Proposed guidelines for preliminary assessments of the physical impacts of wave energy deployments

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***Abstract*— To support development of the wave energy industry in Australia, we present guidance for assessing the influence of arrays of Wave Energy Converters (WECs) on the hydrodynamic attributes of the surrounding ocean, as a means for providing a first level impact assessment for proposed wave energy deployments. These guidelines have been developed as part of the ARENA and CSIRO-funded Australian Wave Energy Atlas Project (AWavEA). A wave energy project cycle typically consists of four stages: Preliminary evaluation; Feasibility study; Project design; and Implementation and operation. The guidelines presented in this paper aim to support preliminary assessments of the suitability of a proposed site to deployment of wave energy converters.**

A series of idealised simulations of WEC array installations using SNL-SWAN was performed to underpin development of the guidelines, under a range of conditions (device types, array sizes and configurations, wave climate conditions, bed slope, distance offshore). Results are generalised via empirical equations to represent the zone of impact (area, cross-shore distance, and longshore width).

These equations provide a basic tool to inform design of more detailed modelling and monitoring assessments of the environment adjacent to proposed wave energy developments.

***Keywords*—Wave Energy; Physical impacts; Environmental assessment**

I. Introduction

One challenge facing the growth of a global wave energy industry is the uncertainty of the consenting processes, particularly in regards to the environmental impact assessment for the development and operation of ocean energy facilities [1,2].

To support development of the wave energy industry in Australia, we present guidance for assessing the influence of arrays of Wave Energy Converters (WECs) on the hydrodynamic attributes of the surrounding ocean, as a means for providing a first level impact assessment for proposed wave energy deployments. These guidelines have been developed as part of the ARENA and CSIRO-funded Australian Wave Energy Atlas Project (AWavEA). A wave energy project cycle typically consists of four stages: Preliminary evaluation; Feasibility study; Project design; and Implementation and operation. The guidelines presented in this paper aim to support preliminary assessments of the suitability of a proposed site to deployment of wave energy converters.

The development of the guidelines combines information obtained from a large suite of idealised numerical modelling experiments, using a model configuration which has been calibrated and validated with observations from a dedicated field experiment – the Garden Island field study.

The Garden Island field study was carried out as part of the AWavEA project, with the generous support of Carnegie Clean Energy Ltd who enabled access to their Perth Wave Energy Project site, to monitor the attenuation of wave energy in the lee of an array of deployed CETO-5 WECs [3]. This enabled the direct measurement of the wave energy extracted from a deployed wave energy converter and the assessment of SNL-SWANs [4] suitability for use in the development of the guidelines. The focus here is on providing preliminary estimates of the extent of impact in the mid-to-far field (away from the immediate proximity of the WEC array) for which SNL-SWAN was found to be suitable.

In this paper, we outline how the guidelines have been determined. Section 2 outlines the set of idealised SWAN-SNL simulations carried out for the task; Section 3 details the results of the simulation; Example guidelines are presented in Section 4; with some Discussion and Conclusions provided in Section 5.

II. Idealised SNL-SWAN Simulations

A series of idealised simulations using SNL-SWAN of WEC array installations was performed in order to underpin the development of the guidelines. Factors considered were different device types (four in total plus a 'no device' baseline simulation) with two different array sizes (3 MW and 20 MW) and two configurations (a two-row and a square array). These configurations were modelled under the wave climate conditions of four locations around Australia (Perth, Albany, Port Fairy and Sydney), each of which have good wave energy resource, proximity to population centres and electrical transmission infrastructure. Figure 1 displays the representative wave roses for each considered wave climate, with the coastline rotated to align N-S in each idealised simulation. For each location, the 34 years of hourly wave (sea-state) statistics available from the Australian wave energy atlas [5] amounted to approximately 300,000 data points. To reduce this to a tractable number, an algorithm was applied to the entire set of data points to select a subset of which best statistically represented the data as a whole (similar to that described by [6]). Consequently, the forcing wave conditions were reduced to 500 distinct sea states, with associated probabilities of occurrence, at each location. These data were used to provide forcing at the offshore boundary of the nearshore wave model used for the idealised simulations.

Nearshore wave propagation and dissipation is highly dependent on littoral zone morphology. Here we take a simple approach, with idealised straight and parallel nearshore morphology assumed for two different bathymetric slopes; a steep and a gentle equilibrium profile. These simplifying assumptions were used to construct two simulation domains (one for each profile type): both 12 km wide (long-shore) and 6 km across (cross-shore), with water depths ranging from 0 to at least 40 m deep. WEC arrays were centred in the domain in the shore-parallel direction and on the 25 m deep contour in the shore-perpendicular direction.

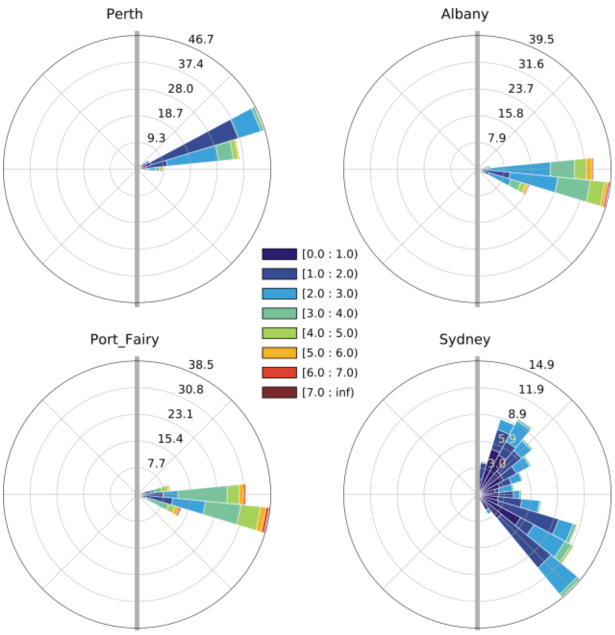

Fig. 1 Wave roses showing the wave climate for the four sites considered. The coastline direction is shown by the solid grey line with ocean to the right. Wave directions use nautical convention and hence indicate the direction from which the waves approach the coast. Travelling clockwise long the Australian coastline, the design coastline bearing is 222° for Sydney, 315° for Port Fairy, 296° for Albany and 353° for Perth.

Four contrasting WEC designs were chosen to represent the range of WECs that might be deployed off the Australian coast. The WECs represent differing device types, which utilise different physical principals for wave energy extraction; the nominal capacities of individual devices range from 200 kW to 3 MW and have performance metrics available in the public domain. The performance metric is based on the respective published power matrices derived from [7] and [8]. While a selection of devices were chosen in order to explore the sample space associated with different devices, it should be noted that the four devices tested are similar in that they target resource offshore. Devices that operate in the breaking zone – for example operating on the principal of the submerged pressure differential – will be poorly represented by these experiments. Table 1 briefly describes the devices selected for assessment.

TABLE I
DESCRIPTION OF WECS SELECTED FOR ASSESSMENT IN THIS STUDY.

WEC Name	Description	Nominal (Nameplate) Capacity (MW)
Bref-SHB	Bottom-referenced submerged heave buoy	0.209
F-OWC	Floating oscillating water column	2.880
B-OF	Bottom fixed oscillating flap	3.332
P-PA	Pitching point absorber	0.457

Different array configurations are characterised by array size, in terms of energy output, and array type, based on the physical layout of the devices. Two array sizes are considered: a 3 MW and 20 MW; and two array types are considered: a two row configuration in which the WECs within each row are staggered with respect to the other row; and a multi-staggered, multi-row configuration making up a square array. This results in a total of four array configurations. The (nameplate) nominal capacity was used to select the number of WECs required for the small 3 MW and large 20 MW arrays. The nominal capacity is the maximum output value in the device power-output matrix. The array configurations for each WEC device type are listed in Table 2.

TABLE III
ARRAY CONFIGURATIONS. THE 'X' SYMBOL REPRESENTS MULTIPLE ROWS OF WECS, E.G. 8X2 IS TWO ROWS OF EIGHT WECS.

WEC Name	Two Rows (small) **3 MW**	Two Rows (large) **20 MW**	Small Square **3 MW**	Large Square **20 MW**
Bref-SHB	8x2	48x2	4x4	10x9+6
F-OWC	1x1	4+3	1x1	3x2+1
B-OF	1x1	3x2	1x1	3x2
P-PA	4+3	22x2	3x2+1	7x6+2

Spacing between devices was set at 60m, as an estimate of half the wavelength of the peak period at which maximum power is returned from each device.

Together, these considerations amounted to 68,000 simulations (4 locations × 2 slopes × (1 baseline + (4 devices x 2 array sizes x 2 array configurations)) x 500 wave conditions).

Despite limitations of the phase-averaged approach, the SNL-SWAN model was used for the idealised simulations, recognising its capability of simulating wave frequency and wave height dependent transmission (absorption) of wave energy based on user-input power matrices, and its ability to simulate mid-far field effects [3]. The grid resolution was set at 30m so that grid cells could be collocated with devices, and the device length would be smaller than the grid length. The resulting grid provided a computationally feasible 200x400 grid points for the thousands of simulations required.

To analyse how conditions differed (between the presence of WEC arrays and without) for each of the 500 sea states, the following wave variables were saved as model output from each simulation:

1. Significant wave height (Hs) climate - an easily understandable indicator of change and also related to other wave field parameters, such as wave orbital velocity.
2. Wave power (CgE) - indicates the change in the energy resource.
3. Maximum near-bottom orbital velocity (Uo) - indicates changes to seabed mobility transport or environmental stressors
4. Dissipation due to depth-induced breaking (Dsurf) - energy dissipation due to surf breaking (in W/m2) indicates how waves will change near the shoreline.

In the immediate proximity of the WEC array, diffraction and radiated wave processes dominate. Given the shortcomings of spectral models to deal with these processes, the focus of this study is not on this region, but rather the mid field which extends from outside the array towards the shore and the far field, which is the region close to the shore (the depth-induced breaking zone).

In this paper, we focus analysis on changes in 70th percentile of significant wave height, measured in the cross-shore direction away from the array towards the shoreline. Other metrics available to measure impact, but not assessed here, include the area of impact and the long-shore width of impact on the shoreline (or 10 m contour).

Model outputs of the potential extent of impact of WEC array deployments on the surrounding wave field are summarised via a set of semi-empirical exponential equations that describe the exponential decay of a variable away from the deployed array.

III. IDEALISED SNL-SWAN SIMULATION

The spatial distribution of the 75th percentile significant wave height (Hs) climate for the control runs without the presence of any WEC array are shown in Figure 2. Largest spatial change, associated with depth induced breaking, occurs within 1km/500m of the coast for the gentle/steep slope simulations.

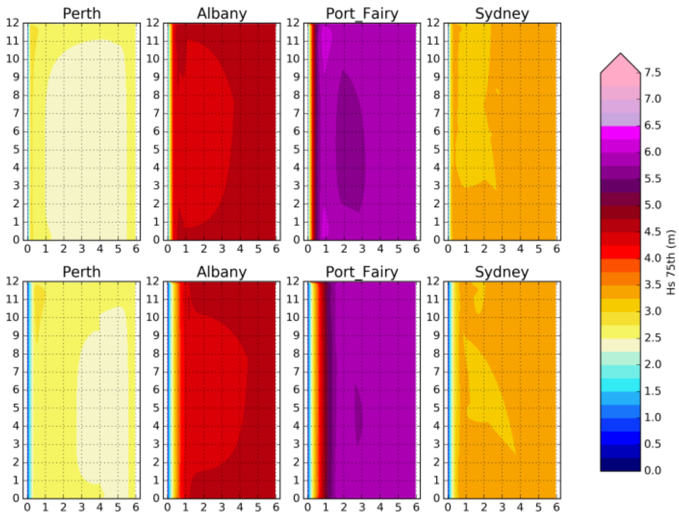

Fig. 2 The 75th percentile climate maps of H_s (m) for the four locations (columns) and for the steep (top row) and gentle (bottom row) bathymetric profiles. The coast is on the left and the figure extends to 6 km offshore.

The difference in the 75th percentile H_s climate between the baseline and WEC array simulations, where a 20 MW square array of P-PA devices is deployed, is shown in Figure 3. Shown are results for each of the four wave climates over the gentle sloping profile. Equivalent figures showing the attenuated wave field for the two row array configuration are shown in Figure 4. The amount of leeward attenuation depends on the incident H_s and T_p climate, and how that passes through the device power matrix. Typically, more attenuation occurs where H_s is larger. The device transmission matrices used in this study have no directional dependence. For some devices (e.g. pitching devices), directionality of waves may be an important factor which we are unable to resolve.

Cross-shore transects of the simulated change in the 75th percentile H_s climate for the 20 MW square array, for all device types, all climates and both bathymetric profiles, are shown in Figure 5. The H_s attenuation associated with the P-PA WEC array (Purple lines) shows incremental steps of increased attenuation as the waves pass through the rows of devices in the near-field, followed by reduced attenuation of the signal at locations further down-wave from the array due to the mixing of waves from oblique angles. The P-PA has the third highest near-field attenuation for all climates, except for Sydney (bottom row of plots), where it is second highest because the F-OWC device (red line) blocks less energy for the shorter period waves which are more prevalent in the Sydney wave climate

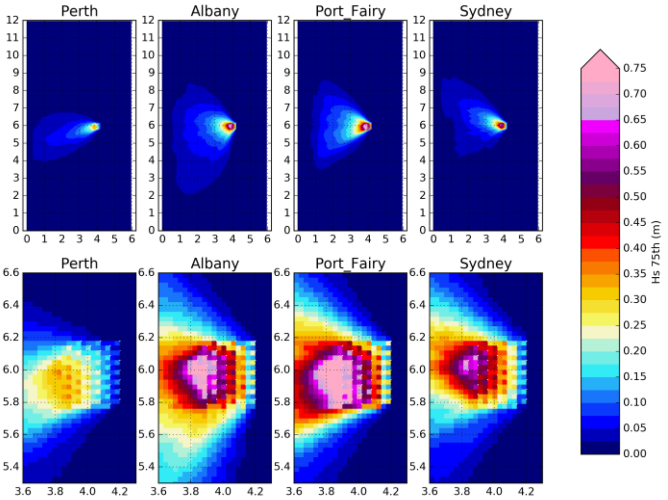

Fig. 3. Maps of change in the 75th Hs climate. Same as previous figure but for four different climates, and for the gentle profile only, using the P-PA 20 MW square row array. Top row is the full model domain showing the mid-field attenuation and the bottom row shows an enlargement over the array. Control wave height values are presented in Figure 2

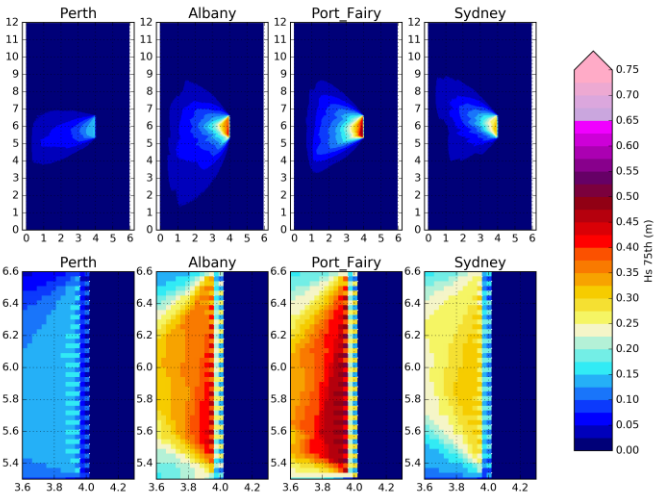

Fig. 4. As for Figure 3, but devices are in a two row configuration.

Down-wave from the WEC array, the larger nameplate capacity devices that extract the required resource using fewer WECs have fewer devices in the longshore direction, hence block less waves for oblique angles than arrays requiring more smaller capacity WECs. Thus, the attenuation down-wave of the array drops off more quickly down-wave of arrays with fewer devices.

The pattern or signal attenuation in H_s shown in figures above, i.e. large changes at the device and more gradual decay of the signal down-wave of the device, is the same pattern as seen for variables *CgE* and *Uo*. The down-wave reduction (attenuation) in wave height due to the presence of the array results in some waves remaining unbroken until they are closer to the shoreline, leading to regions of reduced wave-breaking energy compared to the control simulations. This may result in changes in sediment transport and subsequently shoreline position.

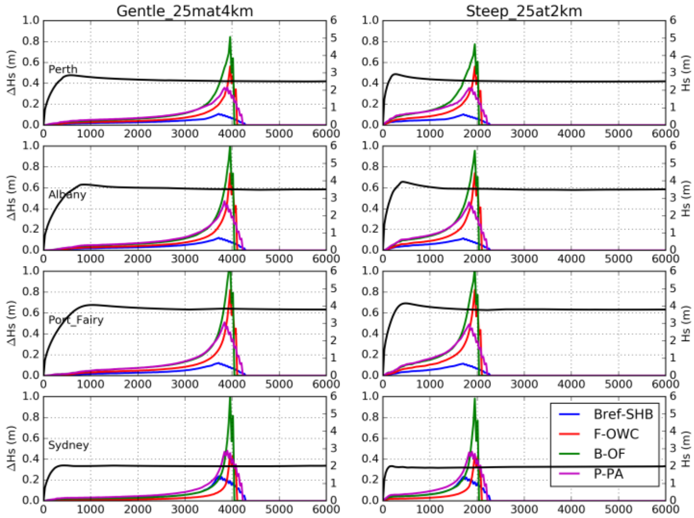

Fig. 5. Cross-shore transects of the change in Hs (ΔHs) for the 75th percentile baseline Hs and the 20 MW square array configuration. Positive values represent attenuation of wave height. Right (left) columns represent the gentle (steep) profile and each row represents a different wave climate. Note that the left vertical axis represents ΔHs shown by the coloured lines and the right axis represents the baseline Hs shown by the black solid line.

IV. Development of Guidelines

To achieve the objective of providing first-order estimates of the spatial extent of environmental effects of WEC array deployments, the results of the 68000 numerical simulations have been summarised in a simple, usable manner. Here, we provide details for a set of semi-empirical equations derived to describe the potential impact (measured using cross-shore distance, although similar equations can be derived for area of impact, or longshore distance) on a given down-wave wave parameter (here H_s, but can also be derived for other variables *CgE*, *Uo* or *Dsurf*). The equations provide a simple means to estimate the impact of different combinations of arrays in different environmental settings as a starting point to inform project stakeholders, and identify the spatial extent over which further consideration may be required. Input parameters for the equation include the incident wave height (H_{s0}) and wave period (T_{p0}) to determine the array absorption and the impacted-change in Hs0, ΔHs (or % Hs0). The equations are derived from the set of numerical experiments, to be independent of (i.e. averaged across) device type (as defined by the power matrix), and different wave climates (overlooks differences in spread of incident direction). For any estimated value of cross-shore distance impacted (the output variable of the derived equations), a standard error (rmse) is provided which captures the uncertainties associated with device specifications and wave climate differences.

The equation to predict the cross-shore impact distance for H_s is defined as:

$$\mathrm{ICS}(\Delta H_s, F_{absorbed}) = a \cdot \exp(b \cdot \Delta H_S F_{absorbed}^{\;-c}) + d \qquad [1]$$

where ΔH_s is the change in wave height selected to be of interest (% H_{s0}) and $F_{absorbed}$ is the expected power absorbed by the array for incident (H_{s0} and T_{p0}) wave conditions. The coefficients a, b, c and d have been empirically-derived from the set of numerical simulations (Table 3). Different sets of coefficients are provided for a range of considerations, including differences in:

- The bathymetric profile of the site of interest (steep or gently sloping)
- The array size (small number of devices [less than 16] in the 3 MW or a large number of devices [>16 and < 100] in the 20 MW array)
- Array configuration (2 row or square).

Further equations can be derived for other variables (CgE, Uo, or Dsurf), and for other metrics of impact (area of impact, or longshore-width of impact), but is left for future work.

TABLE III
TABLE OF COEFFICIENTS FOR EQUATION 1, FOR DISTANCE CROSS-SHORE WHERE SIGNIFICANT WAVE HEIGHT H_S IS IMPACTED BY THE PRESENCE OF WECS IN AN ARRAY OF GIVEN SIZE AND CONFIGURATION, ON A GIVEN SLOPING DEPTH PROFILE. VARIATIONS IN DEVICE, AND WAVE CLIMATE ARE CAPTURED WITHIN THE RMSE (MEASURED IN METRES).

Farm Size	**Array config**	**a**	**b**	**c**	**D**	**RMSE**
Gentle slope						
3MW	two	4086.5	-8190.36	0.72	197.63	294.69
3MW	square	3879.84	-6614.88	0.69	193.19	275.76
20MW	two	4030.35	-2430.42	0.6	250.56	279.64
20MW	square	4126.18	-4292.77	0.67	248.49	219.37
Steep slope						
3MW	two	2391.14	-5102.81	0.71	176.98	147.1
3MW	square	2462.59	-4362.58	0.69	173.05	129.28
20MW	two	2003.17	-1378.23	0.6	193.38	191.64
20MW	square	2473.58	-2794.04	0.67	206.65	164.76

As example, Figure 6 displays the consequent semi-empirical estimate of impact in H_s using Equation 1 for a 20 MW array deployed in a 2-row configuration on a gently sloping profile. To illustrate the skill of the semi-empirical model fit relative to the numerical simulations, Figure 7 presents the impact distance cross-shore in Hs determined from each method, for a 20 MW array deployed in a 2-row configuration, on a gently sloping bathymetric profile. It can be seen that the semi-empirical fit underestimates the results of the numerical simulation, but this difference is largely captured by the quoted error value.

To demonstrate application of the method, we consider a scenario where we wish to resolve the extent (cross shore distance) over which H_s is reduced by 5% or more down-wave of a deployed WEC array. Incident wave conditions are H_s of 2m, and peak period of 8s, such that a 5% decrease corresponds to 0.1m lower wave heights, and the corresponding incident wave power in 20m water depth is 19.93 kW/m. An array of 60 WECs is proposed, where each WEC is 20m wide. Each device has been measured to absorb 50% of the wave field under these conditions. For these conditions, the total power absorbed by the array will be 60*20*19.93*0.5 = 11958kW. This example corresponds with the figures presented in Figure 6. Considering ΔH_s = 0.1m and $F_{absorbed}$ = 11958 kW, we find an impact cross-shore distance of 1940.6m, with a standard error of 279.64m.

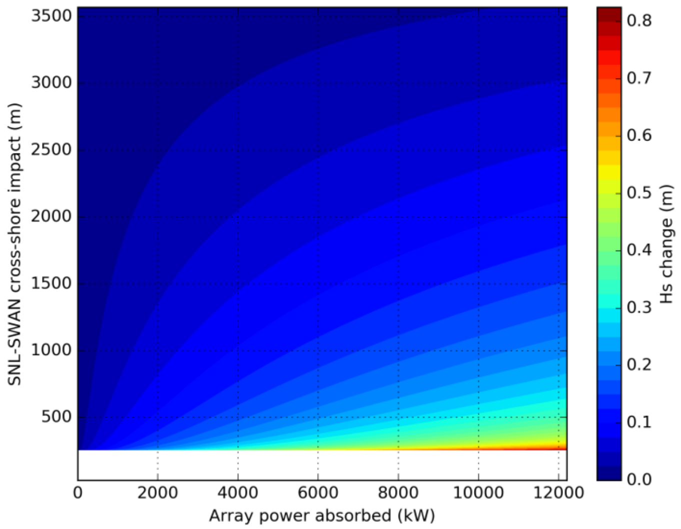

Figure 6. Semi-empirical cross-shore impact distance plotted against change in array absorption. Colours represent the impacted-change in Hs. Values are for all wave climates, the 50th 75th and 95th climate and for all device types in the 20 MW two row array for the gentle profile. Corresponding coefficients are a: 4030.35; b: -2430.42; c:0.6; d: 250.56; RMSE: 279.64.

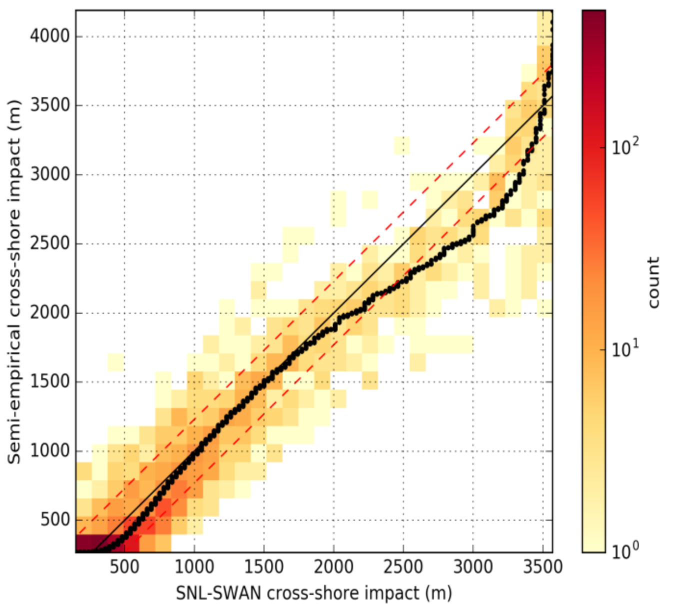

Figure 7. Regression plot of Hs cross-shore impact (ICS) distance estimates for the 20 MW array in the two row configuration for a gentle profile. Colours indicate the density of agreement (count of a 2d histogram). Black dotted-line plots the ordered semi-empirical values against the ordered SNL-SWAN values. Red dashed lines are ± root mean square error (rmse) to the model fit. Values are for all wave climate locations, the 50th, 75th and 95th climate statistic and for all device types in the 20 MW square row array for the gentle profile.

Equation 1 can also be re-arranged to obtain the change in H_s at a given distance down-wave of the array. Using the same example, we can determined that the change in H_s 500m down-wave of the array would be approximately 0.32 m, corresponding to 16% of the 2m upwave conditions.

V. Conclusions

Environmental impact assessments are a critical part of the wave energy approvals process. They must be undertaken for a development to proceed and are important for building social licence to operate. However the industry has acknowledged a lack of tools and guidelines to assist with the assessment of potential impacts in the marine environment. This in turn can lead to costly delays in the approval process [9].

The extraction of wave energy by an array of devices has the potential to alter the characteristics of the surrounding wave field with potential flow on effects to the physical and ecological environment. Reduced energy in the wave field may have both negative and positive effects depending on the values ascribed to the coast. For example, reduced wave energy may adversely impact the amenity of a coastal location for recreational activities such as surfing, yet may reduce sediment mobility and hence help reduce erosional effects that threaten coastal infrastructure. Changes in sediment mobility may drive other impacts, both negative or positive, on seabed habitats and local coastal ecology.

The potential impacts of a WEC array will vary according to the specific attributes of the local environment in which it is to be situated. Therefore, a generic tool that can be applied to assess a wide variety of potential impacts was sought to facilitate the assessment of impact zones. For reasons of computational efficiency in carrying out thousands of simulations of WEC array scenarios, the SNL-SWAN model was used as the basis for building the generic tool. Some key limitations of this modelling approach should be noted. Being a phase-averaged wave model, The SWAN-SNL model poorly captures diffraction of waves around the in-water obstacles. Thus, while the frequency dependent transmission of energy through the WEC array can be parameterised, and thus provide estimates of the mid-to-far field effects on the wave field with reasonable accuracy, the near-field effects surrounding the WEC array are not expected to be well captured. Further to the well understood issue of diffraction with phase-averaged models, the application of these models to wave energy problems is also hampered by the lack of parameterisation of radiated waves from an individual WEC, and associated WEC array effects [10]. The effects of these limitations are expected to be more strongly felt in the near-field around the WECs. Validation of the SWAN-SNL model with data collected from down-wave of an in-sea deployed WEC array [3] supports this expectation, and provides justification for the application of this model.

Whilst valuable information is obtained by field measurements to develop and validate the models, numerical models provide a useful tool to investigate unexplored sensitivity of the system to hypothetical scenarios (including for example larger arrays, different device characteristics, array configurations, and geographical settings, amongst others). The computational efficiency of the SWAN-SNL model has enabled a larger range of situations to be explored than might have been achieved by other models, which may better capture near-field effects. Development of phase-resolving wave models to investigate WEC effects is occurring [11], and presents an advance on the model used here. However, these models are still computationally expensive and WEC device specific, precluding their use in a study such as that outlined here. In this study the analysis has been limited to how the wave properties are impacted by the presence of WEC arrays. This is primarily due to the wave field parameters being the only parameters that have been suitably validated with field data. An anticipated extension of this research is to investigate the effects of WEC array deployment on other morpho-hydro-dynamic factors, such as circulation, sea-bed evolution, and/or ecological consequences.

The limitations of the wave model together with the use of idealised simulations to develop the generic tools necessarily limits its application to providing preliminary assessments and broad guidance of the impact of wave arrays. These preliminary assessments may inform the design of more detailed modelling assessments that account for the specific attributes of the devices and the local environment under investigation. The assessments may also be used to inform monitoring of the identified impacts by providing guidance of the most suitable locations for deployment of instrumentation. Factors such as the wave environment, the wave energy devices, their arrangement in arrays and the total power output have all been considered in developing a quantitative impact equation. The purpose of the equation is to provide preliminary guidance of the extent of potential physical impacts of proposed wave energy installations. Given the idealised nature of the experiments undertaken and the generalisation of the findings into a single impact equation, the guidance provided should be considered to be approximate at best, potentially providing the broad requirements for more detailed modelling in the specific coastal environment under consideration.

Broad findings about how WECs can influence the wave climate in the mid- to far-field down-wave of the WEC array were also identified from the idealised simulations. These are summarised as follows:

1) The impact of WEC arrays containing many devices with lower power ratings will have less intense (point-source) impact on the near to mid field than fewer devices that extract larger amounts of power. Maximising power extraction for a single device will therefore have a larger impact on the near- to mid-field environment.

2) Proximity of an array of WECs to the coast will increase impacts on the breaking zone. Analysis presented here of the coastal impacts of energy removed due to WECs is limited. However, simulations show significant changes in the radiation stress force associated with the predicted energy reductions could be expected. Thus we conclude that if the cross-shore impacted distance in the wave field (e.g., in Hs) intersects the wave breaking depth, then the equilibrium state of the coastal zone will likely be disturbed leading to changes in coastal properties (e.g., shoreline position). This may be considered a positive or negative effect – for example, in some cases, a WEC array might be deployed as a coastal management solution. The recommendation from this study is

if the estimated cross-shore impact distance intersects the 10-m depth contour, a more rigorous impacts study is required for the coastal zone.

3) A directional wave climate that is more widely distributed (e.g. Sydney) will have a less focussed impact on the coastline than a narrow directional wave climate.

References

[1] O'Hagan, A-M., 2016: Consenting Processes for Ocean Energy: Update on Barriers and Recommendations. IEA Ocean Energy Systems. Available at: https://www.ocean-energy-systems.org/documents/55868-report-consenting-processes-2016.pdf/

[2] Copping, A., and Coauthors, 2016: Annex IV 2016 State of the Science Report: Environmental Effects of Marine Renewable Energy Development Around the World., 200 pp.

[3] Contardo, S., R. K. Hoeke, M. A. Hemer, and K. L. McInnes, 2018: *Transformation of wave spectra by an array of Wave Energy Converters*. Submitted to Coastal Engineering.

[4] Ruehl, K., A. Porter, C. Chartrand, H. Smith, G. Chang and J. Roberts, 2015: Development, Verification and Application of the SNL-SWAN Open Source Wave Farm Code. In: *Proc. 11th European Wave and Tidal Energy Conference, 6-11 Sep, 2015, Nantes, France.*

[5] Hemer, M.A., S. Zieger, T. Durrant, J. O'Grady, R.K. Hoeke, K.L. McInnes and U. Rosebrock, 2017: A revised assessment of Australia's national wave energy resource. *Renewable Energy*, 114, Part A, 85-107. doi:10.1016/j.renene.2016.08.039

[6] Camus, P., F.J. Mendez, R. Medina, S.F. Cofino, 2011: Analysis of clustering and selection algorithms for the study of multivariate wave climate. *Coastal Engineering*, 58, 453-462.

[7] Babarit, A., J. Hals, M.J. Muliawan, A. Kurniawan, T. Moan and J. Krokstad, 2011: Numerical benchmarking study of a selection of wave energy converters. *Renewable Energy*, 41, 44-63.

[8] Flocard, F., and R.K. Hoeke, 2017: Coastal protection through wave farms: feasibility assessment using numerical wave modelling and parametric study. *Australasian Coasts and Ports Conference, Cairns, 2017*.

[9] Hemer, M.A., R. Manasseh, K.L. McInnes, I. Penesis and T. Pitman, 2018. Perspectives on a way forward for ocean renewable energy in Australia. *Renewable Energy*, 127, 733-745.

[10] Chowdhury, S. and R. Manasseh, 2017: Behaviour of eigenmodes of an array of oscillating water column devices. *Wave Motion*, 74, 56-72.

[11] Rijnsdorp, D.P., J. Hansen and R. Lowe, 2017: Improving predictions of the coastal impacts of wave farms using a phase resolving wave model. *Proc. 17th European Wave and Tidal Energy Conference,* 25-Aug–1-Sep, 2017. Cork, Ireland.