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07 – INTERACTIONS, MECHANISMS AND IMPACT OF FUTURE COASTAL URBAN FLOODING. A CASE STUDY OF CORK CITY

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Abstract

In coastal floodplains, high river flows and high coastal water levels can result in extensive flooding. Mechanisms of flooding play a crucial role in flood characteristics with distinctive differences in flood wave propagation pattern and geographical extent of inundation. Climate change is expected to alter these flood mechanisms. This paper presents an assessment of urban inundation due to a combined effect of multiple source flooding. Cork City, a coastal city in the south of Ireland, frequently subject to complex coastal-fluvial flooding is used as a case study to investigate changes in flood mechanisms, dynamics and extents due to climate change. Interactions and dependencies between tides, surges and river discharges were computed to understand the likelihood of cooccurrence of compound drivers. The MSN Flood was used to predict potential future inundation patterns for a range of climate scenarios under various hydrological conditions. Scenarios were based on estimates of current, medium-range and high-end projections of extreme river flows and sea levels.

1. INTRODUCTION

Coastal settlements could be at risk of flooding during extreme sea water levels caused by a combination of astronomical, meteorological and climatic factors (Gallien et al. 2011). When high water levels due to tides and storm surges, together with waves occur, the coastal defences can be overtopped or breached, and flood water inundates low-lying coastal areas. The combined effect of surges, tides and waves on total water levels can be devastating for the society and economy. The hazard could be exacerbated in some areas such as deltas and estuaries, the tide-surge-wave flood is amplified by a fluvial component, which due to heavy precipitation during storm events results in high river flows and may, therefore, contribute to coastal flooding. Such flooding is driven by a combination of processes of multivariate conditions that can act simultaneously. When there is a combination of drivers (tides, surges, waves and river discharges) contributing to a single flood event then in addition to the probabilities of individual drivers, the joint probability of simultaneous occurrence of multiple drivers must also be considered. This becomes a multivariable problem that requires a statistical approach to assess the probability of flood events and a sophisticated modelling approach. Complexity is further exacerbated by the presence of interactions or dependencies between drivers, e.g. tide and surge. Moreover, these already complex relationships between the three signals in shallow waters may be modulated on medium to long timescales due to climate changes. To understand the dynamics and impacts of joint coastal-fluvial flood events, these interactions and dependencies between flood drivers needs to be understood.

The research shows that the urban flood risk globally will become more frequent in the future as a consequence of several factors including population growth in flood prone areas, climate change, sea level rise and decaying or poorly engineered flood control infrastructure. Extensive research exists demonstrating that flooding has increased in frequency in recent decades (Hall et al. 2014; Kundzewicz 2012). Predicted increases in sea level, rainfall and storm winds are likely to escalate the risk of flooding in the future (Purvis et al. 2008). This will have significant socio-economic consequences as coastal populations have continued to grow much more rapidly than the global mean population (e.g. McGranahan et al. 2007). Consequently, as a result of climate change and demographic growth in coastal regions, it is envisaged that flood risk and associated costs will increase in the future. In this context, the primary objective of this paper is to demonstrate how numerical model predictions of future hydrological conditions combined with understanding of current flood drivers and interactions between them can be used to simulate extent of future flood inundation in costal urban floodplains.

The coastal city of Cork, in the south of Ireland is selected as a case study. Cork's low average elevation and extensive coastline make the city especially susceptible to coastal hazards. With a projected sea level rise and increased storminess, the flood risk is likely to increase significantly. These aspects are investigated in this paper.

2. CORK CITY FLOODING

Cork's low average elevation and extensive coastline make the city especially susceptible to coastal hazards. With sea level rise and project climate change the flood risk is likely to increase significantly. Cork City is situated on the mouth of the River Lee, on the South-West coast of Ireland (Figure 1). The River Lee, which flows through Cork City, rises in the Sheehy Mountains and drains a catchment area of approximately 2,000 km^2 into Cork Harbour, a 350 km^2 tidal estuary feeding to the the Celtic Sea and wider North-East (NE) Atlantic. Its main tributaries are the Rivers Sullane, Bride and Shournagh. Two operational hydroelectric dams, at Inishcarra and Carrigadrohid (13 and 27 km upstream of Cork City, respectively) partly control the river flow. Both dams are capable of dealing with floods up to an annual exceedance probability of 0.01%. Discharges from these dams, combined with inflows from the downstream Shournagh, Bride and Curragheen tributaries, control the water volumes entering Cork City. The Bride and Shournagh discharge to the Lee just 3.3 km and 8.9 km downstream of Inniscarra dam. Although the Bride is not monitored, flow discharges are considered generally low. The Shournagh is monitored and a makes a substantial contribution of Qmed=70.5 m^3/s to the Lee flow. The median annual flows in the Lee at the river gauge station 19012 just upstream of Cork City is 185 m^3/s. Water levels in the River Lee estuary are governed by sea water levels in Cork Harbour and upstream river flows discharging to it. Seawater intrusion from Cork Harbour also influences fluvial water levels in the River Lee, although this is constrained by the waterworks weir approximately 8 km upstream of the harbour. Astronomical tides dominate water levels and circulation in the harbour. Tidal motion in Cork Harbour is primarily driven by the M2 and S2 semidiurnal constituents of amplitude 1.41m and 0.44m (Cobh station), respectively. In comparison to tides, storm surges are more stochastic phenomena characterised by high variability. Direct connectivity to the NE Atlantic affects the frequency and severity of surges in Cork Harbour which tend to vary seasonally and inter-annually depending upon climate modes such as the North Atlantic Oscillation (Olbert and Hartnett, 2010). When surges propagate into Cork Harbour and coincide with high spring tides, they can result in flooding of low-lying areas of Cork City.

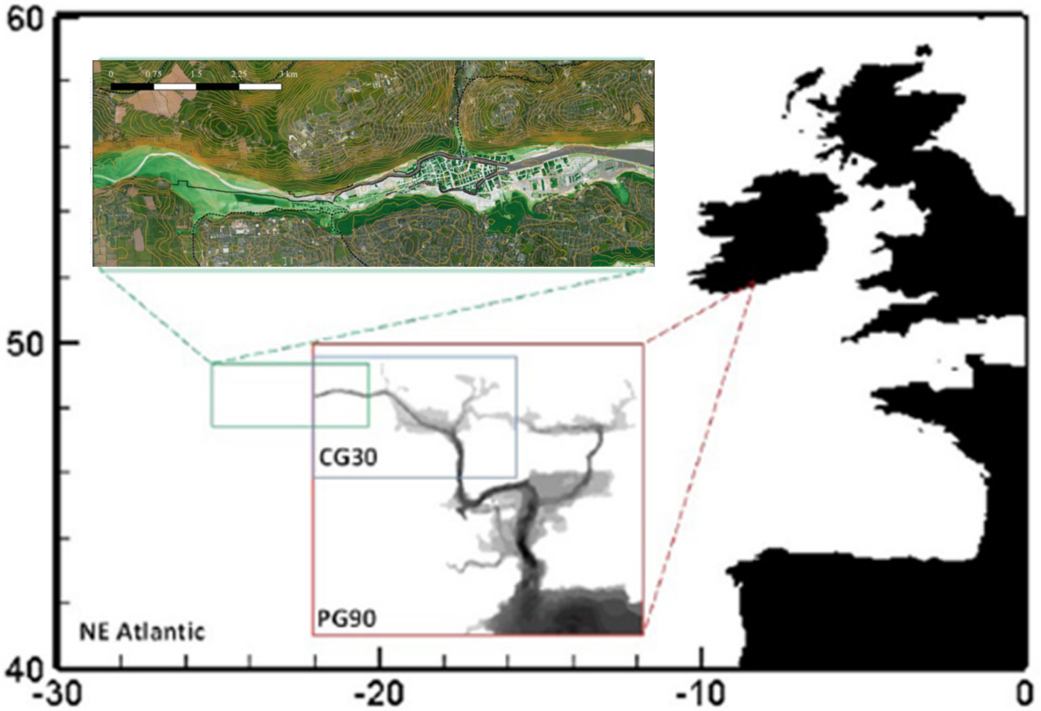

Figure 1. Geographical location of study area of Cork Harbour and Cork City (CG06).

3. METHODOLOGY

The MSN_Flood coastal-fluvial model set-up for Cork City is used to investigate the flood mechanisms and potential impacts of 21st Century climate change on flood inundation. Impact of current and future coastal urban flooding is estimated in a two step process: (1) statistical analysis of extreme conditions, dependencies between multiple drivers and joint probability of their co-occurrence and (2) hydraulic modelling of flood propagation driven by astronomical tides, storm surges and river discharges. A generalized extreme value model (GEV) was used to estimate extreme values of tides, surges and river flows and their return periods. Joint probabilities of exceedance is calculated to estimate the likelihood of extreme events of two different variables occurring simultaneously while χ dependency measure were used to account for interactions between flood drivers.

3.1 Model description

MSN_Flood is a two-dimensional, depth-averaged, finite difference model that solves the depth integrated Navier-Stokes equations that include effects of local and advective accelerations, earth rotation, barotropic and free-surface pressure gradients, wind action, bed resistance and Prandtl mixing length turbulence scheme. The model was developed to deal with multiscale hydrodynamic problems such as flooding where flow phenomena occur at various scales. The main and novel feature of the model is its unique nesting scheme, which utilizes a sophisticated approach to nested boundary formulations. An implementation of so-called ghost cells at the child nested boundary allows 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 Comer at al. (2017) while a full technical description of the model can be found in Nash et al. (2014).

3.2 Model inputs

Figure 1 shows a geographical location of Cork Harbour and bathymetry of urban floodplains of Cork City. The MSN_Flood model bathymetry of 6m resolution covers the area of Cork City and lower River Lee discharging into Cork Harbour. Computational domain of CG06 model that represents the River Lee channel was generated using cross sectional survey data provided by the OPW from an extensive survey of the rivers in the River Lee catchment in 2008. The 6m mesh of 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.

Fluvial discharges and coastal water levels at the western and eastern model boundaries, respectively, are used to force the model. The model is driven by these boundary conditions and was set-up to compute solutions across the model domain at 0.3-second timesteps over a 50-hour duration. In this research, the model was initially run for a variety of scenarios under present climatic conditions. This provided a baseline for the quantification of impacts of climate change. Design return periods of 100 years are considered for both current and future climates.

3.3 Current climate flood scenarios

The CG06 model is forced at the eastern 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 for 1 in 100 years events. The extreme tides and surges are determined from frequency analysis.

In the absence of long term tidal records, frequency analysis of astronomical tides was based on 1,104 data points (24 values per annum) of spring tide maxima. These data were extracted from a 46-year time series of astronomical tides generated from over 60 individual tidal components (NOAA 1982). A maximum high water spring tidal range of 4.53 m above chart datum (CD) has been determined for a 1,000 year return period (Olbert et al. 2013), from which a maximum HWT of 2.23 m above MSL was estimated (Figure 2a). 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 in this research was conducted on a dataset of surge values obtained from surge simulations of 48 storm events over the 46-year period 1959-2005 (Figure 2b). In order to consider the worst case scenario, the maximum surge residual (0.97 m) associated with the largest available return period (1,000 years) was used to represent the impact of surges on tidal signal in this study. Validation of these results can be found in Olbert and Hartnett (2010) and Olbert et al. (2013).

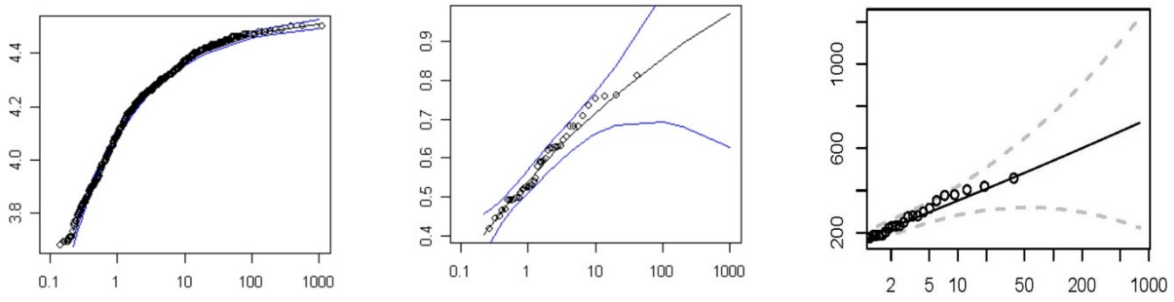

Figure 2: *Return level plot of extreme (a) tides, (b) surge residuals and (c) river flows.*

The eastern later boundary of the model is forced by a variable river Lee discharges. The 100-year return periods for fluvial events in current climate are determined using statistical analysis of extreme values of river flows. A 5.9-year long timseries of river gauge records on the River Lee was used to study the distribution of peak flows (Figure 2c). This provided a discharge of 512 m^3/s associated with a 100-year return period, comparable to the peak flows recorded at 19012 during the 2009 flood event (560 m^3/s). The shape of the hydrograph is determined from PCDs and adjusted based on a hydrologically similar pivot site containing a sufficient record of large flood events. A river flow of 75 m^3/s is considered a reasonable estimate of model inputs from the River Lee during normal (baseflow) conditions.

In total, eight model runs of current conditions were identified for various combinations of river flows, tides and surge signals (Table 1) both individual and combined under current climate conditions.

Table 1: *Model Boundary Conditions*

Mechanism	Current	MRFS	HEFS
Fluvial			
Mean flow	75.0 m^3/s		
Peak flow	512.3 m^3/s	+15.8%	+42.1%
Coastal			
Mean HWT	1.40 m above MSL		
Max. HWT	2.23 m above MSL		
MSL + Subsidence	0.00 m	+0.50 m	+0.63 m
Peak Surge Residual	0.97 m	-17.76%	+15%

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3.4 Future climate flood scenarios

A total of 88 model runs were identified for mid-range and high-end future climate scenarios. Identified runs consider changes to both individual flood mechanisms and combinations of different flood mechanisms.

Table 1 presents the 100-year return level discharges that force west model boundary (fluvial) under current and future climate scenarios. East model boundary is forced by a synthetic maximum tidal elevation with maximum surge residual for current, MRFS (medium range future scenario) and HEFS (high end future scenario) surge signals.

4. RESULTS AND DISCUSSION

4.1 Interdependencies between flood drivers

Although, the method for the determination of extreme water levels due to the independent actions of tides, surges and river flows gives reasonably good estimates of flood risk they are known to be inaccurate due to due to the combined effect of all three signals and associated potential dependencies between variables (Haigh et al., 2010a). The interdependence between flood drivers can lead to compound effects (e.g. Wahl *et al.* 2015) and modelling individual flood drivers separately can lead to inaccurate characterisation of flooding (Moftakhari *et al.* 2017). The interactions and dependencies are than an important consideration for effective flood prediction and management.

In assessing the potential flood risk of a coastal region like Cork City, the likelihood of occurrence of joint extremes of tide, surge and river discharges may have needs to be accounted for. Olbert et al.

(2013) confirm that extreme sea levels in Cork Harbour are the product of a moderate-to-high surge coinciding with high water spring tide. Figure 3 shows that Cork Harbour exhibits a characteristic pattern where surges tend to peak during a rising tide, around half-way between mid-flood and high water. Surges show then a temporal variation due to modulation by tides. This mechanism of tide-surge wave modulation was described by Prandle and Wolf (1978) and Horsburgh and Wilson (2007). the level of dependency was quantified using a χ^2 statistical model to find a low degree of interaction between surge and phase of tide and no dependency between surge peak and tidal height. As a result, in this research a tide-surge independency is assumed as a conservative solution.

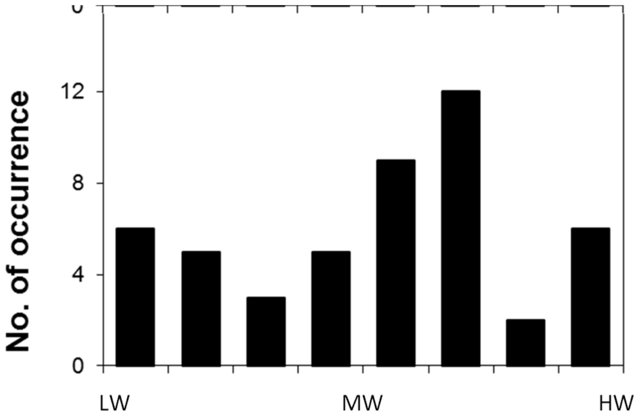

Figure 3: *Frequency of surge peak occurrence at eight tidal phases. LW- low water, MW – mid water, HW – high water.*

Considering that high river flows and surges can be generated by one driver, a low pressure weather system, the likelihood of both events occurring simultaneously can be high. The dependency measure χ (Coles et al., 2000) between river gauge data and storm surge residuals was calculated to show a significant dependency level between pairs of daily mean river level and daily maximum surge residual. Hence, it can be assumed that surges may co-occur at time of high river discharges. As such, it can be expected that high coastal waters may restrict fluvial discharge and cause a stacking of water along the riverbanks resulting in exacerbated flooding as explanied in Hoitink & Jay (2016). Kirkpatricka nd Olbert (2020) found that this results in reduced coastal inundation with the increased river discharges as increased volumes and velocities of freshwater inflows restricts the propagation of tides upstream.

4.2 Simulation of flooding

The frequent occurrence of urban flooding in Cork City triggered a series of studies that investigated the mechanisms of flooding (e.g. Comer et al. 2017; Olbert et al. 2017). These studies showed that the majority of flood events in Cork City are primarily fluvial where run-off exceeds the conveyance capacity of the River Lee channel and spills into the street network. Autonomous modelling of fluvial flooding has shown that fluvial events are the primary contributor to extreme flood events under the current climate scenario (Figure 4). In the past, coastal mechanisms did not impose a serious threat to coastal flood defence structures, except when combined with high river flows when they then contributed to flooding, particularly in the downtown streets (Olbert et al. 2017). However, with increases in mean temperatures and rising global sea levels as projected for the 21st Century by the Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report (IPCC 2013), this pattern has been changing. There is a good body of knowledge that shows that two main results of elevated temperatures will be elevated sea levels and increase in the mean precipitation rate and therefore the frequency of extreme precipitation events. These changes are likely to exacerbate flooding in North-

Western Europe (Lehner *et al.* 2006; Murphy & Charlton 2008). However, the exact impact on flood mechanisms, particularly on a catchment scale, is difficult to ascertain.

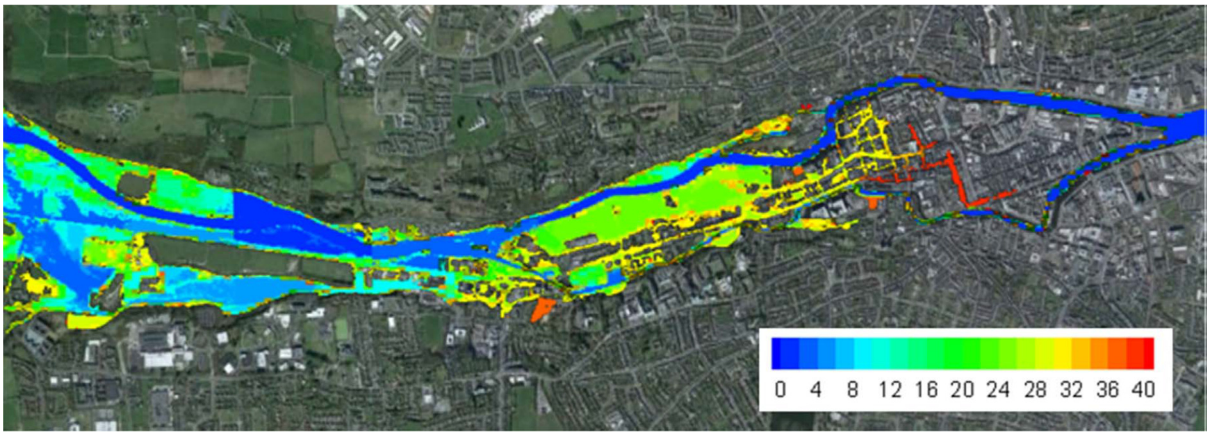

Figure 4: *Progression of flood inundation over upper and lower floodplains of Cork (CG06) during November 2009 event. Contours represent 2-hour intervals.*

Kirkpatrick and Olbert (2020) further extended the investigations of Comer et al (2017) and Olbert et al. (2017), and projected the effects of climate change on future flooding in Cork City. As shown in Figure 5, flooding due to river discharge generated by the current 100-year return period flow (512 m3/s) results in 187 ha of inundation. A significant portion of this comprises agricultural lands and semi-natural areas to the west of the city while the most affected area of the city itself is the low-lying island between the north and south channels of the Lee. The simulations of flooding in response to a MRFS and HEFS show an increase in flood inundation by a 12% and 30% over the current scenario, respectively. Additional areas of inundation are largely located within the city centre. This increase results from greater volumes of water overtopping defences upstream, resulting in greater flow velocities and propagation of floodwaters further east, rather than additional overtopping in the lower reaches of the channel.

Simulations indicate that coastal mechanisms are also capable of triggering inundation. As expected, for current sea levels no flooding is simulated within the model domain under average or spring tidal conditions. Flood defence systems in the tidal section of the river are capable of protecting against coastal-driven floods under average tidal conditions for both a MRFS and HEFS MSLR. However, significant inundation is simulated to occur for a HEFS MSLR under spring tidal conditions.

The effect of water levels due to surge residuals peaking on spring tides is pronounced. Simulations indicate that notable flooding can occur from the co-occurrence of the current peak surge residual with spring tidal conditions with a total of 38 ha of inundation regardless of climate change. Under a MRFS and HEFS sea level, simulations indicate that the co-occurrence of the current peak surge residual with spring tides has the potential to cause significantly greater flooding than at present. Under these scenarios, the majority of the city centre street network becomes inundated; large areas of flooding occurs in the Marina industrial area to the south of the river, largely due to waters overtopping the south bank along Albert Quay and Kennedy Quay, and spreading eastwards down Victoria Road and Centre Park Road. The maximum inundation simulated from coastal flooding mechanisms, is a total of 191 ha, resulting from the co-occurrence of a HEFS surge event for a HEFS MSLR. This scenario impacts the majority of the city centre and eastern industrial areas as shown in Figure 6.

Although both the fluvial and coastal mechanisms have the potential to cause substantial flooding on their own, the combined impact of high river flows and high coastal water levels cause the greatest overall inundation across the model domain. In the worst-case scenario, the combination of spring tides with a HEFS surge event under a HEFS MSL and the HEFS peak flows results in severe flooding with the a total of 387 ha of inundation. The entirety of the city centre street network becomes inundated under this scenario, with fluvial flooding of the city downtown exacerbated by coastal flooding (Figure 7). The extensive coastal inundation occurs to the east of the city centre - in the Tivoli and Marina industrial areas, and in urban areas to the south of the Lee, east of Morrison's Island.

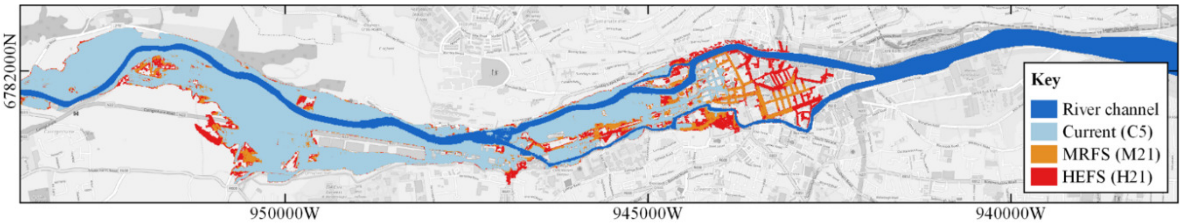

Figure 5: *Flood extent resulting from current, medium-range (MRFS) and high-end future scenario (HEFS) 100-year return period fluvial events*

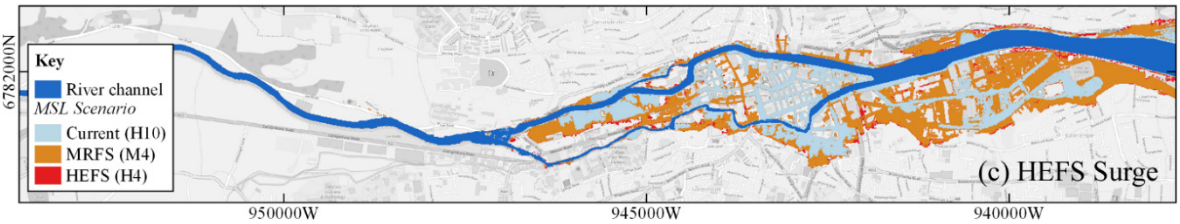

Figure 6: *Flood extent resulting from high-end surge residuals under current and future mean sea levels on spring tides*

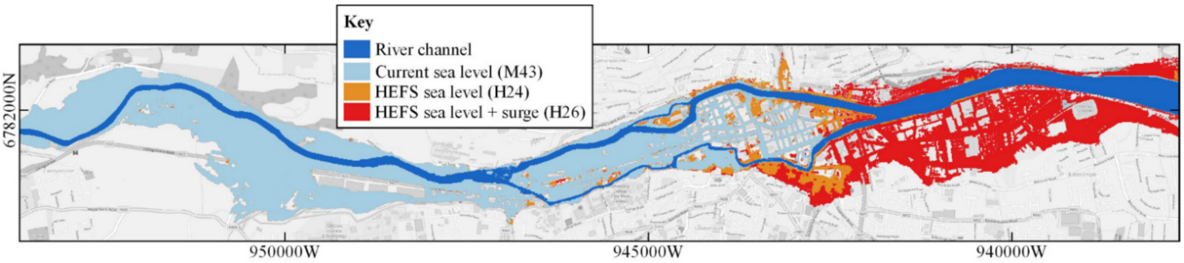

Figure 7: *Flood extent resulting from the high-end fluvial flood event on current sea levels, on high-end future sea levels, and on high-end sea levels with a high-end surge residual, all on spring tides*

5. CONCLUSIONS

As twenty-first century climate changes are expected to be pronounced, this paper presents an investigation of changes in mechanisms, dynamics and extents of urban coastal -fluvial floods due to climate change. This investigation was applied to a case study site - Cork City, Ireland. Interactions and dependencies between tides, surges and river discharges were computed to understand the likelihood of cooccurrence of compound drivers. A hydrodynamic flood model MSN_Flood was used to compute potential future inundation patterns for a range of climate scenarios based on estimates of current, medium-range and high-end projections of extreme river flows and sea levels.

The study shows that tide-surge interactions in Cork Harbour modulate the phase and magnitude of their combined signal and have a damping effect. As a result, the total water levels are lower than they would be in the absence of interactions. In contrast, dependency between the surge residual and river flow amplifies the risk of flooding. The assumption of no interaction between tides and surges and high dependency between surges and river flows were used as the most conservative approach to determine the ensemble scenarios and associated boundary conditions.

The simulation of joint 100-year fluvial and coastal flooding shows for current climate that the most extreme flood events occur due to a combination of peak river flows and high coastal water levels. The fluvial mechanism is a critical driver of flooding in Cork City, however, coastal mechanisms are also capable of inundating urban floodplains.

The ensemble simulations for a range of climate changes scenarios show that climate-driven increases in both fluvial and coastal mechanisms will create a significant threat to the populace across the majority of the city. Climate-driven increases in fluvial flows have the potential to increase the inundated area by 30% compared to current fluvial peak conditions, with waters propagating further downtown into the city centre. Climate-driven changes in both MSL and surges could result in a significant increase in coastal inundation when compared to current climate. Relative increases in coastal inundation under future climate scenarios, in comparison to the current climate, are much greater than those modelled for fluvial events. The knowledge can provide significant support for long term planning and investment decisions on flood defence infrastructure in Cork City and to quantify probable flood damages of economic, social and environmental natures.

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