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Combined statistical and hydrodynamic modelling of compound flooding in coastal areas - Methodology and application

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ABSTRACT

This paper presents a robust cost-effective framework for assessment of coastal-fluvial flooding due to compound action of multivariate dependent drivers. The methodology is an 8-step process that links statistical and hydrodynamic models to determine probabilities of multiple-driver flood events and associated hazards. The method involves individual and combined extreme value analysis, assessment of dependencies and interactions between flood drivers, multivariate joint probability determination accounting for dependencies, high-resolution hydrodynamic modelling of flood scenarios derived from multivariate statistical analysis, and ultimately mapping of inundation.

Using Cork City, on the south coast of Ireland, as a study case, the research shows that the interactions and dependencies between tides, surges and river flows affect flood severity when they occur jointly. Tide-surge interactions have a damping effect on the total water level, while dependence between the surge residual and river flow amplifies the risk of flooding. The multivariate joint exceedance probability occurrence of high discharges and water levels represents a more realistic representation of the spatially variable water surface profiles then the combined univariate marginal scenarios. Multivariate analysis allows also considering multiple combinations of joint probability solutions along RP *iso*-curves. The results show that the quantification of compound flood impacts must be performed along the entire RP probability curve. This is because the physical/hydrological impacts of multiple-driver same-RP flood events can be very different leading to substantially different characteristics of flooding. The multi-scale nested flood model (MSN_Flood) was used to simulate flood wave propagation over urban floodplains for an ensemble of statistically derived flood scenarios. The hydrodynamic runs provide inundation maps that can be used to draw inferences about flood mechanisms and impacts.

1. Introduction

Coastal conurbations are at risk of flooding caused by a combination of astronomical, meteorological, hydrological and climatic factors (Gallien et al., 2011). In the future, urban flood probability and risk will increase as a consequence of several factors including population growth in flood-prone areas, climate change and decaying or poorly-engineered flood control infrastructure (Kirkpatrick and Olbert, 2020; Gallegos et al., 2009; Bevacqua et al., 2019).

Many large population centres are located along the coastline, and many of these are along estuaries where freshwater flows merge with tidally-driven sea water (Orton et al., 2012). These centres lie most commonly in intertidal zones where water levels are directly affected by the upstream flow and the downstream coastal conditions. Naturally, such coastal zones can be vulnerable to flood events from a single source or several sources acting in combination (Archetti et al., 2011) that leads to compound flooding (Leonard et al., 2014; Moftakhari et al., 2017; Zscheischler et al., 2018). The coastal tidal wave composed of astronomical tide, mean sea level and non-tidal residual constituents (storm surges, inter-annual variability, baroclinic processes) may propagate up

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the river channel network and cause a flood far from the coast (Hendry et al., 2019). Variable coastal water levels change both the river stage and discharge and form the downstream river boundary of unsteady and non-uniform flow. These water levels may impede river drainage to an estuary by a backwater effect as their upstream propagation may reverse the seaward flow in a river (Ganguli and Merz, 2019; Hoitink and Jay, 2016). On the other hand, a river discharge may raise mean coastal water levels and generate friction that makes tides lose energy and shrink in amplitude (Piecuch et al., 2018; Moftakhari et al, 2016). In summary, river-coastal interactions can contribute to subtidal friction, modulate tidal amplitudes and impede flows impacting river discharge downstream (Sassi and Hoitink, 2013).

The dependencies between non-tidal residuals of coastal water levels and fluvial peak discharge may be significant as both events may result from a common meteorological cause. Severe storm periods are often associated with high winds and low-pressure systems that generate storm surges, while at the same time causing orographically enhanced high precipitation on coastal catchments resulting in high peak river discharges (Kew et al., 2013). Such simultaneous or successive occurrence of high coastal and river water levels may produce extreme impacts even when hazards from individual drivers in isolation would be unlikely (Bevacqua et al., 2017).

Commonly, coastal flood hazard assessments rely on univariate statistical modelling methods where river discharges and extreme sea levels are considered separately (Ganguli and Merz, 2019). Such approaches assume stationary and unconditional distribution of flood signals, and therefore may not correctly estimate the probability of a given hydrologic event (Salvadori and De Michele, 2004; Moftakhari et al., 2017). Since coastal cities are at risk of compound flooding effects from multiple drivers, univariate approaches should not be used to characterize the flood hazard (Moftakhari et al., 2017). More recently, the influence of compound events on flood hazards was studied using physically-based and stochastic models (van den Hurk et al., 2015). Most efforts on compound flooding to date are based on a joint probability bivariate flood hazard assessment that accounts for compound flooding from river flow and coastal water level. Some of these methods account for dependencies among multiple drivers (Hendry et al., 2019). Most recently, the copula-based models have been used to analyse the joint frequency of compound floods (Bevacqua et al., 2017; 2020; Yazdandoost et al., 2020; Zhong et al. 2021; Moradian et al., 2023). These simulations, however, do not take account of the likelihood and intensity of fluvial floods conditional on coastal water levels, or the severity of coastal water levels conditional on river discharges (Ganguli and Merz, 2019) and, therefore, do not explore all possible flood scenarios.

Regardless of the compound event approach employed, the aforementioned statistical methods do not provide important information on compounding effects of spatially distributed interactions between the river discharge and downstream ocean level in tidal channels and estuaries. Most commonly, the bivariate models of coastal-fluvial flooding use time series records of river discharge at the reach entry, and water level measurements at the downstream end of the reach. In a long complex estuary, these data could be representative of two different hydrodynamic regimes (Moftakhari et al., 2019). This issue can be addressed by linking the statistical and hydraulic models. The two-model approach allows one to hydrodynamically determine mechanistic routing of flood water onto urban floodplains under statistically derived exceedance probabilities. Ultimately, this information can be used to assess flood hazards (e.g., depth and velocity) and understand the impact of such flood events (Gallien et al., 2011; van den Hurk et al., 2023; Gallien et al., 2018; Uddin et al., 2022).

While statistical models have been widely used, their linkage to hydraulic models is not so common. Although simplistic bathtub models have been widely applied for estimating coastal flooding hazards, they may potentially lead to underestimation of flood consequences due to their inability to vary flood stage with distance inland due to river-tidal interactions (Lanzoni and Seminara, 1998) and variable non-linear flood dynamics (Gallien et al., 2014; Sanders, 2017). In a broader sense, mapping flood hazard in complex estuaries using approaches that ignore local hydrodynamics can underestimate flood extent and depth (FEMA 2015). While hydrodynamic modelling of rapid flood events in urban environments is a very complex and challenging task, a number of successful investigations into combined coastal-fluvial flooding has been demonstrated in recent years (e.g Yang et al., 2012; Comer et al., 2017; Moftakhari et al., 2017; Olbert et al., 2017; Gallien et al., 2018; Griffiths et al., 2019). However, none of these studies links hydrodynamic and statistical models in a way that considers flood impacts for a spectrum of statistical conditions of a certain return period. As such answering the following fundamental questions: 'How severe these events can be? or 'What combination of extreme signals can result in the most hazardous events?' is impossible. Importantly, many different compound events have the same return period despite its *iso*-curve representing different combinations of river flow, tide and surge signals. Now, these different events result in the specification of a range of flow, tide and surge boundary conditions in the model having the same return period. Each different set of boundary conditions can give rise to spatially different flooding conditions throughout the model domain for one given return period. In this complex problem, model linking is possibly the only way to assesses the compound nature of coastal sea levels and river discharges (and specifically to quantify severity of compound floods for a combination of extreme signals) and by that to facilitate a comprehensive management of flood hazards (Luke et al. 2018). It is quite clear that a robust and integral assessment of compound flood hazards should leverage the intrinsic characteristics of both modelling approaches into a coupled approach (Muñoz et al., 2020).

In this context, the objective of this research is to develop a statistical-hydrodynamic modeling toolbox and to provide a methodology for assessing the combined effects of multiple-source flooding in urban areas. The toolbox comprises: (1) statistical models of frequency analysis, extreme value of storm surges, tides and river flows, and ultimately the joint probability models for calculating joint exceedance return periods; and (2) a hydrodynamic numerical model as the central engine, where flood inundation under numerous coastal and fluvial flood scenarios derived from the statistical model are simulated. Such a statistical-hydrodynamic modeling system allows to model coastal-fluvial floods across the joint probability spectrum for a given return period event, and this is a very important consideration for flood management. Modelling within this complex system thus allows to forensically investigate all possible impacts of a flood hazard and clearly disentangle between coastal and fluvial effects, and by that provide a useful information for flood management engineers and policy makers. To the Authors' knowledge the across JP-spectrum modelling and hazard quantification have not been presented in a detail yet.

This new statistical-hydrodynamic system is very significant for flood management, as illustrated by the following 2 points:

(i) It is important to realise, in a coastal flooding context, that modelling the flood extent of one set of boundary conditions jointly having a particular return period, say 50 years, will not provide an answer to the question: 'What are the flood extents having a return period of 50 years'.

(ii) As in the system application described in section 3 below, when a river boundary is located upstream of the modelled domain and the tide/surge boundary is at the opposite end of the domain, a joint event having a return period of, say, 50 years, may give significantly different inundated depths and extents if we combine a relatively low river flow with a high combination of tide and surge than if we combine a relatively high river flow with a low combination of tide and surge.

Thus, to obtain the full extent and depth of inundation having a return period of 50 years a series of joint events must be simulated and the results processed to identify the particular compound event causing maximum flooding in all grid cells of the modelled domain.

The need and usefulness of the new toolbox has been demonstrated in this research for the case of the River Lee in Cork City; this is located on the south coast of Ireland and it regularly experiences compound coastal and fluvial flooding. The impact of flooding is quantified based on a range of physical aspects such as coastal-fluvial flood inundation extent and water depth. The toolbox has been developed in a general-purpose approach and so can easily be applied to other case studies.

The paper is structured as follows. Section 2 details the methodology, where the numerical models and their setups are described along with the statistical approaches to extreme value analysis and determination of joint probabilities. Section 3 compares numerical model results for various flood scenarios and mechanisms. It also presents extreme value analysis results which provide the boundary conditions and scenarios for the numerical models. Finally, Section 4 presents conclusions from the research and discusses the usefulness of the methodology and the implications of the results.

2. Methods

In this section the methodology for assessment of flood probability and severity is briefly described followed by the review of statistical approaches used for extreme value and joint probability (JP) analyses and the descriptions of the flood modelling system used for Cork City.

2.1. Flood assessment methodology

In the absence of a systematic approach to statistical-hydrodynamic modelling of floods, an 8-step methodology for urban flood assessment is developed in this paper and presented on Fig. 1. As shown in this flowchart, for compound flood events, the analysis requires statistical and hydraulic modelling used jointly in a multi-step process. Each driver must first be statistically analysed individually in order to estimate its independent frequency of occurrence, following which JPs can be estimated and flood events modelled. A number of flood scenarios (S) for a range of extreme conditions must be developed from extreme value analysis to establish univariate and multivariate boundary conditions for the numerical model. Three scenarios are considered in this research:

- S1 - A marginal river discharge scenario of fluvial flood only (T-year RP discharge and non-extreme coastal water level)
- S2 - A marginal coastal water level scenario of coastal flood only (T-year RP sea water level and non-extreme river discharge)
- S3 - An AND scenario of joint probability occurrence of high discharges and water levels of T-year RP

The hydrodynamic model is forced with a range of boundary conditions that represent a combination of flood drivers for conditional (S1, S2) and joint probability (S3) scenarios and various T-year RPs. A synthesis of hydrodynamic modelling results is used to map inundation levels under various extreme conditions and to quantify physical compounding effects.

2.2. Statistical modelling

In the first stage of statistical modelling, astronomical tides, surge residuals and river flows are subject to univariate frequency analysis and modelling of their extremes. In the second stage, a multivariate joint probability of their occurrence is estimated. This analysis takes into account the potential multivariate dependencies between drivers. The following sections briefly outline the methods used to calculate extreme values, multi-driver dependencies and joint probabilities of their co-occurrence. Outputs from these analyses will be subsequently used to investigate flood hazards due to extreme events.

2.2.1. Extreme value analysis

Univariate frequency analysis is used to determine extreme values of individual flood drivers. Probabilistic models from the field of extreme value statistics are usually adequate to quantify variables in terms of their extreme values and associated return periods (Moftakhari et al,

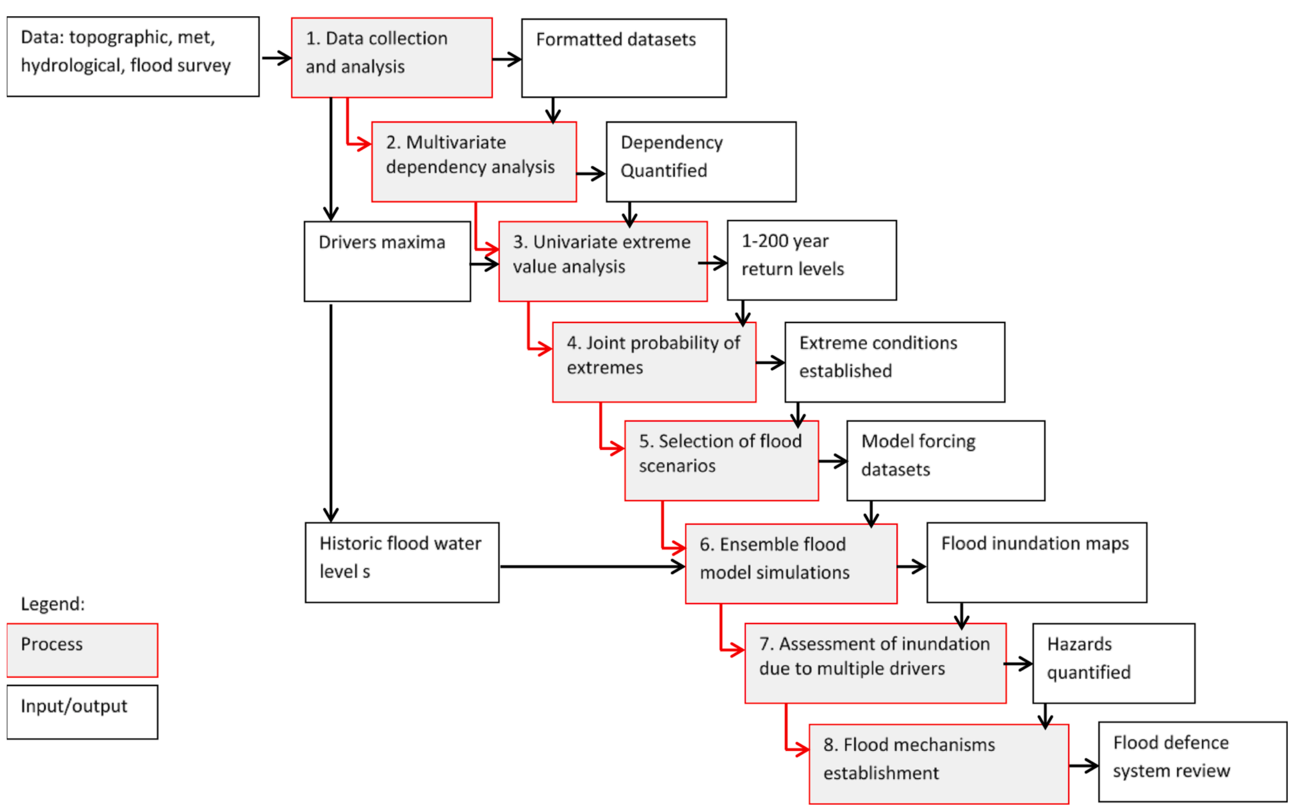

Fig. 1. Flow chart of flood assessment methodology.

2017). Many studies including Lowe et al. (2001), Butler et al. (2007), Olbert et al. (2013) and Sun et al. (2017) demonstrate their suitability to the analysis of tides, surges and/or river flows.

The probability that a water level z will be exceeded by any water level × in any given time period is termed the probability of exceedance of the water level z, P(z), and is mathematically expressed as:

$$P(z) = 1 - F(z) = \int_{z}^{\infty} f(x)dx \tag{1}$$

where $F(z)$ nd $f(x)$ re the cumulative distribution function (CDF) and probability density function (PDF), respectively. The return period (RP) time T represents the average time between consecutive occurrences of water levels equal to, or greater than the given level z:

$$T = \frac{1}{p(z)} = \frac{1}{[1 - F(z)]} \tag{2}$$

A generalized extreme value model (GEV) (Coles, 2001) was used to estimate extreme values of tides, surges and river flows and their RPs. The CDF of the GEV is expressed as

$$F(z) = \exp\left\{ - \left[1 + \xi\left(\frac{z-\mu}{\sigma}\right)\right]^{-1/\xi} \right\} \tag{3}$$

where μ is a location parameter, σ a scale parameter and ξ a shape parameter. The value ξ determines the asymptotic extreme value distribution and hence the type of distribution; $\xi = 0$ epresents a Gumbel distribution, $\xi > 0$ Frechet distribution and $\xi < 0$ Weibull distribution.

2.2.2. Multivariate dependencies

In order to accurately calculate the joint probability of extreme events, dependent interactions between any of the variables must be first assessed. The method utilised here is the χ dependency measure based on tail dependence (Coles et al., 1999):

$$\chi(u) = 2 - \frac{\ln P(U \leqslant u, V \leqslant u)}{\ln P(U \leqslant u)} \quad for \quad 0 \leqslant u \leqslant 1 \tag{4}$$

where u is the upper threshold of the uniform distribution. U and V are transformed variables with uniform margins [0,1] such that

$$P(U \leqslant u, V \leqslant u) = \frac{Number\ of\ (X,Y) pairs\ such\ that\ X \leqslant x^{*}\ and\ Y \leqslant y^{*}}{Total\ number\ of\ (X,Y)} \tag{5}$$

and

$$P(U \leqslant u) = \frac{1}{2} \frac{Number\ of\ \ X \leqslant x^{*}}{Total\ number\ of\ X}\ \frac{Number\ of\ \ Y \leqslant y^{*}}{Total\ number\ of\ Y} \tag{6}$$

where (X, Y) s an observational pair from the original data series while (x^{*}, y^{*}) s the threshold level for the observed series of the same probability of exceedance P. Coles et al. (1999) suggest interpretation of total dependence as $\chi = 1$ nd total independence as $\chi = 0$ Partial dependence for example, $\chi = 0.1$ means that there is a 10% risk of the two variables exceeding their threshold at the same time, with the threshold for each variable corresponding to the same probability.

2.2.3. Joint probability

JP can refer to the exceedance of river discharge and coastal water level (referred to here as AND scenarios), or the exceedance of river discharge or coastal water level (referred to here as OR scenarios). There is a wide range of parametric and non-parametric methods developed for bivariate frequency analysis. The copulas functions (Sklar, 1959) are used to formulate joint distributions of bivariate pairs (Moftakhari et al., 2019, Bevacqua et al., 2017). Sadegh et al. (2018) use a Bayesian framework with copula functions and dependence structure.

In this study, where a dependence between two variables exists, the JP RP of an event $T_{x,y}$ where both variables exceed their thresholds is represented as

$$T_{x,y} = \frac{1}{\left(1 - \frac{1}{\sqrt{T_x T_y}}\right)^{2-\chi(u)} + \frac{2}{\sqrt{T_x T_y}} - 1} \tag{7}$$

In cases where there is no dependency between two components, a method developed by Pugh and Vassie (1980) and revised by Tawn (1992) is proposed. For a given water level z, if the PDF of one variable is $f_x(\eta - s)$ nd the PDF of another variable is $f_y(s)$ the PDF of the total water level $f(\eta)$ s a combined probability of two variables occurring simultaneously is

$$f(\eta) = \int_{-\infty}^{\infty} f_x(\eta - s) f_y(s) ds \tag{8}$$

The joint probability RP, $T_{x,y}$ of an event where both variables occur simultaneously can be expressed as:

$$T_{x,y} = 1/[1 - F(z)] \tag{9}$$

where $F(z)$ s the joint CDF for a given extreme sea level z efined as:

$$F(z) = \int_{-\infty}^{z} f(\eta) d\eta \tag{10}$$

In the RJPM method given in equation (8), the normalized PDFs of two variables (i.e. tides and surges) are then used to construct a joint probability matrix. In this matrix, each diagonal represents a probability of joint occurrence of two variables due to a certain combination of variable one and variable two. The sum of each diagonal representing a certain joint value (i.e water level due to tide and surge) gives the probability of occurrence of that joint variable. The example of construction of joint probability matrix is presented in Pugh and Vassie (1980). Ultimately, probabilities are converted to RPs using equation (9) as explained in Tawn (1992).

The outputs from the univariate and multivariate statistical analyses of river discharges and coastal water level pairs are used to construct flood hazard scenarios for hydrodynamic runs.

2.3. Hydrodynamic modelling

In this research, modelling of coastal-fluvial flood inundation extent and water depth was carried out using a state-of-the-art multi-scale nested (MSN_Flood) hydrodynamic flood model. 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. The nesting structure of the model comprises a two-level cascade of dynamically linked nested grids at 6 and 2 m resolutions. A 6 m parent grid model provides water level conditions from the greater Cork region to a 2 m ultra-high-resolution nest which covers the downstream section of the River Lee channel and Cork City (Fig. 2). 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 may alternatively flood and dry. Extensive model validation at each of the nested levels can be found in Nash and Hartnett (2010) and Comer et al. (2017) while details of model parameterization, sensitivity and comprehensive validation of the 2 m model can be found in Olbert et al. (2017). Since the same model configuration is used in this research, readers are referred to Olbert et al. (2017) for the model description and performance assessment.

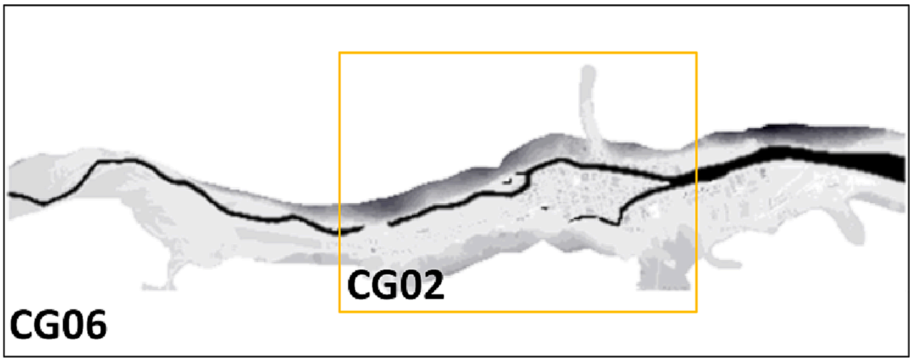

Fig. 2. Model bathymetry with River Lee channel (CG06) and Cork City urban floodplains (CG02).

3. Results

In this section, the outputs from statistical-hydrodynamic modelling are presented. Statistical modelling involves the analyses of frequency, extreme value of storm surges, tides and river flows, and JPs of exceedance. The JP values are used to construct the boundary forcing conditions for the hydrodynamic model which is used to simulate coastal-fluvial floods for a range of extreme events and across the joint probability spectrum (*iso*-curves) for each of the RP event. An ultimate set of results are the maps of inundation extents and water depths for a combination of river flows and sea levels of given RP.

3.1. Univariate analysis of individual flood drivers

In the proposed methodology the univariate statistical analysis of extremes (step 3) is performed to establish extreme conditions of individual drivers for marginal scenarios (S1, S2) and joint probabilities of multiple drivers for multivariate flood scenarios (S3). Statistical analysis of extreme values of River Lee discharges and coastal water levels (decomposed to tides and surge residuals) in Cork estuary are based on records of peak-over-threshold (POT) data. The extreme value analysis of surge residuals was conducted on a dataset of surge values obtained from surge simulations of 48 storm events over the 46-year period 1959–2005. Only the maximum surge value from each of the simulated events was extracted to guarantee independent events; this yielded a dataset of 48 maximum values, the highest of which was 0.81 m.

Astronomical tides extracted from a 46-year time series for Tivoli, Cork (NOAA 1982), located on the eastern boundary of the 6 m model domain, were used in the frequency analysis. The accuracy of this dataset was corroborated by comparison against a harmonic dataset constructed from existing records for Tivoli tidal gauge station and the nautical almanac (Hewitt and Lees-Spalding, 1982). The 38 largest river discharges were identified from a 5.9-year long timeseries of river gauge records on the River Lee (gauge number 19012).

The frequency analysis was used to estimate the probability of occurrence of any of the three flood components considered here. For the exceedances to be considered extreme, high threshold values were set in the POT analysis; the POT levels for surge and river flow were 0.4 m and 70 m^3/s, respectively. A GEV statistical distribution was fitted to the POT data. The uncertainty associated with the selection of a probability density function was significantly reduced by ignoring the lower bound values.

The computed RPs are presented in Table 1 and Fig. 3. Although the fitted distributions provide frequencies of occurrence of up to 1000-year RP, only the values of the 50 and 200-year RPs were considered in the analysis. Davie (2008) recommends that the extrapolated RPs should not exceed twice the length of the dataset, while Hall et al. (2006) found that analysis over a timescale of 30–100 years introduces uncertainties. The method may introduce a degree of model uncertainty for some variables (e.g. sea level) as a result of interferences produced by climatic signals such as climate modes or climate change.

Table 1
Tide, surge, river flows and total sea water levels for selected RPs.

Return period [years]	Tide [m OD]	Surge [m]	River flow [m^3/s]	Tide and surge JP [m OD]
2.00	4.76	0.56	198.33	5.02
5.00	4.78	0.65	287.51	5.16
10.00	4.80	0.70	347.63	5.25
20.00	4.81	0.75	406.10	5.32
50.00	4.82	0.81	482.98	5.39
100.00	4.83	0.85	541.49	5.45
200.00	4.83	0.89	600.57	5.49
500.00	4.83	0.93	679.71	5.55
1000.00	4.84	0.97	740.45	5.58

3.2. Extreme water level analysis

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 is important. 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 but no universally accepted approach exists for determination of the water level due to the combined effect of all three signals (Haigh et al., 2010a). The treatment of potential dependencies between variables in a multivariate problem is a main reason for the difficulty. There is a good body of evidence showing that tides and surges interact (e.g. Olbert et al., 2013; Idier et al., 2012) and river flows and surges can be dependent when driven by the same meteorological conditions (Orton et al., 2012). The analysis of dependency between tides, surges and river flows is the second step of the methodology, and is used in conjunction with the univariate extreme analysis (step 3) to estimate joint probabilities of occurrence of multiple flood drivers (step 4).

3.2.1. Tide-surge interactions

Extreme sea water levels result from a combination of astronomical tides and non-tidal processes such as storm-driven surges, wind waves and baroclinic flows. These flood drivers may interact and exhibit dependencies. Olbert et al. (2013) found that extreme sea levels in Cork Harbour are the product of a moderate-to-high surge coinciding with high water spring tide; nonetheless, the likelihood of the simultaneous occurrence of these two signals requires in-depth analysis.

Fig. 4 shows the temporal variation of surges and tides and their contribution to total water levels in Cork City during a 2009 flood event. The characteristic pattern is that the surge tends to peak during a rising tide, around half-way between mid-flood and high water, so its temporal variation, although driven by meteorological conditions, seems to be modulated by tides. Prandle and Wolf (1978) and Horsburgh and Wilson

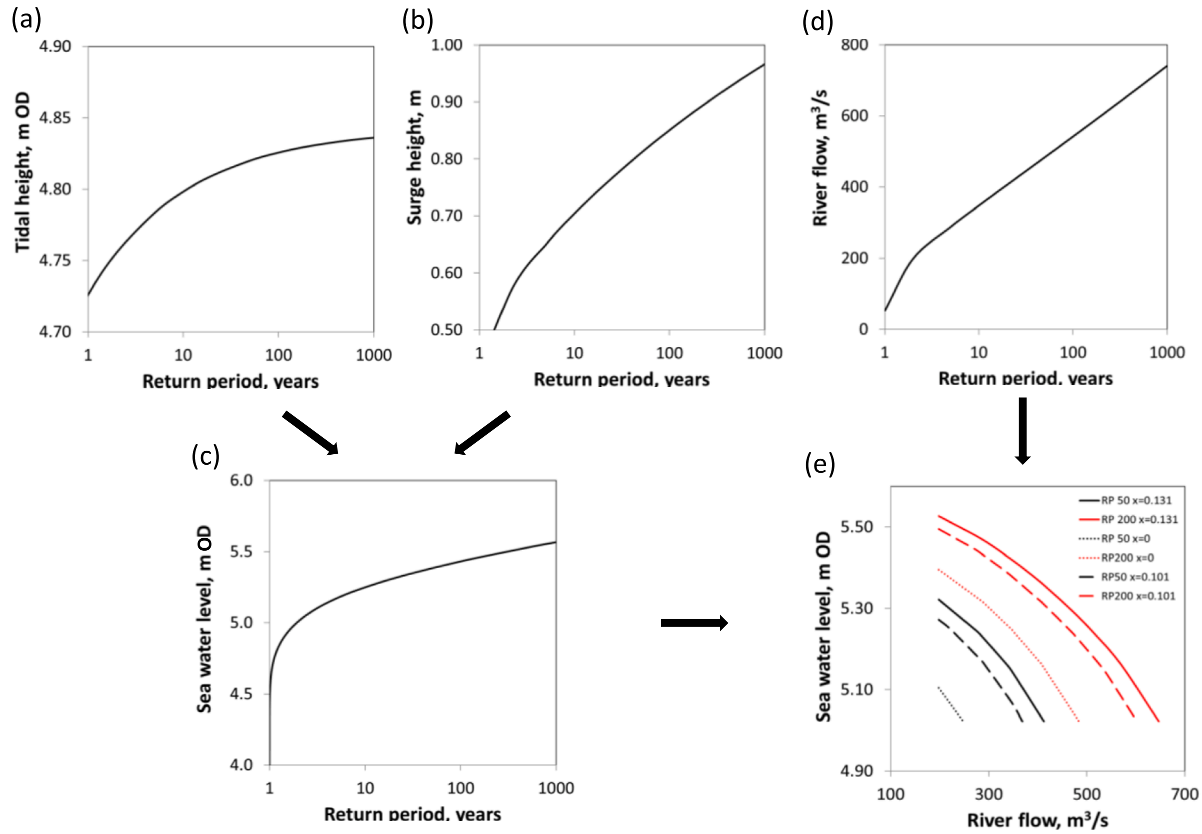

Fig. 3. Statistics of extreme (a) tides, (b) surges, (c) JP coastal water levels, (d) river discharges and (e) trivariate *iso*-probability curves of bivariate JP sea water levels and river discharges for 50- and 200-year RPs and various dependence levels.

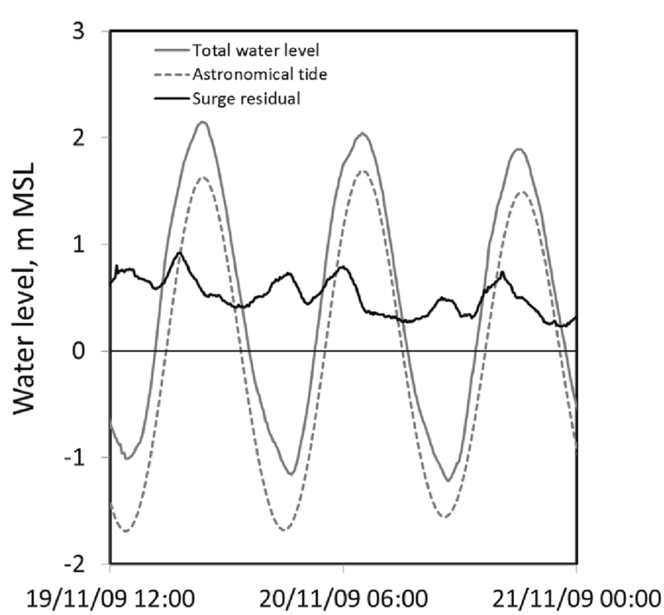

Fig. 4. Total water levels, astronomical tides and surge residuals (m MSL) at Tivoli during the flood event in November 2009.

(2007) describe this mechanism of tide-surge wave modulation in detail. This pattern is not an isolated incident - it occurred in over 50% of the 48 surge events investigated. Fig. 5 shows surges classified into one of eight groups, each representing a particular phase of tide. While there is no clear relationship between the surge magnitude and phase of tide, the distribution of surge peak occurrence over a tidal cycle indicates the presence of non-linear interactions (Haigh et al., 2010b). Olbert et al. (2013) analysed this type of interaction in Irish coastal waters and found that the level of interaction varies geographically. A χ^2 statistical model was used to quantify the level of dependence at the 95% significance level and n-1 degrees of freedom ($\chi^2_{7,0.95} = 14.07$ In the above research $\chi^2 = 12.0$ was found for Cork; this implies a low degree of interaction between surge and phase of tide despite the fact that surges tend to peak on rising tide more frequently than on other phases (Fig. 5). Interestingly, no dependence between surge peak and tidal height was found and surge heights do not vary across tidal phases. As tidal currents are stronger than surge currents in Cork, tides modulate the interaction in a non-linear manner. The quadratic bottom friction, being here the principal cause of tide-surge interactions in this region (Olbert and Hartnett, 2010), attenuates and smooths the amplitude of the surge as explained in Dinápoli et al. (2020). Taking a conservative solution, an assumption of tide-surge independence was used in the joint probability calculations.

3.2.2. *Surge-river flow dependence*

Recent studies clearly show that dependence may exist between river discharge and either coastal water level or storm surges, and not accounting for dependencies in joint probability analysis may underestimate the compounding effect (De Michele et al., 2005; Ward et al., 2018). In coastal sites, the dependence between river flow and total sea water level or surge often results from a common meteorological cause (Kew et al., 2013), so they may occur simultaneously. The time lag between river flow and total water level is another aspect to consider in the dependence analysis. The time-lagged analysis accounts for the fact that the storm surge peak may arrive at a different time than the river flow peak, despite both being generated by the same storm event.

Fig. 6 presents a scatter plot of daily mean river levels and daily maximum surge residuals. The dependence measure χ (Equation (4)

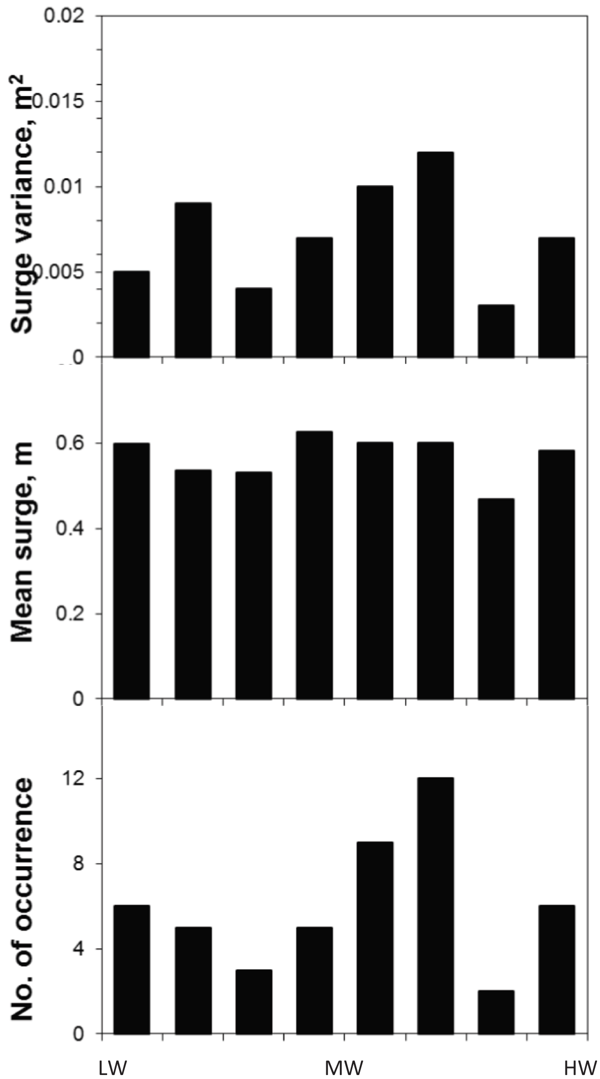

Fig. 5. Frequency of surge peak occurrence, mean surge residual and surge variance at eight tidal hights. LW- low water, MW – mid water, HW – high water.

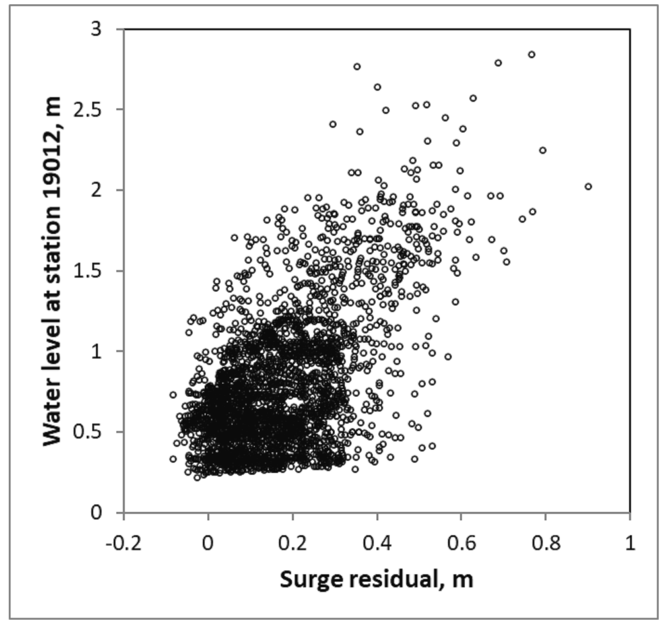

Fig. 6. Scatter plot of daily mean River Lee levels (station 19012) and daily maximum storm surges in Cork Harbour.

between river gauge data and storm surge residuals was calculated for pairs of daily mean river level and daily maximum surge residual. The thresholds for surge residual and river flows converted to water levels are 0.488 m and 1.8 m respectively. The dependence analysis was carried out for two scenarios: (a) maximum values occurring on the same day or (b) time-lagged scenarios. The lagged analysis was to determine whether or not a significant time lag existed between the response of the two processes. Results from these analyses are shown in Fig. 7. For the same day occurrence scenario, the dependence measure χ between surge residual and river flow of 0.101 is considered to be significant at the 5% significance level ($\chi_{0.05} = 0.06$) the 5% and 95% confidence intervals of χ dependence are 0.012 and 0.207, respectively. For the time-lagged analysis the daily maximum surge residuals were selected corresponding to daily maximum discharge values with time lags of −3 to +3 days. The χ values calculated when surge precedes river level are greater than the values calculated for the opposite scenario or the same day dependence. When surge precedes river level by one day the highest dependence of 0.131 is exhibited. This 1-day lag dependence between high river discharges and coastal water levels is in line with observations from the west/south of the UK (Hendry et al., 2019) where meteorological conditions are often part of the same large scale weather systems common to the UK and Ireland. Moreover, according to Hendry et al., 2019 this phenomenon is characteristic of relatively small catchments with a low baseflow such as River Lee is (1,253 km^2, 40.4 m^3/s).

Since the high river discharges occur on the day of, or just after, peak surge, compound flooding is still a concern. The flood modelling results of Olbert et al. (2015) clearly show that the time between river and tide peaks in Cork is too short for initial floodwaters to recede. As the most conservative approach, the 1-day dependence level was therefore used to derive joint exceedance probability of high river flows and surge residuals.

3.2.3. Multivariate joint probability

In step 4 of the methodology, the multivariate join probabilities of compound floods are estimated. A number of JP methods were considered (described in section 2), however, the methodology adopted in this study, being a combination of bivariate and trivariate analyses, is best suited for multivariate problems with various levels of dependencies between variables. Accurate assessment requires the dependencies (if they exist) to be included to account for lower marginal exceedance probabilities. The JP analysis is a multistep process illustrated in Fig. 3. The first step is the bivariate JP analysis of the extreme sea levels. The extreme sea levels are calculated using the revised JP method (RJPM) of Tawn (1992) given in equation (8). In this method, assuming tide-surge independence, tides and surges are firstly independently modelled using the statistical GEV model and their normalized PDFs are then used to construct a JP matrix. The sum of each diagonal in the matrix, being a probability of a water level due to a certain combination of tide and surge and representing a certain water level gives the probability of occurrence of that water level. The extreme water levels due to the combined action of tide and surge calculated using the RJPM are presented in Table 1 and Fig. 3(c). For the 50- and 200-year RPs, the coastal water levels are 5.39mOD and 5.49mOD above MSL, respectively.

For a complete set of conditions contributing to flooding, high river flows (Fig. 3b) and their interactions with surges are accounted for using trivariate joint probability. The trivariate joint RP is calculated using equation (7) for a combination of the selected RPs of water levels (from bivariate joint probability of occurrence of tides and surges) and RPs of river flows. Dependence between two variables is quantified through χ equation (4).

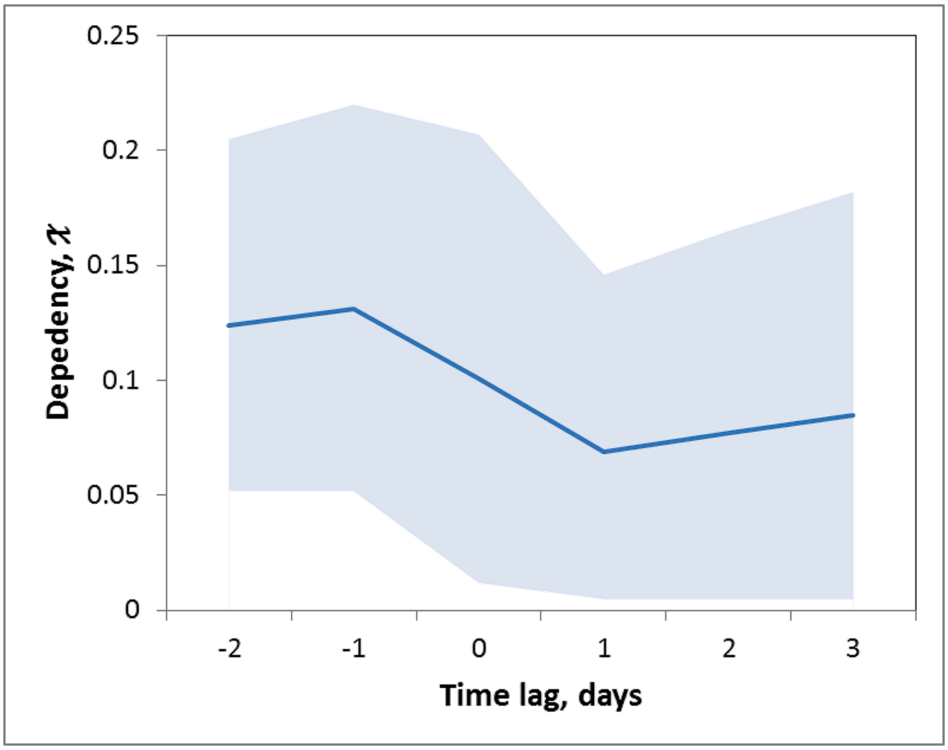

Fig. 7. Dependence measure χ between surge residual and river gauge flow for same day and time lagged analyses.

The 50- and 200-year *iso*-curves of joint exceedance RPs for a combination of river flows and sea levels calculated for the AND hazard scenario are presented in Fig. 3(e). While the RPs *iso*-curves represent the joint events of the same exceedance probability, the physical/hydrological impact of such events can be very different leading to substantially different characteristics of flooding. Flood inundation maps for these *iso*-curves are generated in step 6 using a hydrodynamic model.

3.3. Flood hazard modelling

The statistical-hydrodynamic methodology proposed here is possibly the only way to comprehensively assesses the compound nature of coastal sea levels and river discharges. The high-resolution numerical model of Cork City covers the downstream reach of the River Lee and the adjoining floodplains of Cork city-centre. The upstream boundary was prescribed as the river discharge while the downstream boundary was forced with a variable water elevation to simulate the tidal signal and non-tidal residual. The boundaries were placed far enough apart to let compounding effects develop within the domain. The boundary conditions were generated from the univariate and bivariate analyses for the S1-S3 flood scenarios defined in section 2.1. The hydrodynamic runs for each scenario were used to generate maps of extreme water levels for the selected RPs. This is a simple and efficient assessment approach that requires only a small computational effort while delivering comprehensive quantification of flood hazards across a spectrum of conditions including compounding events. Each map presents the maximum flood extent and the maximum flood water depth on floodplains based on the maximum water level recorded over an unsteady simulation covering the rise and fall of a flow peak with the rise and fall of a coastal water level.

3.3.1. Coastal flooding

The hydrodynamic simulations of coastal flood only represent the hazards associated with a single-driver marginal scenario of a flood event driven by an extreme sea water level. Fig. 8a presents the maximum water depths simulated for the marginal scenario of 200-year RP sea levels and average river discharge where the extreme sea levels were derived from a joint probability analysis of the independent occurrence of tides and surges. This scenario only results in a small number of very localised floods along the river channel that do not constitute a major flood threat to the City which indicates that the Cork City flood defence systems are well able to protect against the 200-year coastal flood. Indeed, the existing coastal defence structures along urbanized areas of Cork Harbour coastline had been designed to prevent spring tides from causing flooding, and therefore also they may protect against the high surges that peak on low-to-moderate tides.

By comparison, Fig. 8b presents the maximum water depths simulated for the more unlikely scenario of 50-year RP tide with 200-year RP surge peaking at high water and average river discharge. This scenario not only produces widespread flooding along the riverbanks but also in the business/commercial downtown city area. The timing of the surge peak plays a crucial role in flooding extents. As demonstrated in section 3.2.1, the acceleration of a surge wave when travelling along with the tidal wave in Cork Harbour, prevents the surge from peaking on a high tide. This interaction is attributed to a shallow water effect (Idier et al., 2012) and significantly alleviates flooding. Comparing the flooded area from a simulation where the surge peaks on the flood tide (Fig. 8c) to that in Fig. 8b where it peaks at high water, there is a 30% reduction in the inundation area.

3.3.2. Fluvial flooding

The univariate flood hazard assessment for the marginal river flow scenario was conducted by running an ensemble of river discharge simulations, conditional on the mean high water level on the eastern tidal boundary representing average spring tide conditions with no surge. The fluvial flood events in Cork City occur when the run-off exceeds the conveyance capacity of the River Lee channel and spills into the street network.

Fig. 9 shows maximum water depths due to the river flood wave propagating through the city floodplains for 50 and 200-year RP river flows. Once the conveyance capacity of the river channel is exceeded, the flow starts to spill into floodplains at numerous locations along the

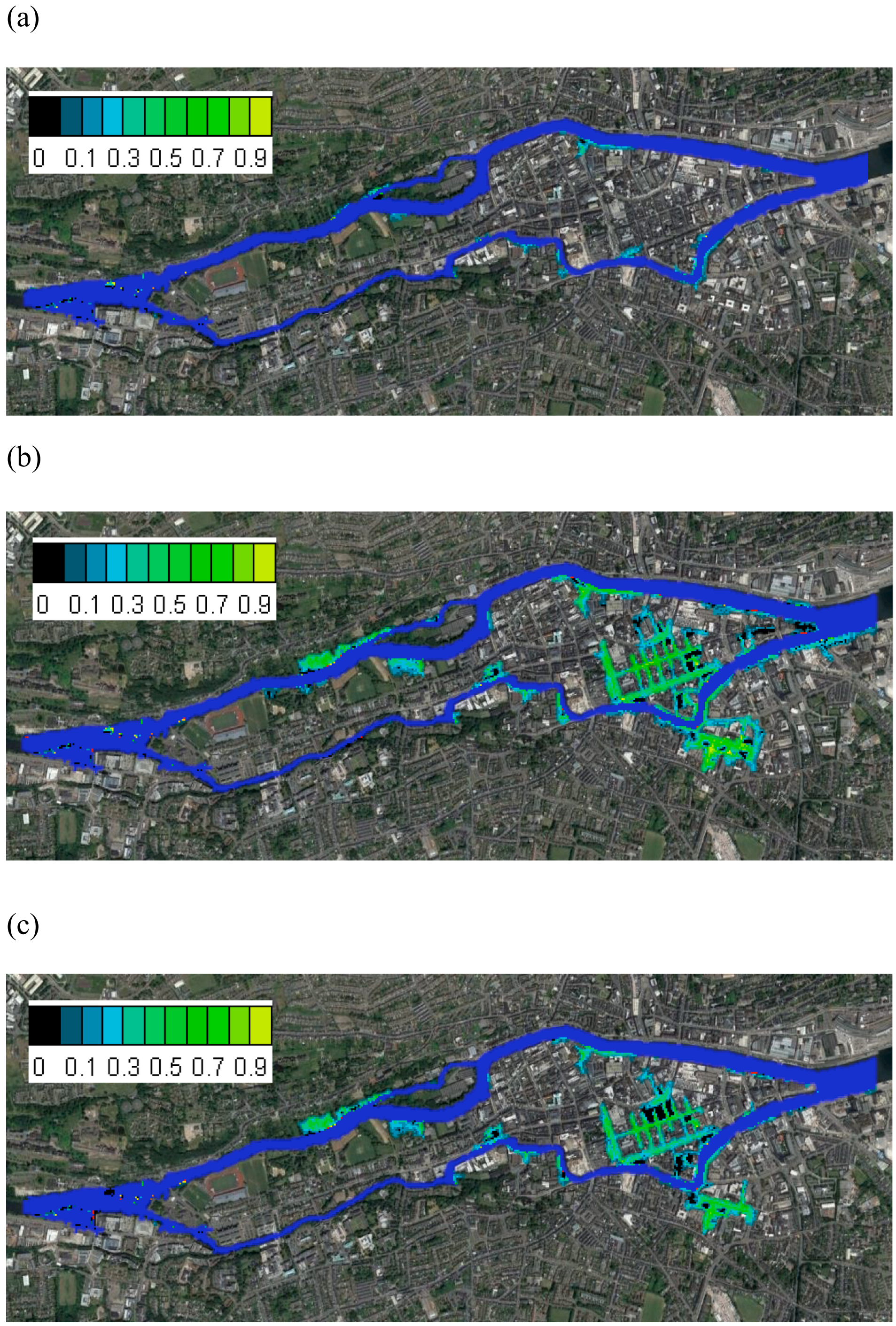

Fig. 8. Maps of maximum water depths (m) due to coastal flooding for (a) 200-year RP joint exceedance levels and (b) 50-year tide coinciding with a 200-year surge peaking at high water, (c) 50-year tide coinciding with a 200-year surge peaking at mid flood.

riverbank. For both 50- and 200-year RPs, flooding progresses very rapidly to reach maximum extents approximately 10 h later. During this period, the flood wave propagates along preferential flow paths in the main west-east direction through recreational fields along the river and major streets before reaching the ponding areas of the low-lying downtown city streets. While the downtown zone is only marginally flooded at RP 50 (Fig. 9a), the RP 200 peak results in a significant portion of the city centre being submerged (Fig. 9b).

3.3.3. *Marginal scenario flooding*

Comparing the pattern of flood water distributions for marginal coastal and fluvial scenarios, some distinctive differences in flooding characteristics emerge. The results show that there is a shift in the flood hazard patterns along the length of the river reach depending on the dominant mechanism controlling the flood. The coastal water levels control the outlet, with floods mostly affecting the downtown area, while the river discharges control flood hazards further inland. The fluvial floods dominate in the upstream city suburbs along the north channel corridor before spreading downtown during larger flood events (>50-year RP). The length of riverine control is much longer than the tidal length which spans a relatively short downstream reach of the tidally active River Lee. As such, the pattern of flood defence systems

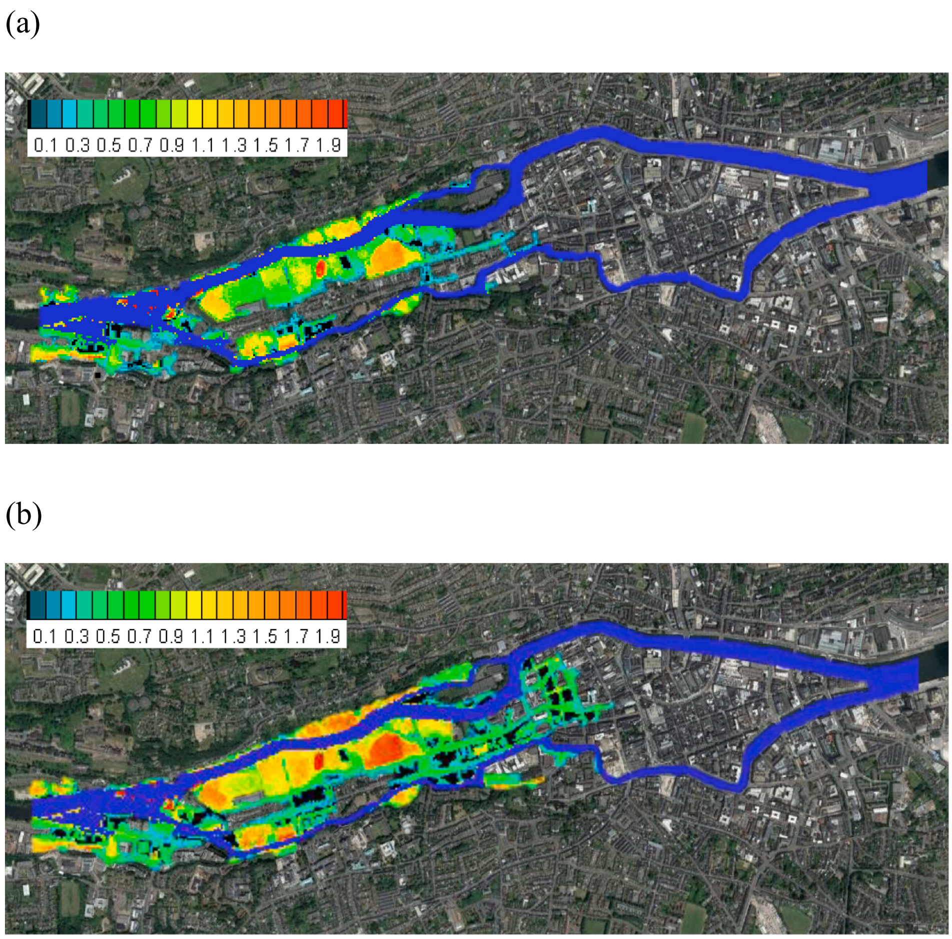

Fig. 9. Maps of maximum water depths (m) due to fluvial flood wave moving through Cork City. River discharge of (a) 50-year RP and (b) 200-year RP.

overtopping is remarkably different for both mechanisms. During coastal flooding, the major inundation stems from south channel spillage while fluvial flood waters enter floodplains primarily from the north channel with limited overtopping of flood defences along the south channel. In addition, the extent of flooding for the 200-year RP is substantially greater for the fluvial scenario. The composite maximum water depths due to marginal coastal and fluvial floods generated by superimposing marginal fluvial over marginal coastal flood water depths are shown in Fig. 10. These results do not account for interactions and joint occurrence of fluvial-coastal drivers. Fig. 10b presents a synthetic map of 1 in 200-year fluvial flood and a highly unlikely low probability coastal flood of RP200 surge coinciding with a RP50 tide.

3.3.4. *Combined coastal and fluvial flooding*

The final step of the methodology is to quantify the flood hazard due to combined action of tides, surges and river flows, and the interactions between them. In the tidally active reach of River Lee, the raising sea level pushes ocean tides upstream. As the tidal signal propagates inland from the estuary, the aggravated interaction between the river and coastal signals causes the backwater river profile to develop. An elevated water overtops the riverbanks and spills into urban floodplains.

The hydrodynamic model was forced with *iso*-probability pairs of river discharge and sea water levels (Fig. 3e) generated for 50- and 200-year RP events considering dependence between the drivers. The *iso*-probability curves were composed of the joint exceedance return values calculated using the trivariate statistical analysis of univariate river discharges with bivariate sea levels. The curves present combinations of sea levels and river flows ranging from extreme sea levels and moderate flows on one end, to extreme river flows and moderate sea levels at the other end. This type of combined analysis allows one to draw inferences about compound flood hazards using only a limited number of simulations.

While the flood probabilities are equal along a joint probability curve, the severity and therefore risk may be different along the curve. This is because the joint probability curves are constructed from a combination of flood drivers of various probabilities (i.e. low probability discharge and high probability sea level, or high probability discharge and low probability sea level). The risk and hence impact of each driver is different and varies spatially. The flood severity for a flood event of a given RP depends on flood defence systems (design and stability) and hydraulic properties of the floodplains such as topography, bed slope and roughness. The case study of Cork clearly illustrates that the flood risk is a function of probability and severity.

Fig. 11 shows maps of maximum inundation for a combination of flood drivers contributing to the 200-year joint exceedance event assuming dependence between drivers. The total area inundated by each of these events is summarized in Table 2. As can be inferred from these plots and table, the most severe floods are associated with events characterized by high river discharges and, therefore, driven primarily by the fluvial mechanism. However, sea water levels due to tides and surges pose an elevated risk of flooding. The fluvial flooding is initiated from the upstream area of the north channel of the River Lee. After overtopping the defences, flood waters spill away from the river channel travelling eastward across the central part of the city and flowing downhill towards the most eastward part of the downtown area. In contrast, when the flood is controlled by the coastal mechanism, the major inundation originates from the south channel and propagates northward and southward. The overall coastal inundation is relatively

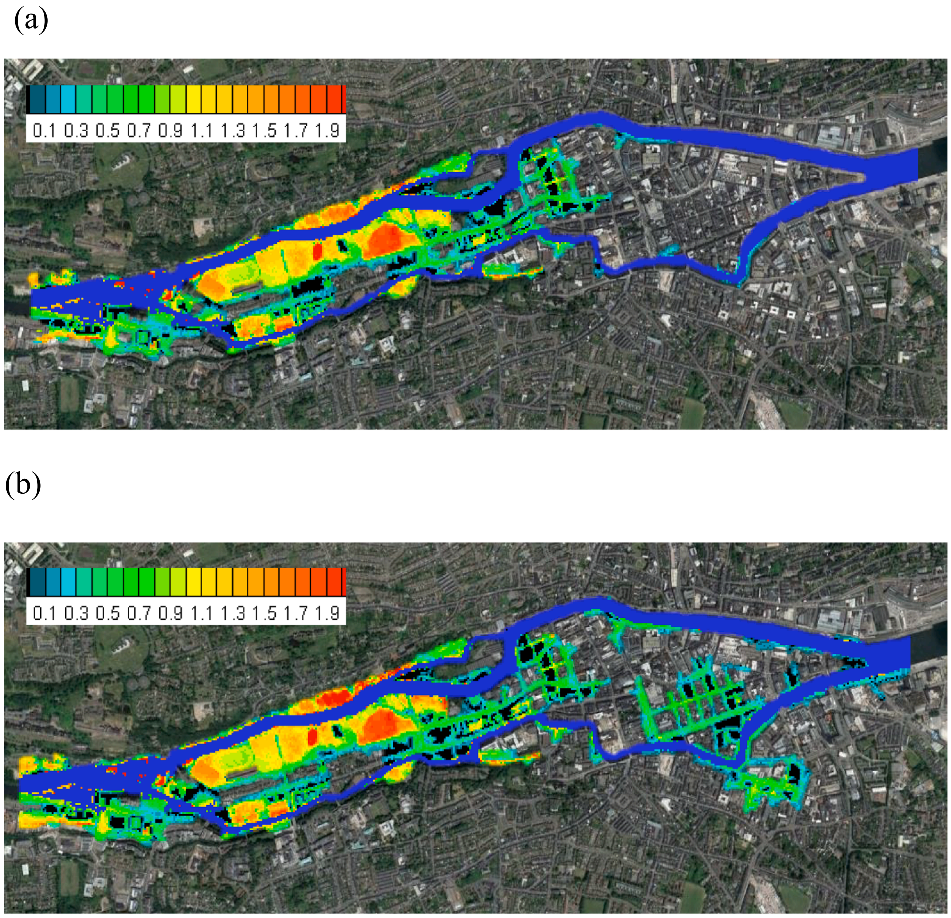

Fig. 10. Synthetic maps of maximum water depths (m) due to independent fluvial and coastal flood events occurring disjointly in Cork City for (a) 200-year fluvial and coastal floods and (b) 200-year RP fluvial flood and coastal event of 200-year surge coinciding with 50-year tide.

small, which suggests that the flood defence systems in the tidal section of the river are capable of protecting against 200-year coastal-driven floods. For the worst-case scenario (Fig. 11f), the 200-year RP flood is severe and results in 75.9 ha of urban inundation. This is due to a combination of high river flow (647.1 m^3/s corresponding to a 343-year RP event) and moderate sea water levels (4.98 mOD representing a 2-year RP event).

The level of dependence between flood drivers is another aspect to be considered in the joint probability analysis. As shown in Fig. 3e the magnitudes of flood drivers for a given joint occurrence probability vary depending on the level of dependence between the drivers. The higher the dependence, the larger the joint exceedance values for a given probability of occurrence, and consequently the larger the flood extents. Fig. 12 summarizes the total area of inundation due to 200-year RP joint probability coastal and fluvial flooding for the three dependence scenarios; only the worst-case fluvial-dominated scenarios are presented. As expected, the most severe inundation results from a compounding event of high dependence between flood drivers such as high discharges prescribed at upstream boundary coinciding with medium to high sea water levels at downstream boundary. Additionally, the co-occurrence generates interactions between river discharges and the upstream-propagating tidal wave. The unsteady, non-uniform upstream wave impedes the river flow, slows down the rate of draining to the estuary and generates a backwater profile upstream with elevated water levels in the intertidal reach. The interaction also can modulate the amplitude and shape of the tidal wave itself.

The effect of driver interactions was investigated by comparing flood hazards due to the joint probability AND scenario (Fig. 11) and the combined marginal scenarios (Fig. 10). The difference in the prediction of flood water depths and extents between simulations is clear in the tidal reaches of the river where water levels are subject, and sensitive, to both riverine discharge and sea levels. In the floodplains of the intertidal zone, the water depths and velocity magnitudes are generally higher for the AND scenario then for the two combined marginal predictions. Interestingly, this happens despite much lower water levels at the upstream and downstream boundaries of the AND scenario (i.e. Fig. 11e – 568 m^3/s, 5.18 mOD) when compared to the two marginal scenarios combined (Fig. 10a – 600 m^3/s, 5.49 mOD). This is due to physical compounding effects and nonlinear interactions between the discharge and water level described by shallow-water wave theory. For the AND scenario with no dependencies (Fig. 12 with $\chi = 0.0$), the flood extent is very similar to that of the combined marginal scenario (600 m^3/s, 5.49 mOD) despite significantly lower boundary values of the AND scenario (483 m^3/s, 4.98 mOD) which clearly implies the amplifying effect of the interactions. In contrast, the AND scenario predicts lower flood hazard levels in the non-tidal zone (upstream river reach) compared to the marginal profiles (not shown here) because the river discharges contributing to the joint probability event are lower than those contributing to the riverine flooding only.

4. Discussion

Flood risk is a function of the probability of flooding and the consequential damage, integrated over all possible flood events (Hall et al., 2006). Both variables in this function are subject to large uncertainties. This paper presents a robust methodology for assessment of a hazard associated with a compound flood, which can be further used to draw inferences about risks associated with such complex events.

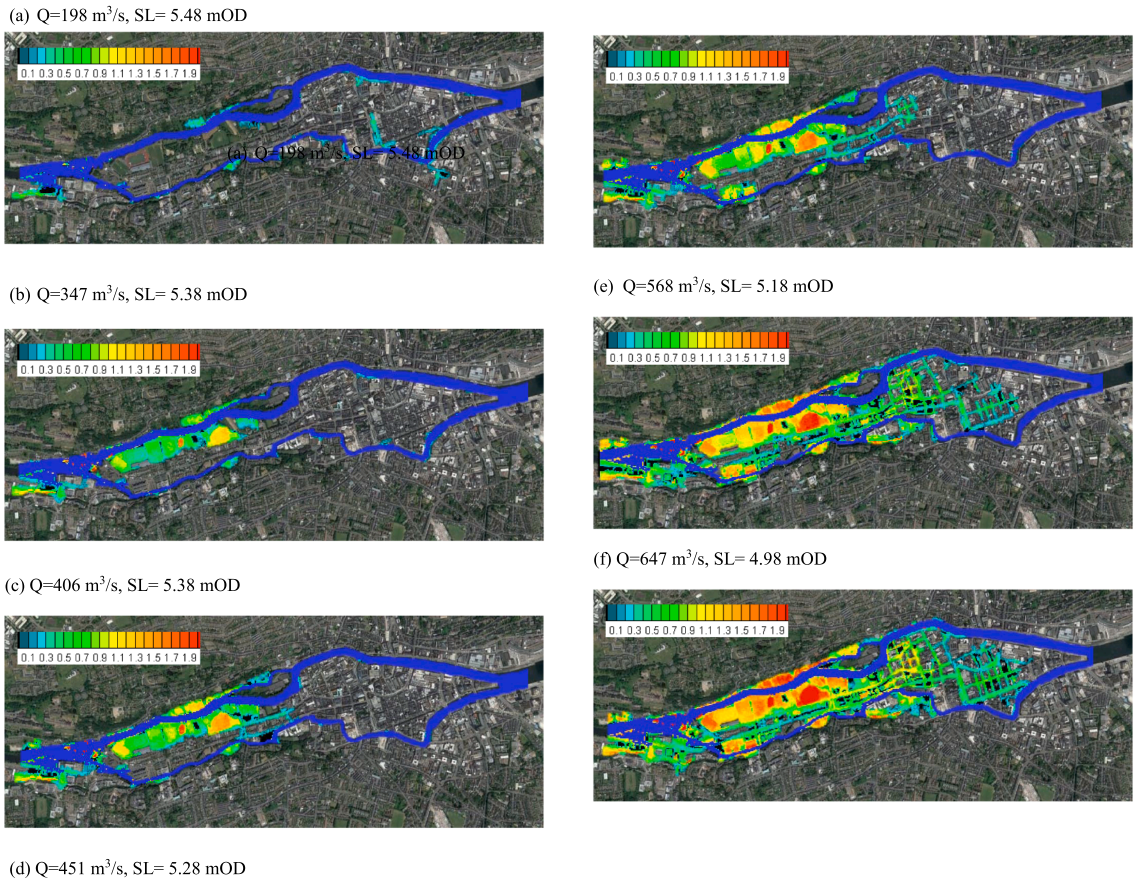

Fig. 11. Maps of maximum water depths (m) due to coastal-fluvial flood wave moving through Cork City for a 200-year joint exceedance RP event being a combination on river discharges (Q) and sea levels (SL).

Table 2
Total inundated area for 50- and 200-year RP water levels.

		RP 50 years						RP 200 years					
River flow	m^3/s	198.3	274.2	287.5	335.0	347.6	412.3	198.3	347.6	406.1	451.5	568.5	647.1
Sea water level	mOD	5.28	5.28	5.18	5.18	5.18	4.98	5.48	5.38	5.38	5.28	5.18	4.98
Inundated area	ha	3.6	11.5	14.4	22.2	23.9	32.8	8.4	23.9	32.3	39.8	63.7	75.9

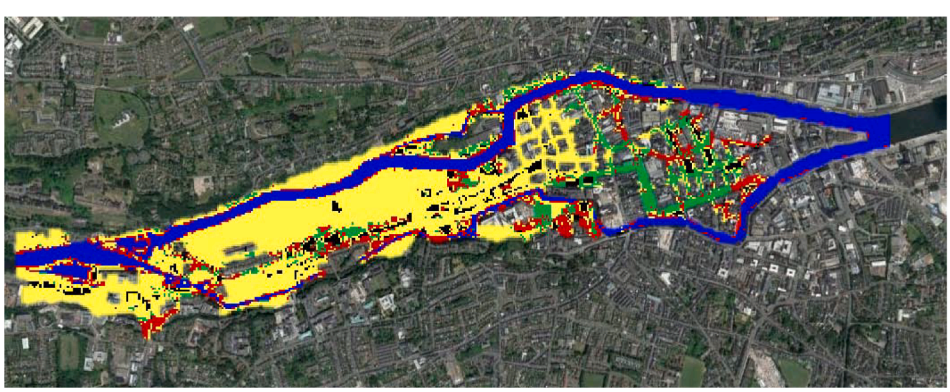

Fig. 12. Maximum inundation extent due to joint coastal and fluvial flood wave through Cork City for 200-year RP and for various dependence levels $\chi = 0$ (yellow), $\chi = 0.101$ (yellow and green) and $\chi = 1.3$ (yellow, green and red). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

If there is only one driver responsible for flooding, the accuracy of flood probability depends on the data availability and statistical methods used in assessment of extremes. In Cork, when flooding is primarily driven by one driver only (fluvial or coastal), the univariate GEV analysis of long timeseries of river flows or sea water levels provide a relatively accurate assessment of return levels for upper tail - low probability events. However, when flooding is compound and driven by both drivers, in addition to the probabilities of individual drivers, the joint probability of simultaneous occurrence of the two drivers must also be considered. Data for Cork imply that majority of flood events are compound, but the contribution of each driver to the flood event may vary from one event to another. Complexity is further exacerbated by the presence of interactions (tide and surge) or dependencies between drivers (river discharge and surge). As such Cork City is a good example to demonstrate that to fully understand the complexity of multi-driver flood dynamics and the overall impact of a flood hazard, the drivers need to be assessed in an integrated manner using the modelling methods. The methodology proposed here is an eight-step process that combines statistical and hydrodynamic modelling.

4.1. Data collection and analysis

The first step concerns a collection of data/records of flood drivers, from which the multivariate dependencies (step 2) and univariate extreme distributions (step 3) can be generated. In general, the longer the record, the more hydrologically meaningful the estimate of low frequency peaks. To fulfil this requirement, where availability of long-term gauge data is problematic (as in many coastal areas), a partial duration series or model simulations may be used instead. This hybrid approach was used for Cork case study where the limited-length tidal gauge records for surge residual univariate analysis were complemented by the hindcast model data obtained from hydrodynamic model runs for known past high surge events. In the methodology proposed here the upper tail datasets of tides, surge residuals and rivers discharges are used to inform the multivariate joint probability analysis and hydrodynamic modelling.

4.2. Multivariate dependence analysis

In order to accurately calculate the joint probability of extreme events (step 4), dependent interactions (step 2) between any of the variables must be first assessed. Recent studies clearly show that dependence may exist between river discharge and either coastal water level or storm surges, but very few of them provide return levels of compounding events. Moreover, only a small number of studies quantify a flood risk due to compounding effects of extreme coastal-fluvial water levels. De Michele et al. (2005) found that ignoring dependencies may result in over- or underestimation of flood risk. In coastal sites, where storm surges are small relative to astronomical tides, the correlation between total water level and river discharge is not statistically significant (Moftakhari et al., 2019). However, correlation may be found between river discharge and the non-tidal residual such as surge. Considering that high river flows and surges can be generated by the same mechanism, such as a low-pressure weather system, the likelihood of both events occurring simultaneously can be high (Khanal et al., 2019). Hence, the second step of the methodology concerns the multivariate dependence analysis and an assessment of correlation structure for a pair-combination of flood drivers. There is a range of linear and rank correlation coefficient measures that are used to quantify dependencies (Hawkes et al., 2002; Heffernan and Tawn, 2004; Coles et al., 1999). The rank-based Kendall's rank correlation and Spearman's rank correlation are robust against outliers. However, correlation coefficient only detects the degree of association between two variables and does not capture the dependencies well in low probability, extreme ranges (Ganguli and Merz, 2019). For this reason, in this research the dependence is quantified through the χ tail dependence (Coles et al., 2000). The results show that there is a statistically significant dependence between surge residual and river flows. On the south of Ireland, where Cork Harbour is located, the storms are generally generated by low-pressure systems to the south-west of Ireland and strong south-westerly winds with propagation patterns towards the north and northwest (Olbert and Hartnett, 2010). These storm track patterns may justify the dependence between the two drivers in Cork. According to Hendry et al. (2019), the dependence between high river discharges and high surges occurs at sites where storms that generate these events are typically similar in characteristics and track across on comparable pathways.

The time lag between river flow and total water level is another aspect to consider in the dependence analysis. Ward et al. (2018) showed that the lagged occurrence of river and coastal peaks can influence overall inundation extent, and thus need to be considered for hazard mapping and planning of emergency responses. The time-lagged analysis accounts for the fact that the storm surge peak may arrive at a different time than the river flow peak, despite both being generated by the same storm event. In large catchments, a storm approaching the coast may generate a high storm surge before travelling inland and generating high precipitation and elevated river discharge. Likewise, a storm may travel over land before reaching the coast so the peak in river flow may precede the surge peak. Hendry et al. (2019) imply that surges coincide with high river discharge in catchments characterised by a lower base flow, smaller catchment area, and steeper bed slope, while the peak river flow may occur several days after the surge in large catchments with a high base flow and mild elevation gradient. In case of Cork, the highest dependence was found when surge precedes river level by one day. This time-lag dependence in River Lee characterised as a relatively small catchment with a low baseflow (1,253 km^2, 40.4 m^3/s) confirms findings of Hendry et al. (2019). These results are in line with observations from the west/south of the UK where meteorological conditions are often part of the same large scale weather systems common to the UK and Ireland (Hendry et al., 2019). The surge-discharge analysis shows that dependence is not only a function of geographical position of river catchments versus coastline and storm trajectory, but also depends on the response time of a river as a function of catchment characteristics such as size or elevation gradients (Holtan and Overton, 1963). Ward et al. (2018) show that where high river discharge and high sea levels are exceeded and these drivers are dependent, the joint probability of events can be several magnitudes higher compared to the independent scenario. Since not accounting for surge-discharge dependencies in joint probability analysis may underestimate the compounding effect, the need to include them is paramount.

In a multivariate dependency analysis, another set of variables to consider are the components of total sea water level. Generally, in sheltered coastal locations, waves do not affect water levels because of a limited direct impact of winds relative to open coastlines (Melet et al., 2018) and storm-driven residuals are often weak, or significantly smaller than astronomical tides, so that surge impacts are only significant when they coincide with high spring tides. Along the European coast, extreme sea levels are typically generated by moderate surges co-occurring with spring astronomical high tides (Haigh et al., 2010b). This is also the case for extreme sea levels in Cork Harbour, which are typically the product of a moderate-to-high surge coinciding with high water spring tide. This phenomenon is due to the interaction between storm surges and tides that prevent the surges from peaking on high water; in fact, the maximum surges are more likely to peak on the rising tide, 3–5 h before tidal high water, which can amplify the surge magnitude (Idier et al., 2012). This holds true for many coastal sites around Ireland (Olbert et al., 2013). In Cork however, while surges tend to peak on rising tide more frequently than on other phases, these interactions are weak and statistically not significant. Therefore, it is reasonable to assume an independence between tides and surges, and take a more conservative approach in the joint probability analysis. This means that extreme sea water levels may be higher as surge residuals may peak on a high-water tide.

4.3. Univariate extreme value analysis

In step 3 of the methodology the probabilistic models from the field of extreme value statistics are used to calculate extreme values of individual flood drivers. Such models can be used to draw inferences about extremes from relatively extreme values alone and so do not require multi-year timeseries of data like analytical methods do. However, they are sensitive to the choice of the distribution and the fitting procedures and so involve some uncertainty around the often-subjective fitting of statistical distributions (Woth et al., 2006). For all three drivers in Cork, the GEV model exhibits a very good fit to peak-over-threshold data so the extreme values and associated RPs seem to be adequately quantified.

4.4. Multivariate joint probability

In the fourth step of the methodology, the univariate extreme values (step 3) for three individual flood drivers are combined with dependence results (step 2) to estimate joint probabilities of occurrence of multiple flood drivers. Salvadori et al. (2016) defines joint probability as (1) the exceedance of river discharge AND coastal water level or (2) the exceedance of river discharge OR coastal water level. While flood events can be driven by either AND or OR scenarios, in an estuary where an upstream discharge and downstream water level co-occur the AND scenario of joint exceedance probability is more appropriate, particularly when dependencies exist. In fact, Moftakhari et al. (2019) found that the OR scenario significantly overestimates the return levels given by univariate analysis (marginal scenarios) and the joint probability AND scenario. The OR scenario with unrealistically high extreme values in areas of low probability density represents the highly unlikely, highly conservative approach, and therefore it is not considered in the joint probability analysis of this study. The multivariate joint probability of the three signals: tides, surges and river discharges was firstly calculated as bivariate probability of tides and surges occurring simultaneously with no dependency to obtain total sea water levels, and then probabilities of sea water levels coinciding with river discharge were considered in so-called trivariate joint probability. The *iso*-curves of joint probabilities of all three signals occurring simultaneously are the final statistical outcome. Each curve represents a combination of drivers' magnitudes that jointly generate a condition of certain probability of occurrence. While the RPs *iso*-curves represent the joint events of the same exceedance probability, the physical/hydrological impact of such events can be very different and hence leading to substantially different flood risk maps. Therefore, when assessing flood risk, it is crucial to evaluate flood impacts across the whole spectrum of exceedance probabilities, and this has been done in this study using a hydrodynamic model.

In the multivariate joint probability analysis, the effect of inclusion dependencies was also considered. RPs *iso*-curves generated with various levels of dependencies for Cork show that the occurrence of dependencies modifies the joint extremes, and the stronger dependencies, the higher the joint exceedance values along the curve of a certain RP. Dependencies between flood drivers in the inter-tidal river reach in Cork lead to higher flood risks in this zone, and this is confirmed by hydrodynamic modelling. Ward et al. (2018) also found that where high river discharge and high sea-levels are exceeded, and these drivers are dependent, the joint probability of events can be several magnitudes higher compared to the independent scenario. Accounting for joint occurrence of multiple flood drivers is important for hazard mapping, designing flood protection infrastructure and planning emergency responses.

4.5. Selection of flood scenarios

The step 5 of the methodology concerns the selection of flood scenarios for hydrodynamic runs. In total four sets of runs for Cork were performed: two sets of runs considered univariate marginal scenarios (fluvial flood or coastal flood only), one run considered combined marginal coastal and fluvial runs, and finally one set of runs considered AND joint probability scenario. In reality, observations show that Cork City floods are due to a combination of drivers (with varying degree of contribution), and sole action of one driver would be rare and linked to river/flood defence management rather than meteorological conditions and storm-modulated co-occurrences of drivers. Anyway, in this study all the four sets of conditions were investigated to explore all potential risks.

4.6. Ensemble flood model simulations

Step 6 concerns hydrodynamic modelling of flood scenarios. There have been many studies in recent years that investigate joint occurrence of river flows vs coastal water levels and dependencies between them (e.g. Wahl et al., 2017; Khanal et al., 2019; Klerk et al., 2015; Bevacqua et al., 2020). Although these studies are useful to understand processes that drive flooding, they do not answer the fundamental questions of how severe these events can be and what combination of extreme signals can result in the most hazardous events. Moftakhari et al. (2019) go a step further and link statistical analyses with a hydrological model to answer first of these questions. This research builds on Moftakhari et al (2019) to answer both questions. While the present study uses a similar methodology to Moftakhari et al. (2017), it is more heavily focused on the hydrodynamic component and provides a full quantification of impacts along the entire RP probability curve and across various flood scenarios. Moreover, the hydrodynamic model accounts for the effect of friction, inertia and topographic complexity in flooding dynamics as well as physical compounding (e.g., backwater, wave damping/amplification) due to riverine and/or tidal forcing that change flood stage and routing. These aspects have not been analysed in-depth yet.

4.7. Assessment of inundation due to multiple flood drivers

Step 7 concerns an assessment of inundation due to multiple drivers. Comparing modelled inundation extents with those observed historically for similar flood conditions, it is apparent that the joint probability AND scenario represents a more realistic representation of the spatially variable water surface profile then the combined marginal scenarios or individual univariate marginal scenarios. Interestingly, water depths and flood wave velocities are higher for the AND scenario than for the combined marginal scenarios for the same RP event despite the fact that the AND scenario is driven by substantially lower extreme univariate conditions. That confirms the amplifying effect of the coinciding drivers in their moderate ranges. Another aspect of multivariate analysis is a consideration of multiple combinations of joint probability solutions. The extent of a flood varies greatly for various combinations of drivers' magnitudes although each combination drives a flood event of the same probability. Hence for Cork City, much more impactful are events where the contribution of a fluvial component is larger than a coastal one, and this is because the City is better protected against high sea water levels rather than high river discharges. The hydrodynamic analysis shows that flood impacts may vary greatly along a single probability curve so statistical modelling need to be accompanied with hydrodynamic modelling to include all possible combinations of drivers and their joint impact. Therefore, the statistical-hydrodynamic methodology proposed here is perhaps the only way to comprehensively assesses the compound nature of coastal sea levels and river discharges. Also, it is apparent from the analysis that the multivariate approach is more accurate than the traditional univariate assessment methods. Moreover, the proposed method requires only a limited number of hydrodynamic simulations to map flood hazards. These findings have particularly important socio-economic implications for Cork as the intertidal reach is adjacent to floodplains characterized by high urbanization with a significant accumulated economic wealth.

4.8. Flood mechanism establishment

Step 8 concerns assessment of the flood mechanisms. The flood investigation based on the proposed statistical-hydrodynamic method allows one to draw inferences about flood mechanisms, propagation dynamics and hazards under various flood probabilities. The hydrodynamic model gives an opportunity to test multiple scenarios so a good understanding of fluvial coastal mechanisms can be gained. The hindcast runs for Cork's past flood events, validated against observations, confirm that the City is more vulnerable to fluvial driver as the fluvial floods often originate in the rural areas far upstream and propagate to the City centre through the streets sloping along the river channel. Also, the costal flood defence systems are designed to protect against a 200RP sea level event. The mechanism however is likely to shift in future climate towards coastal component and have more pronounced effect on floods as demonstrated in Kirkpatrick and Olbert (2020). Estimating the potential risk to flooding and understanding flood-controlling conditions greatly aids flood risk management so that flood prevention or alleviation schemes can be evaluated and/or optimized.

5. Conclusions

The paper presents a development of a statistical-hydrodynamic modeling toolbox and proposes a methodology for assessing the combined effects of multiple-source flooding in urban areas. The proposed methodological framework is an 8-step process that combines multivariate statistical analysis and dependence analysis with hydrodynamic modelling. The method involves individual and combined extreme value analysis, assessment of dependencies and interactions between flood drivers, multivariate joint probability determination accounting for dependencies, and high-resolution hydrodynamic modelling of flood scenarios derived from the multivariate statistical analysis. The probability and severity of individual drivers and their compounding effects on flooding are investigated by analysing the pattern of flood wave propagation, inundation depths and overall extent of inundation. The methodology was applied to a case study site - Cork City, Ireland, for which the 2D urban flood model MSN_Flood was applied. While a successful attempt to link statistical and hydrodynamic model exist (Moftakhari et al., 2017; Moftakhari et al., 2019), the methodology for combining statistical-hydrodynamic modelling developed in this research is heavily focused on the hydrodynamic component and proves a necessity for quantification of impacts along the entire RP probability curve and across various flood scenarios. This is the single most important finding from this research. Other main conclusions regarding the methodology are:

- In the absence of long-term records, a statistical analysis of water level extremes provided reliable long-term estimates of flood driving conditions; the GEV model exhibited a good fit to data.
- Interactions and dependencies between tides, surges and river flows affect flood severity when they occur jointly and therefore need to be included in the analysis of extreme water levels.
- The bivariate and trivariate joint probability AND scenarios provide plausible results for joint exceedance return levels of water elevations and account for compound effects. The multivariate methodology approach is superior to the traditional univariate assessment methods based on synthetic water profiles derived from combined marginal scenarios.
- Multivariate analysis allows also considering multiple combinations of joint probability solutions along a RP *iso*-curve. While the RPs *iso*-curve represents the joint events of the same exceedance probability, the physical/hydrological impact of such events can be very different leading to substantially different characteristics of flooding. For these reasons combining the statistical and hydrodynamic modelling is very important.
- A high-resolution urban flood model forced with joint probability boundary conditions can be used to draw inferences about flood mechanisms and extents in urban environments. The MSN_Flood model used here proved very robust and ran stably under quite severe inflow conditions such as those designated by 1 in 500-year river flow and 1 in 200-year sea water level. Flood mapping requires only a limited number of hydrodynamic simulations derived from a multivariate analysis without a need for large ensemble simulations for a combination of extreme univariate conditions. As such the proposed methodology provides a cost-effective, practical approach for delineating compound flood hazards driven by complex multivariate mechanisms.

The methodology proposed in this paper provides a robust framework for mapping coastal flood hazards in tidally active river channels that takes advantage of recent advances in multivariate statistical modelling and hydrodynamic coastal flood modelling. The method also facilitates better understanding of the conditions that control flooding under multivariate sources (tide, surge and fluvial) and allows an estimation of the compounding effects of multiple flood drivers. Estimating the potential risk of flooding and understanding flood-controlling conditions is extremely important for flood risk assessment so that the flood prevention or alleviation schemes can be designed, evaluated and/or optimized. This is a critical task given a typical design life of coastal defence structures of 50 to 100 years. The information derived from the application of this methodology can provide a significant support for long term planning, investment decisions on flood defence infrastructure, and quantification of probable flood damage of economic, social and environmental natures.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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