Wind-driven waves in a shallow estuarine lake with muddy substrates: St Lucia, South Africa

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ABSTRACT

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Wind-waves in shallow lakes or estuaries with muddy substrates can drive sediment re-suspension and cause high turbidity levels that can negatively impact the productivity of photosynthetic organisms. This investigation evaluates the efficacy of a simple semi-empirical model (Young and Verhagen, 1996 : Coastal Engineering, 29, 47–78) for predicting the wave characteristics in these systems in order to include their effects in ecosystem models. The southern basin of the St Lucia estuarine lake in South Africa was used for a case study. Average depths are about 1 m with fetches up to approximately 10 km. Substrate materials vary from sandy to muddy with deeper locations predominantly the latter. An array of pressure sensing wave poles was deployed to measure significant wave heights and periods to compare with model predictions. The influence of the wind speed, fetch, fetch-averaged depth, and substrate composition were evaluated. Most of the observed waves were fetch limited during the conditions that prevailed during the two field trips. The results indicate that the model adequately captures the high energy wave events for persistent wind speeds and directions, but that there is considerable variability in its performance generally. Some of this variability can be attributed to difficulties in estimating appropriate fetch and depth parameters for variable winds and in the context of a lake with compound shape and variable bathymetry. There was no clear evidence of significant wave attenuation due to the muddy substrates.

ADDITIONAL INDEX WORDS: *wind-driven waves, fetch and depth limitations, muddy substrates, Lake St Lucia.*

INTRODUCTION

The biological functioning of shallow lakes or estuaries with muddy substrates can be significantly influenced by wind waves that drive sediment resuspension and associated high turbidities. For example high turbidity affects primary production processes (Cloern , 1987) while zooplankton may also be adversely affected with reduced feeding rates and increased mortality rates (Carrasco et al., 2013).

To apply simple quantitative biological models to explore these issues requires a means to estimate wave energy directly from easily accessible parameters such as wind speeds, fetches and depths. For shallow lakes and estuaries the growth of wind-waves are often affected by fetch and/or depth limited conditions. The prediction of wave characteristics under these conditions was addressed by Young and Verhagen (1996) who proposed a semi-empirical model based on an extensive field study at Lake George in Australia. However, Young and Verhagen (1996) did not consider the effects of muddy substrates on the growth of wind-waves, since their case study site had sandy substrates. It is well know that waves can be attenuated by the dissipative effects of induced shear stresses within the fluid-mud layers of shallow systems (e.g. Mehta and Jiang, 1990; Kranenburg et al., 2011; Elgar and Raubenheimer, 2008; Sheremet et al., 2003; Winterwerp et al., 2007; Torres-Freyermouth et al., 2010). Apparently these effects have not yet been incorporated into simplified semi-empirical models.

Lake St Lucia is a large estuarine lake system located in KwaZulu-Natal, South Africa (Fig. 1). It is part of the iSimangaliso Wetland Park, which was declared a UNESCO World Heritage site in 1999. The area is also a Ramsar wetland of international importance due to its significant role as a biodiversity hotspot (Perissinotto et al., 2013). The shallow lake conditions and muddy substrates make the estuarine habitat particularly susceptible to the effects of high turbidity due to the stirring effects of wind-driven waves. The system is increasingly threatened by increased catchment sediment yields due to land-use changes and land degradation. Similar challenges are faced by many estuarine and lake systems worldwide due to intensive developments of their catchments (e.g. Wolanski, 2007). There is a need to develop models that can be used to understand and evaluate the impacts of these changes, and to manage and mitigate them in the future.

This study aims to contribute towards developing and testing simplified models to investigate the above-mentioned issues. In particular a key question addressed was whether substrate characteristics need to be explicitly included in the model?

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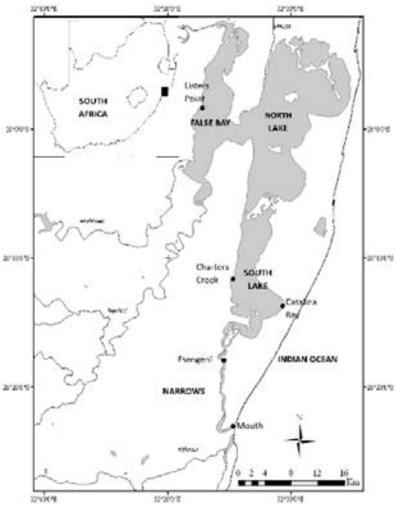
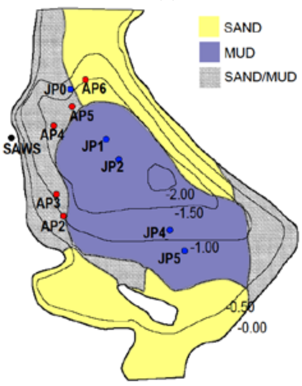


(a)



(b)

Figure 1. a) Map of St Lucia estuarine lake system on the east coast of South Africa. (b) Detailed map of the southern basin showing bathymetry, substrate distribution, location of wave measuring stations (APx – stations used in April 2013, JPx – stations used in July 2013, for details see Field Measurements), and location of the weather station (SAWS).

METHODS

Study Site

The St Lucia lake system comprises three interconnected basins – False Bay, North Lake and South Lake – that are linked to the sea via a 22 km long sinuous channel called the Narrows (Figure 1(a)). The inlet to the system from the sea can close for prolonged time periods due to near-shore littoral transport processes (Lawrie and Stretch, 2011a, b). Tidal effects are present for about 14 km up the Narrows when the inlet is open - the lake itself is not tidal.

The lake has a surface area of approximately 350 km^2 and an average depth of 1.0 m when the inlet is open and when water levels are near the estuary mean water level (EMWL), which is a datum that is 0.25m above sea level. When the inlet is closed the water level can differ strongly from EMWL depending on rainfall, river inflow and evaporation. We measured waves in the lower part of Lake St Lucia South Lake in April and July 2013 (Figure 1(b)). For the period of this investigation, the water level was ±0.3 m above EMWL. The lower South Lake has a surface area of approximately 30 km^2, extending approximately 6 km from north to south and 5 km east to west. The sediment of lower South Lake shows spatial variability with sandy areas around the edges and muddy area around the deeper center of the lake (Figure 1(b)).

The wind climate is characterised by prevailing north-easterly and south-westerly winds, with north-east winds being dominant in the summer (Perissinotto et al., 2013). These wind directions were characteristic of the strongest winds observed during the course of this investigation. There is a strong diurnal cycle in the wind. Typical wind speeds during the day are 4ms^{-1} or higher, whereas during the night wind speeds tend to be below 4ms^{-1}. The lighter night-time winds tend to come from the west and are thermally driven land breezes.

Field Measurements

We measured waves at ten different locations over a total period of 15 days in April and July 2013 using pressure transducers (Figure 1(b)). Each pressure transducer and its digital controller and logger was mounted inside a perforated tube to form a “wave pole” (Figure 2). In April the wave poles were arranged approximately parallel to the main wind directions (north-easterly and south westerly) to provide data for wave growth along a varying fetch. The poles were placed at depths between 1 and 1.7m at positions with a mix of mud/sand sediments. The poles deployed in July were arranged in a way that kept the fetch fairly constant for the north-easterly wind direction and the depth at the poles ranged from 0.9 to 2.1m with mainly muddy sediment. The water depth at each wave pole was measured using a survey staff. This allowed us to gauge the accuracy of average water depth changes derived from the pressure transducers’ measurements.

Each pressure transducer was contained inside an air-tight, flexible plastic bag and attached to the end of an impermeable plastic manometer tube. The flexible plastic bag automatically adjusts for variations in atmospheric pressure so that the transducer measures differential pressures due to water level changes alone. The transducers were statically calibrated to establish the relationship between their voltage output and depth below the water surface. Measured pressures were logged to an SD memory card at a burst sampling frequency of 4Hz for durations of 5 minutes (1200 readings) every 15 minutes. The plastic manometer tube was weighted and the depth at which it was initially set was typically 0.5 m. The pressure transducer (MPX5010) had a range of 10 kPa (1 m of water) and an accuracy of about 0.5%. The output voltage of the sensor (0–5 V) was digitised with 10 bit resolution using an Arduino microcontroller. The electronics and battery power supply were packaged together with the pressure sensor in the waterproof bag installed at the top of the pole.

Data Analysis

The recorded pressure data were transformed into significant wave heights (Hs) for each five minute sampling period. In this procedure, the pressure time series were decomposed into Fourier modes, each with a specific frequency. These modes were individually corrected for attenuation of the pressure with depth according to linear wave theory. An inverse Fourier transform was then used to recreate the actual observed wave heights. The amplitude a of a surface wave of wavelength L and period T can be related to the pressure p measured at depth z in water of total depth h by (e.g. Holthuijsen, 2007)

$$\frac{p}{\rho g} = a\sin(kx - \omega t)\frac{\cosh[k(h+z)]}{\cosh(kh)} \quad (1)$$

with $k = 2\pi/L$, $\omega = 2\pi/T$, $L = (gT^2/2\pi)\tanh(kh)$, and where ρ is the water density and g is acceleration due to gravity. The significant wave height H_s can be computed as the average of the highest one third of the wave heights recorded during each five minute sampling period. Other parameters derived from the recorded pressure fluctuations were the peak period and the average water depth.

Significant wave heights smaller than 50mm were excluded from further analysis because the attenuation of the pressure signal from these small waves were not accurately resolved by the pressure transducer.

Wave Model

We used a simple semi-empirical model (Young and Verhagen, 1996, YandV henceforth) to predict significant wave heights at the individual wave pole positions based on fetch, average depth over the fetch and wind speed. We then compared the predicted wave heights with the measured wave heights to test the efficacy of the YandV model for Lake St Lucia. Our study site differs from the system used for calibration by YandV by having a smaller surface area and having muddy sediment instead of sandy sediment. The fetch was estimated for each of the pole positions under the different wind directions using Google Earth™ imagery. The average depth over the fetch was estimated using a bathymetry contour map (refer to Hutchison (1974), Figure 1(b)).

Wind speeds and directions were provided by the South African Weather Service, which collects wind data from a weather station located near the western bank of the lake (SAWS in Figure 1(b)) with the anemometer installed at a height of approximately 10 m.

The YandV model is formulated in terms of non-dimensional quantities. The relevant dimensionless depth and fetch from the field measurements were calculated for each five minute data set at each wave pole position. These dimensionless values together with the corrected wind speeds were used as inputs to the model. The dimensionless forms of the wave energy (E), depth (d) and fetch (x) used for the model are defined by

$$\varepsilon = \frac{g^2.E}{U^4}, \quad \delta = \frac{d.g}{U^2}, \quad \chi = \frac{x.g}{U^2}. \tag{2}$$

YandV suggested a semi-empirical relationship between ε, δ and χ given by the following equation

$$\varepsilon = C_0 \left[tanh(C_1 \delta^{0.75})\, tanh\left(\frac{C_2 X^{0.57}}{\tanh(C_1 \delta^{0.75})} \right) \right]^{1.74} \tag{3}$$

Table 1. Asymptotic limits of Equation 10 following YoungandVerhagen (1996).

Conditions	Equation 10
Depth limited: $\chi \rightarrow \infty$	$\varepsilon = 1.06 \times 10^{-3} \delta^{1.3}$
Fetch limited: $\delta \rightarrow \infty$	$\varepsilon = 1.6 \times 10^{-7} \chi$
$\chi \rightarrow \infty, \delta \rightarrow \infty$	$\varepsilon = 3.64 \times 10^{-3}$

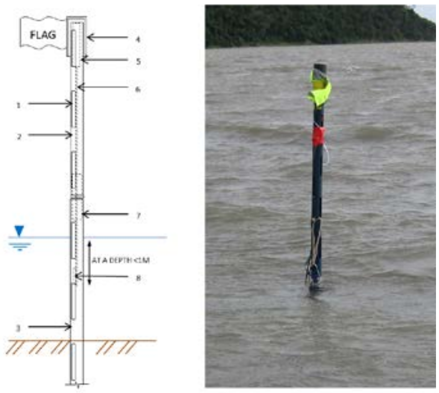


Figure 2. Schematic diagram of the wave pole components. The labelled items are: (1) plastic pole slots; (2) plastic pole; (3) metal base pole; (4) plastic cap; (5) differential pressure transducer device and data logger; (6) plastic manometer tube; (7) connection; (8) weight. A multiparameter sonde containing various sensors (temperature, salinity, pH, DO, turbidity) was attached to selected wave poles during their deployment.

with constants $C_0 = 3.64 \times 10^{-3}$, $C_1 = 0.493$, and $C_2 = 3.13 \times 10^{-3}$. Equation 10 predicts the wave energy in the limits of both depth and fetch limited conditions and is consistent with results deduced from previous experimental data ().

Due to different characteristics of the boundary layer over land compared to water (Walmsley et al., 1989) wind speeds were corrected according to their direction and fetch over the water to the location of the individual wave poles. Winds measured at the weather station were corrected by a factor ΔR as described by YandV, whence

$$U_x = U_i + \Delta R\, U_i \tag{4}$$

where U_i is the (measured) reference wind speed prior to crossing the shoreline, U_x is the wind speed at a fetch x downwind from the shoreline crossing point, and ΔR is a correction given by

$$\Delta R = 0 \qquad , for\ z \geq \delta_i \tag{5}$$

$$\Delta R = \frac{ln(z/z_0).ln(\delta_i/z_{0w})}{ln(z/z_{0w}).ln(\delta_i/z_0)} - 1 \qquad , for\ z < \delta_i \tag{6}$$

where z is the reference height of the velocity, z_0 is the roughness length over water, z'_0 is the upwind terrestrial roughness length, and δ_i is the internal boundary layer height over water given by

$$\delta_i = 0.75 z_0 \left(\frac{x}{z_0}\right)^{4/5} \tag{7}$$

The roughness length over the water z_0 is assumed to vary with wind speed as given by

$$z_0 = A \frac{u_*^2}{g} \quad (8)$$

$$u_*^2 = C_{10} U_{10}^2 \quad (9)$$

$$C_{10} = (0.8 + 0.065 U_{10}) \times 10^{-3} \quad (10)$$

where A=0.0185, u_* is the friction velocity, U_{10} is the wind speed at a reference height of 10 m, and C_{10} is a drag coefficient.

After experimenting with various terrestrial roughness lengths appropriate for the case study site (≈ 0:5 m) it was found that the wind correction factor was generally close to unity i.e. $\Delta R \approx 1$. For simplicity this value was subsequently adopted as a uniform wind correction for all locations and wind directions.

Once the measured wind-speeds have been corrected for roughness changes, and given the measured fetch and depth parameters at each wave pole and for each wind direction, the significant wave height may be predicted from Equation 10 using the definition $H_s = 4\sqrt{E}$. These predicted wave heights can then be compared with the measured wave heights from the wave poles.

Results

Measured wave and time series

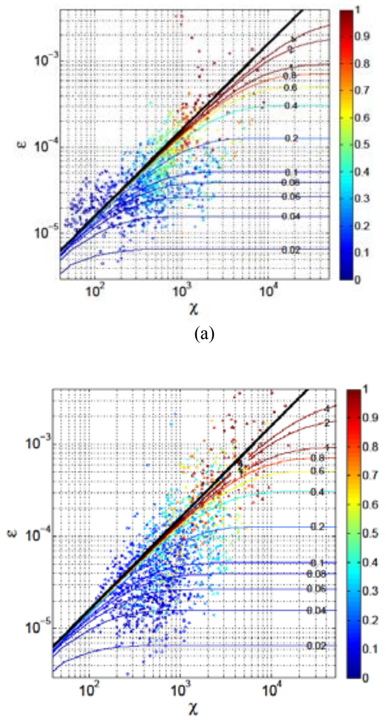
The range of depths, fetches, and wave heights sampled during the field experiments at each of the wave pole locations (Figure 1(b)) are summarised in Table 2. Maximum fetches were about 10 km and mostly associated with winds from northerly directions. Fetch-averaged depths during the July field trip were generally larger than for the April field trip due to the re-positioning of the wave poles.

Figure 5 shows time histories of water levels, wave heights and wind vectors measured during the two field trips in April and July 2013. There are strong diurnal variations in the wind speed at this location, which are evident in the time series. During the night-time hours wind speeds typically reduce to 4 ms^{-1} or less, and comprise of mainly land breezes from the west. Winds greater than 4 ms^{-1} generally occur during the day (peaking in the afternoons) and are typically from the south-west or north-east (Figure 5). It is these stronger winds that drive the generation of waves in the lake with significant waves heights typically in the range 200 – 400 mm.

It is evident from figure 5 that waves increase rapidly as the wind increases and also dissipate rapidly once wind speeds reduce again. The increases in wave energy are accompanied by re-suspension of fine muddy sediments that make the water column highly turbid.

In addition to the generation of waves the surface wind stress also drives significant water exchanges between the lake basins that are evident as changes in average water levels in figure 5. When the wind blows from southerly directions water is pushed north in the system and water levels fall in the South Lake, and vice versa for winds from northerly directions. These wind setup processes and their time scales have been described in detail by Schoen et al. (2014); Hutchison and Midgely (1978). Water level changes of up to 400 mm were observed during the field study (Figure 5). During calm periods after high winds the system relaxes towards a state where the water levels across all the basins are equal.

During the April field trip most of the energetic wave events were driven by winds from the south-south westerly direction (Figure 5). The pole arrangement used (Figure 1(b)) means that almost half of the data set experienced similar fetch conditions.



(a)

(d)

Figure 3. Non-dimensional plots of observed wave energy (ε) versus fetch (χ) for various depths (δ, shown colour-coded). Wave energies predicted by the Young and Verhagen (1996) model are shown as lines for comparison with the measurements. (a) April - all data, (b) April - δ < 0.2, (c) April - δ > 0.2, (d) July - all data, (e) July - δ < 0.2, (f) July - δ > 0.2.

During the July field trip the strongest winds were more evenly split between the northerly and the southerly directions. Fetches for the southerly winds were generally slightly larger than those for northerly winds for this pole arrangement.

Comparison with Young and Verhagen model

Scatter plots show general consistency between the measured and modelled wave heights (Figure 4). The model shows some bias towards under prediction of wave heights for small fetches and/or small depths, but its performance improves at intermediate fetch and depth values. However, considerable scatter is evident in the data.

A more detailed comparison between the model and measurements is given in Figure 4 (a) – (b), that show a series of non-dimensional plots of measured wave energy ε as a function of fetch number χ. Values for the non-dimensional depths δ are colour-coded to the data points. Wave energies predicted by the Y and V model for various depth numbers are plotted for comparison with the measurements, and indicate which conditions were fetch or depth limited in terms of wave growth. It is evident that most of the measurements were in fetch-limited or transitional conditions according to the model, although there are also significant occasions that experienced depth-limited wave growth. The trends in the measurements are broadly consistent with the

Table 2: Range of depths at sampling positions, average depths, significant wave heights and fetches observed during field trips. The average depth is the depth at each sampling position averaged over the fetch (which varies with the wind direction).

SAMPLING LOCATIONS (REFER FIG. 1(b))	POLE DEPTH (mm)		FETCH AVG DEPTH (mm)		FETCH (m)		Hs (mm)	
	min	max	min	max	min	max	min	max
April Field Trip								
AP2	1540	1850	760	1680	660	11600	10	310
AP3	1420	1730	810	1650	50	11000	10	350
AP4	1090	1380	930	1630	600	9600	10	330
AP5	890	1170	930	1630	1000	9000	10	310
AP6	710	990	890	890	1200	9300	10	270
July Field Trip								
JP0	820	1070	540	540	700	10200	10	240
JP1	1640	2160	890	890	650	10300	10	370
JP2	1420	2330	950	950	1400	9700	10	380
JP4	1970	2310	570	570	1700	7500	10	410
JP5	1920	2180	350	350	1800	10300	10	350

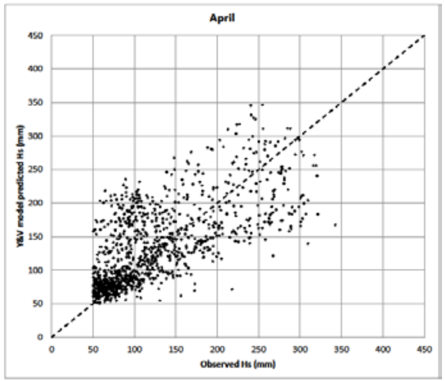
model but again show considerable variability as is evident in the scatter of the data. There are a significant number of measurements that lie outside the predicted bounds i.e. the measured wave energies are lower than predicted by the model.

Given the scatter in the data it is not possible to unambiguously attribute these effects to wave attenuation associated with muddy substrates, but that is one possible explanation. Figure 4 (a) and (b) reveal that the model tends to consistently overestimate the wave energy for small fetch numbers $\chi < 100$ and depth numbers $\delta < 0.1$. These data are from the April field trip and come from the wave poles near the western side of the basin (AP2, AP3 – see Figure 1(b)), and for wind from the south/south-west. Samples of measured and modelled significant wave height time series indicate that the major wind-wave events are generally well captured by the model when the wind comes from specific directions (Figure 5). When the wind speed and/or direction changes the model can produce large prediction errors. This seems to be associated with estimation of the appropriate fetch and depth parameters that are applicable during those periods.

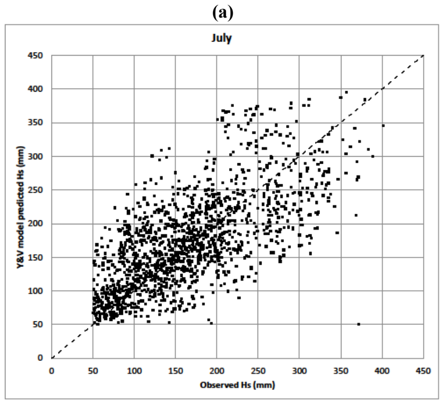
Discussion and Conclusion

In this study we have tested the application of the YandV semi-empirical model for predicting wave heights in a shallow estuarine lake with compound shape and variable bathymetry. A notable difference from previous applications of the model is the substrate's composition at our case study site. St Lucia comprises large areas with soft, unconsolidated muddy substrates, particular in the deeper locations, while previous case studies have focussed mainly on systems with sandy substrates. This difference was a key motivation for the present study, namely to evaluate how muddy substrates affect wind-wave predictions from simple models.

The comparison between modelled and measured significant wave heights showed broad consistency with considerable variability in the results. There were examples of both significant underestimation as well as overestimation of wave energy, but the reason(s) for these errors are difficult to isolate. Some of the model underestimation seems to be associated with short fetch and/or shallow water, which is consistent with findings of previous investigators (e.g. Young, 1997).



(a)



(b)

Figure 4. Wind vector and water level time series from the (a) April field trip, pole AP3; (b) July field trip, poles JP4 and JP5 (concatenated). The pole positions are shown in (Fig 1(b). Wind measurements (uncorrected) are from the weather station shown as location SAWS in Fig 1(b).

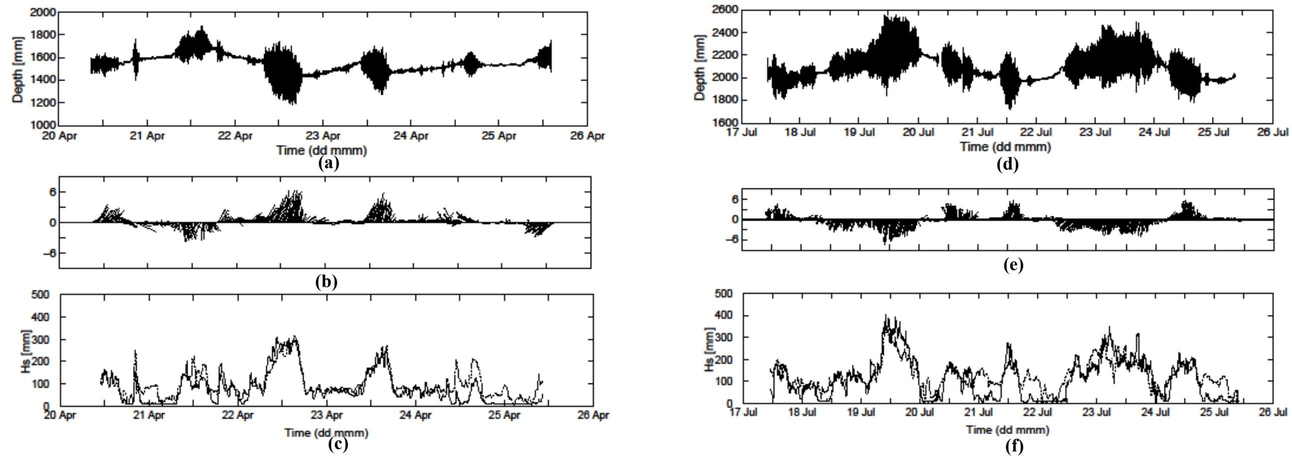


Figure 5: Water level (a), wind vector (b) and time series (c) from the April field trip, pole AP3; (d), (e) and (f) are corresponding data sets from the July field trip, poles JP4 and JP5 (concatenated). The pole positions are shown in (Fig 1(b)). Wind measurements (uncorrected) are from the weather station shown as location SAWS in Fig 1(b). Sample time series show measured (solid lines) and predicted (dashed lines) wave heights for wave poles (c) AP5; (d) JP4 and JP5 (concatenated).

No clear evidence of wave attenuation due to the muddy substrates was evident from the data. These effects, if present, may have been masked by scatter in the results. The compound shape of the lake system means that the estimation of the applicable fetch and depth parameters was difficult to do and is prone to errors that may explain much of the variability in the data and model predictions. For example small changes in wind direction can make large differences in the estimated fetch and associated fetch-averaged depths. Furthermore the method of correcting the wind from a single local terrestrial weather station to account for roughness changes over the water is also difficult to do accurately and can also significantly impact the model predictions.

If simple semi-empirical models such as the Young and Verhagen model are to be used to model wind-wave generation in shallow, muddy systems with complex geometry, our results suggest that considerable care is required to accurately specify insitu wave- generation parameters such as wind speed, direction, fetch, and fetch-averaged water depth. The simultaneous measurement of insitu wind speeds and directions for calibration of the wave-generation model may reduce some of these uncertainties. However, alternative modelling approaches, such as the 2D spectral wave model SWAN (Booij et al., 1999; Winterwerp et al., 2007; Kranenburg et al., 2011), can account for complex lake geometry and bathymetry in a natural way and may therefore be preferable in these cases.

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