DESK STUDY TO OPTIMISE WAVE INSTRUMENTATION IN LARGE AND SHALLOW LAKES

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Abstract: Since 1997, Rijkswaterstaat carries out a continuous measurement programme in Lake IJssel and Lake Sloten in the Netherlands, considering wind, water levels and waves. At present, the waves are measured with capacitance wires, as these seemed the most suitable instruments for shallow water with limited fetch. However, after some years, capacitance wires turned out to have significant drawbacks, especially in relation to soiling (algae) in summer and ice damage in winter. Hence, Rijkswaterstaat reconsidered its choice for the wave instrumentation to be used. A first step into this re-evaluation was a desk study to identify the most promising types of wave instruments. The results of the desk study are summarised in a multi-criteria analysis, which suggests that ADP's and downward looking instruments would be the most suitable instruments for Lake IJssel and Lake Sloten, and shore-based radar the least suitable.

INTRODUCTION

Two institutes of Rijkswaterstaat are involved in a long-term wave measurement campaign on shallow and rather large lakes. The first institute is the regional directorate Rijkswaterstaat IJsselmeergebied (henceforth *RWS IJG*), the second is the Institute for Integral Water Management and Waste Water Treatment (Rijkswaterstaat/RIZA, henceforth *RWS RIZA*). The wave measurements are carried out at six locations in two Dutch lakes: Lake IJssel and Lake Sloten, see Figure 1.

The key application of the measurement campaign is related to the design conditions for the dikes surrounding Lake IJssel and Lake Marken, and the tuning and validation of the wave models that are used to evaluate those design conditions (see Bottema et al., 2003). Hence, it is of great importance that accurate wave measurements are carried out during severe storms. In addition, wave model tuning requires a great diversity of physical conditions such as fetches, wind speeds and water depths. The present measurement network offers a range of fetches and water depths of 0.8-25 kilometres

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and 1.5-6 metres respectively. The wind speeds measured so far are up to 24 m/s (almost 10 Beaufort). Measurements during still higher wind speeds (up to 34 m/s) are desirable to capture the strongly depth limited wave growth conditions that are expected for such cases (De Waal, 2001). The site specific features mentioned above result in maximum individual wave heights H_{max} up to 3m (spectral significant wave height H_{m0} up to 1.6m), wave peak periods T_p of 1 to 6 seconds, and variations in still water depth (including wind induced water set-up during storms) of the order of 1 metre. All this requires measuring instruments that can measure both relatively small high frequency waves (H_{m0} ~0.1 m; T_p ~1 sec.) and larger waves during storms (H_{max} ~3 m; T_p ~6 sec.). The number of field experiments carried out in these conditions is rather small – Lake George probably is the best known in this respect (Young & Verhagen, 1996).

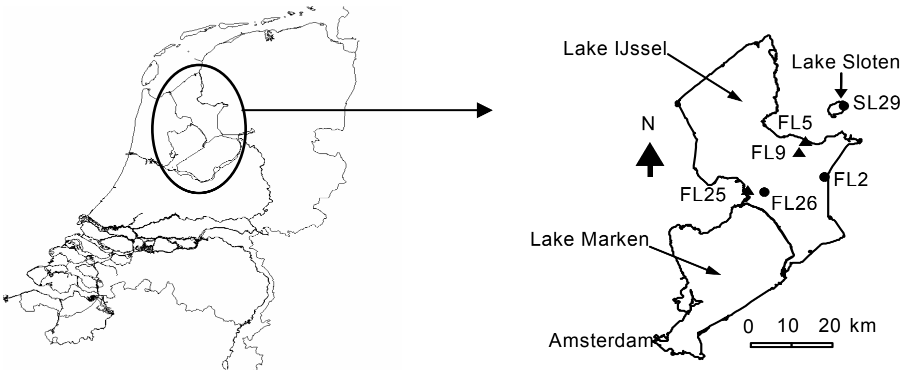

Fig. 1. Overview of Lake IJssel and Lake Sloten and its measurement locations. Triangles: wave data only. Circles: wave and wind data

Currently, the wave instrumentation in Lake IJssel and Lake Sloten consists of capacitance probes. Due to soiling and – occasionally – drift, these probes require frequent maintenance. Therefore, and given recent developments in wave instrumentation, RWS RIZA and RWS IJG are considering the possibility of using new wave measurement instruments within their measurement program. A first step to this end was a desk study to evaluate the different types of available wave instruments.

The desk study started with a literature study (e.g. Rademakers, 1993; Krogstad, 1999; Anonymous, 2003, Foristall et al., 2004; Grønlie, 2004, Van Rijn et al., 2000,), supplemented with questionnaires for suppliers as well as interviews with experts and wave instrument users. All this information is condensed into a multi-criteria analysis from which a ranking and selection of potentially suitable measurement principles and wave instruments is made. The first section of this article deals with the presently used equipment and the problems that are faced. Next the available measurement principles will be shortly discussed. Finally, the results of the present study will be presented using a multi-criteria analysis. As RWS IJG and RWS RIZA do not intend to develop their own instruments, only commercially available instruments will be considered.

PRESENT SITUATION

Since 2001, capacitance probes are used at all the measurement locations in Lake IJssel and Lake Sloten. Its measuring principle is based on the electrical capacitance between a teflon coated wire and a metallic reference tube, which directly depends on the instantaneous water level. The capacitance probe is, after calibration, highly suitable for continuous level measurements and limit detection in liquids, but its response is quick enough ($O(10^{-3}$ s)) to measure waves in both laboratory and field conditions. At all the wave measurement locations except FL25 the sample frequency is 4 Hz. The fetch at FL25 is smaller than 1 kilometre resulting in very short waves and therefore the sample frequency at this location is 8 Hz.

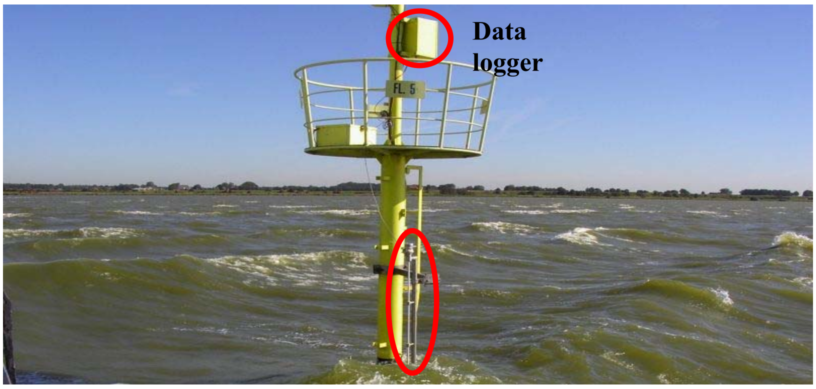

Fig.2. Measurement pole with capacitance probe.
By courtesy of RWS IJG

The capacitance probe is fixed at a measuring pole, see Figure 2. The data from the capacitance probe (and of other instruments, which are situated at the pole, like the wind sensors) are initially stored by a data logger, from which they are transferred to a shore station by telemetry on a daily basis. This allows for frequent quality controls and a quick data availability for hindcasts etc. Telemetry is also used for on-line verification of the instruments performance.

The problems related to the presently used capacitance probe, can be separated in two parts:

- <u>Failure of the instrument</u> related to damage caused by ice, lightning, driftwood or vandalism, or to spontaneous electronic failures.
- <u>Unreliability of the wave measurement data</u> caused by soiling (algae), ice accretion, non-linearities in the probes' behaviour and – occasionally – drift.

The capacitance probes turned out to be sensitive to soiling and therefore require a lot of maintenance. This maintenance is crucial because RWS RIZA and RWS IJG want measurements on a daily basis, not just some interesting but rare events like severe storms. Currently the probes are cleaned at least ten times a year, together with a field test to monitor and quantify the effects of soiling and instrument drift. Figure 3 presents the results of such a field test before and after cleaning.

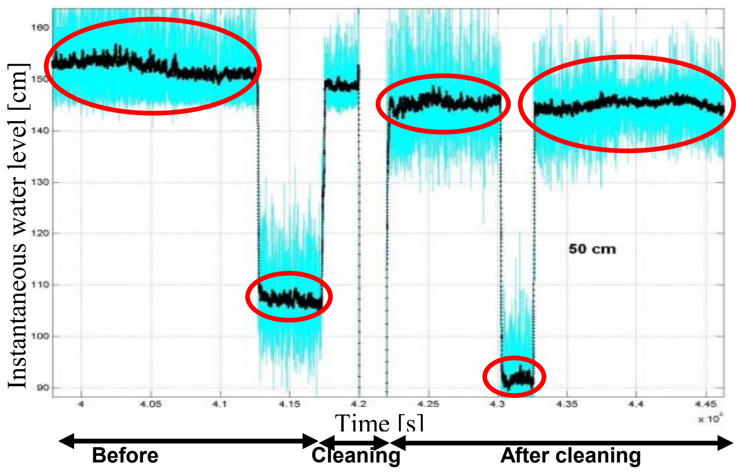

Fig .3. Field test showing effect of cleaning of the capacitance probe

During the test, the probe is displaced upwards by 50 cm, both before and after cleaning. The measured water level difference before cleaning is 43 cm; after cleaning it is 53 cm. The differences before and after cleaning (both in the water level and wave signal) clearly demonstrate the effect of soiling and the necessity of cleaning. In addition, the present results suggest the presence of some drift (6%) of the capacitance probe.

WAVE MONITORING TECHNIQUES

The following measurement techniques are considered in this study:

Step gauge measurements: The step gauge consists of a pole with a number of equidistant electrodes. Using electronic scanning technique the lowest dry electrode is detected. The sensor below is, by definition, the actual water level. The main advantages are the absence of drift, the low power consumption (internal batteries work for 10 years) and the suitability to measure high frequency waves. The main disadvantages are the non-negligible spacing of the individual electrodes (typically 5 cm, but also 2 cm for some newer instrument types), the sensitivity to marine growth, the risk of ice damage and ice, and – especially for some older types, the probability of spontaneously occurring problems with electronics. In this study the step gauge with 2cm resolution is considered only.

Capacitance probe measurements: The capacitance probe is presently used at the measurement locations in Lake IJssel and Lake Sloten. A description of this instrument is given in the previous section.

Buoy measurements, are based on the movement of the buoy using accelerometers and tilt sensors. Some systems use the GPS measurements phase measurements to deduce wave parameters. The advantages of wave buoys are linked to the fact that they follow the wave surface, are not affected by large amounts of white capping or spray (non GPS buoy), are accurate, are used at many locations and are simple to install as they do not require any special measuring poles or platforms.
The disadvantages are:

- A buoy's heave is not sensitive to wavelengths less than the buoy's diameter so that high frequency waves can not be measured, at least not reliably
- Buoys with an accelerometer are insensitive for small accelerations (long waves)
- GPS buoys lose contact with the GPS satellites when spray is washed over their GPS-antenna
- Buoys have to be removed during periods with ice.

ADP: Acoustic Doppler Profilers (ADP) have to be mounted on the bottom. The ADP's have 3 or 4 slanted beams to measure current profiles. This orbital wave motion can be used to compute wave heights, wave directions and near-surface velocities. Additional methods to compute the wave heights and wave periods from an ADP are:

- using the signal of a pressure sensor included in most ADP's
- using the surface distance from each of the slanted beams mentioned above
- using a special Acoustic Surface Track (AST) facility

This Acoustic Surface Track (AST) method uses a short acoustic pulse to detect the surface more accurately than the "current beams". In addition, its "footprint" on the surface is relatively small. The advantages of ADP are that high frequency waves can be measured (at least if AST is used), that the availability of different analysis techniques allows for internal verification of wave measurement quality, that it provides an additional current measurement, and that it is not sensitive for marine growth or weather conditions. The ADP disadvantages are related to a relatively complex installation procedure and the fact that an underwater cable connection between pole and instrument is required.

Downward looking range measurement technique: This measuring technique measures instantaneous water levels by measuring the time difference between transmitting and receiving a signal. This interval is proportional to the distance to the surface. This technique avoids direct contact with the water surface. When mounted in an array, wave directions can be measured as well. For an acoustic instrument, the speed of sound is a few orders higher in magnitude than the maximum vertical velocity of the water surface (or wave). Therefore the interference of the vertical "wave" velocity on the measured distance between the instrument and the water surface is expected to be small. The same applies for the radar and radio based measurement systems. The advantages are; simple installation and maintenance, no re-calibration required (acoustic instruments generally correct for temperature related sound speed fluctuations), the possibility of accurate and high frequency sampling. Disadvantages are; radar, radio and acoustic beams have a relative large opening angle (5°) so that for short waves, the radar beam tends to be biased towards the concavely shaped part of the wave (the through). Also, reflected acoustics signal can be influenced by storm conditions, whereas laser reflection can be influenced by water vapour (spray or fog).

Pressure measurement technique: Measured pressures at a given level are converted into a wave signal using the linear wave theory. For a good signal-to-noise ratio, and given the fact that wave-induced pressure fluctuations decrease exponentially with depth, a pressure gauge must be located within a quarter of a wavelength of the surface. Advantages of the pressure gauge are the low price, the fairly easy installation, and the relative insensitivity to marine growth. An important disadvantage is the fact that the optimum sensor height strongly depends on the wave conditions and on the mean water level as it should be below the wave troughs, but close to the mean water level. Both are not known beforehand, so that in practice, a fairly large vertical array of pressure sensors is needed to measure high frequency waves.

Point current and pressure measurement technique: This 'PUV-technique' is a combination of pressure measurement for wave heights and point current measurements for deriving orbital velocities and wave directions. The system is fairly cheap but its disadvantage is that both the pressure and orbital signal strength quickly decrease with depth, which yields similar limitations as in the case of pressure sensors only (see above).

Remote sensing (wave mapping techniques). Wave related parameters can be deduced from the reflected signal from the sea surface received by ordinary navigation radar ('clutter'). Wave length, wave direction and wave period can be deduced applying spatial Fourier techniques. Wave heights are based on the signal strength and on a location-dependent calibration using a conventional type of wave sensor. The system is more suitable for wind sea than for swell as the return signal depends on the presence of ripples on the water surface. The advantages are that the equipment can remain onshore, and that it provides spatial wave and current information. The disadvantages are the inaccuracy of the wave heights, especially during conditions with ''light' weather and low waves.

Two options that could be considered as wave measurement equipment but that are not commercially available and not used in the instrument selection are:

Zwarts pole measurements; The Zwarts pole, (Verhagen 1999), acts as the equivalent of a coax cable with the pole consisting of two concentric tubes. Holes in the outer tube allowed the water to flow freely into the gap between the tubes thus maintaining the same water elevation within the pole as outside. The air-water interface provides a discontinuity in the dielectric properties of the "cable" and causes a "reflection" of an electric wave. The period of this wave is directly proportional to the length of the dry column between the top of the pole and the air-water interface. The advantages are a stable calibration, a high accuracy, a high sample frequency and the low cost of the instrument. The disadvantages are the sensitivity to marine growth (which tends to block the holes in the outer tube) and the fact that the mean offset is temperature sensitive.

Downward looking Laser technique: The advantage in comparison to the other downward looking range measurement techniques is the smaller footprint due to the narrow laser beam. The main disadvantage is that water vapour, rain and spray may influence the measurement.

INSTRUMENT SELECTION

Wave measurement instruments and their suitability for the measurements at the Lakes IJssel and Sloten were analysed by applying a multi-criteria analysis. A matrix was set up that contains columns with the different criteria and rows with the different selected instruments. This matrix was populated with assessment scores that quantify the suitability of the different instruments with respect to the chosen set of criteria. First the choice and the weighting of the criteria are briefly discussed.

The objective of these specific wave measurements is to obtain reliable accurate and year-round measurements in a wide range of wind and fetch conditions (10-34 metres per second and 0.8-25 kilometres respectively). The resulting wave height and wave periods ranges are $H_{m0} = 0.1 - 1.6$ metres and T_p is $1 - 6$ seconds. In our case, the lower bounds need special attention because they are significantly lower than the conventional measurement range at sea.

In the present set of criteria (Table 1), the ability to measure high frequencies has been given a large weight in order to make sure that the instrument to be selected is suitable to measure the initial stages of wave growth. The criteria 'resolution', 'accuracy small waves' and 'sample frequency' are also relevant for initial wave growth. Their weight however, is fairly low. This is to account for the partial overlap between some criteria. Besides this, an important aim of this project is to measure waves during severe storms, in conditions with intense wave breaking and spray. Little is known about wave instrument performance in those conditions so the weight of the related criterion is relatively low. For non-breaking large waves, the criterion for 'wave frequency range – low' and especially the criterion 'accuracy high waves' supplement the criterion for breaking waves. In all cases, the 'accuracy' criteria not only comprise the technical limitations of the instruments, but also the expected (in)accuracies due to for example marine growth, rain, fog and spray.

The remaining criteria relate to general accuracy and reliability, the practical implementation of the instrument, and extra options. The latter mainly consists of directional wave information. The practical implementation criteria are related to the interface with the present equipment, to power consumption, data transfer, logger capacity, and – last but not least – the maintenance cost. The general accuracy and reliability criteria are related to the sensitivity to marine growth and weather conditions, and to the general robustness of the instrument. The former is at present an important source of measurement errors, the latter is a requirement for a continuous measurement programme with a minimum of missing data. Besides this, criteria are defined for the probability of instrument drift and for the type of measurement technique (direct without assumptions, or indirect with assumptions, like linear wave theory).

The weighting factors of the criteria are given in Table 1, together with the range limits which define the minimum and maximum score (0 or 10) respectively. It should be noted that the choice for the criteria and the weighting factors are site specific. Table 1 should be read as an example used for the Lake IJssel and Lake Sloten situation.

Table 1. Criteria and Weighting Factor

Criteria	Weighting factor	Minimum score if	Maximum score
Wave frequency range (high)	10	<=0.25 Hz	>=2Hz
Wave frequency range (low)	3	>=0.1 Hz	No low frequency limitations
Resolution	4	>10 cm	<=1mm
Accuracy small waves(< 0.2m) Height inaccuracy (Hmo) Period inaccuracy (Tp)	4	>= 10cm, >1 s	<= 1cm, 0s
Accuracy high waves (> 1 m) Height inaccuracy (Hmo) Period inaccuracy (Tp)	8	>=15cm >1s	< 5cm 0s
Breaking waves, wave asymmetry	5	if breaking occurs it can not be deduced from the data	Accurately measuring the surface even under breaking waves
Wave direction	3	Non directional	Multi directions at the same frequency
Direct/indirect	4	Indirect	Direct
Sample frequency	3	<0.5 Hz	>=8Hz
Power consumption	8	>100W	<= 1W
Daily data production/Transfer data	5	Mapping instrument no radio connection feasible	1 parameter logging no problems with data transfer
Internal memory, logger capacity	2	No internal storage	Stand alone operation possible
Calibration/drift, need for field checking	3	Unstable calibration, and frequent field check needed	No calibration or drift.
Maintenance cost	10	Monthly visits	No visits / maintenance not required
Interface present equipment	7	Not possible to fit	Easy to fit in existing pole configuration
Soiling / marine growth	7	Strong effects expected during the summer half year	No effect expected
Robustness	7	Unreliable and above the water	Reliable proven technology and not vulnerable for vandalism
storm/ice/fog/spray	7	Sensitive for storm ice and fog	Not sensitive for storm ice and fog

The resulting multi-criteria analysis is presented in Table 2. The score of an instrument on each criterion is based on the instrument specifications, questionnaires, literature, user experiences, engineering judgement and the boundaries as attributed in Table 1. The maximum score an instrument can obtain in this multi-criterion analysis is 100, by scoring a ten on each criterion. Note that the scores result from interpolation between the range limits of Table 1. As a first example, the resolved wave frequency range is about 1.5 Hz for downward looking radio, and about 1 Hz for a buoy, resulting in a score of 7 and 4 respectively. The accuracy of high waves is generally good, except for shore based radar with expected H_{m0}-errors of 10 cm (score 5). The power consumption varies from over 100 W for shore-based radar (score 0) to about 6 W for downward looking radar (score 5) to less than 1 W for ADP’s and some other instruments (score 10). As a final example, the maintenance score is equal to 10 points minus the number of required visits in a year.

Table 2. Multi-criteria analysis wave equipment selection

Type of instrument	Score	Wave frequency range (high)	Wave frequency range (low)	Resolution	Accuracy (small waves)	Accuracy (high waves)	Breaking waves, wave asymmetry	Wave direction	Direct/indirect	Sample frequency	Power consumption	Daily data production/Transfer data	Internal memory, logger capacity	Calibration/drift, need for field checking	Maintenance cost	Interface present equipment	Soiling, marine growth	Reliability/robustness/vandalism	Storm, ice, fog, spray
Weighting factors	**100**	**10**	**3**	**4**	**4**	**8**	**5**	**3**	**4**	**3**	**8**	**5**	**2**	**3**	**10**	**7**	**7**	**7**	**7**
Wave ADP (AST)	**88**	10	10	10	10	10	5	10	10	9	10	3	10	10	9	5	9	9	10
Downward looking radio	**81**	7	10	10	10	10	7	0	10	10	6	10	0	10	9	8	10	5	9
Downward looking Acoustic	**79**	7	10	10	10	10	7	0	10	10	6	10	10	10	7	8	10	5	6
Downward looking Radar	**78**	7	10	7	9	10	7	0	10	10	5	10	0	10	9	8	10	5	9
Step gauge (2cm)	**77**	10	10	7	9	10	7	0	7	10	10	10	0	10	5	10	5	5	7
Pressure gauge (sensor only)	**70**	4	10	10	4[*1]	10	0	0	0	10	10	10	0	8	7	10	6	8	10
Staff gauge/ capacitance probe	**66**	10	10	9	4	10	7	0	7	10	8	10	0	3	1	10	2	5	7
Wave buoy	**66**	4	5	7	8	10	10	0	10	10	6[*2]	8	10	10	5	3	8	5	7
Remote sensing	**39**	2	5	1	0	5	0	6	0	3	0	0	0	8	8	0	10	8	8

1 small long waves can be measured accurately, small short waves cannot be measured due to practical implication
2 radio link between pole and buoy required

When using the above results, it is important to note that the applied set of weighting factors has been determined especially for the present area of interest: Lake IJssel and Lake Sloten. Inevitably, the weighting factors from Table 1 are somewhat subjective, all the more so as they not only reflect the reliability of the instrument but also an range of operational aspects like for example the maintenance cost. On the other hand, the scores are mainly based on technical specifications and are more objective.

CONCLUSIONS AND RECOMMENDATIONS

In the above, a multi-criteria analysis is used to identify which type of instruments potentially are the most suitable for application in two specific sites with short fetch and shallow water in the Netherlands: Lake IJssel and Lake Sloten. The choice of the criteria is such that both frequently occurring situations with moderate wind and low waves and situations with gale-force winds and breaking waves get significant weight.

The main conclusions of this study are:

- The total score of capacitance probe in Table 2 is relatively low in comparison with other wave instruments. This is partly due to the length of the measurement campaign and to the present procedure of extensive quality monitoring of the measurements. By this, several error sources and operational inconveniences were discovered that otherwise would have gone unnoticed. On the other hand, this study shows that it is definitely worthwhile to search for alternatives for the present capacitance probes.
- The bottom mounted ADP (AST) appears to be the most promising instrument type to be used in the specific context of wave measurements in Lake IJssel and Lake Sloten. This mainly due to its Acoustic Surface Track (AST) feature, allowing for a high sampling rate (4 Hz) and – with its narrow 1.8^{o} upward looking beam – its small surface footprint.
- For various reasons, downward looking instruments (radar, radio, acoustic) and step gauges all seem promising as well. The latter is somewhat surprising and reflects some considerable improvements (resolution, electronic stability) in the design of step gauges during the last decade.
- Pressure gauges seem to be less suitable in the present case. This is because its accuracy requirement – placement within a quarter of the wave length below the water surface – is difficult to satisfy in the present situation, where both the wave heights and the water levels are highly variable. In practice, one would require a fairly large vertical array of pressure sensors, but this makes the monitoring technique very complex.
- Wave buoys are the most widely used wave measuring gauges, but they are less favourable for especially the short fetch and/or moderate wind conditions at the Dutch Lakes IJssel and Lake Sloten. The reason is that buoys have difficulties in following high frequency waves, so that especially on Lake Sloten, a significant part of the wave spectrum would be biased or lost.
- The shore-based Wave Radar seems to be the least suitable option for the present case. This is mainly due to the low accuracy of wave height measurements and the incapability of short waves.

The recommendations for future work are as follows:

- Carry out a wave flume test so that the (dis)advantages of both the present instrumentation and the recommended equipment can be investigated under controlled conditions. The preparations for this have almost been finished and the wave flume test will soon be carried out.
- Carry out a field intercomparison test to investigate those instrument properties that can not be investigated easily in a wave flume (e.g. effect of soiling, drift) and optimise the criteria and scoring factors using these field results.
- It might be useful to use tailor-made equipment, rather than commercially available wave probes. For example, the tailor-made Zwarts' poles were quite successfully used in Lake George. Downward looking laser is another type of tailor-made instrument that may be worth considering.

- The present measurement network is designed to measure in a variety of fetch and depth conditions. It may be useful to redesign or extend the network in order to be able to focus on some specific wave processes (such as wave growth, wave development near foreshores, etc.).

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