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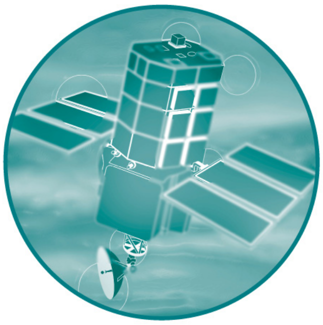

UK Climate Impacts Programme 2002 Climate Change Scenarios: Implementation for Flood and Coastal Defence: Guidance for Users

R&D Technical Report W5B-029/TR

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Department for Environment Food and Rural Affairs

Environment Agency

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This document provides information for flood risk and coastal management in England and Wales about use of the UKCIP02 climate change scenarios. It constitutes an R&D output from the Joint Defra / Environment Agency Flood and Coastal Defence R&D Programme.

Keywords
Climate change, flood risk, precautionary allowance, rainfall, river flow, sea level rise, wind speed, wave, flood defences, river and coastal, UKCIP02.

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FOREWORD

This work was funded by the Environment Agency, as R&D Project W5B-029: Climate change scenarios UKCIP02: Implementation for flood and coastal defence. The Project Manager for HR Wallingford was Dr Peter Hawkes, assisted by colleagues Dr Paul Samuels, Dr Alan Brampton and Dr Keith Powell. The Project Manager for WS Atkins Consulting was Dr Steven Wade, assisted by colleagues Dr Rob Wilby and Jonathan McCue. The Client Project Manager for the Environment Agency was originally Dr Nick Reynard and subsequently Dr Suresh Surendran. The project was undertaken under the joint Agency / Defra research theme Risk Evaluation and Understanding of Uncertainty, headed by Ian Meadowcroft.

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No climate change modelling was undertaken within the present project. The UKCIP02 scenarios were prepared and interpreted by the Tyndall Centre, the Hadley Centre and UKCIP, with funding provided by Defra.

EXECUTIVE SUMMARY

This report provides guidance for use of the UKCIP02 climate change scenario information within the flood and coastal defence community of England and Wales. It is presented in user manual format, including specific guidance for particular activities within the general areas of 'Coastal' and 'Rivers' (referring to input and derived hydraulic parameters) and 'Decisions' (referring to economic decisions).

The widely used 'appropriate precautionary allowances' recommended by Defra were reviewed in the light of the new information in UKCIP02. The advantages of maintaining continuity with current allowances were thought to outweigh the value of any refinements that might be made to the allowances. However, a new allowance for high and extreme wave conditions is recommended, and it is noted that ongoing research may soon permit refinement of the rainfall and river flow allowances.

Parameter	Current practice	Recommendation and comment
Mean sea level	For Environment Agency Regions: – 6mm/yr for Anglian, Thames, Southern and North East (South of Flamborough Head) – 5mm/yr for South West and Wales – 4mm/yr for North West and North East (North of Flamborough Head)	No change, but note comment below for extreme sea level
Extreme sea level	Usually assumed to be as for mean sea level	No change, but review if higher extreme values especially around the Thames Estuary and Anglian Region are supported by future modelling
High and extreme rainfall and river flow	Test sensitivity to additional 20% in peak flow or volume over 50 years	No change to sensitivity allowance, but ongoing research may lead to refinements
High and extreme wind speeds and offshore wave conditions	None	Add 10% sensitivity allowance to offshore wind speeds and wave heights by 2080s (and 5% to wave periods) – new recommendation – needs to be considered in relation to depth limited conditions inshore

The allowances, approaches and demonstration calculations are not intended to stifle the use of more exhaustive or sophisticated methods in major studies such as strategy studies, national flood risk assessments or CFMPs. However, they are recommended as appropriate in studies where climate change assessment is a relatively small part of the total study, and/or where necessary to maintain consistency with other similar studies, for example in prioritisation of defence schemes competing for funding.

The accompanying Project Record (Environment Agency / Defra, 2002b) reviews the requirements and opinions of potential users and sets them alongside the information available from the UKCIP02 climate change scenarios. Where necessary, it recommends further research needed to facilitate consistent use of the future climate change information within the flood and coastal defence community.

CONTENTS

ACRONYMS

CEH	Centre for Ecology and Hydrology
CFMP	Catchment Flood Management Plan
Defra	Department for Environment, Food and Rural Affairs
FEH	Flood Estimation Handbook
FSR	Flood Studies Report
MAFF	Ministry of Agriculture, Fisheries and Food (now Defra)
MDF	Mean Daily Flow
POL	Proudman Oceanographic Laboratory
PR	Project Record
SAAR	Standard Annually Averaged Rainfall
SMD	Soil Moisture Deficit
SMP	Shoreline Management Plan
TR	Technical Report
UKCIP	United Kingdom Climate Impacts Programme
UKCIP02	UKCIP climate scenarios 2002

1. INTRODUCTION

1.1 General introduction

The government's standard for assessing risks to and from the environment is based on the 'source - pathway - receptor' model (DETR, Environment Agency and the Institute for Environment and Health (2000), Cabinet Office (2002)). Climate and weather are *sources* of risk for most flood and coastal defence problems. The *receptors* include economic and environmental assets, and people vulnerable to flooding. Decision-makers need to understand the risks and uncertainties arising from climate change in order to manage those risks.

Risk assessment supports policy, strategic planning, process or operational decisions (FCDPAG4, MAFF (2000) and Environment Agency / Defra (2002a) FD2302/TR1). It usually addresses the following key questions:

- What might happen in the future?
- What are the possible consequences and impacts?
- How likely are different consequences and impacts?
- How can the risks be managed?

Climate change has for many years been a factor in investment appraisal for capital schemes. These involve planning over the long term - typically 50 years. Defra guidance for economic appraisal (FCDPAG3, MAFF, 1999) specifies sea level rise to be taken into account in project appraisal. Guidance on risk (FCDPAG4, MAFF, 2000) covers climate change from the point of risk, including the recommendation to examine sensitivity of fluvial projects to a 20% increase in peak river flows. The overview (FCDPAG1, MAFF, 2001) sets out the basis for consideration of climate change including the use of precautionary measures in some cases.

Risk assessment supports other flood and coastal management activities including operations, flood mapping and development planning and control. Climate change may be taken into account in these other spheres. For example, guidance on development, planning and flood risk (PPG25) refers to the need to account for the effects of climate change on flood risk.

Climate change scenarios provide a starting point for assessing climate change vulnerability, impact and adaptation. The United Kingdom Climate Impacts programme released new climate scenarios in April 2002. This project addresses the use of the future climate change information within the flood and coastal defence community of England and Wales. The Project Record (Environment Agency / Defra, 2002b) reviews the present situation, and the requirement for climate change information. The Technical Report (this document) provides more detailed guidance on the application of the scenarios, intended for day-to-day use in flood and coastal engineering studies.

It is intended that this report will initially be read in conjunction with the Project Record and UKCIP02 (UKCIP, 2002a, 2002b) and that it will then serve as a user manual for use of UKCIP02 in flood and coastal defence.

It is hoped that this report will be seen as providing consistent and implementable guidelines for estimating future changes in waves, water levels, rainfall, river flows etc. around the UK, together with notes on which variables need to be considered for particular design and assessment procedures. Different types of decisions require different levels of climate change assessment. Where practical, it is noted which input data to use, whether full modelling of a derived variable is needed or whether a design curve approach would be adequate, and whether full modelling of a structure variable or decision is justified or whether a sensitivity test would be adequate.

The background and scope of the present project are described in the Project Record. Development of the UKCIP02 scenarios is outlined in the Project Record, and its elements are reviewed to see which are relevant for use in flood and coastal engineering. Where necessary to facilitate take-up, further research, modelling and data processing requirements are identified.

These reports, together with the UKCIP02 information and any subsequent research which may be needed to facilitate take-up, are intended for use throughout the flood and coastal defence community. Users will include: Defra, the Environment Agency, local authorities, consultants, developers etc. Activities will include design and assessment of defences, catchment and shoreline management plans (CFMP and SMP), flood risk mapping (including Section 105 mapping), project appraisal, valuation of national assets at risk etc.

1.2 Precautionary allowances for future climate change

Prior to release of UKCIP02, appropriate precautionary allowances had been established (Richardson, 2002) for future changes in sea level and river flow, chosen towards the upper end of the range of expectations. The current allowances, summarised in Table 1.1, are used consistently in most flood and coastal engineering applications. UKCIP02 indicates the possibility of significantly higher extreme water levels in the Thames Estuary and slightly higher extreme water levels in East Anglia than the national contingency allowances would suggest, but these new results carry a low level of relative confidence.

Table 1.1 Appropriate precautionary allowances for climate change

Parameter	Current practice	Recommendation
Mean sea level	4, 5 or 6mm/yr for different regions	No change
Extreme sea level	Usually assumed to be as for mean sea level	No change, but review if higher values for Thames and Anglian are supported by other models
High and extreme rainfall and river flow	Add 20%* over 50 years	No change to sensitivity allowance, but ongoing research may lead to refinements, possibly by region and/or duration
High and extreme wind speeds and wave conditions	None	Add 10% sensitivity allowance to offshore wind speeds and wave heights by 2080s (and 5% to wave periods)

* The 20% allowance is a relatively arbitrary figure originating from very limited research, but it is considered to be a reasonable range to adopt at the present time, pending further research, and taking account of other uncertainties.

In the light of UKCIP02 and the relative level of confidence in its projections, the current national allowances were reviewed and the recommendations are given in Table 1.1. It is recommended that the current national allowances for sea level should not be changed until the higher rates of change for Thames and Anglian projected in UKCIP02 have been reproduced by other climate models. A new national allowance, also listed in Table 1.1, is suggested for high and extreme wind speeds and wave heights, again chosen towards the upper end of rather uncertain wind speed results in UKCIP02.

1.3 Climate scenario testing

In order to maintain consistency and fairness across different studies, national precautionary allowances for sea level, rainfall, river flow and wave heights (Table 1.1) are appropriate and sufficient for most investment decisions. In major studies, alternative climate change scenarios, applied *in addition* to scenarios based on the national allowances, may provide a helpful insight into the uncertainties involved and the range of outcomes. For example, they may draw attention to the possibility of a significantly more severe flood risk or potential loss in the future.

Scenario testing is sometimes thought of as 'what if' testing, but in the case of UKCIP02, the four emission scenarios broadly cover the range of future possibilities. Although they carry no particular probabilities of occurrence, they can be used in a consistent and authoritative way across many different types of climate impacts studies. In flood and coastal engineering, scenario testing would involve repeating key calculations using the alternative results given in UKCIP02 for different scenarios, ideally in combination with assessment of the many other uncertainties involved in the calculations. Some of the marine parameters listed in Chapter 6 of UKCIP02 are given for only two (Low and High Emissions) or only three (Low, Medium-High and High Emissions) of the four UKCIP02 scenarios, and so it is a matter of choice whether to use two, three or all four scenarios.

2. APPLICATIONS AND USERS

Table 2.1 lists a number of tasks in the field of flood and coastal defence that might involve consideration of future climate change. Entries in Column 2 refer to the relevant table in Chapter 3 (Coastal), Chapter 4 (Rivers) or Chapter 5 (Decisions) in which information specific to that task is given. Entries in Column 3 indicate the present level of confidence in the use of climate change information in that task. 'Projection' indicates that a change is expected, and that the direction (higher or lower) of change is known even if the magnitude is uncertain. 'Contingency' indicates a realistic and consistent allowance, towards the upper end of a range of possibilities, but with low confidence in the actual magnitude of change. 'Sensitivity' implies 'what if' calculations with no confidence that particular scenarios of change will actually occur. (The words projection, contingency and sensitivity are comparable with the high, medium and low relative levels of confidence used in UKCIP02, but the terms are not interchangeable). Entries in Column 4 indicate where relevant research is under way, recommended or may help in the future.

Table 2.1 Tasks potentially involving climate change information

Task	Table	Confidence level	More research?
Mean sea level	3.1	Projection	Ongoing climate res.
Extreme sea level	3.2	Projection	Recommended now
Wave climate	3.3	Contingency	Recommended
Extreme wave conditions	3.4	Contingency	Recommended
Joint probability	3.5	Sensitivity	Possibly
Rainfall	4.1	Projection	Ongoing climate res.
Catchment wetness	4.2	Projection	Possibly
Urban drainage volume	4.3	Contingency	Recommended now
Pumped drainage volume and head	4.4	Projection	
River flow	4.5	Projection	Under way
Extreme river flow and level	4.6	Contingency	Under way
Overtopping rate	3.6	Projection	
Breach probability	3.7	Sensitivity	
Beach profile	3.8	Sensitivity	
Littoral drift	3.9	Sensitivity	Possibly
Area of river flooding	4.7	Sensitivity	
Probability of river flood	4.8	Projection	Possibly
Area of coastal flooding	3.10	Sensitivity	
Probability of coastal flood	3.11	Projection	Possibly
Standard of service	5.1	Projection	
Cost benefit assessment	5.2	Projection	
Planning assessment	5.3	Contingency	

Each of Chapters 3 (Coastal), 4 (Rivers) and 5 (Decisions) is in two parts. The first part consists of a series of stand-alone standard format guidance notes, one for each task listed in Table 2.1. The second part consists of longer descriptions of analysis or modelling techniques where these are needed in support of the notes in the first part.

Each standard format note includes the following information:

- The importance of climate change to this task (in the context of the other uncertainties and natural variability involved)

- The input variables for this task, either taken directly from UKCIP02 (e.g. wind speed, rainfall) or derived as described elsewhere in this report (e.g. river flow, waves)

- The relevant sections in UKCIP02 (i.e. page and figure numbers) or in the present report (i.e. table numbers)

- The reliability of climate change scenarios or allowances for these variables

- The appropriate level of climate change assessment for this task (e.g. none, national allowance, site-specific allowance, modelling, sensitivity testing, scenario testing, economic impact, scheme decision)

(and if relevant after the above):

- Notes on how to undertake the task in the form of a sensitivity test based on a national allowance (e.g. add 0.3m to water level or 20% to river flow)

- Notes on how to undertake the task using modelling, analysis and/or scenario test techniques (more comprehensive if not necessarily more reliable)

- The loading variables derived within this task (e.g. waves, river flows)

- The structure variables derived within this task (e.g. overtopping, recession rate)

- The economic variables derived within this task (e.g. flood risk, cost-benefit ratio)

- The investment decisions made within this task (e.g. whether or not to build or upgrade defences)

(and if helpful after the above):

- Demonstration calculations

3. COASTAL APPLICATIONS

3.1 Summary guidance tables

Table 3.1 Mean sea level

Importance of climate change to this task	High
Input variables in UKCIP02 or this report	Mean sea level
Relevant sections in UKCIP02 or this report	Chapter 6 of UKCIP02, particularly mean sea level rise in Table 12 (Page 75)
Confidence in climate change information	Medium

Appropriate level(s) of climate change assessment	The national allowance is probably adequate in all situations as *mean* sea level (as opposed to extreme sea level) is not a critical parameter for flood and coastal defence.
National allowance plus sensitivity test	Add established mm/year national allowance (MAFF, 1999) to present-day extreme levels. If it is relevant to consider a range of values, then Table 12 of UKCIP02 provides separate results for mean sea level rise for the Low and High Emissions scenarios.
Modelling	

Derived loading variables	Mean sea level
Derived structure variables	
Derived economic variables	
Investment decisions	

Demonstration calculations

The appropriate allowances for future sea level rise for England and Wales from MAFF (1999) are reproduced here for convenience. The number of years over which to estimate future sea level rise is a design decision outside the scope of this report, but for example, 100 years of sea level rise on the Anglian coast would increase the present-day mean sea level by 100x6mm = 0.6m. (Table 12 of UKCIP02 indicates a range of 0.22-0.82m for mean relative sea level rise over 100 years for Eastern England.)

Anglian, Thames, Southern and North East (south of Flamborough Head)	6mm/year
North West and North East (north of Flamborough Head)	4mm/year
South West and Wales	5mm/year
(and by inference for Scotland)	(4mm/year)

NB The present appropriate precautionary allowance for future sea level is based on a given rate of increase in mean level. At present, any change in the extreme sea levels required for most flood and coastal defence work is calculated based on the assumption of the same rate of rise. Although it is not recommended that this practice should change, UKCIP02 and other recent research at POL is capable of modelling valid differences between rates of rise for mean and extreme levels which could be used in the context of scenario modelling. Hence slightly different guidance tables for mean (Table 3.1) and extreme (Table 3.2) sea level.

Table 3.2 Extreme sea level

Importance of climate change to this task	High
Input variables in UKCIP02 or this report	Mean and extreme sea level
Relevant sections in UKCIP02 or this report	Chapter 6 of UKCIP02, particularly mean sea level rise in Table 12 (Page 75) and extreme sea level rise in Figure 73 (Page 76)
Confidence in climate change information	Medium

Appropriate level(s) of climate change assessment	The national allowance for *mean* sea level rise is appropriate and consistent, and should remain the standard approach for the moment. However, extreme levels may increase by amounts different to mean sea level, particularly in areas with a complex coastline or bathymetry, and scenario testing and/or tidal flow modelling may provide greater insight into the range of possibilities in major projects.
National allowance plus sensitivity test	Add established mm/yr allowance for future increase in mean sea level (MAFF, 1999, reproduced in Table 3.1 of this report) to present-day extreme levels. If it is important to consider a range of values, then Figure 73 of UKCIP02 provides separate projections of extreme sea level rise for the Low, Medium-High and High Emissions scenarios.
Modelling	Apply scenario modelling using results from Figure 73 of UKCIP02 for the Low, Medium-High and High Emissions scenarios to assess the range of outcomes which may occur under future climate change. Tidal flow modelling is recommended for major studies in complex areas such as estuaries, using 'national' figures for sea level rise to provide offshore boundary conditions. It may also be relevant to consider different periods of time into the future, for example the 2020s, 2050s and 2080s as used in UKCIP02.

Derived loading variables	Extreme sea level
Derived structure variables	
Derived economic variables	
Investment decisions	

Demonstration calculations

The standard allowances for future mean sea level rise for England and Wales were reproduced in Table 3.1. The present standard approach is to assume that extreme sea level will increase by the same amount. The number of years over which to estimate future sea level rise is a design decision outside the scope of this report, but for example, 100 years of sea level rise on the Anglian coast would increase the present-day extreme sea level by 100x6mm = 0.6m.

Figure 73 of UKCIP02 indicates a range of 0.4-1.2m for extreme sea level rise over 100 years for Eastern England, due to an increase in surge elevation on top of mean sea level rise, but the climate model resolution is relatively coarse in this area. These figures give an idea of the range of possibilities and the uncertainty involved, but pending further research on extreme levels, it is not recommended that they be used in design or cost-benefit analyses.

Tidal flow modelling demonstrates that sea level (and hence water depth) rise can cause a tidal range change in estuaries and that sea level rise in the estuary can be different to the open sea.

NB: See NB for Table 3.1.

Table 3.3 Wave climate

Importance of climate change to this task	Medium
Input variables in UKCIP02 or this report	Wind speed over the sea and sea level
Relevant sections in UKCIP02 or this report	Sections 6.5 and 6.6 of UKCIP02, particularly percentage marine wind speed change by 2080s in Figure 76 (Page 79)
Confidence in climate change information	Low

Appropriate level(s) of climate change assessment	A standard contingency allowance plus sensitivity testing is adequate, given the uncertainties involved, but wave modelling may provide greater insight in major projects.
National allowance plus sensitivity test	There is no established allowance or procedure for wave climate change, but given the range of wind speed changes in Figure 76 of UKCIP02 (up to 10% reduction in Summer and 6% increase in Winter) a contingency of 5% increase in deep water wave height by the 2080s seems realistic. Potentially more important at the coast is the fact that sea level rise may increase the depth of water and hence wave heights adjacent to sea defences. As a rule-of-thumb the depth-limited significant wave height will be about 60% of the water depth.
Modelling	Wave generation depends on wind direction and persistence as well as wind speed. Some responses to wave conditions depend on wave period and direction as well as wave height. If time series wind velocities are available then wave hindcast modelling may be helpful in understanding the implications of climate change in the context of natural variability. See modelling approaches outlined in Section 3.2. There is very little difference in daily averaged wind speed between the four UKCIP02 scenarios and so scenario modelling is unlikely to be helpful in understanding wave climate change.

Derived loading variables	Wave height (and if modelling used, wave period and direction)
Derived structure variables	
Derived economic variables	
Investment decisions	

Demonstration calculations

If at present, the deep water wave heights exceeded 10%, 1% and 0.1% of the time are 3m, 4m and 5m, then after addition of the suggested 5% contingency allowance, wave heights with the same frequencies of occurrence would increase to 3.15m, 4.20m and 5.25m.

If at present, wave heights are strongly depth-limited at the toe of a seawall, then a 0.4m increase in water depth due to sea level rise would increase the depth-limited significant wave height by about 0.6x0.4m=0.24m.

NB: See Table 3.4 for a slightly higher allowance for extreme waves.

Table 3.4 Extreme wave conditions

Importance of climate change to this task	Medium
Input variables in UKCIP02 or this report	Wind speed over the sea and sea level
Relevant sections in UKCIP02 or this report	Sections 6.5 and 6.6 of UKCIP02, particularly percentage marine wind speed change by the 2080s in Figure 76 (Page 79)
Confidence in climate change information	Low
Appropriate level(s) of climate change assessment	A standard contingency allowance plus sensitivity testing is adequate in most situations, given the uncertainties involved, but wave modelling may provide greater insight in major coastal projects.
National allowance plus sensitivity test	There is no established allowance or procedure for wave climate change, but given the narrow range of wind speed changes in Figure 76 of UKCIP02 and the additional uncertainties involved in extremes analysis, a contingency allowance of 10% increase in extreme deep water wave heights (with a corresponding increase of 5% in wave periods) by the 2080s seems realistic. Potentially more important at the coast is the fact that sea level rise may increase the depth of water and hence maximum wave heights adjacent to sea defences. As a rule-of-thumb the depth-limited significant wave height will be about 60% of the water depth.
Modelling	Wave generation depends on wind direction and persistence as well as wind speed. Some coastal responses to wave conditions depend on wave period, and shallow water wave transformation may depend upon direction, as well as wave height and sea level rise. If time series wind velocities are available then wave hindcast modelling may be helpful in understanding the implications of climate change in the context of natural variability. See modelling approaches outlined in Section 3.2. There is very little difference in extreme daily averaged wind speed between the four UKCIP02 scenarios and so scenario modelling is unlikely to be helpful in understanding change in extreme wave conditions. However, it may be helpful to consider different periods into the future, using say 5%, 8% and 10% increases in extreme wave height to represent the 2020s, 2050s and 2080s, respectively, with corresponding allowances for increased extreme sea level.
Derived loading variables	Extreme wave height (and if modelling used, wave period and direction)
Derived structure variables	
Derived economic variables	
Investment decisions	
Demonstration calculations If at present, the deep water wave heights with return periods of 1, 10 and 100 years are 5m, 6m and 7m, then after addition of the recommended 10% contingency allowance, wave heights with the same return periods would increase to 5.5m, 6.6m and 7.7m. If at present, wave heights are strongly depth-limited at the toe of a seawall, then a 0.4m increase in water depth due to sea level rise would increase the maximum depth-limited significant wave height by about 0.6x0.4m=0.24m.	

Table 3.5 Joint probability of large waves and high water levels

Importance of climate change to this task	Low
Input variables in UKCIP02 or this report	Wave heights and water levels
Relevant sections in UKCIP02 or this report	Chapter 6 of UKCIP02 and Tables 3.1-3.4 of this report
Confidence in climate change information	Low
Appropriate level(s) of climate change assessment	While there remains no reason to think that the dependence between large waves and high water levels will change, there is no point doing anything more for climate change than one would do for present-day uncertainty. However, any assumptions about change in wave heights alone or in water levels alone should be taken through to joint probability analysis.
National allowance plus sensitivity test	Apply any separate climate change allowances for high and extreme water levels (Table 3.2 of this report) and for wave heights (Tables 3.3 and 3.4) to the joint probability results. In the case of wave heights being depth-limited, either over the generation area or nearshore, climate change allowances should be applied to both waves and water levels prior to any depth-limitation allowances. It is unlikely that any realistic prediction of future change in the dependence between high water levels and large wave heights will be developed, but dependence could be varied and sea conditions re-worked as a sensitivity test.
Modelling	
Derived loading variables	Extreme sea conditions
Derived structure variables	
Derived economic variables	
Investment decisions	
Demonstration calculations	
Climate change allowances would be a composite of those in Tables 3.2-3.4 of this report.	

Table 3.6 Overtopping rate

Importance of climate change to this task		Medium/High
Input variables in UKCIP02 or this report		Large waves and high water levels
Relevant sections in UKCIP02 or this report		Tables 3.1-3.5 of this report
Confidence in climate change information		Medium
Appropriate level(s) of climate change assessment	Application of national allowances for sea level rise may be sufficient for sensitivity testing, but full re-calculation of water levels, waves and overtopping rate will usually be necessary, and scenario testing may be helpful in understanding the uncertainties involved.	
National allowance plus sensitivity test	Add established mm/year allowance for future increase in mean sea level (MAFF, 1999, reproduced in Table 3.1 of this report) to present-day water levels. (If it is relevant to consider a range of values, then Figure 73 of UKCIP02 provides separate indications of extreme sea level rise for the Low, Medium-High and High Emissions scenarios.) Add the recommended allowances for wave condition change (Tables 3.3 and 3.4 of this report): if depth-limited, re-calculate wave conditions at the seawall toe and associated overtopping rate.	
Modelling	Model several aspects of the processes involved, including sea level change, wave condition change and possibly joint probability and foreshore change (Sutherland and Wolf, 2002) for the three alternative scenarios illustrated in Figure 73 (extreme water levels, Page 76) of UKCIP02. In a major study it may be helpful to consider gradually increasing sea levels (and wave conditions) over a long period of time by re-calculating overtopping for a number of different periods into the future, possibly for different climate scenarios and/or design options.	
Derived loading variables		
Derived structure variables		Overtopping rate
Derived economic variables		Value of damage resulting from increased volume of overtopping water, and of additional risk of breach or other failure thus induced
Investment decisions		Provision for increased drainage or wall crest elevation and appropriate timing of such investments in relation to changing risk levels

Demonstration calculations

1) Change in overtopping rate for fixed defence design

Apply sea conditions with particular frequencies of occurrence to overtopping rate calculations. Re-work conditions after allowances for future sea levels and wave conditions (Tables 3.2-3.5).

> Consider overtopping of a smooth sloped seawall, toe elevation at 0.0mOD, crest elevation at 8.0mOD. Consider wave conditions of H_s = 4.0m, T_m = 8.0s occurring in conjunction with sea levels of 3.7mOD (1 year joint return period), 4.0mOD (10 years) and 4.3mOD (100 years). Assuming that H_s at the toe is limited to 55% of the toe depth, the depth-limited heights for the three cases are 2.04, 2.20 and 2.37m. The overtopping rates, calculated using the Owen formula for the three cases, are 7.5, 15 and 29 litres/metre/second.
>
> Now add allowances for future climate change over 80 years, adding 0.4m to sea level (and therefore toe depth, with corresponding increase in depth-limited wave height), 10% to wave height and 5% to wave period. The revised overtopping rates are 26, 47 and 83 l/m/s, ie around three times higher than present-day rates in this example.

2) Change in overtopping frequency for fixed defence design

More complicated and possibly iterative, focussing on particular overtopping rates and looking at frequencies of occurrence of sea conditions causing those rates.

> Using the above example, the 29 l/m/s overtopping rate has changed from a 100 year return period (present-day) occurrence to a 1-2 year return period (80 years hence) occurrence, suggesting an increase in frequency for this example of a factor of about one hundred.

3) Change in crest level for specified overtopping rate

As 1) then iterate towards new future crest level needed to return to present-day overtopping rate.

> Using the above example, an increase in crest level of 0.9m (roughly twice the sea level rise allowance) would be required to restore the 29 l/m/s overtopping rate to its original 100 year return period.

4) Gradually changing overtopping

As 1), 2) or 3) but apply sea level and wave condition changes in, say, 10 year increments. This would be required, for example, to evaluate options or appropriate timing of mitigation works.

Table 3.7 Breach probability

Importance of climate change to this task	Medium
Input variables in UKCIP02 or this report	Large waves and high water levels
Relevant sections in UKCIP02 or this report	Tables 3.1-3.5 of this report
Confidence in climate change information	Low/Medium

Appropriate level(s) of climate change assessment	Breaching of seawalls and shingle banks is difficult to predict even without climate change. Application of national allowances for sea level rise may be sufficient for sensitivity testing, but full re-calculation of water levels, waves and impact on structures will usually be necessary, and scenario testing may be helpful in understanding the uncertainties involved.
National allowance plus sensitivity test	Add established mm/year allowance for future increase in mean sea level (MAFF, 1999, reproduced in Table 3.1 of this report) to present-day water levels. (If it is relevant to consider a range of values, then Figure 73 of UKCIP02 provides separate indications of extreme sea level rise for the Low, Medium-High and High Emissions scenarios.) Add the recommended allowances for wave condition change (Tables 3.3 and 3.4 of this report): if depth-limited, re-calculate wave conditions at the toe of the defence and the associated structural response.
Modelling	Model several aspects of the processes involved, including sea level change, wave condition change and possibly joint probability and foreshore change (Sutherland and Wolf, 2002) for different scenarios. Breaching itself is difficult to predict, but if conditions can be estimated under which breaching might occur, then the increase in probability of those conditions can in turn be estimated for different climate change scenarios and periods into the future.

Derived loading variables	
Derived structure variables	Change in risk of breaching
Derived economic variables	Value of damage due to this increased risk of flooding and changes over appraisal period
Investment decisions	

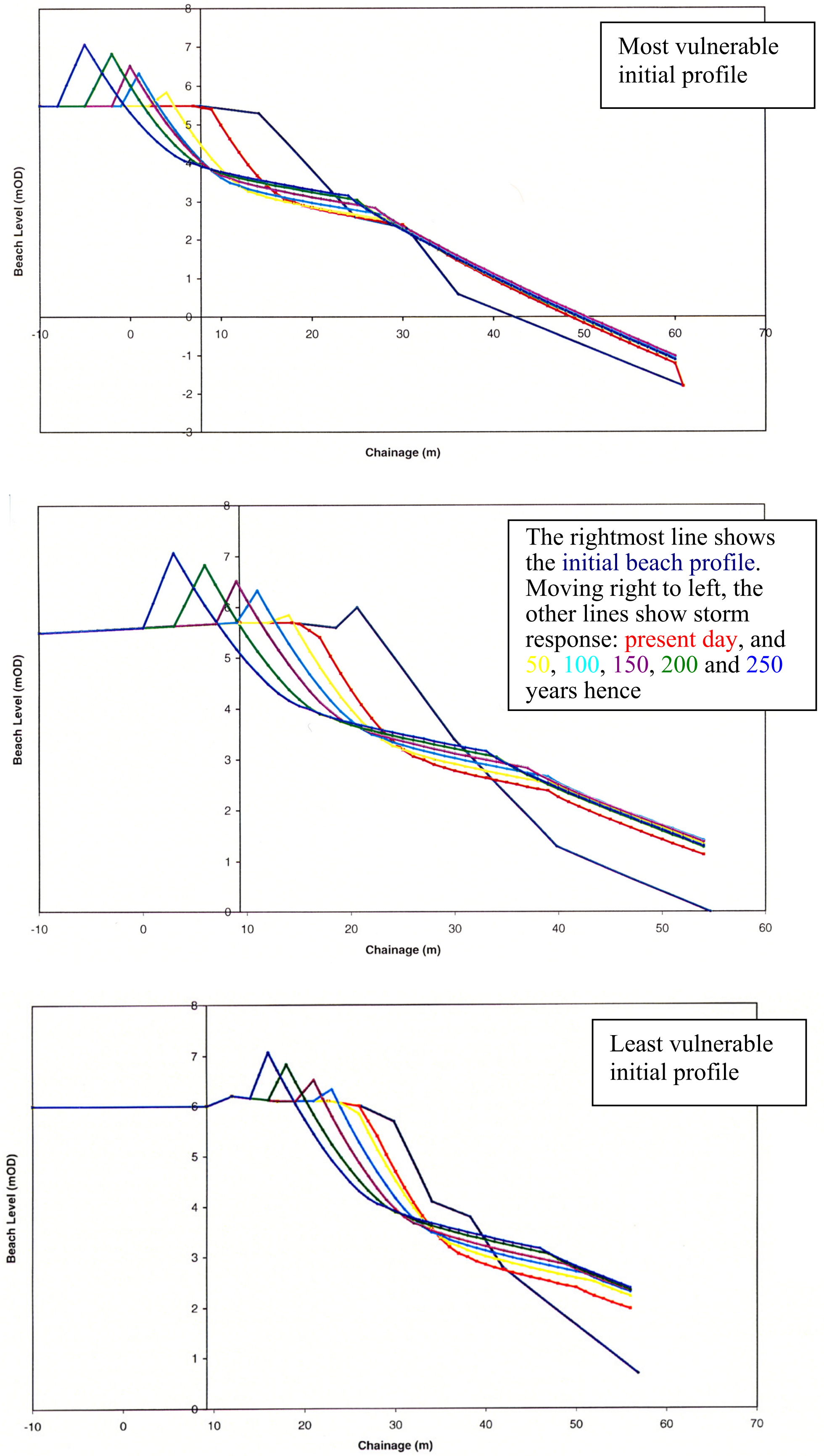
Demonstration calculations

The probability of breaching of a hard defence is difficult to estimate, but the probability of breaching of a shingle bank can be estimated in a slightly more objective way. The example below is intended purely for illustrative purposes and not as a guide to best practice.

The HR SHINGLE model takes as input an initial beach profile. It predicts the new profile that will exist immediately after a storm, expressed in terms of sea level, H_s and T_m. The new profile tends to be shallower at the toe of the slope, but steeper at the back of the beach with a higher crest set back from its original position. If the model predicts that the back face of this new crest has retreated beyond the beach area, for example onto a field or road, then this is taken to suggest that breaching may occur. If the model predicts that the peak of the new crest would have retreated beyond the beach area, this is taken to indicate that breaching will occur.

Consider three original beach profiles, plotted in dark blue (the rightmost profile in each case) below, from an actual British site, where only the shingle beach protects the land, unsupported by hard defences. Consider the profile response, plotted in red (the second rightmost profile in each case) below, to present-day 1 year return period sea conditions, comprising a 3.0mOD sea level and 3.0m / 6.0s wave conditions. Now consider the responses of the same original profiles, shown in other colours below, to the same sea conditions, moved 50, 100, 150, 200 and 250 years into the future, based on a 4mm/yr sea level allowance, 10%/80yr wave height allowance and 5%/80yr wave period allowance. The vertical black line, at a chainage of around 10m, indicates the boundary between the beach and the land.

The first profile is close to breaching even in present-day conditions and would certainly fail under the equivalent condition in 50 years time, suggesting an increase in breach probability from about 25-50% in any one year at present to about 80-90% in any one year in 50 years time. The second profile would survive the 50 years hence condition, would be close to breaching under the 100 years hence condition and would fail under the 150 years hence condition. This suggests less than 10% chance of breaching in any one year in 50 years time, increasing to about 25-50% in any one year in 100 years time, and to about 80-90% in any one year in 150 years time. The third profile survives in all tests, although the post-storm profile moves further back for each successive time increment, suggesting a low but increasing probability of breaching in the future.



Beach profile responses to 1-year return period sea conditions: British south coast site

Table 3.8 Beach profile

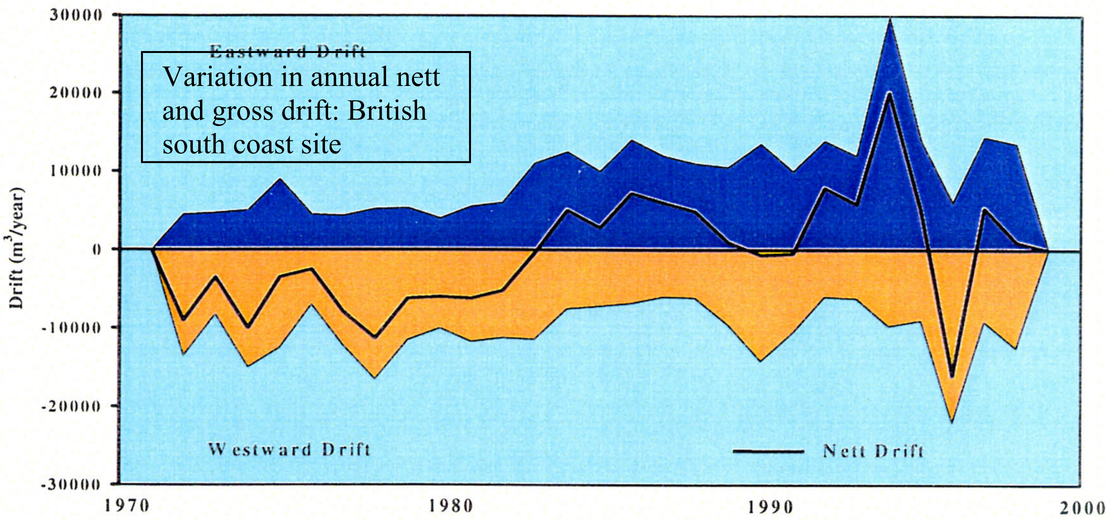
Importance of climate change to this task		Low
Input variables in UKCIP02 or this report		Large waves and high water levels
Relevant sections in UKCIP02 or this report		Tables 3.1-3.5 of this report
Confidence in climate change information		Low
Appropriate level(s) of climate change assessment	Application of national allowances for water level and wave conditions is probably adequate in view of the other uncertainties involved, unless more detailed calculations of sea conditions have been prepared for some other purpose.	
National allowance plus sensitivity test	Add established mm/year allowance to present-day water levels, and the recommended allowances for waves, then re-calculate wave conditions at the toe of the beach and the associated beach response.	
Modelling		
Derived loading variables		
Derived structure variables		Beach profile, probably for input to further seawall calculations, eg breaching, stability and overtopping
Derived economic variables		
Investment decisions		
Demonstration calculations		
See example beach profile model calculations in Table 3.7.		

Table 3.9 Littoral drift

Importance of climate change to this task	Medium/Low
Input variables in UKCIP02 or this report	Wave climate
Relevant sections in UKCIP02 or this report	Table 3.3 of this report
Confidence in climate change information	Low
Appropriate level(s) of climate change assessment	In view of the uncertainties involved in future wave climate prediction and in conversion to equivalent drift rates, it seems unnecessary to undertake a full modelling study, but instead to use contingency allowances for wave height and direction changes, coupled with a simple annual drift calculator.
National allowance plus sensitivity test	Modify present-day wave climate, for example assuming a 5 degree change in wave direction and the recommended contingency allowance of a 5% addition to wave heights. Re-calculate gross and net drift rates and associated erosion and siltation issues.
Modelling	To assist understanding of the uncertainties involved, it may be helpful to repeat drift rate calculations for a series of small changes in wave direction. To assist understanding of natural variability, it may be helpful to divide the present-day wave climate data into a series of one or two-year blocks to illustrate the inter-annual variability.
Derived loading variables	
Derived structure variables	Drift rate
Derived economic variables	
Investment decisions	

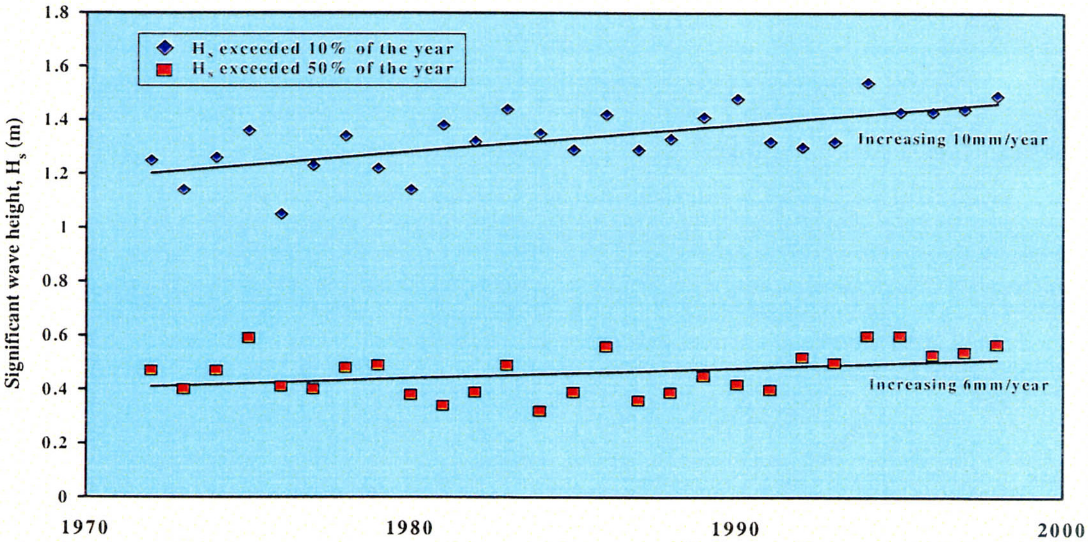
Demonstration calculations

The two diagrams below illustrate the inter-annual variability of wave height and drift rate derived from numerical modelling for a south of England site, driven by long-term sequential wind data. They illustrate the difficulty involved in predicting even the present-day drift rate, the natural variability of wave height and drift rate being greater than would be assumed in applying future climate change allowances to present-day averaged conditions. The dark line in the upper diagram indicates a reversal of the nett drift direction in about 1982, caused primarily by a small change in wave direction rather than by a general increase in wave height (which would affect westward and eastward drift equally).



Variation in annual nett and gross drift: British south coast site

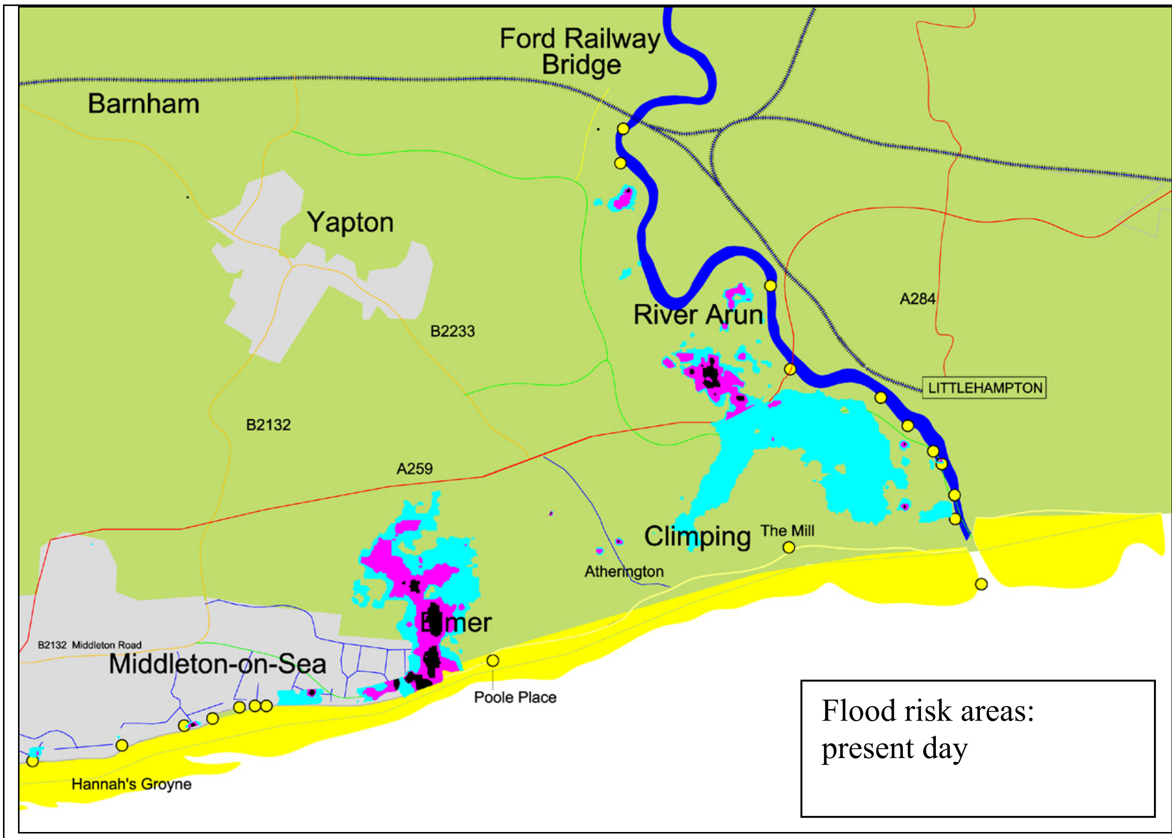
Inter-annual variability in wave height exceeded 10% and 50% of the time: British south coast site



Without an understanding of the underlying driver for past (observed) change, 30 years is a relatively short time from which to draw any inference about future trend. The diagrams are intended to illustrate the idea that natural inter-annual variability in littoral drift may be as important as trend.

Table 3.10 Area of coastal flooding

Importance of climate change to this task	Medium
Input variables in UKCIP02 or this report	Large waves and high water levels; overtopping and breach scenarios
Relevant sections in UKCIP02 or this report	Tables 3.2, and 3.4-3.7 of this report
Confidence in climate change information	Medium/Low
Appropriate level(s) of climate change assessment	This task is too complex for a quick look to be helpful. Application of national allowances for water level, together with repeated flood mapping calculations may be sufficient for sensitivity testing. However, full re-calculation of water levels, waves, overtopping rate and flood mapping will usually be necessary, and scenario testing may be helpful in understanding the uncertainties involved.
National allowance plus sensitivity test	A preliminary estimate of the impact of climate change on flood extent may be possible without hydraulic modelling. For a breach scenario, based on future change in sea level and wave run-up, estimate present and future contour levels up to which flooding might extend. For an overtopping scenario, based on future change in total volume of overtopped water over a high tide, estimate present and future flood extents from land depth/volume calculations.
Modelling	In most cases, the substitution of flood propagation modelling for the simple contouring approach described above would be a significant improvement. Additional improvements might be achieved by modelling several aspects of the processes involved, including sea level change, wave condition change, possibly joint probability and foreshore change (Sutherland and Wolf, 2002) for different scenarios, as input to flood mapping calculations. As above, the two main flood types are the breach scenario, characterised by sea level and run-up, and the overtopping scenario, characterised by a volume of water introduced over a given period of time. As part of the Defra / Agency Extreme Flood Outline project (Atkins, 2002a) a series of models are being developed that could be used to estimate the area of tidal flooding under the climate change scenarios around the entire coastline of England and Wales.
Derived loading variables	
Derived structure variables	Flood area
Derived economic variables	Value of damage over the area and changes over the appraisal period
Investment decisions	
Demonstration calculations The two maps below show the areas at risk of flooding around Littlehampton, first from present-day sea levels, and then after addition of 50 years of sea level risk at 6mm/year, both without wave action. The black, purple and blue areas correspond to return periods of 10, 200 and 500 years, respectively. (If viewed in black and white, the black and purple areas can be seen as black and dark grey, but the blue cannot be seen). The total vulnerable area is slightly higher following the assumed future sea level rise. Perhaps more striking is the projection that the area with a one in 500 chance per year of being flooded today will have a one in 200 chance per year of flooding in 50 years time.	


Ford Railway Bridge
Barnham
Yapton
B2233
River Arun
A284
LITTLEHAMPTON
B2132
A259
Climping
The Mill
Atherington
mer
B2132 Middleton Road
Middleton-on-Sea
Poole Place
Hannah's Groyne
Flood risk areas:
present day

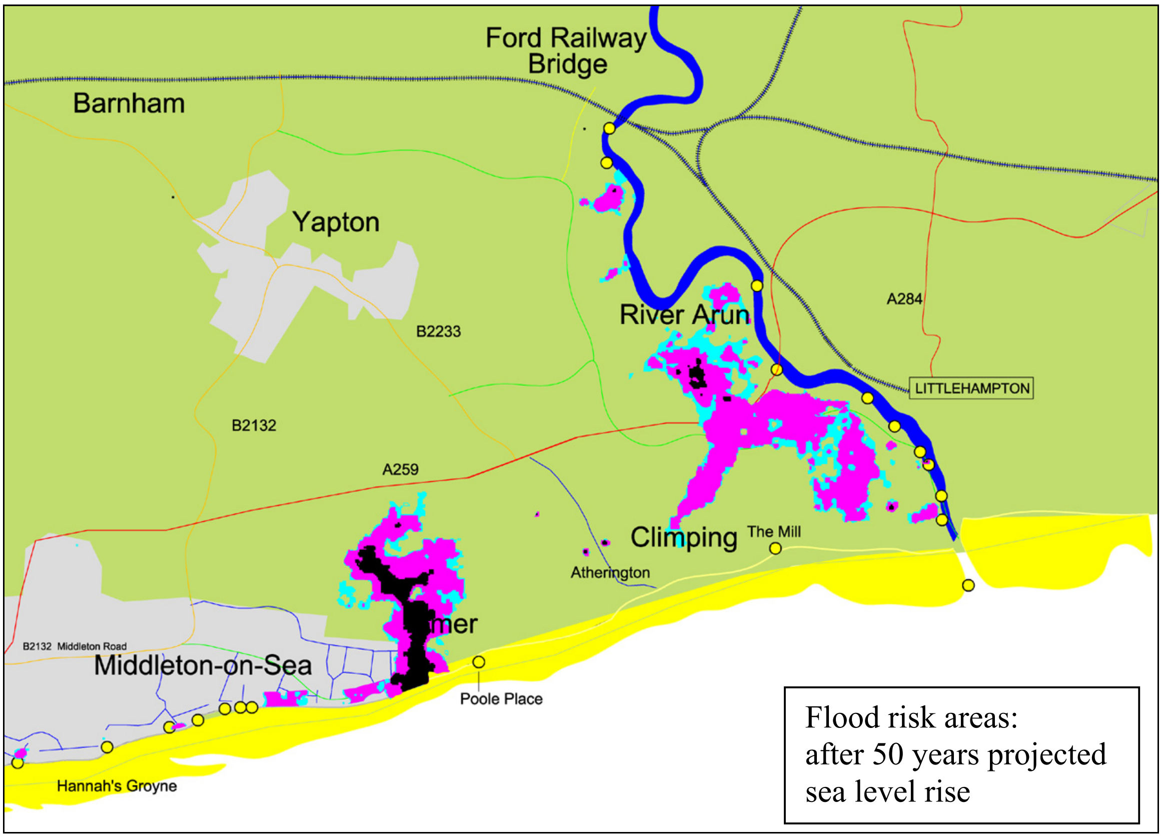

Ford Railway Bridge
Barnham
Yapton
B2233
River Arun
A284
LITTLEHAMPTON
B2132
A259
Climping
The Mill
Atherington
mer
B2132 Middleton Road
Middleton-on-Sea
Poole Place
Hannah's Groyne
Flood risk areas:
after 50 years projected
sea level rise

Table 3.11 Probability of coastal flooding

<table>
<tr><td colspan="2">Importance of climate change to this task</td><td>High</td></tr>
<tr><td colspan="2">Input variables in UKCIP02 or this report</td><td>Large waves and high water levels</td></tr>
<tr><td colspan="2">Relevant sections in UKCIP02 or this report</td><td>Tables 3.1-3.5 of this report</td></tr>
<tr><td colspan="2">Confidence in climate change information</td><td>Medium/Low</td></tr>
<tr><td colspan="3"></td></tr>
<tr><td>Appropriate level(s) of climate change assessment</td><td colspan="2">Application of national allowances for water level may be sufficient for sensitivity testing, but full re-calculation of water levels, waves and some measure of flooding will usually be necessary, and scenario testing may be helpful in understanding the uncertainties involved.</td></tr>
<tr><td>National allowance plus sensitivity test</td><td colspan="2">Add established mm/year allowance to present-day water levels, re-calculate wave conditions at potential inundation points and estimate the increased probability of occurrence of sea conditions assumed to cause flooding.</td></tr>
<tr><td>Modelling</td><td colspan="2">Model several aspects of the processes involved, including sea level change, wave condition change and possibly joint probability and foreshore change. Without actually modelling flooding, it should be possible to estimate the change in frequency of occurrence of a number of sea conditions thought to cause flooding.</td></tr>
<tr><td colspan="3"></td></tr>
<tr><td colspan="2">Derived loading variables</td><td></td></tr>
<tr><td colspan="2">Derived structure variables</td><td>Change in risk of flooding</td></tr>
<tr><td colspan="2">Derived economic variables</td><td>Value of damage due to this risk and changes over the appraisal period, cost of upgrading to new defence level</td></tr>
<tr><td colspan="2">Investment decisions</td><td>Whether or not to upgrade defence level</td></tr>
<tr><td colspan="3"></td></tr>
<tr><td colspan="3">Demonstration calculations

See example frequency of overtopping and breaching calculations in Tables 3.6 and 3.7.</td></tr>
</table>

3.2 Wave climate and extremes

This report recommends a new precautionary allowance for possible future changes in wave conditions, consisting of a 5% addition to all wave heights and periods, plus a further 5% on extreme wave heights. Confidence in future wind predictions is low, and time series wind data are not routinely available at a short enough time step to be useful in wave modelling, and so a precautionary allowance is probably adequate for most studies.

Wave modelling and/or sensitivity tests may be helpful where additional parameters are needed or where a greater insight into the range of potential impacts is needed. A number of modelling approaches to estimating future wave climate have been demonstrated in previous HR Wallingford studies. Each of the four approaches outlined below provides some information on possible changes in mean wave height and extreme wave height. All but Approach (2) also provide information on possible changes in wave direction (important for beach modelling).

Approaches (1) and (2) (or similar) would provide information on a reasonable range of perturbations from existing conditions, from which to determine a realistic range of sensitivity tests. Approaches (3) and (4) (or similar methods involving future time series wind conditions) involve much greater time and expense, and in practice would only be used in specialist climate impacts research.

1. **Guidance from past climate variability**
   UKCIP02 suggests that future wind (and hence wave) climate change will be fairly small. Future change in annually averaged wave conditions will probably be within the range of inter-annual variability of present-day wave conditions. If a long enough period of hindcast wave data are available, these can be divided into successive time slices, for example rolling 5-year averages centred on each year over a period of 20 years. For each slice a number of representative parameters can be extracted, depending on the intended use of the results. These might include 10%, and 1% exceedence wave heights and wave periods, derived 1 and 10 year return period wave heights and (for nearshore data) a representative direction. These figures can be examined for trend (if any) and variability, to assist in making any assumptions about future wave climate change. For example, if 90% of values for each wave height parameter lie within ±15% of the mean value for that parameter, this might suggest a 15% allowance for possible future wave height change. A significant variability in mean wave direction, might suggest high uncertainty in future beach drift rates (see example in Table 3.9).

2. **Modelling based on mean wind speed information**
   Wave height is approximately proportional to wind speed, and so percentage change figures for wind speed provide a reasonable estimate of corresponding changes in wave height. However, a better estimate can be obtained by applying monthly or seasonally averaged changes in wind speed (available from the UKCIP02 scenarios web-site) to individual records throughout an existing time series of present-day wind data. The original and transformed wind data sequences are run through the same wave model to obtain an estimate of the overall impact on wave conditions (Brampton and Harford, 1999).

3. **Modelling based on wind rose information**
   Wind roses illustrate the distribution of wind speed against direction. Wind direction information is not routinely available from UKCIP02, but it is possible, at cost, to extract it from the original climate model runs upon which UKCIP02 is based. Differences between future and present-day wind roses can be expressed as about 10-20 separate small changes, for example ‘5% of data originally in sector 15-45°N has moved to sector 45-75°N’ and ‘wind speeds above 8m/s in sector 165-195°N have increased by 10%’. These small changes are then applied hour-by-hour to an existing time series of wind data, retaining the persistence and seasonality of the original series, but adopting the distribution of the future wind rose. The original and transformed wind data sequences are run through the same wave model to obtain an estimate of the overall impact on wave conditions (Jelliman, Hawkes and Brampton, 1991).

4. **Modelling based on time series wind data**
   Wave modelling requires time series wind speed and direction information over a period of years, at a time step of no more than six hours. Depending on the size of the modelled area, it may be adequate to have data at just one location, or it may be necessary also to know the spatial variability over the wave generation area. These wind data are not routinely available from UKCIP02, but it is possible, at cost, to extract them from the

original climate model runs upon which UKCIP02 is based. The present-day and future wind data sequences are run through the same wave model to obtain an estimate of the overall impact on wave conditions (Sutherland and Wolf, 2002).

4. RIVER APPLICATIONS

4.1 Summary guidance tables

Table 4.1 Rainfall

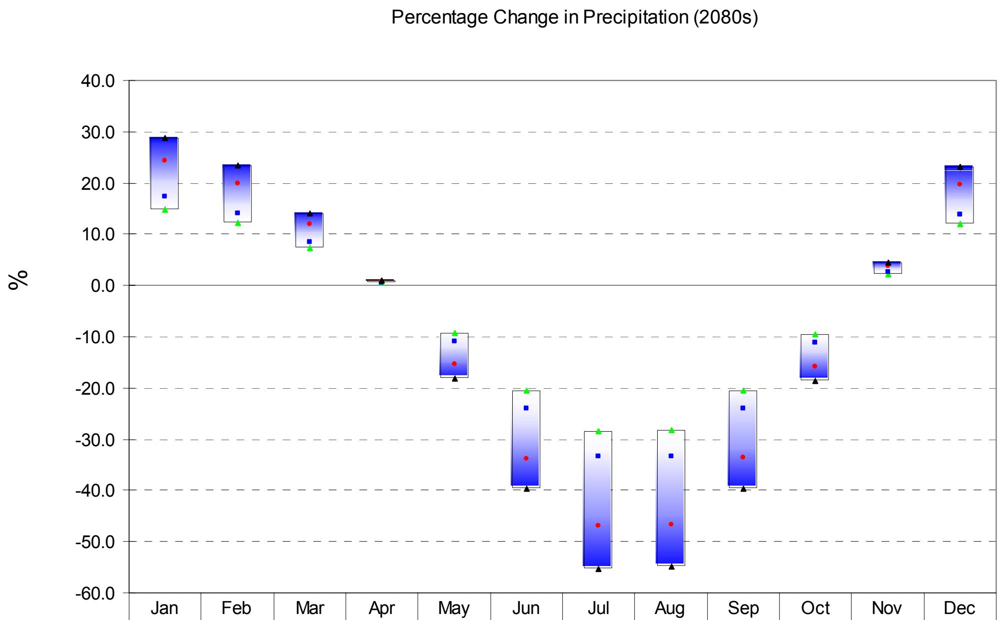
Importance of climate change to this task	High
Input variables in UKCIP02 or this report	Mean seasonal and extreme daily rainfall
Relevant sections in UKCIP02 or this report	Chapters 4 and 5 of UKCIP02, particularly percentage changes in extreme daily averaged rainfall in Figure 55 (Page 59) and annually averaged rainfall in Figures 35-38 (Page 33-36)
Confidence in climate change information	High (Increased winter rainfall depths and intensity) Medium (Decreased summer rainfall)
Appropriate level(s) of climate change assessment	A national contingency allowance plus sensitivity testing is appropriate and consistent, but scenario testing may provide greater insight into the range of possibilities in major projects.
National allowance plus sensitivity test	Add the established percentage increase allowance to present-day levels. At present, the 20% allowance (MAFF, 2000) for river flow is probably best applied to all rainfall durations, but refined recommendations may be developed in the near future.
Modelling	Apply scenario modelling using information from Chapters 4 and 5 of UKCIP02 for the four different scenarios to assess the range of outcomes which may occur under future climate change. The scenarios provide information only on daily, monthly and seasonal rainfall, and for the moment, there is no additional information for other rainfall durations. The typical approach to rainfall in climate impacts models involves applying monthly rainfall change factors to historic daily rainfall series. A rainfall change factor is the climate scenario rainfall depth (for a defined period) divided by the 1961-1990 rainfall depth. For any study the factors may be derived from the most appropriate UKCIP 50km^2 grid square. Alternatively the climate scenario data may be interpolated but this may give a false impression of precision. The simple approach of interpolating between UKCIP grid squares has some shortcomings, and in some cases it may be appropriate to use a statistical downscaling model such as the SDSM developed by Wilby *et al*. (1998, http://www.sdsm.org.uk/).

Derived loading variables	Rainfall depths
Derived structure variables	
Derived economic variables	
Investment decisions	

Demonstration calculations

The percentage change in rainfall for all four climate scenarios for the Ouse catchment is shown below.

Change in average monthly rainfall for the 2080s for the Sussex Ouse catchment



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Low Emissions	14.9	12.1	7.3	0.5	-9.3	-20.5	-28.6	-28.3	-20.5	-9.6	2.3	11.9
Med-Low Emissions	17.4	14.2	8.5	0.5	-10.9	-24.0	-33.4	-33.4	-23.9	-11.2	2.7	13.9
Med-High Emissions	24.4	19.9	12.0	0.7	-15.3	-33.7	-47.0	-46.6	-33.6	-15.8	3.7	19.6
High Emissions	28.8	23.5	14.1	0.9	-18.1	-39.8	-55.4	-55.0	-39.7	-18.6	4.4	23.1

Source (Atkins, 2002b, forthcoming)

NB: Daily averaged rainfall is directly useful only for large catchments but, pending further research, the percentage changes for daily averaged rainfall probably represent best estimates for other durations as well. When planning a study, it should be remembered that there are many uncertainties about the structure and sequencing of rainfall that limit the predictability of changes in extremes, no matter how much modelling is undertaken.

Table 4.2 Catchment wetness

Importance of climate change to this task	Medium
Input variables in UKCIP02 or this report	Soil moisture
Relevant sections in UKCIP02 or this report	Soil moisture section of Chapter 4 of UKCIP02, particularly Table 50 (Page 50)
Confidence in climate change information	High (decreases in summer and autumn in the south east) Medium (increases in winter and spring in the north west) Low (if used for individual catchment studies)

Appropriate level(s) of climate change assessment	Qualitative consideration only. The impact of soil moisture contents on flood risk is covered elsewhere (Table 4.5). The catchment scale or local impacts of changing soil moisture contents can only be estimated using appropriate modelling techniques. In flood defence design studies that use FSR / FEH rainfall-runoff modelling, sensitivity analysis of the impact of catchment wetness on peak flow should be completed irrespective of any climate impacts assessment.
National allowance plus sensitivity test	None
Modelling	Catchment soil moisture contents can be modelled using rainfall-runoff models (Table 4.5).

Derived loading variables	Catchment wetness
Derived structure variables	
Derived economic variables	
Investment decisions	

Demonstration calculations

Table 4.3 Urban drainage volume

Importance of climate change to this task	High
Input variables in UKCIP02 or this report	Chapter 5 of UKCIP02, particularly percentage changes in extreme daily averaged rainfall in Figure 55 (Page 59)
Relevant sections in UKCIP02 or this report	Table 4.1 of this report
Confidence in climate change information	Medium/Low

Appropriate level(s) of climate change assessment	The general national allowance for rainfall plus sensitivity testing is probably the best that can be done for the moment. Scenario testing may provide greater insight into the range of possibilities in major projects.
National allowance plus sensitivity test	Add the standard national precautionary allowance to present-day volumes. For the moment the 20% allowance for river flow can be applied to all rainfall durations, but refined recommendations may be developed for the much shorter duration relevant to urban drainage.
Modelling	Apply scenario modelling using results from Chapter 5 of UKCIP02 for the four different scenarios to assess the range of outcomes which may occur under future climate change. The scenarios provide information only on daily, monthly and seasonal rainfall and, for the moment, there is no additional information for other rainfall durations. The use of weather generators to derive sub-daily rainfall series is now widespread amongst drainage engineers. Climate change could be built into these software tools but further research is required in this area before any definitive guidance can be given. UK Water Industry Research Ltd has funded a major project into changes in daily and sub-daily rainfall intensities but this research is not in the public domain.

Derived loading variables	Rainfall intensity and drainage volume
Derived structure variables	
Derived economic variables	
Investment decisions	

Demonstration calculations

NB: Daily averaged rainfall may provide a poor representation of high intensity (short duration) rainfall but, pending further research, the percentage changes for daily averaged rainfall probably represent best estimates for other durations as well.

Table 4.4 Pumped drainage volume

Importance of climate change to this task	High
Input variables in UKCIP02 or this report	Chapter 5 of UKCIP02, particularly percentage changes in extreme daily averaged rainfall in Figure 55 (Page 59)
Relevant sections in UKCIP02 or this report	Table 4.1 of this report
Confidence in climate change information	High for mean sea level (Table 3.1) High for winter rainfall increase (Table 4.1) Medium for summer rainfall decrease (Table 4.1)
Appropriate level(s) of climate change assessment	The general national allowances for rainfall and mean sea level rise, plus sensitivity testing is probably the best that can be done for the moment. Scenario testing may provide greater insight into the range of possibilities in major projects.
National allowance plus sensitivity test	Add the standard national precautionary allowance to present-day levels. For the moment the 20% allowance for river flow can be applied to all rainfall durations, but refined recommendations may be developed for the shorter duration relevant to pumped drainage.
Modelling	Apply scenario modelling using results from Chapter 5 of UKCIP02 for the four different scenarios to assess the range of outcomes which may occur under future climate change. The scenarios provide information only on daily and seasonal rainfall, and for the moment, there is no additional information for other rainfall durations. However, the typical slow response of pump drained fenland catchments means that percentage changes to daily rainfall is probably sufficiently refined for initial analysis of impacts.
Derived loading variables	Rainfall volume
Derived structure variables	Pump sizing and operational cost changes over time
Derived economic variables	Frequency of flood damage through capacity exceedence
Investment decisions	Pump operational procedures, renewal and replacement cycles
Demonstration calculations	
NB: Daily averaged rainfall may provide a poor representation of shorter duration rainfall but, pending further research, the percentage changes for daily averaged rainfall probably represent best estimates for other durations as well.	

Table 4.5 River flow

Importance of climate change to this task	Medium
Input variables in UKCIP02 or this report	Rainfall intensity
Relevant sections in UKCIP02 or this report	Chapters 4 and 5 of UKCIP02, particularly extreme daily rainfall in Figure 55 (Page 59)
Confidence in climate change information	Medium

Appropriate level(s) of climate change assessment	National contingency allowance for possible river flow increase plus sensitivity testing may be adequate, but modelling is probably justified for assessment of new defence schemes.
National allowance plus sensitivity test	Add established 20% allowance to present-day winter river flow rates (but ongoing Defra /Agency research at CEH may provide a refinement to this allowance).
Modelling	Use catchment or site-specific rainfall and evapotranspiration scenarios as input to continuous simulation river modelling (see detailed technical statement in Section 4.2.3).

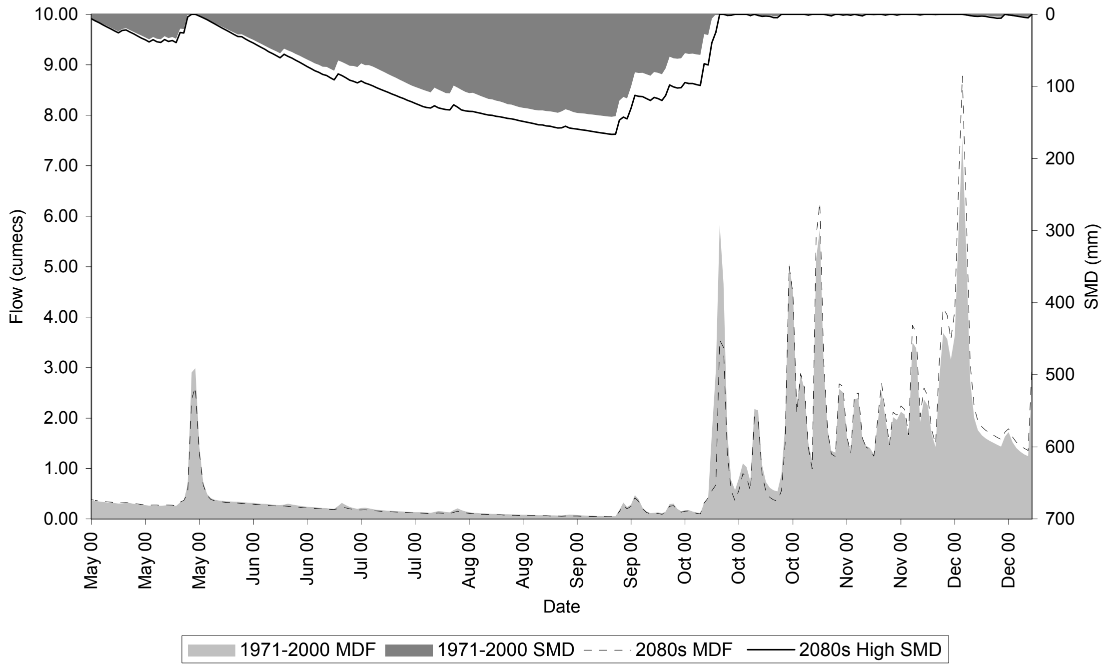
Derived loading variables	River flow
Derived structure variables	
Derived economic variables	
Investment decisions	

Demonstration calculations

The Ouse at Ardingly was modelled from 1971-2000 and for the UKCIP98 2080s High climate change scenario. Rainfall and evaporation were considered in the model using the approach described in Table 4.1.

The graph below shows the Mean Daily Flow (MDF) and Soil Moisture Deficit (SMD) for the catchment between May 2000 and January 2001. This period covers the peak flows during the Autumn 2000 floods.

In this example the average increase in annual maximum of MDFs between the 2080s and the 1971-2000 period was 7% and the increase in the Autumn 2000 flow was 17%. Soil moisture deficits were larger during the summer due to increased evaporation and reduced rainfall. Peak flows in the summer months were reduced.



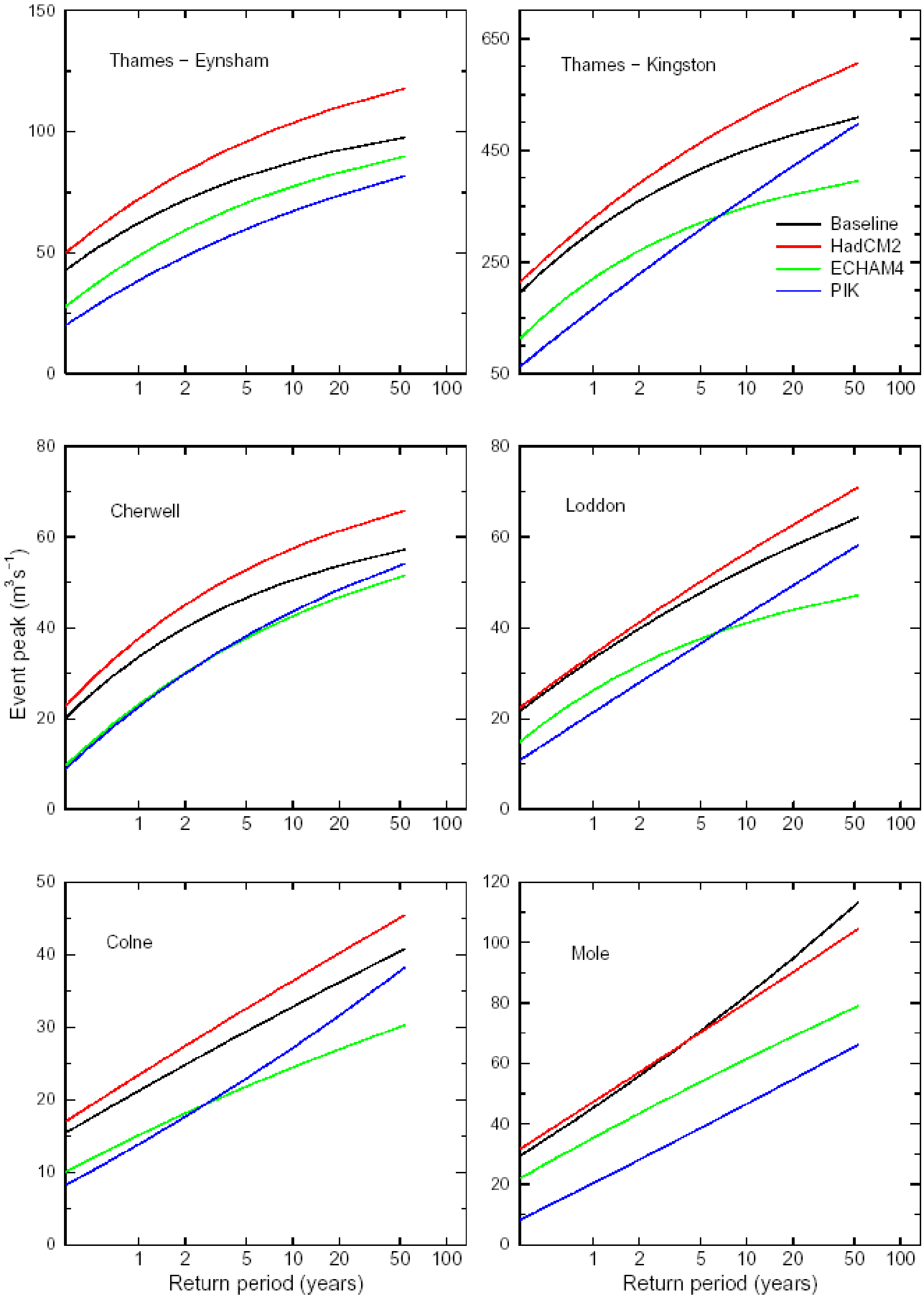
Mean Daily Flow and Soil Moisture Deficit: Upper Ouse, Sussex

Table 4.6 Extreme river flow and level

Importance of climate change to this task	Medium/High
Input variables in UKCIP02 or this report	Rainfall intensity and river flow
Relevant sections in UKCIP02 or this report	Chapters 5 of UKCIP02, particularly extreme daily rainfall in Figure 55 (Page 59) and Table 4.5 of this report
Confidence in climate change information	Medium
Appropriate level(s) of climate change assessment	National allowance plus sensitivity testing may be adequate, but modelling and economic impact are probably justified for assessment of new defence schemes.
National allowance plus sensitivity test	Add established 20% allowance to present-day river flow rates and extremes (but ongoing Defra /Agency research may provide a refinement to this allowance).
Modelling	Use site-specific rainfall predictions as input to continuous simulation river modelling and/or FEH analysis to predict change in river flow (see detailed technical statement in Section 4.2).
Derived loading variables	Extreme river flow
Derived structure variables	Extreme river level, defence crest level
Derived economic variables	
Investment decisions	
Demonstration calculations	

1 Thames catchment example

The following example from the EUROTAS project Task 3 on the River Thames Catchment (Samuels, 2001, http://www.hrwallingford.co.uk/projects/EUROTAS) shows the sensitivity of the flood frequency estimates to the climate change model (HadCM2 and ECHAM4) and the method of downscaling adopted. The PIK scenario uses expanded statistical downscaling on the ECHAM4 scenario data, which produces a change in character of the flood frequency distribution for the Thames at Kingston. All results were produced using the CLASSIC continuous simulation model by CEH Wallingford.

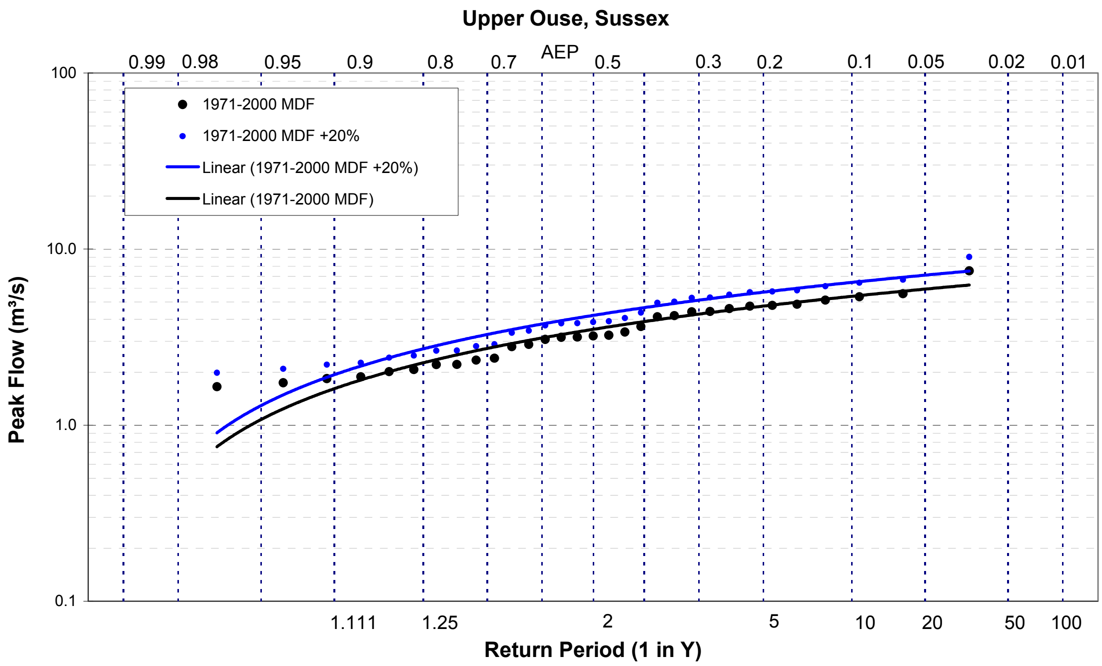


Flood frequency curves for the baseline period (1961-1990) and with three climate change scenarios for 2041-2070

2 National allowance example

The statistical approach to flood estimation involves fitting curves to annual maximum flow data. The example below shows a flood frequency curve fitted to a 30-year record from Ardingly gauge in the headwaters of the Sussex Ouse.

The national allowance of 20% was added to the annual maxima data and a new curve was fitted to the adjusted data.



3 Use of the national allowance in the River Aire Section 105 Study

As part of the River Aire Section 105 Study, flows were increased by 20% at the inflows to an ISIS hydraulic model. This increase was equivalent to using a 200 year return period flood rather than a 100 year return period flood and amounted to an average increase of 0.25m in water levels after the increased flows had been run through the hydraulic model.

4 Analysis of outputs from continuous simulation

The graph below plots the annual maxima produced by continuous simulation. In this example there is no significant change in the Mean Annual Flood and there is a smaller increase in the 1 in 20 year and above flood events. In statistical terms, there is no increase in the average flood but there is an increase in the variance of the flood frequency curve.

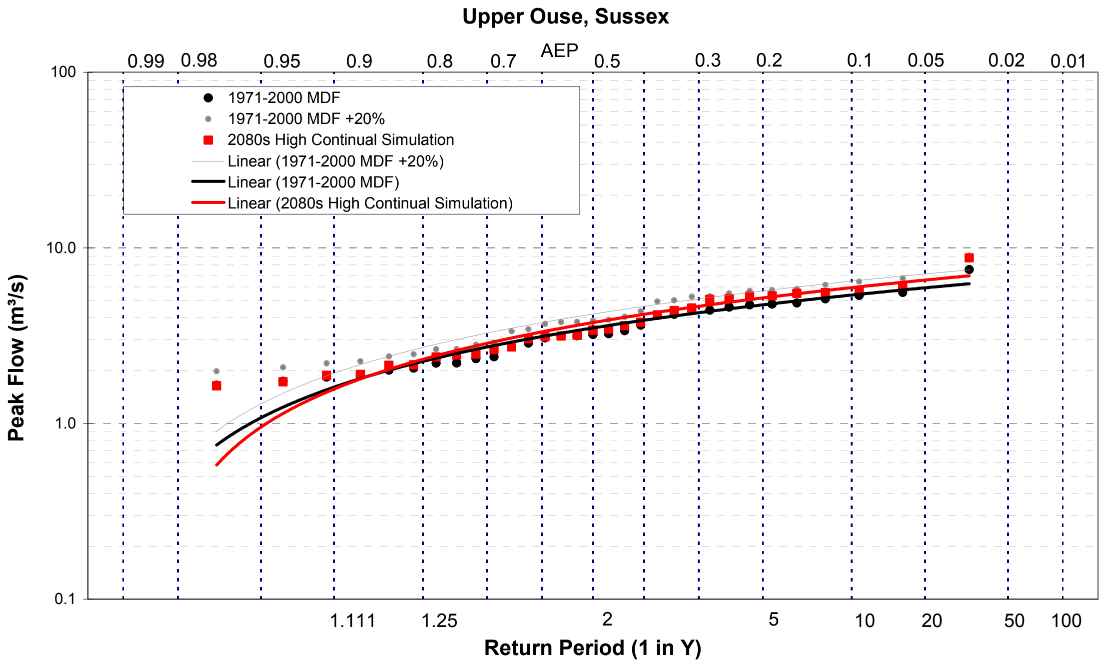


Table 4.7 Area of river flooding

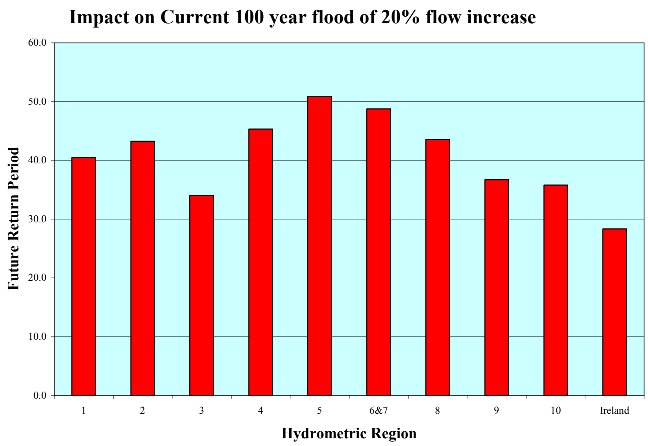
Importance of climate change to this task		Medium
Input variables in UKCIP02 or this report		River flows and high water levels
Relevant sections in UKCIP02 or this report		Tables 3.1, 3.2, 4.5 and 4.6 of this report
Confidence in climate change information		Medium
Appropriate level(s) of climate change assessment	Application of national allowances for river flow and water level may be sufficient for sensitivity testing, to determine the change in extreme river level, the volume of water over the banks and the consequent increase in flooded area. However, full re-calculation of river level, and flood propagation and mapping will often be necessary, and scenario testing may be helpful in understanding the uncertainties involved.	
National allowance plus sensitivity test	For each flood condition of interest, add the established mm/year allowance to the present-day water level (if in an area of tidal influence) and the established percentage allowance to river flow. Due to topography, the plan extent of flooding may not be significantly affected by marginal changes in flow/level unless these cross thresholds of overtopping of either primary or secondary defences. A preliminary desk assessment may be sufficient to demonstrate little change in flood area.	
Modelling	If the desk assessment suggests a significant change in flood area, move on to model several aspects of the processes involved, including sea level, river flow change and flood propagation, possibly for the four alternative scenarios and/or different periods into the future (see detailed technical statement in Section 4.2).	
Derived loading variables		
Derived structure variables		Flood area
Derived economic variables		Value of damage due to flood
Investment decisions		
Demonstration calculations		

Table 4.8 Probability of river flood

Importance of climate change to this task	Medium
Input variables in UKCIP02 or this report	River flows and high water levels
Relevant sections in UKCIP02 or this report	Tables 3.1, 3.2, 4.6 and 4.7 of this report
Confidence in climate change information	Medium
Appropriate level(s) of climate change assessment	Application of national allowances for river flow and water level may be sufficient for sensitivity testing, to determine the new probability at which the threshold for flooding is reached. However, full re-calculation of river level may be necessary, and scenario testing may be helpful in understanding the uncertainties involved.
National allowance plus sensitivity test	For a range of high loading conditions with estimated probabilities of occurrence, add the established mm/year allowance to the present-day water level (if in an area of tidal influence) and the established percentage allowance to river flow. Then estimate the new probabilities of occurrence of the same loading conditions after climate change.
Modelling	Model several aspects of the processes involved, including sea level and river flow change, possibly for the four alternative scenarios and for different periods into the future, allowing for the fact that flood events could be of different types following climate change. (See detailed technical statement in Section 4.2).
Derived loading variables	
Derived structure variables	
Derived economic variables	Cost of flood, flood frequency, cost of upgrading to new defence crest level
Investment decisions	Whether or not to upgrade defence level

Demonstration calculations

A sensitivity analysis was undertaken in the second phase study of the national assets at risk of flooding and coastal erosion (Defra, 2001). The approach was based upon applying a percentage increase to the river flows at all return periods to the dimensionless regional growth curves of the FSR and interpreting the result as a change in annual frequency for the given value of peak discharge. The underlying growth curve was assumed to be unchanged (this assumption amongst others is open to question). The results given below are for the future return period of the current 100 year flood estimate of the FSR by FSR region.



4.2 Rainfall-runoff modelling techniques

4.2.1 Comments on guidance for river applications

Tables 4.1 to 4.8 outline some simple sensitivity tests and modelling approaches that can be used to estimate the possible impacts of climate change on fluvial flooding. There are two levels of assessment; firstly, the application of the national allowance of an increase of 20% on rainfall or peak river flow. In terms of the physical processes of rainfall-runoff and hydraulics, this appears to be inconsistent because any increase in rainfall will be stored within catchment vegetation and soils and attenuated in headwater floodplains. However, the application of a clear simple rule has clear advantages.

The ongoing Defra / Agency research at CEH Wallingford (Project W5B-01-050) into climate change and continuous simulation may result in a revision of the simple 20% rule.

Prior to the publication of the CEH research, some flood studies may require more detailed modelling as described in Tables 4.5 and 4.6. The section below provides some further information on standard flood studies modelling techniques and the linkages between runoff and climate variables.

4.2.2 The Flood Studies Report (FSR) and Flood Estimation Handbook (FEH)

It is widely recognised that the FSR / FEH rainfall-runoff approach requires updating as it is still based on the original FSR dataset extending only to the 1970s. The use of the statistical method (Table 4.5) and continuous simulation are also far more robust approaches for flood estimation than the FSR rainfall-runoff method. Nevertheless it is useful to understand the linkages between climate variables and predicted flood flows developed as part of the original FSR losses model.

If the FSR model is to be used for sensitivity analysis or climate impacts assessment the following are required:

- Control and scenario rainfall storm duration, depth, profiles – direct from Regional Climate Model rainfall statistics. (Before RCM rainfall statistics are used they require validation against observed records for either the 1961-1990 or 2071-2100 period.)

- Control design Tp, BF and SPR for control period (1961-1990) and either scenario values/factors or *pdfs* for BF and SPR and the correlation between them.

Table 4.9 below summarises some of the key variables. The level column indicates the level of complexity in terms of testing the sensitivity of runoff to changes in climate variables.

Table 4.9 Key variables in rainfall-runoff modelling techniques

Level	FEH Variable	UKCIP02 Variable	Notes
1	SAAR	Annual average rainfall	Basic FEH parameter. Catchment SAAR could be derived directly from UKCIP02 scenarios.
1	The Median Flood Flow QMED	None	Historically a 0.5 correlation between SAAR and QMED
2	Standard Percentage Runoff SPR	Historic SPR plus dynamic components derived from rainfall? RCM Runoff is not directly comparable.	Most sensitive component of FSR losses model to climate change. SPR is an event based statistic.
2	Percentage Runoff PR_{rural}	Runoff (see above)	*FEH Vol.4. 2.3* See comments relating to SPR $PR_{rural} = SPR + DPR_{CWI} + DPR_{RAIN}$ $DPR_{CWI} = 0.25\ (CWI - 125)$ If $P <= 40$ mm, $DPR_{RAIN} = 0$, Else $DPR_{RAIN} = 0.45(P\text{-}40)^{0.7}$
3	Catchment Wetness Index CWI	Derived from daily rainfall or Daily SMD	FEH CWI = 125 + API5 – SMD Note that FSR/FEH guidance of <u>design</u> CWI based on SAAR
3	Soil Moisture Deficit SMD	SMD from UKCIP02 is not directly comparable because it is based on $50km^2$ grid squares	The UKCIP02 RCM SMD data have not been validated against more detailed rainfall-runoff models. The probability of flooding increases when SMD is 6mm or less. It would be useful to present the RCM SMD data in the form of the number of days that the soil is “wet” i.e. the PROPWET variable. This may be a useful flood risk indicator.
3	Antecedent Precipitation Index API5	Derived from daily rainfall	$API5 = 0.5^* [P_{d-1}+0.5\text{^}2^*P_{d-2}+0.5\text{^}3^*P_{d-3+}0.5\text{^}4^*P_{d-4}+0.5\text{^}5^*P_{d-5}]$
2	PROPWET	SMD	The fraction of time that the catchment is wet.
2	Tp	None	Time to peak - climate change should have no significant effects.
2	BF	None	Baseflows are relevant in permeable catchments – likely to increase on average with climate change. Can be estimated as f(CWI, SAAR and AREA) – $BF = \{33(CWI\text{-}125)+3.0.SAAR + 5.5\}10^{-5}.\ AREA$
By comparison			
4	None	Continuous simulation using a rainfall-runoff model	While much of the research has used PDM a simpler model, such as a Penman model may be more appropriate. The Environment Agency, CEH and NEECA consultants between them have a good selection of models and databases of model parameters. **Far too complex for general use so the models need to be run for a range of catchments and the results presented for particular types of catchment.**

4.2.3 Continuous simulation modelling

A number of rainfall-runoff models that can be used to estimate the impacts of the UKCIP02 climate change scenarios on peak river flow are outlined in Table 4.10.

Table 4.10 Rainfall-runoff model summary

Model	Model Type	Description	Comments on use of continuous simulation of flood peaks
HYSIM	Conceptual (Mass balance)	Seven store conceptual model coupled to a simple hydraulic routing model.	Physically based model but with a large number of parameters. Generally used for water resources studies rather than flood studies.
CATCHMOD (TCM)	Conceptual (Mass balance)	Penman 3 parameter model, requiring division of the catchment into different response zones, representing areas with different runoff characteristics.	A simple model developed within Thames Region of the Environment Agency. It has been used for estimating the impacts of climate change on river flows in both Thames and Southern Region of the Environment Agency (e.g. Atkins, 2002b).
IHACRES	Transfer Function/UH	A systems type model based on the Unit Hydrograph. It has two modules: the first calculates effective rainfall (ER) from rainfall and temperature and the second converts ER to stream flow.	A simple model but not used widely within the Environment Agency.
Probability Distributed Model (PDM)	Conceptual	A mass balance model that uses a probability density function rather than single parameter to represent storage within a catchment.	This model is being used by CEH for evaluating the impacts of the UKCIP02 scenarios on peak flows. It is used in flow forecasting systems in England. This model is now available as part of HR Wallingford's ISIS suite of models.
NAM	Conceptual	A mass balance model based on the relationship between storage, process thresholds and flow routing through several non-linear reservoirs.	This model forms part of the Danish Hydraulic Institute's MIKE11 suite of models. It has been used for flood forecasting systems in East Anglia and Section 105 flood studies in Wales.

5. DECISIONS

5.1 Summary guidance tables

Table 5.1 Standard of service

Standard of service is defined as the adequacy of a defence, measured in terms of the annual probability of the event which causes a critical condition (e.g. breaching, overtopping) to be reached.	
Importance of climate change to this task	Medium
Input variables in UKCIP02 or this report	River flows, high water levels, waves, probabilities of damage and/or flooding
Relevant sections in UKCIP02 or this report	Tables 3.2, 3.4-3.8, 3.11, 4.6 and 4.8 of this report
Confidence in climate change information	Medium
Appropriate level(s) of climate change assessment	Determine the most important failure mode(s). Application of national allowances for relevant loading parameters may be sufficient for sensitivity testing. Full re-evaluation of all loading variables and failure probabilities will usually be necessary, for example for cost-benefit assessment. Scenario testing may be helpful in understanding the uncertainties involved.
National allowance plus sensitivity test	Apply national allowances to the variables involved, re-work the failure calculations and estimate the increased probability of occurrence of loading conditions causing failure. The standard of service, expressed as an annual probability, then follows from the probability of failure.
Modelling	Model several aspects of the processes involved, including all loading variables and their combined probability of occurrence. Determine the probability of the failure mode(s). Assessment of these rare combined probabilities would be assisted by long-term simulation coupled with joint probability analysis. Scenario modelling would be helpful in understanding the uncertainties involved. Although the absolute accuracy of the derived standards of service may be low, any comparisons between present-day and future scenario values should be valid.

Derived loading variables	
Derived structure variables	
Derived economic variables	Standard of service for a defence, expressed as the annual probability of an event which it would protect against, and the way in which this is likely to change over time
Investment decisions	Whether to do nothing, repair the defence, upgrade an existing defence, or construct a new defence, and appropriate timing of investment in relation to changing risks

Demonstration calculations

1) Sea level above an estuary wall

Consider a hypothetical estuary wall on the south coast of England, assumed to have failed in its service if the sea level, unaffected by waves or flow, exceeds the wall level.

> Let the present-day extreme water levels be 2.14, 2.26, 2.34, 2.42, 2.60, 2.72 and 2.90mCD for return periods of 1, 2.5, 5, 10, 25, 50 and 100 years, and the wall level be 2.90mOD. The annual probability of the event that the wall would protect against is 0.01. Increasing all sea levels by 6mm/yr to represent conditions in 25, 50 and 100 years time would increase the extreme water levels by 0.15, 0.30 and 0.60m, respectively, and hence the annual probability of failure to about 0.02, 0.04 and 0.3, respectively.

2) Overtopping of a sea wall

Consider a hypothetical sea wall on the east coast of England, assumed to have failed in its service if the overtopping rate exceeds 40 litres/metre/second.

> Consider overtopping of a smooth sloped seawall, toe elevation at 0.0mOD, crest elevation at 8.0mOD. Consider wave conditions of H_s = 4.0m, T_m = 8.0s occurring in conjunction with a sea level of 3.7mOD (1 year joint return period), 4.0mOD (10 years), 4.3mOD (100 years) and 4.6mOD (1000 years). Assuming that H_s at the toe is limited to 55% of the toe depth, the depth-limited heights for the four cases are 2.04, 2.20, 2.37 and 2.53m. The overtopping rates, calculated using the Owen formula for the four cases, are 7.5, 15, 29 and 56 l/m/s. The annual probability of the event that the wall would protect against is about 0.003.
>
> Now add allowances for future climate change over 80 years, adding 0.4m to sea level (and therefore toe depth, with corresponding increase in depth-limited wave height), 10% to wave height and 5% to wave period. The revised overtopping rates are 26, 47, 83 and 148 l/m/s, increasing the annual probability of failure to about 0.2, ie fifty to one hundred times greater.

3) Breaching of a shingle bank

See example calculations in Table 3.7.

Table 5.2 Cost benefit assessment

The 'cost' is the present value of whole life costs involved in any defence options considered, including maintaining the present position, and any proposed improvements. The 'benefit' is the reduction in present value of economic losses due to flooding etc. over the whole period of the evaluation, relative to the do-nothing position, attributable to the proposed option.	
Importance of climate change to this task	Medium
Input variables in UKCIP02 or this report	River flows, high water levels, waves, probabilities and cost of damage and/or flooding
Relevant sections in UKCIP02 or this report	Tables 3.2, 3.4-3.7, 3.10, 3.11, 4.3, 4.4, and 4.6-4.8 of this report
Confidence in climate change information	Medium
Appropriate level(s) of climate change assessment	For each option determine the most important condition(s) in which various levels of flooding would occur and the economic value of the associated losses at the present time. Apply national allowances to relevant loading parameters for future time steps (e.g. 10 year intervals) over the evaluation period and use the results to sum the economic value of losses using agreed discount factors. Determine the whole life costs of each option and use these to derive benefit/cost ratios and incremental benefits and costs for each option.
National allowance plus sensitivity test	As above, apply national allowances to the variables involved, re-work the flooding calculations and estimate the increased probability of occurrence of loading conditions causing flooding. The benefit/cost ratio for each combination of defence strategy and scenario can then be calculated using normal calculation methods. Appropriate scenario testing around the recommended allowances may be helpful in understanding the uncertainties involved.
Modelling	Model several aspects of the processes involved, including all loading variables and their combined probability of occurrence. Determine the probabilities of the various flooding events. The benefit/cost ratio for each combination of defence strategy and scenario can then be calculated using normal calculation methods. Assessment of these rare combined probabilities would be assisted by long-term simulation coupled with joint probability analysis. Such scenario modelling would be helpful in understanding the uncertainties involved for large or significant investment projects (but see note below).

Derived loading variables	
Derived structure variables	
Derived economic variables	The changes in costs and benefits of different investment options over specified period(s) of time in the life of an existing or proposed defence
Investment decisions	Whether to do nothing, or repair / replace / construct the defence; appropriate timing of investment in relation to changing risks

Demonstration calculations

As both costs and benefits may be different under different climate scenarios, it cannot be assumed without doing full calculations that the benefit/cost ratio will necessarily increase or decrease, or that the preferred option will remain the same under climate change. The two sets of illustrative results below are based on a recent study in England, where climate change was represented by the appropriate precautionary allowance for sea levels, with the consequent increase in depth-limited wave heights.

Location 1 has a promenade and low shingle beach, protected in parts by rock armour and in parts by groynes. The potential threat is high overtopping and consequent damage to infrastructure, but the present standard of defence is 100-300 years, varying slightly through the defence length. The *do nothing* option would allow continued erosion of the shingle and a rapid increase in the frequency of overtopping. The *maintain* option assumes repair of groynes and renourishment of shingle beaches to hold their present state. The *sustain* option would involve minor additions to the maintain option to bring the entire length up to the 200 year standard of defence and sustain that position under climate change. The *improve* option would involve more significant new works to bring the standard of defence above 300 years for the whole defence length. All benefits increase slightly under climate change and *maintain* remains the preferred option.

Option	Benefit (£M)		Cost (£M)		B/C ratio		Comments on defences
	Now	After	Now	After	Now	After	
Do nothing	200 year defence but potentially rapid deterioration						
Maintain	10.31	10.37	2.81	2.81	3.7	3.7	Maintain 200 year standard
Sustain	10.58	11.06	3.27	3.27	3.2	3.4	Sustain 200 year standard
Improve	11.33	11.09	3.52	3.52	3.2	3.2	Improve to over 300 years

Location 2 has a coastal defence protected by a nourished shingle beach and breakwaters, apart from one small area where continued erosion between two breakwaters would begin to allow larger waves to pass. The potential threat is breaching in the lee of the erosion, but at present the whole area has a high standard of defence of over 200 years, although under the *do nothing* option this would drop rapidly in the small area affected by erosion. The cost of the maintain option increases under climate change, reducing the B/C ratio, and changing the preferred option from *maintain* (Now) to *sustain* (After).

Option	Benefit (£M)		Cost (£M)		B/C ratio		Comments on defences
	Now	After	Now	After	Now	After	
Do nothing	200 year defence but potentially rapid deterioration in one area						
Maintain	6.56	7.38	0.89	1.39	7.4	5.3	Maintain 200 year standard
Sustain	6.56	7.80	1.39	1.39	4.7	5.6	Sustain 200 year standard

NB: For national investment programmes an important aspect is that different projects competing for funds are appraised on a consistent basis. Therefore, whilst decisions on option choice should take full account of the potential impacts and uncertainties, it is generally preferable that the final results are reported in relation to agreed allowances that are designed to provide an appropriate precautionary response.

Table 5.3 Planning assessment

Importance of climate change to this task		Low/Medium
Input variables in UKCIP02 or this report		River flows, high water levels, probability of flooding
Relevant sections in UKCIP02 or this report		Tables 3.2, 3.10, 3.11, 4.7 and 4.8 of this report
Confidence in climate change information		Medium
Appropriate level(s) of climate change assessment	Application of national allowances for river flow and/or water level may be sufficient for sensitivity testing, to estimate present-day and future probabilities of flooding. Modelling of river / water level, and flood propagation and mapping will only be necessary for major developments and/or where new building may affect flood propagation. As established planning policy is more important than precise calculation of risk, scenario modelling is unlikely to be helpful (except perhaps in developing new policy).	
National allowance plus sensitivity test	Application of national allowances for river flow and/or water level to estimate present-day and future probabilities of flooding.	
Modelling	Modelling of river / water level, and flood propagation and mapping where a major development is proposed and/or where new building may affect flood propagation.	
Derived loading variables		
Derived structure variables		Changes in probability of flooding over the life of the development
Derived economic variables		Cost of flood damage or of mitigation measures required and their potential impacts elsewhere
Investment decisions		Whether or not to allow development as a sustainable option
Demonstration calculations		

5.2 National policy and national assets at risk

Guidance on development of national policy and assessment of national assets at risk in the context of climate change is not given in this report, as these tasks would not be undertaken by non-specialists. Defra and the Environment Agency have funded a number of recent studies of the national value of assets at risk from river and coastal flooding, how that risk might increase following climate change, and the investment needed to maintain the current level of risk. The most recent publication on assets at risk is Defra (2001), but National Flood Risk Assessment 2002 is due to report soon.

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