DEPARTMENT for ENVIRONMENT, FOOD and RURAL AFFAIRS **CSG 15**

Research and Development

Final Project Report

(Not to be used for LINK projects)

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Project title	Joint probability of extreme estuarine water levels
DEFRA project code	**FD0206**
Contractor organisation and location	HR Wallingford Ltd Howbery Park, Wallingford Oxfordshire OX10 8BA
Total DEFRA project costs	£ 196,420
Project start date	01/04/97
Project end date	31/07/2000

Executive summary (maximum 2 sides A4)

1 OVERALL SUMMARY

The intention of the project was to refine methods for determining the return periods of extreme (design) water levels in estuaries, taking account of the joint occurrence of tides, surges, flows and waves. It included a review of data sources, single variable extrapolation methods, data requirements, methods of assessing and representing dependence between variables, and multi-variable extrapolation methods.

For situations where two or more source variables are important, this project addressed the issue of how those variables should be combined, to determine a combined event with a given probability of occurrence, before input to hydraulic models or design methods. It would be relatively easy to deal with the combination of either independent or fully dependent variables, but in practice the variables are usually slightly correlated to an extent best determined from site-specific data.

Joint probability methods developed for the combined action of large waves and high sea levels on sea defences were adapted to the potentially more complex problem of the combined action of river flows, sea levels and waves in estuaries and rivers. No new hydraulic modelling techniques were developed, but the statistical methods developed, tested and validated should allow better estimation of the frequency of occurrence of extreme conditions driven by two or more of the primary input variables.

The present project followed on from several years' work on joint probability analysis methods aimed at refining predictions of extreme sea conditions at the coast. These methods were disseminated for use by UK coastal engineering consultants, and have now come into routine use in UK studies. Further development of the methods to the potentially more complex situation of overall water levels in estuaries was a natural continuation of the joint probability theme, funded by MAFF (now Defra) over a 3-year period beginning in Summer 1997.

Preliminary exploratory analysis is an important part of the joint probability approach, to check that all relevant input variables are included in an appropriate way, and to discover if any potentially relevant variables can be excluded from full analysis without significant reduction in accuracy. This preliminary stage also investigates dependences and time lags between peak values of variables, and determines a suitable 'event' definition needed for data handling.

The statistical analysis determines the distributions and extremes of the input variables, and any dependences between them, before using these fitted distributions to synthesise a very large sample of data with the same joint probability density as the original input data. This sample can then be used to derive joint exceedence extremes, if required. The extrapolated joint density or the joint exceedence extremes are converted to end variables of interest (overall water level, failure, economic loss etc) using hydraulic models or structure function formulae.

A separate element of the project examined the dependence between high surges and high river flows on the east coast of England and Scotland. The analysis covered the likelihood of high values of both variables occurring simultaneously at a single location, and also any spatially or temporally separated dependences. This provided information for use in river flood risk studies and assisted understanding of the underlying meteorological reasons for dependence.

These joint probability developments are not intended to replace better established methods for flood studies, but rather to assist in selecting appropriate combinations of inputs, and to refine the corresponding prediction of overall return periods.

A small project extension involved the preparation and presentation to a number of invited UK specialists of a workshop at Wallingford in December 1998 on joint probability methods and applications.

As FD0206 was one of an ongoing series of MAFF (now Defra) funded joint probability projects at HR Wallingford, several publications were produced during the project on related work on the same theme. Although development may not have been funded directly under FD0206, these publications are listed within the bibliography in the scientific report below.

2 SUMMARY OF EACH YEAR'S WORK

During 1997/98, the project began by reviewing data sources, single variable prediction methods, data requirements, methods of assessing and representing correlation between variables, and extrapolation methods. Standard two-variable joint probability analyses were applied to waves plus sea levels, waves plus flows, and sea levels plus flows. A workable three-variable (river flow, wind/wave and open sea level) analysis method was thus developed and demonstrated.

During 1998/99, the three-variable approach was developed further for more routine use, in the form of a Tri-Variate version of the existing Bi-Variate Normal statistical model. This was tested for several simulated data sets and different degrees of correlation between the three related variables. Joint probability methods for prediction of extreme estuarine water levels were classified into six alternative categories, based on the number and type of variables involved and the combinations of hydraulic and statistical modelling used. Different combinations of variable types, river models and statistical approaches can be used depending on data available and on which variables are important. The Severn was chosen to demonstrate and test different aspects of the methodology, with several other estuaries being used on an opportunistic basis to test individual site-specific analysis methods.

During 1999/2000, data for the Severn and Taff were gathered, and hydraulic models were re-commissioned and validated. Long simulations were undertaken for both rivers to demonstrate the various statistical approaches to derivation of extreme water levels. Results from the different approaches were compared and validated against measurements at intermediate points in the rivers. Constitution of an 'event' proved to be a much bigger issue than in coastal joint probability: for example, whether to use all hourly data, one event per tide, peaks over threshold, annual maxima etc; also, having determined the nature of an event in physical terms, how to represent it numerically in a way that could be used within the analysis.

Also during 1999/2000, the dependence was determined for a large number of long time series for the east coast of the UK, relating to river flows, sea levels and rainfall. Each pairing of data sets (whether of the same type or across different types, or for nearby or distant gauges) was examined for signs of dependence between the highest values. Where such evidence was found, this was further assessed for its significance in terms of meteorological and/or hydraulic links. The hope was to provide help in estimating correlation between the relevant variables in cases where no simultaneous data are available.

During 2000/01, final research efforts prior to production of an interim overall report concentrated on refining, automating and validating various aspects of the data preparation, analysis method, interpretation of results and assessment of uncertainties. At a late stage in the project, the opportunity arose to apply one of the new developments within the Thames Tidal Walls Strategy Study. This involved the use of joint probability analysis of wind speeds and sea levels at Southend, from which varying water levels and wave conditions could be determined by hydraulic modelling throughout the study area. The work on surge, river flow and precipitation was completed. Interesting indications, with tentative meteorological explanations, can be seen in the correlation results, including some time-lagged correlations and some noteworthy lacks of correlation. A project report was issued and a journal paper was prepared.

During 2001/02/03/04, the methods were applied on a number of consultancy studies and an overall final report on the project was issued.

Scientific report (maximum 20 sides A4)

1 Introduction

Project FD0206 reviewed, developed and demonstrated methods for determining the return periods of extreme (design) water levels in estuaries, taking account of the joint occurrence of tides, surges, flows and waves. It was guided and monitored by an external Joint Probability Topic Group, meeting three or four times per year. Progress reports were prepared and discussed at the meetings. Closely related research was undertaken within completed Project FD1704 (Joint probability: Dissemination, beta-testing and alternative applications) and ongoing Project FD2308 (Joint probability: Dependence mapping and best practice) due for completion in February 2005.

The main element of FD0206, undertaken by HR Wallingford, is described in Section 2, covering joint probability analysis of variables coming together to cause high water levels in estuaries and rivers. A second element, undertaken by CEH Wallingford, is described in Section 3, focusing on the dependence between surge, river flow and precipitation in eastern Britain. A third small element, undertaken by HR Wallingford, is described in Section 4, relating to continued dissemination of joint probability methods developed previously. Section 5 mentions further dissemination of the results of earlier work at HR Wallingford on swell and bi-modal seas. Section 6 lists the papers, reports and presentations associated with FD0206.

2 Joint probability extreme estuarine water levels

The project began by reviewing data sources, single variable prediction methods, data requirements, methods of assessing and representing correlation between variables, and extrapolation methods.

One of the main theoretical developments was a workable three-variable (river flow, wind/wave and open sea level) analysis method. This was demonstrated using 20 years of field data from an estuary in south-west England. Standard two-variable joint probability analyses were applied to waves plus sea levels, waves plus flows, and sea levels plus flows. Results were combined to produce a three-dimensional surface representing the three-variable joint probability of waves, flows and sea levels, from which the overall extreme water levels could be determined. The three-variable approach was developed further for more routine use, in the form of a Tri-Variate version of the existing Bi-Variate Normal statistical model. This was tested for several simulated data sets and different degrees of correlation between the three related variables.

The decisions and steps involved in applying joint probability analysis are summarised below:

1. Clarify which end-variable(s) and/or decision(s) are required (e.g. overall water level, economic loss, whether to improve defences); also the value of the work, to give an idea of the appropriate level of modelling and analysis.
2. Search for existing data, models and reports for the estuary area of interest; set up a numerical river model if necessary; consider whether river control structures and/or out-of-bank flows may affect the use of statistical distributions.
3. Conduct preliminary trials to determine which variables are important in different areas, and how much of each is already included in any measurements to be used.
4. Pre-process the input data, possibly involving hydraulic modelling, to reduce the number of primary variables or to produce more directly relevant variables.
5. Determine the appropriate event (record) definition, including the time interval between records, taking account of hydrograph duration, the need for independence between records, and the later need to re-construct events from a limited number of parameters.
6. Select and execute a statistical analysis method to simulate the joint distribution and extreme combinations of the input variables.

7. Decide the form and parameters of the main results to be produced by the analysis and how they will relate to the required end-variable or decisions to be made.
8. Calculate extreme water levels from the statistical results (this will often involve hydraulic modelling).
9. If possible, check the results against independent simpler methods or expectations.

The statistical analysis approach adopted is highly dependent on what data are available, on which are the most important variables at the location of interest within an estuary, and on the intended use of the analysis results and the decisions to be made. Hydraulic modelling may be an integral part of the procedure, to reduce the number of variables prior to analysis, or may be needed to make practical use of two- or three-variable statistical outputs.

The classification system adopted here is based on the number and type of primary variables (sea level, river flow, waves and/or estuarine water level) used in the statistical analysis. Table 1 summarises the defining characteristics of six alternative classes of analysis method.

Table 1 Classification of alternative statistical approaches

Method No	No of primary variables	Type of input variables	Product of statistical method
1	1	Measured overall water level data near to the site (e.g. nearby tide gauge)	Direct 1-variable extrapolation of measured overall water level
2	2 (reduced to 1)	Flow and sea level data transformed by hydraulic modelling to equivalent overall water level data at the site	Direct 1-variable extrapolation of synthesised overall water level
3	2	Measured flow and sea level data, used directly in two-variable statistical analysis	2-variable simulation and extreme combinations of flow and sea level; use as input to hydraulic modelling
4	2	Synthetic wave data, and measured or transformed sea or river level data, used directly in two-variable statistical analysis	2-variable simulation and extreme combinations of waves and sea or river levels; may be directly useful or may require the use of structure functions
5	3 (reduced to 2)	Synthetic wave data, plus flow and sea level data transformed by hydraulic modelling to equivalent water level (due to sea level and flow) data at the site	2-variable simulation and extreme combinations of waves and water levels; may be directly useful or may require the use of structure functions
6	3	Synthetic wave data, and measured flow and sea level data, used directly in three-variable statistical analysis	3-variable simulation and extreme combinations of waves, flows and sea levels; use as input to hydraulic modelling
Note: Secondary variables such as wind set-up, wave set-up and wave period can be incorporated as a function of wave height, but for inclusion of wind set-up in Methods 2 and 3, additional calculations may be needed.			

Methods 1 and 2 are single-variable approaches, working directly in terms of the structure variable of interest. Method 1 could be used only if long-term measurements of water level were available close to the location of interest, when an appropriate single-variable extrapolation method could be applied directly to the measured data. Method 2 relies on similar long-term water level data being able to be generated from corresponding long-term flow and sea level measurements, probably by continuous simulation using a numerical river model, followed again by single-variable extrapolation of the river water level data.

Methods 3 and 4 are two-variable joint probability approaches, working in terms of the joint distribution of flow and sea level, or of waves and sea level, respectively. (Waves and flow could be treated similarly, but this is an unlikely combination). A two-variable approach would be applicable if it had been shown in preliminary work that the two variables concerned were important and that the third variable (waves in Method 3 and flow in Method 4) was not important. It also requires that simultaneous sequential data are available for the two variables (in the case of waves, this would probably mean the wind data needed for hindcasting, rather than measured wave data being available). In Method 3, the resulting combinations of flow and sea level (now with estimated probabilities of occurrence) would probably be used as input to numerical river modelling. Similarly for the results from Method 4, except that structure functions such as overtopping or armour size would be used instead of a river model.

Method 5 is applicable where sea level, flow and waves are all important, but where the three variables can be reduced to two, using continuous simulation numerical river modelling to reduce the separate flow and sea level data to equivalent river water level predictions for a particular location. The resulting two-variable analysis is then applied to water level (due to sea level and flow) and waves. The resulting combinations of water levels (due to sea level and flow) and waves would probably be used as input to structure functions such as overtopping or run-up.

Method 6 is a full three-variable joint probability approach for use where sea level, flow and waves are all important enough to be considered as partially dependent primary variables. How to use the resulting three-variable combinations of flow, sea level and waves may not be obvious, and should be considered before embarking on the analysis. It would probably involve a mix of hydraulic modelling and structure functions, applied to a large number of combinations of conditions, perhaps in order to determine an overall probability of flood risk or an overall flood management decision.

Figure 1 highlights some of the factors to consider in selecting an appropriate class of joint probability analysis method for use in estuaries and tidal rivers. It is not intended to be prescriptive, but rather to illustrate the importance and relevance of some of the main decisions involved in making an appropriate choice from amongst Methods 1-6. Figure 1 includes four questions (in diamond-shaped boxes) and allows for six alternative answers (in rectangular boxes with rounded corners) to the question ‘What data are available’ leading to one of the six alternative methods (in bold in Figure 1).

Because of the data, previous reports and hydraulic models already available, and their representation of two different types of river, the Severn and the Taff were chosen to demonstrate and test different aspects of the methodology. Data for these rivers were gathered, and hydraulic models were re-commissioned and validated. Long simulations were undertaken for both rivers to demonstrate the various statistical approaches to derivation of extreme water levels. There were time series sea level data from Avonmouth, flow data at Haw Bridge and elsewhere, and wind data from Cardiff from which to hindcast waves (and wind set-up). JOIN-SEA showed a small positive correlation between river flow and sea level. Combinations of upstream river flow and downstream sea level were run in the iSIS numerical river model. Results from the different statistical approaches were compared and validated against measurements at intermediate points in the river.

Constitution of an ‘event’ proved to be a much bigger issue than in coastal joint probability: for example, whether to use all hourly data, one event per tide, peaks over threshold, annual maxima etc; also, having determined the nature of an event in physical terms, how to represent it numerically in a way that could be used within the analysis.

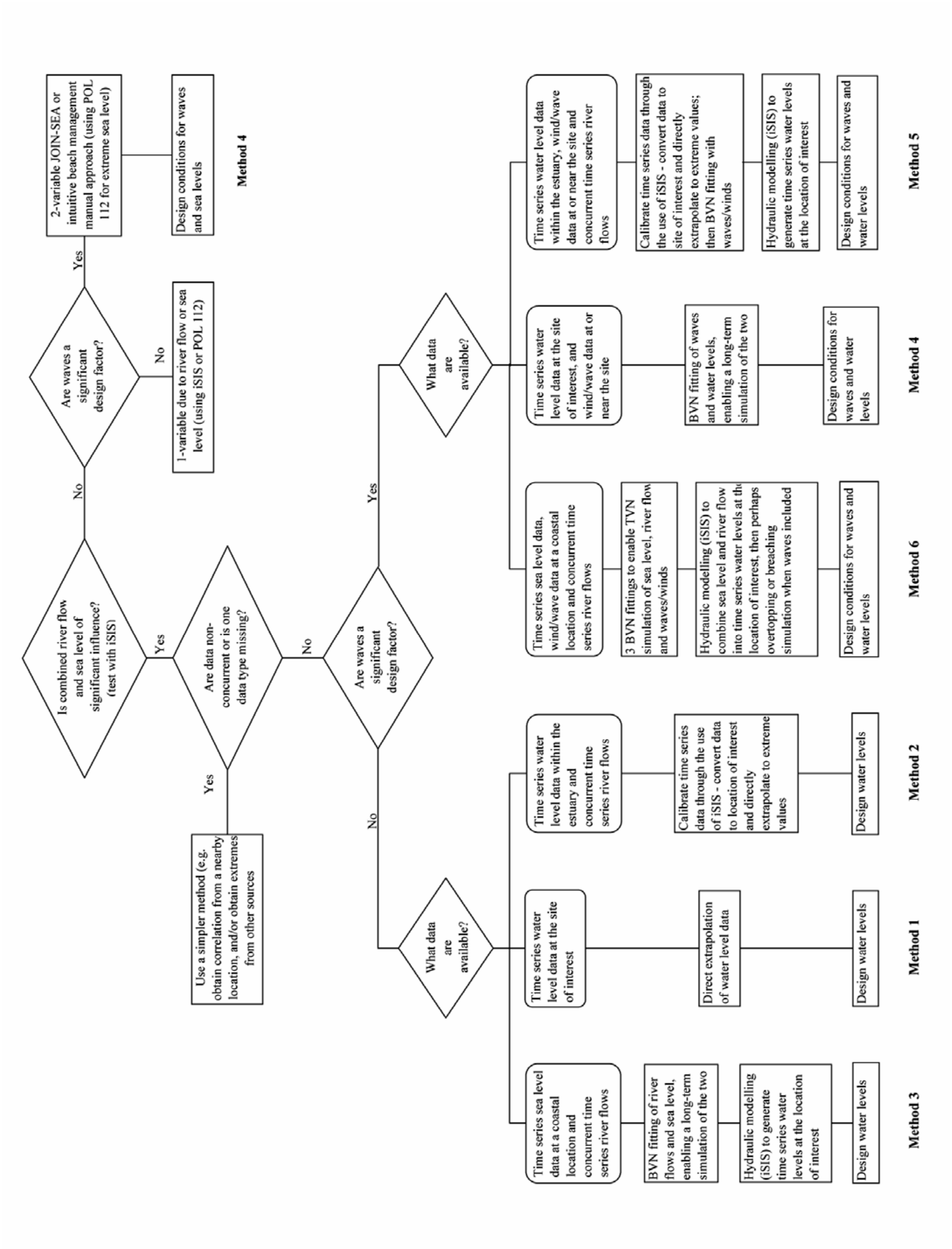

Figure 1 Selection of analysis method from alternative statistical approaches

Final research work during the project period concentrated on refining, automating and validating various aspects of the data preparation, analysis method, interpretation of results and assessment of uncertainties. At a late stage in the project, the opportunity arose to apply one of the new developments within the Thames Tidal Walls Strategy Study. This involved the use of joint probability analysis of wind speeds and sea levels at Southend, from which varying water levels and wave conditions could be determined by hydraulic modelling throughout the study area.

Following the formal end of the project, the methods were applied in several further consultancy studies at HR Wallingford. Interesting points from some of these studies, including preparation of data and selection of statistical approach, have been summarised in the overall project report (Defra / Environment Agency, 2003) as examples of how the methods might be applied.

<u>3 CEH Wallingford subcontract on dependence between surge, river flow and precipitation in eastern Britain</u>

The approach was to analyse a large number of long time series for the east coast of the UK, relating to river flows, sea levels and rainfall. Each pairing of data sets (whether of the same type or across different types, or for nearby or distant gauges) was examined for dependence between the highest values. Where such evidence was found, this was further assessed for its significance in terms of meteorological and/or hydraulic links. The hope was to be able to identify natural dependence between these measured data sets to provide help in estimating correlation between the relevant variables in cases where there are no simultaneous data available. Significant indications, with tentative meteorological explanations, can be seen in the correlation results, including some time-lagged correlations and some noteworthy lacks of correlation. A project report (Svensson and Jones, 2000) and a journal paper (Svensson and Jones, 2002) were produced. (The analysis was later extended to the whole of England, Wales and Scotland, as part of the subsequent Defra-funded research project FD2308.) The abstract of the journal paper is reproduced (with slight editing) below.

Flooding in estuaries may be caused by both high river flows and by high sea levels. In order to investigate whether these tend to occur simultaneously in eastern Britain, the dependence between high sea surge (observed sea level minus predicted astronomical tide), river flow and precipitation was studied using a measure of dependence specially developed for extremal dependence. Extreme events were interpreted using meteorological maps. This new analysis found that the strongest flow-surge dependence occurs between river flow on the north shore of the Firth of Forth and sea surge at Aberdeen, Wick and Lerwick. In contrast to most other catchments in eastern Britain, the area to the north of the Firth of Forth is not sheltered from south-westerly winds by any major topographical barrier. Therefore, precipitation from this direction may be orographically enhanced as it encounters the hills on the northern side of the firth, and high river flows may ensue. Events resulting in both high river flow and surge in the northern part of the study area were found to be caused by cyclones travelling north-eastward to the north of Scotland. High surge events, only, were associated with similar storm tracks, but without much precipitation from the fronts. High river flows, only, were associated with rain-bearing east-west-directed fronts over northern Britain, with slow-moving depressions located over or to the west of the British Isles where they are unable to generate a strong surge in the North Sea. The dependence between river flow and surge was found to be stronger during winter than summer, and a lagged analysis revealed that the dependence is strongest when flow and surge occur on the same day, but was also strong for lags of plus and minus one day. For precipitation, the dependence with both flow and surge is strongest when precipitation precedes them by one day.

<u>4 Joint probability of large waves and high sea levels (continued dissemination of earlier related work)</u>

A MAFF-sponsored specialist workshop on extreme water levels and joint probabilities was held at HR Wallingford on 3 December 1998. About fifteen external specialists were invited, in addition to MAFF and the researchers involved. Reports on the joint probability methods were presented and distributed. There was a lively discussion, and a desire for further industry dissemination, testing and development of the methods. (Further work along these lines was subsequently commissioned by MAFF, now Defra.)

There was one technical development. A slightly simpler to use five (as opposed to seven) parameter version of the mixture of Bi-Variate Normals statistical dependence model was developed and tested. However, increases in computer speed meant that this version was not widely used, and the seven parameter version remains the standard within JOIN-SEA.

Final versions of the earlier project reports (issued in draft form in November 1998) were agreed with MAFF (now Defra) and were re-issued in final form (HR Wallingford with Lancaster University, May 2000, two reports).

5 Swell and bi-modal seas (continued dissemination of earlier related work)

Funding for the series of projects on swell and bi-modal seas had ended in March 1997. However, two additional outputs were produced during FD0206. A conference paper (Coates and Hawkes, 1998) was presented at the Conference of Coastal Engineers in Copenhagen in 1998. A journal paper (Hawkes, 1999) was published in the ICE journal Water, Maritime and Energy.

6 Reports, papers and presentations (**direct outputs from FD0206 in bold**)

T T Coates and P J Hawkes, 1998. Beach recharge design and bi-modal spectra. Proceedings of the International Conference of Coastal Engineers, June 1998, ASCE, New York.

Defra / Environment Agency, 2003. Extreme estuarine water levels in estuaries and rivers: The combined influence of tides, river flows and waves. Defra / Environment Agency R&D Technical Report FD0206/TR1 (also referenced as HR Wallingford Report SR 623).

P J Hawkes, 1999. Mean overtopping rate in swell and bimodal seas. Water, Maritime and Energy, Volume 136, ICE, December 1999.

HR Wallingford and Lancaster University, 2000a. The joint probability of waves and water levels: JOIN-SEA – A rigorous but practical new approach. HR Wallingford Report SR 537, originally issued in draft form in November 1998, **re-issued in final form May 2000**.

HR Wallingford and Lancaster University, 2000b. The joint probability of waves and water levels: JOIN-SEA – User manual. HR Wallingford Report TR 71, originally issued in draft form in November 1998, **re-issued in final form May 2000**.

HR Wallingford, 2001. Joint probability: Dissemination, industry beta-testing and alternative applications. Final project report (MAFF, now Defra form CSG15) on Project FD1704.

Cecilia Svensson and David Jones, 2000. Dependence between extreme sea surge, river flow and precipitation: a study in eastern Britain. CEH Wallingford Project Report C01392, October 2000. (Draft report previously circulated for Joint Probability Topic Group review, August 2000.)

C Svensson and D A Jones, 2002. Dependence between extreme sea surge, river flow and precipitation in eastern Britain. International Journal of Climatology, 22 (10), 1149-1168.

Specialist workshop on extreme water levels and joint probabilities. One-day workshop for invited specialists, HR Wallingford, 3 December 1998; notes of the discussion were circulated on 15 January 1999.

Joint Probability Topic Group meetings. One-day meetings to present and review progress on FD0206 and related projects; progress notes and lengthy minutes produced for most meetings:

11 August 1998 at the Proudman Laboratory;
25 September 1998 at Lancaster University;
4 December 1998 at HR Wallingford;
22 March 1999 at HR Wallingford;
15 June 1999 at HR Wallingford;
12 November 1999 at HR Wallingford;
21 January 2000 at HR Wallingford;
21 March 2000 at HR Wallingford;
13 June 2000 at HR Wallingford;
12 September 2000 at HR Wallingford.

Extreme water levels in estuaries: The combined influence of tides, river flows and waves: Interim report on Phases I and II (of three in FD0206). Interim report circulated for review by the Joint Probability Topic Group, May 1999.

Joint probability extreme estuarine water levels: Outline of overall project report. Note circulated for review by the Joint Probability Topic Group, January 2001.

The joint probability of waves and water levels. Presentation at the HR Wallingford Associate Members' Day, Spring 2000.