A flood system risk analysis model with dynamic sub-element 2D inundation model, dynamic breach growth and life-loss

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Abstract

Risk analysis models of fluvial and coastal flood systems have been in use for over a decade. They have been applied to support a wide range of flood risk management decisions, including long term strategic planning and shorter term asset management. Models that are currently applied in practice make a number of simplifying assumptions. The development of a new model that offers a major improvement over these methods is described. The new model incorporates: a unique dynamic 2D inundation model that captures sub-mesh element topography (RFSM EDA); a new computationally efficient model of embankment breach growth (AREBA) and extends the range of consequences considered to include the loss of life. The model has been applied on a pilot site to demonstrate its capabilities.

1. Introduction

Floods are a global problem. Whilst there are many natural hazards, floods account for about one-third globally, Adhikari *et al*. (2010). Between 1995 and 2004 flood related loss of life has been estimated at 94,000 Adhikari *et al*. (2010). Recent research, Pall *et al*. (2011), provides evidence that suggests anthropo-genic greenhouse gas emissions have already significantly influenced flood risk. This risk is likely to increase in the future as a result of sea level rise and climate change IPCC (2007). It is now well recognised that portfolios of mitigation measures are required to mitigate flood risk, Samuels *et al*. (2006). Flooding is complex and identifying those mitigation measures that are most effective in reducing flood risk is challeng-ing. It is necessary to consider the characteristics and performance of the existing flood system and how these change in time as a result of a variety of influences including: deterioration of the flood protection infrastruc-ture, land use changes and increased urbanisation and climate change, for example. Models of flood systems which account for the performance of flood protection infrastructure, are well established as the most appro-priate methods for quantifying flood risk and hence evaluating the performance of different mitigation measures. These models have their origins in the US, USACE (1996), and have been further developed and widely applied in England and Wales, Hall *et al*. (2003), Gouldby *et al*. (2008) and Germany, Apel *et al*. (2004), Vorogushyn *et al*. (2010), for example. They have been used for a wide range of purposes, including, national flood risk assessment, Environment Agency (2009), strategic planning, Gouldby *et al*. (2008a), cli-mate change impact assessment, Evans *et al*. (2006) and adaptation planning, Woodward *et al*. (2011).

The fluvial and coastal flood system risk method that is in current widespread use by the Environment Agency of England and Wales, Gouldby *et al* (2008), has recently been developed into a decision support software system, MDSF2, Environment Agency (2011). This software system incorporates a computationally efficient but simplified volume spreading inundation model. Due to the widespread use of the system, there has been emphasis to further develop and improve the model to reduce uncertainties, NAO (2011). Additionally, for a number of years, the Environment Agency has had an interest in assessing consequences, other than direct economic damages, from flooding, including loss of life, Environment Agency (2006).

This paper describes a number of developments to the methodology that is in wide use by the Environment Agency. The developments include, the incorporation of a new computationally efficient time stepping inundation model; a new computationally efficient breach growth model and the ability to assess the risk to life from floods. The application of the new methodology to a pilot site at Torrelavega in Northern Spain is used to demonstrate the capability of the new system.

2. Background to flood system risk models

The models of fluvial and coastal flood risk systems that are currently applied in practice typically define risk through an assessment of aleatory uncertainty associated with the random nature of extreme flood events and the epistemic uncertainty associated with the structural failure of the flood protection infrastructure. There are of course many other sources of uncertainty, Hall and Solomatine (2008) and some approaches have been developed that seek to quantify some of these sources, Merz and Thieken (2009), Gouldby *et al*. (2010), for example. These approaches are not commonly applied in practice, primarily due to the computational burden associated with the implementation of the methods.

Flood system risk analysis models typically include:

- a representation of hydraulic loads, described by extreme value distributions,
- the performance (or reliability) of flood protection infrastructure, defined by fragility curves,
- estimation of breach size, given failure,
- flood inundation simulation
- functions that relate the simulated floods to consequences.

Flood protection systems are defined as discrete lengths, with fragility curves prescribed for each length. These fragility curves can be derived in a variety of ways, USACE (1996), Simm *et al*. (2009), Vorogushyn *et al*. (2009), Kingston *et al*. (2011) and Schultz *et al*. (2010), for example. The performance of each reach, or section of the flood protection system, is assumed to be independent from one another and each section is assumed to exist in two possible states, breached (ie structurally failed) or not. The risk, typically expressed in terms of the Expected Annual Damage (EAD), is therefore given by:

$$EAD = \int \sum_{i=1}^{2^n} P(d_i|X) f_X(X) g(d_i, X) dX \qquad (1)$$

where n is the number of defence lengths, f_X is the joint probability density of hydraulic loads over the defence lengths, d_i is the defence system state (a vector that comprises a representation of the state of each defence) and g is a function that comprises the inundation model and relates the defence system state and hydraulic loads to the consequences of flooding.

The number of defences in a flood system can be large (>100) and hence a Monte-Carlo sampling procedure is employed in preference to simulating all of the possible combinations of defence system states.

The derivation of the joint density of the hydraulic loads, including the dependence in the extreme values, can be complex to define, particularly over large flood protection systems. Extreme value methods that address this problem have however, been developed, Hawkes *et al*. (2002), Heffernan and Tawn (2004), Lamb *et al*. (2010), for example. These multivariate extreme value methods have been applied in the context of system risk models, by Dawson and Hall (2006) and Wyncoll and Gouldby (2012). The approaches do however, require an additional layer of Monte Carlo sampling that introduces a significant additional computational burden. In current practice within England and Wales, a simplifying assumption is therefore introduced. The hydraulic loading conditions are assumed to be fully dependent within a flood area. This enables the integration of the joint density of the hydraulic loads over the consequence function to be undertaken in terms of a simple integration procedure:

$$EAD \approx \sum_{i=1}^{q} P\left(\frac{x_{i-1} + x_i}{2} < X \leq \frac{x_i + x_{i+1}}{2}\right) \bar{g}(x_i) \qquad (2)$$

where $\bar{g}(x_i)$ is the expected economic damage for the hydraulic load x_i and q is the total number of hydraulic loading levels (return periods), used for the analysis. In practice the number of loading levels varies between 5 and 40. The number of system states that are simulated with the inundation model, for each return period, can rise to several thousand. The total number of flood inundation simulations required to evaluate EAD can therefore easily exceed 4-5 thousand.

The new modeling system comprising developments relating to three separate aspects of the current methodology, introduction of:

- Time-stepping 2D inundation model
- Dynamic breach growth model
- Loss of life estimation.

These aspects are described below.

3. Description of new model

3.1. Sub-grid 2D inundation model

The inundation model that is used within the existing MDSF2 system is a simplified volume based approach that distributes water according to the floodplain topography, the Rapid Flood Spreading Model (RFSM), Gouldby *et al*. (2008) and Lhomme *et al*. (2008). Whilst this model is exceptionally computationally efficient, an essential requirement given the number of simulations that are required, it has a limited representation of the physical processes and is therefore constrained in accuracy. The model only outputs a final flood extent, rather than maximum, and due to the absence of the temporal aspects, velocities are not estimated. To address these issues a time stepping version has been developed Lhomme *et al* (2012). This has recently been further refined by Jamieson *et al*. (2012) and implemented within the risk analysis model. This new model, RFSM EDA (Explicit Diffusion wave with Acceleration term) uses the same meshing system as the original RFSM, Gouldby *et al*. (2008), Lhomme *et al*. (2008). This meshing system requires the analysis of the floodplain topography using a pre-processing algorithm. This pre-process establishes:

- Geometry of the irregular Impact Zones, used for the flow calculations,
- Connectivity of the Impact Zones,
- Volume/level relationship for each Impact Zone,
- Detailed representation of the topography across boundaries between the Impact Cells.

The pre-processing is a critical aspect of the sub-element nature of the model. It results in the production of a relatively coarse mesh for the flow calculations, whilst retaining the detailed topographical information available from fine resolution Digital Terrain Models (DTM´s). The flow calculations that are performed on the coarse grid are defined using the well known diffusion wave approach Bates and De Roo (2000), that has recently been refined by Bates *et al*. (2010) to include a local acceleration term.

A full description of the RFSM EDA and its verification against a range of benchmark tests, Environment Agency (2010), is provided byJamieson *et al*. (2012) . An example of one of the benchmark test comparisons undertaken (Test 2A) is shown in Figure 2. This test comprises a square domain of 16 topographic depressions. The more traditional models discretised the topography with ~10,000 elements (approximately 20m resolution), RFSM-EDA used only 16 elements. The RFSM EDA model did however, utilise the full 2m resolution DTM that was available, within its sub-element topography. Figure 2 shows a water level time comparison, at a specified test point, of RFSM EDA with a well respected commercial inundation model, that uses a finite volume solution of the full Shallow Water Equations (Infoworks 2D). It is evident that RFSM EDA is able to reproduce the same characteristics as the full SWE Model. On a number of the tests, it is able to achieve these results in a fraction of the runtime of the more traditional models that do not use a sub-element aspect, Jamieson *et al*. (2012). A selection of these model runtime results are provided in Table 1.

Table 1: Comparison of 2D model runtimes for a range of benchmark tests.

Model	Benchmark Test Number					
	1	2	3	4	5	8
RFSM EDA	**0.03**	**0.015**	**0.01**	**0.48**	0.75	**2.9**
JFLOW GPU	n/a	1.83	0.46	02.3	10.2	16.2
InfoWorks ICM	0.27	0.73	0.17	06.5	0.7	27.1
LISFLOOD ACC	n/a	n/a	0.03	1.97	0.68	n/a
Fastest other	0.05	0.4	1.0	1.27	**0.6**	4.0
Slowest other	5.82	130	1.23	282	350	307.8

Table entries are model runtimes (min.).

Bold indicates fastest model for that test.

This fast runtime is particularly relevant given the probabilistic nature of the analysis required in the system model. It is important to note the RFSM EDA retains the capability of the original RFSM to track the propagation of the water from its originating source (ie specific defence section) across the floodplain. This enables the spatial floodplain risk, expressed in terms of economic damages and now life loss, to be attributed to each defence section. This is of importance to asset management activities, where decisions on the priorities for maintenance and refurbishment of existing infrastructure are required. It is often preferable to target this type of investment on those protection assets that offer greatest benefit, in terms of risk reduction.

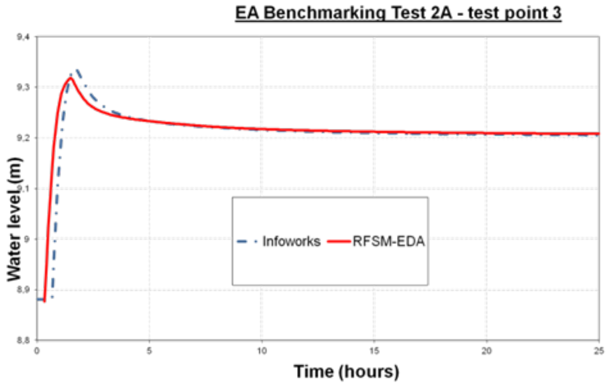

Figure 1: Comparison of the RFSM EDA inundation model, with a full SWE model (InfoWorks 2D), on Test 2 of the Environment Agency's benchmark tests.

3.2. Dynamic breach model

Within the risk modelling system, fragility curves describe the likelihood of breaches occurring. Given a breach occurs, there is then a need to estimate the discharge rate through the breach and into the floodplain. The approach for estimating breach dimensions and associated volume discharge in the current system is simplified. It comprises a simple function of the magnitude of the hydraulic loading. The rate of breach evolution and final dimensions, critically influences the quantity of water discharged into the floodplain and the associated consequences of flooding, and hence risk. It is of particular note that the velocity of floodplain flows can be highest in the vicinity breaches due to the transient nature of the flows in these areas. Flow velocity is a significant influence on the potential for life loss (section 3.3).

The simulation of the physical process of breach growth in embankments has seen extensive research for more than a decade, see Morris *et al*. (2008), for a review. The primary stages in the development of breaches are defined by Morris *et al*. (2008), as

1. Embankment is stable and functions well.
2. The embankment starts to overflow and water percolates into the embankment. Material is progressively removed from the inner slope which retreats towards the upstream slope.
3. Erosion of the downstream slope reaches the outside slope and the flow slowly starts to increase.
4. Rapid increase in flow velocity with erosion of the outside slope and simultaneous widening of the breach. The breach widens laterally. Flow velocities are super critical.
5. Breach flow starts to get affected by the rise of the downstream water level, and / or the fall of the upstream water level and the breach flow starts to decrease to the point that the flow velocities become so small that the erosion process stops.

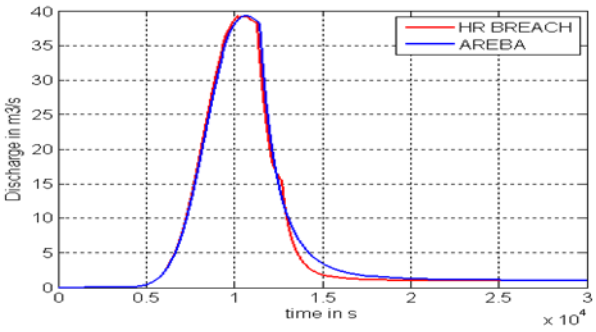

Figure 2: Comparison of the outflow discharge from a levee using the AREBA dynamic breach growth model and the well-established HR BREACH Model Van Damme *et al* (2012).

The HR Breach model was developed around a decade ago, Mohamed (2002). This model has been widely used for simulating breaches in dams and embankments. It is however, too computationally demanding for use in system risk analysis models that are applied in practice. A simplified model, AREBA, has therefore been developed, Van Damme *et al*. (2012). AREBA simulates embankment breach processes that arise as a result of erosion from overflowing water, or internal erosion due to pipes that are formed through the embankment. Discharge through the breach depends on the breach depth and width, or pipe dimensions. AREBA analyses surface erosion failures, headcut erosion failures or piping failures. AREBA has been validated through comparison with the more complex HR BREACH model (Figure 2) as well as data from full scale breach experiments. Full details of the model and its validation are provided by Van Damme *et al*. (2012).

3.3. Life loss

Loss of life modelling, in relation to flooding, has been undertaken for many years. Example methods for evaluating life loss include the LIFESIM model, originally developed for use in dam related floods, Aboelata and Bowles (2005) and now fully embedded within the HEC flood modelling suite of the USACE, Needham (2010). More simplistic, empirically based methods have been developed by a number of researchers. Jonkman *et al*. (2008) provides a thorough and comprehensive review of these methods as well as describing a new approach. This approach has been further verified by Di Mauro and de Bruijn (2012). Relatively recently, Agent, or Individual, based models have been increasingly developed and applied to support emergency planning and evacuation modelling in relation to floods, BC Hydro (2004), Dawson *et al*. (2011) and, for example. The Environment Agency has also developed a generic but simplistic method, Environment Agency (2006) Penning-Rowsell *et al*. (2005). This method has been applied in the UK and further extended for application for a range of catchment types within Europe, Priest (2007).

The computational effort required to run the Agent Based approaches is prohibitive for practical system risk analysis models. In principle, however, any of the more simplistic approaches could be applied. Initially, here, the Environment Agency loss of life methodology has been implemented within the system risk model, but this can be readily extended to include other approaches. Given the uncertainty associated with the loss of life methods, implementation of a broader range is likely to yield useful insights on the model structural uncertainties associated with these functions.

The Environment Agency approach comprises a series of factors to determine the injury and mortality rate:

$$N(f) = 2N(I)\frac{HR}{100} \tag{3}$$

where, *N(f)* is the number of fatalities *N(I)*is the number of injuries (this is a function of the number of people within the flooded area, their vulnerability and the nature of the area). HR is the Hazard Rating defined as:

$$HR = d(v + 0.5) + DF \tag{4}$$

where *d* and *v* are depth and velocity respectively and DF is a debris factor.

The RFSM EDA outputs depth *(d)* and velocity *(v)* for each Impact cell. This information is used in the estimation of life-loss.

3.4. Implementation of the new components

The new modeling system retains the same basic structure as the existing system, Eqn 2. The new inundation model places a requirement for time varying boundary conditions, for discharges into the floodplain. For embankment breaches the discharge hydrographs are provided from AREBA. For overflow of fluvial flood systems, these can be calculated using standard techniques for hydrograph generation, eg analysis of flow data. For coastal systems, the time varying flow can be calculated using a combination of discharges obtained from wave overtopping methods, Pullen *et al*. (2007) and weir flow. The RFSM EDA provides maximum flood depths and velocities within each impact cell at each time step. The maximum flood depth is extracted for each cell, for each flood simulation and depth damage functions, Penning-Rowsell *et al*. (2005), are used to define economic damages.

For the risk to life estimation, the hazard rating is calculated at each time step of every flood simulation and then combined with information relating to the number of people associated with each cell to determine the maximum mortality rates. These are then aggregated in the same way as economic damages, Eqn. 2, to determine Expected Annual Life-loss (EAL). This information can be displayed spatially or attributed to individual sections or components of the flood protection system, using the flow tracking capability of the inundation model.

4. Pilot site application

4.1. Site description

The city of Torrelavega is located in the region of Cantabria, Northern Spain. The city is located at the confluence of the rivers Saja and Besaya that have an upstream catchment area of more than 1000 km^2. Historically the urban centre has been affected by floods from both rivers, with a significant influence from natural tributaries. More specifically, two natural tributaries that cross the city are now engineered subsurface pipe systems. The development of the city has given rise to the construction of major river defenses to prevent flooding. In particular, in the south-west of the city, Covadonga is protected by a series of embankments and extending to a vertical wall in the industrial zone of Malecon.

A model of the flood system of Torrelavega has been constructed. It is however, important to note some modifications to the system have been made to facillitate demonstration of the concepts and principles of the new modelling system. The results that are shown do not therefore reflect the reality of the flood hazard and risk in Torrelavega itself. Figure 3 provides an overview of the study area.

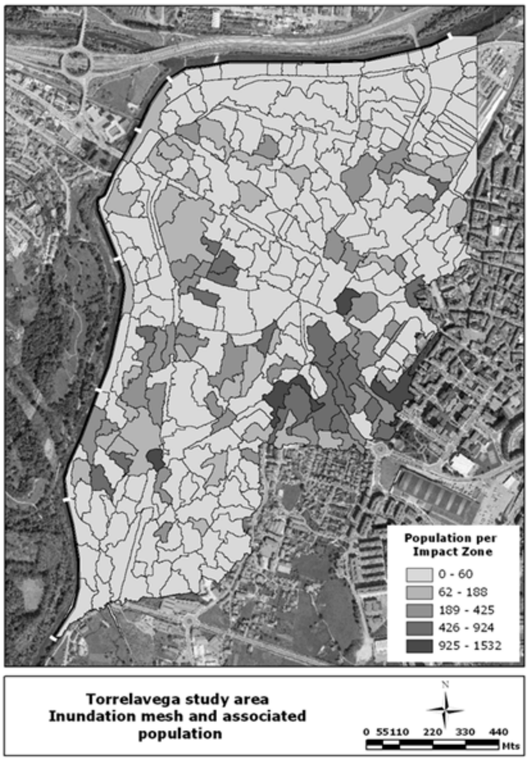

Figure 3: Map of case study area, showing inundation mesh, defence sections and associated population density.

A DTM obtained from LIDAR data with 1m horizontal resolution was analysed using the pre-processing algorithm of the RFSM EDA model. The resulting mesh system is shown in Figure 3. The flood protection system was separated into a series of 6 discrete defence sections, based on protection type (see Figure 3). Fragility curves were assigned to each discrete section, using a pre defined set of curves, Environment Agency (2007). The two predominant defence types were an earth embankment and a mass concrete wall. A 1D HEC-RAS model that was available from a previous flood mapping project was used to obtain the hydraulic loading conditions on the flood protection system. The output from the HEC-RAS model was used to define the boundary conditions for the inundation model. Time varying boundary conditions were derived for the overflow and breach cases, for each defence section. For the embankment, the floodplain inflows for the breach scenarios were derived using the AREBA model. An example floodplain inflow hydrograph from the AREBA model is shown in Figure 4.

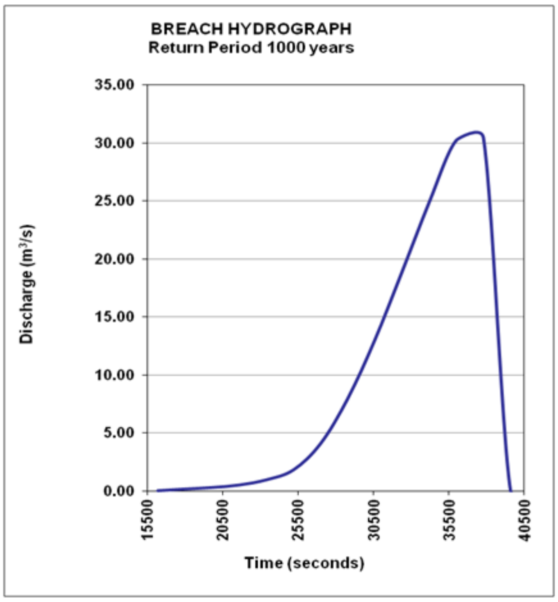

Figure 4: Output from the AREBA model for an embankment at Torrelavega.

The depth and velocity output from the RFSM EDA model has been used to calculate the Hazard rating (Eqn. 4) and subsequent estimation of life loss. A map showing an example of the estimated life-loss for a nominal 200 year return period and a single realisation of the defence system state is shown in Figure 5.

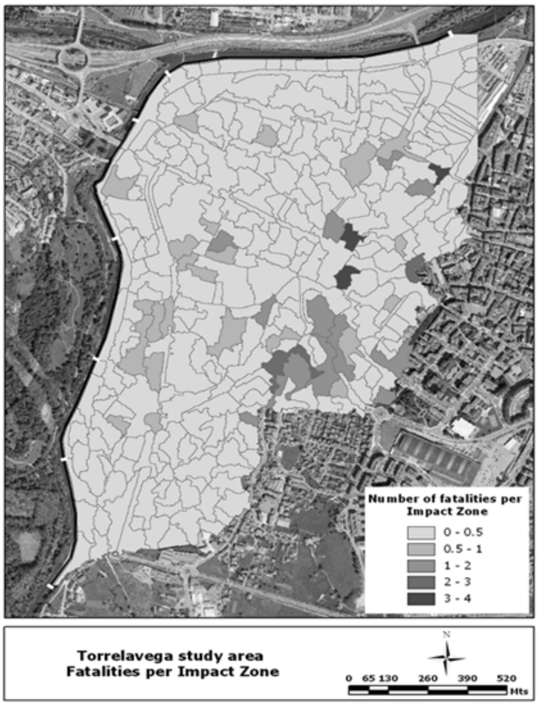

Figure 5: Number of fatalities for a nominal 200 yr. event with an assumed defence system state.

5. Conclusions

The new modeling system described in this paper offers a potential step change in the performance of existing flood risk analysis modeling systems that are applied in practice in England and Wales. The RFSM EDA inundation model is able to closely reproduce the behaviour of more traditional SWE models in terms of the physical process and also offers benefits in terms of the resolution of the DTM it can operate with and the fast runtime. It is capable of using the available fine resolution topographical data even when operating at large spatial scales. The fast computational runtimes make it suitable for use in systems models of flood risk, where the simulation of flood events with multiple return periods and system states is required. Replacing the existing volume spreading approach with the time stepping RFSM EDA, improves the accuracy of the flood depth calculation and also lends itself to the calculation of velocity.

The estimation of life loss from flooding depends on both depth and velocity. The new developments therefore facilitate the estimation of risk to life from flooding, as well as improved estimates of economic damages. Flood velocities, and hence potential life-loss, can be highest in the vicinity of breaches and it is therefore important to consider the physical processes of the breach development within the risk modeling system. The AREBA model offers a computationally efficient alternative to the well-established HR BREACH model. The fast model run times make it particularly compatible with the RFSM EDA. The dynamic approach of AREBA offers a significant improvement over the simplified equations that are used in current practice in England and Wales.

The application of the new modeling system to a pilot site in Northern Spain, has demonstrated some of the potential benefits of the new approach.

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