and JONSWAP and along the wave direction for Donelan. In practice, the fetches were taken mostly as the arithmetic average of the fetch lengths measured at 1° intervals over a range of ±15°. However, range of ±1° and ±7° were also used for some data sets, but seemed to have little effect on the results whichever method was considered.

Using measured wind speed at the sites of two waverider buoys, the results of the three methods were compared with the measured waves, and showed that:

1. The SMB method overpredicted wave heights, but wave periods were about correct;

2. The JONSWAP method gave good agreement for wave height, but overpredicted wave period;

3. The Donelan method slightly underpredicted wave height and period, but was the only method to give information on wave direction.

It is important to realise, however, that Lake Ontario is about 300km long and about 70km wide. The two waverider buoys were situated towards either end of the lake and were located 12 and 15km respectively offshore, which therefore represents the minimum fetch length at each site.

Unfortunately, no information was given on wind directions or wind strengths, so the range of actual or dimensionless fetch lengths is not known.

5 WIND CONDITIONS OVER RESERVOIRS

Almost all wave prediction formulae use wind speeds and directions measured at a height of 10 metres above the water surface, with wind conditions assumed to be constant along the full length of the fetch. However, when a new reservoir is being designed the engineer invariably has to rely on wind data obtained at an anemometer situated on land. When the reservoir is completed, the wind conditions over the water surface can be significantly different from those measured at a nearby land-based anemometer. This can be due to several reasons including:

(a) Differences in topography between the reservoir site and the anemometer site;

(b) Differences in surface roughness and temperature between land and water.

Reservoirs are often constructed in deep valleys flanked by steeply rising mountains: this configuration can cause a marked funnelling effect on the winds, which both increases the wind speed and tends to shift the local wind direction towards the line of the reservoir. Because the construction of the reservoir will have partly filled the valley, wind conditions over the water surface may be quite different even from those measured in the same valley pre-construction. A different topographical effect will occur if a storage reservoir is built up above the general level of the surrounding plain: In this case winds will be accelerated as they pass over the raised surface. These topographical effects must be considered very carefully, probably in conjunction with the local meteorological office, because the differences in wind speed can be substantial.

Even where there are no topographic differences between the site of the anemometer and the reservoir, wind speeds will increase as the wind passes from the relatively rough land surface to the smooth water surface. The size of the increase depends on the wind speed, on the fetch length, and on the difference in temperature between the land surface and the water. Resio and Vincent (Ref 36) suggested that the ratio overwater wind speed/overland wind speed could vary between values of about 2.0 at very low wind speeds, to 0.9 at high wind speeds (greater than 18.5m/s - 41mph). This was based on wind measurements on the Great Lakes of North America. For wave prediction around UK coasts the Meteorological Office can give recommended values for the ratio, based on wind speeds measured at coastal anemograph stations. However, in no instance do they recommend a value of less than 1.0. Despite the inclusion of Resio and Vincent's results in the Shore Protection Manual (Ref 37), those results should therefore be treated with considerable caution when applied to reservoirs, and values less than 1.0 should be used only when there is strong local evidence to support it. Wherever possible the choice of design wind speed should be discussed with the Meteorological Office.

6 CONCLUSIONS

1. A review has been carried out of all available literature on wave measurement and prediction in reservoirs and lakes. The review found very few published reports of wave measurements in reservoirs or small lakes, although extensive measurements have been made in the Great Lakes of North America.

2. The most comprehensive study of waves in reservoirs which is reported in the literature was carried out in the early 1950's by the US Army Corps of Engineers. When compared with contemporaneous wave prediction formulae (the 'SMB' method) the results showed that wave heights and periods were smaller than expected when winds were blowing along the direction of a long narrow fetch, but were greater than expected when winds were blowing at an angle to that fetch. These observations led to the concept of "effective fetch" which allowed existing formulae for wave prediction in open waters to be used also for wave

prediction in reservoirs and other long and relatively narrow fetch situations. When coupled with the SMB wave formulae, this became the standard method for wave prediction in reservoirs for more than 25 years.

3. Since the early 1970's considerable effort has been devoted to deriving more accurate formulae for wave prediction in open waters. The most recent formulae (eg JONSWAP) all suggest that the SMB formulae tend to overpredict wave heights and periods for short fetches and high wind speeds. These are the very conditions of most interest in the designs of dams and reservoirs.

4. Recent American research suggests that the concept of effective fetch is not necessary for wave prediction along narrow fetches if modern wave prediction formulae are used. This recommendation to use 'straight-line' fetch is based mainly on the results of extensive measurements of wave conditions in the Great Lakes of North America, which are about 100 times larger than most reservoirs. There is a report in the literature that this recommendation is also applicable to reservoirs, but the published evidence for that statement is very sparse.

5. The use of modern wave prediction formulae does not explain the observation in the original Corps of Engineers' measurements that wave heights and periods were larger than expected for winds blowing at an angle to a long narrow fetch. Some method of adjusting the straight-line fetch would still seem to be necessary in this situation. Donelan argued that the predominant wave direction will always be biassed towards the direction of the longest fetch, and that the fetch direction

should therefore be measured along the predominant wave direction. Seymour's method of calculating the effective fetch length also introduces a bias towards the longest fetch direction. Again however neither Seymour's nor Donelan's methods were derived from reservoir data.

6. The only wave measurements in reservoirs reported in the literature since more modern wave prediction formulae became available were at Megget Reservoir in Scotland. Compared with the JONSWAP formulae, the results could not be fully explained using either the straight-line fetch, or Seymour's method. Using the straight-line fetch, predicted wave heights were greater than measured for winds blowing along the reservoir, but smaller than measured for winds blowing across. With Seymour's method wave heights were smaller than measured for all conditions. Comparisons were not made with the original SMB-effective fetch method, or with Donelan's method.

7 RECOMMENDATIONS

1. In order to remedy the great shortage of data, especially under UK conditions, further measurements of winds and waves should be carried out in reservoirs of different length/width ratios.

2. All existing published data on wind and waves in reservoirs, together with the additional data acquired above, should be re-analysed in the light of recently suggested methods of wave prediction.

3. If necessary, new ways should be derived for adopting modern wave prediction formulae (eg JONSWAP) for use in wave prediction in reservoirs.

8 REFERENCES

1. US Army Corps of Engineers, 1962. Waves in inland reservoirs. Tech Memo No 132, Beach Erosion Board.

2. Hydraulics Research Limited, 1986. Wind and wave measurements at Megget Reservoir. Report No EX 1477, HR Ltd, Wallingford.

3. Brebner, A & Le Mehauté, B, 1961. Wind and waves at Cobourg, Lake Ontario. Report 16, Civ Eng Dept Queens Univ, Ontario, Canada.

4. Liu, P C, 1976. Applications of empirical fetch - limited spectral formulas to Great Lakes waves. Proc 15th Coastal Eng Conf, Honolulu, Hawaii.

5. Schwab, D J et al, 1980. Wind and wave measurements taken from a tower in Lake Michigan. Journ Great Lakes Res, Vol 6, No 1.

6. Liu, P C, 1980. A measurement of slope, curvature and directional spectra of wind waves in Lake Michigan, Proc 17th Coastal Eng Conf, Sydney, Australia.

7. Resio, D T & Vincent, C L, 1977. A numerical hindcast model for wave spectra on water bodies with irregular shoreline geometry. Misc paper H77-9, US Army Waterway Expt Station, Vicksburg, August.

8. Marine Environmental Data Service, 1977. A summary of available wave data products, Fisheries and Marine Service, Environment Canada, Ottawa.

9. Ploeg, J, 1971. Wave climate study, Great Lakes and Gulf of St Lawrence, Report WH107A, Nat. Res. Council of Canada, Ottawa.

10. Brusching, J & Schneiter, L, 1978. Caracteristiques des vagues dan les lacs profound. Publication No 172, Ecole Polytechnique Federale Lausanne, Switzerland.

11. Stevenson, T, 1853. Observations on the relation between the height of waves and their distance from the windward shore. Edin New Phil Journ, Vol 54, p 378.

12. Sverdrup, H U & Munk, W H, 1947. Wind, sea and swell: theory of relations for forecasting. Pubn No 601, US Navy Hydrographic Office, Washington.

13. Bretschneider, C L, 1952. Revised wave forecasting relationships. Proc 2nd Conf on Coastal Engineering, Amer Soc Civ Engrs.

14. US Army Coastal Engineering Research Center, 1973 and 1978 editions. Shore Protection Manual, US Govt Printing Office, Washington.

15. Hasselmann, K et al, 1973. Measurements of wind wave growth and swell decay during the Joint North Sea Wave Project (JONSWAP). Deutsche Hydrographische Institut, Hamburg.

16. Hasselman, K et al, 1976. A parametric wave prediction model. Journ Phys Oceanography, Vol 6, No 2, March.

17. Bishop, C T, 1983. Comparison of manual wave prediction models. Proc ASCE, Journ Waterway, Port & Coastal Eng, Vol 109, No 1, February.

18. Hydraulics Research Station, 1981. Severn tidal power, hindcasting extreme waves. Report No EX 978, HRS Wallingford, March.

19. Donelan, M A, 1980. Similarity theory applied to the forecasting of wave heights, periods and directions. Proc Canadian Coastal Conf, Nat Res Council, Canada.

20. Darbyshire, M & Draper, L, 1963. Forecasting wind-generated sea waves. Engineering, Vol 195, pp 482-484.

21. Mitsuyasu, H, 1968. On the growth of the spectrum of wind-generated waves (I). Reports of Res Inst of App Mech, Kyushu Univ, Fukuoka, Japan, Vol 16, No 55.

22. Lin, J T, 1986. Empirical prediction of energy spectra for wind-generated gravity waves at limited fetches. Proc 20th Coastal Eng Conf, Taiwan.

23. Barnett, T P, 1968. On the generation, dissipation and prediction of ocean wind waves. Journ Geophys Res, Vol 73, No 2, January.

24. Golding, B, 1983. A wave prediction system for real time sea state forecasting. Quart Journ Roy Met Soc, Vol 109, pp 393-416.

25. Ewing, J A, Weare, T J & Worthington, B A, 1979. A hindcast study of extreme conditions in the North Sea, Journ Geophys Res, Vol 84, pp 5739-5747.

26. US Army Corps of Engineers, 1955. Waves and wind tides in shallow lakes and reservoirs - Lake

Okeechobee. Corps of Engineers, Jacksonville District, June.

27. Saville, T, 1954. The effect of fetch width on wave generation. Tech Memo No 70, US Army Corps of Engineers, Beach Erosion Board, December.

28. Saville, T et al, 1962. Freeboard allowance for waves in inland reservoirs. Proc ASCE, Vol 18, No WW2, May.

29. Institution of Civil Engineers, 1978. Floods and reservoir safety: an engineering guide. ICE, London.

30. Taylor, K V, 1973. Slope protection on earth and rockfill dams. Proc 11th Congress on Large Dams, Madrid, Spain.

31. Pierson, W J, Newman, G & James, R W, 1955. Practical methods for observing and forecasting ocean waves by means of wave spectra and statistics. Pub No 603, US Navy Hydrographic Office, Washington.

32. Longuet-Higgins, M S, Cartwright, D E & Smith, N D, 1963. Observations of the directional spectrum of sea waves using the motions of a floating buoy. In Ocean Waves Spectra, Prentice Hall, New Jersey, USA.

33. Mitsuyasu, H et al, 1975. Observations of the directional spectrum of ocean waves using a cloverleaf buoy. Journ Phys Oceanography, Vol 5, pp 750-760.

34. Hawkes, P J, 1985. Hindwave - a wave hindcasting method. Report No IT 288, Hydraulics Research Limited, Wallingford.

35. Hydraulics Research Limited, 1985. Underkeel allowance for deep-draughted vessels in the Dover Strait: phase 1, preliminary study to establish critical parameters. Report No EX 1309, HR, Wallingford, June.

36. Resio, D T & Vincent, C L, 1979. A comparison of various numerical wave prediction techniques. Proc 11th Offshore Tech Conf, Houston, Texas, pp 2471-2481.

37. US Army Coastal Engineering Research Center, 1984 edition. Shore Protection Manual. Waterways Expt Station, Vicksburg, Mississippi.

Table 1

Comparison of Observed Wave Heights (H_3) to Wave Heights Predicted from Effective Fetch (H_2) and Straight-Line Fetch (H_1) Methods

Site	Date	Time	Straight-Line Fetch (miles)	Effective* Fetch (miles)	Wind** Speed (knots)	H_1 (ft)	H_2 (ft)	H_3 (ft)
Strait of Canso	75/01/02	0900	6.5	1.5	28	2.6	1.2	2.6
		1200	6.5	1.5	25	2.4	1.1	2.9
		1500	6.5	1.5	29	3.0	1.4	3.8
		1800	6.5	1.5	34	3.5	1.6	3.5
		2100	6.5	1.5	43	4.4	2.0	3.0
	75/01/03	0000	6.5	1.5	32	3.2	1.5	3.1
		0300	6.5	1.5	34	3.4	1.6	2.4
		0600	6.5	1.5	29	3.1	1.4	3.2
Lake Ontario:								
Toronto	72/04/22	0600	150	66	28	6.8	4.7	7.0
	72/11/14	0300	150	66	34	11.4	7.5	11.2
Main Duck	72/09/30	1200	140	61	24	5.5	3.3	4.9

* Effective fetch estimate from length to width ratio of water body as in Saville.

** Winds are measured by anemometer over land and converted to overwater wind speed
Table reproduced from Ref 36

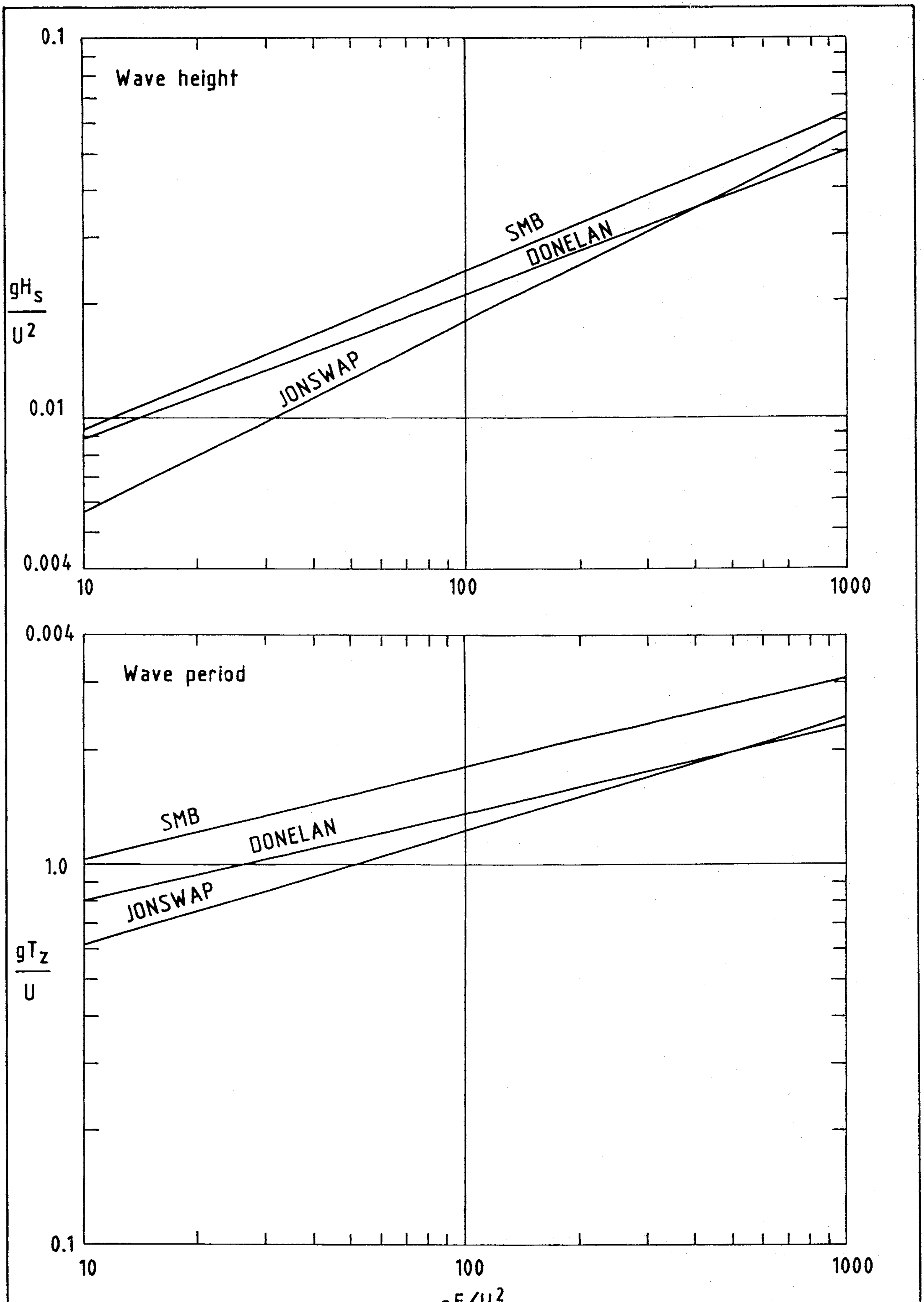
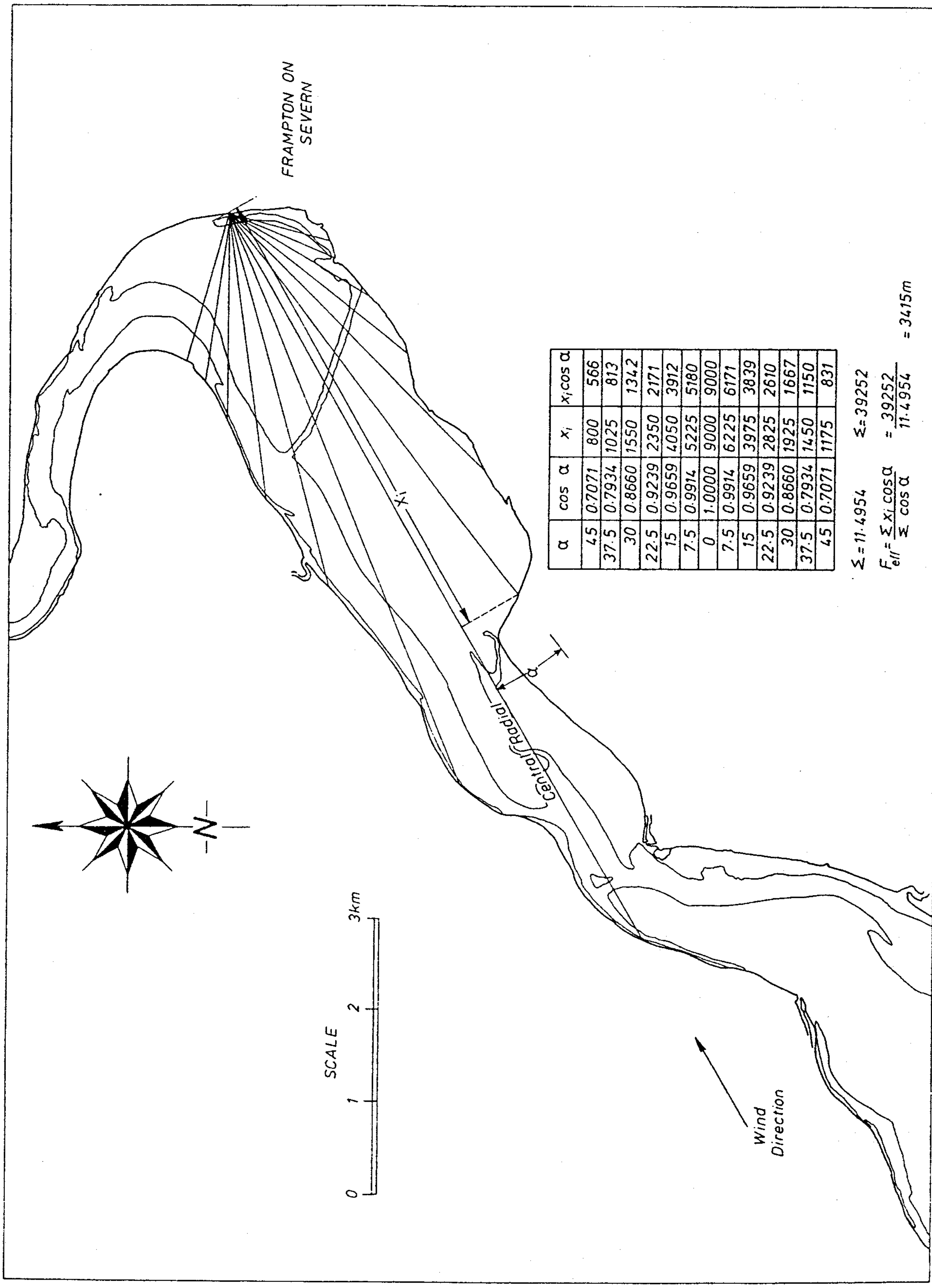


Fig 1 Comparison of wave prediction methods for short fetches



α	cos α	x_i	$x_i \cos \alpha$
45	0.7071	800	566
37.5	0.7934	1025	813
30	0.8660	1550	1342
22.5	0.9239	2350	2171
15	0.9659	4050	3912
7.5	0.9914	5225	5180
0	1.0000	9000	9000
7.5	0.9914	6225	6171
15	0.9659	3975	3839
22.5	0.9239	2825	2610
30	0.8660	1925	1667
37.5	0.7934	1450	1150
45	0.7071	1175	831

$\Sigma = 11.4954$ $\quad \Sigma = 39252$

$$F_{eff} = \frac{\Sigma x_i \cos\alpha}{\Sigma \cos\alpha} = \frac{39252}{11.4954} = 3415m$$

Fig 2 Example calculation of effective fetch lengths