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<td>Author(s)</td>
<td>Olbert, Agnieszka Indiana; Comer, Joanne; Nash, Stephen; Hartnett, Michael</td>
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<tr>
<td>Publication Date</td>
<td>2017-01-31</td>
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<tr>
<td>Publisher</td>
<td>Elsevier</td>
</tr>
<tr>
<td>Link to publisher's version</td>
<td><a href="https://doi.org/10.1016/j.coastaleng.2016.12.006">https://doi.org/10.1016/j.coastaleng.2016.12.006</a></td>
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<td><a href="http://hdl.handle.net/10379/16342">http://hdl.handle.net/10379/16342</a></td>
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<td><a href="http://dx.doi.org/10.1016/j.coastaleng.2016.12.006">http://dx.doi.org/10.1016/j.coastaleng.2016.12.006</a></td>
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High-resolution multi-scale modelling of coastal flooding due to tides, storm surges and rivers inflows. A Cork City example.

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Abstract

This paper demonstrates the capability of a new state-of-the-art flood modelling system consisting of multiple nested models to simulate urban coastal flood inundation. A flood event in Cork City, Ireland which occurred in November 2009 is analysed in detail. The new flood modelling system comprises of two dynamically linked models: an ocean model (POM) of the northeast Atlantic (ca. 5 km grid) and a coastal flood model, MSN_Flood, which resolves the hydrodynamics of Cork Harbour and its sub region at four spatial scales 90m, 30m, 6m and 2m through a cascade of four nested grids. Flood water propagation through Cork City floodplains is simulated by the 2m grid model.

The POM-MSN_Flood modelling system, presented for the first time in this paper, was used to investigate the dynamics of coastal flooding resulting from a complex set of tides, storm surges, rivers inflows and the interactions between them. Unlike many flood models, the modelling system used in this research provides a full description of water levels and flow regimes, both in coastal waters and urban floodplains. Validation results clearly demonstrate that the model is capable of resolving hydrodynamics at scales commensurate with flow features including the large scale processes of the NE Atlantic Ocean and the fine resolution circulation of coastal waters. With regards to urban flooding, the model was found to accurately determine flood wave propagation patterns, flood wave heights, speeds and
inundation extents. Ultimately, the model was used to investigate mechanisms of flooding resulting from multiple process drivers and to assess flood risk to human safety. Such an analysis facilitates better understating of the mechanics and dynamics of complex coastal urban flooding and would therefore be of interest in the field of coastal management.

Keywords: Hydrodynamic modeling; ocean model; coastal nested model; Coastal flooding; Urban flooding; Flooding mechanism;

1. Introduction

Due to fertile soils, abundant food sources and access to the sea coastal zones are generally densely populated. As of 1990, population densities in coastal zones are three times the global mean and over 1.2 billion people are living within 100 km of the coast in areas where the land height is less than 100 m above sea level (Small and Nichols, 2003). A significant portion of that population is concentrated around the world’s largest coastal cities that constitute a considerable percentage of global GDP and wealth (Bates et al., 2005); these regions therefore represent a significant value in property and infrastructure. The downside of coastal zone development is their exposure to natural hazards such as storm surges, waves, tsunamis and/or high river flows. These hazards may have catastrophic consequences on human settlements and result in loss of life, damage to properties and disruption to services. Coastal flooding is one such natural disaster.

Coastal flooding occurs in low-lying coastal areas when high water levels due to tides and storm surges, together with waves, overtop or breach coastal defences and inundate low lying areas. While astronomic tides are a deterministic component of sea surface elevations, storm surges and waves are stochastic in nature generated by storm events. Storm surge is a water setup resulting from synoptic variations of atmospheric pressure and wind blowing towards the coast (Flather, 2001). Surge propagation and characteristics on the European Continental Shelf as well as the relation between wind and pressure-driven components of surge are explained in Olbert and Hartnett (2010). Wind waves result from strong winds blowing over adjacent seas; the mechanism of their generation is understood in principle (Gill, 1982). Nevertheless, the combined effect of surges, tides and waves on total water levels still needs
further research due to complex interactions between the three signals in shallow waters. In some areas such as deltas and estuaries, the complexity of the tide-surge-wave flood mechanism can be further exacerbated by a fluvial component, which due to heavy precipitation during storm events results in high river flows and may, therefore, contribute to coastal flooding. These processes are of particular importance and interest in the field of coastal flood risk assessments.

Historic events show that coastal flooding can have devastating social and economic effects. In the southern North Sea, the 1953 storm surge, apart from severe damage, caused ca. 1800 deaths in the Netherlands and over 300 deaths in the United Kingdom (Gerritsen, 2005). The 1991 Bangladesh storm surge caused the deaths of about 140,000 people (Madsen and Jakobsen, 2004). More than 440,000 people have been killed in two storm tide events occurring in 1970 and 1991 in Bay of Bengal. More recently, in the United States of America, the devastating Hurricane Katrina in 2005 caused over 1,800 deaths, while the storm surge from Cyclone Nargis in 2008 killed over 130,000 people in low-lying delta of the Irrawaddy, Burma. Typhoon Haiyan which hit the Philippines in November 2013 affected 14 million people and caused ca. 6,200 deaths.

Mid latitude storms, as often developed in the north east (NE) Atlantic, are usually less devastating and easier to predict than the tropical cyclones (Wolf, 2009). Storms generated in the Atlantic ocean frequently pass through, or are in close proximity to, the European Continental Shelf; the majority of most severe storms occur during winter months (Wakelin et al., 2003). During such events, storm surges both propagated from the deep ocean to the shelf and generated locally together with wind waves tend to cause a significant rise of water level above the expected tidal level (Olbert and Hartnett, 2010).

The island of Ireland, located most westward on the north west (NW) European Continental Shelf, and therefore directly exposed to atmospheric and oceanic conditions present in the NE Atlantic, is at particular risk of coastal flooding. Here, storminess generating water setups and intense precipitation is responsible for both coastal and fluvial flooding and is considered as the major threat to flood-defence structures. Since developments and infrastructure along the Irish coastline are concentrated around urbanized embayments, sheltered to some extent from ocean swell and large wind waves occurring at open coast, the impact of swell and waves on coastal flooding is of secondary importance; this is similar to many regions of the world (e.g. Gallien et al., 2011, Lian et al., 2013). However, wind waves may have an effect on storm
surge development (Bertin et al., 2012 and 2014) and therefore indirectly contribute to coastal flooding; this effect will be discussed in the paper. Nonetheless, in Ireland flooding of the coastal hinterlands is generally caused by three phenomena: high astronomical tides, storm surges and high river flows or a combination of all three (OPW, 2003). Over the last 30 years, storms caused serious flooding around the Irish coastline with overall damage cost running to hundreds of millions of euro. Although, the majority of flood events occur primarily from fluvial mechanism (August 1986, November 2002, November 2009, June 2012), the most devastating are those driven by extreme sea levels in coastal areas (where extreme storm surge coincides with high spring tide) or high sea levels (where extreme sea level is a product of a combination of moderate-to-high-surge occurring at spring tide or an extreme surge occurring with moderate-to-high tide) exacerbated by large river inflows from heavy precipitation. The severe tidal flooding on the east coast of Ireland in February 2002 due to combined high spring tides and extreme surge, generated by a 930 hPa depression passed to the NW of Ireland, impacted most acutely Dublin port areas and coastal residences of Dublin city; this event resulted in 1,200 houses flooded and an estimated damage of €60 M. The tidal flood of October 2004 hit the south of Ireland strongest with severe floods in Cork City and communities along Cork Harbour. Similar scale event was also observed in June 2012. However, the most severe tidal flood on record was reported in January of 2014 where extreme surge coincided with a high tide and exceptionally heavy rainfall in many parts of Ireland resulting in loss of 2 lives and €69 M in damage.

The dynamics of coastal flooding resulting from a particular combination of multiple process drivers is very complex. Understanding flooding mechanisms, predicting extents of inundation and potential damage become important issues in coastal management. One of the key measures to prevent and reduce losses due to floods is to identify future flood-prone areas and provide reliable information to the public about the flood risk. This can be achieved through flood inundation maps which also may also serve in rescue and relief operations post flooding (Cook and Merwade, 2009). Towards this direction, the 2007 Flood Directive adopted by European Union obliges all member states to produce flood inundation and risk maps for their territory by 2015. Technologies exist for producing and delivering flood assessments, such as LIDAR data and GIS for mapping topography, high resolution bathymetry data, dense networks of tidal and river gauges and a range of modelling frameworks, yet these tools are still rarely integrated by authorities into best practice guidelines on how to assess flood risks.
Approaches of varying complexity based on computer models have been used to assess coastal flood extents; they can be either static or dynamic in their implementation. The most simplistic approach is the static inundation method which utilizes total sea water level to inundate locations hydraulically connected with the sea. While this method is relatively accurate for small distance between the coastline and the landward boundary (Breilh et al., 2013) or steep terrains (Ramirez et al., 2016), it significantly over-predicts flood extents for mildly sloping landscapes or larger distances (Ramirez et al., 2016; Vousdoukas et al., 2016; Gallien, 2016). In the semi-dynamic method, the water volume discharge to floodplains in calculated based on timeseries of modelled water levels, hence the flooding is considered as non-instantaneous. Although this is an improvement in comparison to the static method, it still exhibits over-predictive tendencies (Vousdoukas et al., 2016). The advantage of both methods, however, is their quick deployment and therefore ease of flood maps production (Hinkel et al., 2010). The flood intensity index method (Dottori et al., 2016) is another semi-dynamic approach based on a mathematical index considering local topography and flood scenario information. Although, it is found to provide satisfactory predictive skill of flood extent (Vousdoukas et al., 2016), the detail and accuracy of the method cannot be compared with that of hydraulic models (Dottori et al., 2016). Considering that high population densities, valuable assets and critical infrastructure are often located in coastal floodplains, accurate modelling of inundation in coastal areas is critical. In this context, hydraulic modelling is a tool, not only to allow one estimate water levels for particular flood events and flood extents but also to facilitate adequate flood risk management and assist the design of coastal defence structures including the effects of future climate change. The implementation of hydraulic models to simulate inundation progress and ultimate inundation extent can be considered as a dynamic method of coastal flood hazard mapping.

In recent years, along with the availability of high resolution altimetry data (such as LiDAR) and improved computational capabilities, a considerable effort in the development of hydraulic models has been made. The complexity of these models varies greatly from simple 1D hydraulic models (eg. Mark et al., 2004) through, reduced complexity 2-D models (Bates et al., 2010; Skinner et al., 2015), 1D-2D linked models (e.g. Kashefipur et al., 2002; Fewtrell et al., 2011), shallow-water mass and momentum conserving 2D (e.g. Hunter et al., 2008; Mignot et al., 2006, Brown et al., 2007) and 3D models (e.g. Yang et al. 2012) to short wave energy, flow and infragravity wave propagation models (McHall, 2010) or coupled wave-circulation models (Sheng et al., 2010; Bertin et al., 2014). Advantages and disadvantages of
some of these models in regards to model accuracy and computational cost are briefly discussed in Comer et al. (2016) and will be further elaborated in this paper. Usually, satisfactory model accuracy incurs the computational expense of high resolution or, vice versa, low model accuracy is compensated by the lower computational effort of coarse resolution. In this research, a new modelling framework involving multiscale nesting is applied; this approach was developed recently by Nash and Hartnett (2010) and their multiscale nested model (MSN) was found to achieve a good balance between accuracy and computational effort. An additional advantage of MSN is its unique method of treatment of flooding and drying on a complex nested boundary. This aspect is particularly beneficial in flood modelling where sections of the numerical domain are subject to flooding and subsequent drying. For these two reasons, the MSN model seems perfectly suited for coastal flood modelling and thus was used to develop MSN_Flood.

The main aims of this paper are to

(1) demonstrate modelling capability of the new state-of-the-art framework consisting of multiple nested models to simulate urban coastal flood inundation
(2) provide a methodology for comprehensive and accurate assessment of flooding through
   (a) determination of flood wave propagation patterns
   (b) assessment of flood wave heights, speeds and inundation extents
   (c) understanding of coastal and fluvial mechanisms of flooding
   (d) assessment of flood risk to human safety

Such analysis facilitates a better understanding of the mechanics and dynamics of coastal urban flooding. The November 2009, extreme, coastal-fluvial flooding of Cork City, located by Cork Harbour in the south west of Ireland, is selected as a study case. This particular event resulted in extensive floods of residential and commercial property causing damage of €100 M and widespread disruption to services.

In this paper, section 2 presents the Cork City 2009 flood case study while Section 3 presents the methodology including a description of the MSN_Flood model framework, model setup and input datasets. Results including model validation, simulation of flooding and flood risk assessment are presented in section 3. Section 4 contains conclusions from this research.
2. Case Study: 2009 Cork City Flood Event

The 2009 extreme coastal-fluvial flooding of Cork City is used as a test case for model validation. Cork City is a coastal urban agglomeration on the south of Ireland located at the mouth of River Lee that drains into Cork Harbour. The exceptionally high River Lee inflows occurring simultaneously with high sea water levels on the 19th and 20th of November 2009 caused overtopping and/or breaching of the river banks and resulted in widespread inundation across Cork City and surrounding areas. A detailed description of the case study site and meteorological conditions preceding the event is in Appendices A and B, respectively. The summary of Cork City flood causes is given below.

The main reason for the flooding was a release of high volumes of water from two dams upstream of the River Lee as they reached capacity after the extended periods of rainfall in mid-to-late October and the heavy downpours on the 18th and 19th of November. Over the course of one day the Inniscarra dam discharge was increased from 150 m$^3$/s to 560 m$^3$/s; average discharges from the dam are in the region of 40 m$^3$/s. Additionally, limited storage capacity of wet antecedent soil in the catchment resulted in exceptionally high runoff into the River Lee and its rapid flood response tributaries which drain to the River Lee just upstream from the urban area of Cork City. In the lower section of River Lee, water levels were additionally amplified by coastal water intrusion from high sea levels as high surges (0.67 m on November 19th and 0.53m on November 20th) coincided with a high spring tide of 1.8 m above MSL. Interestingly, the surge peaks occurred at rising tide around half way between mid flood and high water (Figure 2). This pattern is consistent with model findings for historic storm events at Cork (Olbert et al. 2013) and with observations elsewhere (Prandle and Wolf 1978, Horsburgh and Wilson 2007).

3. Methodology

The coastal flood inundation modelling system presented here dynamically links a storm surge model of the NE Atlantic with a nested 2D hydrodynamic flood model - MSN_Flood. The modelling system was applied to Cork Harbour in order to simulate the extreme coastal-fluvial flooding event of November 2009. The model theory and setup is now presented.
3.1 Modelling framework

In the modelling system proposed here a cascade of four nested coastal hydrodynamic models (MSN_Flood) of various resolutions is used in conjunction with an ocean model (POM) to describe hydrodynamics at various scales with particular interest in water elevations and velocity fields over the inundated area. The ocean model provides storm surges over the NE Atlantic as water level boundary conditions to MSN_Flood. The novel nested modelling system facilitates the refinement of spatial resolution in Cork Harbour from 90 m in the outer reaches of the harbour down to 2 m in the streets of Cork City.

3.1.1 Ocean model

The storm surge model was developed using Princeton Ocean Model (POM), a three-dimensional hydrodynamic model. Full, 3D primitive equations with hydrostatic assumption and the Boussinesq approximation are solved using the finite difference method. Details of the hydrodynamic formulations can be found in Blumberg and Mellor (1987) and Mellor (2001). A detailed description of storm surge model setup for the NE Atlantic and validation can be found in Olbert and Hartnett (2010) thus only a brief outline is given here.

The computational domain, shown in Figure 1a, covers the area of north east Atlantic and is delineated by the coordinates: 30-0W and 40-60N. The domain extents ensure that the model captures the development of storm surges in the deep ocean, propagation to the shore and transformation into shallow waters (Olbert et al., 2013). The bathymetry was constructed through an amalgamation of the General Bathymetric Charts of the Oceans (GEBCO) 2004 dataset and high resolution data form the Irish National Seabed Survey (INNS) data interpolated onto 1/12 degree longitude by 1/24 degree latitude grid.

The model is forced by variable surface elevations and meteorological conditions. At the lateral boundaries a radiation condition relates the normal component of the depth mean current to the sea surface elevation accounting for tidal input. Tidal spectra consisting of five constituents (K1, O1, M2, N2 and s2) were extracted from the FES99 dataset (Lyard et al., 2006) and interpolated onto the model grid using the bilinear interpolation scheme of Kidner et al. (1999). At the surface boundary, the model is forced by temporally and spatially variable wind stresses in the form of pressure and wind fields climatology. The low pressure system conditions of 17th-19th November 2009 were specified to the POM model as a dataset...
of mean sea level atmospheric pressure and 10m wind fields obtained from the regional analysis ERA-40 model (Uppala et al., 2005) and the operational model level first-guess dataset (Simmons et al., 1989), both provided by ECMWF. Pre-processing of the dataset involved temporal linear interpolation of the 3-hour instantaneous values to the surge model timestep (to ensure a smooth transition from one set of forcing to the other), and spatial bilinear interpolation from 0.5 degree resolution to that of the surge model.

The ocean model is coupled with the coastal model through a bidirectional open boundary in the coastal model so that the ocean model generates a water level curve at the open boundary of the coastal model allowing flows into and out of the coastal model.

3.1.2 Coastal model

MSN_Flood was developed by the authors to simulate urban flood inundation. This is the first time that MSN_Flood has been applied to hindcast a historical flood event. A full technical description of the model can be found in Nash (2010) and validation is presented in Nash and Hartnett (2010 and 2014); a shortened model description is presented here. MSN_Flood is a two-dimensional, depth-averaged, finite difference model that solves the depth integrated Navier-Stokes equations and includes effects of local and advective accelerations, earth rotation, barotropic and free-surface pressure gradients, wind action, bed resistance and Prandtl mixing length turbulence scheme.

A novelty of the model is its unique nesting scheme, which utilizes a sophisticated approach to nested boundary formulations to allow the location of nested boundaries in the flooding and drying zones. This means that large sections of the boundary alternatively flood and dry. The nesting scheme is described in detail in Nash and Hartnett (2010 and 2014) and only a brief outline is given here. The procedure is based on a one-way nesting approach where one or more inner child grids (CG) are nested within a parent grid (PG). Multiple nesting is also permitted so that child grids may also be parents to other child grids. As there are no limits to the number of nesting levels specified, theoretically any required spatial resolution can be obtained. Through nesting, MSN_Flood offers improved accuracy over the lower resolution parent grid model similar to that of a single grid high resolution model; however, the improved accuracy is achieved at a significantly reduced computational effort to the single grid high resolution model.
PG and CG models are dynamically coupled and synchronous, and the parent-child model interactions and nesting procedures are analogous to those of other nested models (Holt et al., 2009; Korres and Lascaratos, 2003; Nittis et al., 2006). The exception is the novel approach to nested boundary formulation. In this approach, the nested boundary consists of internal boundary cells and adjacent to them exterior ghost cells. A sample nested boundary configuration is shown schematically in Figure 3. In contrast to other approaches involving ghost cells, here PG boundary data is specified to both the ghost cells outside the CG domain and to the internal boundary cells. In such a configuration, the governing equations at the nested boundary grid cells are formulated in a similar manner to interior grid cells. Using this boundary formulation and a novel adaptive linear interpolation procedure when specifying boundary data, the nested boundary is essentially converted into a dynamic internal boundary. The boundary operator comprises Dirichlet boundary conditions and a linear interpolation technique as they were found to give the highest level of conservation of mass and momentum between the coarse and fine grids. The nested boundary is highly stable and robust meaning it can be placed in any chosen location including the flooding and drying zone. When placed in such a zone, the boundary can dynamically change its length through flooding and drying becoming a so-called moving boundary. This feature of MSN_Flood is particularly applicable to flood modelling.

3.1.3 Model setup

The flood model system comprises of two externally linked models: an ocean model of NE Atlantic (ca. 5 km grid) providing boundary conditions to a nested coastal model of Cork Harbour that resolves the hydrodynamics of the region at four spatial scales 90m, 30m, 6m and 2m. Water levels consisting of tide and surge signals generated by the ocean model are spatially and temporally interpolated and fed into the Cork Harbour model at each model timestep. In the four-level cascade of nested grids, data from the each coarser grid (PG) are interpolated in space to fill boundary arrays for the next level finer child grid (CG). The structure of the nesting cascade and extent of each grid is shown in Figure 1.

The PG model resolves the hydrodynamics of the entire domain of Cork Harbour at a grid spacing of 90m and a timestep of 18s (PG90). The first level nest CG30 embedded within PG90 downscales the area of interest to the Lough Mahon region at a 3:1 nesting ratio and computes hydrodynamics at 30m grid spacing and 6s timestep. At a nesting ratio of 5:1, the
CG30 model provides boundary conditions to the eastern boundary of CG06 which focuses the area of interest to the River Lee and its estuary. CG06 is resolved at a grid spacing of 6m and timestep of 0.6s. Finally, the highest resolution CG02 is embedded in CG06 at a 3:1 nesting ratio such that the grid spacing is 2m. CG02 resolves the hydrodynamics of the River Lee and its floodplains including the urban area of Cork City.

At the surface boundary, MSN_Flood is forced with atmospheric conditions identical to those used by the ocean model. The lateral boundary of the PG model is forced with the total water elevation composed of tidal and surge signals extracted from the ocean model. This information is further dynamically cascaded down to the highest resolution model. The western open boundary of the partially embedded nest CG06 is a flow boundary specified with the River Lee flow data (gauge station 19011) provided by the Office of Public Works (OPW), Ireland. The location of the boundary was chosen to coincide with the location of the river gauge. The river gauge is positioned downstream of two reservoirs, hydroelectric dams and major tributaries, and therefore captures a significant portion of surface flow from the catchment. The abrupt releases from the Inniscarra reservoir are thus modelled through the flow rate specified at the western boundary of CG06. The rainfall rates are not incorporated directly in the model but are accounted for through river flows in the downstream section of the catchment.

The topography and bathymetry data sources and the process of constructing bathymetry files for the nested Cork Harbour/City models are described in Appendix C.

3.2 Model skill verification

The skill of different aspects of MSN_Flood was evaluated by statistically comparing observations with model results or by comparing results of models at different resolutions. The verification comprised of the application of the following statistical measures that provide a summary of the correlation of two datasets in terms of their:

- correlation coefficient

\[
COR = \frac{1}{N \sum_{n=1}^{N} (y_n - \bar{Y})(x_n - \bar{X})}{SD_x SD_y}
\]  

(1)
• centered root mean square difference

\[
RMSD = \left[ \frac{1}{N} \sum_{n=1}^{N} \left( Y_n - \bar{Y} - (X_n - \bar{X}) \right)^2 \right]^{1/2}
\]  
(2)

• normalized standard deviation

\[
NSD = \frac{SD_x}{SD_y}
\]
(3)

• root mean square error

\[
RMSE = \left[ \frac{1}{N} \sum_{n=1}^{N} (Y_n - X_n)^2 \right]^{1/2}
\]
(4)

• root mean square difference between model and observations

\[
RMSdiff = \left[ \frac{1}{N} \sum_{n=1}^{N} (Y_n)^2 \right]^{1/2} - \left[ \frac{1}{N} \sum_{n=1}^{N} (X_n)^2 \right]^{1/2}
\]
(5)

where \( \bar{X} \) and \( \bar{Y} \) are the mean values, and \( SD_x \) and \( SD_y \) are the standard deviations of variables \( X \) and \( Y \), respectively.

Visual appraisal of model performance was provided using a Taylor diagram (Taylor, 2001) which summarizes statistics of a collection of different models. In a single diagram, CORs, RMSDs and NSDs between model and corresponding observations are used to statistically quantify performance of multiple simulations in a transparent manner. This allows straightforward inter-comparison between various models and, therefore, is particularly applicable at the stage of model verification.

4. Results

4.1 Model validation

Numerical models can provide information about important hydrodynamic features and physical processes such as flooding which can, in turn, be used to provide scientific advice to policy makers and coastal managers to facilitate decision making such as during flood relief
operations. However, the usefulness of a model depends on how well its accuracy has been validated. In this section, model validations at ocean, coastal and urban scales are assessed.

4.1.1 Ocean model validation

The ocean model was extensively validated using water surface elevations and surge residuals for several historic storm events. Surge residuals were extracted from the records using harmonic analysis removing the dominant tidal signal from observed water levels. Results from various coastal locations along the semi-enclosed Irish Sea (Bangor, Fishguard and Holyhead) and Celtic Sea (Cork) were assessed. Water level records for Cork were available through Office of Public Works, while data for Bangor, Fishguard and Holyhead were obtained from British Oceanographic Data Centre. Timeseries of numerical model output and tidal gauge records at Bangor and Cork for one storm event are compared in Figure 4ai and bi, respectively. The numerical model is able to reproduce magnitudes and times of surge peaks. This is confirmed by statistical diagnostics of COR and RMSE of 0.83 and 0.098m for Cork, respectively, and 0.84 and 0.108m for Bangor.

The long-span records from Fishguard (since 1963) and Holyhead (since 1966) allowed an extensive qualitative comparison of surge peak magnitudes. The visual appraisal of correlation shown in Figure 4aii and bii is supported by COR of 0.75 and 0.83 for Fishguard and Holyhead, respectively. The discrepancies between model and observations are likely a result of using 3-hr atmospheric forcing as well as the low frequency of records prior to 1993 (1 per hour) as opposed to high frequency of the model output (1 per 15 minutes). More validation results can be found in Olbert and Hartnett (2010) and Olbert et al. (2013).

4.1.2. Coastal model validation

The application of MSN_Flood to Cork Harbour is described in detail in Comer et al. (2016). Due to space limitations, only key model validation results are presented herein. Figure 5a compares current velocities simulated by the low resolution PG90 with those from a high resolution 30m single grid (SG30) model and measured spring tide velocities. The PG90 and SG30 models have identical physical conditions and coverage. The SG30 solution agrees well with the measured data and significantly outperforms the PG90 solution which under-
predicts velocity magnitudes during slack water. This inter-comparison demonstrates a significant improvement of model skill at higher spatial resolution.

At level 1 nesting, the accuracy of the CG30 model was tested by comparing simulated water elevations and velocities against both PG90 and SG30 model solutions. From Figure 5b and c, it can be seen that while all three models simulate water elevations equally accurately, CG30 significantly outperforms PG90 in the prediction of current velocities by producing results almost identical to those of the SG30 model. These comparisons reveal a need for higher resolution computation in Cork Harbour and the need for nested models.

The performance of the second-level child nest, CG06, is tested against tidal gauge measurements during the November 2009 flood event in Figure 6a. In general, there is a very good agreement between the model and Tivoli tidal gauge data with COR and RMSE of 0.992 and 0.142m, respectively. The final step of model validation involves a comparison between the CG06 model and CG02 model being of particular interest to this research. Figure 6b compares timeseries of water elevations at north canal (point M in Figure 1c). In general, the higher water elevations computed by the coarser CG06 model suggest overpredictive tendencies of the CG06 model. There are some random oscillations in the water levels computed by CG06 which indicate some instability in the model solution. These are not observed in the CG02 water levels, implying that the 2m spatial resolution is sufficiently high to ensure numerical stability of calculations.

4.2 Urban flood modelling

A final assessment of MSN_Flood comprised of an extensive validation of the ultra-high resolution urban flood grid, CG02, against available data for the flood event. One of the main factors limiting the application of urban flood models is uncertainty regarding their accuracy, which is associated with a lack of validation data. Gauges offer reliable measurements of water levels but their confinement to the channel limits their spatial coverage. In contrast, water marks provide information of maximum extent and maximum water surface elevation at the flood peak, but they do not convey temporal information essential for investigating flood dynamics. By their nature, water marks are also usually restricted to urban environments.

After the November 2009 flood event, a good body of evidence of extent and level of flood inundation into Cork City was collected. Water level marks were collated and post-processed
by OPW at 45 survey points across the flooded area. These data, shown in Figure 9, are used to calibrate and validate the MSN_Flood model of Cork City. Initial sensitivity tests showed that the parameter having the greatest effect on the water levels was the roughness coefficient of the channel bed and floodplains.

4.2.1 Bottom roughness parameterization

Determination of the bottom roughness coefficient is a complex task as it is influenced by a wide range of factors including bed material, average grain size, bed forms (ripples, dunes), flow obstructions (e.g. trees or debris), geometry changes or vegetation cover. In a numerical flood model, apart from the channel nature and floodplain structure, the roughness parameter often needs to additionally compensate for the inaccurate discretization of the model topography and/or approximations of physical processes.

Predetermination of the bottom roughness values in the urban flood model of Cork City involved identification of land use types across the model domain. A bed roughness map was generated as a by-product of constructing DTM maps containing information on objects necessary for flood flow classification as through flow (short vegetation, hedges trees) or overflow (roads, man-made surfaces). The surface of the model domain varies widely, and so across-model domain roughness values vary from the section of the floodplain upstream of the city comprising open fields and parkland, to the downstream section containing the urban environment. To reflect local conditions, it was necessary therefore to use different roughness values along different reaches of the model domain. Areas of the floodplain were classified based on land type such as vegetation, roads, upper river reaches and lower tidal reaches. Detailed information on floodplain land use type was aggregated to form five classes of roughness: upper channel, lower channel, upstream floodplain, city floodplain and roads. In total, 104 model runs were carried out, comprising 5 ensembles (Table 1), each of which constituted a combination of various roughness parameters for a particular land use type. For each run, different sets of roughness heights were chosen from the range 0.1 - 1.1m. Model performance was assessed statistically against 38 maximum water levels recorded during the flood.

The Taylor diagram, shown in Figure 7, presents assessment of the model skill for various roughness calibration runs; for clarity, only 25 runs are presented. The Taylor diagram is particularly useful in this study as allows straightforward inter-comparison between
competing models. For two identical datasets, the analysis would yield the following values: COR=1, NSD=1, RMSD=0. It is clear from Figure 7 that results tended to aggregate to form four clusters identified in Table 1. Cluster 1 (green and black dots in Figure 7) comprising of ensemble 1 and 2 is characterized by low roughness heights (0.1m) in roads and city floodplains and high values ranging from 0.9m to 1.1m in the upper and lower channel. Cluster 2 (red dots) representing ensemble 3 is constructed from low roughness heights in roads and city floodplains and values anywhere else ranging from 0.1m to 0.9m. Cluster 3 (ensemble 4 - blue dots) is characterized by high roughness values (0.7-1.1m) everywhere across the numerical domain. In cluster 4 (ensemble 5 - magenta dots), upper and lower channels, as well as upstream floodplains, have wide ranges of roughness values (0.1-1.1m) while roads and city floodplains have fixed roughness heights at 0.5m level.

The best fit model yielded statistical values of COR=0.97, RMSD=0.26, NSD=1.08 and was obtained for roughness values in: upper channel=0.90, lower channel=0.90, upstream floodplain=0.3, city floodplain=0.1 and roads=0.1. This model falls into cluster 1, which comprised the set of most accurate simulations. Interestingly, bottom roughness heights for the upstream floodplain, which were varied from low values (ensemble 1) to high values (ensemble 2), were found to have relatively little effect on model accuracy. Cluster 2 also shows a good match with observations. In contrast, simulations in cluster 4 significantly underestimated the extent of flooding while overestimating the height of the flood wave.

It is apparent from the analysis that the model is sensitive to the roughness of different land use types and, in particular, that of roads and city floodplains. Low ranges of roughness for these two classes significantly improve model performance (clusters 1 and 2). By contrast, little sensitivity to channel friction allows the model to reproduce observed water levels reasonably well for a broad range of roughness values in the channel (cluster 2). Similarly, specification of bottom roughness height for the upstream floodplain is deemed to be of secondary importance to the accuracy of the model. Converting bottom roughness heights to Manning’s roughness coefficient, the best fit model yields coefficients ranging from 0.021 for the lower part of the river to 0.045 for the upper part of the river; this range is in line with other studies (e.g. Yang et al. 2012). It can be seen from the roughness analysis that the correct model parameterization can greatly enhance model performance. Although the parameterization process is rather time consuming and computationally expensive, it is an important step toward successful model construction.
Table 1. Ensembles of bottom roughness heights. Heights in meters

<table>
<thead>
<tr>
<th>Ensemble</th>
<th>upper channel</th>
<th>lower channel</th>
<th>roads</th>
<th>city floodplain</th>
<th>upstream floodplain</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.9 – 1.1</td>
<td>0.7 – 1.1</td>
<td>0.1</td>
<td>0.1</td>
<td>0.9 – 1.1</td>
</tr>
<tr>
<td>2</td>
<td>0.9 – 1.0</td>
<td>0.9 – 1.0</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1 – 0.3</td>
</tr>
<tr>
<td>3</td>
<td>0.1 – 0.9</td>
<td>0.1 – 0.9</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1 – 0.9</td>
</tr>
<tr>
<td>4</td>
<td>0.7 – 1.1</td>
<td>0.7 – 1.1</td>
<td>0.7 – 1.1</td>
<td>0.7 – 1.1</td>
<td>0.7 – 1.1</td>
</tr>
<tr>
<td>5</td>
<td>0.1 – 1.1</td>
<td>0.1 – 1.1</td>
<td>0.5</td>
<td>0.5</td>
<td>0.1 – 1.1</td>
</tr>
</tbody>
</table>

4.2.2 Urban flood model validation

In the process of urban flood model validation a qualitative flood extent is a proxy used as a standard practise. This is an intuitive method that provides a first guess assessment of model performance before a quantitative approach is applied. Figure 8 compares flood extents hindcasted by the model with observed inundated areas compiled by OPW. There is very good agreement between both datasets with a miss rate of merely 1% over the upper and lower floodplains; the discrepancies are localized in the most downstream section of the city at the final leg of flood evolution. Due to rough field assessment of flooding extents, a comprehensive quantitative comparison of the flood extent using statistical tools cannot be performed.

A quantitative validation was based on maximum flood levels, though this method is sensitive to topography errors associated with LiDAR data and terrain details not captured due to the grid resolution. Moreover, good estimates in some locations do not necessarily mean an accurate simulation of a flood event. Using this approach, the modelled flood levels were compared with maximum flood levels at the time of the flood event. In total, 38 points in the downstream section of the river and 7 points in the upstream section were surveyed. The surveyed points were relatively uniformly distributed; for analysis purposes they were categorized into five groups: upper floodplains, north river channel, south river channel, city downtown and lower floodplain where the river bifurcates into north and south channels.

Figure 9a shows differences in water levels between model and observations at points where observations were available. In general, there are no clear trends in the geographical distribution of water level difference values; this is further confirmed by a visual comparison.
between two datasets shown in Figure 9b. In all selected regions there is a very good agreement between model and observations as model solutions against corresponding survey points lie approximately on the 45° line. This implies that model does not have clear regional overpredictive or underpredictive tendencies.

Two datasets for selected regions are also statistically compared in terms of their COR, NSD and RMSE. As shown in Table 2, the average, and absolute maximum, water level difference for all 45 points are 0.060m and 0.148m, respectively, and the contribution to this difference is significantly greater from the upper floodplains than from the lower floodplains. This could be attributed to the fact that hydrodynamics in the upper floodplains are resolved by the 6m CG06 model while the lower floodplains are resolved by the 2m CG02 model. While correlations are very high (>0.85), indicating similar patterns between model and observations, the high RMSEs (>0.15m in most locations) indicate overpredictive tendencies in the model. The exception is the zone of flow bifurcation where RMSE is 0.101m but this is accompanied and contrasted by a relatively low correlation of 0.707. Interestingly, lower RMSE and, hence, better agreement was found for survey locations in the floodplains as opposed to points adjacent to the river bank. Nonetheless, the agreement between model and observations along the river channel is very good. Overall, the validation results confirm that the urban flood model is capable of accurately reproducing the flood event of November 2009.

Table 2. Statistical comparison of observed and computed water levels during flooding at selected regions of Cork City. Differences and RMSE in meters.

<table>
<thead>
<tr>
<th></th>
<th>Number of survey points</th>
<th>Average difference</th>
<th>Average absolute difference</th>
<th>COR</th>
<th>NSD</th>
<th>RMSE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Whole region</td>
<td>45</td>
<td>0.060</td>
<td>0.148</td>
<td>0.987</td>
<td>1.050</td>
<td>0.207</td>
</tr>
<tr>
<td>Upper floodplain</td>
<td>7</td>
<td>0.043</td>
<td>0.165</td>
<td>0.993</td>
<td>1.061</td>
<td>0.160</td>
</tr>
<tr>
<td>Flow bifurcation zone</td>
<td>8</td>
<td>-0.010</td>
<td>0.014</td>
<td>0.707</td>
<td>1.410</td>
<td>0.101</td>
</tr>
<tr>
<td>River channel</td>
<td>7</td>
<td>0.006</td>
<td>0.031</td>
<td>0.983</td>
<td>1.154</td>
<td>0.186</td>
</tr>
<tr>
<td>South canal</td>
<td>8</td>
<td>0.029</td>
<td>0.037</td>
<td>0.975</td>
<td>1.069</td>
<td>0.209</td>
</tr>
<tr>
<td>City downtown</td>
<td>9</td>
<td>0.013</td>
<td>0.027</td>
<td>0.854</td>
<td>1.038</td>
<td>0.163</td>
</tr>
</tbody>
</table>
4.3 Evolution of flood inundation

In this section, the temporal and spatial development of the November 2009 flood inundation into floodplains of Cork based on the model hindcast is detailed. As explained in section 2.2.2, the flood was triggered by both fluvial and coastal mechanisms when exceptionally high river discharges coincided with high water elevations due to spring tides and moderate surge. Progression of the flood waters into the rural grounds of upper floodplains and lower urban floodplains is shown in Figure 10 using maps of 6-h instantaneous water levels simulated by the CG06 model. The dynamics of flooding in the urban environment of Cork City are shown using inundation maps at 4-hr intervals from the CG02 model (Figure 11). The visual presentation of inundation extent is supported quantitatively through volumetric and aerial measurements. Temporal progression of the inundation is shown as total inundated area (Figure 12a) and total volume of water outside the river channel (Figure 12b).

Around 21:00 on November 18th, the River Lee starts to overtop and/or burst its banks at numerous low-lying locations in the upper floodplains (Figure 10a). Over the course of 24 hours the inundation occurs mainly in the rural area of the upper floodplains. As Inniscarra dam discharge continues to increase, the progress of inundation is fast (Figures 10a-g). Flood waters spill into urban floodplains around 04:00 on the morning of November 19th (Figure 12a-b) when river flows exceed 200 m$^3$/s while the sea water levels at the river mouth reach 1m above MSL and are rising. By 17:30 approximately, 113 hectares of upper floodplains and over 16 ha of urban floodplains have been flooded. Over the next two hours, the rate of urban flooding significantly accelerates as the flood water starts to spread through the south bank towards the city centre. As can be seen in Figure 12a, between 17:30 and 19:30 the inundated area of the city floodplains doubles to 32ha. This is a combined effect of gradual increase in river discharge, incoming flood high tide and surge of 0.56m peaking around 17:45. The flooding continues to increase for another two hours as the tide reaches its maximum height and river discharges further increase. At 21.30 (Figure 11b), almost 45 ha of urban land is submerged by approximately 365,000 m$^3$ of water. During the early hours of November 20th, the flood wave further propagates through the street network, though at slower rate as the tide is ebbing (Figure 11c). The rate of flooding intensifies again on the subsequent rising tide and, despite decreasing river discharges (max discharge reached at 04:00), the maximum extent of flooding is reached at 09:30 on November 20th (Figure 11e).
around the time of high spring tide. As can be seen from Figure 12a-b, 62.6 ha of the Cork City area is estimated to be flooded at that stage by approximately 535,000 m$^3$ of water. The total inundated area, including the upper floodplains, reaches almost 200 ha at this juncture, with a total flood volume of 2.8 x 10$^6$ m$^3$.

The flood wave evolution shown in Figures 10 and 11 clearly shows that once the flood water overtops the river banks, the pattern of spatial evolution of flooding is floodplain geometry-driven. When overbank waters start to fill the floodplains, the floodplains begins to behave as a channel conveying the flood water wave. The west-east sloping of the urban floodplains towards the downtown area dictates a generally eastward flow direction, although the complex topography of the floodplains makes the flow pattern intricate with rapid transitions. Flood waters initially move fast, eastward along the river banks through recreational grounds and gradually slow as they reach the dense network of narrow streets in the downtown area. In this zone, a transition from river to coastal flood dominance occurs. These mechanisms are explained in the following section.

4.4 Flooding mechanisms

As explained in the methodology, the mechanism of the November 2009 flooding is complex due to the combined effect of fluvial and coastal dynamics and the contribution of individual components to the flood event has not yet been understood. Based on the topography of Cork City, it is expected that the most eastward downtown area is exposed to flooding due to high sea levels while the upper reaches (west) and mid-city are affected by high river discharges. The western downtown section is a transition zone where flooding is a combination of mechanisms.

In this section the flood event is analysed in respect to the separate effects of coastal and fluvial mechanisms. The extent of sea water propagating upstream into the River Lee results from the concurrence of tide and surge. As shown in Figure 2, during the flood event the total sea water levels consisted of high spring tides of amplitude 1.8 m (return period < 1 year) and moderate surge residual. The maximum surge peak of 0.67 m, corresponding to 1 in 7 years return period (Olbert et al., 2013), coincided with the rising tide just after the mid-flood level. This pattern of tide-surge co-occurrence is characteristic of Cork Harbour and results from interactions between tide and surge which result in surges tending to peak at a particular
phase of tide. In their analysis of 48 historic storm surge events, Olbert et al. (2013) clearly show that surges in Cork are more likely to peak around the time of mid-water rather than at low or high water. Such interactions prevent water levels from reaching their maximum possible levels by surges peaking on high tide.

With regards to fluvial flooding, the River Lee causes frequent flooding of Cork City as a result of heavy precipitation in the Lee catchment (Halcrow, 2008). Extensive statistical analysis of dependency (not presented here) between 6 river gauges and 10 rain gauges in the Lee catchment indicate that the fluvial component of flooding in Cork City is directly controlled by discharges from the Inniscarra dam rather than local precipitation rate. The peak dam discharge of 560 m$^3$/s was the highest on record since the commencement of dam operation in 1957.

Flooding in Cork City can be due to coastal mechanisms, fluvial mechanisms or a combination thereof. Considering flooding separately for fluvial and coastal mechanisms, it is clear that the coastal component does not cause flooding on its own but it exacerbates the effect of fluvial flooding. The maximum water level of 2.12m above mean sea level is well below the 50-year return period value of 2.44m. Existing coastal defence structures prevent flooding from such low return period events. Nonetheless, the contribution of sea water to urban flooding is significant, as can be inferred from Figure 12c showing the temporal progression of inundated area for various sea water level conditions. When high river discharge coincides with astronomical spring tides of amplitude 1.8m (surge excluded), the maximum inundated area constitutes 93% (58.5ha) of that (63ha) resulting from the combined effect of high river discharge, spring tide and moderate surge. This 7% difference represents then the effect of surges on extent of flooding. In contrast, when neap conditions (1.0 m) are considered, the corresponding flood inundated area is 81% (50ha) for tide only and 82% (51.4ha) for tide and surge case. The occurrence of surge peak on a neap tide does not effectively contribute to flooding. This quantitative analysis is complemented by a qualitative analysis showing the spatial development of flooding as a function of time (Figure 13). Comparing spatial distributions of flood water due to river discharges with spring tides (Figure 13a) against river discharges with neap tide (Figure 13b) a marked difference in flood pattern arises. Although the fluvial mechanism is a main driver of flooding in the majority of city locations, the analysis demonstrates that the coastal mechanism is most effective in the narrow dense streets of the city centre district. This is a transition zone where both mechanisms act jointly so the flood coverage in this area is determined by the extent of tidal
activity up the river. Flooding here is driven by a combination of moderate-to-high river flows coinciding with extended periods of relatively high ocean levels restricting outflow rather than being caused by exceptionally high, shorter duration ocean peak levels on low river discharge.

4.5 Assessment of flood risk to people

Flooding can result in substantial economic and social impacts on human settlements. Overall loss due to flooding is traditionally estimated simply from flooding depth-damage curves; such an approach has inherently a large degree of uncertainty (Apel et al., 2008). Fewtrell et al., (2011) notes that there are other additional important factors including wave velocity or duration of inundation that should also be taken into account. The wave velocity in particular poses a significant risk to people as it affects their ability to stand upright in floodwaters. There is a wide range of studies on people safety in flood waters (e.g. Abt et al., 1989; Jonkman and Penning-Rowsell, 2008). In this research, the method of Keller and Mitsch (1993) relating people stability to flow velocity and water depth is adopted. This method makes use of a functional relationship between velocity and depths in the form of instability curves. Although the method is an approximation as it does not consider crucial aspects such as local flow pattern, terrain, person wellbeing (Fewtrell et al., 2011), it is considered a good estimator of the general risk to people safety. Instability curves for people safety in floodwaters estimated separately for a child and an adult are reproduced from Keller and Mitsch (1993) and are shown in Figure 14. Applying these curves for given maximum water depths and velocities, the degree of hazard for people (HD) can be quantified using the formula of Xia et al., (2011) as

\[ HD = \min(1.0, U / U_c) \]  

(6)

where \( U \) is a flood water maximum velocity and \( U_c \) is a critical velocity for given water depth.

The above method was applied to the November 2009 flood event to estimate the degree of flood hazard to people safety. The maximum water depths were between 0.2 and 0.5m in the majority of the flooded street network while they approached 1.5m in the zones adjacent to the main river channel. The adjacent river floodplain becomes a single wide channel unit.
during the flood event sloping in an eastward direction towards the downtown district. This topographical feature, together with a reduced transverse variability in flow depth across the floodplain, acts as a mechanism for flow conveyance. Floodplain geometry effects then a pattern of floodplain flow such that flows become fast (0.7 – 1.4m/s) with rapid transitions while flowing through the shallow waters of steep recreational grounds along river banks. The flood wave spreading eastward gradually loses its momentum and the downtown city district is a ponding area with relatively stagnant waters (0.1 – 0.4m/s).

Modelled maximum water depths and velocities, and critical velocities extracted from Figure 14, are inserted to equation 6 to give estimates of flood hazards used to delineate danger zones for children and adults. As shown in Figure 15a, a considerable portion of the inundated area poses a risk to child safety (HD close to 1.0) including the green areas adjacent to the river bank as well as some sections of main roads and residential estates. Risk to adults (Figure 15b) is much less pronounced and is confined mostly to recreational areas adjacent to the river channel. This analysis clearly demonstrates how MSN_Flood can be used to provide detailed flood risk maps.

5. Discussion

The aim of this paper is to better understand the mechanics and dynamics of coastal urban flooding. This can only be achieved with the help of a numerical model and/or extensive post-flood event survey data. The second requirement is often unreliable due to insufficient amounts of data and therefore most of the effort relies on numerical model analyses. This, however, is challenging for numerous reasons including the model adequacy and data availability necessary for model forcing and calibration. With regards to flood modelling, floodplain representation (grid size), discretization (2d shallow water model) and numerical solver complexity are the main issues to address (Fewtrell et al., 2011).

In general, 2D models are capable of resolving flood dynamics characterized by sub- and super-critical urban flows at <2m structured grid resolution (Olbert et al., 2016a, Brown et al., 2007, Hunter 2008) or variable resolution unstructured mesh (Gallegos 2009; Schubert et al. 2008). Regardless of the mesh structure used, they constitute a compromise between detail and computational effort. Even increasingly popular unstructured grid models still exhibit a threshold under which certain details cannot be represented (Li et al., 2013). The nesting of
structured grid models such as MSN_Flood used in this study provides an attractive solution by offering increased accuracy at relatively low computational effort.

Hunter et al. (2008) performed benchmarking of a range of two-dimensional, 2m resolution models to demonstrate good predictive capabilities of these models in urban flood modelling but, surprisingly, despite variations in the complexity of numerical solutions (governing equations, turbulence schemes, discretization, shock capturing skill and time-stepping), the topography error and friction parameterization were the main causes of model inaccuracies. This could be due to the fact that the models are so sensitive to those parameters they can compensate for other processes that are un- or mis-represented in the model (e.g. Bates et al. 2005, Hunter et al., 2006). The MSN_Flood four-nest model with a 2m mesh in the urban flood domain is capable of resolving flood wave hydrodynamics through the complex geometry urban floodplain, but required a substantial amount of model tuning through bottom roughness parameterization. As discussed this may be necessary perhaps to compensate for some process misrepresentation in the model, rather than to parameterize bed friction solely. Nonetheless, bed parameterization was found to significantly improve model performance and this is confirmed by the very good flood validation results. Some examples of model constraints/process misrepresentation are covered in the following discussion.

One of the most significant processes misrepresented in the model is turbulence. The simple zero-equation Prandtl mixing length (PML) turbulence model is implemented in MSN_Flood as the default turbulence scheme. The PML model relates eddy viscosity to local mean flow and bottom friction. This means that the eddy viscosity magnitudes in space follow the patterns of velocity fields. While this approach is valid and often successful for flows where turbulence is generated primarily by bottom friction, it is invalid for flows where turbulence is produced by horizontal shear stresses, such as recirculating flows, as it ignores the effect of horizontal stresses. Moreover, in PML the level of generated turbulence is tuned through a non-dimensional experimental coefficient that requires predefining prior to the model simulation; this coefficient has a fixed value is space and time. Such parameterization of the turbulence coefficient changes eddy viscosity linearly across the domain and therefore it does not reflect regional changes in the state of turbulence due to sources of turbulence other than the bed. Olbert et al. (2016b) showed that employing a universal constant is not applicable to complex flows, such as urban flows, where flow characteristics and turbulence properties vary dynamically in space and time. Nonetheless, application of more complex turbulence schemes such as the two-equation $k$-$\varepsilon$ model results in higher computational cost, which makes the multi-nested model approach impractical.
Inaccurate and inadequate model forcing is another example of process misrepresentation in the model. Although a significant effort was placed on collecting and utilizing the best available datasets to force the model some processes such as wind and wave action were not accounted for. As explained in the introduction, due to the location of Cork City, the River Lee estuary is sheltered from ocean swell and large waves so the effect of waves on the hydrodynamics of upper Cork Harbour are negligible. However, this is not true at the mouth of Cork Harbour located along the Celtic Sea coastline where mean annual significant wave height reaches up to 1.25 m. The coupled North West European Shelf model of Hashemi and Neill (2014) and Hashemi et al. (2015) clearly demonstrates that Irish coastal waters are subject to wave-current interactions which result in mutual modification of wave and tidal amplitudes. Such analysis is particularly relevant to surge modelling (Sheng et al., 2010) as used in the present approach where wave-surge interactions are likely to occur (although this aspect has not yet been explored). Bertin et al. (2015) clearly showed for the Bay of Biscay that wave radiation stress gradients may locally induce a >0.4m surge setup along the coastlines fully exposed to ocean waves and 0.1-0.2m in more sheltered harbours. This means that coupled wave-storm surge modelling is essential for accurate surge forecasting. The modelling system used here does not incorporate wave-surge interactions, and although, the ocean modelling outputs for the particular November 2009 flood event provide satisfactory agreement with available data, the wave-current coupling will be considered in future developments of the modelling system. The heavy computational burden of such systems (Bertin et al. 2015) may be overcome by coupling the high resolution circulation model (~10m) with a coarser wave model (~100m).

With regards to model performance, the accuracy of flood models depends on the spatial resolution of the model (Schumann et al., 2014). A coarse resolution model will have a smoother terrain and may thus lack some hydrologically important features leading to significant errors in estimated water depths and hence, uncertain flood maps (Ramirez et al., 2016). This is particularly important at local urban scale of floodplains, where the accuracy of floodplain flow seems to be strongly controlled by the model resolution. This is in line with Horritt et al. (2006) who found greater model sensitivity to mesh resolution than to topographic sampling. As explained in Comer et al. (2016), the model resolution acts as a terrain filter which removes small scale features with mesh coarsening so they become sub-grid phenomena. These features can be accounted for to some extent by bottom roughness parameterization, however, when the wet-dry cell alignment of the numerical domain changes the bottom roughness cannot remedy alterations in flow patterns dictated by the new structure of the numerical domain. While this may be of secondary importance where the floodplain acts as a floodwater store and becomes a stagnant pond, the mesh resolution is a critical aspect in floodplains acting as a route for flow conveyance. Moreover, a high resolution is critical to accurately represent hydraulic features such as domain boundaries, bridges or piers. Fewtrell et al. (2011) showed that adequate representation of the afflux and head loss through inclusion of bridges can accurately
simulate local increases in water level and backwatering effects. Thus, representation of hydraulic structures in a model is a critical aspect of urban flood modelling and deserves consideration; future studies will focus on incorporating effects of hydraulic structures as another step towards improving the current modelling system.

In general, despite the model limitations discussed, MSN_Flood is shown to be capable of accurately hindcasting flood events due to a combination of coastal and fluvial mechanisms. For the first time for Cork City, the model provides a good understanding of flood mechanisms and their interactions, as well as inundation dynamics. Consequently, the model may aid determination of circumstances under which flooding may occur and identification of flood-prone areas under various flood scenarios. These are crucial information for flood risk management and flood relief operations. Finally, the high accuracy and expeditious execution time of MSN_Flood (unlike many flood models) mean that it has the potential for operational flood forecasting.

6. Conclusions

In this paper, a flooding event of Cork City which occurred in November 2009 is analysed in detail using a new flood modelling system comprising of two dynamically linked models: an ocean model (POM) of the northeast Atlantic (ca. 5 km grid) which provides water level conditions to the new coastal flood model, MSN_Flood. The driving mechanisms of this particular flood were a complex set of tides, storm surges, rivers inflows and the interactions between them. MSN_Flood is used to model the waters of Cork Harbour through a cascade of four nested models which resolve the hydrodynamics of the region at four spatial scales 90m, 30m, 6m and 2m. The 2m horizontal grid resolution is used to simulate flood water propagation through the urban environment of Cork City. This high resolution modelling system provides a comprehensive assessment of flood wave dynamics such as propagation routes, wave speeds, inundation extents and water levels and it is shown how this knowledge can ultimately be used to inform about associated risk to people safety.

The key findings of the research are as follows:

- The POM-MSN_Flood modelling system was found to be capable of resolving hydrodynamics at scales commensurate with flow features. The spatial extent of the ocean model was large enough to allow the dynamics of the NE Atlantic Ocean and
The evolution of storms therein to be resolved, while the resolutions of the nested models within MSN_Flood were sufficient to adequately resolve coastal hydrodynamics at a range of scales. This system enabled externally-generated surge and tide waves to propagate from ocean to inshore through the semi-enclosed coastal embayment of Cork Harbour and upstream into the River Lee. The model was also found capable of simulating strong flow conditions in the upper section of the River Lee due to abrupt releases of high volumes of water from Inniscarra reservoir.

- The flood inundation in both the upstream rural floodplains and in the downstream network of dense streets was accurately reproduced by the 2m urban flood model. However, the model was found to be very sensitive to bottom roughness and required specification of different roughness values for the different land use types in the model domain. Low ranges of roughness heights for roads and city floodplain classes were found to significantly enhance model performance, whereas specification of bottom roughness heights for the lower and upstream channel or upstream floodplains was found to be of secondary importance to model accuracy.

- High-resolution LiDAR terrain data is crucial for accurate assessment of urban flood inundation; however, post-processing of datasets was required to correct the presence or absence of some surface objects such as trees and hedges which were found to have an effect on flow fields due to misrepresentation of through-flow and overflow.

- Analysis of fluvial and coastal flood mechanisms clearly demonstrates that river discharges were largely responsible for the November 2009 flooding in Cork City. Coastal mechanisms did not impose a threat to coastal flood defence structures, except when combined with high river flows when they then contributed to flooding, particularly in the downtown streets.

- Unlike many flood models, the modelling system used in this research provides a full description of water levels and flow regimes, and therefore be used for assessment of flood risk to people and property. Flood water levels and flood flow speeds obtained from the model were related through an adopted empirical function to assess safety of adults and children in flood waters.

In this research, it was demonstrated how a numerical nested model can facilitate the understanding of the dynamics of flood wave inundation through a detailed temporal and spatial analysis of flood propagation. This approach can be further used for flood management through identification of future flood-prone areas, flood risk timeframes,
inundation extents and flood water heights. The information garnered from such analyses can also serve rescue and relief operations post flooding.

Acknowledgements
This publication has emanated from research conducted with the financial support of Science Foundation Ireland (SFI) under Grant Numbers SFI/12/RC/2302 and SFI/14/ADV/RC3021. The authors would like to thank OPW, Ireland for hydrological dataset and ECMWF for meteorological data.

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Appendix A

A. Site description

Cork City, the second largest city in Ireland, is located on the southern seaboard. The city is dominated by the River Lee which corridor runs from west to the east splitting to the north and south channels around city centre to merge again before entering Cork Harbour (Figure 1c). The river is tidal in the urban area and sea water propagation is bounded by the large waterworks weir 2.5km upstream of the city proper.

The River Lee catchment comprises of an area of approximately 2,000 km$^2$ including all main rivers and tributaries. Two operational hydroelectric dams on the River Lee (Innishcarra - 13 km upstream and Carrigadrohig - 27 km upstream) capable of dealing with floods up to an annual exceedance probability of 0.01% , along with the Bride and Shournagh rivers which are characterized as rapid flood response systems, dictate River Lee flows in the urban area of the city. Flows in the most downstream section for 2- and 100-year return periods are 208.6 and 307.7 m$^3$/s, respectively. Cork City is vulnerable to flooding from both river flow
and tidal influences, and there is a strong history of severe floods in the area (Halcrow, 2008). Fluvial flooding is associated with catchment hydrology and management of the two hydroelectric dams. Tidal flooding in Cork City results from extreme sea water levels in Cork Harbour due to a combination of high astronomical tides and storm surges.

Cork Harbour is a micro-tidal estuary with typical spring tide ranges of 4.2m. It has approximately 120 miles of coastline, average water depth of 8.4 m below mean sea level (MSL) and the deepest point of 29m below MSL occurs in the entrance channel to the lower harbour (Figure 1b). 2 and 100-year return levels for tides are 4.45 and 4.52 m above chart datum (Cobh, lower harbour), respectively, while surge levels for the same return periods are 0.56 and 0.85 m (Olbert et al., 2013).

Appendix B

B. Meteorological conditions

On November 19th and 20th 2009 the River Lee burst its banks and extreme flooding was widespread across Cork City and surrounding areas. The flooding resulted from severe meteorological conditions directly preceding the event and was amplified by significant precipitation occurring in the previous month.

The second part of October 2009 was a period of unsettled weather, as a series of Atlantic depressions and their associated fronts moved over Ireland bringing heavy rains and strong winds. This pattern continued throughout almost all of November with a series of fast-moving deep Atlantic depressions responsible for exceptionally high rates of precipitation. Rainfall totals for November were the highest on record at 79% of Ireland's 440 rainfall stations, 370 of which had records for longer than 10 years (Walsh, 2010). At Valentia Observatory (south of Ireland) a total of 360 mm rain was the highest recording of any month since observation began in the area in 1866. In the Cork area, monthly averages of precipitation for October and November were 166.6 and 245.3 mm, respectively. The most extreme rainfall was recorded on the 19th November (51.2 mm at Cork airport); this particular rainfall event was associated with a depression, central pressure 960hPa, off the west coast of Ireland that generated storm conditions with strong south to south-westerly
winds. Synoptic charts showing the development and movement of this storm system are presented in Figure B.1.

Appendix C.

C. Topographic and bathymetric data

The channel of the River Lee was included in the model using cross sectional survey data provided by the OPW from an extensive survey of the rivers in the River Lee catchment in 2008. Admiralty Chart data were used to develop the remainder of the bathymetric model of Cork Harbour.

In order to create the urban flood bathymetry model, urban topography data for Cork City were combined with seabed data to allow flood waters to seamlessly flow over the river/estuary channels, across the floodplain and through the city streets. The urban topography was constructed from airborne digital terrain LiDAR data provided by OPW. This technique provided a raster dataset of 2m resolution with a RMSE vertically of about 10cm (Neelz et al., 2006). The data consisted of both DSM (digital surface model) which included buildings and DTM (digital terrain model) which represented ground surface only (i.e. excluding buildings, etc). Post-processing was required to merge the DTM and the raw DSM in order to include buildings and structures that would greatly impede the flow of water. During development of the terrain model, LiDAR data was found to under-represent the width of the River Lee channel as overhanging tree cover was taken as channel banks. This was due to the common problem in LiDAR post-processing (Naesset, 1997; Gomes-Pereira and Wicherson, 1999) of separating ground hits from hits on surface objects (vegetation, buildings). The truthful representation of full channel width was constructed by modifying LiDAR data with the help of aerial maps. These data were combined and interpolated onto 6m and 2m regular Cartesian grids for the area of interest to produce the floodplain topography shown in Figure 1.
Figure 1. Cork Harbour coastal model with selected locations (a) and bathymetry of NE Atlantic Ocean model with locations used in model validation: B-Bangor, C-Cork, H-Holyhead and F-Fishguard (b)
Figure 2. Movement of depression system in the NE Atlantic over the period of 17-19th of November 2009. Blue thin contours denote sea level air pressure (hPa). Red, blue and purple thick lines denote warm, cold and occluded fronts, respectively.

Figure 3. Total water levels, astronomical tides and surge residuals at Tivoli
Figure 4. Schematic illustration of the internal boundary configuration for 3:1 nesting ratio

Figure 5. Four-level nesting structure of the coastal model
Figure 6. Cork City 2m digital LIDAR terrain data (m) combined with River Lee seabed bathymetry. White rectangles delineate coverage of CG02 and CG06 models. Yellow dot denotes a point in Figure 9b

(a)

Figure 7. Comparison of modelled and observed surge residuals time series at Bangor (ai), Cork (bi) and surge residuals peaks at Fishguard (a(ii)) and Holyhead (b(ii))

(a)

(b)

(c)
Figure 8. Comparison of current speeds at Passage West point P1 (a), water elevations in Lough Mahon point C1 (b) and current speeds in Lough Mahon point C1 (c). Point locations shown in Figure 1a

(a)  (b)

Figure 9. Timeseries of water elevations at Tivoli tidal gauge station measured and simulated by CG06 (a) and in the north canal of River Lee simulated by CG02 and CG06 (location of the point shown in Figure 6 as a yellow dot) (b)
Figure 10. Taylor diagram showing model parameterization using various bottom roughness heights. Dot colours denote simulation ensembles explained in Table 1.

Figure 11. Map of Manning’s roughness coefficients for the best fit model
Figure 12. Maps of flood inundation observed (a) and simulated by the model (b)

Figure 13. Maximum water level differences (m) between model and observations at survey locations
Figure 14. Comparison of modelled and observed water elevations (m) at 45 surveyed locations (a), upper floodplains (b), north canal (c), south canal (d), city downtown (e) and flow bifurcation zone (f)
Figure 15. Progression of flood inundation over upper and lower floodplains of Cork. Contours represent water depth (m)
Figure 16. Progression of flood inundation in urban area of Cork City. Contours represent water depth (m)
Figure 17. Timeseries of total inundated area (a) and total volume of water outside river channel (b) within CG06 and CG02 model regions

Figure 18. Timseries of inundated area due to high river flows and various sea water level conditions modelled by CG02

(a)
Figure 19. Evolution of flood wave through Cork City during November 2009 flood event due to high river discharges coinciding with spring tide 1.8m amplitude (a) and neap tide 1.0m amplitude (b). Contours represent 2-hour intervals.
Figure 20. Relationship between flow velocity and water depth on child and adult stability in floodplains (from Keller and Mitsch, 1993)

(a)

(b)
Figure 21. Contours of maximum water depths (m) (a) and velocities (m/s) (b) during the simulation period

(a)

(b)

Figure 22. Distribution of maximum hazard degrees to children (a) and adults (b)