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Hydrodynamic modelling for nearshore predictions

Version 1

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Contents

1 Introduction

Hydrodynamic (numerical) models are widely used tools for marine prediction across a large range of spatial (and time) scales, from ocean basins down to individual ports and beaches. Models used to predict physical processes such as ocean (wind-)waves and circulation (currents), at the scale of ocean basins to continental shelves down to smaller regional scales, are relatively mature and numerical weather prediction (NWP) centres such as the Australian Bureau of Meteorology routinely run such models to support ocean forecasting. This is largely because, at regional (and larger) scales, ocean waves and circulation can be treated as separate processes for most forecasting applications (NWP centres normally run these as separate models with no coupling or exchange of fluxes); and also because the numerical solutions of models at this scale can be effectively constrained (through data assimilation) and/or verified by extant global or regional observation networks of buoys, drifting floats and satellites in a standardised way. This is not the case for nearshore (littoral zone) models and there are very few (if any) examples of their use in routine NWP operations.

As waves approach the coastline, they shoal and dissipate (e.g. through wave breaking) imparting momentum to the water column and driving local phenomena such as longshore and rip currents. This process is typically the most energetic driver of circulation (and related water column mixing) in the shallow nearshore zone (Battjes, 1988). Hydrodynamic models supporting littoral operations or other activities at the scale of individual beaches and harbours therefore generally cannot treat waves and circulation as separate processes. However, coupling wave and circulation models (or fully dynamically simulating their interaction within the same model) is complicated by a number of factors. As waves propagate into increasingly shallow water, their non-linearity increases, which increases the difficulty of accurately parameterising wave breaking, momentum transfer, enhanced mixing, wave runup and other associated dynamics; furthermore, these physical processes typically need be resolved at a very fine spatial resolution over complex shallow coastal features (Fringer et al., 2019). This means that littoral-nearshore models often come with extremely high computational demands; they generally require accurate high spatial resolution input data (see morphological white paper), which is often not available; and the observation networks used to constrain (i.e. through assimilation) and/or verify larger scale ocean models generally do not resolve processes within the nearshore zone. Despite these considerable challenges, a number of littoral-nearshore models, employing a variety of simplifications and numerical solutions, have been developed over the last several decades. While many are capable of making highly accurate predictions of certain nearshore physical variables, none of them resolve all the physical processes that occur in the nearshore zone. Consequently, littoral modelers typically choose a model depending on their objective (e.g. research into littoral processes versus forecasting) and on accuracy and time (computational) cost considerations. Research is ongoing to improve the accuracy and efficiency of existing numerical schemes and develop new ones for the littoral zone.

The goal of this paper is two-fold: (1) to provide a summary of the different numerical schemes employed by a number of commonly used nearshore hydrodynamic models; and (2) to briefly review littoral model software packages and provide recommendations for various use cases, with an emphasis on short-term forecasting applications for surf-zone operations. The latter is by no means intended to be an exhaustive list of models or their capabilities, rather it is an overview of a number of commonly used models which cover the various numerical schemes, per the experience and expertise of the authors. In the following sections, we provide a more rigorous definition of the littoral-nearshore zone; provide an overview of nearshore hydrodynamics and the two broad categories of numerical solutions applied; list several commonly-used nearshore models in these categories; and finally, provide recommendations for various use cases.

2 Nearshore hydrodynamics

The littoral zone may extend (definitions vary slightly) from the edge of the continental shelf to the point of development of vegetation on the land side. The marine portion of the littoral zone is represented in Figure 1. It divides into offshore and nearshore zones, separated at the breakpoint, where wave breaking starts and waves reach their maximum height (following shoaling). The nearshore includes several regions: the breaker zone, the surf zone and the swash zone. The breaker zone is the portion where irregular waves become unstable and break. The seaward limit of the breaker zone is the breakpoint. The surf zone is the portion where bore-like waves propagate following breaking. The swash zone is the portion where the beach face is alternately covered by the wave run-up and exposed by the back-swash. The shoreward limit of the swash zone is the shoreline.

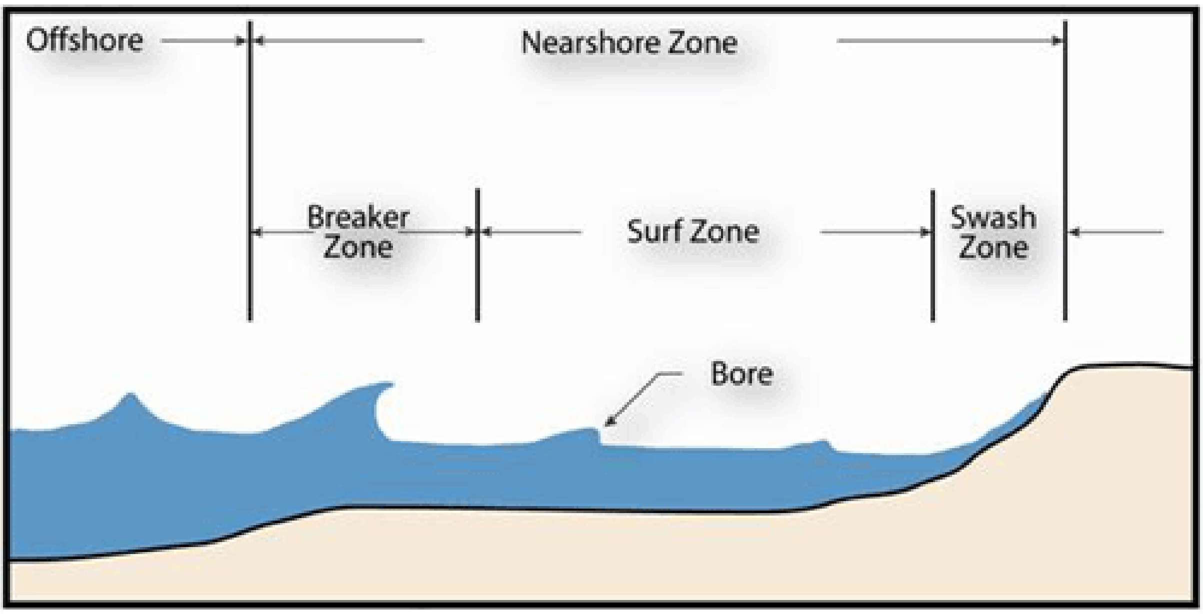

Figure 1 Marine portion of the littoral zone (reprinted from Komar, 1998)

The propagation of wind waves, where gravity is the restoring force, can be modelled using linear wave theory. Under the assumptions of linear wave theory (see Dingemans, 1997) the propagation speed of wind waves is governed by the dispersion relationship:

$$\lambda = \frac{g}{2\pi} T^2 \tanh(2\pi h/\lambda) \qquad \text{Equation 1}$$

where λ is the wavelength, T is the wave period, g is gravity and h is the water depth. The phase velocity ($c = \lambda/T$) of a wave described by linear wave theory depends on the wavelength and water depth, resulting in ocean waves undergoing frequency dispersion. In deep water ($h > 0.5\,\lambda$), $\tanh(2\pi h/\lambda) \rightarrow 1$ and the phase velocity depends only on the wave period ($c = gT/2\pi$). In shallow water ($h < 0.05\,\lambda$), $\tanh(2\pi h/\lambda) \rightarrow \frac{2\pi}{T}\sqrt{h/g}$ and the phase velocity depends only on the water depth ($c = \sqrt{gh}$). As ocean waves propagate from offshore into the nearshore they undergo a transition from deep-water wave dispersion to shallow-water wave dispersion. Shallow-water waves undergo limited frequency dispersion, however non-linear amplitude dispersion (where larger waves travel faster than smaller waves) becomes increasingly important.

Nearshore circulation is dominated by wave-induced forces associated with shallow-water wave breaking (Battjes, 1988). As wind waves propagate into shallower water, they become increasingly nonlinear and dissipative. They are increasingly asymmetrical and skewed until they break. Depth-induced breaking is the primary dissipation mechanism in the nearshore. However, it is poorly understood, and it is mostly represented in modelling by empirical formulations. Three types of breakers are identified, spilling, plunging and surging, depending on the surf similarity parameter:

$$\xi = \frac{\tan\alpha}{\sqrt{H/\lambda}} \qquad \text{Equation 2}$$

where α is the depth gradient (local slope) and H is the wave height. For higher values of ξ (steep slope and relatively small waves), breaking waves have a plunging form while for lower values of ξ (mild slope and relatively large waves), waves have spilling form.

The transport of wave-induced momentum is called radiation stress (Longuet-Higgins & Stewart, 1962). Horizontal variations of radiation stress occur following variations in the wave amplitude or depth. Changes in momentum transport (e.g. due to wave breaking), forming a gradient in radiation stress, are balanced by changes in potential energy, affecting local sea levels (Holthuijsen, 2007). Wave shoaling causes a setdown (decrease in mean water level seaward of the surf zone) and a setup (increase in mean water level) occurs when waves break. This in turn drives surf zone circulation, such as rip and longshore currents.

Radiation stress gradients associated with the presence of wave groups generate infragravity (IG) waves, or long waves, with periods ranging from 20 seconds to three minutes. Bound long waves are locked to the group and their troughs (crests) correspond to crests (troughs) on the wave group envelope, i.e. they are in antiphase with the wave group envelope, as illustrated in Figure 2. The expression for horizontal radiation stress, in the cross-shore direction, is:

$$S_{xx} = \left(2n - \frac{1}{2}\right)E \qquad \text{Equation 3}$$

where E is the wave energy and n is the ratio of group velocity over phase velocity. n tends to 0.5 in deep water and to 1 in shallow water, so bound long waves are increasingly energetic as depth decreases. Additional long waves are generated as wave groups propagate into shallow water, in response to radiation stress gradients associated with depth variations (Contardo et al., manuscript in progress) and wave group breaking, as released bound long waves (Masselink, 1995) or breakpoint forced long waves (Contardo et al., 2018; Contardo & Symonds, 2013; Symonds et al., 1982). Those long waves are free, i.e. they propagate at the free wave celerity (faster than the groups and bound long waves). The free long waves propagate towards the shoreline and are responsible for the dominant portion of the oscillating component of the runup on intermediate beaches and during storm events (Roelvink et al., 2017).

There are (broadly speaking) two categories of numerical nearshore wave models (Battjes, 1994; Buckley et al., 2014; Monbaliu, 2003): Phase-averaged (or wave averaged) models, also called spectral models, and phase-resolving models. Phase-averaged models generally describe the evolution of the wave energy spectrum (a superposition of waves at different frequencies and directions described by their energy) in a statistical manner, assuming a random phase and the wave processes are described in a stochastic way. Their formulation makes them incapable of directly simulating currents; they are often coupled with a circulation model when this is required. In contrast, phase-resolving (wave resolving) models describe individual wave motions, including direct, dynamical simulation of non-linear transformations and wave-driven flows, including transient effects (within the limitations of their formulations). However, these models require resolutions that are a fraction of the wave lengths and wave periods of interest, i.e. grid spacing is usually on the order of 1 m. This makes them computationally expensive and they are therefore generally not used as 'operational' models.

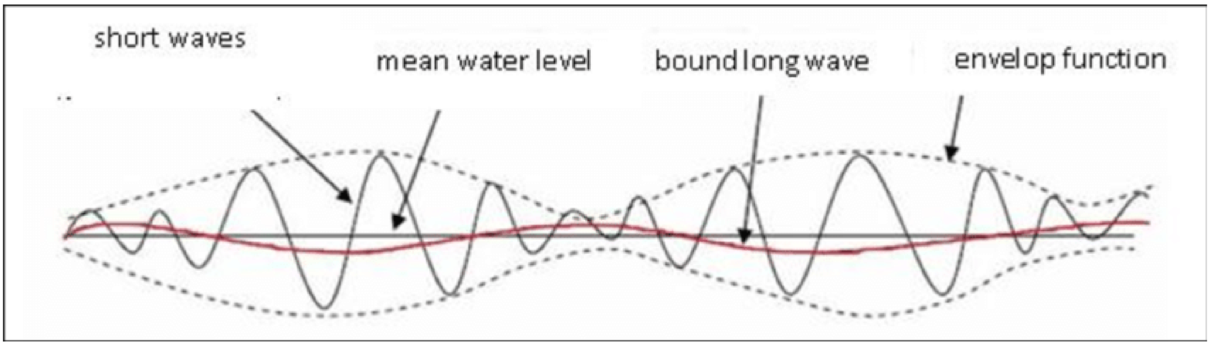

Figure 2 Schematic representation of the formation of bound long waves as short-wave groups approaching the shoreline (reprinted from Kularatne and Pattiaratchi, 2006)

3 Phase-averaged models

The concept of phase-averaged models has existed since the 1950s, and led to the first-generation wave models representing the directional spectrum with a discrete number of bandwidths (Khandekar, 1989). Findings from the JONSWAP field experiments (Hasselmann et al., 1973) led to the second generation of models, which use a parametric representation of the wave-wave interaction process, as originally proposed by Hasselmann et al. (1976). The third generation of wave models were initiated with a new method to compute efficiently the nonlinear transfer integral (S. Hasselmann et al., 1985). The first operational third-generation model, called WAM (WAve Modelling) (Klaus Hasselmann et al., 1988), was developed on global and regional domains. WAM has been replaced by WaveWatch-III (Tolman, 2009) as the most commonly used global and regional scale wave model used by NWP centres. The first spectral model applied specifically to the nearshore, SWAN (Simulating WAves Nearshore; (Booij et al., 1999), was developed in the 1990s. SWAN traditionally has advantages over WaveWatch-III in the nearshore zone (e.g. implicit numerical solutions better suited for numerical closure in shallow water) and it is much more commonly used for such applications. Both models are under continued development however, and drawbacks of using WaveWatch-III in nearshore areas have decreased in the last several years (e.g. Smith et al., 2018).

Phase-averaged models simulate waves in a stochastic manner with empirical formulations. They are based on spectral energy balance equations. The third-generation models solve the wave action balance equation, which describes the evolution of the wave spectrum in wave frequency and direction and in time and space (Rusu, 2012). The wave action equation can be formulated as follows:

$$\frac{\partial A}{\partial t}+\frac{\partial (c_x A)}{\partial x}+\frac{\partial (c_y A)}{\partial y}+\frac{\partial (c_\theta A)}{\partial \theta}+\frac{\partial (c_\sigma A)}{\partial \sigma}=\frac{S_{tot}}{\sigma} \qquad \text{Equation 4}$$

where ϑ represents the wave incidence angle and σ the relative radian frequency. A is the wave action and is equal to the wave energy density on σ; c_i represents the propagation velocities in the x, y, ϑ and σ spaces. S_{tot} is the source and sink term and typically includes transfer of energy from the wind (i.e. generation of waves by wind) and dissipation due to white-capping and wave breaking. SWAN specifically includes parametric terms to include non-linear transfer of wave energy due to quadruplet interaction, and more specifically for the nearshore, bottom friction, depth-induced breaking, and nonlinear triad interactions; a parameterisation for diffraction is also included, although this is difficult to approximate with a phase-averaged model, and hence is not very reliable (Fringer et al., 2019). SWAN also has capability to utilise unstructured mesh (M. Zijlema, 2010); unstructured mesh has the capacity to resolve small scale coastal features without increasing model resolution where it is not needed. Note that a number of other phase-averaged wave models exist for the coastal zone (some of which are mentioned in the sections below); however, they are all broadly similar to SWAN and in some cases are based in large part on the same underlying code.

The wave-averaged, spectral evolution approach of these third-generation models is a good approximation for the description of wind generated waves (particularly in deep water) and allows computational grid mesh size to be largely independent of wavelengths; e.g. for ocean-scale implementations, grid spacing of 50 km or more is not uncommon; this makes them relatively computationally efficient. However, they are not capable of direct dynamical simulation of non-linear transformations, such as diffraction and infragravity wave generation, nor are they capable of simulating currents (wave-driven or otherwise).

In order to resolve the time-averaged wave driven circulation, phase-averaged wave models are often two-way coupled with coastal circulation models, whereby wave forcing is supplied to the circulation model to force (or modify) nearshore currents and water levels that are communicated back to the wave model in an iterative fashion. Coastal circulation models typically numerically solve the Reynolds-Averaged Navier–Stokes Equations utilising the hydrostatic approximation, which assumes horizontal scales of motion are much larger than vertical scales – an effective approximation for simulating along-shore and cross-shore flow, but not simulating wind-waves themselves (the phase-resolved wave models provide the forcing for these effects). Such coupling has been shown to be effective at estimating nearshore waves and currents at the same time-mean timescales that phase-averaged wave models operate; however, they miss certain transient phenomena at wave-group and smaller timescales (Fringer et al., 2019; Kirby, 2017). For a more extensive overview on such coastal wave/flow model coupling, including the two most common numerical approaches to achieve coupling, see (Kirby, 2017). In the remainder of this section, we provide a cursory overview of several such phase-averaged wave/hydrostatic flow modelling systems in common use.

COAWST

The Coupled Ocean–Atmosphere–Wave–Sediment Transport (COAWST) Modeling System utilises the Model Coupling Toolkit (https://www.mcs.anl.gov/research/projects/mct/) to exchange data fields between the ocean (circulation) model ROMS (https://www.myroms.org/), the atmosphere model WRF (https://www.mmm.ucar.edu/weather-research-and-forecasting-model) and the SWAN wave model. Note ROMS is probably the most widely used regional modelling system (Fringer et al., 2019); and includes biogeochemical, bio-optical, sediment, and sea ice modules. COAWST also includes modules for sediment transport (Warner et al., 2010) and (more recently) infragravity wave generation (Memmola et al., 2020), conceptually similar to XBeach-SB (see below) are also available. All of COAWST component models/module codes are open source. At the time of writing, COAWST and ROMS only supports structured rectilinear or curvilinear computational grids, i.e. unstructured mesh grids are not supported.

Delft3D/Delft3D-FM

The Delft3D modelling system is based around a (hydrostatic) flow model with a numerical solution similar to that of ROMS, capable of coupling with SWAN (Lesser et al., 2004). It also includes sediment transport, water quality and other modules. Starting around 2015, Delft3D was extended to support flexible (unstructured) mesh (Delft3D-FM), with elements ranging from linear (one-dimensional, e.g. for streams or canals) to six sided. At the time of writing, however, Delft3D-FM could only be coupled with structured rectilinear or curvilinear SWAN grids. The Delft3D/Delft3D-FM modelling suite has broad use in both the coastal research and coastal engineering/consultancy communities; the key hydrodynamic modules' codes are open source.

ADCIRC+SWAN

The ADvanced CIRCulation (ADCIRC, adcirc.org) model utilises a tight coupling on the same unstructured Delaunay triangle-based mesh as SWAN, eliminating some of the computational overheads of interpolation between different (wave and circulation) grids and information passing between the models, particularly on parallel computing systems (Dietrich et al., 2012). ADCIRC has broad use (and development) primarily by the US-based academic research community and the US Army Corps of Engineers. The modelling source code is not open source but is made available by the developers for research purposes.

MIKE

The MIKE 21 and Mike 3 hydrostatic circulation models and the Mike 21 spectral wave (SW) model form part of a large suite of environmental modelling software developed by the Danish Hydraulic Institute (DHI). These coupled models utilise an unstructured mesh computational grid comprising triangles or quadrilateral elements and is in wide use in the ocean engineering, marine transport and related consultancy sectors; the MIKE suite also includes Boussinesq-type and non-hydrostatic models discussed in the next section. The model source code is proprietary and using the models requires purchasing a commercial licence.

<u>SCHISM</u>

The Semi-implicit Cross-scale Hydroscience Integrated System Model (SCHISM, Zhang et al., 2016) is a relatively recently developed model which uses a number of pragmatic, hybrid approaches in its numerical solutions and discretizations compared to many previous models (Fringer et al., 2019), and is gaining traction among researchers and operational forecasting environments. It uses an unstructured mesh comprising triangles or quadrilateral elements; the spectral wind-wave module (WWM-III, (Roland et al., 2012)), which shares large parts of its code base with the unstructured implementations of Wave Watch III and SWAN, is an internal module of SCHISM. It also includes sediment transport, water quality, particle tracking and other modules. SCHISM was designed for seamless simulation across a range of scales (creek-lake-river-estuary-shelf-ocean), and has been used for many purposes including general circulation, tsunami and storm-surge inundation, water quality, oil spill, sediment transport, coastal ecology, and wave-current interactions. All model codes are open source.

<u>XBeach</u>

The XBeach model has two modes: a hydrostatic and a non-hydrostatic; the non-hydrostatic mode is discussed in Section 4b. While the hydrostatic “surf beat” (SB) mode is technically a phase-averaged wave model coupled with a hydrostatic circulation model, its approach is quite different from the other models presented in this section (and it is the model selected for implementation in the ROAM system). Unlike the other model systems presented in this section, which were mostly originally developed for regional scale coastal applications (but showed value at nearshore scale), XBeach was originally developed to predict local extreme beach response to storm conditions (Roelvink et al., 2009).

The modelling approach used in XBeach-SB is unique and offers the advantage of resolving long wave motions while limiting the computational demand, as short waves are phase-averaged. XBeach-SB solves the wave-action equation with time-dependent forcing to simulate short waves and the shallow water equations to model the low-frequency and mean flows (Roelvink et al., 2009).

In the application of the wave action equation (Equation 4), the directional distribution of the action density is taken into account, whereas the frequency spectrum is only represented by one frequency (Gunson & Symonds, 2014), so complex frequency spectra (e.g. bimodal) cannot be represented within the domain. In the source term in Equation 4, XBeach includes only dissipation terms (friction and breaking). Unlike SWAN, the wind-generated wave growth is not represented. This limits the validity of the model in certain situations when locally generated wind waves are important to hydrodynamic processes (Drost et al., 2019), this is the case, for example, when a direct storm impact is evaluated or in the case of wide lagoons or within ports /harbours (i.e. Port Moresby). However, this does not normally present a problem, since XBeach domains typically do not extend far from shore and may be nested in a model which includes wind-generated waves (such as SWAN).

XBeach-SB uses the wave spectra at its offshore boundary (input either as spectral, from e.g. SWAN or calculated from input wave heights periods and directions as JONSWAP spectra) to calculate the wave group envelope, and then solves the variation of short-waves envelope (wave height) on the scale of wave groups. This variation in turn drives infragravity waves within the depth-integrated hydrostatic solver, approximating transient behaviours and swash dynamics in the nearshore zone, unlike the other models in this section. XBeach may otherwise be run in ‘stationary’ mode (XBeach-Stationary), in which case, infragravity waves are not simulated.

While the model is designed for beaches, it also performs well on reefs as demonstrated by comparison with laboratory experiments and in-situ observations (Buckley et al., 2014; Van Dongeren et al., 2013; Pomeroy & Lowe, 2012). However, it has been shown to underestimate infragravity runup (Palmsten & Splinter, 2016; Stockdon et al., 2014).

4 Phase-resolving models

Phase-resolving models are based on conservation laws but may also include empirical formulations. They require a high-resolution grid and consequently a small time-step, so they are computationally demanding. As such, their use is often restricted to lower frequency motions, small-scale, short duration, or one-dimensional studies. There are two main approaches for phase-resolving modelling (Marcel Zijlema et al., 2011): Boussinesq-type models and non-hydrostatic wave-flow models. Both of these approaches, due to their simplifying assumptions, are generally non-dispersive or weakly-dispersive, and as such are generally not suited for simulating propagation of waves in deep water (relative to their wavelength) or the related generation of wind waves.

4.1 Boussinesq-type models

The Boussinesq equations (Boussinesq, 1872) represent the depth-integrated equations for the conservation of mass and momentum for an incompressible and inviscid fluid (Nwogu, 1993). They include the lowest-order effect of frequency dispersion and nonlinearity, but are limited to relatively shallow water (Nwogu, 1993). The Boussinesq equations, expressed in one horizontal dimension (for simplicity), are (Holthuijsen, 2007):

$$\frac{\partial \eta}{\partial t} + \frac{\partial [(d+\eta)u]}{\partial x} = 0 \qquad \text{Equation 5}$$

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + g\frac{\partial \eta}{\partial x} = \frac{1}{2} d \frac{\partial^3 (du)}{\partial t \partial x^2} - \frac{1}{6} d^2 \frac{\partial^3 u}{\partial t \partial x^2} \qquad \text{Equation 6}$$

where *t* represents the time, *u* is the vertically averaged horizontal velocity component, *d* is the depth, *η* is the sea surface elevation and *g* is the gravitational acceleration. These are the nonlinear shallow water equations (continuity and momentum equations), with a correction for the vertical acceleration (right-hand term in Equation 5), to account that, for short period waves, the horizontal velocities are not uniform over the water column and the pressure is nonhydrostatic. They are classically derived using a perturbation expansion of two parameters (Kirby, 2016). The Boussinesq equations are applicable up to certain frequency dispersion and degree of linearity. The frequency dispersion, μ, is measured by the product of the wavenumber and the water depth, and the degree of nonlinearity, δ, is represented by the ratio of wave amplitude to depth.

The development of Boussinesq-like equations (extended versions of Boussinesq equations) started in 1967 with Peregrine's work (Peregrine, 1967). While originally still limited to weakly linear and weakly dispersive cases, their applicability was further extended. One important improvement was the implementation of wave breaking first via the concept of 'surface roller' (Svendsen, 1984) which was followed by other formulations (Veeramony & Svendsen, 2000). Improvement of the dispersion characteristics of the classic equations extended their applicability to deeper water (Nwogu, 1993) and full nonlinearity was added (Kirby, 1997). However, they require the use of complex empirical formulations and numerical schemes to model the surf zone, which increases the uncertainty of the results, complexifies the implementation and reduces the numerical stability and robustness.

These various options led to the development of what are termed Boussinesq-type models (BTMs), with a range of orders and nonlinearity, different breaking implementations and numerical approaches.

<u>FUNWAVE</u>

The FUlly Nonlinear Boussinesq wave model (FUNWAVE) is a high order, fully nonlinear Boussinesq Wave Model (Chen, 2006; Kirby et al., 1998; Shi et al., 2012). It solves the weakly dispersive and fully nonlinear depth-integrated Boussinesq equations. FUNWAVE has been used to simulate nearshore circulation (Choi et al., 2015; Johnson & Pattiaratchi, 2006) and tsunamis (Watts et al., 2002). Recently the model code has been reimplemented with GPU acceleration (Yuan et al., 2020).

<u>COULWAVE (Cornell University Long and Intermediate Wave Modeling Package)</u>

COULWAVE solves the nonlinear shallow water wave equations and weakly dispersive Boussinesq-type equations (P. J. Lynett & Liu, 2002). Its primary applications include landslide tsunami generation and propagation, nearshore tsunami evolution and inundation, and nearshore wind wave modelling (Acuña, 2005; Wiebe, 2013).

<u>BOUSS-2D</u>

BOUSS-2D solves the weakly and fully nonlinear equations in the time domain using a finite-difference method (Nwogu & Demirbilek, 2001).

<u>MIKE21 Boussinesq Waves (BW)</u>

MIKE21-BW solves weakly nonlinear equations at a low order (Madsen & Sørensen, 1992).

4.2 Nonhydrostatic (NH) wave-flow models

Nonhydrostatic (NH) models are the more recent type of nearshore hydrodynamic models, with their development starting 20 years ago (P. Lynett & Liu, 2004). They were developed to offer a simpler alternative to the BTM, for which latest versions required extremely complex systems of equations and numerical schemes (Kirby, 2017; P. Lynett & Liu, 2004).

NH wave-flow models are able to describe strong non-linearity (Rijnsdorp et al., 2014 ; Li et al, in review JGR). The governing equations are the non-linear shallow water equations, including a non-hydrostatic pressure correction. The Navier-Stokes equations, expressed in one horizontal dimension, for the flow of an incompressible, inviscid fluid are (Marcel Zijlema & Stelling, 2008):

$$\frac{\partial u}{\partial x} + \frac{\partial w}{\partial z} = 0 \qquad \text{Equation 7}$$

$$\frac{\partial u}{\partial t} + \frac{\partial u^2}{\partial x} + \frac{\partial wu}{\partial z} + \frac{g}{\rho}\frac{\partial \eta}{\partial x} + \frac{1}{\rho}\frac{\partial q}{\partial x} = 0 \qquad \text{Equation 8}$$

$$\frac{\partial u}{\partial t} + \frac{\partial uw}{\partial x} + \frac{\partial w^2}{\partial z} + \frac{1}{\rho}\frac{\partial q}{\partial z} = 0 \qquad \text{Equation 9}$$

where *z* represents the vertical direction, *w* is the mean vertical velocity component, *q* is the non-hydrostatic pressure and *ρ* is the sea water density. The local pressure is split into two components, hydrostatic, *g(η-z)*, and non-hydrostatic, *q*. Equation 6 is integrated over the depth to obtain the free surface elevation.

The discretisation of the water column into two or more layers makes the models similar to BTMs, without requiring additional correction for vertical acceleration (Holthuijsen, 2007; P. Lynett & Liu, 2004; Torres-Freyermuth et al., 2010; Marcel Zijlema & Stelling, 2008). The fundamental difference with BTM models is that BTMs rely on higher derivative terms to improve the frequency dispersion, while it is improved in NH models by increasing the number of layers (Marcel Zijlema & Stelling, 2008).

While these models are very efficient, they are also very computationally expensive. For instance, the grid size would need to be about 5 times smaller in both x and y directions compared to a phase-averaged model run, which means approximately 25 times longer to run.

NH models are still new, and only a few of them exist, and their formulations are similar.

XBeach Nonhydrostatic (NH)

The non-hydrostatic module extends XBeach's capability to model non-linear waves, wave-current interaction and wave breaking in the surf zone. It is based upon (Stelling & Zijlema, 2003). The model can be used as a short-wave resolving model in intermediate to shallow water depths, up to *kh* = 2.5, where *k* is the wavenumber and *h* is the water depth (Roelvink et al., 2017).

SWASH (Simulating WAves till SHore)

SWASH was based on the original non-hydrostatic module of XBeach. Compared to XB-NH, SWASH allows for multiple layers. In SWASH, the vertical structure of the flow is a part of the solution and good linear frequency dispersion is expected up to *kh*= 7.

SWASH was demonstrated to successfully simulate nonlinear wave evolution in the surf zone (Rijnsdorp et al., 2015), wave runup (Fiedler et al., 2018; Ruju et al., 2014) and wave overtopping

(Suzuki et al., 2017). SWASH also has the same model interface as SWAN; all source code is open source.

NHWAVE

NHWAVE is a non-hydrostatic wave model (Ma et al., 2012). The model has demonstrated good capabilities at predicting dispersion, shoaling, diffraction, refraction and wave breaking, as well as reproducing tsunami-generated waves. This model's source code is also open source.

MIKE 3-NH

MIKE 3-NH is the only non-hydrostatic model the authors are aware of that utilises unstructured mesh. Unfortunately (like many of the models in the MIKE modelling suite), very little information on this model is available in the peer-reviewed literature. This model's underlying source code is proprietary and using the model requires a commercial license.

5 Discussion and conclusion

Due in large part to the highly variable nature of the geomorphic features and forcing in the nearshore zone, the nature of nearshore hydrodynamic modelling tends to be site- and application-specific. As such, a diversity of modelling approaches exists, in contrast to the more unified modelling frameworks seen in the regional coastal modelling community (Fringer et al., 2019), and no "best" model exists for nearshore prediction. We attempt to summarise the various strengths and limitations of the modelling systems mentioned in the previous sections in Table 1.

Non-hydrostatic wave-flow models are the most accurate hydrodynamic models currently available for simulating nearshore surf-zone processes, particularly transient effects, such as swash-zone dynamics and rip current formation. They are an improvement compared to the BTM models, being more stable and robust than the latter. Both types of wave phase-resolved models however, have limitations. A critical limitation, particularly for operational applications, is their significant computational cost. This generally restricts their use to small-scale or short-duration studies. For instance, experience at Secret Harbour, Western Australia, a site used in a number of studies by authors of this report (e.g. Contardo et al., 2018; Segura et al., 2018), shows that the non-hydrostatic numerical simulation is slower than real-time, i.e. an XBeach-NH run may take four hours to execute an hour of simulation (20 CPUs, 720 x 1100 m domain). Despite these limitations, non-hydrostatic models remain extremely useful for the study of fundamental physical processes in the nearshore.

Conversely, while phase-averaged wave models are generally incapable of simulating transient surf-zone processes, they do not have the duration/domain size limitations of phase-resolved models, and (when coupled to hydrostatic circulation models) have demonstrated reasonable accuracy simulating many aspects of nearshore dynamics, including time-averaged surf-zone circulation (e.g. Gomes et al., 2016; Guérin et al., 2018; Hoeke et al., 2013; Kumar et al., 2015). This generally makes them more appropriate for operational oceanography and forecasting. Such wave-flow model modelling systems also increasingly utilise unstructured mesh computation grids. Unstructured mesh offers greater flexibility in placing the desired resolution at the required locations, allowing improved representation of complex coastlines, islands, reefs, inlets or other coastal features, while maintaining lower resolution in areas of deeper water and/or lower bathymetric relief. Note also that many of these modelling systems include sediment transport/morphological change and/or bio-geo-chemical (BGC) predictive capacities, although an assessment of these is beyond the scope of this report.

XBeach Surf Beat (XBeach-SB) offers an additional advantage compared to other phase-averaged models in its ability to resolve infragravity waves. There are few studies which directly compare phase-average models to phase-resolving models. Buckley et al. (2014) undertook an evaluation of three nearshore wave models, SWAN, XBeach-SB and SWASH. They conclude that all three models predict short wave height with reasonable accuracy and that SWASH and XB-SB were also able to reproduce IG wave height. Lashley et al. (2018) undertook a comparison, which show that XBeach-SB performs as well as XBeach-NH in fringing reef environment. Quataert et al., (2020) ran XBeach-SB and XBeach-NH over a 2D domain and found XBeach-NH to better represent the runup, but that XBeach-SB was more adequate for extreme conditions because of the considerably lower computational effort. Although XBeach-SB does not operate on an unstructured mesh and does not include wind wave growth, these limitations can be overcome by using a coupled wave-flow model that does include wind-generated waves to provide boundary conditions for the XBeach-SB model.

Research and model development into approximations of transient surf zone processes such as infragravity waves based on phase-averaged wave input (e.g. Memmola et al., 2020) and on numerical speed-ups for fully phase-resolved models (e.g. through GPU-acceleration, Yuan et al., 2020) is ongoing, so it can be expected that new, improved physics-based solutions will emerge in the coming years. Also, in many areas of environmental prediction, physics-based simulations are being combined with data science tools to train “hybrid” machine learning frameworks (Fringer et al., 2019). For instance, in the coming years, it may be possible to pre-compute large, probabilistic scenario libraries of nearshore hydrodynamics (for locations known ahead of time), and then use a computationally inexpensive machine learning algorithm to generate the forecast. In the interim, development of nearshore prediction frameworks, which can accommodate and integrate different models and modelling approaches, provide the most robust solution to a range of nearshore prediction problems, operational or otherwise.

Table 1- Advantages and limitations of nearshore hydrodynamic models

Model	Deep water wave dispersion	Wind wave growth	Time averaged wave-induced currents	Wind driven currents	IG waves/ transient surf zone processes	Swash-zone processes	Vertical structure of current field	Un-structured mesh capability	Computational Expense	Open Source	Notes
Phase-averaged wave/hydrostatic circulation modelling systems											
COAWST	Yes	Yes	Yes	Yes	No*	No*	Wave averaged	No	Low	Yes	*New module to estimate IG in recent publication?
Delft3D/Delft3D-FM	Yes	Yes	Yes	Yes	No	No	Wave averaged	Yes*	Low	Yes	*Delft3D-FM utilises unstructured mesh, but can only be coupled with structured SWAN
ADCIRC+SWAN	Yes	Yes	Yes	Yes	No	No	Wave averaged	Yes	Low	No*	*Source code available for research purposes
MIKE21 (HD+SW)	Yes	Yes	Yes	Yes	No	No	Wave averaged	Yes	Low	No	
SCHISM-WWMIII	Yes	Yes	Yes	Yes	No	No	Wave averaged	Yes	Low	Yes	
XBeach-Stationary	Yes*	No	Yes	Yes	No	No	No	No	Low	Yes	*Single short-wave frequency
XBeach-SB	Yes*	No	Yes	Yes	Yes**	Yes**	No	No	Medium	Yes	*Single short-wave frequency **Only IG waves
Phase-resolved Boussinesq-type models											
FUNWAVE	No	No	Yes	Yes	Yes	Yes	No	No	High	Yes	
COULWAVE	No	No	Yes	No	Yes	Yes	No	No	High	Yes	
BOUSS-2D	No	No	Yes	No	Yes	Yes	No	No	High	Yes	
MIKE21-BW	No	No	Yes	No	Yes	Yes	No	No	High	No	
Phase-resolved non-hydrostatic models											
XBeach-NH	No	No	Yes	Yes	Yes	Yes	No	No	High	Yes	
SWASH	No	No	Yes	Yes	Yes	Yes	Yes	No	High	Yes	
NHWave	No	No	Yes	Yes	Yes	Yes	Yes	No	High	Yes	

6 Recommendations

For applications where the primary focus is short-term forecasting for surf-zone operations within a limited area, and there is a need to estimate transient processes such as wave run-up and variations in rip current strength, XBeach-SB is currently the most appropriate model. This is due to its capacity for:

i. reliable performance, demonstrated in several studies;
ii. coupling of phase-averaged wave forcing to nearshore circulation;
iii. ability to resolve infragravity waves; and
iv. reasonable computing requirements, enabling multi-day forecasts on typically available multi-processor computing systems.

However, there are foreseeable situations in which XBeach-SB may not be the most appropriate (nearshore) model. These include when local wind forcing of waves is important (as may be the case with large embayments, harbours or lagoons) and/or when larger (sub-regional) areas need to be modelled; when multi-modal wave spectra may be present; or when knowledge of the vertical structure of currents is required. In these cases, other phased-averaged wave-circulation coupled models of the type discussed in the previous sections and listed in Table 1 may be more appropriate. Successful application and interpretation of nearshore models as operational forecasting tools depends to a large degree on the forecaster understanding the limitations (and strengths) of the different modelling approaches. In many cases, a hierarchy of models will provide the most accurate results, e.g. a sub-regional wave-circulation model, forced by regional (or global) models, with small XBeach domain(s) nested within it.

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