MODELLING MEMORY OF COASTAL FLOOD SYSTEMS

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Flooding and coastal erosion is a frequent and widespread natural hazard in the UK. With increasing urban development pressures on flood systems and changing global climate, frequency and severity of flooding is rapidly increasing. Temporal clustering of flood events in time has a critical effect in reducing the ability of systems to recover to the pre-flood 'norm', leading to amplified flood damages in the second flood event. This can be considered as system memory, the timeframes of which will be highly variable and range from days to years according to system components. The current assumptions of flood risk are based on single-event simulations and fail to consider the spatio-temporal dynamics of morphological memory due to coastal erosion. The floodMEMORY project attempts to address this issue through a continuous flood simulation framework based on temporal clustering of flood drivers.

Keywords: coastal flooding, storm sequence, XBeach, morphodynamic change, statistical storm analysis

INTRODUCTION

Coastal flooding is a major and increasing natural hazard. Extreme weather patterns and rising sea levels resulting from global climate change increase the frequency and severity of flood risk all over the world. At present, it is estimated that 4 million people and properties are under the threat of flooding which account for £140 billion worth of economic costs, human losses and unmeasurable social costs in England and Wales alone OST, 2004; DEFRA, 2005).

Flood risk management research has made substantial recent advances recognising the need for a systems approach where coupled human and environmental risk is implicit. Such advances include conceptual frameworks applied to natural, built and human systems and quantitative risk methodology with detailed physically based models or simplifications such as fragility curves. The Flood Risk Management Research Consortium (FRMRC), which was funded by the UK Engineering and Physical Science Research Council (EPSRC) ended in 2012 leaving a gap in our capacity for fully-coupled integrated flood modelling appropriate to social, economic and environmental planning. Implicit is identified weakness in our continued use of "return periods" for flood analysis. ***Non-stationarity*** in flood drivers is well recognised; in fluvial flooding we find "*flood rich and flood poor*" periods with origins in the Atlantic climate as well as catchment management drivers, whilst multivariate analysis of combined coastal environmental variables (surge, wave, tide *etc*.) is highlighted as one of the discipline's most challenging and pressing research questions relating to flooding.

Temporal clustering of flood events in time has a critical effect in reducing the ability of systems to recover to the pre-flood 'norm', leading to amplified flood damages in a proceeding flood event(s), which may be the consequence of extreme conditions or due to more typical conditions now able to impact the more vulnerable system state. This can be considered as system "***memory***", the timeframes of which will be highly variable and range from days to years according to the system components. Thus, where consecutive floods occur within the memory period accurate flood inundation and associated risk modelling must incorporate the dynamics of the boundary conditions (natural and human); this requires a step change in how we perform flood modelling practice, moving away from single-event modelling towards multi-event continuous simulation. Whilst we recognise that spatial dependence in flood hazard (*i.e.* simultaneous flooding in multiple locations) is now receiving considerable attention motivated by concern from re-insurance, infrastructure reliability and emergency response, the effects of clustering in *time* have not been analysed.

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There are multiple complex system components exhibiting memory which interacts with the clustering of events in time. The best known in the role of beach morphodynamics is the modulating response to extreme storm conditions in coastal flood systems. While a large storm event may erode a coastline thus leading to widespread flooding, the calm weather conditions following a storm may continuously change the shape of the beach toward a dynamic equilibrium. This means that the system has a memory of previous floods. Occurrence of a second large storm event within the timescale of system recovery, will impact on a beach which has different receptor characteristics to those at the time of the first storm. Thus, current assumptions of similarity of flood risk based on single-event simulations are incorrect as they fail to consider the spatio-temporal dynamics of morphological memory on coastal erosion. As beach erosion increases the risk of wave overtopping and flood inundation to coastal settlements increases, the temporal dynamics of both natural and engineered beaches are therefore fundamental to accurate flood risk analysis.

Single-event, joint probabilistic approaches remain commonplace in coastal flood risk analysis in a manner excluding storm sequencing and temporal variations (*e.g*. sea level rise or climate change) (e.g. Callaghan, 2008) which precludes accurate analysis of flood events occurring within the timeframe of system memory. The proposed study aims to address this issue by driving simulation models with stochastic series of storm clusters to estimate beach and river bed erosion/deposition, breaching and failure, overtopping and flooding of both natural and engineered systems.

FloodMEMORY PROJECT

UK Engineering and Physical Science Research Council (EPSRC) held a SANDPIT event on ‘Innovative solutions to flood risk’ to support transformative, multidisciplinary, novel research projects, in response to the Living With Environmental Change (LWEC) Flooding and Coastal Erosion Risk Management Research Strategy, in 2012. As a result, a three-year m multidisciplinary research project was funded to investigate the ‘memory’ of flood receptor systems to frequent clustered storm event. The project known as ‘FloodMEMORY – Multi event modelling of risk and recovery’, will be delivered by ten UK Universities and a research organization, in partnership with a set of stakeholders. The project is led by the University of Newcastle, with partners from Swansea University; University of Southampton; Queen Mary College, London; University of Nottingham; Cranfield University; University of West of England; Heriot-Watt University; University of Aberdeen and National Oceanography Centre (NOC), Liverpool.

The overall aim of the project is to investigate the effects of temporal clustering of flood events on natural, built and socioeconomic systems with memory, in order to identify critical vulnerabilities, better allocate resources for protection and recovery, and improve flood resilience. The project has six specific objectives:

1. To analyse historical extreme event series with state-of-the-art statistical methods and develop novel stochastic models for generating sequences of rainfall and extreme sea level with realistic clustering and accounting for projected climate change;
2. To develop detailed models of the key components of flood systems which may be natural, built or human, and their response to individual storm events using physically-based and agent-based methods where appropriate;
3. To develop two integrated models of flood systems in a coastal and a fluvial setting, extending the concept of fragility curves for describing system response to loadings, in order to simulate response to series of floods and the impact in terms of performance, economics, health etc.
4. To investigate the role of memory in reducing resilience for components and whole systems;
5. To investigate the impact of non-stationarity on resilience and asset management;
6. To explore and identify critical combinations of events and vulnerable systems and propose strategies for improving resilience over multi-time scales.

Methodology

The methodology used to deliver the objectives of the project multi-disciplinary, combining modelling and analysis using statistical techniques, physically based models of natural systems, simplified reliability modelling of engineered systems and agent based modelling of human systems. A major challenge of the project is to integrate a number of detailed models of system components into a framework for analysis of overall system performance and resilience under a range of hazard scenarios. The project is therefore organised into five interactive work packages as shown in Fig. 1.

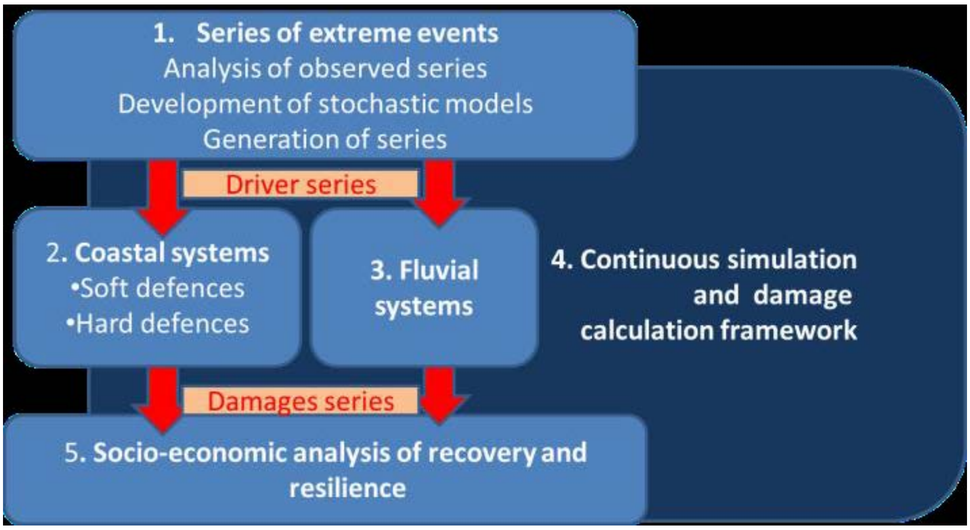

Fig. 1: Organogram of the project structure.

Key cross-cutting aspects of the project are the use of stochastic methods for generating hazard sequences, the use of fragility curves for efficiently encapsulating complex and detailed outputs of physically based models coastal systems, and the use of agent-based models to represent the responses of the actors in the receptor towns/communities.

A case study site along the Sefton Coast, Liverpool Bay, UK is proposed to demonstrate the methods developed during the project. Sefton has been chosen because it is a complex beach system comprising natural beaches, rapidly eroding dunes, flood-prone urban and rural hinterland and hard & soft defence systems with areas of overlap. Vast datasets are available from both model hindcast and monitoring of hydrodynamics, beach profile & shoreline surveys.

PROJECT STRUCTURE

Delivery of the FloodMEMORY project objectives is being organised through five interlinked work packages shown in Fig. 1. Only the project components linked coastal flood modelling, are presented in this paper.

WP1 Clustered processes

The project will employ super-statistical techniques (Beck, 2003) for the analysis of historical time series of extreme sea level and waves with the aim of specifying stochastic models that reproduce the higher-order statistics of the underlying stochastic processes at multi-timescales. The results will be used to either develop new simulation tools or to improve existing ones. First, the relevant temporal scales on which the extremes fluctuate will be established, including an analysis of systematic variation due to *e.g.* climate change. Given those time scales the corresponding probability densities of the relevant parameters will be extracted. This information, together with a multi-scale analysis of correlation functions, will be used to construct optimized point process models and generalized stochastic differential equations with memory kernels that generate spatio-temporal stochastic processes with the same higher-order statistics as the observed data.

On the practical side, the project intends to develop novel quantitative measures of clustering. Also, better risk estimates of successive flood events will be obtained, a better understanding of the various time scales and relaxation times involved will be obtained, and analytic results for some simplified models will be determined. At the coast, extreme water levels arise as a combination of four main factors: tide, surge, mean sea level and waves. The deterministic tidal component interacts with the stochastic meteorological components so the different components of and their non-linear interactions will be analysed separately for clustering metrics, before the combined total water level time-series are considered. Water level data will include tide gauge observations (starting from 1915) from the UK national tide gauge network and wave measurements from WAVENET. In addition, a 140-year (1960-2100) modelled time series of water levels and waves in Liverpool Bay will be assessed, alongside the measured data, to examine the characteristics of historic and potential future changes in extreme water level event clustering over a wider spatial and long temporal scale.

WP2 Coastal flood systems

A coupled hydrodynamic-morphodynamic simulation system is required to investigate coastal system response to storm clusters. The effects of repeated flooding from storm clusters on the Sefton Beach will be investigated using the XBeach coastal area model (Roelvink et al., 2009).

WP2 integrates three different tasks: Large scale models covering the entire Sefton beach system will be developed in Task 2.1 and 2.2 for the natural and engineered beaches located at Sefton respectively. Task 2.3 involves more detailed modelling of the most vulnerable swash region close to the shoreline.

Task 2.1 Modelling beach change and wave overtopping of natural beaches

Modelling morphodynamics, overtopping and flooding of natural beach systems is a challenging problem. The XBeach model will first be modified to (i) extend its application to coarse grain beaches, (ii) include beach recovery during calm periods between successive storm events and (iii) to integrate with a new wave over-washing/overtopping model. The modified XBeach model will then be setup for Sefton Coast and calibrated & validated against hydrodynamic and beach morphodynamic data for a range of storm events and calm sea conditions. The calibrated and validated model will then be used to simulate beach change and wave overtopping driven by scenarios of storm clusters developed in WP1. The offshore wave and water level boundary conditions will be provided by the POLCOMS-WAM model (Brown et al., 2010a,b). The initial sea bed bathymetry will be determined from historic bathymetric surveys of Liverpool Bay. Each simulation will provide time series of beach change and wave overtopping over periods of decades. Beach change time series will be used to determine beach width at mean water shoreline which will be used as the indicative parameter to determine beach stability. The probabilistic beach response to storm sequences will then be derived and presented as fragility curves for natural beach system. Overtopping volumes will be used to determine coastal flood boundary conditions in order to calculate flood inundation.

Task 2.2 Modelling beach change and wave overtopping of engineered beaches:

Wave overtopping and structural stability are key aspects of coastal flood defence systems. Bed scour at the toe of a coastal structure may also alter the performance of the structure by reducing structural stability. We propose to develop a wave-structure-morphology model to simultaneously simulate this complex interaction by integrating an existing wave-structure interaction module (Briganti and Dodd, 2009) in Xbeach. The model will then be used to develop fragility curves for engineered beach systems, which describe in probabilistic terms the flood defence response to loading (*i.e*. water levels). Previous studies (*e.g. Allsop et al., 2007*) developed a general methodology to obtain fragility curves for different types of coastal structures. However, in those studies, morphodynamic involvement in wave overtopping is not taken into account. The model will be validated using available data from Sefton. The validated model will be used to simulate engineered beach system response to loading and wave overtopping s in order to derive fragility curves. The offshore wave and water level boundary conditions for the modified XBeach model will be provided by the same models used in Task 2.1.

Task 2.3 Swash zone subsurface flow and morphodynamics model

During storm events significant sediment transport occurs in the swash zone, especially in coarse grained beaches. Infiltration into the beach and air encapsulation are dominant processes governing surface/subsurface exchange across the beach surface, which in turn influence swash hydrodynamics, sediment transport and resulting morphodynamics. Existing Darcian models fail to quantify sub-surface flows on coarse grain beaches (Steenhauer et al., 2012). We propose to develop a novel sub-surface swash model using non-Darcian flows as well as air movement using Finite Volumes combined with a tracking algorithm for air/water interfaces. The model will be validated using available lab data and built into the existing hydromorphodynamic model of Briganti et al. (2011) for a comprehensive fully-coupled model. The model will be used to study the morphodynamics of single swash events in order to define the appropriate level of complexity for larger scale morphodynamical models. Based on these results the subsurface model will be incorporated in XBeach. Finally, the long-term simulations for a set of selected storm scenarios will be repeated using the updated XBeach code in order to assess model sensitivity to subsurface processes.

WP4 Continuous simulation and inundation framework

This WP aims to develop a continuous simulation framework and use it to calculate series of damages and impacts arising from inundation in the receptor settlements. This will be achieved in two tasks:

Task 4.1 Continuous simulation framework

For each case study, using generic methods where possible, this will be a framework with flexible time-scales allowing high resolution modelling within events and lower resolution updating between events. The framework will provide (a) clustered time series of extreme driving events assimilated from WP1 (b) non-extreme continuous drivers between storm events for updating or simulating “slow” processes for antecedent conditions. The concept of fragility curves will be extended to allow generic specification of the response of various flood components (natural, built and socio-economic) based on the detailed outputs of WP2 and 3. The work will have 2 phases: *Iteration 1* The framework will use simplified initial estimates of system characteristics to allow end-to-end simulation, from driver to response. This will use literature-based, non-time-varying fragility curves. Continuous and long term updating of some components is required, possibly with agent based models providing feedbacks. Detailed simulation of failure/overtopping and inundation of urban areas is only carried out on an event basis.

Iteration 2 Time-varying system characteristics, including fragility curves will be included from WP 2 and 3 when results are available allowing more dynamic behaviour to be represented. A range of driving conditions from WP1 will be selected including more and less variable clustering, trends in the mean and variability of hazard, and representative future climate projections.

Task 4.2 Breaching, inundation and damages modelling

An existing finite volume Godunov-type model will be extended to model event-based breaching, inundation and urban damages at high resolution receptor system in Sefton Coast (Wang and Liang, 2011). The model incorporates dynamic adaptive grids and GPU parallel computing and is 100s of times more efficient than a CPU fixed grid counterpart. First the coastal defence overtopping volumes from WP2 will be used to drive flood inundation in the receptors. Next, interactive and time-varying boundary conditions from the Sefton coastal system will be addressed with a new model which can calculate dune breaching processes and quantify the flood risk under dynamic morphological adjustment. The GPU adaptive grid based inundation model will be improved by coupling to carefully selected formulae for unsteady sediment transport and bed morphological change, which allows automatic calculation of erosion rate and soil transportation capacity in different stage of breaching. Other important processes, *e.g.* mass collapse from the sides of a breach, can be represented by slope stability analysis. With breaching acurately represented, the inundation modelling becomes more physically-based and takes into account the global effects of an event. The inundation model will provide high resolution spatial flood depth and velocities for assessing damages so outputs to WP5 will allow socio-economic postcode and sectorial analysis.

SEFTON COAST FIELD STUDY SITE

The Sefton is a convex shape coastal system located between the Mersey and the Ribble estuaries in Liverpool Bay, UK (Figure 1a) (Brown et al., 2010a,b) and has numerous urban settlements, recreational sites, conservation areas and sites of national significance. The coast, which is about 36 km long, consists of natural beaches/dunes, engineered beaches protected by seawalls, groynes and revetments and, rubble beaches covered with building material debris and rock armours (Figure 1b). The dunes within the system extend about 4 km inland, reach about 30 m in height above mean sea level at some locations. These dunes form an effective natural coastal flood defence for the local urban areas. The site is a strategic research area and has hosted numerous previous research projects such as FREE COFEE (http://badc.nerc.ac.uk/view/badc.nerc.ac.uk), EU MICORE (Williams et al., 2011), iCOASST (Nicolls et al., 2012). In the project (WP2) the focus areas will be Formby Point (Task 2.1) and Crosby (Task 2.2), which represent both natural and engineered beach systems respectively.

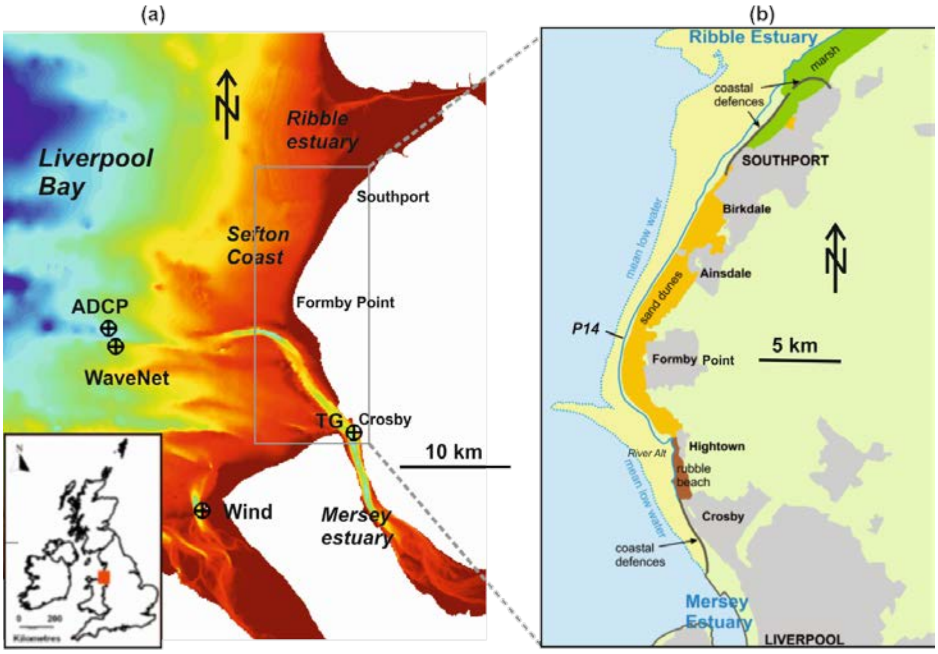

Fig. 2 (a) Location and (b) Characteristics of the Sefton coast.

The tidal regime at Liverpool Bay consists of an alongshore propagating semi-diurnal hyper-tide with a mean spring tidal range reaching about 8.2 m at some locations (Brown et al., 2010a; Palmer, 2010). Regional dynamics of the area are strongly influenced by the adjacent Mersey and Ribble Estuaries.

The application of the methods to Sefton site will comprise hydrodynamic and morphological data collection, model setting up, model calibration and validation and long term simulations of storm clustering scenarios. All available data from the UK Met Office, Environmental Agency and Sefton County Borough Council comprising LiDAR and beach profiles, bathymetry and topography, historic wave measurements, tide gauge readings, wind data will be considered to achieve the best possible model setup.

A large scale model covering the Sefton coast will be setup using Delft3D and SWAN (Lessr et al., 2004), which will provide wave and hydrodynamic boundary conditions to a high resolution small scale XBeach morphodynamic model of the most dynamic and flood prone areas of the coast. The models will be validated using measured beach profile and shoreline data by the Sefton County Borough Council and during MICORE (Williams et al., 2011) project. The models will be designed to identify coastal morphological change associated with repeated storms and overtopping and evolution of coastal dunes.

The models will then be used to simulate coastal morphodynamic change and dune overtopping from storm clustering scenarios identified in WP1, in addition to recent observed storm clustering during the winter period 2013-2014, which caused large scale damage across the UK.

CONCLUSING REMARKS

The FloodMEMORY project is formulated to investigate the impacts of temporal clustering of extreme events that lead to frequent sequential flooding on flood receptor systems. Novel superstatistical methods will be developed to model event clustering process and a continuous simulation process will be adopted to model system change during both the extreme events and interval between events in order to investigate the role of system memory on the systems resilience to flooding over different timescale. The successful delivery of the project and its application will provide a major advance in reliable flood forecasting in future and will inform local stakeholders of process interactions to support shoreline management plans.

Acknowledgement

The authors wish to acknowledge the financial support of the EPSRC to the FloodMEMORY (EP/K013513/1) project.

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