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source   pathway   receptor

The risk of widespread flooding – Capturing spatial patterns in flood risk from rivers and coasts

Flood and Coastal Erosion Risk Management Research and Development Programme

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It's our job to make sure that air, land and water are looked after by everyone in today's society, so that tomorrow's generations inherit a cleaner, healthier world.

Our work includes tackling flooding and pollution incidents, reducing industry's impacts on the environment, cleaning up rivers, coastal waters and contaminated land, and improving wildlife habitats.

This report is the result of research commissioned by the Environment Agency's Evidence Directorate and funded by the joint Environment Agency/Defra Flood and Coastal Erosion Risk Management Research and Development Programme.

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Keywords:
Spatial dependence, extremes, flood risk

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Project Number:
SC060088

Prodcut code:
SCHO1011BUBS-E-E

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- **Delivering information, advice, tools and techniques**, by making appropriate products available.

Miranda Kavanagh

Director of Evidence

Executive summary

Overview

This is the final proof of concept report for the Environment Agency R&D project SC060088 'Spatial coherence of flood risk', which is a scoping study to identify, develop and trial methods for determining the likelihood of spatially extensive floods from single or multiple sources.

The project is about how we can estimate the risk (likelihood, severity and consequences) of flooding in more than one location. We need to be able understand this spatial aspect of risk is order to properly estimate the probability of catastrophic emergencies and of economic losses at a regional and national scale.

The overall objective of this project is to develop and test methodologies to assess the risk of widespread flooding, incorporating both the analysis of sources of flooding and the consequences at different spatial scales, up to regional or national level.

The first objective is to review and develop methods for analysing and modelling dependence between multiple variables that affect flood risk, in particular the spatial dependence of extreme river flow or level and sea levels.

The second objective is to show how the spatial and between-variable dependence can be extended to include risk pathways (such as defence failure) and receptors of risk to add a spatial dimension to probabilistic flood risk assessment methods that the Environment Agency is using or developing elsewhere.

Project reports

This report sets out proof of concept results that were presented to an invited audience of Environment Agency and external stakeholders on 18 March 2009. The workshop presented material produced by the research contractor JBA Consulting using methods they have developed for flood risk modelling in conjunction with analysis carried out as part of this project for the Environment Agency.

A companion technical methodology report contains a detailed description of the methods used in creating these results and further discussion of the assumptions and limitations of the methodology. It also sets out a programme of work for implementation of the methods.

Proof of concept

The proof of concept study has shown how the methods applied in this project can generate regionally aggregated, probabilistic estimates of the risk of flooding, including the full distribution function (consequence vs. probability curve), illustrated with examples showing:

- The aggregated economic damage over all rivers in a region.

- The aggregated number of properties at risk in five separate areas along the coast.

In addition, the methods have been used to study the collective risk of wide scale inland river flooding and coastal flood.

Contents

Figures

1 Background

In recent years Defra (Department for Environment, Food and Rural Affairs) and the Environment Agency have led the way in promoting risk-based policies and practices for flood management through Making Space for Water, the Flood Foresight project and changes to policy and process. Many of these changes have been supported by projects in the R&D programme.

Historically, the methods used for flood risk management had limited capability to deal with the spatial dependence structure in the sources of risk since they focused on single points or local systems rather than on a wider area. In other words, it has not been possible to answer questions such as "what is the chance that many different locations will be affected by severe flooding?" or "what is the chance that widespread river flooding will coincide with high tides and storm surge?"

This limits our ability to manage flood risk. We do not have the tools to identify and assess the range of possible flood events that we must manage, and we do not have reliable tools to assess the national risk 'profile' to describe the relative likelihoods of different scales of flood event.

1.1 Overall objectives

This project is a scoping study to identify, develop and trial a method for assessing flood risk when aggregated over large spatial scales.

The overall objective of this project is therefore to develop and test methodologies to assess the risk of widespread flooding, incorporating both the analysis of sources of flooding and the consequences at different spatial scales, up to regional or national level.

The first objective is to review and develop methods for analysing and modelling dependence between multiple variables that affect flood risk, in particular the spatial dependence of extreme river flow or level and sea levels, so as to assess the likelihood of spatially extensive floods from single or multiple sources.

The second objective is to show how the spatial and between-variable dependence can be extended to include risk pathways (such as defence failure) and receptors of risk to add a spatial dimension to probabilistic flood risk assessment methods such as the Risk Assessment for Strategic Planning (RASP) approach that underlies the Environment Agency's National Flood Risk Assessment (NaFRA).

1.2 Approach

Meeting the objectives of this project requires understanding and quantification of the probability and consequences of flooding at different spatial scales. A suitable statistical approach is needed to meet these aims.

After a review of requirements and possible approaches, the project has built upon a statistical method developed by Heffernan and Tawn (2004) and first applied to river flow and rainfall data by Keef (2007). The method provides a very flexible model for the joint probability of large sets of interrelated variables, including the probability of extreme values being experienced in more than one of those variables. This makes it

well suited to model the physical sources of flooding, such as high river flows and sea levels.

The work in this project has shown how the existing statistical model can be linked conceptually into an integrated flood risk model, based on the Source – Pathway – Receptor approach adopted by the Environment Agency. This provides a conceptual framework for adding a spatial dimension to assessments of flood risk that consider defence system performance ('pathways') and economic or other consequences of flooding ('receptors'), which has the potential to enhance our assessment of flood risk regionally and nationally. The scope for realising these benefits has been demonstrated in three 'Proof of Concept' demonstrations, which are presented in this report.

1.3   Scope

The scope of the project is to examine fluvial and coastal (tide and surge) flooding. Urban 'surface water' flooding and groundwater flooding are excluded.

Rainfall is not included in this study because the primary requirement is to model the statistics of high river flows and observations of river flows are a much more direct measure. It is important to note that the modelling approach is not a time series model for river flows but instead captures the statistics of observed high flow events. Hence it has not been necessary to model antecedent conditions because river flow data in effect gather together temporal and spatial variations in rainfall.

However, the statistical methodology that has been used is based on a general approach to representing the joint probability of multiple variables. It should therefore be suitable, in principle, for extension to include rainfall information or other sources of flooding.

1.4   Contents of this proof of concept report

This report summarises the proof of concept results that were presented at a stakeholder workshop on 18 March 2009. The report is structured as follows:

Section 1	Current introduction	
Section 2	Proof of concept approach	Summary of how proof of concept has been established.
Section 3	Fluvial flood risk	Proof of concept results for North East region.
Section 4	Coastal flood risk	Proof of concept results for five coastal locations on the north east coast.
Section 5	Joint inland and coastal flood risk	Initial findings from joint analysis of regional river flood risk and coastal flooding.
Section 6	Integration with NaFRA	Commentary on proposed approach to integrate spatial analysis into NaFRA.
Section 7	Stakeholder workshop	Report and discussion of a workshop held to seek feedback from interested stakeholders.
Section 8	Proof of concept conclusions	

1.5 Contents of the Technical Methodology Report

This report should be read in conjunction with the accompanying methodology report. The methodology report outlines a generic conceptual model for flood risk analysis that supports aggregation of risk calculations at multiple spatial scales and inclusion of existing probabilistic methods for representing flood defence system performance and economic damage assessments. The conceptual model conforms to the Source – Pathway – Receptor approach. The methodology report sets out in detail the statistical modelling approaches that have been adopted for the project and the rationale for the choice of method. The contents of the methodology report are as follows:

Section 1	Background	
Section 2	Conceptual model	Overview of the generic conceptual model adopted for the project.
Section 3	Flood risk methods review	Review of existing methods and tools for flood risk analysis.
Section 4	Statistical methods review	Review of the statistical features required for a spatial flood risk model and relevant statistical methods.
Section 5	Statistical model	The model adopted for this study.
Section 6	Simulation method	How the statistical model can be applied.
Section 7	Integration of pathway and receptor models	The proposed method for linking the spatial model to existing tools to represent flood defence systems and consequences of flooding.
Section 8	Uncertainty and confidence	Commentary on sources of uncertainty and quantification of confidence in the results.
Section 9	Methodology conclusions	

1.6 Project management

1.6.1 R&D programme

The project was managed through the 'Modelling and Risk' (MAR) theme of the Defra/Environment Agency joint Flood and Coastal Erosion Risk Management (FCERM) research programme. The MAR theme leader is Suresh Surendan.

The Environment Agency's project manager for this contract was Stefan Laeger. Ian Meadowcroft was the Environment Agency's project executive.

1.6.2 Research contractors

The research was carried out by a consortium of JBA Consulting (Dr Rob Lamb, Dr Caroline Keef, Paul Dunning, Dr Crispian Batstone) and Professor Jonathan Tawn. The contractor's project manager was Rob Lamb of JBA Consulting.

1.7 Scoping study programme and outputs

The project began in January 2008 and completed in Autumn 2009. The main outputs of the project are listed below.

- Environment Agency R&D Summary.

- Proof of Concept Summary Report (this document).

- Methodology Report.

- Paper at FCM>08 conference, Manchester (July 2008).

- Paper at 'UK Extremes' statistics conference, Lancaster (September 2008).

- Paper at FloodRisk2008 conference, Oxford (October 2008).

1.8 Strategic programme

This scoping study is phase one of a potential longer term initiative to support a more integrated approach to flood risk management and will be particularly relevant to national policy and investment, catchment, coastal and estuary strategies, asset management, flood incident management, development control and mapping process.

Depending on the findings of this study and the prevailing development priorities, a second phase would see the proposed techniques integrated with Flood Risk Management tools such as the National Flood Risk Assessment (NaFRA), and the Modelling and Decision Support Framework (MDSF2).

2 Proof of concept approach

2.1 Demonstration case studies

The three proof of concept demonstration cases that have been identified are:

- Fluvial flooding.

- Coastal flooding.

- Combined fluvial and coastal flooding.

The case study results each demonstrate different types of risk assessment within the same overall conceptual framework, as described below.

Case	**Outcomes**	**Main outputs**
River flooding	Economic analysis of aggregated risk over North East region including extreme and non-extreme events.	Economic risk profile showing relationship between economic loss and annual exceedance probability. Comparison of three models: • Correct, modelled, spatial dependence. • False assumption of complete spatial dependence. • False assumption of independence.
Coastal flooding	Property analysis of aggregated risk between Spurn Head and Newcastle.	Property risk profile showing relationship between numbers of properties flooded and annual exceedance probability. Comparison of three models: • Correct, modelled, spatial dependence. • False assumption of complete spatial dependence. • False assumption of independence.
Combined	Regional analysis of joint probability of severe inland and coastal flood.	Joint distribution of extreme river flows within the region occurring in combination with extreme sea levels.

2.2 Source, pathway, receptor analysis

2.2.1 Overview

The statistical methods used in this project for spatial analysis of risk include a joint distribution model for sources of flooding (river and coastal) and a simulation method for integration of the pathway and receptor components of flood risk.

The proof of concept demonstrations show the results of combining the two pieces to provide a 'risk profile' (that is, a statistical distribution function for the consequences of flooding) for a region.

2.2.2 Source analysis

The source variables (river flows and sea levels) have been modelled using the statistical model described in the accompanying Technical Methodology Report. Further statistical verification tests for the model are shown for the case studies here.

2.2.3 Pathway and receptor (consequence) analysis

The overall approach is modular, in that different choices can be made about how the source, pathway and receptor components of risk are modelled. We have used methods readily available to us at the time of this study to represent the pathways and receptors. These methods are considered technically valid in their own right for broad-scale analysis of flood risk. They include data and methodology already in use by the Environment Agency. They are less detailed in some respects than the RASP processes used in NaFRA but can be regarded as conceptually equivalent in terms of demonstrating proof of concept for this project.

For future integration with these existing national Environment Agency tools, the pathway and receptor analysis used here can easily be substituted with data produced using RASP. This is discussed in Section 6.

2.2.4 A note about the data used for proof of concept

In our proof of concept study, we have used substitute data for economic damages or numbers of properties flooded derived from work carried out by JBA Consulting either for the Environment Agency or for internal development. The data sets used to compute these conditional damages are considered valid estimates of broad-scale consequence and are in some respects as detailed as the data used in NaFRA.

However, whilst we have included a probabilistic treatment of defence performance in constructing the conditional damage curves, it is important to be clear that this treatment does not exactly replicate the processes used within RASP. Hence the damages presented for the proof of concept are not directly comparable with NaFRA and have therefore been re-scaled to show relative values rather than being presented on an absolute, monetary scale.

2.3   How can we establish proof of concept?

Proof of concept has been evaluated in terms of:

- Technical outputs:

    o   Characterising spatial dependence in sources of risk.

    o   Incorporating pathways and receptors.

- Feasibility and practical implementation of methods.

- Potential and realised benefits to flood risk management at process and policy levels at national and regional level.

- Potential benefits to emergency planning at national and regional level.

In the technical methodology report we have considered technical demonstration of the methods and how they might be implemented practically (the first two main points above). Demonstration of the methods and identification of benefits for stakeholders are discussed in this report.

3 Case study 1: Regional analysis of risk from river flooding

3.1 Rationale

This example provides demonstration results for river flooding at a regional scale. It builds on existing work for the Environment Agency North East Region to include pathways and receptors and hence to produce a full 'risk profile' for the region.

The key features of this analysis are:

- Demonstration of a regional dependence model for flood flows.

- Demonstration of a simulation approach based on the multivariate joint distribution of river flows in the region.

- Demonstration of spatial mapping of source variables over a region of interest with the mapping consistent with the simulation of the multivariate joint distribution of the source variables at a set of sites in the region.

- Incorporation of a defence 'pathway' component (providing a conceptual link with the RASP approach).

- Analysis of impacts at receptor level (providing a conceptual link with MDSF2).

3.2 Methodology

The methodology is split into two parts, which are (1) the statistical model of the joint distribution of the fluvial flood risk source component (river flow) and (2) a simulation approach to integrate the distribution, optionally including defence pathways, with flood depth and economic damage data to estimate the risk profile for the region.

The joint distribution model for the source component is the conditional exceedance model outlined in the Technical Methodology Report.

The simulation approach to integration follows a generic approach based on stratified sampling to allow efficient use of detailed 2D hydraulic simulations of flood depths already carried out for 19 return period scenarios in work done by JBA Consulting for the North East region of the Environment Agency.

3.3 Data sources

The data used are:

- Fluvial joint distribution and dependence model based on National River Flow Archive (NRFA) daily flow data.

- Flood depth grids produced for the Environment Agency North East region.

- Public domain economic damage curves published in the Multi-Coloured Manual (FHRC, 2005).

- National Properties Database (NPD).

3.4   Outputs

A conditional exceedances model, which had been fitted to NRFA river gauging station data prior to the start of this project, has been used to model the joint distribution of river flows at gauging stations in and around the North East region, taking into account temporal dependence as discussed in the December 2009 interim report.

The river network and gauging stations are shown in Figure 3-1, along with major urban areas.
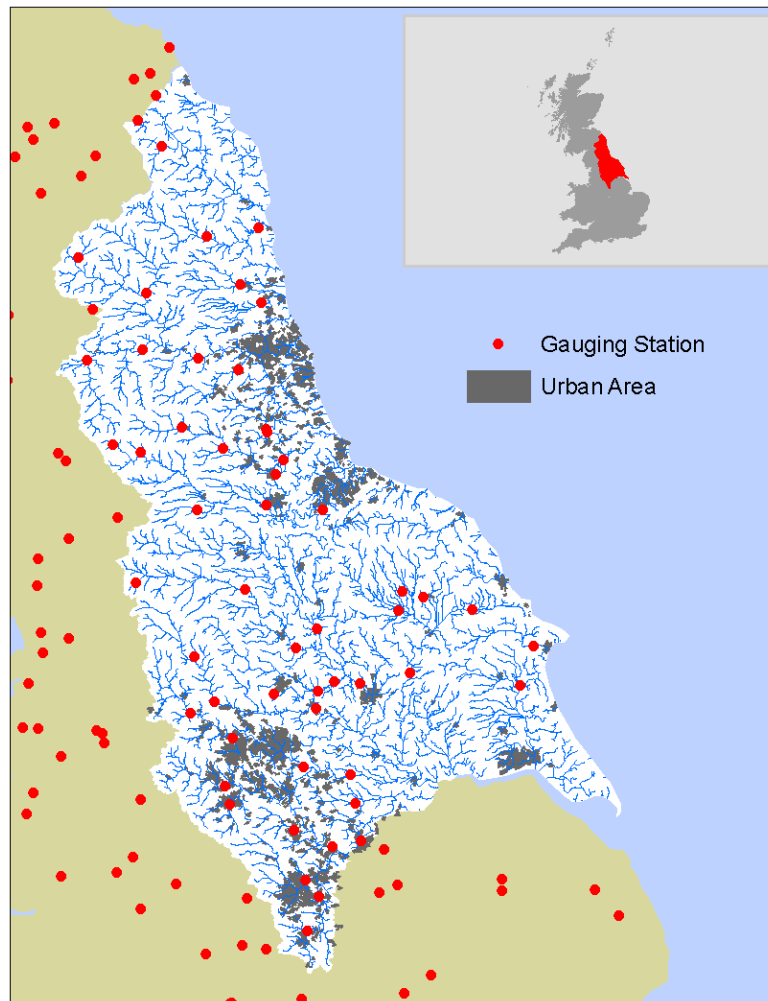
Figure 3-1. River and gauging station network

The conditional exceedances model is used to generate a Monte Carlo simulation of river flow events (on a standardised probability scale) at each gauging site. To capture network routing effects, this represents the maximum flow over a seven-day window. The standardised data are then interpolated between gauges using a distance-weighted, catchment centroid-based method. The same approach can also be applied to real events sampled from the gauged record (for times when at least one gauging station had a large flow).

An example of one such event and its interpolated counterpart is shown in Figure 3-2.
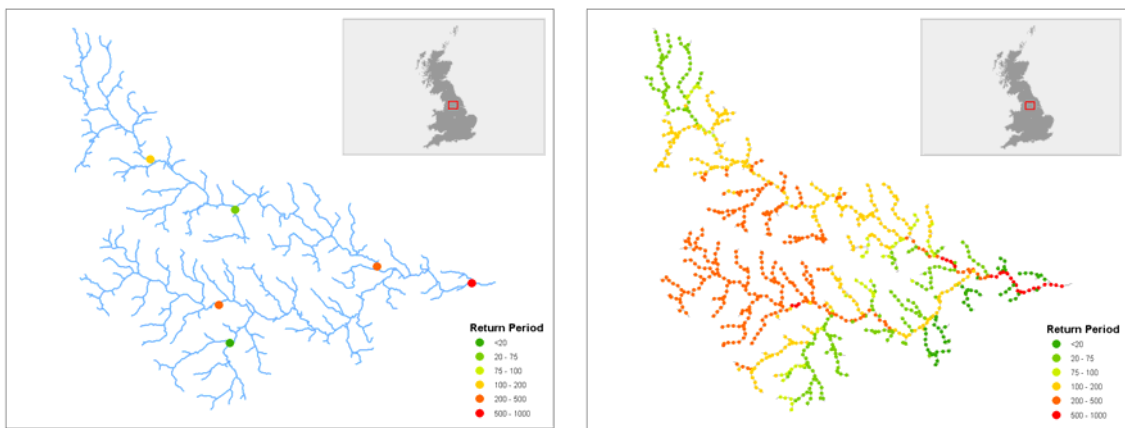
Figure 3-2. Left: Gauging station data for high flow event. Right: Interpolated network values for the same event.

Note that the interpolation is not a physical interpolation of river flows. Rather it is an interpolation of event probability. The validity of the interpolation has been tested using the statistical technique of cross validation, where many samples are generated with one real data value missing, and the samples used to estimate the value expected at the missing point, which can then be compared with the (withheld) real data.

The results of the cross validation should show strong correlation between data generated during the 'leave-one-out' test procedure and the real data that were withheld during the procedure. All but one correlation coefficient is greater than 0.85 and three quarters are greater than 0.9. The median correlation coefficient is 0.92. Examples of the cross validation plots are shown in Figure 3-3.
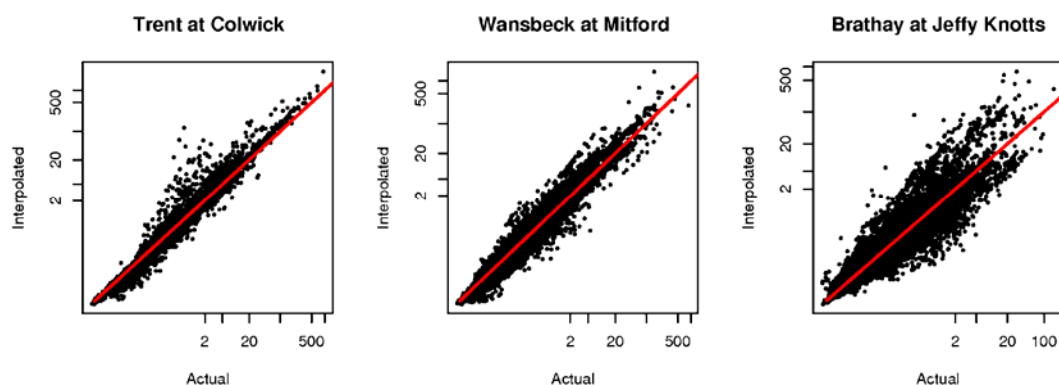
Figure 3-3. Example cross validation plots for river flow data at three gauging station sites (data plotted on return period scale).

A Monte Carlo simulation of 10,000 events at gauging stations was generated. Data were interpolated over the entire river network at 1km spacing for each event. This spacing can easily be changed and can take different values in different parts of the network to provide greatest detail in the most important risk areas, for example.

10   SC060088 Proof of Concept Summary Report

For each simulated event, the river flow probabilities generated as above were associated with properties in the National Properties Database by a nearest neighbour search from each property to the nearest river point. The economic damage per property per event was then estimated using curves giving the expected economic damages per property conditional on the hydraulic load (where 'load' is expressed on a probability scale, rather than a physical scale, for convenience).

The curves giving conditional expected damages were generated by a procedure based on probability-weighted averaging of 19 different flood depth grids produced by JBA Consulting for the Environment Agency as part of a broad scale modelling study for the North East Region. The procedure incorporated fragility curves to describe defence performance and economic damage calculations based on the Multi Coloured Manual (FHRC, 2005). Conditional damage curves were computed for every property. For a particular return period the conditional expected damage is equal to the defended damage times, P(defence holds), plus the undefended damage times, P(defence fails), where P(A) is the probability of a given event 'A' occurring.

The important point to note for proof of concept is that the equivalent quantities (conditional damages) can be produced by the RASP processes as currently implemented in NaFRA. Hence this step in the analysis is considered to prove the concept that the spatial model applied in this project can be linked with RASP to provide additional information that is aligned with current or future NaFRA outputs. This is discussed further in Section 6. For illustration, expected damage curves used here are shown in Figure 3-4, with a selection of properties of different type and location.
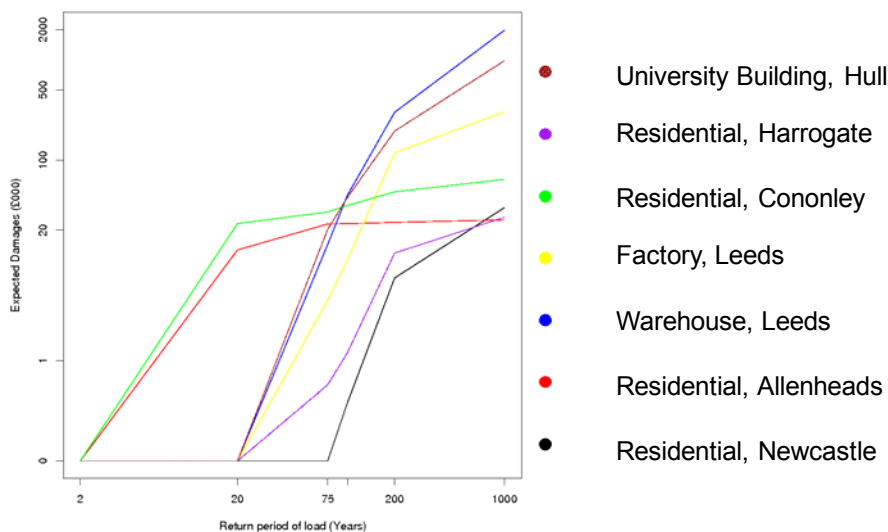
Figure 3-4. Examples of conditional damage curves.

By combining the per property conditional damage curves with the simulated river event data, simulated event damage can be obtained for each property and for every event. By combining this data with the occurrence rate of the events, the probability distribution of damage on an annual exceedance scale can be computed for any one or more properties.

Figure 3-5 shows the resulting probability distribution, or 'risk profile', for the region (by aggregating the damages per event over all properties), where the damages have been re-scaled to lie between 0 and 1. Also shown are risk profiles for two alternative

scenarios, one in which it has been assumed that there is complete spatial dependence in river flooding and one in which it has been assumed that there is no dependence at all. It is clear that either of these inappropriate assumptions leads to significant bias in the results.
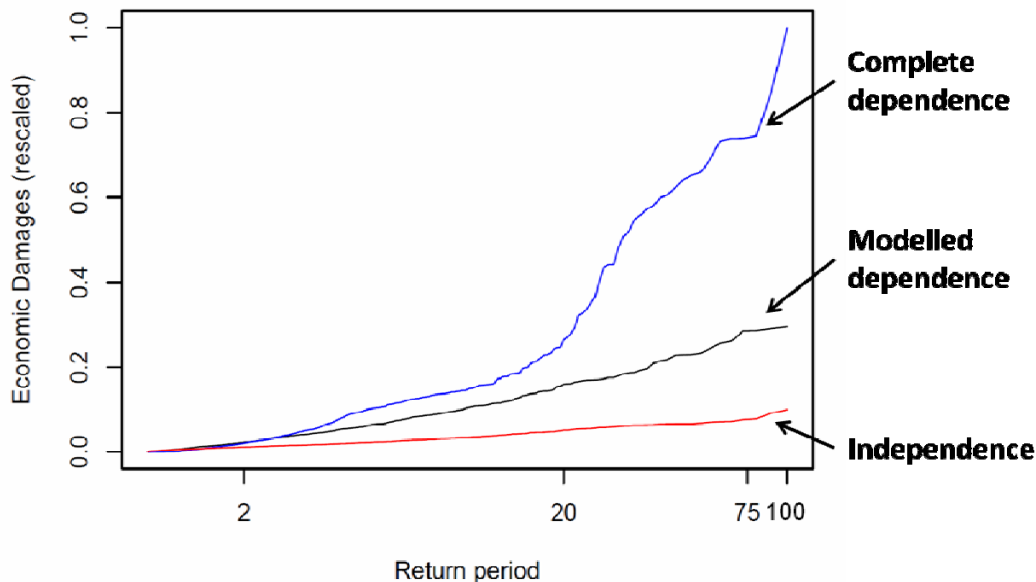
Figure 3-5. Economic risk profile for river flood in North East Region.

3.5 Discussion

This case study demonstrates for the first time a quantitative evaluation of the aggregated economic flood risk profile for a whole region. In theory there is an infinite number of combinations of flood events within the region that could contribute to the aggregated economic damage. For example, there are countless combinations of severe and minor flood events on different rivers that could occur together. The spatial model evaluates, to a close approximation, the full range of possible combinations and assigns them appropriate probabilities.

The results present a new way of understanding flood risk at a regional level. Existing approaches can represent the probabilities of a range of annual economic damages at each individual location. But over the whole region only the average annual damage is available, which does not reveal how likely it is that the region might suffer a much more severe level of economic loss from flooding in a major, widespread event. The new results provide a more complete understanding of the risk of the economic consequences of flooding over the region, including the risk of extreme losses.

4 Case study 2: Aggregated coastal flood risk

4.1 Rationale

This example demonstrates the modelling of extreme sea levels over multiple sites. The intention of this proof of concept demonstration is to show that the conceptual model of dependence can form the basis of a geographically extensive model of extreme sea levels.

The key features of the analysis are:

- Demonstration of a general dependence model for extreme sea levels at a pair of coastal sites.

- Joint analysis of astronomical tide and storm surge, incorporating recent research on 'skew surges'.

The demonstration case integrates pathways and receptors in much the same way as in the fluvial case, using a series of flood depth data produced by JBA Consulting as part of a coastal flood model. Instead of calculating economic damages, the National Properties Database has been used to calculate numbers of properties flooded in this example (note that it would be equally feasible to compute economic damages instead.)

4.2 Methodology

The analysis uses the same generic approach as in the fluvial demonstration (that is, simulation from a joint distribution of the flood 'source' variable to integrated pathway and receptor) but in this case the source variable to be modelled is sea level rather than river flow.

The sea level dependence model is based on analysis of surge and tide data from Class A tide gauges at North Shields, Whitby and Immingham. The coastal area modelled in this demonstration case is shown in Figure 4-1. There are two tide gauges as shown, and sea level probabilities are estimated by interpolation at 1km intervals (as with the rivers case, this interval can be varied).

It would also be feasible to make use of data generated by a high resolution numerical storm surge model, such as the model produced by JBA Consulting for national flood mapping to provide long records at more locations. The reason we use the gauge data here rather than sea levels from the numerical model is that the dependence between sites in the model is slightly higher than in the observed gauge data. This small increase in dependence appears to be because there is some structure imposed through the model grid mesh and also by the driving weather data, which is generated from gridded re-analysis and numerical weather prediction (NWP) models. This is to be expected for all such numerical models. It is worth noting in this context that the statistical analysis of the joint spatial distribution has the potential to be used as a powerful evaluation tool to compare numerical model data with observations. It would be possible to use the numerical storm surge model data to interpolate sea levels

between the tide-gauge locations. The reason we did not was for simplicity in the proof of concept work.
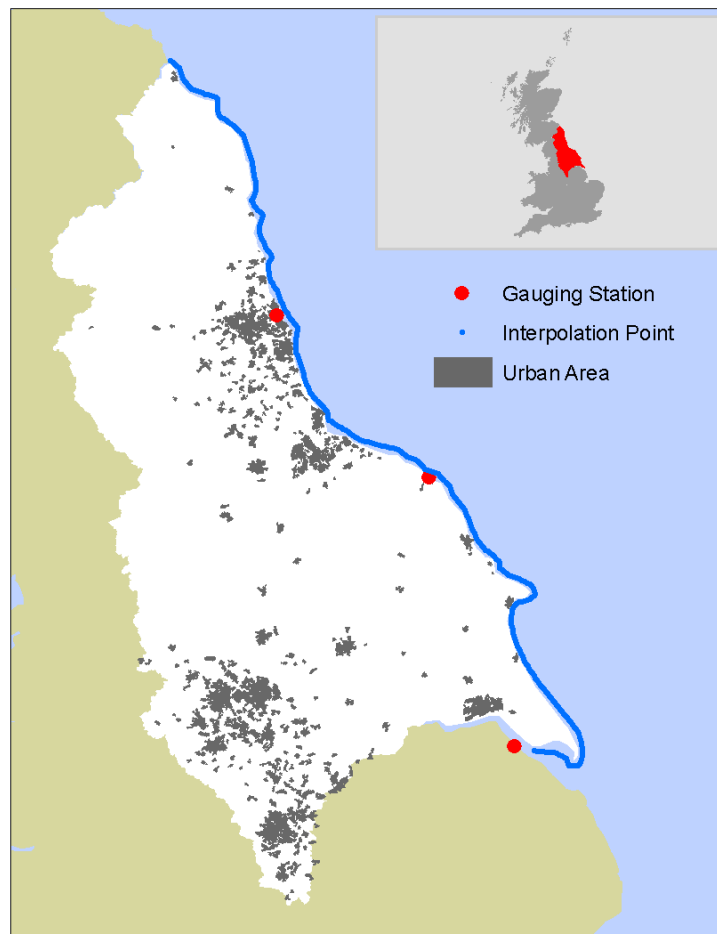
Figure 4-1. Map of coastal study area

For coastal extremes, it is necessary to separate out the storm surge from the astronomical tide because the tide is a deterministic process that imposes a dependence structure up to a certain threshold, whereas the surge can be treated as a stochastic process that contributes the additional sea level elevation responsible for flooding.

Temporal sequencing is important because the timing of the surge relative to the tidal cycle can make a big difference to the peak total sea level. The analysis makes use of skew surge data to resolve the problem of tide-surge interaction. The problem of differences in timing of an individual surge as it travels along the coast is solved in the same way as the problem of fluvial floods occurring at different times in the same river system. The skew surge is the difference between the maximum recorded total sea level and the maximum predicted tide level for the cycle

The dependence model we use is capable of handling an arbitrary number of variables (locations) and it is therefore theoretically possible to include every coastal grid cell in the analysis. For convenience, in the proof-of-concept demonstration case we have worked with only the three locations named above. As for the fluvial case, simulated sea level data are successfully interpolated between the gauges on a transformed probability scale.

4.3   Data sources

- Tide gauge data from British Oceanographic Data Centre (BODC) Class A tide gauges at Immingham, North Shields and Whitby.

- Tidal flood zone data (for information).

- JBA coastal flood map data.

- National Properties Database.

4.4   Outputs

Real and simulated skew surge data are shown in Figure 4-2 for the three gauges, showing that the conditional exceedance model is able to reproduce and extrapolate features observed in the data.
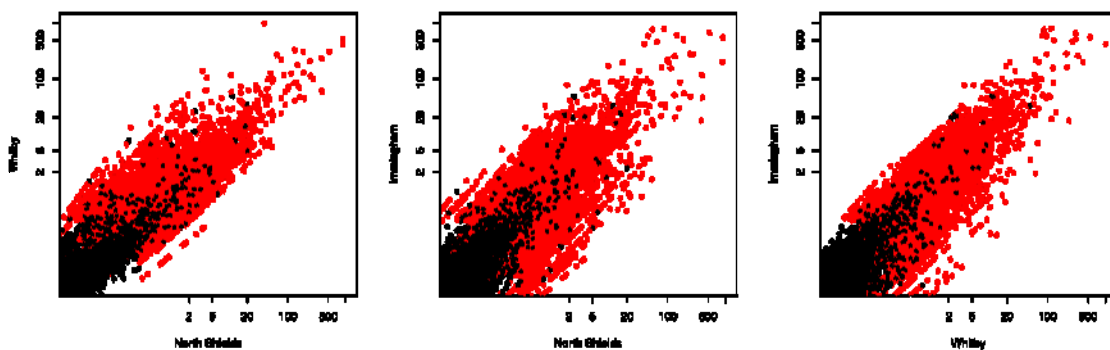
Figure 4-2. Real (black dots) and simulated (red dots) skew surge data for North Shields, Immingham and Whitby tide gauges plotted on a common return period scale.

Skew surge is defined as the maximum difference between astronomical tide level and total sea level over a cycle (Figure 4-3). It is statistically independent of the tide, as shown in Figure 4-4, and therefore avoids the need to account for tide surge interactions.
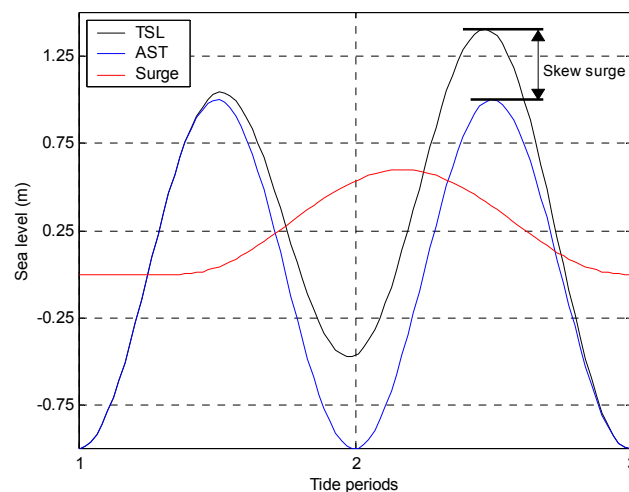
Figure 4-3. Definition of skew surge.
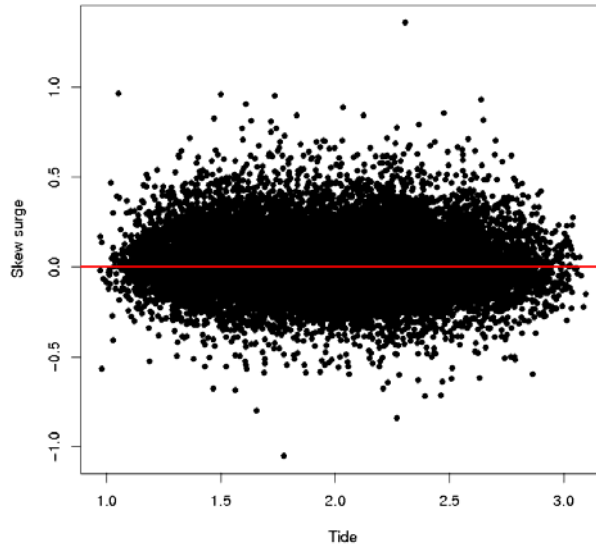
Figure 4-4. Independence of skew surge and tide. Example showing data plotted on original scale (metres above datum) for Whitby.

By sampling tides and skew surge randomly from their respective distributions and adding the components, a Monte Carlo simulation of synthetic total sea level values (representing maxima over a three-day window, to capture the full surge) has been created for all tide gauges on the north east coast. The analysis presented here does not include separate treatment of different seasons or states of the tidal cycle. It resamples the historical astronomical tide levels and so spring and neap tides occur with the correct frequency. Coles and Tawn (2005) found that more detailed modelling of the seasonal timing of surges did not significantly improve the accuracy of modelled extreme sea level probabilities and so the current approach is considered sufficient.

Figure 4-5 shows results of a simulation of total sea level for 800 full years of record compared with gauged data for North Shields, Immingham and Whitby.
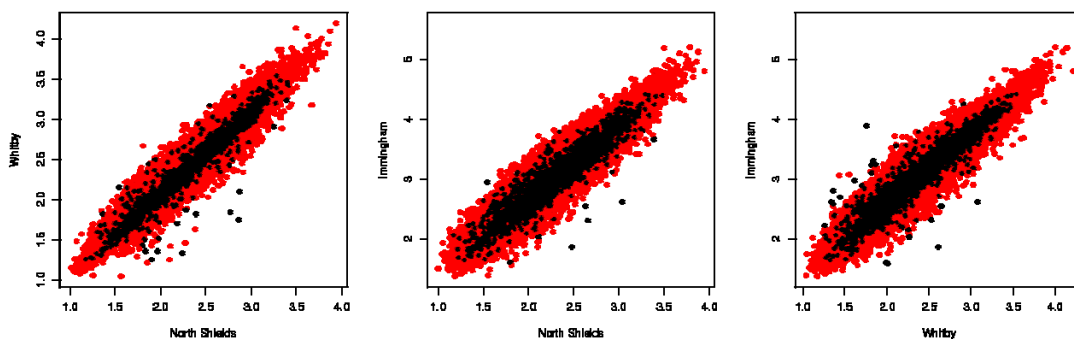
Figure 4-5. Simulated (red dots) and gauged (black dots) total sea level data plotted on original scale (metres) for North Shields, Immingham and Whitby.

Similar plots and related tests have been examined for all pairs of tide gauges to verify the conditional exceedance model. Total sea level data simulated from the model can therefore be used with confidence to represent the joint distribution of sea levels at any

combination of sites. For simplicity we use only three sites here, but as demonstrated by the fluvial analysis, a very large number of sites can be included in practice.

Using the NPD dataset we have associated each property along a buffer strip inland of the coast to the nearest sea level interpolation point. For each property, the nearest sea level interpolation point is used. It is therefore possible to calculate the number of properties that are modelled as being flooded for a given extreme sea level at every interpolation point.

This analysis can include a probabilistic element to account for defence system performance. For the current proof of concept, we have used flood depth grids for four return periods (1000, 200, 100, and 75 years). This is a coarse sample but is sufficient for illustration. We have included a fragility curve concept to differentiate defence performance and standards between urban and rural locations. The probabilistic analysis is based on a simple linear interpolation of depth grids between the log return periods.

As for the fluvial example, the important point is that the pathway and receptor components of risk are being represented in the form of data that describes the expected consequence (number of properties in this case) conditional upon the load. This type of output can be produced from RASP methods if desired (see Section 6).

For the coastal analysis, the simulation approach differs slightly to the fluvial case. A simulation of 800 years has been carried out. For each year, 122 samples of the three-day sea level maximum have been generated as above and the number of properties estimated to flood from each event over the whole coastal region has been aggregated to give a series of annual totals. From these annual totals, the risk profile can be calculated, as shown in Figure 4-6.
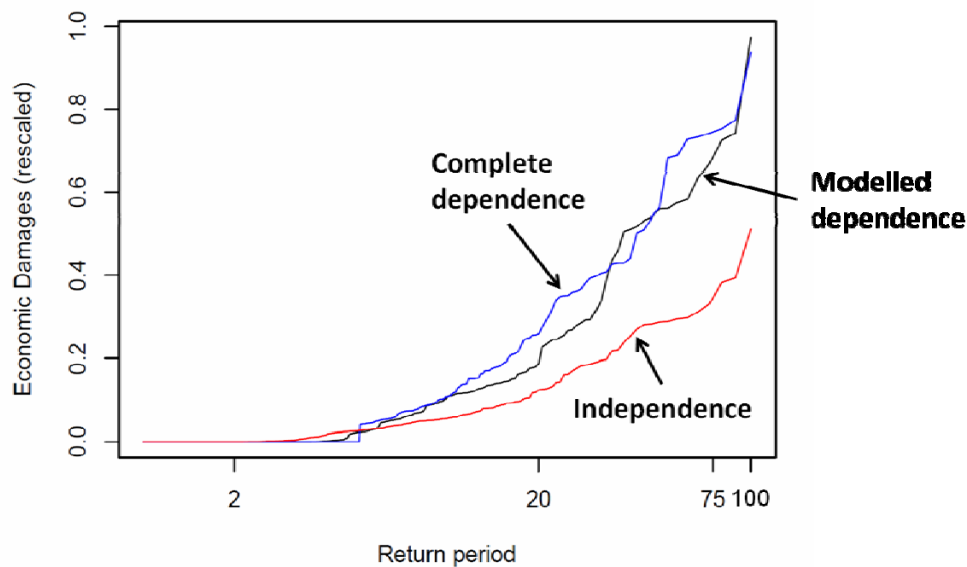
Figure 4-6. Risk profile for coastal flood.

4.5   Discussion

The result shown in Figure 4-6 confirms knowledge that extreme sea levels along the relatively uniform north east coast are strongly spatially dependent. The spatial model

used for sea levels has therefore picked up this dependence in the data and correctly represented it in the final risk profile curves.

Aggregation over other coastal zones might show a different result. The spatial dependence in extreme sea surge varies over different parts of the coastline, with west coast and east coast surges being less well connected. The spatial model shown here is able to incorporate any dependence structure and hence provide a way of understanding the combined risk of damage from coastal flooding for any spatial extent of coastline, including the whole coast.

In this coastal demonstration, the analysis of damages has been based on numbers of properties flooded, rather than economic loss in monetary units. This has been done to illustrate that different measures of flood consequence can be used within the same framework.

5 Case study 3: Combined risk of widespread inland flooding and sea surge

5.1 Rationale

This example demonstrates the quantification of combined river and coastal flood risk at a regional scale.

The demonstration originally proposed was to model joint flood risk for two estuaries. However, this would be a natural extension of the two cases already considered. An issue that has not yet been addressed is analysis of the chance of severe inland river flooding within a region occurring at the same time as flooding on the coast. This type of event, although rare, would potentially represent a catastrophic emergency. The tools applied in this project enable this risk to be examined.

5.2 Methodology

The analysis makes use of the type of dependence model already fitted to river flows and sea level data. In this way the tide gauges are effectively treated as additional flow gauges. The simulation involved generating events equivalent to 800 years of records.

An event set of same day skew surge and river flows, conditional upon there being at least one river flow threshold exceedance, was generated in the same way as for the fluvial and coastal studies. To take the seasonality of river flooding and high tides into account, each event in the event set was assigned a 'year day', these were obtained by sampling the dates of events in the gauged record when at least one threshold exceedance was observed somewhere in the region. With approximately 45 years of gauged records, this approach is able to represent well the seasonal distribution of high river flows. The tide for that event was then taken to be one of the observed tides on the sampled 'year day' for a complete 18-year tidal cycle running from 1990 to 2007. The total sea level is then obtained by summing the skew surge and tides for each location for each event.

5.3 Data sources

As for the fluvial and coastal demonstration cases.

5.4 Outputs

The combined fluvial and coastal simulated events allow analysis of questions about the combined chance of damaging inland and coastal flooding. There are a number of specific questions that can be answered. Initially, we have looked at only the simplest, which is to assess the probability of there being a high flow event somewhere in the north east region at the same time as a high sea level.

This analysis ignores the pathway and receptor components of the risk. This is for convenience, and because a process to integrate these components has already been demonstrated in the fluvial and coastal cases separately.

Figure 5-1 shows the maximum return period observed in the simulated data at any point on the coast given the maximum return period of river gauging stations in the region. Hence a point towards the top right of the graph represents an event in which at least one river gauge has extreme flows combined with at least one tide gauge showing an extreme sea level.
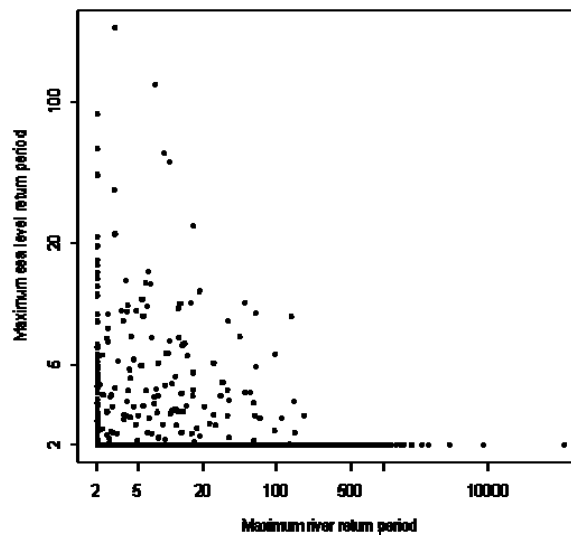
Figure 5-1. Occurrence of high river flows and sea levels in north east region above a two-year return period threshold in a simulation of 800 years of data

The density of points reveals the chance that events at certain thresholds might occur together. It can be evaluated immediately by eye, there being a very low chance of events occurring where both river flows and sea levels are high. At higher thresholds, there is negligible chance of joint occurrence of extremes.

Figure 5-2 shows an alternative view of the same data. Here, the x-axis is the return period for the largest river flow observed at any gauging station in the region for a given event. The y-axis shows how many times, in the simulation of 800 years of data, that there was a high sea level at the same time as the given river flow return period. This analysis is shown for three definitions of 'high sea level', where 'high' means a two-year, five-year or ten-year return period. It can be seen that the chances of experiencing a combination of extreme inland river flows and a high sea level are small, although not zero. These findings are broadly comparable with those from the research project FD2308 (Department for Environment Food and Rural Affairs/Environment Agency, 2005), which found low levels of dependence between flows and surge for this region. The improvement that this current project adds to these findings is the ability to quantify the probability of simultaneous fluvial and coastal flood events over the whole region (or a larger area, in a future full implementation of the method).

This type of analysis confirms that the joint risk for the part of the north east coast considered here is relatively small, especially so if we consider that the probabilities shown are for source variables only and so ignore the role of defences. The same type of analysis can be carried out for other regions or coastlines, where the results could

SC060088 Proof of Concept Summary Report

differ. There could also be some interest in repeating this type of analysis with climate change modifications to the original data to examine future risk scenarios.
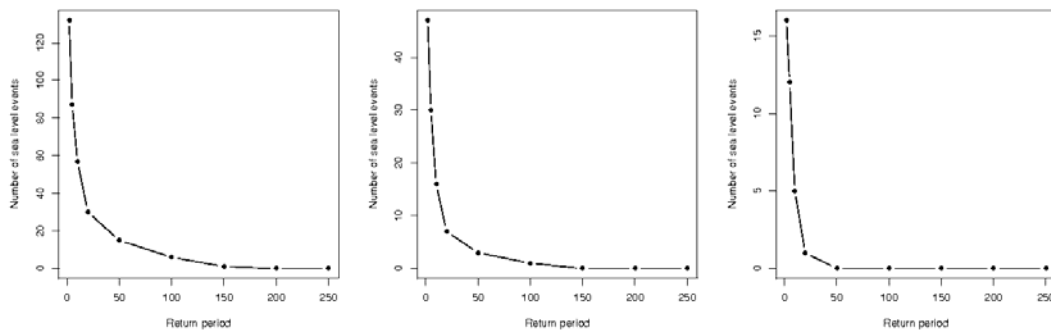
Figure 5-2. Number of occasions in an 800 year simulated sample when there was a high sea level above a threshold given the maximum river flow return period over the whole region shown on the x-axis. Choice of sea level threshold, left: two years, middle: five years, right: ten years.

5.5   Discussion

This example illustrates one way in which the spatial joint distribution models for rivers and sea levels can be combined to answer a question like 'what is the chance of severe river flooding and coastal flooding affecting a region at the same time?' The question is broader than assessing the joint probability of the river flow and sea level for an estuary, which essentially involves only two points (although this analysis can also be done).

In the case of the North East, the results show a very small chance of extreme flooding from the river system and from the coast at the same time. Similar analyses could be performed to look at the chance of both events happening in any given year, or over different regions. The very low probability of joint occurrence for the north east region is consistent with the findings of FD2308 (and its precursor projects) where weak dependence was found between surge and river flows in the region. Stronger dependence was found in other parts of Britain and so the probability of combined flooding could be different elsewhere.

The analysis methods used in FD2308 and related studies could not quantify the probabilities involved, but simply measured one aspect of the dependence. The methods applied here represent an advance in being able to capture the joint distribution, including various aspects of the dependence, and hence compute probabilities for different types of flood scenario.

6 Integration with NaFRA

6.1 Overall approach

Our approach to integration of the spatial joint distribution model for sources of flood risk with NaFRA (or other RASP-based tools and products) is based around identifying data that can be exposed by both pieces with the aim of achieving a modular, flexible and open process.

6.1.1 Modularity

The proposed approach is modular because it achieves a separation of the overall risk calculation into distinct component parts, each producing clearly defined intermediate outputs that are meaningful in their own right.

6.1.2 Flexibility

It is therefore a flexible approach, allowing for future changes in any one component without necessarily having to re-run or change other components. It permits the component data, including both spatial simulation data and 'pathway-receptor' data, to be linked by relatively lightweight 'integration code' that may easily be varied, for example to obtain results at different scales of aggregation.

6.1.3 Openness

The proposed approach is open because intermediate data will be exposed that can be interrogated, reviewed and understood. It easily permits alternative algorithms, codes or input data to be included in future, and has the potential to help different project teams to cooperate in producing the final, combined outcome because it does not require management of a single, monolithic source code development.

6.2 Relevant RASP data

The critical data required from the RASP engine within NaFRA has been identified as the conditional economic damage (or other consequence measure, such as number of properties) given a specified hydraulic load. This quantity is in principle embedded within any RASP calculation. For illustration, Figure 6-1 shows sample curves for expected economic damage conditional on the hydraulic load (averaged over a river reach), aggregated over all NPD properties within the reach. The curves shown here are for the built up areas of Leeds and York. The curves have been derived from the Environment Agency North East Region broad scale model data. This large spatial scale of aggregation has been used for illustrative purposes only and we would anticipate much finer scales being used in practice, down to postcode or property level.
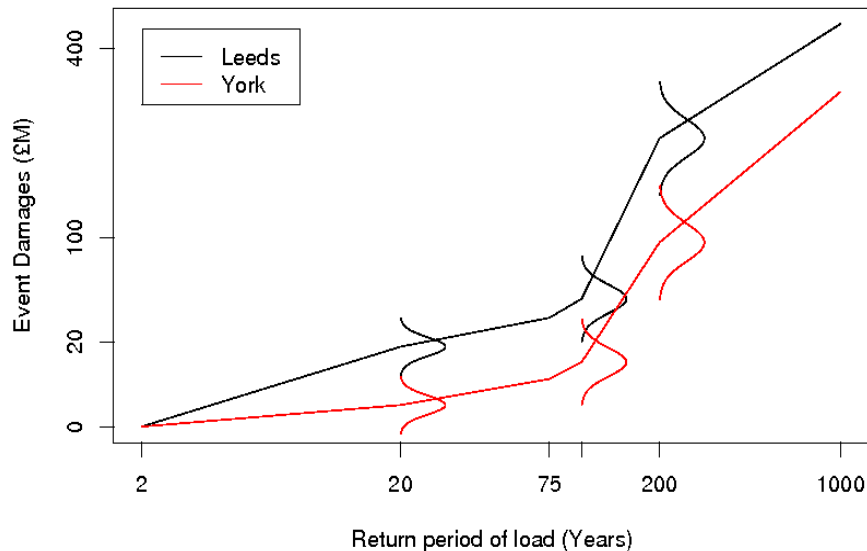
Figure 6-1. Sample conditional economic damage curves

The solid curves show the conditional expected damage, that is, the mean obtained by a probability-weighted combination of multiple loading and defence performance scenarios. This is the simplest summary information that would permit integration of RASP outputs with the spatial model applied in this project.

Also shown on the plot are distributions about the expected damage at selected hydraulic load levels, which represent uncertainty in the expected damage given the assumptions made about defence performance. Information about this spread of damages conditional on load would help to improve the accuracy of spatially aggregated risk estimates by allowing for the rare possibility of a given hydraulic load causing an unexpectedly severe defence failure and hence very large damages.

6.3   Practical feasibility

6.3.1   Conditional damages data

The technical methodology report discusses in more detail how the data of the type described above are inherently present in the RASP calculation process and should hence be available in principle from the RASP engine.

We have subsequently held separate telephone conferences, chaired by the Environment Agency, with Halcrow Limited and HR Wallingford Limited to establish the practical feasibility of exposing conditional damages data from within RASP. At both conferences, and in subsequent email correspondence, it was confirmed that it is possible in principle to expose the data identified above with small modifications to the RASP engine codes.

The information needed to represent uncertainty about conditional expected damage is inherently generated as part of a RASP calculation. There are several possible choices about how best to summarise that information, which range from exposing every intermediate damage calculation in the RASP engine to calculating and exposing simple summary measures such as variance and skew. The former would be the most detailed approach in principle, but would be computationally expensive and demand a

large amount of data storage. The latter would be much more efficient in practice and probably sufficient. A short test and simulation exercise would be useful to choose the right balance between detailed and summary measures in this case.

6.3.2   Integration

Process

Assuming that conditional damage (or other consequence) curves can be exposed from RASP or equivalent processes, then the integration of these data with the spatial model approach applied in this project is a relatively simple matter of database queries and summation. The approach is set out in the technical methodology report, but in short the process is as follows:

- Establish a spatial association between simulated load points in the spatial model (such as river or coastal nodes) and conditional damage data points (which may be individual properties, impact cells, impact zones or other spatial units).

- For each simulated spatial event, use the association table to look up the damage corresponding to the simulated load at each point, either taking the expected damage or sampling a value from the distribution about the expected damage.

- Aggregate the resulting damages per event at any chosen spatial scale.

- Form the distribution function of damages from the data generated in the previous step.

It is worth noting that real, historical flood events may also be analysed in this way, providing a consistent method to analyse probability and consequence for those real events.

Computational load

The four-step procedure summarised above was used for the river and coast demonstration cases reported in Sections 3 and 4. For the river case, approximately 250,000 properties were queried from the NPD. There were 10,000 simulated spatial events defined at approximately 11,500 node points on the river network. The total processing required to compute the distribution of damages over the entire region took less than one hour using one processor core on a mid-range desktop PC. The adopted 1km node point spacing is relatively coarse. Increasing the detail to, say, between 100m and 250m spacing would increase the computing time, although it may be reasonable to vary the node point spacing to increase detail only in areas where there is significant risk.

The timing given above was based on development code already in place at JBA and using individual text files to store each of the 10,000 spatial events. We expect that for any practical application 'tuned' for a phase two Environment Agency application, an optimised code using database software would be considerably faster. Additionally, the calculation process involves completely independent query functions for each simulated spatial event, and can therefore easily be run as a parallel process. This would allow almost linear speed up with additional processors, whether by using multi-

threading to take advantage of multi-core CPUs or simply by spreading the load across a number of machines, each one processing different portions of the dataset.

We therefore consider that it will be possible to process an aggregated economic risk profile for the whole of England and Wales as a within-day or overnight process. This should be feasible using typical office workstation computers and standard database software such as SQLServer or Oracle. Certainly processing time does not appear likely to be a significant practical barrier.

7 Stakeholder workshop

7.1 Introduction

A workshop was held on 18 March 2009 to present the findings of the project to a group of interested specialists. The workshop was by invitation and was attended by 13 delegates from Defra, the Environment Agency, flood risk consultants and university groups. Areas of expertise and responsibility covered:

- Flood risk policy.

- Investment planning.

- Emergency planning.

- Incident management.

- Flood risk R&D.

- Coastal risk management.

- Urban flood risk.

7.2 Discussion points

The main points discussed at the workshop have been grouped and categorised in the following sections.

7.2.1 Process representation and scale

Where is it appropriate to move from a statistical model to a physical hydraulic model? This is important when it is necessary to handle interactions where hydraulic processes, for example breach or storage, can modify the dependence between sites on a river. This would be needed to enable scenario tests in some situations. It is also a question for RASP in terms of assumptions about dependence of load and pathway. It may not be of practical importance at regional or national scale of aggregation.

7.2.2 Economic calculation

The economic impact of a large flood is not just the sum of individual property damage. This is not currently accommodated by present tools. With its spatial event basis, the risk model demonstrated here provides a capability to apply a wider scale economic analysis. This may include more realistic analysis of costs relating to aspects such as critical infrastructure and cost capping for multiple events in a year.

7.2.3 Multiple sources

It was recognised that the method has potential for extensions to help include rainfall and other sources of flooding. A hybrid strategy building on the significant existing work on rainfall modelling would seem likely.

7.2.4 Climate change

The methods used in this project could incorporate climate change if suitable modifications of river flow and sea surge distributions can be identified. However, the capability of climate models to represent the spatial structure of extremes at the required spatial scales is not proven. The analytical approach might also be useful in understanding how climate models represent the current climate in terms of extremes and dependence at multiple spatial scales.

7.3 Detailed workshop notes

The following table records comments made by workshop participants and details of the subsequent discussions at the workshop.

No.	Comment	Discussion
1	The importance of moving away from single site approaches [which are not very suitable for regional and national assessments].	This is one of the main motivations for the methodology.
2	Changes with time due to climate change impacts are also important and should be considered.	Scoping of phase two will touch on this.
3	Extrapolation from only 50 years' worth of data introduces uncertainties.	This is a common problem in flood risk management in general. The chosen statistical model was specifically developed to be safer for extrapolation beyond the range of observed data than standard statistical models. It is considered the best such model available, but as with any model it is not perfect. If we can assume that more extreme events have the same characteristics as observed events then the extrapolation should be safe. However, if more extreme events have different spatial structures than observed events then any extrapolation will be less safe.
4	The model is based on historic data which does not take into account changes in the flooding system due to land use, non structural measures. How could	Discussed at the workshop. Part of the general issue about processes and scale (see above).

No.	Comment	Discussion
	these effects be included?	
5	HR Wallingford are now applying Heffernan and Tawn (2004) approach as part of the FRACAS project.	
	Does the interpolation work well for smaller head water catchments? Where are the upstream limits of applicability?	There doesn't seem to be any consistent difference in performance of the interpolation method between smaller headwater catchments and larger catchments. It is likely that there will be a point at which a rainfall-based approach will perform better, but exactly where this point is has not been investigated.
6	This approach could also help to set situation inflow points for regional scale modelling studies, such as Catchment flood management plans (CFMPs).	This has been incorporated into the Flood Studies Update for Ireland (Office of Public Works, Dublin).
7	Can we comment on the uncertainty around the joint distribution [and the wider model] due to the limited observed record length?	Yes. We plan to calculate the uncertainty for a pairwise case for inclusion in the final report.
8	Would it be possible to show the worst case of a particular flooding scenario rather than the results of a seven day average?	Yes.
9	'Capping issue' – Method assumes the same damages can occur again during subsequent flood events (that is, within one year).	This looks like an area for further research. See note on economics above.
10	It would be of practical interest to investigate cumulative effects of subsequent events for emergency response planning purposes	
11	What is the sensitivity of the model to the event length?	Event length can affect the results. This is flexible. Event definitions can be imposed to suit a particular purpose (fixed durations) or determined by analysis of how the dependence varies over time and space, which has already been done within the project.
12	Event length for coastal cases should cover two spring tides (14 days).	This can be incorporated in phase two of the project, however see note in demonstration case two and reference to Coles and Tawn (2005).
13	How often is there a need to	Could be updated every few years to take advantage of better underlying data

No.	Comment	Discussion
	update the analysis?	(for example, flow data, NAFRA data) or better flood depth or economic damage models.
14	It would be good to compare the results against some work IBM did for Defra on actual flood damages	To be considered if national analysis is carried out.
15	Approach/outputs could be very useful for strategic emergency response planning [for example, number of pump engines]	
16	Is there any potential for real time use?	The method is motivated by risk modelling rather than real time forecasting.
17	Being able to assess the probability of past events (for example in response to media enquires) could also be useful and more meaningful then the current point estimates.	The method allows probability and consequence of specified scenarios or historical events to be estimated.
18	Would it be possible/beneficial to generate scenarios for flood event exercises (such as TRITON)?	Yes.
19	Is assessing flood probability based on flood peaks (rather than flood volumes, for example) the right way forward?	The method includes a concept of return period of 'load', which is typically assumed to be peak flow/level, but could also be expressed in terms of a volume, where appropriate.
20	Event duration and volumes can sometimes be important [but the most common flooding mechanism in the UK is through flood peak levels].	
21	Surface water flooding is caused by different weather systems. Spatial patterns in flood risk could change with the scale on which they are investigated [and what sources of flooding are considered]. For example, the probability of two localised thunderstorms could be of interest.	The method used in this project can be applied to rainfall data (for example, Keef *et al*., 2009).
22	Would it be possible to link certain scenarios to dominant weather patterns?	FD2308 did some brief work on this.
23	Potential of UKCP9 data for analysing changes in future? Link to Environment Agency R&D project 'regionalised river flows	To be touched upon in scoping for phase two.

No.	Comment	Discussion
	under climate change'.	
24	Approach seems very useful for insurance industry.	
25	Is it possible to investigate effects on other receptors?	In principle yes, if spatial data is available.
26	The Environment Agency/Met Office Flood Forecasting Centre should be aware what kind of R&D is already be done.	
27	A real national risk profile would be very useful for national asset investment and planning purposes.	
28	Probability of 'instantaneous hit' which could be expected under certain flooding scenarios would be interesting. Likely audience Cabinet Office.	
29	It could be challenge to communicate the outputs in simple terms.	Aggregate curve of regional or national damage against return period is one simple expression of the outputs.

7.4   Summary

The feedback received during the workshop showed that there is interest for the kind of outputs to quantify spatial dependence in flood risk that are now possible through the methods developed and tested under this project.

The main end users would be seen in national investment and planning (and other strategic functions of the Environment Agency), Defra, or the re-insurance industry, which may all require a quantified understanding of the exposure to flood risk faced by the country as a whole under certain realistic spatial flooding scenarios. These scenarios could include, but are not limited to, different probabilities of occurrence, different spatial patterns, different numbers of exceedances occurring simultaneously, different expected damages and different numbers of properties affected.

In addition, delegates felt that there may be some benefit for other applications in flood and coastal risk management, such as strategic emergency planning, more realistically assessing the probability of past flood events, and defining more realistic boundary conditions for regional strategic studies, such as CFMPs. However, further research and development is still required to allow for the project outputs to be used operationally.

Areas for improvement and further development include considering the impacts of climate change and extending the analysis to other sources of flooding. Since it quite a complex subject, it will also be very important to communicate and visualise possible outputs and applications as clearly as possible

8 Proof of concept conclusions

8.1 Technical demonstration of method

This proof of concept has demonstrated a coherent model of aggregated flood risk that is suitable over a range of spatial scales. The technical basis for the model is documented in the accompanying technical methodology report. We have shown how the model can be used to deliver new products in the form of:

- An economic 'risk profile' showing the probability of experiencing differing levels of economic loss from flooding over a whole region.

- A regional risk profile for non-monetary measures of consequence (such as numbers of properties flooded).

- Quantified estimates of the combined risk of river and coastal flooding in a region.

The outputs have been demonstrated for the north east region but the methodology is applicable at any large scale, from catchment scale up to national. The demonstration has shown how a modular approach can combine a spatial model of sources of flooding with existing data to describe pathways (such as flood defences) and receptors (such as economic consequences).

The results were presented to interested stakeholders at a workshop held in March 2009.

8.2 Technical opportunities for enhancement

A number of technical opportunities have been identified and were discussed at the stakeholder workshop.

The new spatial, event-based approach offers opportunities to build in more realistic assessment of economic consequences of flooding. There may also be scope for applications to help assess risk from multiple sources.

The methods were identified as suitable for large scale (catchment, regional or national) risk analysis. At smaller scales, it becomes more important to represent detail in physical hydraulic processes. The methods applied here can be used to help set inflows to detailed river models. An area identified for further development is how to incorporate 'reach scale' hydraulic effects, such as downstream impacts of breaching, within the statistical risk model.

8.3 Benefits

8.3.1 Stakeholder feedback

Discussion at the workshop feedback identified that the methods could bring benefits by adding new information for:

- Investment planning.

- Emergency resource planning.

- Extending and enhancing current national risk assessments.

The new methods offer a different way to understand and express flood risk, by giving a sound basis for calculating the likelihood not only of a particular flood water level but also of the consequences (economic or otherwise) of flooding for a catchment, region or country.

8.3.2 Specific benefits to flood risk management questions

Specific benefits were identified by framing flood risk management questions that the new methods can help to answer. These include:

Economic risk assessment

Relevant questions include:

- What is the T-year economic loss from flooding for a catchment, region or whole country?

- What is the return period of the economic loss suffered in previous flood events?

Answers to questions such as these will help to provide a sound, scientifically-based understanding of how exposed are we are to losses from extreme flooding. As well as providing clear estimates of risk for large-scale investment strategy, this type of information will also help communicate risk to the public and to policy makers.

Emergency planning

Relevant questions include:

- What is the probability of two or more critical infrastructure facilities being flooded at the same time within a region?

- What is the maximum number of emergency response resources, such as pumps or rescue boats, that are likely to be needed in any one flood event?

- What is the best strategy for locating emergency response resources so that they are most likely to be in the right place when floods happen?

- How many flood recovery resources are we likely to need in a 'worst case' flood event within a given planning time horizon?

Answers to these questions will help in understanding the large scale exposure to flood risk in our emergency response planning. This is of benefit to strategic thinking about the appropriate deployment and overall level of resources for flood recovery. It is also of use in helping to set realistic scenarios at different levels of risk for emergency planning exercises. For example, the new methods make it possible to generate a library of flood scenarios that would be expected to occur on average once in a T-year period, expressed in terms of number of population centres affected, total economic loss or occurrence of combined coastal and inland flooding.

Strategic flood risk assessment

Relevant questions include:

- What strategy should we adopt to minimise the risk that habitat sites all flood in any one year?

- What inputs to a catchment scale model are sensible to generate a 'T-year flood'?

The first question is similar to the analysis of critical infrastructure, and is made possible by the capability to quantify risk for multiple locations.

The second question is a catchment scale application of the statistical methods used in this project to analyse joint probability. The approach is already being applied in work in the Republic of Ireland for setting guidance for river modelling.

8.4   Phase two implementation

This R&D project, SC060088, is a technical scoping study to develop and test methods.

The final outputs of the project include a technical methodology report, which contains a detailed plan for implementation of the methods, taking account of stakeholder feedback and identification of benefits outlined in this proof of concept report.

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