03 - MECHANISMS OF FLOODING IN CORK CITY

Agnieszka Indiana Olbert[1], Michael Hartnett[1], Joanne Comer[1], Stephen Nash[1]
[1]*National University of Ireland, Galway, School of Engineering and Informatics*

Abstract
Flooding is one of the most frequent and devastating natural disasters. Many urban developments are located in estuaries where river flow and sea water merge. Cork City situated in the River Lee estuary is frequently the subject of extensive fluvial and coastal floods and is one such vulnerable location. It is chosen in this study to investigate the roles of the flood mechanisms on the extent of urban inundation.

This paper provides a methodology for determination of mechanisms of urban flooding and their effects. Multiple drivers such as coastal and fluvial processes are considered to occur individually or jointly. In the assessment, interactions and dependencies between flood drivers are also included and accounted for in joint probability analysis. The patterns of flood wave propagation are investigated to establish roles of the individual flood drivers. The analysis of flooding is a multistep process involving both probabilistic and deterministic modelling where a probabilistic model provides inputs in terms of extreme sea water levels (coastal flooding) and river flows (fluvial flooding) as boundary conditions to a deterministic coastal model which simulates flood wave propagation and the extent of inundation. The MSN multi-scale nested ultra-high resolution numerical model is used to simulate 50- and 200-year extreme floods in the urban area of Cork City.

Results show that the mechanism of flooding plays a crucial role in flood characteristics and inundation patterns. While coastal flooding affects mostly the downtown section of the city, fluvial flooding dominates initially in city suburbs in the upper section of the river before channelling downtown through a network of east-west oriented streets and recreational areas towards the city centre. With regards to flood probabilities, coastal and fluvial defence systems in the tidal section of the river are capable of protecting against the 1 in 200-year coastal driven flood, while the river flows exceeding 50-year return period may solely cause flooding. Fluvial mechanisms in the Cork area is a critical driver of flooding and the most severe floods in Cork City result from extreme river flows combined with moderate-to-high sea levels.

The research allows us to understand the mechanisms of flooding in Cork City, and by that to identify flood-prone areas for low-frequency high risk flood scenarios.

1. INTRODUCTION

Flooding is one of the most frequent natural disasters and may constitute a risk to human settlements such as loss of life, damage to properties and disruption to services. Many urban developments are situated on estuaries where freshwater flow and sea water merge (Orton et al., 2012). Such coastal cities may be subject to both a single source flood event or several sources acting in combination (Archetti et al. 2011).

If there is only one driver responsible for flooding, the accuracy of flood probability estimates depends on the data availability and statistical methods used in assessment of extremes. The situation is more complex when flooding is driven by a combination of processes as in the case of estuaries where multivariable conditions such as astronomical tides, surges and wind and/or high river discharges can act simultaneously to generate flooding. Here, beside probabilities of individual drivers, a probability of occurrence of multiple phenomena simultaneously needs to be considered jointly. The complexity is further exacerbated by a presence of interactions or dependencies between these variables. When coastal and fluvial flooding contribute to a single flood event, the complexity of

such a multivariable problem requires a sophisticated statistical approach to assess the probability of flood event and advanced modelling approach to understand dynamics of such flood event.

Flooding of coastal hinterlands is generally caused by three phenomena: high astronomical tides, storm surges, high river flows or a combination of thereof. While astronomic tides are easily predicted deterministic component of water elevations, storm surges and river flows are of stochastic nature and usually difficult to forecast. Very often both surges and river flows are driven by one process such as storm. Ireland due to its geographical position and direct proximity to North East Atlantic is exposed to atmospheric and oceanic conditions present in the ocean and therefore, is at increased risk of coastal flooding. Storms generated far offshore in Atlantic propagate towards or nearby European continental shelf generating water setups and intense precipitation at the coastline. When this happens tidal and fluvial flooding may occur jointly resulting in severe flooding.

Flood risk being a function of the probability of flooding and the consequential damage, (Hall et al. 2006) is naturally greater when both coastal and fluvial flooding are likely to occur simultaneously. In this context, this paper focuses solely on flood probabilities and presents methodology for assessment of mechanisms of urban flood events and their effects. 50-year and 200-year return period flood scenarios are considered. The individual and joint occurrence of multiple drivers such as coastal and fluvial processes are examined. In the assessment interactions and dependencies between flood drivers are also included and accounted for in joint probability analysis. The ultimate goal is to establish roles of the individual flood drivers and their effects on flood inundation. This is achieved in the course of multistep process that involves both probabilistic and deterministic modelling where probabilistic model provides inputs in terms of extreme sea water levels (coastal flooding) and river flows (fluvial flooding) as boundary conditions to deterministic coastal model which simulates flood wave propagation and ultimate extent of inundation. Cork City located in the most downstream part of the River Lee which drains to Cork Harbour, subject recently the extensive floods due to fluvial (November 2009) and coastal (February 2014) mechanisms is chosen as a study case.

2. METHODOLOGY

An assessment of flood probabilities and extents of inundation due to flood events is a multistep process where probabilities of flood event outputted from a probabilistic model provide boundary conditions to deterministic coastal model which ultimately simulates flood wave propagation and extent of inundation.

2.1. Coastal model

Dynamics of flooding resulting from a combination of multiple process drivers such as tide, surge and river inflows is very complex and can only be comprehended using modelling methods. In this research, the Multi-Scale Nested (MSN) model is used to resolve hydrodynamics of River Lee and Cork City floodplains. This model is a two-dimensional, depth-averaged, finite difference model that solves the depth-integrated Navier-Stokes equations; technical details can be found in Nash (2010). Wetting-drying options and nesting structure are two important and unique characteristics of the model. These two features are critical in context of flood modelling, as when combined, allow flooding and drying of the nested boundary. This is a novel approach to boundary formulation.

In this approach the nested boundary consists of internal boundary cells and adjacent to them exterior ghost cells so the parent model data are specified to both lines/rows of cells. Nested boundary configuration is shown schematically in Figure 1. Boundary data in parent grid model is specified to both the ghost cells outside the child grid domain and to the internal boundary cells. In such configuration the computation of the child grid solution at the internal boundary by the child model is prevented. Indeed, the governing equations at the nested boundary grid cells are formulated in a similar manner to interior grid cells. This new boundary formulation coupled with an adaptive linear interpolation at the boundary, specifically designed for this model, converts the nested boundary into a dynamic internal boundary. Such solution to the nested boundary enables stable flooding and drying

of the boundary. Additionally, linear interpolation as a boundary operator and a Dirichlet boundary condition further enhance model performance as they are found to give the highest level of conservation of mass and momentum between the coarse and fine grids. The nesting scheme is described in detail in Nash and Hartnett (2010 and 2014). With such defined nested boundary, the MSN model offers improved accuracy over the lower resolution parent model but the accuracy is similar to that of the high resolution model at significantly reduced computational effort. As shown in Nash and Hartnett (2010) the new technique is very robust and therefore particularly applicable to this research.

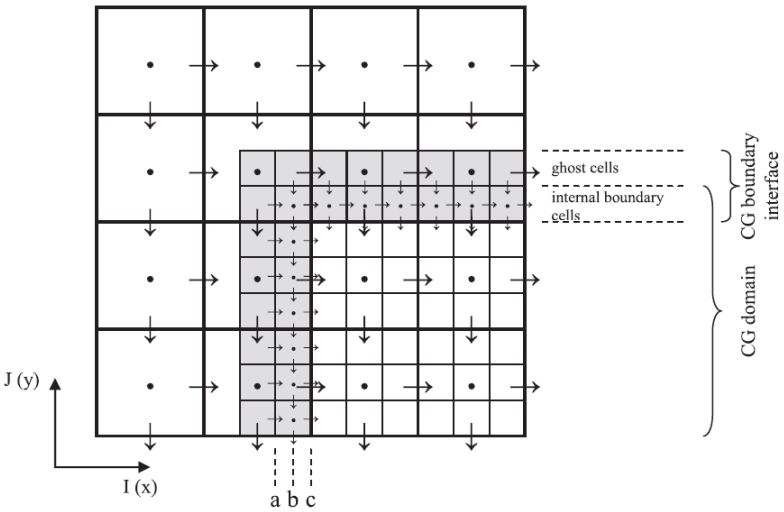


Figure 1. *Schematic illustration of the internal boundary configuration for 3:1 nesting ratio.*

2.2 Model setup

The nesting procedure in MSN model is based on one-way nesting approach where one or more inner child grids (CG) are nested within the parent grid (PG). Multiple nesting is also permitted so that child grid model may also be a parent to another child model. As there are no limits to a number of nesting levels specified, theoretically any required spatial resolution can be obtained.

In this research, the modelling system consists of a cascade of four nested coastal hydrodynamic models of various resolution in order to refine hydrodynamic processes of Cork Harbour from 90m resolution down to 2m grid in the Cork City floodplains.

The PG model and its CG models are dynamically coupled and synchronous. Figure 2 shows nesting structure and geometry of nests. The PG model resolves hydrodynamics of entire domain of Cork Harbour at a grid spacing of 90m (PG90). The first level nest CG30 embedded within the PG downscales the area of interest to Lough Mahon region at 3:1 nesting ration and computes hydrodynamics at 30m grid spacing. At nesting ratio 5:1 the CG30 model provides boundary conditions to east boundary of the CG06 model which narrows down the area of interest to River Lee and its estuary. And finally, the finest resolution 2m grid model (CG02) embedded within the 6m at 3:1 nesting ratio resolves hydrodynamics of River Lee and its floodplains covering urban area of Cork City.

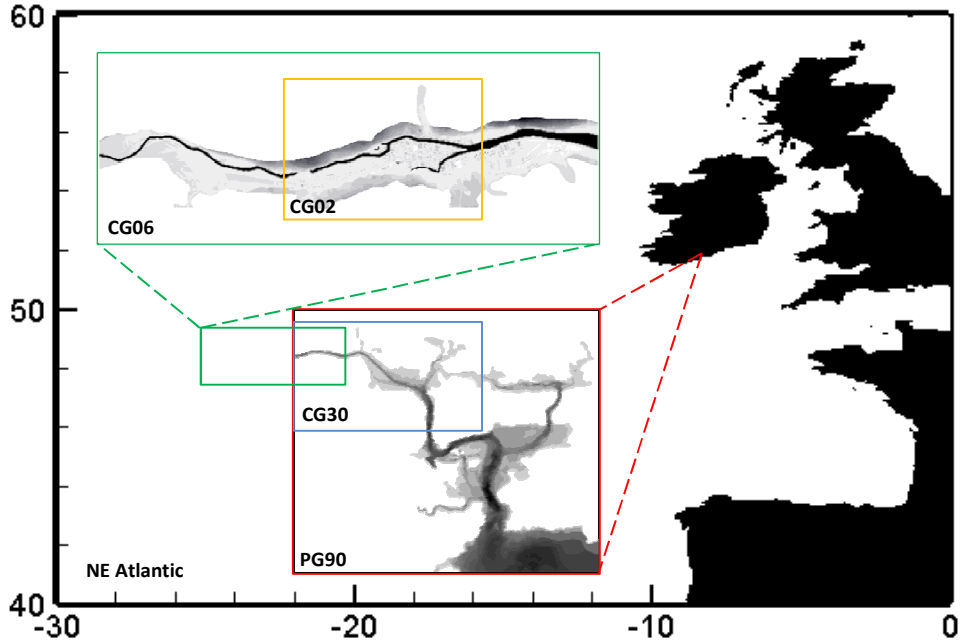


Figure 2. *Four-level nesting structure and extent of each model*

2.3 Model inputs

Computational domain of the Cork Harbour model was constructed through an amalgamation of Irish National Seabed Survey data and admiralty charts interpolated on 90 m regular grid. The channel of the River Lee was included in the CG30 and CG06 nest models using cross sectional survey data provided by the OPW from an extensive survey of the rivers in the River Lee catchment in 2008. The urban topography was constructed from 2m resolution airborne digital terrain LiDAR data provided by OPW. The data was consisting of both DSM (digital surface model) which included buildings and DTM (digital terrain model) which represented ground surface only.

The parent model PG90 is forced at the lateral open boundary by a variable surface elevation due to astronomical tides and surge residuals. These water levels are synthetic datasets of extreme water level conditions that would represent a hypothetical coastal flood event scenario of a certain return period. The time series are generated by combining tidal and surge curves, both reflecting extreme conditions such as 1 in 50 or 1 in 200 years events. The extreme tides and surges are determined from frequency analysis.

Tidal time series is a synthetic tidal curve of amplitude corresponding to particular return period level obtained from frequency analysis of astronomical tides. In the absence of long term tidal records, this data was extracted from a 46-year long time series of astronomical tides generated from over 60 individual tidal components (NOAA 1982). The accuracy of this dataset was corroborated by comparison against harmonic dataset constructed from existing records for Tivoli tidal gauge station in Cork Harbour and nautical almanac (Hewitt and Lees-Spalding, 1982).

The extreme value analysis of surge residuals was conducted for a dataset of surge values obtained from 48 storm events over the 46-year period (1959-2005). Each of these events was hindcasted by the POM hydrodynamic model. Only maximum surge value from each of the simulated event was extracted and used in the frequency analysis. The dataset comprises then of 48 maximum values with the highest value of 0.81m. Time series of these events for Cork Harbour are summarized in Figure 3. Validation of these results can be found in Olbert and Hartnett (2010) and Olbert et al. (2013).

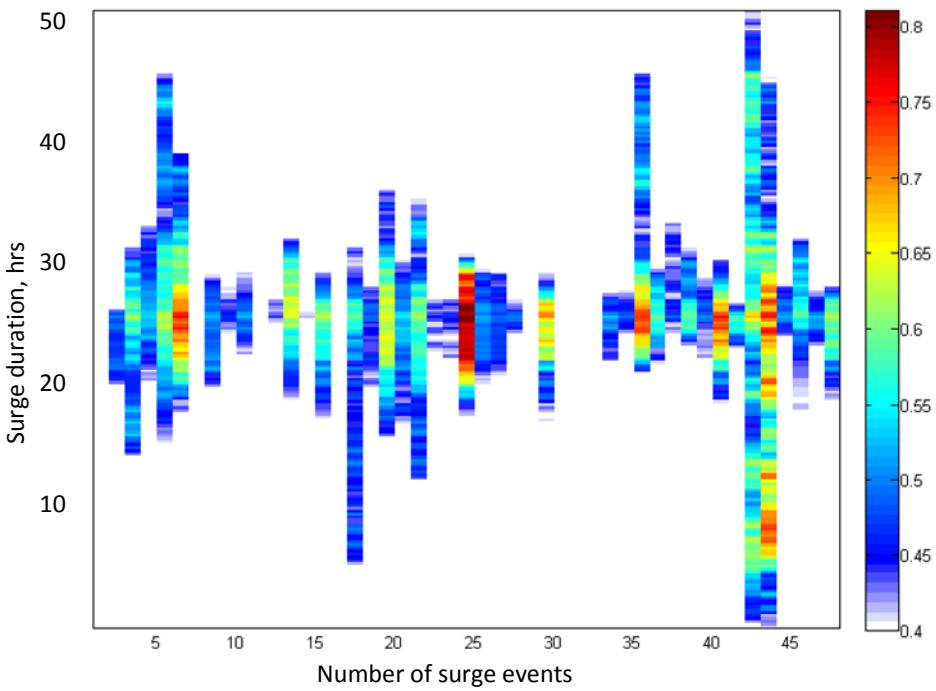


Figure 3. *Temporal evolution of surge residuals for each of the 48 storm events. Colour scale denotes the magnitude of surge residual (only magnitudes over 0.4m shown)*

As historical evidence shows, very high flows in the River Lee are responsible for fluvial flooding in Cork City. The river discharge input to the model is specified at the western flow-type boundary of the CG06 6m nested domain. This dataset is provided as a synthetic curve of a maximum flow corresponding to a certain return period event derived from a frequency analysis. A time series of long-term river gauge records on the Lee River (gauge number 19012) was used to study the distribution of peak flows. In total, 38 largest events were isolated from this data to construct a probability distribution.

The GEV statistical model was used to fit extreme values of tides, surges and river flows. In all three cases the model was found to give a good fit to the numerical model outputs and field records as shown in Figure 4.

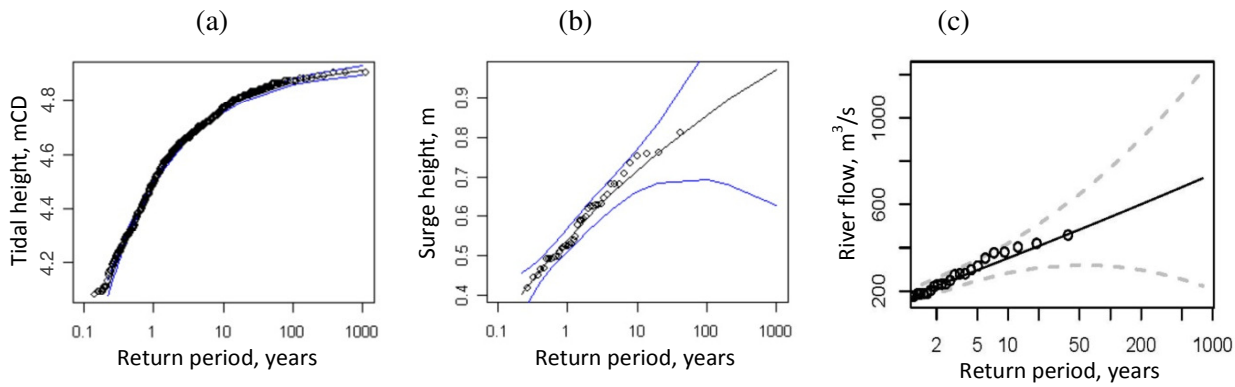


Figure 4*. Return level periods for extreme levels of tides (a), surges (b) and river flows (c). Comparison between data and GEV model.*

3. RESULTS

3.1 Model validation

Due to the space limit, only the most relevant flood event outputs are shown in this section. For validation purposes, the November 2009 fluvial event is reconstructed using the MSN model. The accuracy of the model results is examined by comparing available data with outputs of the rural-urban CG06 model and ultra-resolution CG02 2m model.

In the aftermath of the November 2009 flood event, there was a large body of evidence of extent and level of flood inundation in Cork City. Water level marks were collected and post-processed by OPW at 45 survey points across the flooded area; these data are used to calibrate and validate the urban flood model. Since this paper is intended to address mechanisms rather than precision of flood estimates in Cork, readily available quality checked data was used without analysis of potential improvements, such as data ground model and catchment runoff. Initial sensitivity tests showed that the parameter with the most effect on the water levels was the roughness coefficient of the channel bed and floodplains. In the process of model calibration, roughness values ranging between 0.1 and 1.1m were assigned to different reaches of the model domain. The Taylor diagram shown in Figure 5 provides the statistical summary of model skill for various roughnesses. Overall, the model is sensitive to distributed land use type roughness and in particular to roads and city floodplain land classes. The best fit model shown as a red dot yields correlation of 0.97, root mean square difference of 0.26m and normalized standard deviation of 1.08. This was obtained for the following roughness values: upper channel = 0.9m, lower channel = 0.9m, roads = 0.1m, city floodplain = 0.1m and upstream floodplain = 0.3m.

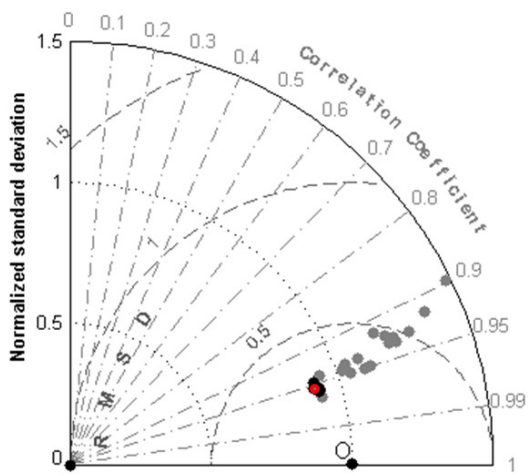


Figure 5. Statistical summary of model skill. Red dot denotes best fit model used for flood event validation

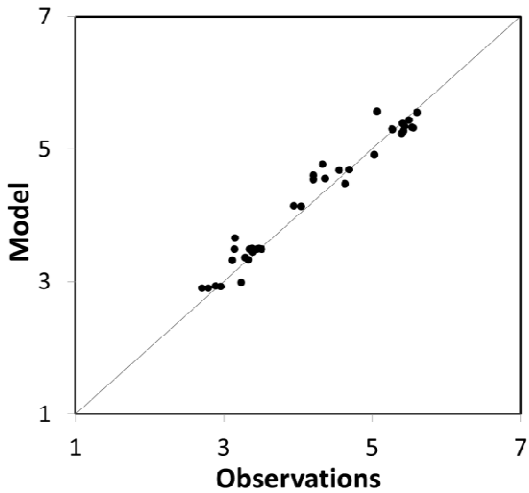
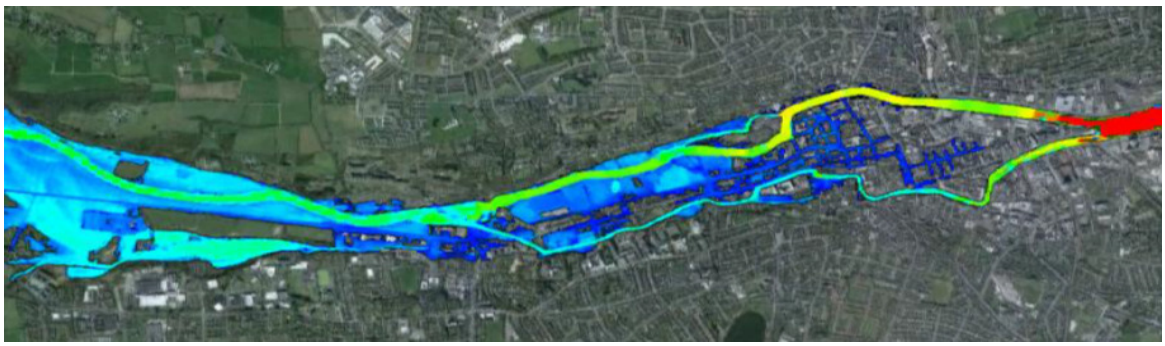


Figure 6. Comparison of modelled and observed maximum water elevations at 38 stations

A visual check on the best-fit model against 38 survey point observations is shown in Figure 6. In general, there is a good agreement between the two datasets as the model solution falls on the 45° line; this is further corroborated by correlation of 0.98. Spatial extent of modelled urban inundation was assessed through a comparison with field observations collated by OPW (2012). As can be seen from Figure 7 the hindcasted extent of inundation matches very well that observed during the flood event.

(a)



(b)

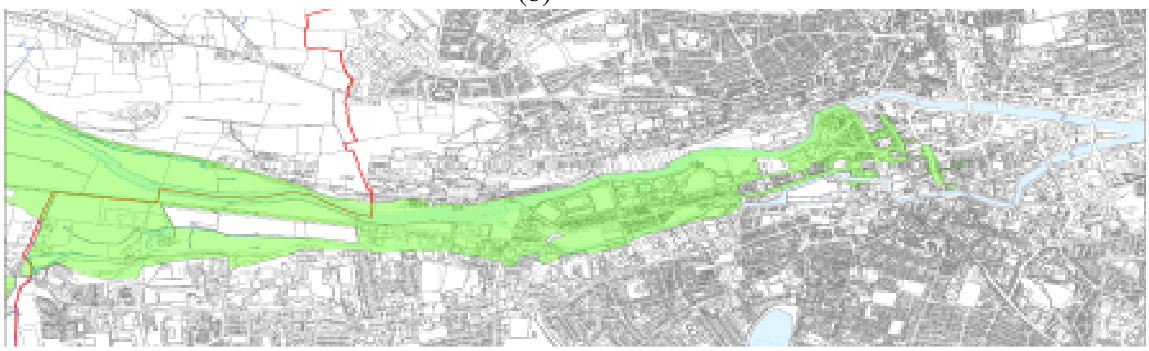


Figure 7*. Flood inundation simulated by (a) the model and (b) observed (from OPW, 2012).*

3.2 Coastal flooding

Although, Cork City was flooded on a number of occasions in recent years, mechanisms of flooding were incompletely understood due to complex dynamics of such events. In this section, the evolution and impacts of coastal flooding are explored for a combination of extreme tides and surges. A 50-year return period tide coinciding with 200-year surge is selected to examine extreme coastal flooding. Particular attention is placed on effect of tide-surge interactions on inundation extent. Olbert et al. 2013 analysed in detail such interactions in Irish coastal waters and found for Cork that, although dependency between tide and surge surges is statistically low, surges tend to peak at particular phase of tide (half way between mid flood and high water). In this research, the importance of these interactions was examined by simulating flood scenarios with a surge imposed to peak at high water and on rising tide, respectively. Temporal flood evolution is shown for these two scenarios in Figures 8 and 9; the phase of tide on which surge peaks has remarkable effect on the extent of flooding. There is significant 25% increase in inundation area when surge occurs on high tide in contrast to rising tide. The spatial extents of inundation for two scenarios can be viewed in Figure 10. Coastal flooding generates a widespread inundation not only along river banks but also in the Cork City downtown.

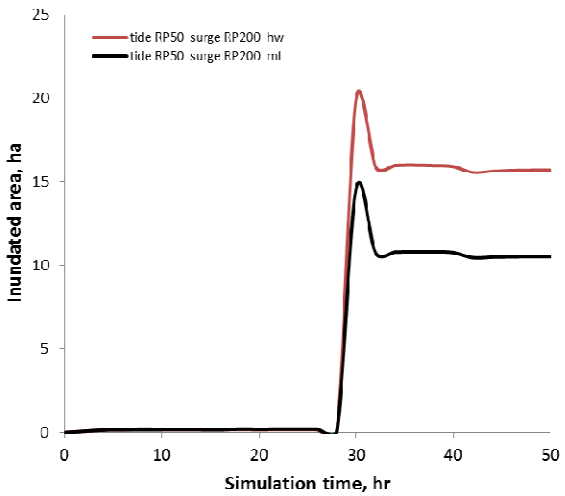


Figure 8. *Timeseries of urban inundation due to coastal flooding*

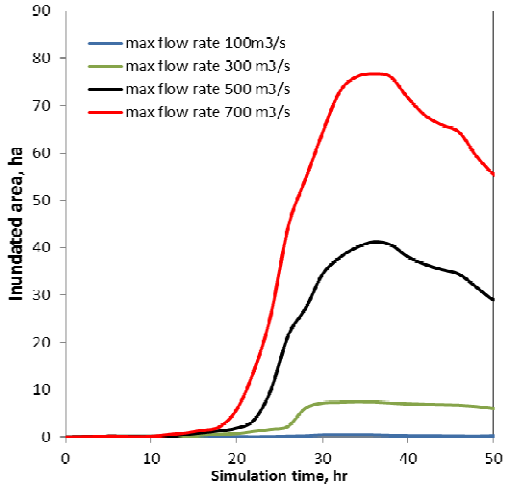


Figure 9. *Timeseries of urban inundation due to fluvial flooding*

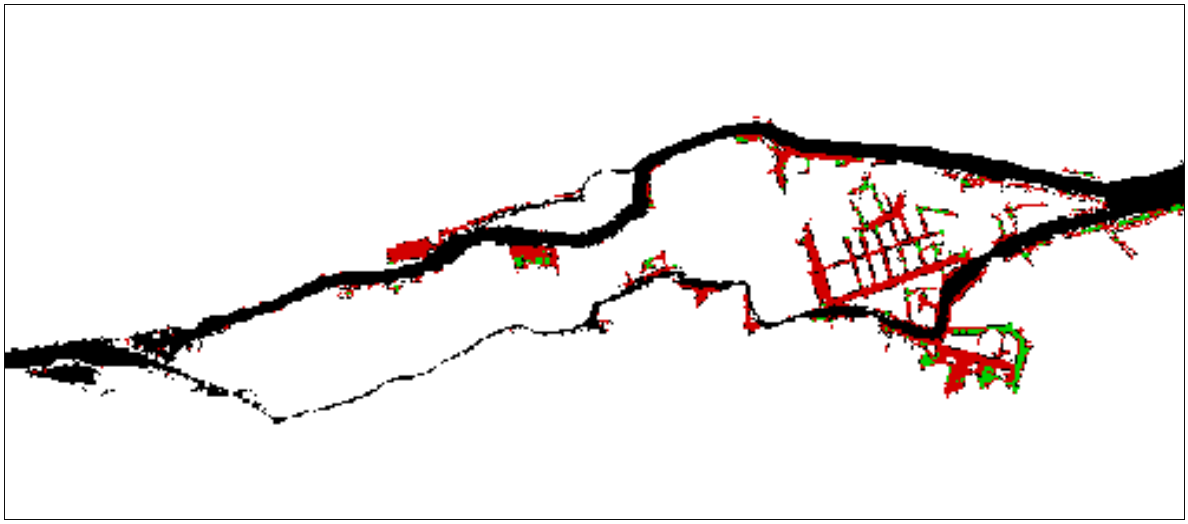


Figure 10. *Map of coastal inundation due to 50-year RP tide and 200-year RP surge. Red area indicates extent of flooding due to surge coinciding with rising tide, green colour represents flood area due to surge peaking on high water.*

3.3 Fluvial flooding

In this investigation, the effect of river flow on flood extent is examined by running an ensemble of simulations with variable river flows and tidal conditions representing neap tide of 1.0 m amplitude. The shape of the flow evolution curve replicates the temporal distribution of river discharges during the November 2009 event. The maximum flow corresponds to 100, 300, 500 and 700 m^3/s for each of ensemble runs, respectively. The flow magnitude increases gradually from the base flow of 40 m^3/s to reach a maximum approximately 26 hours later.

Figure 10 shows a temporal progress of Cork City inundation for each of the simulated river flows. There is a dramatic increase in inundation as discharge rate rises. For example, increasing maximum flow rate from 500 to 700 m^3/s causes almost doubling of inundation area. A map of ultimate inundation of rural and urban floodplains for three selected river flows at neap tide are shown in Figure 11. Flood wave propagates eastward from upstream rural floodplains down to narrow streets of city downtown to severely flood the west and partially the east of the city between the north and south channel .

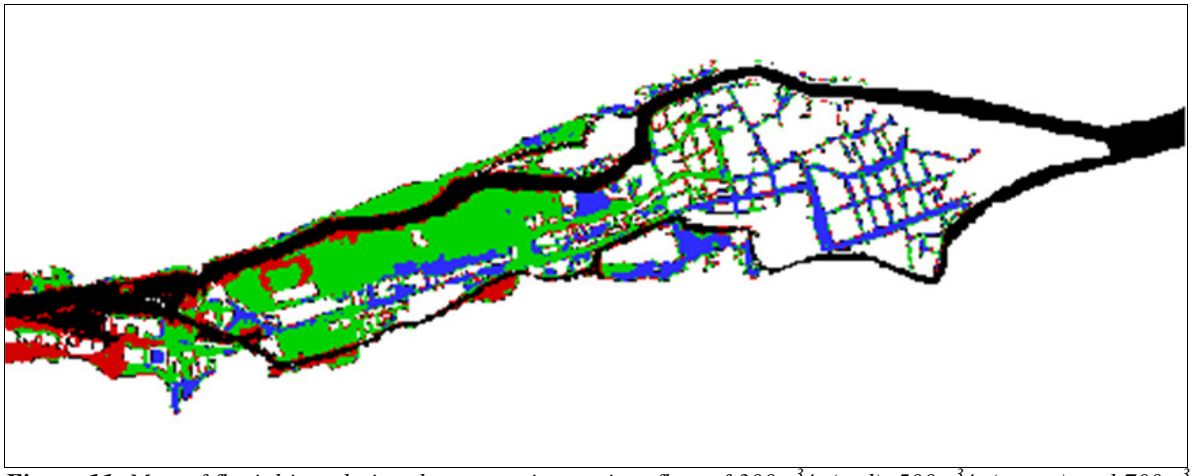


Figure 11. *Map of fluvial inundation due to maximum river flow of 300m^3/s (red), 500m^3/s (green) and 700m^3/s (blue)*

3.4 Joint coastal and fluvial flooding

In this section the probability distributions of tides, surges and river flows were merged in trivariate joint probability analysis to compute extreme water levels due to combined action of all three variables. The trivariate joint exceedence is calculated using the method of White (2007) assuming dependency between surges and river flows. The highest dependency measure χ (Coles et al., 2001) of 0.131 was obtained for lagged analysis where surges precede river flows by one day. Figure 12 presents joint probability solutions for 50- and 200-year return periods; the joint exceedence return values are combinations of high sea water levels (tide plus surge) and moderate river flows on one end or extreme river flows and moderate sea water levels on another end. The most severe floods are associated with high river discharges events and, therefore, driven by the fluvial mechanism. However, sea water levels due to tides and surges pose an extra risk to flooding; high sea levels push water up the river restricting outflow and therefore cause piling water along the river banks. In the worst case scenario, the 200-year flood results in 76ha of urban inundation and is a combination of high river flow and moderate sea water levels.

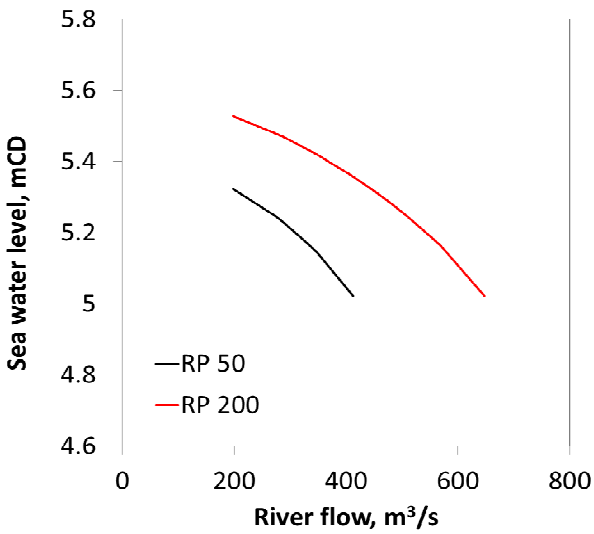


Figure 12. *Trivariate joint probability of river flows, surges and tides*

A map of flood inundation due to the 50- and 200-year joint exceedence return period event is shown in Figure 13. The analysis of spatial evolution of inundation shows that flood waters overtop river

banks in the upper section of the North Channel and slope gradually through floodplains in eastward direction across the central part of the city towards downtown. Fluvial flooding of the narrow dense street network of city downtown is additionally amplified by coastal mechanism through south channel, where waters overtop river banks in several locations.

Figure 13. *Map of inundation due to 50-year (red) and 200-year (green) joint costal and fluvial flooding.*

4. CONCLUSIONS

This paper provides methodology for assessment of mechanisms of urban flooding due to multiple source flood drivers. The effect of coastal (tide and surge) and fluvial flooding is considered separately for individual mechanisms and their joint occurrence. Interactions and dependencies between flood drivers are accounted for in joint probability analysis. The analysis of 50- and 200-year flooding is a multistep process involving both probabilistic and deterministic modelling. Such method allows not only to determine flood extremes and their effect on the extent of inundation but also the roles of flood mechanisms on characteristics of flooding. Cork City subject to fluvial and coastal flooding is chosen as a study case.

Mechanism of flooding plays a crucial role in flood characteristics and propagation pattern. While coastal flooding affects mostly downtown section of the city, fluvial flooding dominates initially city suburbs in the upper section of the river before channelling downtown through a network of east-west oriented streets and recreational area sloping towards city centre. With regards to flood probabilities, coastal and fluvial defence systems in tidal section of the river are capable of protecting against 1 in 200-year coastal driven flood, while the river flow exceeding 50-year return period may solely cause flooding. Fluvial mechanism in Cork area is a critical driver of flooding and the most severe floods in Cork City result from extreme river flows combined with moderate-to-high sea water levels. The research gives a good insight into the mechanisms of flooding in Cork City. By that it allows to understand spatial and temporal evolution of flooding and hence identify flood-prone areas for hypothetical low-frequency high risk flood scenarios.

5. ACKNOWLEDGMENTS

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.

6. REFERENCES

Archetti, R., Bolognesi, A., Casadio, A., Maglionico, M. (2011) Development of flood probability charts for urban drainage network in coastal areas through a simplified joint assessment approach. Hydrol Earth Syst Sci 15, 3115-3122

Coles, S.G. (2001) An introduction to statistical modelling of extreme values. Springer, London.

Hall, J.W., Sayers, P.B., Walkden, M.J.A., Panzeri, M. (2006) Impacts of cliate change on coastal flood risk in England and wales: 2030-2100. Phil. Trans. R. Soc A 364, 1027-1049
Hewitt, R.L., Lees-Spalding, I.J. (1982) The Maximillan and Silk Cut nautical almanac. The Macmillan Press Ltd

Nash, S. (2010) Development of an adaptive mesh inter-tidal circulation model. PhD Thesis Collage of Engineering and Informatics, National University of Ireland, Galway.

Nash, S., Hartnett, M. (2010) nested circulation modelling of inter-tidal zones: details of nesting approach incorporating moving boundary. Ocean Dynamics 60, 1479-1495

Nash, S., Hartnett, M. (2014) development of a nested circulation model: boundary error reduction. Environmental Modelling and Software 53, 65-80

Olbert, A.I., Hartnett, M. (2010) Storms and surges in Irish coastal waters. Ocean Modelling 34: 50–62.
NOAA (1982) Computer Applications to Tides in the National Ocean Survey. Supplement to the Manual of Harmonic Analysis and Prediction of Tides (Special Publication No. 98). National Ocean Service, National Oceanic and Atmospheric Administration, U.S. Department of Commerce, January 1982.

Olbert, A.I., Nash, S., Cunnane, C., Hartnett, M. (2013) Tide-surge interactions and their effects on total sea levels in Irish coastal waters. Ocean Dynamics.

OPW (2012) Flooding Cork City November 2009. Flood event report. OPW

Orton, P., Georgas, N., Blumberg, A., Pullen, J. (2012) Detailed modelling of recent severe storm tides in estuaries of the New York region. Journal of geophysical research 117 C09030.

White, C.J. (2007). The use of joint probability analysis to predict flood frequency in estuaries and tidal rivers, PhD Thesis, School of Civil Engineering and the Environment, University of Southampton, p343.