The application of componentised modelling techniques to catastrophe model generation

Royse, K R [1*], Hillier, J. K.[2], Wang. L [1,], Lee, T. F.[1,2], O'Niel, J.[2], Kingdon, A.[1], Hughes, A.[1]

[1]British Geological Survey, Keyworth
[2]Loughborough University, Loughborough, LE11 3TU, UK.
*Corresponding author

Abstract.

In this paper we show that integrated environmental modelling (IEM) techniques can be used to generate a catastrophe model for groundwater flooding. Catastrophe models are probabilistic models based upon sets of events representing the hazard and weights their likelihood with the impact of such an event happening which is then used to estimate future financial losses. These probabilistic loss estimates often underpin re-insurance transactions. Modelled loss estimates can vary significantly, because of the assumptions used within the models. A rudimentary insurance-style catastrophe model for groundwater flooding has been created by linking seven individual components together. Each component is linked to the next using an open modelling framework (i.e. an implementation of OpenMI). Finally, we discuss how a flexible model integration methodology, such as described in this paper, facilitates a better understanding of the assumptions used within the catastrophe model by enabling the interchange of model components created using different, yet appropriate, assumptions.

i. Introduction

Global economic losses related to natural hazards are large and increasing. Total economic losses reached US$130 billion in 2010, US$380 billion 2011 and US$160 billion in 2012 (Munich Re 2011, 2012). Insurance is a method of managing these financial risks, the objective of purchasing insurance is to avoid a loss large enough to cause failure by spreading the cost. However, natural hazards or 'perils', can affect many insured properties across a wide area (e.g. 100s of km across) in a limited time window (e.g. <72 hours). For example, Hurricane Andrew in 1992 caused an estimated $26.5bn in losses to property, leading to the failure of 13 insurance companies (AIR 2002; Cummins 2007). To protect against this, insurers buy reinsurance. The reinsurers have to cost this insurance by estimating the insured losses caused by extreme events, such as hurricanes and earthquakes and then predicting the probable likelihood of such an event occurring. The difficulty is that insurers previous claim experience is often of little use when trying to predict insured losses. This is because extreme events are rarely directly comparable, and insured property 'exposure' changes rapidly. For example inflation, real growth in property values, varied insurance penetration, and changes in properties' locations within a portfolio must be accounted for to create a figure for likely insured losses (Tower Perrin, 2005; Swiss Re 2007). Catastrophe models, developed over the last ~25 years (Grossi et al., 2005), are one solution to this problem.

The aim of this paper is to demonstrate a proof-of-concept by showing how Integrated Environmental Modelling (IEM) methods and techniques can be used to construct a catastrophe model using the example of groundwater flooding risk of the Marlborough and Berkshire Downs in the UK. Although there is extra effort required to make models linkable once a linked modular catastrophe model has been constructed, several advantages can be gained, for example an increased flexibility by allowing for the interchange of compatible components. Linked modelling can facilitate both an improved understanding of and better insight into the interactions between model components, in part because of the need to fully document and define the models and datasets being exchanged between components.

This paper will firstly look at flooding in the UK and UK insurance policy; we will then discuss how the insurance industry use catastrophe models to improve loss calculations and how IEM modelling methods and techniques could be adopted to generate catastrophe models. The second part of the paper will work through a case study example of groundwater flooding in the Marlborough and Berkshire downs.

ii. Flooding and the UK Insurance industry

Unlike many other countries, in the UK, the majority of domestic and business flood damage losses are covered by the insurance market rather than government funds. Under the

'Statement of Principles', an agreement setup in 2000 between the British Government and the Association of British Insurers (ABI), insurers committed to providing cover for almost all properties, other than where the risk is deemed significant and no plans are in place to manage the risk within a 5 year time period (DEFRA 2011). In the last 10 years in the UK, there have been several major flood events. The biggest and most catastrophic were the 2007 floods which consisted of a mixture of surface and groundwater flooding events which affected large areas of Yorkshire, the Midlands and the West of England. This demonstrated without doubt that flooding in the UK can be devastating, from social impacts such as loss of life, dislocation of thousands of people and major economic impacts which cost insurers over £3 billion (Pitt 2008). Two years later, the 2009 floods affecting a smaller area of Cumbria, West Wales, Dumfries and Galloway, still cost insurers over £1.5m (Munich RE, 2010). The Association of British Insurers has put the average cost of flood damage (all types) in the UK to homes affected at between £20,000 and £40,000 each (Dailey et al. 2009).

In this paper we concentrate on groundwater flooding, because it is both poorly understood (e.g. Finch et al. 2004; Hughes et al. 2011), and often confused by non-specialists with surface water flooding. Groundwater flooding presents a substantial problem, but is not widely recognised either in the UK or internationally (Kreibich and Thieken 2008). Hughes et al. (2011) suggest four types of groundwater flooding based on their origin:

a) A high water table in regional aquifers
b) Short-circuiting of flood defences
c) A rise of the water table due to cessation of mine dewatering
d) Barriers to subsurface flow caused by underground structures

In the example used in this case study; the risk is primarily of Type 1 resulting from extremely high intensity and/or long duration rainfall.

The costs and impacts of just groundwater flooding events in the UK are significant and almost certainly underestimated (Green et al., 2006, Royse 2011) because unlike surface water flooding, groundwater floods tend to be longer-lasting, typically remaining for the order of weeks or months. Groundwater flooding can be defined as flooding caused by the emergence of water originating from subsurface permeable strata (Cobby et al. 2009). The latest estimates suggest 1.6 million properties may be at risk in the UK (Jacobs, 2004), the most vulnerable being those located on the exposed Chalk aquifers of southern England e.g. south Oxford in 1997 (Macdonald et al. 2007, 2008), but events also occur elsewhere, such as in Pilmuir in Scotland (Macdonald et al. 2008; MacDonald et al., 2008). Typically, groundwater flooding occurs during winters where recharge is high during the early part of the recharge season and stays above average. The case study that has been used is in the Pang and Lambourn catchments within the Berkshire and Marlborough downs (Fig 3A). The catchments experienced severe flooding during the winter of 2000/1 following unusual meteorological events in the previous 18 months (Adams et al. 2008), and again in the winter of 2002/3 (Hughes et al. 2011).

The actual cost of groundwater flood events, while less nationally than fluvial or marine flooding, can be significant e.g. the estimated cost of a relatively localised groundwater flooding event in 2000 in Brighton was £800,000, excluding the cost of the railway closure (Binnie et al. 2001). Furthermore, groundwater flooding in Hambledon in 2000/01 was estimated by the local council to have resulted in financial losses of some £1.1 million (Green et al., 2006).

After the 2007 flood events in the UK, a review was carried out looking at how the events were managed and what lessons could be learnt (Pitt, 2008). The review was extremely far-reaching, covering building regulations, emergency response, prediction and modelling. A key recommendation was the need to develop a whole system approach to understanding flood risk in the UK. This required that groundwater flood risk should be included within any flood risk management system.

Groundwater flood events often take decision-makers by surprise, as they are not included in conventional flood risk mapping. In recognition of this problem, the EU's Floods Directive (2007/60/EC) dictates that groundwater flood risk now has to be taken into account in any flood risk study. Damage to properties caused by rising groundwater levels is a worldwide issue (Hagerty and Lippert 1982; Hamdan and Mukhopadhyay 1991). Kreibich and Thieken (2008) have noted that loss assessment studies have in general neglected damage caused by groundwater. In order to evaluate the cost effectiveness of, for example, groundwater drawdown measures, the construction of rain surface and floodwater collection networks, there is a growing need to generate reliable loss assessments (Al-Sefy and Sen 2006).

iii. Catastrophe Models

Catastrophe models have been used for the last 25 years by the insurance industry to assess risk by estimating likely losses from extreme events, whether natural or man-made. Catastrophe models are stochastic, event-set based computer models, which allow the potential for large losses from an insurer's current exposure (usually property assets) to be tested by subjecting them to many (e.g. 10,000) events representing scenarios for a hazard within a peril-region (e.g. 'UK flood') and are used to estimate the location, impact and frequency of possible future natural disasters (Grossi and Kunreuther, 2005). The purpose of a catastrophe model is to provide insurers with a better understanding of their liability to events in the year ahead. The models are then used: to "price" catastrophic risk; to control an insurer's risk accumulation; to diversify their risk; to estimate the insurer's reserves in case of loss; to minimise the amount of capital required to cover risks in the insurer's portfolio and finally to estimate the correct price to reinsure or transfer their risk (Chavez-Lopez and Zolfaghari 2010). Most catastrophe models are based on an arrival process and provide tradeoffs between economic losses i.e. an evaluation of the severity and the probability that a certain level of loss will be exceeded on an annual basis (Haimes 2004, Grossi and Kunreyther 2005 and Banks 2006).

Figure 1 provides an illustration of a typical framework for a catastrophe model. The contents, definitions, and names of each of the modules are not standardised and therefore do vary (e.g. Grossi 2005; Qu 2010). However, the broad work-flow as illustrated remains similar. Figure 1 identifies three major 'modules', where processing occurs, and three inputs. In this paper we will only be considering damage to property exposure. However, catastrophe models can look at a variety of exposures, such as: loss of life, business interruption, clean up costs, infrastructure losses etc.

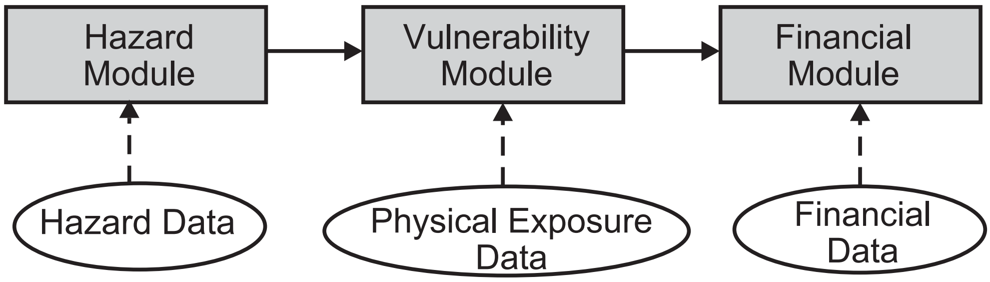

Figure 1: *One possible proposed conceptual framework of a traditional component based catastrophe model. Rectangles are modules, ovals are inputs and arrows indicate the flow of information*.

The 'Hazard' module provides the frequency, intensity and areal extent of events, usually as spatial intensity maps (i.e. contoured footprints of severity), each associated with a probability of occurrence within the next year. For model users (e.g. insurers, brokers), this exists as a static database supplied in whichever product they are using. For model developers, calculations to generate the event set may also be included. The 'Vulnerability' module converts hazard into physical impact, typically via vulnerability (a.k.a. fragility) curves linking hazard intensity (e.g. flood depth) to loss as a percentage of the total insured value of a property. To achieve this, exposure information is input and losses for every property evaluated for every event; therefore, the locations of exposure are critical in calculating loss. Modifiers are used to improve the accuracy of the impact assessment by indicating which variants on the main vulnerability curves could be used for each exposure. Modifiers may include: building construction (e.g. stone, reinforced concrete), number of stories, style of occupancy (e.g. residential, commercial), and year built. Lastly, the 'Financial' module calculates losses by using policy information, primarily the sum the property is insured for. This also uses other information such as limits, deductibles, or treaties that determine who to assign these losses to: financial perspectives e.g. 'ground up', 'net loss pre-cat' (Grossi et al. 2005).

Like other numerical models, catastrophe models are developed based on certain assumptions or simplifications, thus leading to errors (e.g. Grossi 2005) and uncertainties in the loss estimates. Therefore catastrophe models need to be used with due caution (e.g. GC 2011; ABI 2011). To most users, however, catastrophe models are 'black boxes' owned and developed by one of the major catastrophe modelling companies. This suggests that catastrophe models may not always be used to the insurers' best advantage when supporting their decision-making processes. After Hurricane Katrina in 2005, it was recognised that considerable progress had been made in modelling natural catastrophes; however there were significant limitations in the existing models at that time in predicting losses for both personal and commercial risks which caused modellers to launch new efforts to revise their databases and predictive techniques (Cummins, 2007). Catastrophe models produce two main outputs: the Annual Average Losses (AAL), i.e. the insurer's time-averaged costs in payouts, and the Occurrence Exceedance Probability (OEP) curve. OEP is the probability that losses due to any single event will exceed an amount, e.g. an insurer's financial reserves. So, losses due to a low probability high return period event, perhaps the 250 yr OEP loss, are of great interest, as these tail-end events may bankrupt the company.

Even when only the losses resulting from damage to property are considered, models' results differ and are known to be imperfect. First-order sources of error (Grossi 2005) include:

a) Hazard estimates: event sets may be imperfect, for example the 2011 Mw 9.0 Tohoku earthquake was larger than those included in catastrophe models (Avouac 2011; Lay and Kanamori 2011; Ozawa 2011; AIR 2012).
b) Vulnerability curves: these estimated relationships may be incorrect, out of date or may not be applicable to the geographic area under analysis.
c) Exposure data: in the insurance industry, this term is used to describe the physical contact between assets, usually houses (damage), and a peril (hazard). Incomplete or incorrect details about assets on insurers' books such as errors in localisation and identification will lead to erroneous estimates.

The difference that errors including those above can make to estimates of losses can be demonstrated by the initial estimates of losses caused by the European windstorm 'Kyrill' in 2007. The 5 main models variously reported losses as, $3-5bn [RMS], $3.6-8.8bn [AIR], $2.5-5bn [EQECAT], $4-7bn [Hanover Re], $5-7bn [Munich Re], and $3.5bn [Swiss Re] (Willis Re, 2007) whereas the actual property losses were estimated to be at around $5.8bn (Muich Re 2011b). Where catastrophe models exist for perils (and it should be noted that large gaps in the geographic coverage of catastrophe models still remain), there are a number of other issues known to affect the accuracy of loss estimates because they are either imperfectly or incompletely included within current catastrophe modelling methodology. Some of the more notable issues are listed below:

a) Multi-peril correlation (e.g. Woo, 1999): For instance, tsunami and fire following earthquake may be included only crudely, e.g. footprints of a few selected tsunami scenarios, or not at all.
b) Hazard clustering in time (e.g. Lennartz et al. 2008; Rybski et al. 2008; Vitolo et al. 2010): where events do not occur independently of each other; typically, events are assumed to be independent, although clusters in European windstorms has now been included,
c) Unmodelled exposures: physical (e.g. cars or oil rigs) or conceptual. Business interruption is normally included for the firm directly insured, but wider economic losses such as knock-on impact, commercial liability, compensation, and life insurance are generally not considered. For example, \$40bn of losses for the recent flooding in Thailand, \$10bn of which were insured, were mainly due to supply-chain disruption which graphically illustrates the potential impact of these effects (Munich Re 2012; Willis 2012).
d) Demand Surge: an increased cost of repairs due to scarcity and the consequent cost of construction material and labour going up in the largest events.

1. Solvency II

New regulations (Solvency II) (e.g. Eling et al. 2007; EU 2009; ABI 2011) require insurance firms to better understand the assumptions underpinning their solvency calculations. The directive applies to all insurance and reinsurance firms which have gross incomes exceeding 5 million Euros. The directive's main aim is to specify the European Union's requirements on the capital adequacy and risk management of insurers to make certain that they can survive difficult periods. This should protect policyholders and also the stability of the financial system in Europe (Eling et al. 2007). The Solvency II directive went live on the 1st January 2014 (EU 2009). The directive specifies the minimum amount of financial resources that insurers and reinsurers must have in order to cover the risks that they are exposed to, in other words the companies' solvency capital requirements (SCR). Each insurer determines their SCR by using an internal model that has been accepted by the regulator. One component of this model is the catastrophe model. This has very significant implications, because Solvency II makes the insurer responsible for all parts of their internal model (ABI 2011). Therefore, even if they rely, as many do, on a vendor for their catastrophe modelling, the insurer cannot outsource its 'understanding' of or 'responsibility' for any part of the catastrophe modelling process (ABI 2011).

Therefore, in practice, insurers wanting to implement Solvency II have to demonstrate a high level of data quality and management, disclosure and transparency as well as more frequent reporting (ABI 2011). In terms of catastrophe modelling, these new regulations require the insurer's senior management team to understand the strengths and weaknesses of the catastrophe models the company are using, to be aware of potential gaps and quality differences in the company's catastrophic risk modelling landscape, to actively seek the levels of information and detail they need to feel comfortable with taking decisions and finally to ensure that the proper policies and procedures for doing so are in place (ABI 2011). The onus is therefore on the insurance company to understand the limitations of the catastrophe models that it uses, the differences between model outputs and actual loss experience and how the results of their modelling impact the company's internal model for SCR calculation (ABI 2011).

iv. Integrated Environmental Modelling (IEM)

Due to the modular paradigm typically used in catastrophe models as discussed above it is relatively simple to see how an IEM approach could be successfully adopted. For example, each module can be thought of as an individual or group of models that are performing calculations and exchanging data with each other (Zolfaghari 2009). This affords the user and developer greater flexibility in being able to update and change component parts of the model framework as and when new data, models or scientific understanding becomes available.

IEM methods and techniques have been driven by the need of today's policymakers to understand complex environmental problems (Beck 2009). To answer these questions an ever-increasing appreciation of the earth processes and how they interact together is required (Beck 2009). IEM is about linking computer models together that simulate different processes to allow scientists to predict how processes interact in particular situations (Moore and Hughes 2010). The technique is predominantly used in impact analysis, especially when looking at the wider consequences of events and policies, optimising resources or what the resultant societal impact will be of new policies to manage the natural world. IEM focuses on linking models, databases and institutional structures to support decision making. It is not about the individual models themselves (Laniak et al. 2013). However, integrated modelling is concerned with the design and operation of integrated analytical frameworks, accessibility of models, repeatability of results and audit trails, uncertainty passing through the model chain and decision support interfaces (Moore and Hughes 2010).

There is an increasing recognition that it is not practical to construct one large monolithic model which can capture all of the earth-system processes needed for decision making (Argent 2006). Large models are not only wasteful of resources, rarely reusable and difficult to understand but they fail to make use of existing process models (Moore and Hughes 2010). IEM methods can be used to make existing numerical models into components or 'building blocks' that can be assembled or linked together to make more complex models (Warner et al. 2008; Barthel et al. 2008). Using this approach, models become substitutable and the linking mechanism can be more transparent and better documented (Knapen et al. 2013).

A model framework can be used to link models together. Several frameworks are currently available, for example FRAMES (Babendreier and Castleton 2005), CSDMS (Overeem et al. 2013), OMS (David et al. 2002) and OpenMI (Moore and Tindall, 2005). Where these frameworks are based on open standards such as the case with OpenMI, the framework can be made widely assessable to a large user community (Knapen et al. 2013). The choice between modelling frameworks is largely dependent on the project being undertaken and the researchers involved (Knapen et al 2013). Linking models to enable individual models to conduct a simulation collectively is challenging (Bulatewicz et al. 2010). These difficulties can be due to a variety of reasons; for example, it could be how the models have been designed, the programming language or the spatial and temporal discretisation used. A further issue is that of using components based on a consistent set of assumptions, although this is a challenge, whether one uses a monolithic or componentized approach, in the latter case this issue must be addressed if components are going to be interchanged. In situations where there is a need to link models together, it is advantageous to use a standard protocol, as it promotes collaboration and reuse of the individual model components (Knapen et al. 2013).

In this paper we have developed a linked groundwater catastrophe model. However, linking hydrological models to economic models has been done previously in various ways over a long time period (Burt 1964; Brouwer and Hofkes 2008; Koundouri 2004; Harou et al. 2009). Where a modular approach has been taken, the transfer of data has been achieved in several ways with varying levels of automation (Draper et al. 2003; Volk et al. 2008; Ahrends et al. 2008; Jackman and Letcher 2003; Cuddy et al. 2005). For example, Jonkman et al. (2008) developed a surface-water hydrodynamic economic model for the Netherlands to estimate flood damage due to low probability high impact events. Their approach integrated different types of data within a geographical information system (GIS). Bulatewicz et al. (2010) used a more automated approach using an open Framework e.g. OpenMI to integrate agriculture, groundwater and economic models to evaluate the impacts of water-use policies to reduce irrigated water use in semi arid grasslands in America. Bulatewicz et al. (2010) found that the flexible design of the OpenMI framework assisted with the modular approach that was taken and worked well with models from other domains other than hydrology, for which OpenMI was originally designed.

This paper focuses on the use of the OpenMI model framework because it uses an open framework based on well-defined standards. OpenMI was developed because there was a need to answer integrated hydrological catchment questions within the EU 5th Framework programme (Gijsbers et al. 2002)OpenMI was developed by a consortium of European companies, research organisations and universities co-funded by the European Commission as a standard for model linkage in the water domain that would allow models to exchange data at run time (Moore et al. 2005) and was initially developed to facilitate an integrated approach to environmental management as specified in the Water Framework Directive (OpenMI 2009).

OpenMI works by defining what an individual model must be able to do in order for it to become OpenMI compliant. Once model entities are made OpenMI compliant, they effectively turned into objects, or 'components'; multiple components form an OpenMI composition. To achieve OpenMI compliance, the model component must implement a set of OpenMI interfaces. This exposes inputs, outputs and run-time operations of the model to any OpenMI compliant environment and enables its coupling with any other OpenMI-compliant components without source code changes. Once a model element meets these requirements, it is then a linkable component and the model has become OpenMI compliant (OATC 2009).

Once compliance is achieved it allows the model to exchange data by linking the exposed variables. One of the features of OpenMI is that a component's owner selects which of the model variables are accessible by other model components. The owner can also choose the number of variables that the users can manipulate. This feature could help in addressing security issues within catastrophe models for the insurance industry, as it could be used to restrict access to variables within any OpenMI compliant component. Although this appears at odds with the premise of increased transparency we have to acknowledge that, in some cases, security issues outweigh the need for greater openness. Using a model standard such as OpenMI can help ensure that more of the model components remain open to interrogation than might otherwise have been the case.

As well as defining, a standard, OpenMI also has a default software implementation which has been developed by the HarmonIT EU project (https://sites.google.com/a/openmi.org/home/openmi-around-the-world/development-tools). The SDK (Software Development Kit) and graphical environment were developed by the Fluid Earth initiative (2011), and is freely available on SourceForge (http://sourceforge.net/). The implementation has been developed to reduce the amount of work needed to make computational entities OpenMI compliant and to link them together. It includes a software implementation of OpenMI, comprising a SDK and a GUI

(Graphical User Interface) called ‘Pipistrelle’. The SDK allows models (e.g. groundwater flow and climate models) to be adapted into OpenMI compatible ‘components’ in preparation for linking to other models. Fluid Earth’s ‘Pipistrelle’ is a graphical ‘point and click’ interface (Figure 2) that allows users to link components into ‘compositions’ and run them.

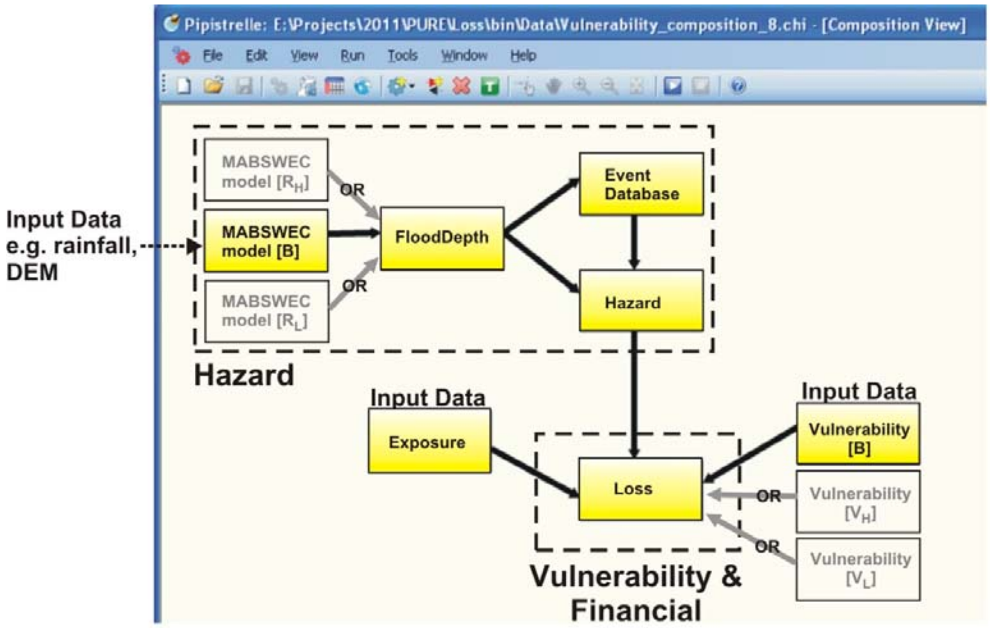

Figure 2: *Annotated screen shot of a Pipistrelle composition for the Groundwater Flooding Catastrophe. Yellow boxes are the 7 components of the ‘baseline’ [B] model, comprising best-estimates of recharge [R], hydraulic conductivity [K], and vulnerability [V]. Arrows indicate data flow detailed in Table 1. Grey text and arrows, added to the screen shot, indicate alternative components that could be swapped into the composition by simply changing the link (arrow).*

v. Case Study: Development of a Groundwater Flooding catastrophe model for the Marlborough and Berkshire Downs

Our case study is located 70 km west of London in the Marlborough and Berkshire Downs and South-West Chilterns (*MaBSWeC*) and covers an area of about 2600 km^2

(see Figure 3A). The elevation of the ground surface ranges from 20 m to the south-east of the area to 250 m towards the north-west of the region. The River Thames flows onto the area near Wallingford and off the region near Windsor, and its tributaries are the Rivers Kennet, Lambourn, Pang, and the Wye (Jackson et al. 2011).

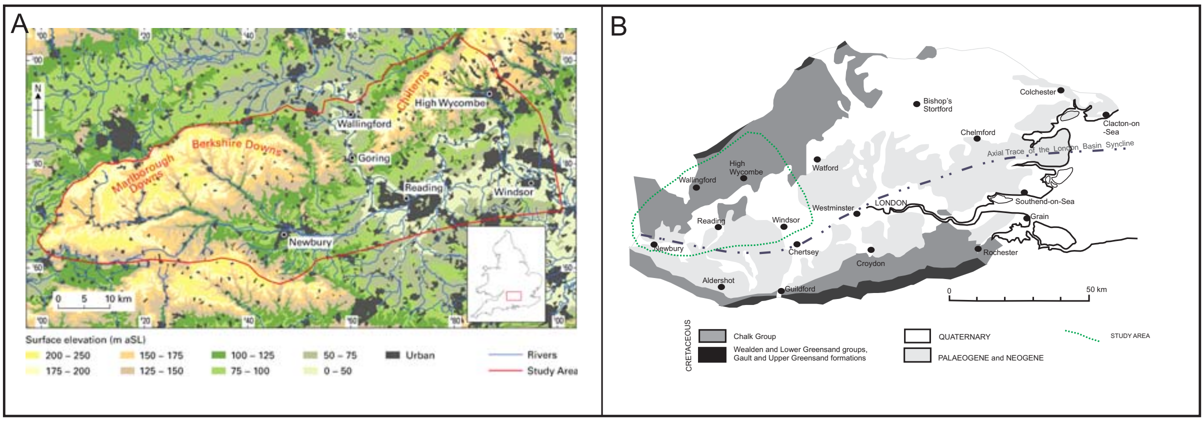

Figure 3:* *(A) *Map of the study area, located by red rectangle in the inset. Red outline depicts the limits of the Marlborough and Berkshire Downs and South-West Chilterns (MaBSWeC) groundwater model used (adapted from* Jackson et al. 2011). ***(B)*** *Geological sketch map of the London Basin. Based on Figure 1 of Sumbler (1996). Note that groundwater flooding is not an issue where clay (Palaeogene) overlies Chalk.*

The region lies at the north-western edge of the London Basin which was formed through the creation of a synclinal geological structure, principally in the soft white limestone of the Cretaceous Chalk (Sumbler 1996; Royse et al. 2012; Figure 3B). The Chalk is the primary aquifer in the area and hence the focus for our groundwater model component. This primary aquifer is also the main source for drinking water in the region. However, it is also a cause of flood events; for example, in early 1994 East Ilsley suffered what were then the worst floods to affect the village for 33 years, caused entirely through groundwater flooding (Newbury Weekly News, 3 March 1994). Groundwater flooding has a number of different manifestations (see Hughes et al., 2010), but in this paper we are only considering the situation where the water table rises and reaches the land surface, resulting in surface flooding

a. Constructing a groundwater catastrophe model for the Marlborough and Berkshire Downs

To create a simple catastrophe model for groundwater flooding in the Marlborough and Berkshire Downs study area, individual models were linked together using OpenMI. We will firstly describe how we make the models compliant and then link the following seven components: *MaBSWeC* model, FloodDepth, EventDatabase, Hazard, Vulnerability, Exposure and Loss. This process is described in more detail below and the components are summarized in Table 1 and as illustrated in Figure 2

To make our models OpenMI compliant the models have to comply with three requirements: the component must implement the *OpenMI.Standard2.IBaseLinkabelComponent* (http://sourceforge.net/p/openmi/code/HEAD/tree/trunk/src/csharp/OpenMI.Standard2/) interface, it must handle specified state-transitions and invocation of certain methods in each state/phase, and finally it must have an associated XML file containing information on each of components, capabilities and availability (OATC 2010). Each component/model (OATC 2010) must be structured so that: its initialization is separated from its computation, it can receive run time controls from an external entity, and it can provide values of the modelled quantities and specify the point or extent in time that the values belong to (these values should be in the public domain). The first stage is to make the model engine linkable and this is done by compiling the engine core of the model into a dynamic link library (OATC 2010). The model engine can, when running in an OpenMI environment, perform as separate operations: initialisation (I), run (R) single time steps/simulations and finalize (F) (i.e. IRF) interface. This can require the engine core to be rearranged in some cases however this was not the case in the components used here. The next step was to use the *MyEngineWrapper* (http://www.openmi-life.org/) to implement the *ITimeSpaceLinkableEngine* (http://sourceforge.net/p/openmi/code/HEAD/tree/trunk/src/csharp/OpenMI.Standard2/TimeSpace/ITimeSpaceComponent.cs) interface this allows the component model to run in an OpenMI environment and the *ITimeComponent* interface can then be run. In order for such a model to link to other models and exchange data we have to define and add the input and output items (OATC 2010). For example the groundwater model (*MaBSWeC* model) generates groundwater level data which are inputted automatically into the Flood depth model (FloodDepth). Any data which are exchanged between component models at run-time must be explicitly defined see Table 1; note that the linking process creates the appropriate cross-reference table negating the need to synchronize terminology. Once this is completed we then tested each component to check that it worked correctly, this was done using the NUnit test tool (http://www.NUnit.org). In this example where we are re-using a pre-existing groundwater model, the preparation of the OpenMI composition took around 100 hours. This includes coding the 6 additional components, making all of them OpenMI compliant, and linking the models and other components together (see figure 2).

A basic workflow used for catastrophe modelling is as presented in Figure 1, but there are some differences from what may be considered standard (Grossi 2005). It should be noted however that the contents, definitions, and names of each of the components within a catastrophe workflow are not standardised and therefore do vary (Grossi 2005; Qu 2010). The modifications that have been made in this case are that the event set generation is included in the hazard module (Qu 2010) and that the financial 'loss' module includes computational elements often split between the vulnerability and financial modules. This is primarily because the available non-proprietary (Penning-Rowsell et al. 2010) vulnerability curves are given in the form 'pounds per house', implicitly combining vulnerability and loss. This highlights the versatility of OpenMI compositions, allowing the user to respond to the available data to implement compositions.

The goal of the hazard module is to produce hazard maps of maximum flood depths. In order to produce these maps the following components need to be tied together: the *MaBSWeC* groundwater model (generates a model of the groundwater system and therefore the groundwater levels at any point in time), FloodDepth (creates maps of flooding and depth), EventDatabase (identifies flood events) and hazard (generates the hazard maps). So in detail the hazard module is constructed based upon a pre-existing groundwater model '*MaBSWeC* Model' which is based on two models: a recharge models built using ZOODRM (Mansour and Hughes 2004) and a groundwater flow model ZOOMQ3D (Jackson and Spink 2004). ZOODRM and ZOOMQ3D were used to build the recharge and groundwater flow models that were combined into the '*MaBSWeC* Model' for the study area. Recharge is water entering the groundwater system; it descends through the soil, then through the underlying unsaturated zone, until it arrives at the top of the saturated zone, the 'water table'. Groundwater flow is water flowing in the saturated zone, from areas of high hydraulic head to low ones. Where it meets the land surface, it discharges. In the UK the significant discharges are rivers, springs and points at which water is abstracted for domestic and industrial supply purposes. The models and the data used to drive them are described in more detail below.

The groundwater recharge model used is ZOODRM, driven by 33 years of daily distributed rainfall (1971-2003) from Centre for Ecology & Hydrology (CEH) and potential evapotranspiration datasets provided by Met Office. ZOODRM calculates surface runoff, routing water based on a 50 m resolution Digital Elevation Model (DEM; Morris and Flavin 1990), and applies the soil moisture deficit (SMD) method (Penman 1948; Grindley 1967) to calculate the actual evaporation, changes in soil moisture and groundwater recharge. A daily time step is used to produce the lowest practical error in the soil moisture balance calculation (see Howard and Lloyd, 1979). The balance between daily rainfall, evapotranspiration, surface runoff and potential recharge across the area are simulated, using information on the spatial variation in the DEM and of land use, geology, rainfall and potential evapotranspiration.

The regional groundwater flow model used in this study was developed using ZOOMQ3D, a quasi-3D finite-difference groundwater flow model. It simulates transient fluctuations in groundwater head, river baseflow, and spring discharge along a chalk scarp slope. The rivers are simulated using an interconnected river network that exchanges water with the underlying aquifer according to a Darcian type flux equation. Details are given in previous applications of ZOOMQ3D (Hughes et al. 2008; Campbell et al. 2010; Guardiola-Albert and Jackson 2011, Mansour et al. 2011). The model contains three laterally extensive layers to represent the vertical variations in the hydraulic properties of the chalk and river valley gravels based on geological models of the lithostratigraphy within the wider London Basin. The groundwater model was calibrated by comparing the modelled results with groundwater heads at 207 observation boreholes and river baseflow at 20 gauging stations (Jackson et al. 2011).

Groundwater heads across the area are computed at daily intervals in the 'MaBSWeC model' component (Fig. 2). The 'FloodDepth' component (Fig. 2) compares these to the DEM used consistently in all models (e.g. CEH-DTM; Morris and Flavin, 1990), creating daily maps of flooding and its depth whenever water height breaches the land surface. This assumes that the surface water system is static and does not flow down topographic gradient. Depths are set to zero where surficial clay deposits (Figure 4) are known to act as barriers which rule out groundwater flood events in those areas.

Next, the 'EventDatabase' component identifies flood events, assigning them a number and probability 1/33 (once in 33 years). Groundwater flooding events are defined when the groundwater level produced by the model was within 0.1 m of the ground surface for at least one month. Given the differences in resolution of the groundwater model and the DEM then the groundwater level was averaged for a groundwater model grid node (2 km by 2 km) and to allow for the variation of ground surface then a tolerance of 0.1 m was used. The start and end period of the event was identified from the flood maps produced by the 'FloodDepth' component. In all 33 events were identified, coincidentally the same as the year of the run. As all occurred in 33 years, and were given equal likelihood specifically a 1 in 33 event probability. The final component of the hazard module is 'Hazard', which creates hazard maps of the maximum flood depths attained during each event. This intensity measure drives flood losses (e.g. Penning-Rowsell et al. 2010).

The 'Loss' component combines exposure and vulnerability information with hazard maps to estimate losses for each event in the database. Exposure has been simplified by assuming that urban areas (Figure 3) have constant housing density (100 houses per km^2), with no exposure outside. Vulnerability uses a residential average for all exposure. Losses for all properties affected by each event are firstly summed to get an 'event loss table' of losses per event, and then OEP curves (e.g. Grossi 2005) are generated. Secondary uncertainty, the uncertainty in losses given that an event has occurred, is not considered. Table 1 details the components and data exchanged between them.

Table 1: *Datasets exchanged by the OpenMI compatible components in the catastrophe model composition. See Gregerson et al., (2005) and Moore and Tindall (2005) for more information on how OpenMI exchanges data.*

Component	Input data	Output data	purpose
MaBSWeC model	• File containing a recharge scenario: gridded for each daily time step. Derived from rainfall, potential evaporation, land-use, topography data. • Files of boundary conditions: Specifically, locations of rivers and springs, and location and rates of groundwater abstraction. • File of hydraulic parameters (hydraulic conductivity, storage coefficients).	• Grid (i.e. map) of groundwater head at each time step.	Simulates the groundwater part of the hydrolgeological cycle. Generates groundwater level information
FloodDepth	• Gridded groundwater heads for each time step. • DEM (Digital Elevation Model) CEH-DTM (Morris and Flavin,1990).	• Distributed depth of groundwater flooding in X, Y, Z format.	Produces maps of where groundwater breeches the land surface
EventDatabase	• Daily distributed flood depth of groundwater flooding in X, Y, Z format. • Lower and upper limits of the range used for calculating the average groundwater flooding depth across the area. Groundwater model calibration is imperfect, so limits are necessary to screen out anomalous values. • Threshold value of average groundwater height exceeded during flooding events.	For each flood event: • Event number • Start time • End time • The distributed depth of groundwater flooding in X, Y, Z format for each day within the event	Identifies flood events and assigns them a probability
Hazard	For each flood event • Event number • Start time	For each event • Event number • Hazard intensity maps	Creates hazard maps of

	• End time • Flood depth maps for each day within the flood in X, Y, Z format.	of maximum flood depth attained during the event	maximum flood depths for each event
Vulnerability	• File of vulnerability curves.	• flood damage costs	Assesses the vulnerability of the assets exposed and damage costs
Exposure	• File containing exposure data.	• Exposure information in X, Y, format	The distribution of assets
Loss	• Hazard intensity maps of maximum groundwater flooding depth for each numbered event • flood damage costs; • Exposure information in X, Y, format	• OEP curves	Combines the hazard information with the vulnerability and exposure to generate losses per event and OEP curves

b. Model Evaluation

Catastrophe models are used in decision-making and as such it is essential that we establish our confidence in the output of such models to justify their continuing use while recognising their limitations (Bennett et al 2013). In a linked modelled system the models must be validated not just as single standalone models but also when they are linked together, to check that, when executed as a collective model, the results are still feasible. This is a particular issue when using simulated data from one model as input data into another model within the linked model chain (Bulatewicz et al. 2010), as any errors within the simulated input data may induce smaller or greater errors in the final model results.

Bennett et al (2013) has suggested a five step evaluation procedure that is beneficial to the modelling process as a whole. This involves assessing the aims, scale and resolution of the model, checking the data to determine that sufficient data is used for calibration and performance, visual analysis of model results, selection of performance criteria and finally refinement of the model (Bennett et al 2013). We have therefore based our evaluation and validation on the steps above assessing each model's performance relative to our understanding of the system and available observational data (Bennett et al 2013, Alexandrov et al 2011 and McIntosh et al 2011). For example, the groundwater model is calibrated and validated by comparing the modelled surface water component (i.e. fast flow in the river) with observation data. The pre-existing ZOOM suite of groundwater models used here has been verified for numerical precision by Jackson and Spink, (2004). Validating the absolute values of the losses of catastrophe models is notoriously difficult. The main commercial models are calibrated to past observed losses, i.e. they are evaluated using claims data held by the insurance industry. In this case, the economic losses generated within the groundwater flooding catastrophe model, have been qualitatively validated against known historical events in the region where losses have been recorded, i.e. the model's performance was compared to available datasets of known financial losses for the region. This showed that the model accurately predicted where the major flood events had occurred and provided an equatable estimate of previous financial loss. A final evaluation of the model's performance can be made by comparing our models results against alternative publically available models; such models currently do not exist. However, as computationally this is a simple model we compared computations carried out in Excel to our model outputs to verify computational accuracy for all components individually throughout the whole linked model and in all cases, model output results matched computations done in Excel.

c. Financial Loss generated from Groundwater Flooding Scenarios

Assumptions used within catastrophe models can make huge differences to the modelled results (Grossi 2005; AIR 2012; Willis Re 2007). However, it is common for most users not to understand or know all the assumptions that have been made. To get around this problem it is considered good practice within the insurance industry to use a variety of models from several vendors, so that an holistic 'multi-model' view of risk is developed (GC 2011; ABI 2011). In this section, we will look at the impact on model results of changing the scenarios used within the groundwater flooding catastrophe model presented above. By using an open framework such as OpenMI to develop the catastrophe model, it would also be possible for whole modules to be freely exchanged and swapped in and out of the composition. In this example we will focus on changing components: different instances of the groundwater model and different vulnerability models.

The *MaBSWeC* groundwater model component is dependent upon rainfall scenarios to drive groundwater recharge; the baseline model uses observed rainfall values (Jackson et al. 2011), the alternative models for high [R_H] and low [R_L] recharge are achieved by scaling rainfall by ±20%. Thus, effectively 3 different groundwater scenario models have been created based upon different climatic assumptions which can be swopped in an out of the linked groundwater catastrophe model. A range of ±20% is chosen since this is typical for a preliminary sensitivity analysis (Sterman 2000) and has been used in assessments of the hydraulic consequences of climate change (e.g. Gleick 1987). We know that in the UK between, 1961 to 2006 there has been a percentage increase in rainfall in the winter in some parts of the SE of up to 20-40% and a corresponding decrease in the summer of between 10-20% (Maraun et al 2008) therefore a value of ±20% provides us with a valid scenario to work from. Hydraulic conductivity [K] was also varied by ±20%, giving scenarios [K_L] and [K_H] (Sterman 2000). This value was identified as being reasonable from the initial calibration of the model (Jackson et al., 2011). The changes in hydraulic conductivity were implemented by changing K within the *MaBSWeC* [B] model, demonstrating that it is also possible to change parameters within model components.

Vulnerability models can also be interchanged. Here, alternative datasets are curves of low [V_L] and high [V_H] property vulnerability, but each could as easily be different vendor databases. The curves are selected from the Penning-Rowsell et al., (2010) to reflect the ranges of houses stock found within the study area giving a known average and a worst and best case scenario. Two types of housing are chosen: Terrace housing and Bungalows. Again, a different component is developed for each one and swapped into and out of the composition.

By choosing to vary recharge and hydraulic conductivity we can develop five different instances of the groundwater flow model (*MaBSWeC* model) and these can be combined with two vulnerability components. This results in seven different components which can be readily interchanged within the composition. This approach has been used to undertake a sensitivity analysis which combines parameter uncertainty (recharge derived from rainfall and hydraulic conductivity) combined with type of housing. Whilst it could be argued that parametric uncertainty can be dealt with in a conventional modelling system, this is a proof of concept and the different components could easily be groundwater models that exhibit fundamental differences (i.e. finite difference vs finite element). The important outcome is that the composition can be re-run to generate the loss information as discussed below.

The insurance industry standard representations of likely loss information are expressed as annual average loss (AAL) and occurrence exceedance probability (OEP) curves. Grossi et al. (2005) details their calculation. Figure 6 presents the baseline [B] OEP curve for groundwater flooding in the study area. Expected losses are in the order of £3.8 million for the largest event in the time-series, a roughly 33yr OEP loss. It should be noted, however, that OEP losses above 10-15 years contain significant uncertainty due to the small number of events defining the curve above this point. In a more formal study, a longer input time-series, perhaps created by a climate model, would reduce the epistemic uncertainty here and allow rarer events to be considered.

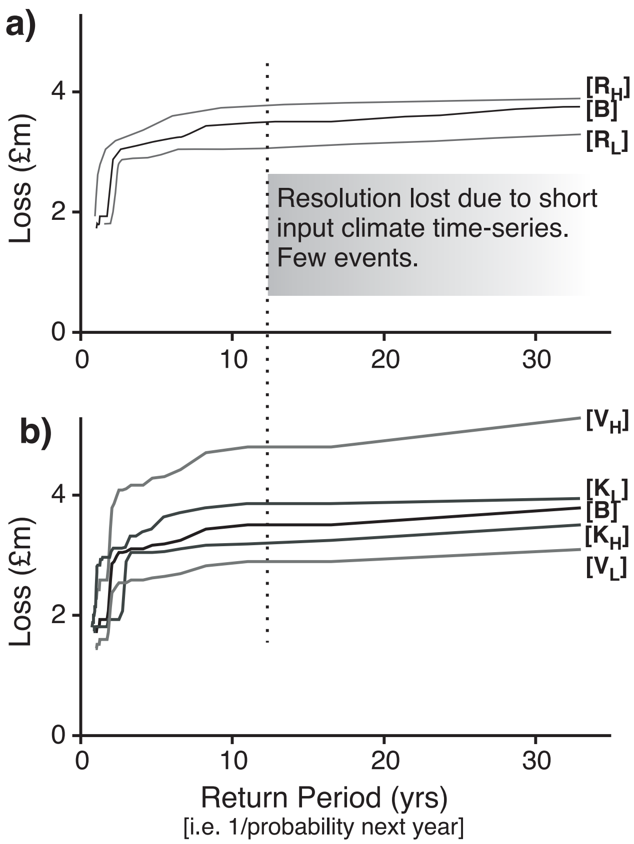

Figure 4: *Occurrence Exceedance Probability (OEP) curves. a) Baseline model [B] is black line, and dark grey lines are for high [R_H] and low [R_L] recharge scenarios, with shading representing a plausible range. b) Baseline as a), dark grey are hydraulic conductivity scenarios [K_L] and [K_H], and light grey are vulnerability datasets [V_H] and [V_L] (Figure 4). Loss at a probability of 0.05 next year is referred to as 'a 20yr OEP loss'.*

Table 2: *Analysis of catastrophe model outputs as assessed by changes within the composition (Figure 2). Expressed as percentage change from baseline scenario. Scenarios denoted in text using letter (B, V, R, K) and a subscript where L is Low, H is High, e.g. V_L. 20 yr OEP values calculated by linear interpolation between data, i.e. as plotted on Figure 4.*

Scenarios			**Output**			**% Change**		
			Events	**20 Year OEP (£m)**	**AAL (£m)**	**Event**	**20 Year OEP**	**AAL**
Baseline (B)	-		33	3.57	2.54	-	-	-
Vulnerability Curves (V)	Terrace (L)	-	33	2.94	2.11	0	-17.50	-16.94
	Bungalow (H)	-	33	4.91	3.42	0	37.65	34.60
Recharge (R)	L	-20%	23	3.16	1.76	-30.30	-11.42	-30.52
	H	+20%	41	3.79	3.58	24.24	6.29	41.18
Hydraulic Conductivity (K)	L	-20%	42	3.81	3.54	27.27	6.77	39.39
	H	+20%	40	3.31	2.66	21.21	-7.22	4.88

On average, one event per year and £2.5M of damages are expected, with worst cases being above £3.6M. Therefore, attritional losses (i.e. losses from high frequency, low severity events) appear to dominate over discrete, devastating events but this in all likelihood reflects the limited time-series and spatial region considered. Tail-end (i.e. high impact, low probability events) groundwater losses will probably be driven by higher return period rainfall (recharge) scenarios causing correlated flooding at sites separated by length-scales of up to ~100s of km across the UK; 2000/1 groundwater flooding occurred in Oxford, Berkshire and Brighton (MacDonald et al. 2008). Whilst loss figures from this study are small, UK-flood is typically an important peril region so will materially affect insurers if they occur in compound with other flood types as happened in Oxford in 2001 (MacDonald et al. 2007) perhaps increasing 25yr OEP losses by as much as 5%.

The results of various scnarios on financial losses derived from the groundwater flooding catastrophe model are presented in Figure 6 and Table 2. Each scenario represents variations upon the assumptions incorporated in the model. These scenarios are not intended to form a comprehensive sensitivity analysis, as here we look at the impact of just varying one factor at a time (OAT). While the short comings of using OAT are known from the literature ie that of the assumption of model linearity and not accounting for parameter interactions (Saltelli and Annoni 2010) some preliminary insights can still be gained. For example, varying the property type within the exposure model from the residential average within the UK (Figure 4) to bungalows had the biggest effect on 20yr OEP increases losses by 37% up to a maximum of £4.9M. The converse was true when the property type was changed to terraced houses resulting in a decrease of 17% in 20 year OEP. When the amount of rainfall was changed this increased/decreased the recharge within the groundwater aquifer affected the number of events rather than their severity. When comparing the effects of changing the amounts of recharge on the model results it clearly impacts AAL more than the 20yr OEP suggesting that differing assumptions made within the model will impact the model results in dissimilar ways with some scenarios making an impact only in specific circumstances. Similarly changes in hydraulic conductivity increases the overall number of events and again effects AAL more than OEP but only when the hydraulic conductivity is low.

The model results are sensitive to simplifications used in each model component. Furthermore, for more complex models this sensitivity is likely to increase significantly. In this paper we have used variations in vulnerability, recharge and conductivity to illustrate how components from different providers could be exchanged in and out of the model chain. The added flexibility afforded through the use of OpenMI has allowed for a far greater level of interrogation to be carried out by the user.

vi. Discussion and conclusions

In this paper we have looked at how IEM modelling methods and technologies can be used to develop catastrophe models for the insurance industry. We have discussed at the beginning of this paper that are several advantages to using IEM methodologies such as increased flexibility due to the ability to interchange components, and increased transparency due to the need to fully document and define models and datasets. In this section we will discuss these in more detail.

We have shown that by using IEM model integration methods to develop a catastrophe model for groundwater flooding, the resulting model chain is repeatable and transparency is increased. This is due to the need, in componentised modelling to provide a detailed explanation of what each component does and what is being exchanged, so that each component can be understood by a community of users, not just the individual modellers involved in the development. With Solvency II regulations being implemented in 2014 there will be a need for insurers to understand and take responsibility for all parts of the catastrophe modelling process. This will mean that they will be required to understand the limitations and assumptions of the models that they use, such as the first-order sources of error (Grossi 2005) discussed in section iii and the fact that there are a number of known elements within catastrophe models that are not perfectly modelled such as multi-peril correlation and hazard clustering, see section iii for further details. This will include models from outside vendors i.e. an increased level of transparency will be required between model developers and their user community. If IEM methods are adopted by the insurance industry this will provide one way of ensuring compliance with solvency II legislation as well as ensuring a better understanding of the use of catastrophe models by insurers.

A lack of openness within the insurance industry has restricted, to some extent, its ability to make use of existing models or new scientific developments. By utilising open source model frameworks such as OpenMI, it is possible to lower the entry barrier significantly for individuals wanting to be involved in catastrophe model development. There is always a worry when lowering entry barriers that this would be detrimental to the quality of the product being produced or developed, however the advantages of increasing the number of models and thereby increasing competitiveness within the community, and preventing over-dependence on a few model vendors are likely to push up the management and quality of the models being produced in fact this has already been recognised with the insurance industry backed OASIS loss modelling framework project (oasislmf.org). This gives several advantages to the insurance industry, for example the ability to attract academic developers who might be able to supply the industry with specialist modelling components, thereby providing the catastrophe modelling and insurance community with direct access into the research community (exploitable research in hazard and vulnerability). It can also provide access to a ready source of model components (particularly for hazard modules which take a considerable amount of time to develop) for areas that don't currently have catastrophe models but may have been an area of active academic research; this could be for a number of reasons such as a low level of perceived financial risk or that the resulting models are unaffordable to the user community. IEM could decrease the time that risk managers currently spend working with catastrophe modelling companies to better understand the assumptions used in the models, running various scenarios of losses under different model assumptions and validating the models by generating their own internal models. Access to a large number of open, well documented modelling components would thereby reduce the time spent in validating models and understanding assumptions used. Finally within the industry there are still risk managers who do not use catastrophe models because they are too expensive so by using an open source modelling framework such as described in this paper it would be possible to increase the use of catastrophe models in insurance.

The flexibility of the OpenMI framework makes it a suitable platform to bring together the various components required (e.g. models, functions and data) to generate such a catastrophe model. Data has been freely exchanged within the model framework, and plausible losses have been produced. By utilising an open standard such as OpenMI, all the components can be reused without the need for additional programming and thus can contribute to a common repository of model components for use in the wider community. This could effectively result in lowering the entry barrier to evaluating problems relating to natural hazards using probabilistic event-set based modelling, opening the door to the participation of different stakeholders (e.g. local government) and perhaps considering problems other than the purely financial.

A repository for models would have many benefits, such as enabling users to test model compositions and demonstrate the effects of model component choice on end results. It would therefore have the potential to assist insurers to fulfil their obligations under Solvency II. For example, in most proprietary catastrophe models, it is not currently possible for users to run different future scenarios of their choice in a realistic manner, without going back to the proprietary models owners.

By using OpenMI's SDK and 'Pipistrelle' interface to link components into 'compositions' and run them the structure of data flows between components is made transparent (for more information: fluidearth.net; Harpham et al. In press). As not only do the components have to be defined and documented but the datasets that are exchanged between the components at run-time must also be explicitly defined. By utilising an IEM model structure, it is easy to make substitutions within the model composition or add components to include models incorporating future climate-change scenarios, or even add a surface water flooding model. Modelling companies and insurers work to maintain security of their intellectual property and data; therefore, using a framework which enables parts of or whole models to remain restricted (e.g. shields proprietary data), will be something that will be required from an industry standpoint. It is possible to do this using OpenMI which in the future could be developed to form the basis of a secure, web-based model framework.

Another use of the IEM modelling system is in generating catastrophe models for areas where none exist currently. Flooding in Thailand (August 2012) highlighted the need for flood risk models for SE Asia. Reasons for not having catastrophe models could be due to a lack of exposure or hazard data, a perceived low level of financial risk or the catastrophe model itself could be unaffordable. Catastrophe models are being used to help create risk transfer mechanisms in the developing world (the Review 2008). Probabilistic catastrophe models have been used to estimate the benefits of disaster risk reduction measures for hurricane risk on residential structures on the island St Lucia and earthquake risk on residential structures in Istanbul, Turkey (Michel-Kerjan et al 2013). The ability of low to middle income countries to cope with natural disasters and limit their economic exposure is becoming a priority (Cummins and Mahul 2008, Michel-Kerjan et al 2013) as when a natural hazard hits countries with limited financial resilience often they will seek support from the international donor community (Cumins and Mahul 2008). Although there is extra effort required to make models linkable and a requirement, if each component is to be reusable, to better manage model components, once a linked modular catastrophe model has been constructed, it is in situations as described above when the increased flexibility of an IEM modelling system comes into its own by allowing for the interchange components parts of the model framework as and when new data, models or scientific understanding becomes available allowing for updates almost instantaneously, if required

Finally, advances made in the understanding of hazard, vulnerability and exposure will bring considerable societal as well as economic benefits. This will translate not only in a reduction in financial losses incurred, but also in lives saved. We will need to develop a better understanding of where our vulnerabilities lie, so that we can adapt, monitor and mitigate against major natural hazard events. It is crucial that all relevant information related to the distribution and severity of natural hazards and a region's vulnerability to particular natural hazards are presented in an accessible, reliable and understandable form so that those that need it are able to make use of the information.

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viii. References

Ahrends, H., Mast, M, Rogers, C., and Kunstmann, H. 2008. Coupled hydrological-economic modelling for optimised irrigated cultivation in a semi-arid catchment of West Africa. Environmental Modelling and Software, 23 (4) 385-395

Argent, R. M., Voinov, A., Maxwell, T., Cuddy, S. M., Rahman, J. M., Seaton, S., Vertessy, R. A., and Braddock, R. D., 2006. "Comparing modelling frameworks – A workshop approach." Environmental Modelling & Software, 21(7), 895-910.

Adams, B., Bloomfield, J., Gallagher, A., Jackson, C., Rutter H., Williams, A., 2008. FLOOD 1 Final Report. Open report OR/08/055, British Geological Survey, Keyworth, Nottingham, UK.

AIR, 2002. Ten years after Andrew: What should we be preparing for now? AIR Special Report, document HASR_0208.

AIR, 2011. Understanding earthquake risk in Japan following the Tohoku-Oki Earthquake of March 11,2011.http://www.air-worldwide.com/publications/white-papers/documents/understanding-earthquake-risk-in-japan-following-the-tohoku-oki-earthquake-of-march-11,-2011/ [last access 07/03/2012]

Al-Sefrey S. and Sen Z. 2006. Groundwater rise problem and risk evaluation in major cities of arid lands – Jeddah case in Kingdom of Saudi Arabia. Water Resource management 20 (1): 314 - 324

Association of British Insurers (ABI), 2011. Industry good practice for catastrophe modelling: A guide to managing catastrophe models as a part of an internal model under Solvency II. http://www.abi.org.uk/Publications/59999.pdf [last access 07/03/2012]

Avouac, J. P. 2011. The lessons of Tohoku-Oki. Nature, 475, 300-301

Babendreier, J.E., Castleton, K.J., 2005. Investigating uncertainty and sensitivity in integrated, multimedia environmental models: tools for FRAMES-3MRA. Environmental Modelling & Software 20 (8), 1043e1055.

Banks E. 2006. Catastrophic risk: Analysis and management. Wiley Finance.

Beck, M.B. 2009. Grand Challenges of the future for Environmental modelling. NSF White Paper.

Braat, L. C. And Lierop, W.F.J. 1987. Integrated economic-ecological modelling. In Braat, L. C. And Lierop, W.F.J. (Eds) Integrated economic-ecological modelling. Amsterdam, North-Holland.

Binnie, Black & Veatch, 2001. Feasibility Study into the use of Flood Warning Sirens in Lewes, July 2001. Report for the Environment Agency.

Brouwer, R. and Hofkes, M. 2008. Integrated Hydro-economic modelling: Approaches, Key issues and future research directions. Ecological Economic, 66: 16-22.

Bulatewicz, T., Yang, X., Peterson, J. M., Staggenborg, S. Welch, S. M. and Steward, D. R. 2010. Accessible integration of agriculture, groundwater, and economic models using the Open Modelling Interface (OpenMI): methodology and initial results. Hydrology and Earth System Sciences, 14, 521-534.

Burt, O.R., 1964. Optimal resource use over time with an application to groundwater. Management Science 11, 80–93.

Campbell, S. D. G., Merritt, J. E.,O Dochartaigh, B. E., Mansour, M. M., Hughes, A. G., Fordyce, F. M., Entwisle, D. C., Monaghan, A. A., Loughlin, S. C., 2010. 3D geological models and their hydrogeological applications : supporting urban development: a case study in Glasgow-Clyde, UK. Zeitschrift der Deutschen Gesellschaft fur Geowissenschaften, 161(2), 251-262.

Chavez-Lopez, G and Zolfaghari M. 2010. Natural Catastrophe loss modelling: the value of knowing how little you know. 14th European Conference on Earthquake Engineering. Orhrid, Republic of Macedonia, 30th August to 3rd September 2010

Cobby, D., Morris, S., Parkes, A and Robinson, V. 2009. Groundwater flood risk management: advances towards meeting the re4quirements of the EU floods directive. Journal of Flood Risk Management, 2 (2): 111-119

Cummins, J. D., 2007. Reinsurance for natural and man-made catastrophes in the United States: Current state of the market and regulatory reforms. Risk Management and Insurance Review, 10(2), 179-220.

Cuddy, S. M., Saguantham, P., Letcher, R. A., Croke, B. F. W. and Saifuk, K. 2005. IWRAM DSS – a modelling approach for integrated water resources assessment and management in northern Thailand, in: SIMMOD 05 International Conference on Simulation and Modelling 2005, edited by: Kachitvichyanukul, V., Purintrapiban, U., and Utayopas, P., Nakornpathom, Thailand, 299– 308, Asian Institute of Technology, Bangkok, Thailand.

Dailey, P., Huddleston, M., Brown, S. & Fasking, D., 2009. The Financial Risks of Climate Change: Examining the financial implications of climate change using climate models and insurance catastrophe risk models *in ABI Research Paper No 19*, pp. 108.

David, O., S.L. Markstrom, K.W. Rojas, L.R. Ahuja and I.W. Schneider, 2002. The Object Modelling System. In: L. Ahuja, L. Ma and T. Howell, Editors, Agricultural System Models in Field Research and Technology Transfer, CRC Press, pp. 317–330.

DEFRA 2011. Flooding and insurance: a road map to 2013 and beyond. Department for the environment food and rural affairs. Version 1.5. 15 pp

Draper, A.J. Jenkins, M.W. Kirby, K.W. Lund J.R. and Howitt, R.E. 2003. Economic-engineering optimization for California water management. Journal of Water Resources Planning and Management, 129 (3): 155ning

Eling, M., Schmeiser, H., Schmit, J. T., 2007. The Solveny II process: Overview and critical analysis. Risk Management and Insurance Review, 10(1) 69-85.

EU, 2009. Directive 2009/138/EC of the European parliament and of the council of 25 November 2009 on the taking-up and pursuit of the business of insurance and reinsurance (Solvency II). pp155. Official Journal of the European Union.

Finch J.W., Bradford R.B. & Hudson J.A. 2004. The spatial distribution of Groundwater flooding in a chalk catchment in southern England. Hydrolog Processes 2004, 18, 959–971.

Fluid Earth, 2011. http://fluidearth.net/ [last access 15/12/2011]

Gijsbers, P.J.A., Moore, R.V. and Tindall, C.I. 2002. Towards OMI, an Open Modelling Interface and Environment to harmonise European developments in water related simulation software, Hydroinformatics, 2002. Fifth International Conference on Hydroinformatics: Cardiff, UK, IAHR, p. 7pp.

Green C, Wilson T, Masterson T and Boothby N. 2006. An assessment of the additional flood losses associated with groundwater flooding: a report to Hampshire county council and Winchester city council. Food Hazard Research Centre. Middlesex University. 52pp

Gregersen, J.B., Gijsbers, P.J.A., Westen, S.J.P, and Blind, M., (2005). OpenMI: The Essential Concepts and their Implications for Legacy Software. Advances in Geosciences, 4, 37-44, 2005.

Grindley J., 1967. The estimation of soil moisture deficits. Meterol. Mag., 96 (1137), 97-108.

Grossi, P., Kunreuther, H., Windeler, D., 2005. An introduction to catastrophe models and insurance p23-42 in Grossi, P., and Kunreuther, H. (Eds) Catastrophe modelling: A new approach to risk management. Springer, New York. ISBN 0 387 24105 1.

Grossi, P., and Kunreuther, H. (2005) Catastrophe modelling: A new approach to risk management. Springer, New York. ISBN 0 387 24105 1.

Guardiola-Albert, C. & Jackson, C.R., 2011. Potential Impacts of Climate Change on Groundwater Supplies to the Doñana Wetland, Spain. Wetlands, 31 (5), 907-920, 10.1007/s13157-011-0205-4.

Guy Carpenter (GC), 2011. Managing catastrophe model uncertainty: Issues and challenges. http://guycarp.com/portal/extranet/insights/reportsPDF/2011/Managing%20Catastrophe%20Model%20Uncertainty.pdf?vid=1 [last access 07/03/2012]

Hagerty, D.J. and Lippert, K. 1982. Rising groundwater-problem or resource? Ground Water 20(2): 217-223

Haimes Y.Y. 2004. Risk Modelling, Assessment and management. Wiley (2nd Edition)

Harou, J.J., Pulido-Velazquez, M., Rosenberg, D.E., Medellín-Azuara, J., Lund, J.R., and Howitt, R.E., 2009, Hydro-economic models: Concepts, design, applications, and future prospects: Journal of Hydrology, 375: 627-643.

Harpham, Q.K., Cleverley, P., Kelly, D. (in press) The FluidEarth 2 Implementation of OpenMI 2.0, Journal of HydroInformatics.

Howard, K.W.F. and Lloyd, J.W., 1979. The sensitivity of parameters in the Penman evaporation equations and direct recharge balance. Journal of Hydrology, Volume 41, Issues 3–4, Pages 329–344

Hughes A., Vounaki T., Peach D., Ireson A, Jacskon C., Butler A., Bloomfield J., Finch J., and Wheater H. 2011. Flood risk from groundwater: examples from a Chalk catchment in southern England. Jnl Flood Risk Management. Vol. 4 issue 3 143-155

Hughes, A. G.; Mansour, M. M.; Robins, N. S. 2008. Evaluation of distributed recharge in an upland semi-arid karst system: the West Bank Mountain Aquifer, Middle East. Hydrogeology Journal, 16 (5). 845-854. 10.1007/s10040-008-0273-6

Jakeman, A. J. and Letcher, R. A. 2003. Integrated assessment and modelling: features, principles and examples for catchment management, Environmental Modelling and Software, 18(6): 491–501

Jackson, C.R., Bloomfield, J.P., Buckley, D.K., Chambers, D.E., Darling, W.G., Hughes, A.G., Mansour, M.M., Newell, A.J., Peach, D.W., Raines, M.G., 2006. Conceptualisation of groundwater flow in the Chalk aquifer around Gatehampton. British Geological Survey Commissioned Report, CR/06/206C.

Jackson, C.R., Meister, R., Prudhomme, C., 2011. Modelling the effects of climate change and its uncertainty on UK Chalk groundwater resources from an ensemble of global climate model projections. Journal of Hydrology, 399, 12–28.

Jackson, C.R., Spink, A.E.F., 2004. User's manual for the groundwater flow model ZOOMQ3D. British Geological Survey, Internal Report IR/04/140,

Jacobs. (2004). Strategy for Flood and erosion Risk Management: Groundwater Flooding Scoping Study (LDS 23). Jacobs, Reading.

Jonkman, S.N., Bockarjova, M., Kok, M. and Bernardini, P. 2008. Integrated hydrodynamic and economic modelling of flood damage in the Netherlands. Ecological Economics 66, 77-90

Knapen, R., Janssen, S., Roosenschoon, O., Verweij, P., de Winter, W., Uiterwijk, M., and Wien, J.-E., 2013, Evaluating OpenMI as a model integration platform across disciplines: Environmental Modelling & Software, v. 39, p. 274-282.

Koundouri, P. 2004. Current issues in the economics of groundwater resource management
Journal of Economic Surveys 18 (5), 703-740

Kreibich, H. and Thieken A. H. 2008. Assessment of damage caused by high groundwater inundation. Water Resource Research. 44: 1-14 W09409, doi 10.1029/2007WR006621

Laniak, G.F., Olchin, G., Goodall, J., Voinov, A., Hill, M., Glynn, P., Whelan, G., Geller, G., Quinn, N., Blind, M., Peckham, S., Reaney, S., Gaber, N., Kennedy, R., and Hughes, A., 2013, Integrated environmental modelling: A vision and roadmap for the future: Environmental Modelling & Software, v. 39, p. 3-23.

Lay, T., Kanamori, H. 2011. Insights from the great 2011 Japan earthquake. Physics Today, 64(12), 33-39.

Lennartz, S., Livinia, V. N., Bunde, A., Havlin, S. 2008. Long-term memory in earthquakes and the distribution of interoccurrence times. EPL, 81(6), doi:10.1209/0295-5075/81/69001

Macdonald D.M.J, Bloomfield J.P., Hughes A.G., MacDonald, A.M., Adams B., and McKenzie A.A. (2008). Improving the understanding of the risk from groundwater flooding in the UK. Proceedings of FLOODrisk 2008, European Conference on Flood Risk Management, Oxford, UK, 30 September to 2 October 2008.

MacDonald, A.M., Hughes, A.G., Vounaki, T., Graham, M.T., Lilly, A., Mansour, M. and Stephens, C.A. (2008). Groundwater and the Forres (River Findhorn & Pilmuir) flood alleviation schemes. British Geological Survey Commissioned Report CR/08/023.

Macdonald, D.M.J., Hall, R., Carden, D., Dixon, A., Cheetham, M., Cornick, S. and Clegg, M. (2007). Investigating the inter-dependencies between surface and groundwater in the Oxford area to help predict the timing and location of ground-water flooding and to optimise flood mitigation measures. Proceedings of 42nd Defra Flood and Coastal Management Conference.

Mansour M.M., Hughes A.G., 2004. User's manual for the recharge model ZOODRM. British Geological Survey internal report no. CR/04/151N, Wallingford, U.K.

Mansour, M. M., Barkwith, A. and Hughes, A. G. (2011), A simple overland flow calculation method for distributed groundwater recharge models. Hydrological Processes, 25: 3462–3471. doi: 10.1002/hyp.8074

Maraun D, Osborn TJ and Gillett NP (2008) United Kingdom Daily Precipitation Intensity: Improved Early Data, Error Estimates and an Update from 2000 to 2006. International Journal of Climatology, 28(6), 833-842

Mckinney D., Cai X., Rosegrant M.W., Ringer C. and Scott, C. A. 1999. Modelling water resources management at the basin level@: review and future directions. International Water Management Institute, Colombo. (SWIM paper 6, 71pp)

Michel-Kerjan E., Hochrainer-Stigler S., Kunreuther H., Linnerooth-Bayer J., Mechler R., Muir-Wood R., Ranger N., Vaziri P. And Young M. 2013 Catastrophe Risk Models for Evaluating Disaster Risk Reduction Investments in Developing Countries. Risk Analysis 33: 984-999

Moore R., P. Gijsbers, D. Fortune, J. Gergersen and M. Blind, 2005. OpenMI Document Series: Part A Scope for the OpenMI (Version 1.0), HarmonIT

Moore, R. and Hughes, A. 2010. International Summit on Integrated Environmental Modelling. British Geological Survey Open Report number OR/12/087

Moore, R.V and Tindall,I., (2005). An Overview of the Open Modelling Interface and Environment (the OpenMI). Environmental Science & Policy 8 (2005), 279-286.

Morris, D.G. and Flavin, R.W. 1990. A Digital Terrain Model for Hydrology. Proc 4th Int. Symposium on Spatial Data Handling. Zurich, 1, 250-262.

Munich Re NatCatSERVICE, 2012. Figures accompany press release on Jan 4th 2012 'Review of natural catastrophes in 2011: Earthquakes result in record loss year. http://www.munichre.com/en/media-relations/publications/press-releases/2012/2012-01-04-press-release/index.html [last access 07/03/2012].

Munich Re, 2011. Overall picture of natural catastrophes in 2010 – Very severe earthquakes and many severe weather events. Press release. http://www.munichre.com/en/media-relations/publications/press-releases/2011/2011-01-03-press-release/index.html [last access 13/12/2011].

Munich Re, 2011b. Significant natural catastrophes 1980 – 2011: 10 costliest winter storms in Europe ordered by insured loss. http://www.munichre.com/site/corporate/get/documents_E1385616822/mr/assetpool.shared/Documents/0_Corporate%20Website/6_Media%20Relations/Press%20Dossiers/50th%20anniversary%20storm%20surge%20hamburg/euope-costliest-storm-surges-en.pdf [last access 14/12/2011]

OATC. 2009. OpenMI Association Technical committee (OATC) Configuration Editor Software, available at : htt://sourceforge.net/projects/openmi , 2009.

OATC 2010. OpenMI document Series: Migrating Models for the OpenMI (Version 2.0) available at: https://sites.google.com/a/openmi.org/home/learning-more/OpenMI%2BStandard%2B2%2BMigrating%2BModels.pdf?attredirects=0

O Dochartaigh, B. E.; MacDonald, A. M.; Darling, W. G.; Hughes, A. G.; Li, J. X.; Shi, L. A.. 2010 Determining groundwater degradation from irrigation in desert-marginal Northern China. Hydrogeology Journal, 18 (8). 1939-1952. 10.1007/s10040-010-0644-7.

OpenMI, 2011. http://www.openmi.org/ [last access 15/12/2011]

OpenMI, 2009. The Open-MI life project website http://www.openmi-life.org/, 2009.

Overeem, I., Berlin, M.M., and Syvitski, J.P.M., 2013, Strategies for integrated modelling: The community surface dynamics modelling system example: Environmental Modelling & Software, v. 39, p. 314-321.

Ozawa, S., Nishimura, T., Suito, H., Kobayashi, T., Tobita, M., Imakiire, T. 2011. Coseismic and postseismic slip of the 2011 magnitude-9 Tohoku-Oki earthquake. Nature, 475, 373-377.

Penman H.L., 1948. Natural evaporation from open water, bare soil and grass. Proc. R. Soc. London, Ser. A, 193, 120-145.

Penning-Rowsell E., Viavattene C., Parode J., Chatterton J., Parker D., Morris, J., 2010. The Benefits of Flood and Coastal Risk Management: A Handbook of Assessment Techniques-2010 (Multi-Coloured Manual). FHRC, London.

Peter H. Gleick 1987 Regional hydrologic consequences of increases in atmospheric CO2 and other trace gases Climatic Change Volume 10, Number 2 137-160.

Pitt, M., 2008. Learning lessons from the 2007 floods, pp. 505 Cabinet Office.

Qu, Y., Dodov, B., Jain, V., Hautaniemi, T., 2010. An inland flood loss estimation model for Great Britain. BHS Third International Symposium, Managing Consequences of a Changing Global Environment, Newcastle. British Hydrological Society.

Royse, K.R., de Freitas, M., Burgess, W.G., Cosgrove, J., Ghail, R.C., Gibbard, P., King, C., Lawrence, U., Mortimore, R.N., Owen, H., and Skipper, J., 2012, Geology of London, UK: Proceedings of the Geologists' Association, v. 123, p. 22-45.

Royse, K.R., 2011, The handling of hazard data on a national scale : a case study from the British Geological Survey. Surveys in Geophysics, v. 32, p. 753-776.

Rybski, D., Bundle, A., von Storch, H. 2008. Long-term memory in 1000-year simulated temperature records. J. Geophys. Res. 113(D2), art. No. D02106, doi:10.1029/2007JD008568.

Sterman J. D., 2000. Business Dynamics: Systems Thinking and Modelling for a Complex World. New York: McGraw-Hill

Stuart, M., Gooddy, D., Hughes, A. G., Jackson, C. R. 2006 A field and modelling study to determine pesticide occurrence in a public water supply in Northern England. Ground Water Monitoring & Remediation, 26 (4). 128-136. 10.1111/j.1745-6592.2006.00113.x

Sumbler, M.G., 1996. British Regional Geology: London and the Thames Valley. HMSO for the British Geological Survey, London.

Swiss Re, 2007, Natural Catastrophes and Man-Made Disasters In 2006: Low Insured Losses, Sigma No. 2/2007. Zurich, Switzerland.

Towers Perrin, 2005. Hurricane Katrina: Analysis of the impact on the insurance industry. White paper.

https://www.towersperrin.com/tillinghast/publications/reports/Hurricane_Katrina/katrina.pdf

Vitolo, R., Stephenson, D. B., Cook, I., Mitchell-Wallace, K., 2009. Serial Clustering of Intense European Windstorms Meterologische Zeitschrift 18(4), 411-424.

Volk, M., Hirschfeld, J., Dehnhardt, A., Schmidt, G., Bohn, C., Liersch, S., and Gassman, P.W., 2008, Integrated ecological-economic modelling of water pollution abatement management options in the Upper Ems River Basin: Ecological Economics, v. 66, p. 66-76.

Warner, J.C., Perlin, N., Skyllingstad, E.D., 2008. Using the Model Coupling Toolkit to couple earth system models. Environmental Modelling & Software 23, (10-11), 1240-1249.

Willis, 2007. Windstrom Kyrill, 18 January 2007. Willis Analytics, London, UK. http://www.willisresearchnetwork.com/Lists/Publications/Attachments/31/Willis%20Windstorm%20Kyrill%20Report%2001%20Feb%202007.pdf

Willis, 2012. 2012 property insurance market update – Jan 2012. http://www.willis.com/Documents/Publications/Services/Property/2012/Property_Market_Update_2012.pdf [last access 07/03/2012].

Woo, G. 1999 The Mathematics of Natural Catastrophes. Imperial College Press. pp292. ISBN 1-86094-182-6.

Zolfaghari M. R. (2009) Application of catastrophe loss modelling to promote property insurance in developing countries. *Disasters.* 34:2, 524-541.

Figure Captions

Figure 1: One possible conceptual framework of a traditional component based catastrophe model. Rectangles are modules, ovals are inputs and arrows indicate the flow of information.

Figure 2: Annotated screen shot of a Pipistrelle composition for the Groundwater Flooding Catastrophe. Yellow boxes are the 7 components of the 'baseline' [B] model, comprising best-estimates of recharge [R], hydraulic conductivity [K], and vulnerability [V]. Arrows indicate data flow detailed in Table 1. Grey text and arrows, added to the screen shot, indicate alternative components that could be swapped into the composition by simply changing the link (arrow).

Figure 3: (A) Map of the study area, located by red rectangle in the inset. Red outline depicts the limits of the Marlborough and Berkshire Downs and South-West Chilterns (MaBSWeC) groundwater model used (adapted from Jackson et al 2011). **(B)** Geological sketch map of the London Basin. Based on Figure 1 of Sumbler (1996). Note that groundwater flooding is not an issue where clay overlies Chalk.

Figure 4: Occurrence Exceedance Probability (OEP) curves. a) Baseline model [B] is black line, and dark grey lines are for high [R_H] and low [R_L] recharge scenarios b) Baseline as a), dark grey are hydraulic conductivity scenarios [K_L] and [K_H], and light grey are vulnerability datasets [V_H] and [V_L]. Loss at a probability of 0.05 next year is referred to as 'a 20yr OEP loss'.

Table Captions

Table 2: Datasets exchanged by the OpenMI compatible components in the catastrophe model composition. See Gregerson et al. (2005) and Moore and Tindall (2005) for more information on how OpenMI exchanges data.

Table 2: Analysis of catastrophe model outputs as assessed by changes within the composition (Figure 2). Expressed as percentage change from baseline scenario. Scenarios denoted in text using letter (B, V, R, K) and a subscript where L is Low, H is High, e.g. V_L. 20 yr OEP values calculated by linear interpolation between data, i.e. as plotted on Figure 6.