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Comparing static and dynamic flood models in estuarine environments: a case study from south-east Australia

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Abstract

Static and dynamic flood models differ substantially in their complexity and their ability to represent environmental processes such as storm tide or riverine flooding. This study analysed spatial differences in flood extent between static (bathtub) and dynamic flood models (Delft3D) in estuarine environments with different morphology and hydrodynamics in order to investigate which approach is most suitable to map flooding due to storm surges and river discharge in estuarine environments. Time series of observed water levels and river discharge measurements were used to force model boundaries. Observational data, such as tidal gauge and water level logger measurements, satellite imagery and aerial photography, were used to validate modelling results. Flood extents were calculated including and excluding river discharge to quantify and investigate its effect on the mapping of flooding. Modelling results indicate that the mature estuarine system, which has largely infilled broad flood plains, requires a consideration of bottom friction and riverine discharge through dynamic modelling techniques, whereas static models may provide an alternative approach to map flooding at low cost and low computational expense in young lake-like estuarine systems that have not been infilled with sediments. Our results suggest that estuarine classifications based on geomorphological characteristics can potentially guide flood risk assessments in estuarine environments.

Keywords

australia, study, comparing, flood, south-east, static, estuarine, models, dynamic, case, environments:

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Comparing static and dynamic flood models in estuarine environments: A case study from southeast Australia.

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Key words: flood modelling; storm surge; coastal flooding; estuarine geomorphology

Abstract

Static and dynamic flood models differ substantially in their complexity and their ability to represent environmental processes such as storm-tide or riverine flooding. This study analyses spatial differences in flood extent between static (bathtub) and dynamic flood models (Delft3D) in estuarine environments of different morphology and hydrodynamics in order to investigate which approach is most suitable to map flooding due to storm surges and river discharge in estuarine environments. Time-series of observed water levels and river discharge measurements were used to force model boundaries. Observational data, such as tidal-gauge and water-level-logger measurements, satellite imagery, and aerial photography were used to validate modelling results. Flood extents were calculated including and excluding river discharge to quantify and investigate its influence on the mapping of flooding. Modelling results indicate that the mature estuarine system, which has largely infilled broad floodplains, requires a consideration of bottom friction and riverine discharge through dynamic modelling techniques, whereas static models may provide an alternative approach to map flooding at low cost and low computational expense in young lake-like estuarine systems that have not been infilled with sediments. Our results suggest that estuarine classifications based on geomorphological characteristics can potentially guide flood risk assessments in estuarine environments.

33 **Introduction**

34 Storm surges are a major driver of coastal flooding leading to substantial socio-
35 economic impacts (Resio and Westerink, 2008), particularly in estuarine environments,
36 where humans traditionally sought for shelter and developed settlements in close
37 proximity to tidal waters. The associated impacts of storm surges are expected to
38 increase (Hinkel et al., 2014; IPCC, 2014, Vitousek et al., 2017), because even minor
39 flood events, so called nuisance flooding, can cause considerable impacts as a result of
40 sea-level rise (Moftakhari et al., 2017). Furthermore, flooding may intensify when a
41 storm surge coincides with a high spring tide (Pugh, 2004) and/or riverine flooding
42 (Lewis et al., 2013; Zheng et al., 2013; Ikeuchi et al., 2017). This combination of
43 extreme water levels resulting from storm-tide and riverine flooding, referred to as
44 coincident or compound flooding (IPCC, 2014; Leonard et al., 2014), is likely to
45 threaten particularly estuarine environments due to their exposure to storm surges and
46 riverine discharges (Olbert et al., 2017). However, the exacerbation of impacts due to
47 additional riverine floodwater appears to depend on the catchment size of an estuary and
48 its response time to extreme rainfall (Kumbier et al., 2018).

49 The identification of areas threatened by coastal flooding is often done by the use of
50 flood maps, which can be generated through static or dynamic modelling approaches.
51 Both flood models differ substantially in their complexity and their ability to represent
52 environmental processes such as storm-tide or riverine flooding. The static modelling
53 approach, also referred to as “bathtub”, “planar” or “bucket-fill” method, has been used
54 widely because of its ability to simply and quickly generate maps of flood extent using a
55 Geographical Information System (GIS) at low computational costs and short times
56 (Poulter and Halpin, 2008; Van de Sande et al., 2012; Seenath et al., 2016). The
57 approach is based on the assumption that areas lower than a certain water level are
58 inundated if there is hydrological connectivity to the ocean. Static flood models allow
59 only for a specific extreme water level as an input and not spatially or temporally
60 varying water levels from different flooding drivers such as those resulting from storm-
61 tides and riverine discharge. The static model has been found to overestimate flood
62 extent mainly due to the omission of important factors influencing flooding such as
63 bottom friction and the spread of floodwater (Bates et al., 2005; Breilh et al., 2013;
64 Seenath et al., 2016; Vousdoukas et al., 2016). Additionally, the static model assumes
65 peak water levels to be maintained for an infinite duration (Ramirez et al., 2016). The
66 dynamic modelling approach utilizes a hydrodynamic model to simulate the flow of

floodwater resulting from storm surges as well as riverine discharges. A drawback of the dynamic modelling is the more complex model setup, requirements for various high-resolution input datasets and significantly longer computational times, which vary with the level of complexity of the selected model (Teng et al., 2017). Dynamic flood models such as Delft3D, Lisflood-FP or Telemac have been applied in several studies where they consistently demonstrated a satisfactory predictive skill (Bates et al., 2005; Breilh et al., 2013; Lewis et al., 2013; Ramirez et al., 2016; Seenath et al., 2016; Vousdoukas et al., 2016). Therefore, flood risk assessments for coastal hazard management moved towards more advanced modelling approaches such as hydrodynamic models (Vousdoukas et al., 2016; Ramirez et al., 2016) and semi-static approaches (Hanslow et al., 2018) to overcome the known limitations of static “bathtub” models.

Comparative studies of static and dynamic flood models suggest, on one hand, to avoid the use of static models in areas of flat topography, and on the other hand, to potentially apply them in narrow low lands in estuaries or back barrier lagoons (Breilh et al., 2013; Ramirez et al., 2016). Similar findings were observed by Vousdoukas et al. (2016), who related modelling differences in flood extent to the slope of landscapes. They observed small differences between static and dynamic modelled extents for coastlines with steep terrain and larger differences for coastlines with mildly sloping terrains. However, to our knowledge, no study has related modelling differences to estuarine morphology, even though process-based classifications may indicate how the floodplains of an estuarine system are formed and which flooding types are affecting it. Given that estuaries appear to be particularly vulnerable to flooding (Rogers and Woodroffe, 2016), a comparison of static and dynamic modelling approaches in these environments is of importance, as such comparison may highlight under which circumstances static models may give satisfactory results.

Roy et al. (2001) classified the fundamentally different types of estuaries in New South Wales (NSW) based on two criteria: first, in accordance with their inheritance of different coastal settings that create distinct estuary types and second, differing rates of sediment infilling that determine how far along their evolutionary continuum the present-day estuaries have progressed. In the context of flood modelling and coastal flood risk assessment, classification schemes such as those of Roy et al. (2001) may help to decide which flood modelling approach to utilize in which estuarine environment. For example, evolutionary stage in barrier estuaries may indicate the

general shape of the floodplain and whether consideration of bottom friction is necessary or not (Figure 1).

Figure 1: Stages of infilling in an idealized barrier estuary reproduced based on Roy et al. (2001).

Estuaries at youthful or intermediate evolutionary stage are incompletely infilled and have only limited floodplains, whereas estuaries of mature evolutionary stage are generally characterised by wide floodplains that may require consideration of bottom friction. Furthermore, catchment sizes given in classification schemes may indicate if riverine discharge is a factor to be considered when mapping coastal flood extents. These connections between estuarine characteristics and coastal flood risk assessments are known and implemented in NSW guidelines on determination of coastal flooding risk (OEHL, 2015), however, detailed comparison and analysis of flood models in different type of estuaries have not been undertaken. Results of such comparisons may indicate opportunities for the application of static flood models.

In this study we present a comparison of static (GIS) and dynamic (Delft3D) modelled flood extents of a storm event in two wave-dominated estuaries at different evolutionary stage in southern NSW, Australia, in order to identify which processes have to be considered to map flooding in estuarine environments. Additionally, we investigate the contribution of river discharge to modelled water levels and flood extents. We use time-series of observed water levels and discharge measurements to force model boundaries, whereas observational data such as tidal gauges, water level logger measurements, satellite imagery and aerial photography are used to validate modelling results. We expect our results to indicate which modelling approach to use for flood risk estimates at the two presented study sites. Moreover, we aim to relate these results to geomorphological differences between the sites in order to highlight where static flood

models may offer a simple alternative to detailed dynamic modelling to overcome restrictions of input data (e.g. scarce bathymetry data, tidal gauge records, etc.).

Materials and Methods

Study areas

The two study sites are located on the wave-dominated microtidal southeast coast of Australia. Tides are semi-diurnal with a maximum spring tidal range of 2 m at the open coast (Roy et al., 2001). The tidal signal displays a significant diurnal inequality and spatially varies with a decrease of 0.2 m from northern towards southern NSW. Lake Illawarra and the Shoalhaven Estuary are approximately 100 km south of Sydney and contrasting estuarine systems in terms of their estuarine evolutionary stage, floodplain characteristics and hydrodynamics, despite being only 40 km from each other.

Lake Illawarra (Fig. 2) has been categorized as a wave-dominated barrier estuary at an early stage of infill (Roy et al., 2001). Elevations in Figure 2 are given in metres relative to Australian Height Datum (AHD), which approximates mean sea-level. The shallow tidal lake of 36 km² water area has an average depth of 1.7 m and a maximum depth of about 4 m. The system receives runoff from two principal catchments totalling an area of approximately 235 km². The infilling of the estuary is driven by marine and fluvial processes, which create distinct facies with fluvially-influenced deltas propagating into the estuary at Macquarie Rivulet and Mullet Creek, and a marine-influenced flood-tide delta propagating into the estuary through the entrance channel (Sloss et al., 2004; Short and Woodroffe, 2009). There are low-lying floodplains of limited extent, flanking the two deltas of Macquarie Rivulet and Mullet Creek. The entrance of Lake Illawarra used to close intermittently, but training works completed in 2007 stabilised and permanently opened the entrance (Wiecek et al., 2016). Nowadays, tides in the estuary are strongly attenuated once the tidal wave travels through the narrow constrained entrance channel. The entrance gauge displays an average spring tidal range of approximately 1 m, but decreases to 0.2 m at Cudgerie Bay, which is 2.5 km from the entrance gauge (MHL, 2012). After this attenuation tidal range remains quite stable between 0.15 m and 0.2 m throughout the estuary.

Figure 2: Lake Illawarra showing location of tidal gauges (red dots). LiDAR-derived topographic data of the floodplain is presented in m AHD.

The Shoalhaven Estuary occurs at the mouth of the Shoalhaven River, which is one of the largest rivers in southern NSW. The estuary has been categorized as a wave-dominated barrier estuary of mature evolutionary stage with a catchment size of approximately 7150 km² (Roy et al., 2001). Discharge of the Shoalhaven River is regulated by Tallowa dam, which is located approximately 68 km upstream from the coast. Broughton Creek is the largest tributary in the northern part of the floodplain, while the southern part is drained by the much smaller Crookhaven River (Fig. 3). The low-lying floodplain of the estuary developed through estuarine infilling during the past 6000 years (Woodroffe et al., 2000). The waterway of the Shoalhaven Estuary is quite unusual, with a permanent opening at Crookhaven Heads and an intermittent entrance at Shoalhaven Heads. This environmental setting of two entrances of different nature results from the construction of Berrys Canal by landowner Alexander Berry in 1822. Originally the estuary had its opening to the Tasman Sea at Shoalhaven Heads, but with the construction of Berrys Canal the discharge has been redirected towards Crookhaven Heads, which is more protected from wave action and permanently open. In

consequence, Shoalhaven Heads turned into an intermittent opening, which only breaches during large storm events (Carvalho and Woodroffe, 2015). The average spring tidal range at Greenwell Point is approximately 1.4 m and just slightly attenuated towards Shoalhaven Heads and Nowra (1.2 m). Further upstream the tide displays even a small amplification (MHL, 2012).

Figure 3: The Shoalhaven Estuary showing location of tidal gauges (red dots). LiDAR-derived topographic data of the floodplain is presented in m AHD.

In June 2016, a storm event caused extensive inundation of the floodplains surrounding Lake Illawarra and the Shoalhaven Estuary. The storm was due to an East Coast Low (ECL), which tracked south along the eastern coastline of Australia. ECLs are low pressure cyclones, which form in certain synoptic situations initially as a trough and move parallel to the coast (Shand et al., 2011). The 2016 event was characterised by strong winds and heavy rainfall of up to 289 mm (weekly cumulative value) at Wollongong weather station (Burstion et al., 2016).

Data

The topographic dataset for the study areas originates from Light Detection and Ranging (LiDAR) measurements downloaded from the server of Geoscience Australia (<http://www.ga.gov.au/elvis/>). This digital elevation model (DEM) has a spatial resolution of 5 m, a vertical accuracy of at least 0.3 m AHD (95 % confidence) and a horizontal accuracy of at least 0.8 m (95 % confidence). Bathymetric data consisting of point measurements vertically referenced to AHD and taken during hydrographic surveys were collected and provided by NSW Office of Environment and Heritage (OEH; <http://www.environment.nsw.gov.au/estuaries/list.htm>). These bathymetric point measurements were interpolated to a raster using an ordinary kriging method, and merged with the DEM to a seamless topobathymetric dataset.

Water level measurements at 15 min intervals for 4 tidal gauges in Lake Illawarra and 5 tidal gauges in the Shoalhaven Estuary were provided by OEH (distributed through Manly Hydraulics Laboratory). Modelling of flooding at Lake Illawarra used time-series of the entrance gauge, whereas modelling at the Shoalhaven Estuary used measurements taken at Crookhaven Heads gauge. Tidal gauges inside the estuaries (Fig. 1 and 2) were used to validate the performance of the dynamic modelling.

Discharge measurements at 15 min intervals for the Shoalhaven River at Tallowa Dam and Macquarie Rivulet were provided by NSW Water. The Shoalhaven River data were modified during several test simulations to enable the modelling of observed peak water levels at the upstream locations of Terara and Nowra (the device stopped recording around peak discharge). The discharge data recorded for Macquarie Rivulet were also applied at Mullet Creek because no data was available here (the adjacent catchments are of similar size).

Wind data consisting of average wind speed, maximum gusts and average wind direction for Port Kembla, which is just south of Wollongong (Fig. 2), were downloaded from the server of the Bureau of Meteorology (<http://www.bom.gov.au/oceanography/projects/abslmp/data/>). Land use data were obtained from OEH (<http://data.environment.nsw.gov.au/dataset/nsw-landuseac11c>).

The areas flooded during the June 2016 ECL were determined by using Sentinel-1 Synthetic Aperture Radar (SAR) imagery provided by Copernicus Sentinel Data,

which was downloaded using the USGS Earth Explorer (<https://earthexplorer.usgs.gov/>). The imagery was taken on 6 June 2016 at 19:15 LT. Inundated areas were identified through processing of the VH polarization band following the method presented in Kumbier et al. (2018). In addition, the SAR-derived observed flood extent in the Shoalhaven Estuary was visually compared and adjusted using 75 oblique aerial photographs provided by the Shoalhaven City Council (Fig. 4). Examples of photographs of the flood extent observed in the Shoalhaven Estuary at around 17:00 LT are presented in Figure 4.

Figure 4: Selection of aerial photographs taken by the Shoalhaven City Council on 6 June 2016 around 17:00 LT showing the flood extent of the June 2016 storm event. Looking from: Nowra towards east into Broughton Creek floodplain (a), Broughton Creek floodplain towards east (b), Shoalhaven Heads towards south at the breached entrance and Comerong Island (c) and Greenwell Point towards northwest into Crookhaven floodplain (d).

Besides the water level measurements of tidal gauges mentioned above, measurements of two water level loggers (HOBO ® U20-001-04) at Comerong Island in the Shoalhaven Estuary were used to validate the wetting and drying of the adjacent floodplain. Modelling results for these devices are presented in Kumbier et al. (2018).

Static flood model

The static flood model uses a Geographic Information System (GIS) to map the extent of flooding for a particular extreme water level. The flood extents for both estuaries were calculated by geographical selection of inundated DEM locations, which were less than or equal to the observed peak water level at the entrance of the estuaries (1.496 m at Lake Illawarra and 1.653 m at the Shoalhaven Estuary). As the dynamic modelling uses a specific spatial resolution at each study site (15 m at Lake Illawarra and 25 m at the Shoalhaven Estuary), the respective DEMs were resampled using a bilinear interpolation in order to enhance the comparability of static and dynamic modelling results. The selected pixels were further limited to areas, which were in direct connection to the estuary or connected by creeks in order to ensure hydrological connectivity (as presented in Poulter and Halpin, 2008; Van de Sande et. al., 2012). Only pixels with a direct or indirect (eight neighbour cells) connection to waterways were assumed to be inundated. Modelling using four neighbouring cells revealed just very minor differences in modelled flood extents. Finally the maximum flood extents were calculated by the number of pixels belonging to the flood extent and the known pixel dimensions.

Dynamic flood model

Maximum flood extents were simulated with the hydrodynamic model Delft3D (Deltares, 2014) following the modelling setup presented in Kumbier et al. (2018). Simulations solving the unsteady shallow water equations on a rectangular grid were run in depth-averaged mode (2D) and used storm-tide and river discharge measurements recorded for the June 2016 storm event.

Figure 5 illustrates the dynamic model setup for both study sites. The computational grid for Lake Illawarra was set to a spatial resolution of 15 m while the Shoalhaven Estuary was modelled using a 25 m grid. The open boundary of the Lake Illawarra model was forced with time-series of water level measurements taken at the entrance gauge, whereas the two discharge locations at Macquarie Rivulet and Mullet Creek were forced with time-series of discharge measurements taken at Macquarie Rivulet. The Shoalhaven model was defined with two open boundaries (Crookhaven Heads and Shoalhaven Heads), because of the breaching of the intermittent entrance at Shoalhaven Heads during the storm. These boundaries were forced with time-series of water level measurements taken at Crookhaven Heads gauge. The discharge measurements of the Shoalhaven River were used to force the upstream boundary of the model. Unfortunately, no discharge data was available for Broughton Creek and the

Crookhaven River, but given the size of both catchments their influence on water levels in the Shoalhaven Estuary is assumed to be negligible. The performance of both models was assessed by comparison of modelled and observed water levels at 4 monitoring points (Fig. 5 – red dots). Water-level loggers were located at Comerong Island in the Shoalhaven estuary (Fig. 5 – orange stars). Maximum observed flood extents at both study sites are indicated in dark blue (Fig. 5).

Figure 5: The hydrodynamic model domains (grey outline), open boundaries (bold red lines), river discharge locations (green rectangles) and monitoring points corresponding to tidal gauges (red dots), as well as water-level loggers (orange stars). The observed flood extent of the June 2016 ECL is indicated in dark blue.

Simulations of flooding due to the June 2016 ECL were carried out including and excluding river discharges in order to assess their impact on modelled water levels and flood extents. Wind was considered spatially uniform due to the comparatively small model domain and limited data availability. Spatially varying bottom friction with respect to different land use types was defined using Manning's friction coefficients taken from literature (Chow, 1959; Fisher and Dawson, 2003; Kaiser et al., 2011) and assigned to the land use data in a GIS. The simulation time of the storm event was set from 4 June 2016 00:00 LT to 6 June 2016 23:00 LT using a time step of 0.04 min for the Shoalhaven Estuary and 0.02 min for Lake Illawarra. No extensive 'spin-up' period was applied to the driving storm-tide data, however, both models simulated the

observed tide across the domains for approximately 2 days prior the storm-tide peak in order to approximate initial conditions.

Verification and validation methods

The model performance was evaluated through the 3 day simulation period using statistical measures R^2 , RMSE and peak water level differences as presented by Skinner et al. (2015) and Kumbier et al. (2018). The predictive quality of the model was quantified by the goodness of fit measure (F) as presented by Bates et al. (2005). Accordingly, the intersected areas of observed and modelled flood extent (correctly estimated areas) are divided by the sum of both. The F value is close to 1 when the observed and modelled flood extent match exactly, and tends to zero when they do not overlap at all. Percentages of the model's correct estimations, overestimations and underestimations were derived through normalization of the three categories by the observed flood extent (as presented in Ramirez et al., 2016).

Results

Dynamic model performance

Time series of dynamically modelled and observed water level for gauges in Lake Illawarra and the Shoalhaven Estuary are compared in Figures 6 and 7. Red lines correspond to simulations including riverine discharge, whereas black lines correspond to simulations without riverine discharge. Blue lines represent the observed water level at the respective gauges.

Statistical measures of R^2 and RMSE of 0.97 and 0.12 m for the Entrance gauge, 0.98 and 0.12 m for Cudgerie Bay, 0.97 and 0.14 m for Koonawarra and 0.94 and 0.21 m for Macquarie Rivulet indicate that the dynamic model setup in consideration of discharge (Fig. 6 - red line) was able to reproduce the magnitude and timing of extreme water levels in Lake Illawarra resulting from the June 2016 event. The difference between modelled and observed peak water level was +0.03 m for the Entrance gauge, +0.01 m for Cudgerie Bay, +0.02 m for Koonawarra and -0.08 m for Macquarie Rivulet. However, modelled lake water levels at Koonawarra and Cudgerie Bay before the

event's peak were slightly lower than observed ones. Modelled water levels at Mullet Creek differed substantially from observed ones due to inaccuracies in the creeks bathymetry data and the model resolution of 15 m.

Figure 6: Observed (blue) and modelled water levels (red and black) for monitoring points in Lake Illawarra.

Comparison of modelling simulations including (Fig. 6 - red line) and excluding river discharge (Fig. 6 - black line) demonstrated that the lake water level at Cudgerie Bay and Koonowarra gauge was elevated by 0.1 m when river discharge was considered. In contrast, simulated water level at the tributary gauge Macquarie Rivulet was enhanced by 0.67 m. Peak water level at the entrance of Lake Illawarra occurred at approximately 21:00 LT on 5 June 2016. However, peak water levels inside the estuary occurred with a shift of 2 to 3 hours, whereas the water level at Macquarie Rivulet peaked already around midday due to high riverine discharge.

Statistical measures of R^2 and RMSE of 0.98 and 0.09 m for Greenwell Point, 0.98 and 0.15 m for Shoalhaven Heads, 0.99 and 0.15 m for Terara and 0.99 and 0.18 m for Nowra demonstrate that the modelling setup including river discharge (Fig. 7 - red lines) replicates the processes involved very well. Furthermore, a comparison of time series of modelled and observed inundation depth at two sites on Comerong Island (Figs

3 and 5) indicated a reasonable reproduction of wetting and drying processes with overestimations of only +0.04 and +0.07 m at the respective sites (Kumbier et al., 2018). The difference between modelled and observed peak water level was none for Greenwell Point and Nowra, -0.33 m for Shoalhaven Heads and +0.01 m for Terara.

Figure 7: Observed (blue) and modelled water levels (red and black) for monitoring points in the Shoalhaven Estuary.

Omission of river discharge led to large underestimations in modelled water levels at the upstream locations of Nowra and Terara (up to 1.8 m), whereas downstream locations such as Shoalhaven Heads and Greenwell Point were just marginally influenced.

Modelled flood extents

According to the validation dataset the June 2016 ECL inundated approximately 1.21 km² of low-lying areas around Lake Illawarra and approximately 43.5 km² of floodplains flanking the Shoalhaven Estuary. The predictive capability of the flood models (F value as defined above) was only assessed for dynamic simulation including river discharge and the static approach. Modelled flood extents of the static and

dynamic approach, as well as their predictive capability in terms of areas correctly estimated, overestimated and underestimated, are summarised in Table 1.

Figure 8: Locations correctly estimated (green), underestimated (blue) and overestimated (red) by static (left) and dynamic (right) modelling approaches in Lake Illawarra (top) and the Shoalhaven Estuary (bottom).

At Lake Illawarra the static model predicted a flood extent of 3.81 km² and correctly represented 92 % of the observed flood extent (Fig. 8a). Overestimations were equal to 209 % (2.56 km²) and located mainly around Macquarie Rivulet, Duck Creek and Mullet Creek. Underestimations of 8 % in the static flood extent were located mainly around Hooka Creek. The flood extent derived by the dynamic model including river discharge was 1 km² larger than the static modelled one. The dynamic model correctly represented 91.1 % of the observed flood extent and in turn underestimated an area equal to 8.9 % (Fig. 8b). The locations correctly estimated and underestimated were the same as predicted by the static model. The overestimations of the dynamic model were

284 % (3.44 km²). Most of these additional overestimations (compared to the static overestimations) were located around Mullet Creek. The dynamic simulation without river discharge calculated a flood extent of 4.01 km² and was therefore 0.2 km² larger than the static modelled flood extent. The F-Value calculated for the static model was equal to 0.24, whereas the dynamic modelled F-Value was 0.3.

At the Shoalhaven Estuary the static model predicted a flood extent of 82.5 km² and correctly represented 96.9 % of the observed flood extent. These correctly estimated locations were mainly located in the northern Broughton Creek floodplain and in the southern Crookhaven floodplain (Fig. 8c). Overestimations of modelled flooding were equal to 92.6 %. Most of these overestimations were located in the Crookhaven floodplain as well as on Comerong and Kurradjong Islands. Underestimations of 3.1 % in modelled flood extent were located mainly in the southern Broughton Creek floodplain. The flood extent derived by the dynamic simulation including river discharge was 7.6 km² smaller than the static modelling flood extent (Fig. 8d). The dynamic model correctly represented 93.4 % of the observed flood extent, whereas underestimations were equal to 6.6 %. Correctly estimated areas were the same as the static predicted ones while underestimations were mainly located in Brundee and Numbaa Swamp in the Crookhaven floodplain. Overestimations of the dynamic model were equal to 79 % of observed flooding and mainly located in the Crookhaven floodplain surrounding Greenwell Point as well as on Comerong and Kurradjong Island. The dynamic simulation without river discharge calculated a flood extent of 53.9 km² and was therefore 28.6 km² smaller than the static modelling flood extent. The F-Value calculated from the static modelling results was equal to 0.50, whereas the dynamic one was 0.52.

Table 1: Observed flood extents and areas correctly estimated, overestimated, and underestimated using static and dynamic models including and excluding river discharge.

	Observed	Modelled			
	Flood extent (km ²)	Flood extent (km ²)	Correct (%)	Over (%)	Under (%)
Lake Illawarra					
static	1.21	3.81	92	209	8
dynamic (incl. river)	1.21	4.87	91.1	284	8.9
dynamic (excl. river)	1.21	4.01	-	-	-
Shoalhaven Estuary					
static	43.5	82.5	96.9	92.6	3.1
dynamic (incl. river)	43.5	74.9	93.4	79	6.6
dynamic (excl. river)	43.5	53.9	-	-	-

Discussion

Dynamic model performance

The modelling of water levels at the entrance of Lake Illawarra showed small instabilities and a slight underestimation of lake water levels prior the storm-tide peak. The instabilities likely result from the location of the open boundary, as it had to be positioned close to the actual tidal gauge, which is located within a winding section of the entrance channel. The underestimation of lake water levels may result from changes in the bathymetry of the entrance channel. The entrance channel of Lake Illawarra has reportedly changed in recent years (Wiecek et al., 2016) and continues to scour in adjusting to the continuously open entrance (Couriel et al., 2013). Differences between modelled and observed water levels at Macquarie Rivulet and Mullet Creek are likely related to inaccuracies in bathymetric data of the tributaries and the model resolution of

15 m that may have smoothed the deepest channel sections during interpolation. Furthermore, the replication of Mullet Creek's discharge was restricted due to unavailable data. Nevertheless, high correlations between modelled and observed water levels at all monitoring points in Lake Illawarra indicate that the ECL event was replicated reasonably well by the dynamic model.

Water levels resulting from the June 2016 storm event were simulated very well at the Shoalhaven Estuary. Nevertheless, uncertainties in modelled water level remain at Shoalhaven Heads, where peak water level was underestimated by -0.33 m. This underestimation most likely relates to the non-consideration of wave action at the intermittent entrance and is discussed in more detail in Kumbier et al. (2018).

Differences in modelled flood extents

When comparing the two applied modelling approaches, one should note that the static modelling approach is not accounting for river discharge. The large overestimations of more than 200 % in modelled flood extent at Lake Illawarra, most likely result from the fact that the data set of observed flooding did not represent the full extent of flooding. This likely underrepresentation of flooding is due to the reflectance of water from sealed urban areas in the SAR imagery, which complicated the differentiation of wet and dry pixels. In addition, the time shift of approximately 17 hours between storm-tide peak and SAR imagery likely created a dataset that underrepresents the actual flooding at Lake Illawarra. Therefore, the F-values of the models predictive skill were comparatively low at Lake Illawarra. Some of the overestimations at the Shoalhaven Estuary appear to relate to the non-identification of areas inundation with less than 0.25 m and vegetation-like reflectance of saltmarsh and mangrove habitats in the SAR imagery. Limitation of remote sensing based flood detection due to dense vegetation cover have also been observed by Teng et al. (2015). Nevertheless, both modelling approaches demonstrated a high predictive (F-Value 0.52 and 0.5) skill for the simulated storm event at the Shoalhaven Estuary. Underestimations in flood extent may be the result of the spatial modelling resolution of 25 m and 15 m. As the 5 m LiDAR DEM was interpolated to the respective computational grids in order to reduce model run time, a loss of topographic detail is inevitable. In consequence, small creeks and channels that distribute floodwater may have been represented incorrectly. This most likely explains the underestimation of flooding in Numbaa and Brundee Swamp at the Shoalhaven Estuary.

Modelling differences in flood extent between static and dynamic approaches at Lake Illawarra were approximately 1 km² and therefore comparatively small. This difference decreased towards a marginal value of 0.2 km² when river discharge was excluded from the dynamic simulation and demonstrates a great similarity between static and dynamic modelling results when flooding drivers are limited to storm-tide only. In contrast, modelling differences at the Shoalhaven Estuary were comparatively large 7.6 km² and increased to substantial 28.6 km² when river discharge was excluded from dynamic modelling. This increase in modelling differences most likely relates to the disregard of landscape roughness in the static approach, and demonstrates the urgent need to consider these forces in floodplains of flat topography. The differences detected are consistent with observations of Ramirez et al. (2016) and Breilh et al. (2013), who suggested using hydrodynamic models in floodplains of flat topography. Overestimations of static modelling have also been observed in other comparative studies (Bates et al., 2005; Seenath et al., 2016, Vousdoukas et al., 2016), however few studies found good agreement between static and dynamic modelled flood extents.

Modelling implications

When interpreting and comparing differences in flood extent between the study sites, one should have in mind the significant difference in the scale of the estuaries. However, a small difference of only 0.2 km² between static and dynamic modelled storm-tide extents in Lake Illawarra demonstrates that landscape roughness may be a negligible force when mapping coastal flooding in youthful estuarine environments such as Lake Illawarra. Furthermore, the comparison of simulations including and excluding the discharge of tributaries highlighted a marginal enhancement of lake water levels (0.1 m). However, flooding around tributaries was highly influenced by their discharges and floodplain management around these tributaries has to consider river discharge.

In contrast, the large differences of 28.6 km² between static and dynamic modelled storm-tide extents in the Shoalhaven Estuary demonstrates that coastal flood mapping in mature estuarine environments, such as the Shoalhaven Estuary, has to account for landscape roughness across floodplains through dynamic modelling. However, as the replicated storm event caused also high riverine discharge, modelling differences between the static and dynamic approach in Figure 8 were decreased to 7.6 km² through the consideration of river discharge. This interaction of storm-tide and river discharge, so-called compound flooding, is also confirmed by differences of up to 1.8 m in

modelled water levels between simulations including and excluding river discharge at the upstream locations of Nowra and Terara. A detailed analysis of the compound flooding that occurred during the June 2016 event at the Shoalhaven Estuary can be found in Kumbier et al. (2018).

Overall modelling differences between the presented approaches most likely relate to geomorphological features such as catchment characteristics and estuarine infilling stages. In this context, the catchment size of an estuary and its response time to extreme rainfall may determine if riverine discharges have to be considered when mapping flood extents and risk. Furthermore, the infilling stage of an estuary may indicate the presence of floodplains and how these are formed. While estuaries of youthful infilling stage are characterised by comparatively narrow low-lying areas, similar to those suggested for static modelling by Breilh et al. (2013) and Ramirez et al. (2016), mature systems are often characterised by wide floodplains of flat topography, which require consideration of landscape roughness through dynamic modelling. Therefore, geomorphological estuarine classifications such as Roy et al. (2001) for east Australia, Cooper et al. (2001) for South Africa or Perillo's supra-regional classification (1995), may guide which flood modelling approach to utilize flood risk assessments in estuarine environments, and can indicate the broader vulnerability of such systems as has been suggested by Rogers and Woodroffe (2016). While the study sites presented were categorized as barrier estuaries (Roy et al., 2001), other classifications may use different terminology such as bar-built estuary or coastal lagoon (Perillo et al., 1995; Bruner de Miranda et al., 2017). At least 35 estuaries with similar geomorphological characteristics to Lake Illawarra and the Shoalhaven Estuary along the southeast coast of Australia demonstrate the significance of the present study and potential application of static flood models for first-order estimates of flood extent.

As these findings are based on the replication of a single storm event, results should be further verified through the simulation of storm events with different characteristics in terms of magnitude, duration and their occurrence within a two-week tidal cycle. The static and dynamic mapping of flooding at Lake Illawarra may differ for smaller storm surges and/or during neap tides, because friction in the entrance channel may attenuate the surge-residual similar to the tidal attenuation that is usually observed. This expansion of modelling can be challenging as the availability of suitable data to validate flood mapping results is known to be underdeveloped (Molinari et al., 2017) and limited

due to various reasons (Smith et al., 2012). This is particularly true for the detection of flooding in urban areas such as around Lake Illawarra.

Conclusions

This study presented a comparison of static and dynamic modelled flood extents for two wave-dominated barrier estuaries during a storm event in June 2016. Our comparison highlighted that the static “bathtub” modelling may provide reliable first-order estimates of flood extent at low cost and low computational expenses in wave-dominated barrier estuaries at youthful/intermediate stages of infill and similar catchment area (<1000 km²) to Lake Illawarra. Results from the Shoalhaven Estuary demonstrate that storm-tide and riverine flooding have to be considered jointly when managing and mapping flood risk in wave-dominated barrier estuaries at mature stages of infill and similar catchment area (>6000 km²) to the Shoalhaven Estuary. Moreover, the wide floodplains of flat topography require consideration of landscape roughness through dynamic modelling techniques. The findings presented here would benefit from simulations of different storm events and comparison of modelling approaches in other estuaries similar to those presented.

Declaration of interest: None.

Author contributions: KK, ATV and CDW designed the study. KK and RCC set-up the modelling approaches and ran the simulations. KK, RCC, ATV and CDW analysed and interpreted the results. KK wrote the paper with substantial input from all co-authors.

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