A guide to 'good practice' storm inundation mapping and modelling

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Executive summary

Predicting the extent of coastal inundation associated with storm tide is complex and significantly affected by the local setting (e.g. beach slope, nearshore bathymetry and onshore topography). The Queensland Government recognises that modelling and mapping coastal inundation for disaster management and development planning is a major challenge for local councils. To assist local government, the Queensland Government together with the Australian Government through the National Disaster Resilience Program (NDRP) has funded a detailed report (Lee et al, 2013) by Griffith University which provides a summary of models and considerations that need to be applied to specific site conditions and physical processes relevant to coastal inundation.

This ‘good practice’ guideline is a condensed version of Lee et al (2013) and aims to provide assistance to local governments and others involved in coastal inundation modelling and mapping for the Queensland coast (referred to as Coastal Hazard Mappers (CHM). The guideline offers insight and recommended methods to analyse complicated coastal inundation but does not include prescriptive techniques that can be applied in all study areas. Technical judgement, experience and understanding of coastal and hydraulic engineering is required to model and map inundation. By following this guideline, CHM can help ensure that future storm tide studies and resultant storm tide levels are comparable and useable for a range of end users including:

- storm tide hazard identification;
- emergency management;
- management and mitigation of storm tide impacts and infrastructure design;
- land use planners (strategic planning and planning controls);
- insurers; and
- the community.

For example, disaster management maps required to respond to the threat of storm tide inundation events have very different requirements than storm tide inundation maps for planning purposes. Therefore, currently two different storm tide studies would be required to provide the relevant information for each end user. By applying the recommendations in this guideline it is envisaged that future inundation studies conducted for Queensland coastal communities would incorporate both planning and emergency management requirements.

For more detailed guidance on modelling of storm surge water levels, wave setup and wave run-up please refer to Lee et al (2013); *Queensland Climate Change and Community Vulnerability to Tropical Cyclones – Ocean Hazards Assessment – Stage 1, 2 and 3* (Harper, 2001; Hardy et al, 2004a and 2004b) and *Caboolture Shire Council South East Queensland Storm Tide Review* (GHD, 2007). Guidance for modelling riverine flooding is provided in *Managing the Floodplain: a guide to best practice in flood risk management in Australia* (Australian Emergency Management Institute, 2013).

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ARI	-	Average Recurrence Interval
CHM	-	Coastal Hazard Mapper
DEM	-	Digital Elevation Model
GIS	-	Geographic Information System
HAT	-	Highest Astronomical Tide
MWL	-	Mean water level
NDRP-		National Disaster Resilience Program
SWL	-	Still water line

1 Introduction

A storm surge is a local rise in sea level caused by the combined action of severe winds and low atmospheric pressure systems (tropical cyclones or east coast lows) (Harper, 2001). When a storm surge is combined with normal astronomical tide and wave setup, the overall water level is referred to as the storm tide. The height of the storm tide or (storm tide level) increases as these factors combine to raise the water level above normal levels and push the water up against the coast. When a storm tide level is higher than the Highest Astronomical Tide (HAT), it is likely to cause inundation and flooding in coastal areas.

The storm tide level must be accurately predicted to determine the likely extent of inundation from a storm. The destructive capacity of a storm tide depends on the height of the tide at the time that the cyclone or east coast low crosses the coast. The higher the tide, the more likely it is that destructive flooding and erosion will take place. Interactions between storm surge and tide can occur in a non-linear manner (Rego, J. L., & Li, C. 2010), due to the meeting between the ebb and flow of the tide and the arriving storm surge.

The inundation produced by a storm tide is exacerbated by wave run-up, overtopping, and localized intense rainfall which can lead to coincident flooding if combined with the effects of riverine (freshwater) flooding. For more information on coincident flooding refer to *Coincident Flooding in Queensland: An audit of existing coincident flooding projects* (Queensland Government, 2012).

Figure 1 (Harper, 2001) illustrates how the different components combine to produce a storm tide. One of these components, storm surge, is caused by the interaction of the extreme wind-driven currents and the coastline, which raises coastal water levels above the predicted tide, producing the still water level (SWL). Extreme wind-generated ocean waves and combinations of swell and local wind waves are also driven towards the coast above the SWL. This causes large volumes of water to be pushed against the coast. As the waves break on the coast, some of their energy is transferred to vertical wave setup, potentially yielding a higher mean water level (MWL). In addition, waves travelling up the sloping beach (wave run-up) combined with the elevated SWL can result in the waves reaching the fore dunes with enough height and energy to cause considerable erosion and contribute to coastal flooding.

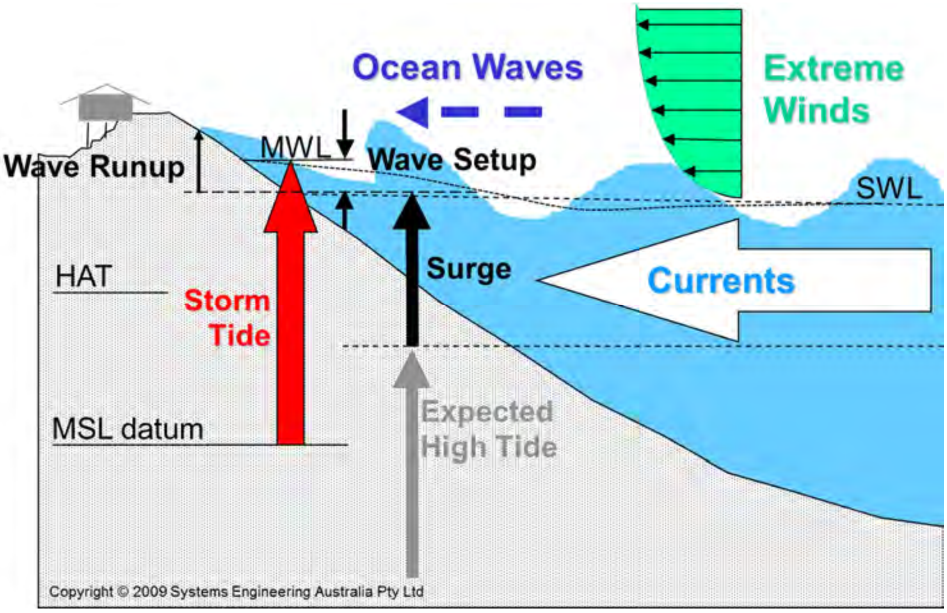

Figure 1: Water level components of a storm tide, after Figure 2.3 in Harper (2001)

Various factors influence storm tide height and inland propagation including storm intensity; storm diameter; angle of approach; storm speed; storm direction; stage of the tide; coastal geometry including offshore coastal shelf width and slope; and coastal topography. Higher intensity cyclones can generate higher storm surges, while larger diameter storms can produce much higher surges than small diameter storms. The faster a cyclone approaches the coast, the more quickly the surge builds up and the greater the impact. Generally, cyclones impacting perpendicular to the coast generate higher surges than those impacting at other angles; however, other impact angles can cause local zones of enhanced surge in areas such as narrow inlets and bays. Wide, gently sloping continental shelves also amplify storm surges. This is because the friction created by the ocean floor over the shallower shelf region slows the storm wind-generated surge, which in turn causes the surge wave length to decrease and the height to increase. Topographic features such as headlands can either amplify or attenuate storm surges, depending upon the prevailing wind direction with respect to the headland. Also surges within enclosed waterways such as bays, estuaries, harbours and inlets can be amplified due to the funnelling of the surge into the smaller shallower area.

When waves enter shallow water they slow down. Under stationary conditions, the wave length is reduced. The energy flux must remain constant and the reduction in group (transport) speed is compensated by a change in wave height.

However, this guideline is more focused on the inland propagation of a storm tide. The potential for inland flooding will depend on the combination of these processes (described in Figure 1) to produce water levels that exceed local coastal barriers and propagate flood waters inland. This guideline will explain how the processes that contribute to coastal inundation will vary in influence based on regional factors, local factors and the relative height of the water.

2 Purpose

This document is intended to provide guidance to state and local government as to ‘good practice’ approaches to inundation modelling and mapping of potential storm tide for both planning and disaster management.

The guideline assists planners and disaster managers (referred to as Coastal Hazard Mappers (CHM)) to assess their inundation modelling and mapping needs to meet their objectives at the appropriate level of accuracy within financial and time constraints. The process, thereby, provides support for an approach that is suitable for the situation, whilst promoting a consistent starting point to decide on a method for delivery.

3 Scope

The next sections provide guidance about the governing coastal processes, their relevant influence along the Queensland coastline, and the number of numerical modelling approaches currently available. Mapping approaches are also provided for the various management needs. This guideline summarises some of the different types of numerical models available to assist the CHM when choosing a model for their study. It is not an exhaustive critical review of all models currently available. This document is a summary of Lee et al (2013). For more detail of particular elements of this guideline, the reader is directed to Lee et al (2013).

This guideline only deals with overland flooding associated with storm tide and not modelling oceanic storm tide processes across the ocean. However, the reader will need a basic understanding of these processes to undertake hydrodynamic inundation modelling. Specific guidance for the modelling of oceanic storm tide processes is provided in the 'Blue Book' *Queensland Climate Change and Community Vulnerability to Tropical Cyclones – Ocean Hazards Assessment – Stage 1* (Harper, 2001) and Hardy et al (2004a and 2004b) and GHD (2007). The two documents should be considered in conjunction when developing a storm tide study, good inundation modelling and mapping needs the support of robust oceanic and coastal assessment to ensure a good outcome.

4 Coastal inundation processes

As described in Section 1, storm tide in the nearshore can be described as the combination of three primary processes:

- the elevation of the water level due to barometric pressure and strong onshore winds associated with the cyclone or east coast low
- the astronomical tides
- wave setup due to increase wave energy pushing water shorewards on sloping beaches.

Although not covered here, the reader is directed to the 'Blue Book' (Harper, 2001) for a detailed description of these processes as they need to be considered when making decisions on inundation modelling.

The potential for inland flooding will depend on the combination of these processes to produce water levels that exceed local coastal barriers such as dunal systems. The processes that contribute to coastal inundation will vary in influence based on regional factors, local factors and the relative height of the water level. For storm tide levels that do not exceed the height of coastal barriers, it is possible to still achieve some inundation due to localised wave run-up and wave overtopping of coastal structures. As the storm tide increases, wave run-up will not be as significant as water overtops the coastal barriers and follows flow paths inland producing fast flowing water. Wave setup may be an important process at this stage to define water levels that overtop the dunes. As the storm tide levels continue to increase, wave setup may become of lesser importance and the hazard may be dominated by water velocities and overland wave propagation, as well as wind pushing the water further inland (note: some of the more complex process such as overland wave propagation by localized wind driven processes are extremely difficult to model inland).

For areas with tidal waterways, the storm tide (less the wave setup) can propagate up the estuaries to flood low lying areas behind coastal barriers that would have otherwise provided protection for the given storm tide level. Wave setup only influences storm tide levels relatively close to the coast (that is within the surf zone).

Inundation models need to represent the natural processes of shallow water flow with distinct processes occurring during the wetting and drying phases over low-lying topography (Nicholas and Mitchell, 2003). Accurate representation of the moving boundary problem and the wetting/drying problem is important, both to realistically capture the shallow water energy losses due to roughness and to correctly predict the extent of inundation. The inundation modelling problem is further complicated when small scale flow interactions such as flow interactions with micro-topography (Walling et al., 1986), vegetation (López and Garcia, 2001) and structures (Meselhe and Sotiropolous, 2000) are taken into consideration. Small scale flow interactions are particularly important along sections of the floodplain that act as pathways for flow conveyance, however, further research is required to better quantify energy losses associated with these processes.

At present bottom roughness is typically used as a proxy to represent energy loss due to micro-topography, vegetation and structures. Many models of floodplain flow presently represent the bathymetry and topography as fixed surfaces for the duration of storm events. During large inundation events, dunes, levees or other protective structures may fail or be breached during an event, which may considerably affect the flow field and flood pathways. Some guidance on this can be found in *Breach of Defences Guidance* (Environment Agency 2017), which provides comprehensive guidance on appropriate methods for including breach scenarios within the model. Due to time and cost constraints, it is recommended to limit such scenarios to locations that can be identified as key structures/ defences.

5 Regional Influence

Five broad geographical regions in Queensland have been defined based on variations in the processes which influence storm tides including wave energy; tidal ranges; influence of cyclones/storms; the proximity of reefs and headlands; anthropogenic activities and geological processes. Figure 2 shows the five regions, namely: Northern Queensland; Central Queensland; Southern Queensland; the Gulf of Carpentaria; and the Torres Strait Islands. For more information refer to the *Queensland Coastal Processes and Climate Change Report* (DERM, 2011).

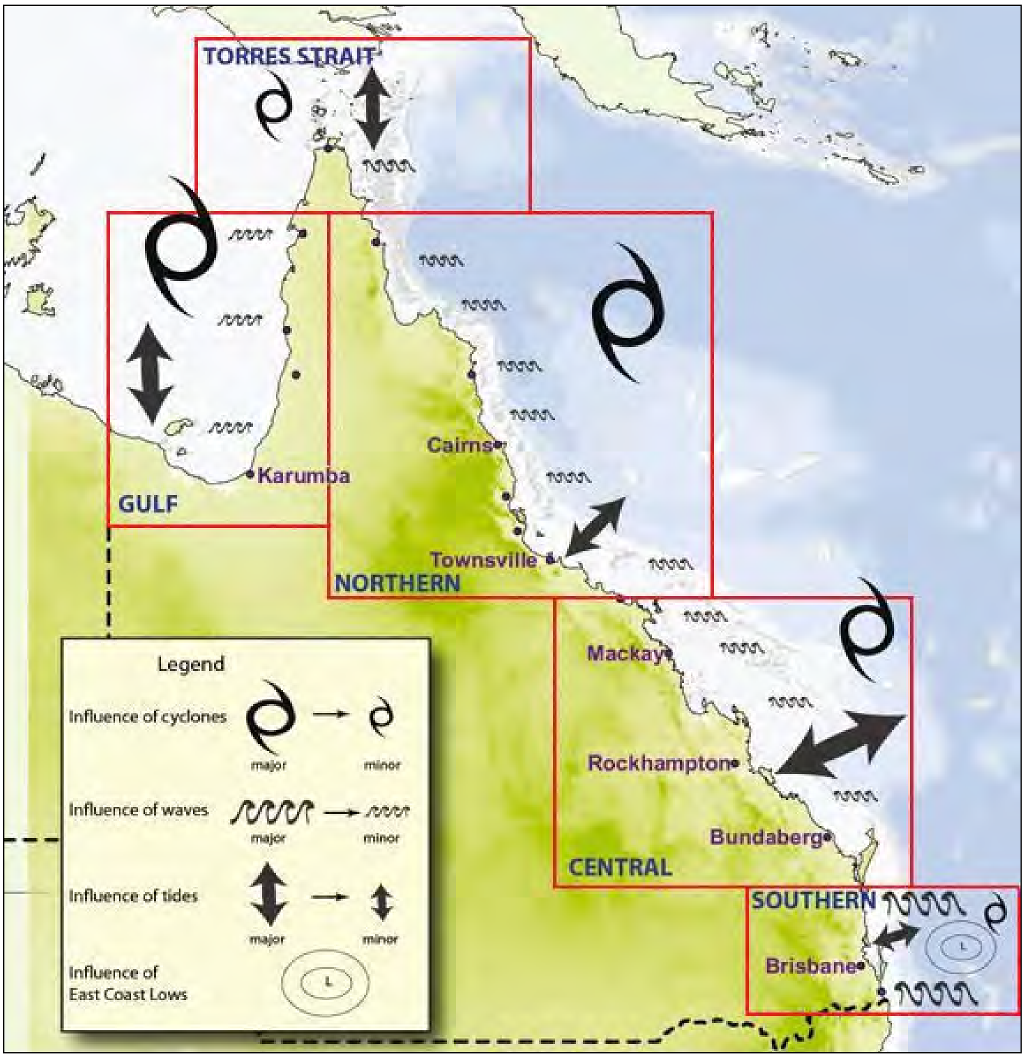

Figure 2: The varying influence of tides, wave, cyclones and East Coast Lows along the Queensland coast Source: Queensland Coastal Processes and Climate Change Report (DERM, 2011).

5.1 Northern Queensland

For the Northern Queensland region from Cape York to Bowen, storm surge due to tropical cyclone events dominates the threat of inundation and can be of larger magnitude than the tidal range. This stretch of coast experiences the highest number of cyclones and the highest incidents of coast-crossing cyclones. The presence of the Great Barrier Reef shelters the North Queensland coast from swell waves, however, high nearshore wind waves associated with tropical cyclones influence storm tide levels. The low dunes typical of the North Queensland coast make it more vulnerable to storm tide inundation.

5.2 Central Queensland

In the Central Queensland region, from Mackay to the northern end of Fraser Island, the interaction of large tides with cyclone-generated storm surge events pose a major threat to coastal areas. The impacts of storm surge will be greater in Mackay where the continental shelf is widest and gently sloping. In this region, the tidal range is of similar magnitude as the expected surge and so the timing of landfall will be important. The wider continental shelf and exposure to south-easterly swell can make wave effects more important, but will depend on location of coastal features.

5.3 Southern Queensland

In the Southern Queensland region, from Fraser Island to Coolangatta, the narrow continental shelf limits storm surge heights so coastal hazards are predominantly due to high wave activity (indicated by the large wave symbol on Figure 2). The combination of storm surge and wave setup acts to increase water depth in the surf zone and rather than breaking on outer and inner bars, waves break on the beach face and beach berm. Under these conditions waves may overtop dunes and coastal infrastructure while the higher wave activity on the beach face transports sediment from the toe of built structures or erodes the berm or fore dune. Wave setup has a greater influence on the height of the storm surge on the Sunshine and Gold coasts, where the continental shelf is narrow and steep. East coast lows as well as cyclones can produce storm surges in Southern Queensland. As east coast lows are slower moving, the storm surges tend to be smaller in elevation but longer in duration. However, the longer the duration of the storm surge the more damage it can do as it is more likely to coincide with high tides.

5.4 Gulf of Carpentaria

The Gulf of Carpentaria is a large shallow sea with a maximum depth of 60 metres, bordered by Cape York and Arnhem Land. In the Gulf of Carpentaria cyclone generated storm surge and astronomical tides are the predominant cause of coastal inundation (Figure 3). The region also experiences yearly riverine flooding during the monsoon season which may further contribute to the inundation of coastal land (coincident flooding). Given the limited fetch for wave growth within the Gulf, and the gently sloping seabed along the coastline, wave setup is relatively minor.

5.5 Torres Strait Islands

The Torres Strait Islands are situated on the continental shelf and the water depth in this region is typically shallow: 15–25 metres deep. Strong tidal currents are the main cause of inundation with tropical cyclones making a lesser contribution to coastal hazards due to the proximity to the equator.

Sustained north-west winds during the monsoon season are also known to contribute to elevated water levels in this region and are a particular threat when they coincide with king tide events.

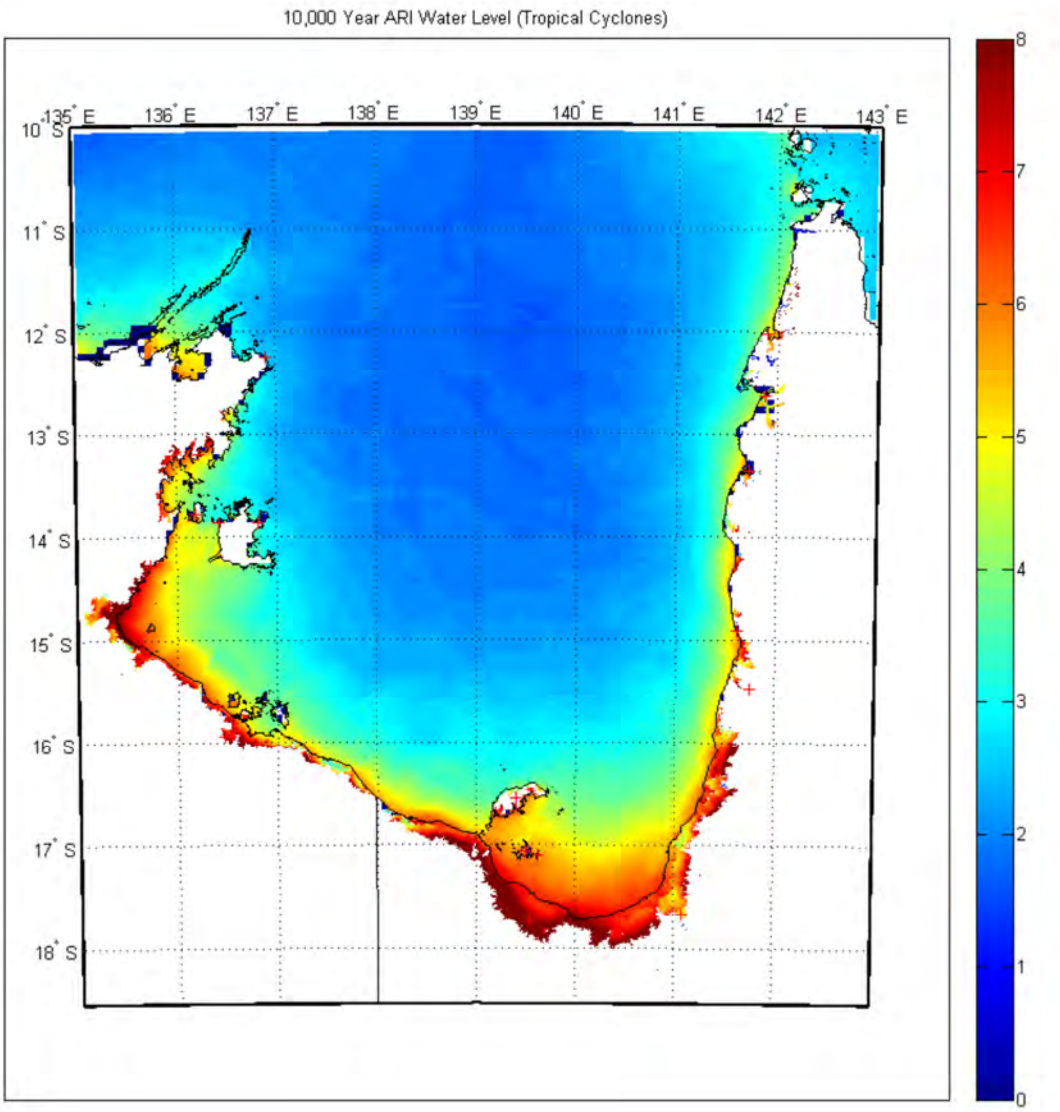

Figure 3: Map showing a modelled 1:10,000 year ARI inundation event for storm tide plus surge for a tropical cyclone at the Gulf of Carpentaria. (Source GHD, 2013).

5.6 Modelling considerations

These regional variations and how they influence storm tide propagation must be considered in the model setup. Embayments along the Queensland coast can amplify storm tide water levels and for this reason particular attention must be given to these areas when investigating coastal inundation. This is particularly the case in the Gulf of Carpentaria, Broad Sound, Repulse Bay, Shoalwater Bay and Hervey Bay regions.

The potential for the storm tide to migrate inland is heavily dependent upon local features such as the topography: geology (e.g. unstable dunes, muddy flats, rocky cliffs, etc.) and land use, including vegetation type; and presence of coastal structures such as seawalls; the presence of structures and urban density are also important variables. Therefore, the influence of both geographical and local factors on inundation processes must be taken into account when modelling inundation.

6 Inundation modelling

As data on actual inundation events is limited, numerical models are typically used to simulate storm tide inundation events and their impacts. These events are influenced by a number of different physical processes and parameters. Traditional approaches to modelling storm tide inundation were limited by the numerical methods available to model the interactive processes, computing technology limitations, and the associated costs. The most common approach involved modelling independently the storm surge using the traditional shallow water formulations, calculating tides and wave setup using empirical approaches, and projecting the combined water level inland as a constant level (known as the ‘bath-tub’ approach).

No single model is presently capable of simulating all the physical processes which contribute to inundation. Therefore, a combination of numerical tools is often used to predict the impact of these severe events on the coast and it is important that the CHM choose a model or combination of models that can accurately model the most dominant processes influencing storm surge for the study area (as outlined in Sections 4 and 5).

6.1 Model basics

To describe the movement of free surface incompressible fluids, the Reynolds averaged Navier-Stokes equations are used. The full 3D version of these equations can be simplified by assuming certain processes are negligible for the desired needs. By assuming depth-averaged flood velocities and hydrostatic pressure distribution, these equations can be simplified to the well-known 2D shallow water or 1D St Venant equations. By simplifying again along the primary flow direction, the 1D St Venant equation can be formulated, which are used extensively for river and channel modelling. For a more detailed description of the 2D shallow water or St Venant equations refer to the *Evaluation of Inundation Models* (Woodhead et al., 2007) or *Benchmarking the latest generation of 2D hydraulic modelling packages* (Néelz, S and Pender, G. 2013.).

To solve this set of complex differential equations, approximate numerical schemes are used that rely on geometrical meshes such that the hydrodynamics at a certain point is determined by the hydrodynamics of surrounding points. Well-known schemes employ finite difference (structured grids), finite volume (flexible meshes) and finite element (triangular meshes).

Generally, the time steps required in these models are directly related to the grid spacing. Increasing the resolution by reducing grid spacing, decreases the time step and dramatically increases computation time. Finite difference approximations can use implicit schemes that can remain stable for longer time steps than the explicit schemes in finite volume approximations. However finite volume use flexible triangular and/or quadrilateral masks that can be adjusted in orientation and resolution in the areas that are need to model complex topographical features.

Although finite difference schemes require a rectilinear grid, nested grids can be utilised to increase resolution. Finite difference schemes can also utilise curvilinear grids that allow the main axis to follow a river or coastline orientation. The equation can be solved on a Cartesian or spherical co-ordinate system, the latter being of importance when modelling at a regional level where the co-ordinate system can no longer be assumed to be rectangular.

6.1.1 Non-model or GIS Approach (Bath-tub)

The non-model or GIS approach, also known as the planar approximation or bath-tub method, is presently the primary approach to estimating storm surge water inundation extent along the

Queensland coast. The bath-tub approach uses mapping tools in GIS to apply a predicted storm tide water level to a digital elevation model (DEM) of an area and any DEM value lower than this is assumed to fill with water, hence the name bath-tub. Maps produced using this technique are inexpensive and fast to produce requiring minimal computing power and specialist knowledge.

The bath-tub approach does not take into consideration the conservation of mass theory, so there is an instantaneous filling of the topography below the given storm tide level regardless of the region being hydraulically connected to the source (no time variable). Therefore, the methodology does not predict flow velocities, inundation flow pathways, or inundation times.

The simplicity of the bath-tub approach can lead to overestimating the areas of inundation in some areas as in reality the water would be flowing into those areas by man-made or topographic features. Mapping accuracy is highest near the shoreline reducing with increased inland distance. To avoid overestimation of the inundation levels it is important to identify if the pre-determined storm tide level used includes wave setup. If it does, this allowance should be limited to approximately 200 metres inland from the dune crest (GHD, 2014) as dissipative processes and inland flow will come into influence.

A recent comparison of bath-tub method versus hydrodynamic modelling for inundation mapping *Comparison of a Regional Bath-tub to Hydrodynamically Modelled Coastal Inundation Levels* (DSITIA, 2014) concluded that while hydrodynamic modelling is more accurate, the bath-tub approach is often the only product available to provide a basic indicator of the inundation risk in many coastal locations in Queensland.

6.1.2 One dimensional storm tide inundation modelling

The modelling of overland flow from storm tides is challenging for strictly 1D models since there may be several flow pathways around and through obstacles, and overland flow paths in coastal areas can be poorly-defined and variable between inundation events. Strictly 1D models are more appropriate for investigating river flooding problems or circumstances where overland flows are confined to predetermined flow paths. Water is assumed to flow in one direction and while actual physical cross-sections vary in two directions the underlying equations assume 1D alignment. It is also assumed that the channel is partitioned, and underlying equations are calculated separately for each partition. Water levels predicted by these models are projected onto elevation maps. As heavy rainfall usually accompanies a cyclone/storm event, the combination of a 1D–2D model can provide a computationally efficient method of modelling the interaction between storm surge and rainfall better than a purely 1D model (Stepinski, 2011). The combined 1D–2D models also have an advantage of being able to model hydraulic structures (e.g. culverts) as 1D elements on the 2D computational grid.

1D wave models rely on alongshore uniformity to simplify the conservation of energy flux equations and do not include complex wave growth terms following the initial breaking. As the bathymetry and topography along natural beaches can be complex, 2D models would be better suited.

6.1.3 Two dimensional storm tide inundation modelling

A number of different methodologies may be used to simulate overland inundation in two dimensions. These include: quasi-2D models; raster-routing techniques; hydraulic models of watersheds in the coastal zone; and hydrodynamic models of coastal waters extended to incorporate adjacent coastal land. These approaches are briefly explained below.

Quasi-2D

The Quasi-2D approach describes the floodplain as a series of cells that correspond to distinct flood compartments typically separated by topographic features. Some 1D modelling packages use this approach by representing off-channel storage as a series of networked flood cells where flow between cells is modelled using Manning’s equations or the weir equations; and level/volume or level/flooded surface area relationships define storage of the floodplain, while 1D St Venant equations describe flow in the main river channel (Syme, Pinnell and Wicks, 2004). When used to model storm surge inundation, quasi-2D models are typically applied to simulate a storm surge propagating up rivers, estuaries or harbours where defined channels are present. Overbank flow either side of the water body may be simulated however overland flow due to a surge propagating directly overland on open coastlines is not modelled. Studies comparing the quasi-2D approaches to 2D and 3D models of storm surge water levels in riverine/estuarine/harbour water bodies show that 2D and 3D models produce more accurate water level results (Mashriqui et al, 2014) but at a higher computation cost.

Raster Routing

Raster routing applies the storage cell concept to a raster Digital Elevation Model (DEM) grid. The floodplain is discretised as a regular grid, and elevation for grid cells is derived from the raster DEM. Inter-cell fluxes are based on the weir equations (e.g. Bates and De Roo, 2000) or uniform flow formulae (e.g. Manning’s equation, Chezy equation). Raster routing methods determine flood pathways based upon DEM data. This approach is scale dependent so accuracy of model output is influenced by the grid size and time step (Syme, Pinnell and Wicks, 2004). The impact of the scale dependency on model accuracy is likely to be more significant when simulating overland flow in regions with highly variable terrain.

2D overland hydraulic models

For 2D hydraulic models, hydrographs describing water level variations at the coast due to storm tides are applied to cells representing the coastline. Wetting and drying schemes are used to simulate the moving water boundary, and the Shallow Water Equations describe the depth-averaged hydrodynamics of the storm tide wave as it moves overland. These equations are solved using finite-difference, finite-element or finite-volume numerical techniques on regular or irregular grids. Elevation data is typically interpreted from DEMs based on detailed ground survey or LiDAR.

Hydraulic models account for bed resistance through the application of friction equations. The user generally has the option of choosing one of a number of various equations (e.g. Manning’s, Chezy) provided for in the modelling package. Common practice is to use mapping of land use, vegetation types, aerial photography and local government planning overlays to identify areas of similar terrain types and assign roughness coefficient values based on published ranges e.g. Queensland Urban Design Manual (Department of Energy and Water Supply, 2013). The roughness coefficients may be adjusted during the model calibration process as a calibration tool to achieve an acceptable model reproduction of a known event.

Some hydraulic models (e.g. SOBEK) now include the option of applying rainfall to the grid as an alternative option to inputting catchment flows as point sources onto the grid. This could be considered for studies involving combined river flooding and storm tide inundation however it is computationally expensive.

Coupled 1D–2D hydraulic models

For basins containing confined flow paths, such as creeks, rivers, stormwater or sewer networks, 2D hydraulic models are often coupled with 1D hydraulic models. This is particularly valuable for large floodplains where modelling the entire system in 2D would require selecting a small grid size to accommodate the confined flow paths, resulting in long model run times. By coupling 2D overland models with 1D models the effect of river flow or flow through constrictions may be modelled computationally efficiently without sacrificing model accuracy. 1D–2D hydraulic models also allow for the modelling of hydraulic structures (e.g. culverts) as 1D elements on the 2D grid which is generally considered a more accurate method of modelling these structures.

While these models are more able to simulate the full range of processes contributing to coastal inundation compared to 1D models, they require more experience with respect to input data and model setup. Improvements in computational efficiency has seen an increase in the use of 2D and linked 1D–2D methods for modelling due to riverine and storm surge inundation.

2D hydrodynamic models

2D depth-averaged hydrodynamic models are similar in many respects to hydraulic overland models, in that the physics, governing equations, numerical schemes (finite-difference, finite-element and finite-volume solved on regular or irregular grids), wetting and drying methodologies, and use of roughness coefficients to represent bottom roughness all apply.

The main difference between hydraulic and hydrodynamic models is the number and location of the open boundaries. Hydraulic models estimate flow in one direction through the open boundaries (e.g. flood models), while hydrodynamic models accommodate flow in two directions through the open boundaries. Overland surge and wave processes can be simulated by coupling a hydrodynamic model to a shallow water wave model. These model setups are now commonly used to investigate the impact of storm tide events including wind-waves on coastal communities.

6.1.4 Three dimensional storm tide inundation modelling

3D hydrodynamic models simulate water movement both horizontally and vertically within the water column by solving the Shallow Water Equations using the hydrostatic and Boussinesq approximations. The same numerical schemes apply for 3D as 2D flow models, i.e. finite-difference, finite-element, and finite-volume solved on either regular or irregular grids. While there are benefits to modelling hydrodynamics in the nearshore region in 3D due to the complex interaction of wave, tide and surge processes with the underlying bathymetry, it comes with a high computational cost. Given that the extent, flow pathways, and flow velocities associated with the overland flow due to storm tide inundation are predominantly horizontal, 2D hydrodynamic or hydraulic models are adequate and more commonly used.

6.2 Model evaluation

Ideally inundation models should provide time series water level, velocity and wave height data at building scale resolutions (for urban areas) in order to predict the extent of inundation, flow pathways to enable the determination of safe evacuation routes, and the likely damage to buildings, infrastructure and vegetation. Numerical models may be constructed to incorporate processes at fine resolutions; however, the more complex the model, the more input data are required for model setup and the more field data are needed, first to calibrate the model, and then to verify the model's ability to replicate each process. Due to the infrequent nature of coastal inundation events, field measurements of overland water levels, velocities and wave heights are typically unavailable, so highly complex models may be unwarranted without suitable input data. The purpose to which the model is to be applied must also be taken into consideration when selecting a model to ensure it can provide model outputs of sufficient accuracy within the necessary time frame.

In order to compare different modelling methodologies,

Table 1 summarises model performance in terms of computational capacity, required expertise, data requirements and financial cost. Given their similarity, 2D regular grid hydraulic and hydrodynamic models are grouped together in

Table 1, as are 2D irregular grid hydraulic and hydrodynamic models. This also applies for 3D model groupings. This table is designed as a guide for coastal managers to select an appropriate model type based upon their needs and the available resources. For a more detailed evaluation of the different modelling types and programs available refer to Lee et al (2013). **Note:** the inclusion of software names is not intended as a recommendation and may not be used for any marketing purposes. Secondly the ability of a model to replicate coastal processes is governed not only by the numerical scheme and the ability of the model to simulate relevant processes, but also by the model setup. Appropriate model setup is vital to the accurate simulation of inundation and engineering expertise is required when using any such model.

Table 1: Summary of model types, their outputs and performance. Single stars represent the lowest rank and five stars represent the highest rank

Model Type	Ability to replicate processes	Ability to predict horizontal extent of inundation	Ability to predict water level	Ability to model flow pathways, temporal changes	Ability to simulate foreshore evolution/erosion	Computational efficiency	Financial cost	Setup time	User expertise	Strengths	Weaknesses
Bath-tub, 0D (e.g. GIS)	★	★★★	★★	NA	NA	★★★★★	★	★	★	Low cost and low computation time.	Does not model flow pathways, temporal water level variations or flow velocity.
1D (e.g. HEC-RAS, CHAMP, MIKE 11, WHAFIS, SOBEK)	★★	★★★	★★★	NA	★★★	★★★★★	★★★	★★★★	★★★★★	Low cost and low computation time. Able to provide time series water level and velocity data at locations along the fixed pathways.	Typically employed for rivers, estuaries or harbours not open coast surge inundation. Cannot simulate inundation between 1D shore normal transects.
Quasi 2D (e.g. ISIS FLOW)	★★	★★★	★★★	NA	NA	★★★★★	★★★	★★★★★	★★★★★	Low cost and low computation time. Simulates horizontal extent of inundation with well-defined flow pathways. Can be used to produce water level time series and velocity time series.	Does not predict flow pathways. Poor representation of complex topographies and urban flood-prone areas. Modelling of velocity is limited. The action of wind waves overland is not accounted for.
Raster Routing (e.g. LISFLOOD-FP)	★★★	★★★	★★★	★★★	★	★★★★	★★★	★★★	★★★	Require relatively little modelling experience. Simple to setup and run. Readily integrated with GIS. Resolutions can be applied which capture important hydraulic and topographic features. Can be used in steady-state or dynamic mode.	Velocity flow data is not well reproduced. Can have poor accuracy depending upon grid cell size and time step. Wind waves overland are not modelled. Potentially long run times.
2D Hydraulic model (finite-difference, finite-element or finite-volume techniques on regular or irregular grids or flexible mesh) (e.g. ANGUA)	★★★★★	★★★★★	★★★★★	★★★★★	★	★★★	★★★★	★★★★★	★★★★★	Can simulate 2D overland flow due to surge, tides and waves. Can model riverine flooding in concert with coastal inundation. Simulates spatial and temporal water level and velocity variations. Able to simulate moving water boundaries.	Complex and requires a high level of expertise to construct. Long computation times.
2D Hydrodynamic models (finite-difference, finite-element or finite-volume techniques on regular or irregular grids or flexible mesh) (e.g. MIKE FLOOD, MIKE 21, TUFLOW, SOBEK, Delft 2D)	★★★★★	★★★★★	★★★★★	★★★★★	★	★★★	★★★★	★★★★★	★★★★★	Can simulate 2D overland flow due to surge, tides and waves. Can employ irregular boundary conditions Simulates spatial and temporal water level and velocity variations. Able to simulate multiple moving water boundaries.	Complex and requires a high level of expertise to construct. Long computation times.
3D hydraulic or hydrodynamic (finite-difference, finite-element or finite-volume techniques on regular, irregular grids or flexible mesh) (e.g. MIKE3, Delft 3D, TUFLOW FV)	★★★★★	★★★★★	★★★★★	★★★★★	★	★	★★★★★	★★★★★	★★★★★	Unlike 2D models which report depth-averaged data. Variations through the water column are simulated in 3D flow models. Simulates 3D flow overland due to storm surge, tides and waves. Able to replicate complex coastal bathymetries/topographies.	High cost and high computational times.

6.3 Model selection

The first stage of an inundation study is to decide the most appropriate model to use given the purpose, dominant processes, available data and resources. It is assumed that storm surge/wave data is either computed as part of the inundation study or is provided as an input parameter (refer to Harper, 2001; Hardy et al., 2004a and 2004b, GHD, 2007). The five steps which influence model selection are discussed below.

6.3.1 Define the purpose of the inundation study to meet end user needs

To determine which model is best fit-for-purpose, the CHM must understand the outputs expected from the model and the required level of accuracy. The expected spatial and temporal resolution will be governed by the purpose to which the model is applied and this must be established before a model is selected. The model outputs expected for both planning and emergency management must be taken into consideration.

6.3.2 Evaluate the most important processes governing water movement overland at the specific location under investigation

Open coasts are subject to inundation from elevated water levels due to surge, wave setup, wave run-up and overtopping as well as barrier breaching. For these coastal environments, separate analyses may be necessary to predict the impact of run-up, overtopping and breaching on inundation since presently they are typically not incorporated into 2D and 3D numerical models and thus must be determined from 1D models or empirical analyses. Data from past storm events should provide information regarding the importance of these processes on inundation for a specific study site. The CHM are expected to use this information to determine if these processes need to be modelled.

The horizontal extent of inundation will be greatest in areas where storm surge is the dominant source of elevated water levels at the coastline. The beach profiles determine the relative contribution of wave setup, run-up and overtopping to coastal inundation. Wave setup, run-up and overtopping are not typically important relative to storm surge in sheltered waters. However, storm surge may be amplified due to funnelling or shoaling in some areas. The location of rivers and estuaries must be considered as coincident flooding may occur when rainfall runoff and river flow combine with storm tide inundation. The importance of catchment flooding, coastal inundation and their combination varies depending on coastal configuration, waterway characteristics, catchment characteristics and the relative vulnerability of the surrounding communities.

The relative importance of modelling small-scale flow interactions differs depending upon the required accuracy of model results. Coastal communities with high population densities and containing critical infrastructure will benefit from more complete inundation models able to represent the influence of small scale features such as buildings, vegetation and land surface irregularities on flow pathways.

6.3.3 Obtain all available field data describing past storm tide and inundation events

Important data includes tide gauge data, wave height data, debris lines, high water marks, meteorological pressure, wind and rainfall data, river discharge (where rivers are present), aerial photos of inundation and shoreline erosion data. Additional sources of information may be provided by local or state government agencies in the form of infrastructure damage reports.

The amount of data available to describe past inundation events may limit the type of model used in an inundation study. If there are insufficient data to calibrate a model then the accuracy of a complex numerical model cannot be determined. For this reason it is important to identify the available field data at a specific location before selecting a model.

6.3.4 Obtain up to date bathymetric, topographic, land use and vegetation data, preferably in digital format

The accuracy of inundation modelling efforts is limited by the accuracy of model input data, in particular topographic and bathymetric data. It is important that the interpretation of topographic data is documented to explain the vertical and horizontal accuracy and, for example, whether buildings have been filtered out or if they are treated as part of the topography. The influence of land use and land cover on overland water flows should be considered and included in the model. For example, altering the bottom roughness coefficient is adequate if only the horizontal extent of inundation is required from the inundation study. However, if flow velocity and flow pathways through urban environments need to be predicted, then buildings must be accounted for.

6.3.5 Model selection.

The flow chart presented in Figure 4 provides some guidance for determining which model methodology is best suited for an inundation modelling and mapping study. The treatment of all processes modelled, or otherwise, must be clearly explained in the reports accompanying a storm tide modelling and mapping study. Inundation modelling may use nearshore shelf sea models extended overland to include the coastal area subject to inundation. Alternatively, a separate overland model may be coupled with a nearshore shelf sea model at the shoreline, with results from the shelf sea model supplying the open boundary conditions for the overland inundation model. To ensure the inundation study meets multiple end user needs, the CHM may opt to use the coupled model setup to produce maps for both planning and emergency management purposes.

Ideally a storm tide inundation study should consider land use planning and disaster management planning needs so that these can be incorporated into the same study.

Disaster management inundation maps have specific requirements including:

- Maps should be referenced to Highest Astronomical Tide (HAT) where HAT is 0 datum.
- The theoretical maximum storm tide (TMST) should also be predicted in addition to determining various annual return year intervals extent of storm tide inundation.
- Horizontal extent of storm tide inundation from HAT to the TMST for a number of increments (such as 0.5 m) should be generated.
- Inundation water depth maps due to storm tide from HAT to the TMST for a number of increments (such as 0.5 m) should be generated.
- Coincident flooding if the study area is also at risk from riverine flooding.

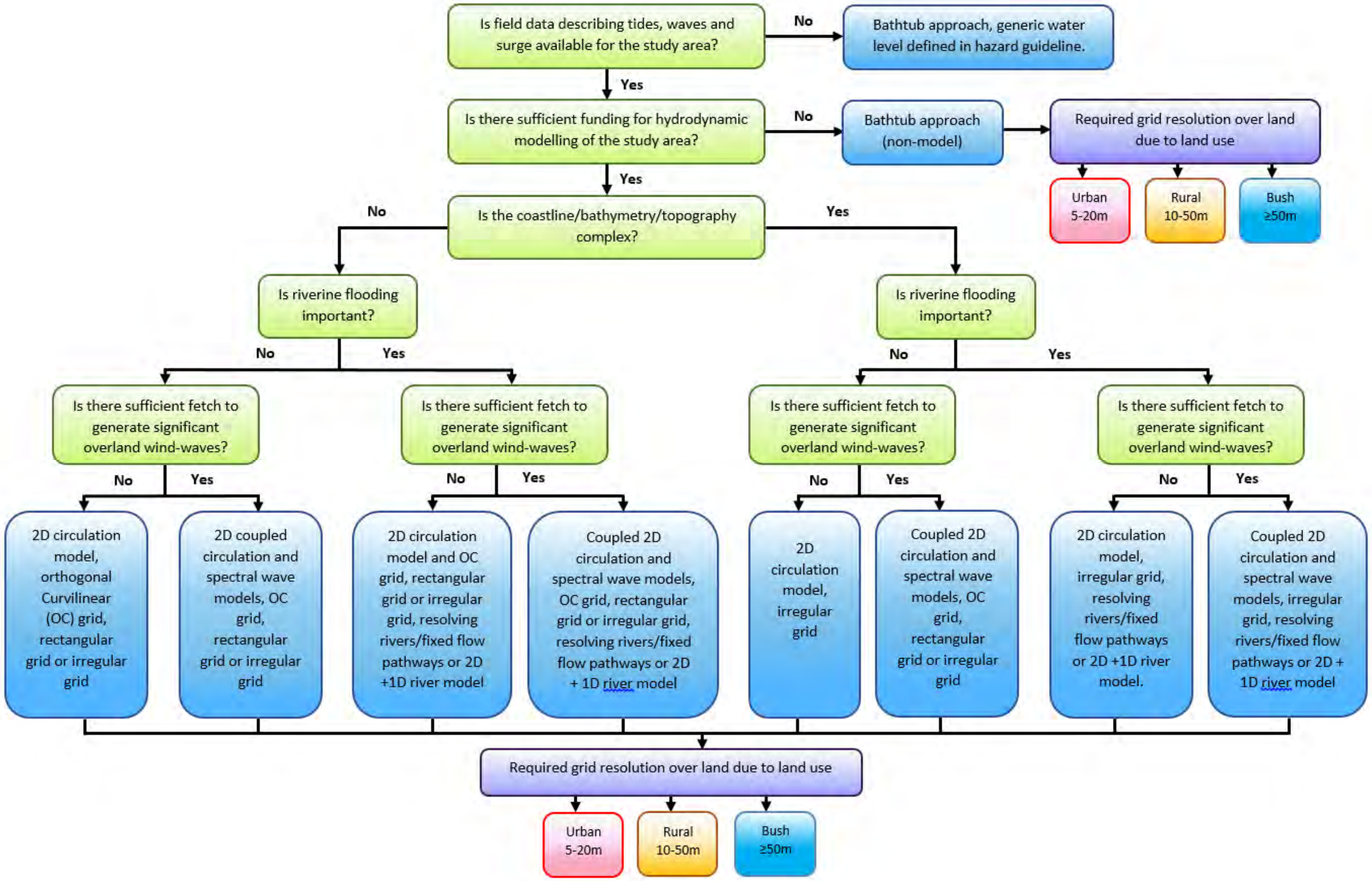

Figure 4: Model selection flow chart.[1]

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[1] The flow chart is designed to guide selection of an appropriate model or combination of models capable of replicating the processes contributing and influencing inundation due to cyclone storm surge and storm generated wind waves. Recommended model types are shown in blue. Recommended grid resolutions are shown in the red, orange and aqua boxes

6.4 Model setup

Model setup considerations are a crucial component of all numerical models and require expertise, experience and skill of the CHM.

6.4.1 Bath-tub

Traditionally, inundation mapping has been primarily based on bath-tub modelling using GIS software. This approach provides the quickest and most cost effective means of obtaining inundation extents. The boundary has typically been defined as a superposition of tide, modelled surge and wave setup determined from empirical formulas.

However the CHM needs to be aware of limitations and possible inaccuracies with this approach. The fundamental assumption is that the water level is constant. In reality, water depth overland will be influenced by the strong onshore winds during an event and flow pathways from waterways and other topographical features. This may result in underestimates and overestimates in depth and inundation extent. Particularly near waterways and over low flat inland areas.

When interpolating a series of coastal storm tide values inland, attempts should be made to take into consideration any topographic features that block inland flooding. Break lines should be constructed to prevent interpolation between river storm tide levels and coastal levels that are separate from higher ground.

The CHM output requirements should also be considered when using this approach. It is often limited in its capacity to include temporal changes in water depth, often important when identifying when a road becomes cut-off for example, Water movement is not considered, excluding outputs such as velocity and hazard mapping.

6.4.2 Grid resolution

Nearshore – Coastal morphological features such as estuaries and other tidal inlets, barrier islands, reefs, lagoons and shoreline configuration strongly influence the prediction of inundation (Shen, et al., 2006). The accuracy of inundation predictions is governed by the ability of the grid to represent these features. Orthogonal curvilinear grids and flexible mesh have significant benefits for applications of complex geometry, or sharply varying flow and concentration gradients. Due to improvements in computational efficiency, flexible mesh or orthogonal curvilinear grids are currently used in preference to the rectangular grids recommended in *Queensland climate change and community vulnerability to tropical cyclones—ocean hazards assessment stage 1* (Harper BA., 2001). Also tides, surge and wave processes are now typically modelled dynamically using coupled circulation and wave models, replacing the linear supposition of tide, surge and wave driven water levels. For coupled wave models, the resolution should include as a minimum 5–10 grid cells within the surf zone. The offshore boundary should also be far enough away from the shoreline to preclude stability and boundary effects in nearshore areas, as this can directly impact inundation levels over coastal structures, such as dunes or defences.

Overland – Refining the nearshore model grid in the overland region may cause numerical stability issues that need to be considered when deciding how best to model inundation. The grid resolution overland must be capable of replicating the terrain. Typically finer grid resolutions will be required to simulate flow paths in urbanised areas where buildings block flow and roadways or spaces between buildings act as conduits for the incoming water. Lower resolution grids may be applicable for coastal areas with slowly varying landscapes or for unpopulated regions where the risk associated with inundation events is relatively low. If inundation extent is the primary requirement and velocities are not needed, then the urban resolution may be relaxed by appropriate adjustment of the roughness.

6.4.3 Wetting and drying

For hydrodynamic/wave models extended from the nearshore zone, overland wetting and drying schemes must be used when determining water levels associated with cyclone events. Hubbert and McInnes (1999) demonstrated that representing the coastline as an infinite barrier caused predicted water levels due to storm surge to be over-predicted. This potential over-prediction must be taken into consideration if using an inundation model forced at the open boundary by a storm surge model.

The CHM must establish whether the storm surge model used a fixed or moving boundary at the shoreline. If the storm surge water level data was supplied by a fixed boundary hydrodynamic model, this must be taken into consideration when determining the accuracy of the inundation model. Typically large scale surge models adopt fixed boundaries to maximise computational efficiencies. Provided the model has been appropriately calibrated and validated, the inaccuracy of this approach should be minimised. These inaccuracies should also be considered in the overall uncertainties associated with climatology, bathymetry and seabed roughness, etcetera.

6.4.4 Sub-grid scale features

Sub-grid scale features include small topographic variations, buildings and infrastructure, coastal structures, fences and vegetation. These features all influence the movement of water overland to differing degrees.

The influence of vegetation is typically accounted for by adjusting the roughness coefficient. This is an area of continuing research. For guidance on the selection of appropriate coefficients refer to Table 2 from Lee et al (2013).

In urban areas buildings may act as barriers to overland flow with water flowing around these obstructions; however, some buildings will present only a minimal obstacle with little influence on flow patterns. Engineering expertise is required to determine whether to incorporate them in the topography (Syme., 2008) or remove buildings from the DEM and represent them in some other way for example, increasing the roughness or friction coefficient (Manning’s n). Guidance is provided in Syme 2008, including recommendation on grid size limitations.

If validation is limited, a sensitivity analysis should be undertaken. If a bare earth DEM is used in urban areas, equivalent roughness values can be assessed by modelling a small urban area with and without buildings included. However comparative studies by Asselman et al., (2009) suggest that grid resolution and topography accuracy may have more of an influence on model accuracy than roughness. For instance, during low flood events, the depths and inundation extent is influenced by adopting a spatial resolution that picks up the roads e.g. 5 m rather than 25 m (Asselman et al., 2009).

Table 2: Manning's coefficients from Lee et al (2013)

Manning’s coefficient for forest and housing			
Aida (1977)		**Kotani et al., (1998)**	
Categories	**Roughness**	**Categories**	**Estimated coefficients**
Dense vegetation	0.07	High density residential	0.08
Relatively dense vegetation	0.05	Middle density residential	0.06
Nearshore including trees	0.04	Low density residential	0.04
Others	0.02	Forest	0.03
		Rice field	0.02
		Water area, rivers and trees	0.025

6.4.5 Model Review

It is recommended that any more complex modelling approach such as 2D hydrodynamic modelling be reviewed (preferably by a competent third party); this should include both the setup of the model and the assumptions made. It is recommended this be conducted before final modelling of scenario’s requested by the client is completed, but after calibration and validation. This will help ensure that model deliverables meet the requirements of end users and that the model receives a good level on confidence whilst accounting for limitations.

7 Recommendations

7.1 Field data

For the future development of inundation models it is vital that a greater effort is made to obtain field data of inundation events. This would allow the proper testing of current numerical models in real-world situations. Inundation events are infrequent; however, advances in meteorological forecasts should allow time to deploy instruments prior to the events. While post-event water marks and debris lines are recorded at some locations, there does not appear to be any consistent requirement for councils to capture this data. However this data combined with instrumental data is essential to improve the council’s ability to predict the likely impacts from future inundation events.

7.2 Modelling

As time and resources become more available it is recommended that all inundation mapping and modelling studies employ at least 2D models to represent overland flow as they can accurately replicate flow pathways in variable landscapes.

7.3 Temporal description of storm surges

Presently storm surge information issued for emergency and disaster management describes the expected height to which water will rise. No information is given about the duration of the elevated water levels. Improved temporal description of storm tide water levels will be beneficial to disaster and emergency managers as well as planners.

7.4 Use and documentation of inundation

In many cases poor decisions made by the end users are due to improper use of storm tide inundation information. Documentation of the background information, assumptions and calibration of the models is essential to the proper use, reliability and consistency of the water levels predicted by storm tide models. Models are designed or made for different purposes and they are not necessarily fit for use. Limits on the purpose and utility of the model should be documented in reports.

TENDER SPECIFICATION AND ASSESSMENT HINTS

- The council or agency commissioning the study needs to obtain the Intellectual Property rights.
- The model is provided as part of the deliverables so that council or agency can value add or run additional scenarios in the future, or reproduce the results if required.
- The tender document should include costs for various model runs.
- ARI probability (1:100) heights should be calculated using a standard methodology (refer to Harper et al., 2001) to allow state-wide comparisons.
- Any levels (ARIs or actual heights) should be separated into individual components i.e. surge, tide and wave setup.
- Error margins / tolerance in outputs i.e. ± 0.5 m should be explicitly stated.

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9 Glossary

Average Recurrence Interval (ARI): A statistical estimate of the average period in years between the occurrence of a flood of a given size or larger than the selected event. For example, floods with a discharge as great as or greater than the 20 year ARI flood event will occur on average once every 20 years. ARI is another way of expressing the likelihood of occurrence of a flood event.

Coastal Hazard Mapper: abbreviated to CHM, is any coastal scientist/engineer employed by government or private organisations who is engaged in studies contributing to the production of Storm Tide Inundation modelling and mapping reports for governments, private companies or private individuals requiring information on the threat of coastal inundation.

DEM: Digital Elevation Models are three-dimensional digital representations of the ground surface topography that show the elevation of the landscape. They represent a 'bare earth' model that excludes vegetation and building.

(Geoscience Australia http://www.ozcoasts.gov.au/climate/sd_digital.jsp)

Finite difference: refers to the numerical solution of differential equations for each node point on a mesh or grid, especially when solving boundary value problems.

Finite element: is a numerical technique for finding approximate solutions to boundary value problems for differential equations.

Finite volume: is a method for representing and evaluating partial differential equations in the form of algebraic equations. Similar to the finite difference method or finite element method, values are calculated at discrete places on a meshed/gridded geometry in hydraulic numerical models. Finite volume refers to the small volume surrounding each node point on a mesh or grid.

Flexible mesh: consists of triangular and quadrilateral elements of different size and shape. Compared to a fixed grid approach this has significant benefits for applications of complex geometry or sharply varying flow and concentration gradients.

Hydraulic modelling: Hydraulic models include the analysis of water flow in waterways; in particular, the evaluation of flow parameters such as water level, extent and velocity (Source: http://www.ga.gov.au/hazards/flood/flood-study-search-help/detail-help.html#hydraulicmodelling)

Hydrodynamic modelling: Hydrodynamic models are able to describe the motion of water in a range of coastal environments. Output can include a time history of water surface elevation, current velocity, temperature, and salinity, as well as transport and fate of constituents included in a coupled transport model. (http://www.nauticalcharts.noaa.gov/csdl/learn_models.html).

Inundation: used to describe the process of land becoming submerged by marine water. Inundation may be caused by surge, tides, wave processes or some combination of all three. The term flooding is used to describe the process of land becoming submerged by fresh water, either from surface runoff or river discharge. A brief description of the above processes is presented in the Introduction section of this report.

Irregular grid: an unstructured (or irregular) grid is a tessellation of simple shapes, such as triangles or tetrahedra, in an irregular pattern. Grids of this type may be used in finite element analysis when the input to be analysed has an irregular shape.

Model calibration: The storm tide inundation levels generated by a numerical model should always be compared or referenced against inundation levels recorded for historical event in the study area.

Modelling: refers to computational/numerical deterministic modelling unless otherwise stated, e.g. physical modelling.

Orthogonal curvilinear grid: is a grid with the same combinatorial structure as a regular grid, in which the cells are quadrilaterals or cuboids rather than rectangles. They allow a wide range of spatial scales while preserving key boundaries and maintaining some of the traditional advantages of gridded representations.

Overtopping: describes the spill-over of waves as they pass beyond the crest of a dune or barrier inundating the land behind.

Regular grid: is a tessellation of n-dimensional rectangles (e.g. bricks) and may be used in finite element analysis as well as finite volume methods and finite difference methods however unstructured grids offer more flexibility than structured grids in finite element and finite volume methods.

Sheltered waters: any body of water that experiences diminished forces from wind and/or wave action relative to the open coast due to the presence of physical barriers, both natural and anthropogenic, either on land or under water. Typical sheltered waters are estuaries and harbours. The Great Barrier Reef Lagoon also fits the definition of sheltered waters.

Storm surge: a temporary increase in the height of the sea at a particular location, due to extreme meteorological conditions (low atmospheric pressure and/or strong winds). The storm surge is the excess height of water above the level expected from tidal variation alone at that time and place.

Storm tide: the absolute combined mean water level reached when storm surge is combined with the normal astronomical tide variation and the wave contribution at the coast. The storm tide level must be accurately predicted to determine the extent of coastal inundation.

Theoretical Maximum Storm Tide (TMST): considers what upper limit of storm surge magnitude might be physically possible through a combination of specifically extreme storm parameters, without regard to their likely joint probability or overall probability of occurrence, and then combines that resulting magnitude with the Highest Astronomical Tide.

Wave run-up: is the extra height reached by broken waves running up the beach/dune/barrier until the wave energy is expended by friction and gravity.

Wave setup: describes the elevated sea level close to the shore produced when energy lost during wave breaking in shallow water is converted into a shoreward momentum flux.