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

SC060088/R3 Spatial Coherence of Flood Risk - Results from a national case study

Flood and Coastal Erosion Risk Management Research and Development Programme

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Miranda Kavanagh

**Director of Evidence**

# Executive summary

## Overview

This note explains and puts into context the results from a national case study to explore the risk of widespread flooding from rivers and the sea. This is based on methods developed and tested under the Environment Agency/Defra (Department for Environment, Food and Rural Affairs) research project SC060088.

Project S060088 is a scoping study to identify, develop and trial methods for determining the likelihood of spatially extensive floods from single or multiple sources as well as representing the likelihood of spatial coherence of flood risk in terms of receptors of risk.  As part of this project we further tested methods to model the impact of spatial dependence in flood risk at both source and receptor level.

The proof of concept work and subsequent consultation, carried out as part of the original project, showed that there is interest for the kind of outputs to quantify spatial dependence in flood risk on a national scale which are now possible through this project.

The aim of this national case study is to show some of the possible practical benefits which can be obtained by applying the methods developed and tested in this project. For the purpose of this case study we assume a stationary climate with no change in the joint distribution of flood risk variables at different locations.

## Links to other reports

This report documents the work undertaken to produce the additional case study results.  It does not document the statistical model used to produce these results. This information is given in the main report.

# Acknowledgements

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# 1 Introduction

## 1.1 Project background

The purpose of this report is to provide some explanation and context to the results from the national case study conducted as part of an extension to the Environment Agency/Defra (Department for Environment, Food and Rural Affairs) research project 'Spatial coherence – risk of widespread flooding'.

The R&D project SC060088 is a scoping study to identify, develop and trial methods for determining the likelihood of spatially extensive floods from single or multiple sources as well as representing the likelihood of spatial coherence of flood risk in terms of receptors of risk. As part of this project we further tested methods to model the impact of spatial dependence in flood risk at both source and receptor level.

The proof of concept work and subsequent consultation, carried out as part of the original project, showed that there is interest for the kind of outputs to quantify spatial dependence in flood risk on a national scale which are now possible through this project.

The aim of this case study is to show some of the possible benefits of the methods used in R&D project SC060088 and provide example answers to typical flood risk management questions. For this exercise we assume a stationary climate with no change in the joint distribution of flood risk variables at different locations.

We propose to express risk in terms of return levels at the set of flow or tide gauging stations. The main reason for this is that the methods proposed in SC060088 for incorporating pathways and receptors were designed to make use of RASP intermediate outputs, which are not yet available. A second reason for using simple, reliable measures of risk is that this case study is intended as an illustrative example to demonstrate what the methods developed in this project are capable of and show potential benefits to the Environment Agency which could be achieved by implementing these methods in practice.

For all of the river flow analysis we have used a subset of the flow gauging stations. Where possible we have chosen these so that there is one gauging station per catchment flood management plan (CFMP) region. Where there is more than one gauging station per region in our original dataset we made our choice based on record length and also favoured downstream stations.

The main reason for choosing this representative subset of gauging stations is that by evening out the spatial distribution of the gauging stations we will simplify the calculation of the national risk profile and the event type definitions. In particular if each gauging station represents a single catchment, counting the number of catchments affected is simply counting the number of gauging stations affected.

The main analysis we have undertaken is to evaluate national risk profiles for both fluvial and tidal events. These different types of flooding have been analysed separately. One of the case studies in the original project showed that, for the north east England at least, there are very few simultaneous coastal and fluvial events. It may be that for different areas of the country this not the case. We have chosen to represent these risk profiles in terms of number of gauge sites that experience a 50-year flow or sea surge because this is a level that is likely to cause a high level of damage.

In addition to the simple number of gauging stations affected, for the fluvial risk profile we have also represented the results in terms of number of Westminster constituencies that experience a 50-year flow. This aggregation is likely to give a better representation of the population affected as areas of high population density have more, smaller constituencies than areas of low population density.

The final analysis contained in the results shows the relative number of events that affect two different sections of the England and Wales coast. The interpretation of this result shows an example of how these types of results can be used from an emergency planning perspective and the relative likelihood of different storm surge events.

## 1.2 Specific objectives

The specific objectives of these extensions are set out below:

- To assess the risk of widespread flooding from rivers and coasts.
- To demonstrate the new methods developed in the main project for assessing flood risk at regional and national scale.
- To show how the results can help to answer common strategic flood risk management questions.

## 1.3 Management questions

The flood risk management questions that we have considered here are:

- What is the risk of experiencing different levels of flooding, within a given year, on any of the rivers or coasts of England and Wales?
- What is the risk of a severe, widespread flood event?
- What is the risk of experiencing a particular type of event, such as:
    - Storm surges on the East and South coasts together?
    - River floods similar to, say, winter 2000 or summer 2007?
- How can we generate plausible emergency planning event scenarios?

## 1.4 Methodology

The statistical method used to generate these case study results is described in detail in the main report. It is based on statistical theory first published in Heffernan and Tawn (2004) and methodology developed by Keef *et al.* (2009). The method uses a statistical conditional exceedance model for river flows and storm surge for 197 river gauging stations covering England and Wales and 24 tide gauges around the English and Welsh coasts.

The statistical model used is based on estimating the joint probability distribution of river flows or storm surges at different locations, where at least one location has an extreme observation. We define extreme to be an exceedance of a ‘high’ threshold. The joint distribution model has two parts. The first is a set of univariate (marginal) distribution functions fitted to each flow or tide gauge record. For river flows these are equivalent to flood-frequency curves at each site. The second part is a model for the dependence structure between all the flow or tide gauges. It is this dependence model that allows us to estimate the probability of floods at multiple locations.

## 1.5 Data

The gauges included in the analysis are shown in Figure 1. The main factors in choosing these records were the length and quality of record, with additional consideration given to obtaining an even spatial coverage. In selecting the river flow gauging stations we also considered the number of gauges chosen in each catchment and the population density of the area in which each gauge was located. We aimed to use one gauge per large catchment, and where sensible we chose these gauges to be located in areas of higher population density. Another consideration in choosing gauges was that they had natural catchments. This has resulted in a lower density of gauging stations in the Fens, where most rivers are pumped.

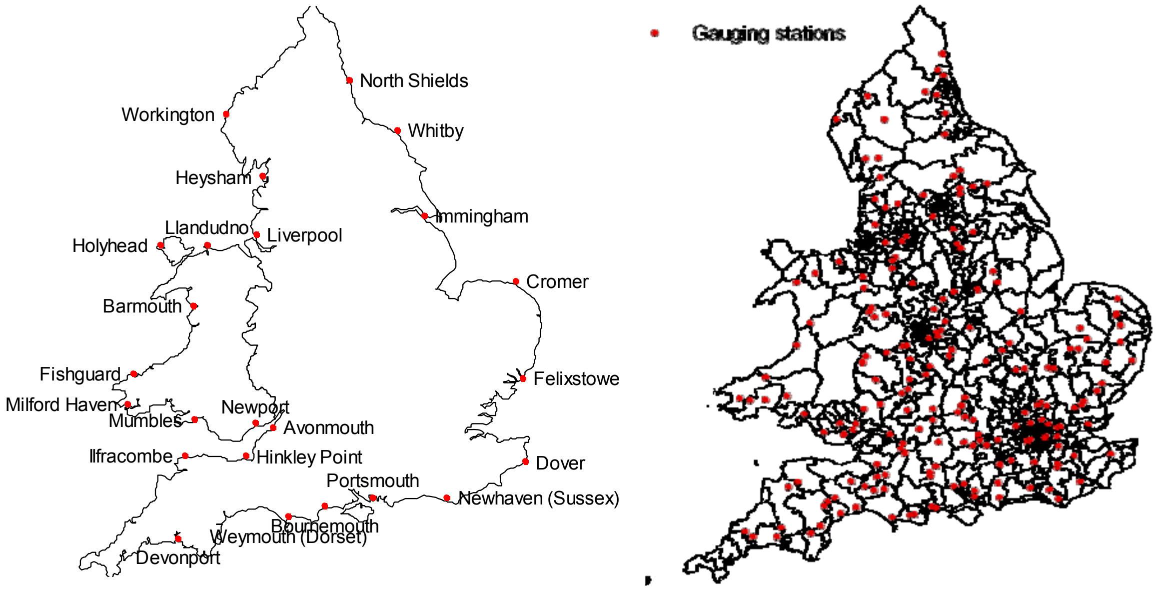


**Figure 1: Locations of gauging stations. Left plot tide gauges, right, river flow gauges. The background map of the flow gauges slows constituency boundaries.**

# 2 Results

## 2.1 National river flooding risk profiles

A national risk profile for river flooding is given in Figure 2. To obtain this risk profile we have had to quantify the annual flood risk in any given year. We have chosen to do this by counting 'units' of flood risk. The annual flood risk is the total 'units' of flood risk that could occur in any given year; these could occur at the same site at different times, or at different sites at the same time. In this example we have defined one unit as one occurrence of a high (greater than 50-year) flow at a gauging stations in any consecutive seven-day period. If two stations have high flows in the same event then that event counts as two units of flood risk. Similarly if one gauging station experiences a high flow in two seven-day periods in the same year, then that station will contribute two units to that year's flood risk.

We have chosen the term 'units of flood risk' to emphasise that flood risk can be expressed in many different ways. The Scoping Study SC060088 has shown how it is possible to use economic damages as units of flood risk. The main project also showed how this model can be combined with data produced using RASP methods to incorporate information about defence systems in the economic damage calculations. The reason we haven't used this information here is that the necessary data are not yet available. Other possible units of flood risk are: numbers of flood warnings triggered; numbers of moveable pumps deployed; numbers of properties flooded; and numbers of power stations flooded.

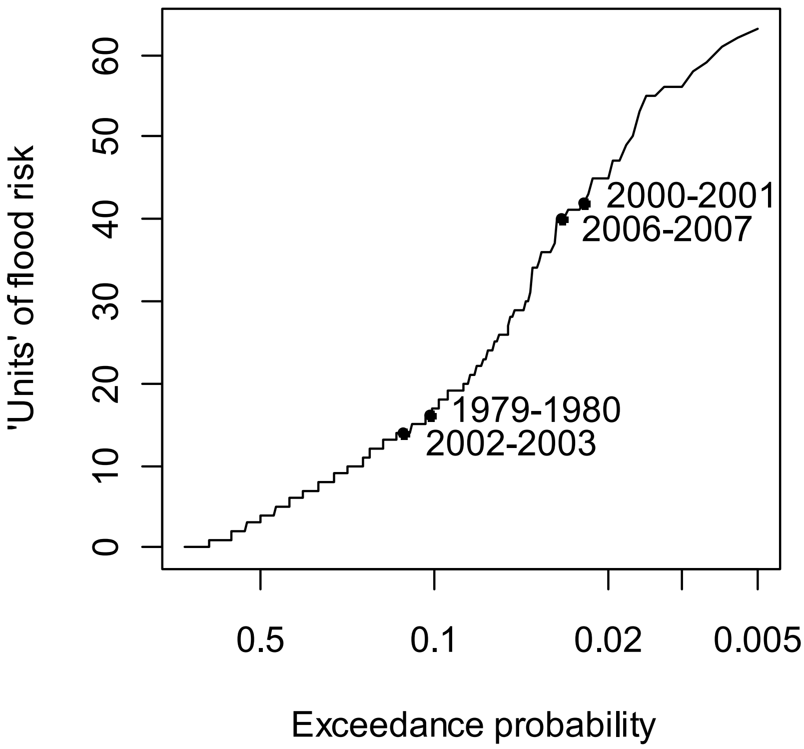


**Figure 2: exceedance probability for a given annual fluvial flood risk in any one year, within England and Wales. Notable years marked, years are taken to run from 1 August to 31 July.**

## 2.2 National coastal storm surge risk profiles

Figure 3 shows how rare it is to have an extreme storm surge at a number of tide gauge sites in any one year. We have defined an extreme surge at each tide gauge if it is likely to be observed only once in 50 years at that site. Storm surge is the amount by which the sea level is elevated above the expected high tide level. This elevation is caused by wind and low atmospheric pressure.

We can see that it is very unlikely for more than eight extreme storm surges to be observed in any given year. Figure 2 only tells us about the risk of storm surges, not the risk of flooding. To calculate the risk of flooding we need to add tide levels and models for flood defences into the analysis. It is possible to do this, but requires more time and data than were available for these case studies. A demonstration of how it can be done is given in the proof of concept results in the SC060088 scoping study.

The SC060088 scoping study has shown how it is possible to relate extreme storm surges to economic damages or other measures of flood risk in the same way as for fluvial flood risk. The reason we haven't used this information here is that the necessary data are not yet available at a national level.

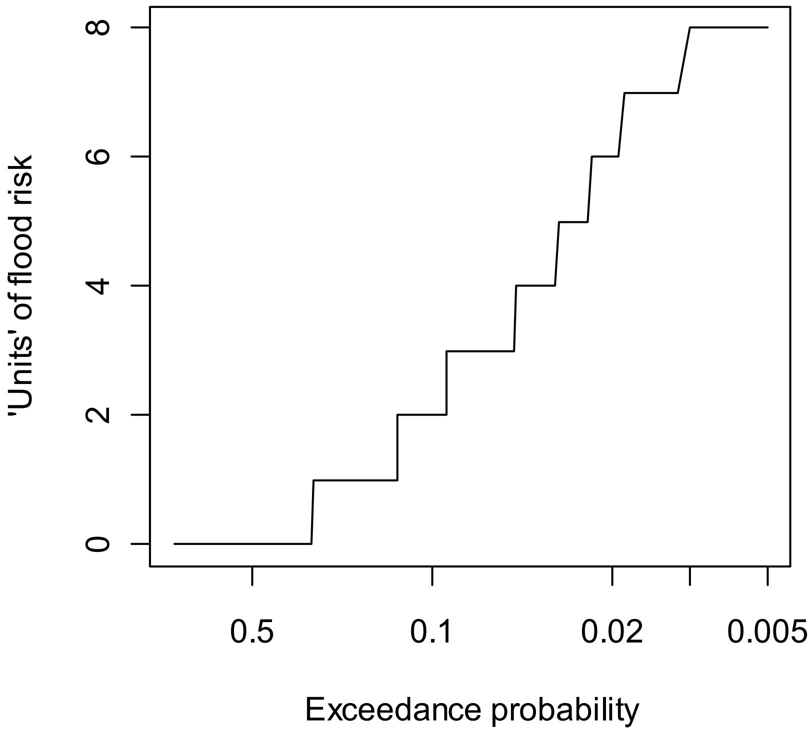


**Figure 3: Return period for a given annual storm surge risk in any one year, within England and Wales.**

## 2.3 What is the risk of a widespread flood event?

Figure 4 shows the probability of observing widespread flood events. We have defined an 'event' as being at least one extreme river flow at a gauging station in any consecutive seven-day period. We have highlighted notable events in the observed record. This event definition assigns the week of 6 November 2000 (the most severe week in the 2000 event) approximately a 1 in 15 chance of being exceeded in any given year. So we would expect to see an event at least as severe as this once every 15 years. The week of 19 July 2007 is assigned a 1 in 28 chance of being exceeded in any given year. We discuss these events in more detail later in this report.

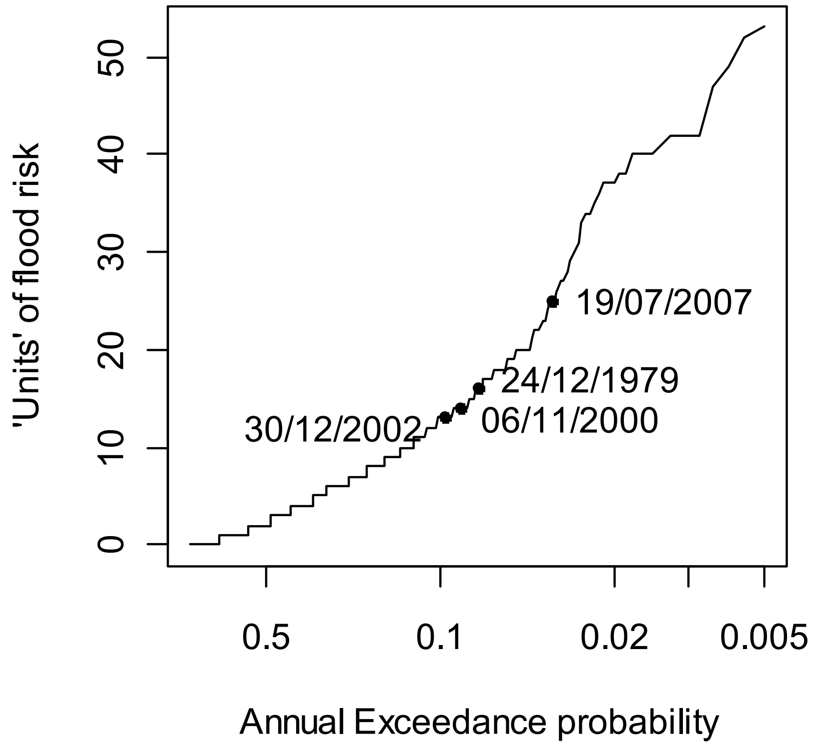


**Figure 4: Annual exceedance probability for a large fluvial flood event within England and Wales. Notable real events highlighted.**

Figure 5 show the same information as Figure 4, but using a different measure of flood risk. Here the severity of the event has been quantified by counting the number of MP constituencies in which a high river flow occurs during a single widespread flood event. The analysis effectively weights the measure of flood severity towards areas with the highest population density. It is an example of how different measures of flood risk can be used in a risk profile. The definition of 'high river flow' and event are as before.

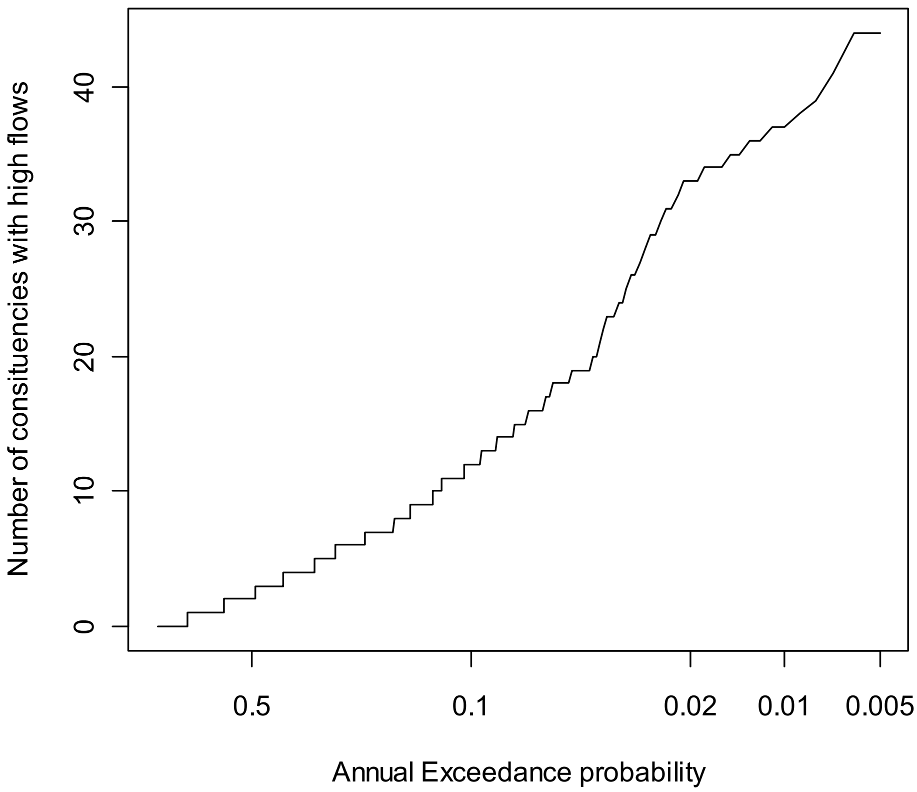


**Figure 5: Annual exceedance probability for a widespread flood event using number of constituencies affected as the measure of flood risk**

## 2.4 What is the risk of a widespread storm surge?

Figure 6 shows the probability of a widespread storm surge event. In this example we have defined an event as a five-day time period in which at least one tide gauge experiences an extreme storm surge. From this graph we can say that is it rare to observe an extreme surge at more than six tide gauges in the same five-day period. We can put this in context by saying that the East coast has six gauges.

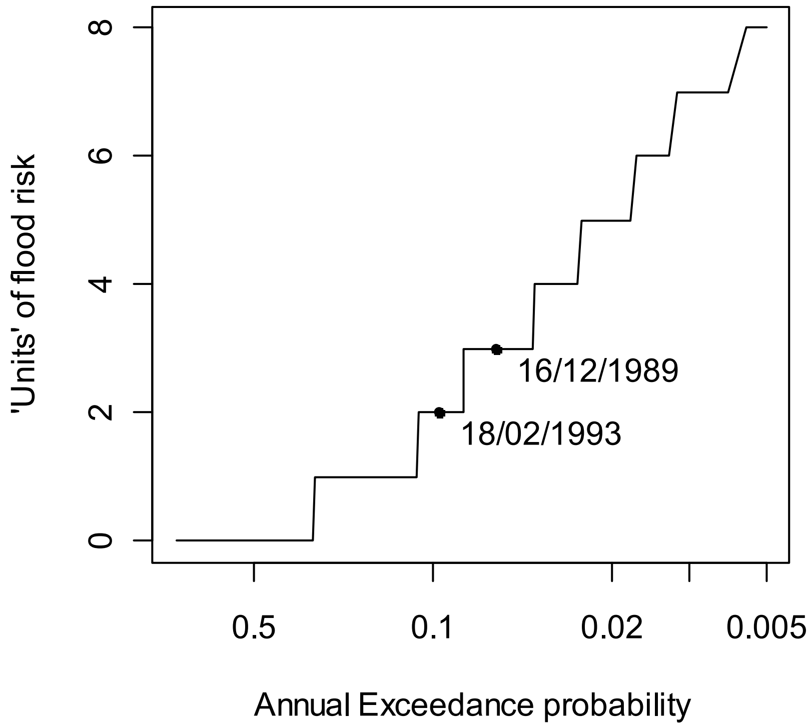


**Figure 6: Annual exceedance probability for an extensive storm surge event**

## 2.5 What is the risk of different types of widespread flood event?

### 2.5.1 What is the risk of different types of storm surge events?

Figure 7 shows the relative frequency of occurrence of different storm surge events using a simple event typology. We have defined events as occurrences of extreme storm surges as two different sections of coastline. These relative frequencies have been defined in terms of number of occurrences in 1000 years of simulated record. Because the numbers of simulated events of each type are very small it is difficult to assign exact probabilities to each type of event. This is because there will be a high level of uncertainty around these numbers. This uncertainty could be quantified by further analysis of the model outputs and may be reduced by generating a larger synthetic period of record.

It is possible to use these results to assign relative likelihoods to the different event types as follows:

- It is very unlikely that the south Wales and the east England coasts will experience a storm surge event at the same time.
- It is unlikely that the east England and north Wales/north west coasts and the south England and north Wales/north west coasts will experience a storm surge event at the same time, but it may be worth considering from an emergency planning perspective.
- There is a greater possibility that the south and east England coasts will experience a storm surge event at the same time and should be considered

from an emergency planning point of view. This result should be used with caution as Dover is included on the south coast, but possibly should be included on the east coast; storm surge at Dover is highly correlated with storm surge at both Felixstowe and Newhaven.

- The situation where south Wales and north Wales/north west England experience a storm surge event at the same time is likely to occur and should be planned for.

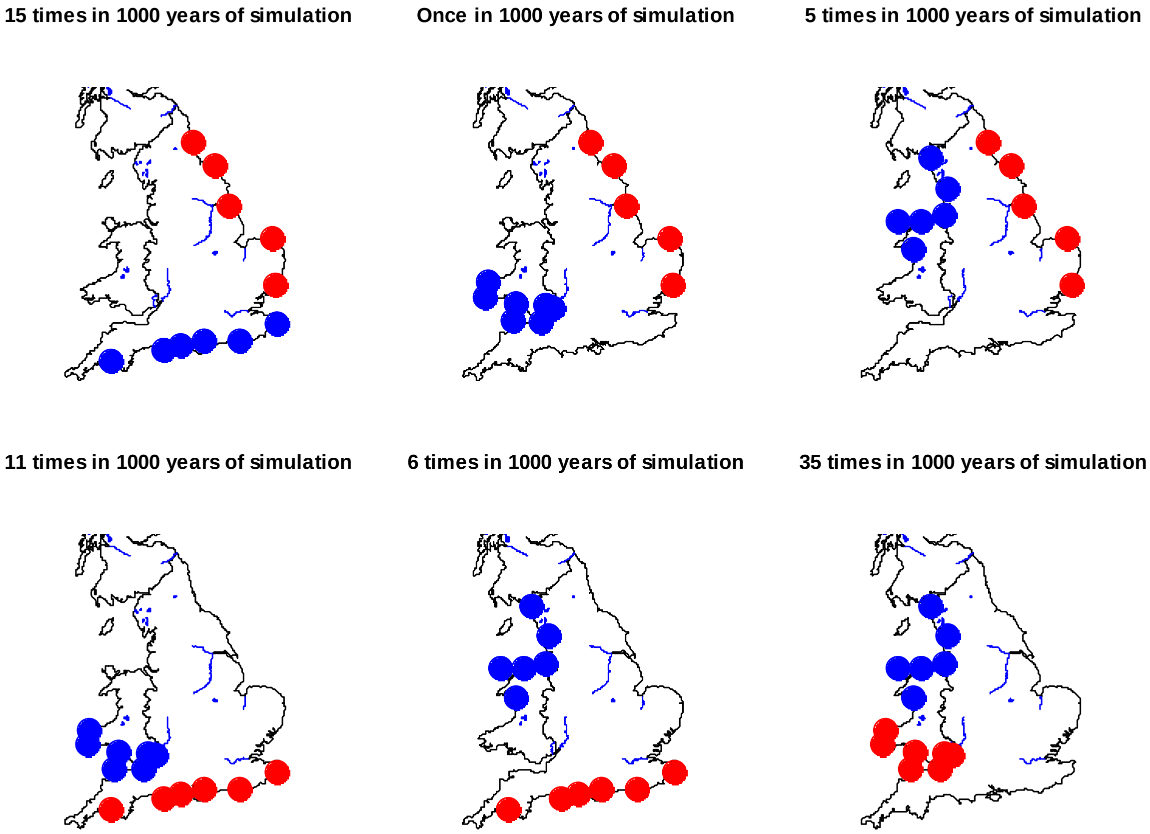


**Figure 7: Number of occurrences of storm events of a certain type in 1000 years of simulated record. Each event type is defined as having an extreme surge at any of the red sites, and at and of the blue sites.**

### 2.5.2 What is the risk of different patterns of river flood event?

There are many different ways in which flood event types can be defined. It is possible to define types as:

- Numbers of locations experiencing a high flow at the same time.
    - Different ways of defining a high flow.
- Numbers of locations experiencing a high flow within a certain time window.
- The proximity of locations experiencing a high flow at the same time.

To simplify the event typology we have used Environment Agency regions to define event types.

*Type 1 - All Environment Agency regions experience a 100-year flow somewhere within a nine-week time period*

This is one way to describe the Autumn-Winter 2000 event and occurred 15 times in the simulated record.

*Type2 – Four Environment Agency regions experience a 250-year flow somewhere within a five-week time period*

This is one way to describe the Summer 2007 event and occurred 52 times in the simulated record.

*Type 3 – Two geographically distinct Environment Agency regions experience a 50-year flow in the same week*

This event was inspired by the Morpeth 2008 event, which happened at the same time as flooding in South Wales. This type of event occurred 37 times in 1000 years of record.

*Type 4 – Two neighbouring regions experience a 50-year flow in the same week*

This type of event occurred 297 times in the simulated record.

*Type 5 – Only one region experiences a 50-year flow in a week*

This type of event occurred 941 times in the simulated record.

This event typology shows clearly that more widespread events are less likely than localised events. However, because each historic event can be described in a number of different ways, these simple event types do not allow us to fully describe the probability of experiencing an event that is similar to a historic event.

### 2.5.3 How unusual is the Autumn 2000 event?

To define this event we describe the most severe week (starting 6 November) in this event in a number of different ways. In this week four regions experienced a flow with an exceedance probability of 0.01 (a 100 year flow) and all eight regions experienced a flow with an exceedance probability of 0.04 (a 25 year flow). We also show how it is possible to define types of events by the numbers of gauging stations with a high flow. In this week 33 (out of 197) gauging stations recorded a 25 year flow and of these six recorded a 100 year flow.

In the simulated record (which is equivalent to 1000 years of record) there were 71 occurrences where at least four regions experienced a 100 year flow somewhere. This gives the week of 6 November 2000 a 1 in 14 chance of being exceeded in any given year.

In the simulated record there were 16 occurrences where at least four regions experience a 100 year flow, and all regions experience a 25 year flow. This gives the week of 6 November 2000 a 1 in 63 chance of being exceeded in any given year.

In the simulated record there were 49 occurrences when at least 33 gauging stations observed a 25 year flow and of these six additional gauges observe a 100 year flow in the same week. This gives the week of 6 November 2000 a 1 in 20 chance of being exceeded in any given year.

These results show that in order to assign a return period to an event, you must be very clear about what aspect of the event you are considering.

### 2.5.4 How unusual is the summer 2007 event?

To define this event we describe the most severe week (starting 19 July) in this event in a number of different ways. In this week three regions experienced a flow greater than a 100 year flow but no additional regions experienced a 25 year flow. In terms of gauging stations affected, 16 gauging stations experienced a 100 year flow, and an additional 10 experienced a 25 year flow.

In the simulated record there were 152 occurrences where at least three regions experienced a 100 year flow somewhere. This gives this week a 1 in 7 chance of being exceeded in any given year.

In the simulated record there were 40 occurrences when at least 26 gauging station observed a 25 year event and of these 16 observe a 100 year flow. This gives this week a 1 in 25 chance of being exceeded in any given year.

## 2.6 Generating event scenarios

The statistical model used in this work allows us to generate realistic, large scale flood event scenarios. In these generated scenarios the patterns of flooding are consistent with observed patterns in the gauged record. What is different to the gauged record is which gauging stations experience extreme flows or storm surges, and also how extreme the events are.

One benefit of this statistical method is that it is possible to extrapolate the observed events, and generate events that are more extreme than have occurred. As part of these additional case studies we have produced a movie file that shows real and simulated event scenarios side by side.

Figure 8 shows three simulated event scenarios, each of which have a 1 in 100 chance of being exceeded, in terms of ‘units’ of flooding, in any given year when units of flood risk are defined as an observation at a gauging stations exceeding the 50 year flow. There is variation between these scenarios in terms of the most extreme observations at any single location, the areas of the country affected, and the geographical spread of the event.

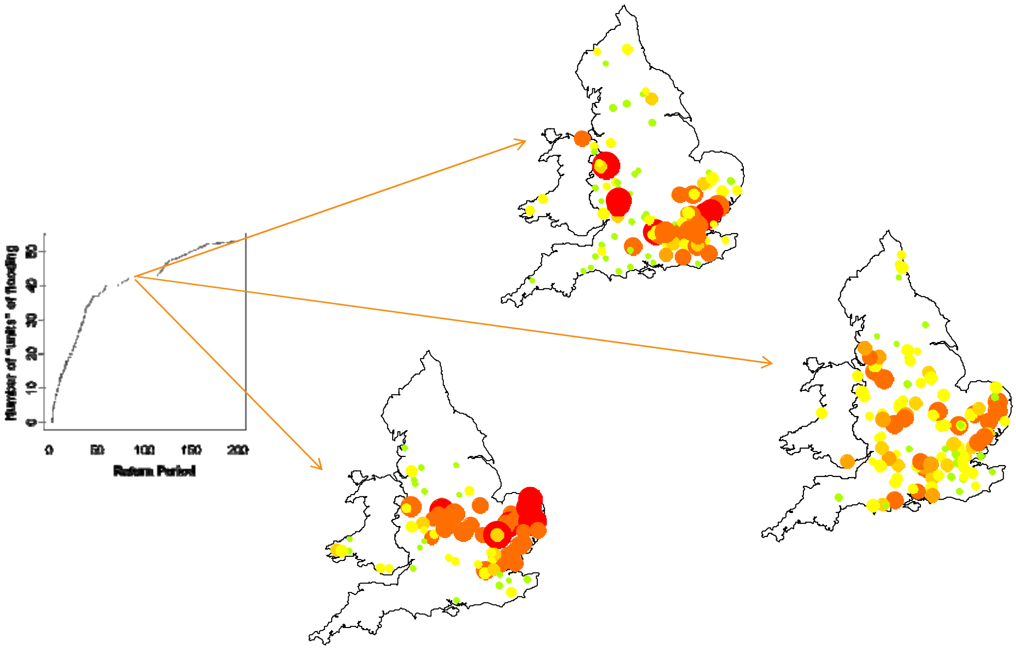


**Figure 8: Three different scenarios, each with a 1 in 100 chance of being exceeded in any given year in terms units of flood risk**

# 3 Conclusions

We have shown how it is now possible to answer a number of strategic flood risk management questions posed by the risk of widespread flooding.

We have demonstrated how national risk profiles for both river flooding and storm surge occurrence can be generated to reflect the risk of widespread flooding. Regional risk profiles can be produced in exactly the same way as these national results, by using a subset of the gauging stations, and any related economic data that relate to a single region. The SC060088 scoping study showed how these results could be extended to model economic damage or other consequences of flooding including the effects of flood defences.

The results shown in this case study illustrate how it is possible to estimate the occurrence probability of different types of flood events. The results shown here could be extended to estimate the probability of occurrence of other real events. However, the results for Autumn-Winter 2000 and Summer 2007 show that care should be taken in defining event types, as each real event can be defined in a number of different ways.

The analysis undertaken here also shows how the method can be used to generate plausible emergency planning scenarios.

One note of caution in using these results is that the period of record we have used is from 1960 to 2006, which is the only period of record for which we have flow data at a large number of sites. The number of flood events per year is not the same in each year, and on average there were fewer flood events in the 1980s than there have been in the 2000s. We have not attempted to assess any bias in our results due to using this relatively short period of record. To carry out any analysis of this type would require a large amount of additional data and also additional statistical modelling.

**Furthermore, the analysis conducted here does <u>not</u> consider the effects of surface water flooding which can play an important role as highlighted through the Summer 2007 floods. In the light of this, the results from this case study should only be seen as illustrations of what kind of applications are possible rather than as a definitive assessment of the likelihood of certain flood events.**

# 4 References

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