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The joint probability of pairs of variables relevant to flood risk: dependence mapping and best practice

Dr Peter Hawkes, Dr Cecilia Svensson & Dr Suresh Surendran

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THE JOINT PROBABILITY OF PAIRS OF VARIABLES RELEVANT TO FLOOD RISK: DEPENDENCE MAPPING AND BEST PRACTICE

Dr Peter Hawkes[1], Dr Cecilia Svensson[2] & Dr Suresh Surendran[3]

[1] *HR Wallingford Ltd*
[2] *CEH Wallingford*
[3] *Environment Agency*

Abstract

Flooding is often associated with the simultaneous occurrence of high values of two or more source variables, for example:

- waves with sea level for coastal flood risk
- fluvial flow with sea level for river flood risk
- intense rainfall with high sea or river level for urban flood risk

This paper introduces the results of a recently completed programme of research into the dependence between flood risk variables in the UK, intended to increase the take-up and reliability of joint probability methods within flood risk analysis and defence design.

Defra-funded joint probability research

Background

Understanding the risk posed by the combined effect of two or more extreme variables is important. MAFF, and now Defra, has funded a programme of research on joint probability, looking at the dependence between variables and how best to quantify their combined impact on flood and coastal defences. Research projects have focused primarily on its applications to waves and sea levels, (Hawkes *et al*, 2002, 2004; HR Wallingford, 2000a, 2000b; Owen *et al*, 1997) and to tides and surges (Proudman Oceanographic Laboratory, 1994, 1995, 1997). Joint probability methods have also been applied to rainfall, surge and river flow (Svensson and Jones, 2000, 2002), to river flow and sea level (Defra / Environment Agency, 2003) and to wind-sea and swell (HR Wallingford, 1997, 1998). For the last few years, joint probability research has been co-ordinated by the Risk Evaluation and Understanding Uncertainty Theme of the Defra / Environment Agency joint research programme.

Specialist joint probability analysis software named JOIN-SEA was developed by HR Wallingford and Lancaster University during the Defra-funded programme of research. The methods have been tested and applied in consultancy studies by the researchers involved, and benefits demonstrated, but take-up within the industry has been patchy. The Proudman Oceanographic Laboratory's published predictions of UK extreme sea levels are widely used in the industry. However, in both cases the subtleties of application have not always been appreciated outside the originating organisations, and in some instances they have not been applied to full advantage.

There are two main reasons given by users and potential users for their reluctance to embrace joint probability methods. One relates to the difficulty in understanding and applying the methods, and the other to the lack of published information on the dependence between variables.

Research project FD2308: Joint probability: Dependence mapping and best practice

The overall aim of the project was to identify and develop best practice guidance for application of joint probability methods to a range of situations, supported by mapping of dependence around England, Wales and Scotland for several relevant pairings of flood risk variables. The project was undertaken by HR Wallingford, CEH Wallingford and the Proudman Oceanographic Laboratory between January 2002 and March 2005. It continues the programme of dissemination and appropriate take-up of joint probability methods in flood and coastal defence design and assessment. No fundamental developments were made during the project. Instead, existing methods, analyses and knowledge were brought together, extended where necessary to include England, Wales and Scotland, and made available, intelligible and relevant to a greater number of users in the UK. The specific objectives of the project were to:

- involve and consult the wider industry including relevant research leaders and framework consultants on their joint probability requirements
- bring together recent joint probability work at HR Wallingford, CEH Wallingford and the Proudman Oceanographic Laboratory
- extend it where necessary to the whole of England, Scotland and Wales
- map dependence around and within England, Scotland and Wales for several variable-pairs relevant to flood and coastal defence
- develop best practice guidelines for when and how to use joint probability methods and results
- enable better use of joint probability methods by practitioners and policy makers, potentially leading to more effective flood risk assessment and management

The project analysed the dependence between flood risk variables around England, Wales and Scotland for several variable-pairs relevant to flood risk. Detailed results are presented in tables, and summary results in map format (Defra / Environment Agency, 2005a). The other main strand of the project was to provide best practice guidelines (Defra / Environment Agency, 2005b) for the use of joint probability methods in the UK. This focuses on a simpler desk study method (accompanied by a spreadsheet) and a more complex method for specialists. A third project report (Defra / Environment Agency, 2005c) provides additional specialist analysis and interpretation for hydrologists. It is hoped that the guidance, coupled with the dependence information, will encourage more engineers to take up joint probability methods.

The project included development of advice for use of joint probability methods in complex areas, affected by several different flood risk source variables (Defra / Environment Agency, 2005b, and a case study for the tidal Thames in HR Wallingford, 2004). It also included an investigation of the possible effects of climate change on dependence (Defra / Environment Agency, 2005a and 2005c). This paper is one of three Defra Conference papers produced during the project: Meadowcroft *et al* (2004) focus on the motivation for the study and the areas in which it might be used; Svensson and Jones (2005) focus on climate change impacts on dependence between sea surge, precipitation and river flow.

Dependence mapping

The flood risk variable-pairs analysed for dependence

The variable-pairs analysed and reported for dependence in Defra / Environment Agency (2005a) are:

- wave height & sea level

- wave height & surge
- tide & surge
- daily river flow & surge
- daily precipitation & surge
- hourly precipitation & sea level
- wind-sea & swell

The source data sets

As far as practical, consistent sources of data were used throughout the analyses. For most variables, this involved use of at least ten years of sequential measured data for at least twenty locations around Britain. One exception was wave data, where long periods of measured data are rare, and instead data were taken from a numerical model covering the seas around Britain. Details are given in Defra / Environment Agency (2005a) but a summary description is given in Table 1.

Not all data were used in all dependence analyses, but in each analysis, the maximum length of simultaneous data on the two variables involved was used. Pre-processing was applied differently to different variable-pairs, depending on the event definition used. This involved de-clustering of otherwise dependent records, selection of peaks over threshold values, division of waves into wind-sea and swell, division of records into seasons or direction sectors, and/or division of sea levels into tide and surge. Details of the analysis and pre-processing methods used are given in Defra / Environment Agency (2005a).

Analysis methods and presentations used

Different analysis methods were used, depending on the nature and resolution of the source data. Results are presented in the project reports (Defra / Environment Agency, 2005a, 2005b and 2005c) both as maps and tables. The maps incorporate a simplified version of the dependence results, common to all variable-pairs, in which dependence is presented as being in one of five colour-coded bands, referred as independent, modestly correlated, well correlated, strongly correlated and super dependent.

Two example dependence maps (based on colour originals in Defra / Environment Agency, 2005a and 2005b) are given in Figures 1 and 2.

Table 1 The source data sets used in dependence analysis

Hourly tide and surge	24 gauges, average duration 30 years, most recent year 2001
3-hourly waves and swell	21 points chosen from a 25km grid, April 1990 to March 2002
Daily river flow	130 measurement stations, 1963-2001
Daily precipitation	44 gauges, 1965-1997 on east coast, 1963-2001 on other coasts
Hourly rainfall	14 gauges (England and Wales only) mixed durations 1 to 30 years

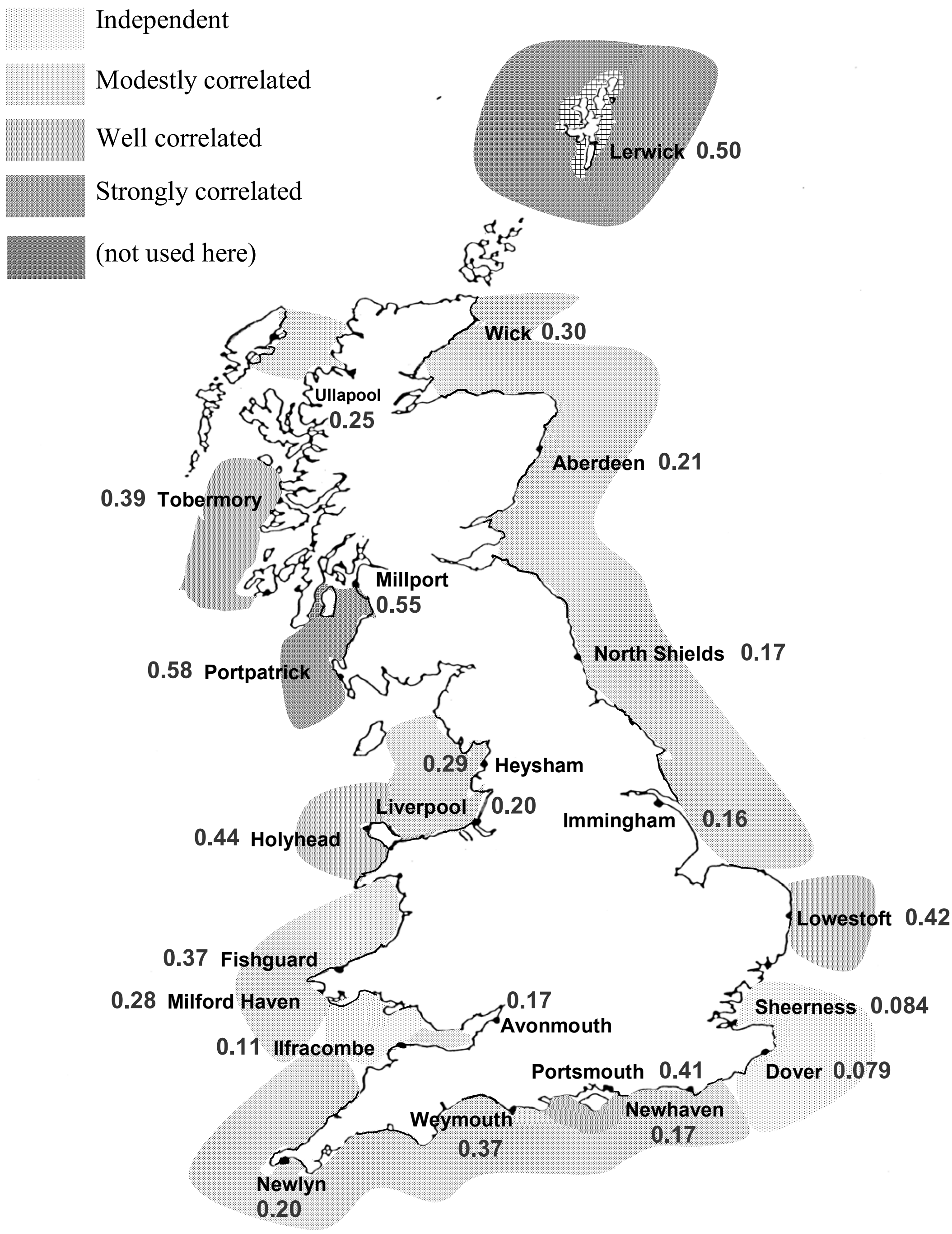


Figure 1 Correlation coefficient between wave height and high tide sea level

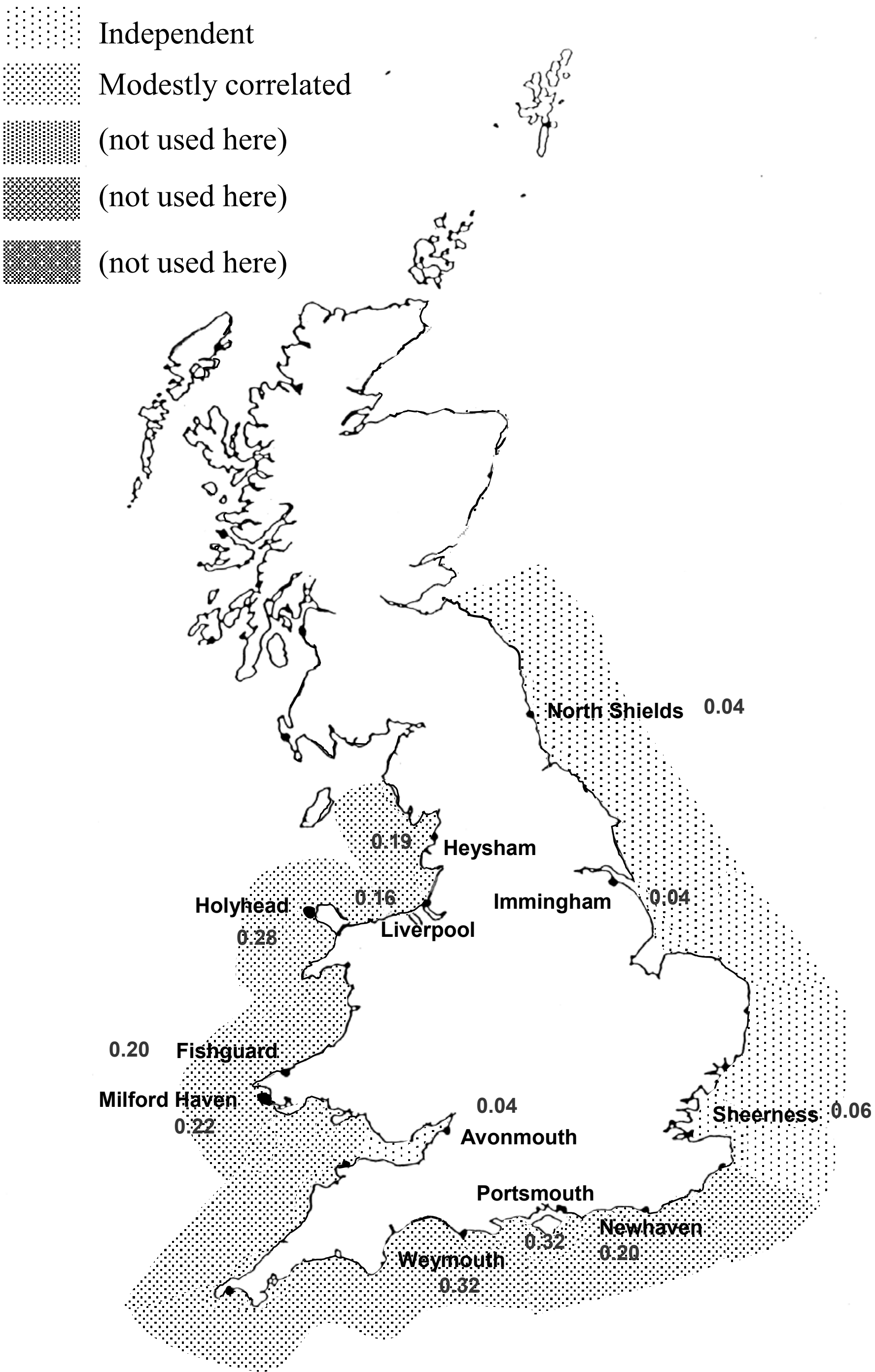


Figure 2 Correlation coefficient between hourly rainfall and high tide sea level

Climate change data sets and analysis

The German ECHAM4 climate model

This model, which has approximately one-degree spatial resolution, provided wind velocity and atmospheric pressure series, used as input to numerical tide and wave models, which produced surge, sea level and wave time series. For five locations around Britain, dependence analysis was applied to wave height and sea level (Defra / Environment Agency, 2005a). There was no significant difference in dependence between the present-day and future time slices at any of the five locations, suggesting no future change in dependence between wave height and sea level.

The Hadley Centre HadRM3 climate model

This 50km grid model, in combination with a shelf-seas tidal model, provided information relevant to both river and coastal flood risk, for 23 locations around Britain. The dependence between high surge and high precipitation was used to represent river flood risk, and the dependence between high surge and high wind speed to represent coastal flood risk. The levels and patterns of dependence around the country (Defra / Environment Agency, 2005a) are reasonably similar to those obtained from measurements, giving confidence in the data source.

The results consistently suggest a significant increase in dependence under the Medium-High Emissions Scenario, both for river and for coastal flood risk. The surge and precipitation analysis indicate approximately a doubling in the likelihood of high surge and high precipitation occurring together on the south and west coasts of the UK, and on the east coast of Scotland, due to increasing dependence. The surge and wind speed analysis indicate about a 50% increase in the likelihood of high surge and high wind speed occurring simultaneously north of a line between Weymouth to Lowestoft, due to increasing dependence. As predictions, confidence in these increases in flood risk would be low, but as projections, they are plausible and consistent with an increase in the number of deep depressions and a change in storm tracking noted to occur in the future climate run.

The best practice report and analysis methods described

The best practice guide

The best practice guide (Defra / Environment Agency, 2005b) is aimed at non-specialist users of joint probability methods, to encourage them to adopt and use joint probability methods without the need for specialist advice. The guide contains enough information for routine use of the joint probability methods. It also includes a 4000-word high level overview, which could be extracted together with example dependence plots, to be published separately in the form of an introductory booklet.

The guide includes a summary of the desk study and analytical approaches to joint probability analysis, and a software tool for application of the desk study approach. It includes advice on data preparation, parameter selection, application of the methods in complex areas, incorporation of climate change allowances, and interpretation of the results of the analysis. The variable-pairs presented, including enough dependence information for design calculations at most locations, are:

- wave height & sea level, relevant to most coastal flood defence studies
- river flow & surge, relevant to most tidal river flood defence studies
- hourly rainfall & sea level, of potential use in drainage studies in coastal towns
- wind-sea & swell, of potential use in coastal engineering studies

The guide includes outline case studies for each of the variable-pairs listed above, for each of the two main analysis methods. These include techniques for use in complex areas and for incorporation of climate change allowances.

This guide is supported by a separate longer technical report (Defra / Environment Agency, 2005a) containing more detailed information and description for experienced users. The technical report includes the project glossary, descriptions of the source data sets, derivation and comparison of the dependence measures used, and descriptions of the desk study and analytical approaches to joint probability analysis. It also includes a record of the industry consultation and a full set of dependence results, with confidence limits, including the additional variable-pairs not reproduced in the guide.

The desk study approach to joint probability analysis

The 'simplified method' for joint probability analysis is described in Section 3.5 of Defra / Environment Agency (2005a). It is based on the method described in Section 3.5.3 of the *Beach management manual* (CIRIA, 1996) for a joint exceedence return period of 100 years. It incorporates all of the CIRIA manual method, which remains valid, but extends it to one additional dependence band, and a number of additional joint exceedence return periods. It involves the use of tables of combinations of two variables, expressed in terms of their marginal return periods, pre-computed for a number of example joint return periods, levels of dependence and numbers of records per year.

The basis of the 'desk study approach' to joint probability analysis is the same but, as a computer assisted version is available, it is not limited to example pre-computed values or to the 'correlation factor' statistical model underlying the simplified method. The approach requires extremes of the first variable, extremes of the second variable and a single-parameter representation of dependence between the two. Time series and climate tables are not required (although they may well have been used in the course of deriving the extreme values).

The analytical approach to joint probability analysis

Only JOIN-SEA is described in any detail in the best practice guide, as its development and testing has been funded by Defra over a period of several years, and to provide a focus for those wishing to begin using a well established method. The focus on JOIN-SEA does not imply discouragement or criticism of similar approaches developed within other organisations, and many of the points made in the guide would also be applicable to other approaches.

The theory behind JOIN-SEA is outlined in Owen *et al* (1997) and Defra / Environment Agency (2005a), and detailed in HR Wallingford (2000a) in which development and testing of the method are also described. The key steps in the analysis are:

- preparation of input data
- fitting of marginal distributions
- fitting of statistical models for dependence
- long-term simulation
- analysis of joint exceedence extremes and structure functions

Outline case studies in the best practice guide

A number of outline case studies are given in the best practice guide (Defra / Environment Agency, 2005b) to illustrate the scope and use of the analysis methods. Parts of some of those case studies are described below.

Example application of the desk study approach to a coastal defence assessment

<u>The hypothetical coastal situation</u>

Consider a typical small coastal engineering study, on the north-east coast of England. The existing seawall, fronted by a shallow foreshore, is potentially subject to damage under attack by large waves and high sea levels, and is to be tested for standard of service based on an acceptable overtopping rate criterion.

<u>Select the variables and any conditions attached to those variables</u>

Although surge and swell may be of some interest, waves and sea level would be the normal variables to select for joint probability analysis in this situation. A preliminary assessment indicates that broadly northerly waves would have the largest wave heights offshore, and higher correlation with high sea levels than waves from more southerly sectors.

Decide whether to use offshore or nearshore wave conditions

The study could involve wave transformation modelling followed by one or more nearshore joint probability analyses, or an offshore joint probability analysis followed by wave transformation modelling. Either approach would work. However, unless the nearshore conditions required can be very closely specified, it is probably better to undertake the joint probability analysis offshore, where the dependence is purely meteorological, and representative of a larger area. Wave transformation modelling introduces hydraulic effects (e.g. wave breaking) into the dependence analysis, which may be extremely site-specific. A small change in location, or in climate change or other uncertainty allowance, may mean that calculations would need to be repeated.

Decide how the variables will be represented

Waves can be represented by specified wave heights and periods for discrete return periods between about 0.1 year and 200 years. Sea level can be represented by specified levels for discrete return periods between about 0.1 year and 200 years. (This step may not be so straightforward for the study of a larger area, or if waves from different sectors needed to be considered separately, but is included for completeness here.)

Obtain extreme values for the first variable, sea level

Extreme sea levels would usually require a brief site-specific review of existing predictions, but for illustrative purposes, the present-day values given in Table 2 were drawn directly from Proudman Oceanographic Laboratory (1997) for a location in north-east England. (Values for return periods below 1 year were estimated by the first author.)

Obtain extreme values for the second variable, waves

Extreme offshore wave conditions would usually require site-specific calculations, but for illustrative purposes, the following present-day values given in Table 3 were estimated, based on a previous HR Wallingford study for a location in north-east England.

Decide the level of dependence between the variables

Figure 1 indicates a correlation coefficient $\rho = 0.17$, or alternatively the ‘modest’ (second of five) level of dependence between large waves and high sea levels for north-east England.

Apply the desk study approach

The tables from which combinations of two variables with given joint exceedence return periods can be determined are given in Section 3.5 of Defra / Environment Agency (2005a). For illustrative purposes, consider only a 100 year joint exceedence return period. The relevant combinations of return periods (taken from Defra / Environment Agency, 2005a) are reproduced in Columns 1 and 3 of Table 4. The corresponding actual sea levels and wave conditions are given in Columns 2, 4 and 5.

Table 2 Example sea level input to coastal desk study

Return period (years)	0.1	0.25	0.5	1	10	25	50	100	250
Sea level (mOD)	2.80	2.96	3.09	3.20	3.53	3.68	3.77	3.91	4.05

Table 3 Example waves input to coastal desk study

Return (years)	0.1	0.25	0.5	1	2.5	5	10	25	50	100	250
H_s (m)	5.0	5.8	6.4	7.0	7.8	8.4	9.0	9.8	10.4	11.0	11.8
T_m (s)	8.0	8.6	9.1	9.5	10.0	10.4	10.7	11.2	11.5	11.9	12.3

Table 4 Example results from coastal desk study

Sea level		Wave conditions		
Return period (years)	Sea level (mOD)	Return period (years)	Height H_s (m)	Period T_m (s)
0.02	2.45	100	11.0	11.9
0.05	2.66	60	10.5	11.6
0.1	2.80	28	9.9	11.2
0.2	2.93	14	9.3	10.9
0.5	3.09	6	8.5	10.4
1	3.20	2.8	7.9	10.0
2	3.31	1.4	7.3	9.7
5	3.43	0.6	6.5	9.2
10	3.53	0.28	5.9	8.7
20	3.64	0.14	5.3	8.2
50	3.77	0.06	4.5	7.6
100	3.91	0.03	3.8	7.1
Each row notes a combination of large waves and a high sea level with a 100 year joint exceedence return period				

Apply the results of the desk study approach
Full results would be in the form of a table, similar to that illustrated above, for each joint return period of interest. Before use at the seawall, the wave conditions might need to be put through a wave transformation model. Following this, the lists of sea conditions can be converted into equivalent lists of overtopping rates, using appropriate equations. The highest overtopping rate calculated for each joint exceedence return period provides an approximation to the overtopping rate with the same return period. If the point at which overtopping rate becomes unacceptable can be decided, then the corresponding joint return period provides an indication of the standard of service of the defence.

Incorporation of precautionary allowances for future climate change
If sensitivity tests are to be made for the effects of uncertainty and/or future climate change, the changes to individual source variables are best applied to the results of the offshore joint probability analysis, before repeating the wave transformation and overtopping calculations. The current precautionary allowances (Defra, 2003) for north-east England involve addition of 4mm/year to sea level and 10% to wave height.

In addition to the climate change allowance for the individual variables, the potential increase in dependence between the variables may also need to be taken into account. The analysis of climate change impact upon dependence suggests a potential 50% increase in coastal flood probability. Sensitivity to this increase would most easily be tested by temporary use of a return period of 150 years in the calculations.

Example application of the analytical approach to an urban drainage assessment

Outline of the case study

Consider a hypothetical drainage flood risk analysis for a large coastal town, on the south coast of England. Stormwater drainage from the town discharges into the sea at a single point, and the drainage system would potentially be at risk of being unable to discharge stormwater runoff during intense rainfall coupled with a high sea level. To simplify the analysis, assume that this is the only possible failure mode of an existing drainage system. Test the system for standard of service based on two criteria, one representing the onset of street flooding, and the other representing the onset of significant flooding of houses.

Selection and preparation of source data

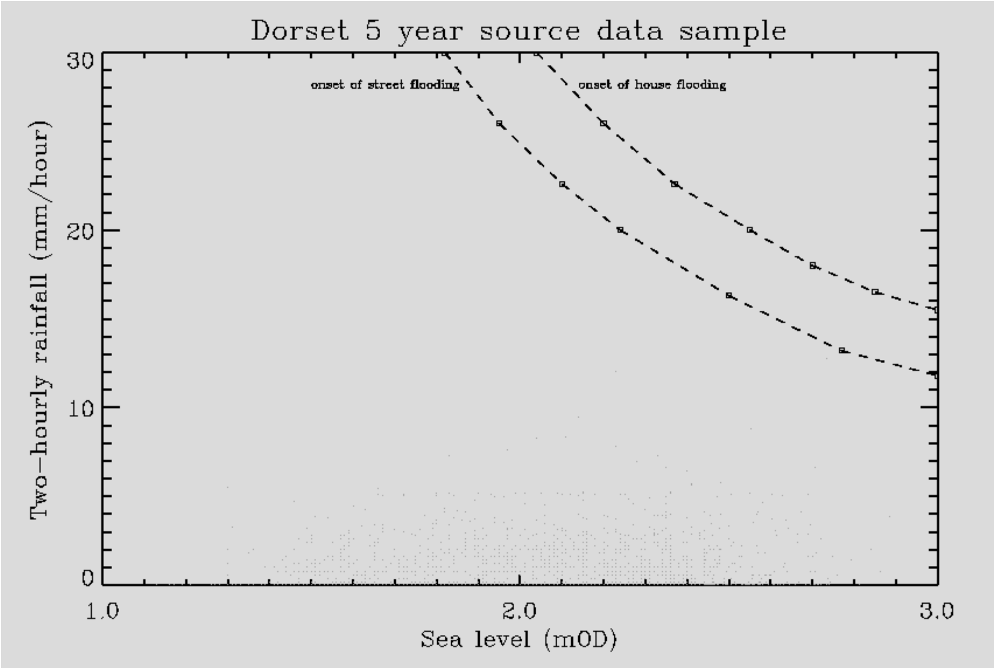
The source variables of interest in this case study are sea level and short duration rainfall. The appropriate duration over which to characterise rainfall depends on the size and speed of response of the drainage system to rainfall. For illustrative purposes, two-hours is used here. As high intensity rainfall and high surge events tend to last for less than one day, a reasonable compromise between the need to use all of the source data and the need for successive records to be independent of each other is to take one record at each high tide. Had there been sufficient data close to the site, the data would have been prepared for joint probability analysis by extracting each high water level, and matching it with the highest rainfall intensity, averaged over two consecutive hours, within six hours of the time of the high tide. Instead, for illustrative purposes, an artificial five-year duration 'source' data sample was prepared, to be reasonably representative of the Dorset coast. The sample contained one record per high tide, i.e. 3535 records over five years. The distribution and extremes of sea level, and its dependence ($\rho = 0.32$, see Figure 2) with rainfall, were based on those measured by the Weymouth tide gauge. High and extreme rainfall was based on the values typical of the south coast of England.

Long-term simulation of rainfall and sea level

Distribution fitting and Monte Carlo simulation of a thousand year sample were carried out using JOIN-SEA (HR Wallingford, 2000a). The 'source' and long-term simulation data sets are shown together in Figure 3, in the form of scatter diagrams of rainfall against sea level. In a real flood risk study, it may be desirable to use the option to re-scale high and extreme values during the long-term simulation, in order to achieve target marginal extremes for rainfall alone and/or for sea level alone, derived outside the joint probability analysis. This was not done here, as it would obscure the link between the source and long-term simulation data.

Estimation of standard of service from the long-term simulation

To illustrate how the long-term simulation could help in estimating flood risk, two hypothetical failure criteria are drawn on each of the scatter diagrams in Figure 3. The area above the lower line ('onset of street flooding') represents combinations of rainfall and sea level where the drainage system would be over-loaded and water would begin to flood into the street. Similarly, the upper line ('onset of house flooding') represents the onset of significant flooding of houses. The positions of these lines might be based on past experience of flooding in the town, or on urban drainage numerical modelling indicating which input conditions cause flooding (and which do not). The probability of occurrence of such conditions can then be estimated by counting the numbers of occurrences above these lines in the scatter diagrams.



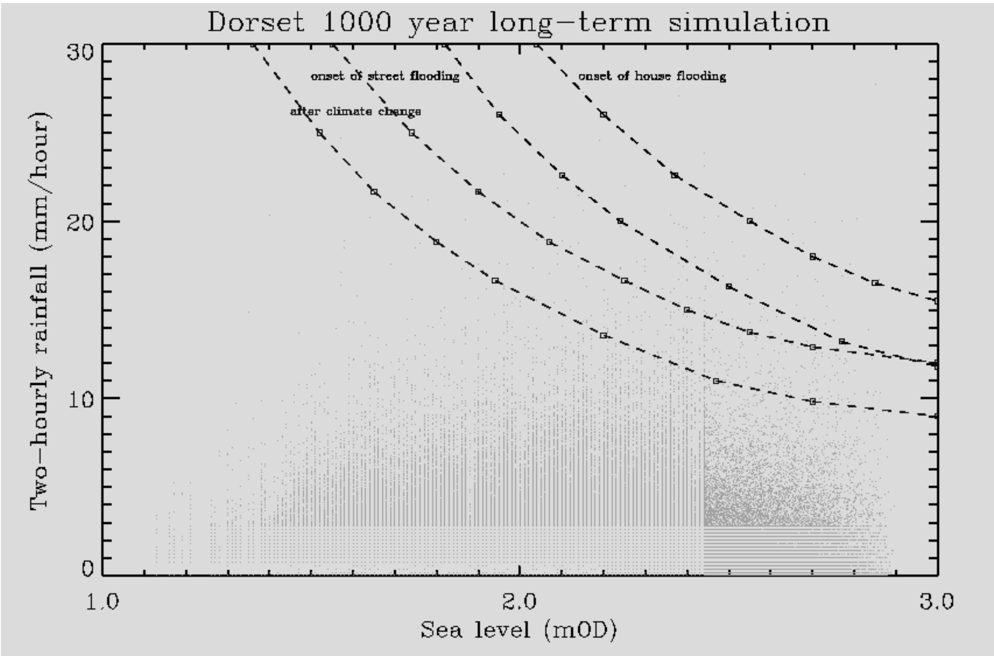


Figure 3 Drainage case study: source and long-term simulation data, failure curves overlaid

The source data plot contains one data point close to the lower failure line, suggesting that street flooding would have been close to occurring once over a five year period, in turn suggesting a return period of a little over 5 years, but with a large margin of uncertainty. Similarly, the source data plot suggests that the return period for house flooding would be much higher than five years. The long-term simulation plot shows 57 points above the street flooding line, including 17 points above the house flooding line, in one thousand years. Although there may still be uncertainties about the source data, the extrapolation, and the drainage system modelling, the long-term simulation thus provides direct estimates of the standard of service, in terms of the two flood criteria, of 18 and 59 years.

Incorporation of climate change allowances
The sensitivity of the effectiveness of a flood defence or drainage system to future climate change can be tested by assuming that the source variables will change in line with current climate change projections but that the defence or drainage system will not change. If future climate change can be represented in terms of simple adjustments to the source variables, then the long-term simulation allows a direct calculation of the sensitivity of the failure probability to those adjustments.

For illustrative purposes, apply future climate change over the next fifty years consistent with the current Defra (2003) precautionary allowances, i.e. 20% increase in high and extreme rainfall intensity, and 0.3m increase in mean and extreme sea level on the south coast of England. In a real study, these two adjustments would be applied to every record in the long-term simulation, and the failure probabilities re-calculated. For ease of comparison in this case study, the source variables are left unchanged, but the two failure curves are re-plotted (over the 1000 year simulation in Figure 3) to reflect the climate change allowances (sea level 0.3m lower; rainfall divided by 1.2).

Using the same counting technique, the return period for street flooding would reduce from 18 years to 3 years, and for house flooding from 59 years to 8 years. One might conclude from this hypothetical assessment that, although the drainage system offers an adequate (20-60 year) standard of service at present, it would become inadequate (3-8 year standard) under the climate change scenario considered.

In addition to the climate change allowances for rainfall and sea level, one might also consider the impact of a potential future increase in dependence between the variables. The analysis of climate change effects upon dependence suggests a potential 100% increase in rainfall-related flood probability, meaning that the future standard of service could fall as low as 1.5-4 years. Alternatively, the impact of this climate change allowance could be investigated through production of a second long-term simulation, incorporating an appropriately higher value of dependence.

Special considerations in complex areas

Joint probability analysis at a single location can usually be reduced to just two primary flood risk source variables. As the area covered by the flood risk analysis grows larger, some of the following difficulties may develop:

- more than two types of source variable may be important, e.g. sea level, waves and river flow
- more than one value of a single type of variable may be needed to represent conditions across the area, e.g. different wave conditions along a frontage, or different river flows in different rivers
- control of spatial coherence between different parts of the area may become an issue for overall flood risk and estimation of extreme losses
- time lag between peak values of different variables may become more important in prediction of their combined effect on flood risk

The last of these points is the easiest to accommodate. An appropriate time lag is estimated beforehand and is carried through the data preparation, joint probability analysis and application stages. The techniques below (which can be combined) offer some assistance in addressing the first three points above. They are illustrated in Defra / Environment Agency (2005b) with reference to how they might be applied in the outer Thames.

Use of conditional analyses (or division of populations)
This technique is common in coastal engineering, where joint probability analysis

of large waves and high sea levels may be divided into a small number of discrete and mutually exclusive direction sectors. It might also be applied to a small number of different durations of rainfall or river flow. Wave direction (or rainfall duration) then becomes the 'condition', and the records meeting that condition provide a 'population'. Each population can then be analysed separately, with the appropriate number of events per year and marginal extremes for the proportion of data meeting the condition. Each set of joint probability results should then be considered as a potential worst case.

Evaluation of a source variable at just one representative location
This is a commonly used technique, in which the joint probability analysis is based on the value of a source variable at just one location, which is later used to reproduce dependent values at other locations. This is usually adequate for sea level, which varies in a fairly predictable way along a length of coast. Similarly it will often be appropriate to calculate wave conditions offshore and then to infer equivalent conditions at several nearshore locations. The method might also be extended, but with much greater caution, to rainfall or river flow, by assuming that conditions are strongly dependent on those occurring in neighbouring catchments.

Use of proxy source variables
This is a similar technique to the previous one, but less often used. It may be possible to work in terms of a different underlying source variable, from which the flood risk variables can later be re-constructed. An example is the use of wind speed (usually conditional upon wind direction) as a proxy variable for later input to multiple wave prediction models. Similarly, rainfall (perhaps conditional upon duration) might be used a proxy variable for later input to multiple river flow prediction models.

Acknowledgements

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In keeping with the aims of the research programme, all direct products of this project are freely available. Items marked with an asterisk in the reference list are available in pdf format on request to the first author at pjh@hrwallingford.co.uk. The main contents of the three project reports (Defra / Environment Agency, 2005a, 2005b and 2005c) will be available from the Defra web-site towards the end of 2005. At the time of writing, interim versions of Defra / Environment Agency (2005a and 2005c) were available from web-page:

http://sciencesearch.defra.gov.uk/Default.aspx?Menu=Menu&Module=FJPProjectView&Location=None&ProjectID=10201#Description

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Working with water

HR Wallingford Ltd
Howbery Park
Wallingford
Oxfordshire OX10 8BA
UK

tel +44 (0)1491 835381
fax +44 (0)1491 832233
email info@hrwallingford.co.uk

www.hrwallingford.co.uk