Department for Environment Food & Rural Affairs
Llywodraeth Cymru Welsh Government
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Environment Agency

delivering benefits through evidence


# Accounting for residual uncertainty: updating the freeboard guide

Report – SC120014

Flood and Coastal Erosion Risk Management Research and Development Programme

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This report is the result of research commissioned by the joint Flood and Coastal Erosion Risk Management Research and Development Programme.

**Published by:**
Environment Agency, Horizon House, Deanery Road, Bristol, BS1 9AH

www.gov.uk/government/organisations/environment-agency

ISBN: 978-1-84911-388-5



Email: fcerm.evidence@environment-agency.gov.uk.

Further copies of this report are available from our

**Author(s):**
Andrew (Eddie) Robinson, Fola Ogunyoye, Paul Sayers, Tijs van den Brink, Owen Tarrant

**Dissemination Status:**
Publicly available

**Keywords:**
uncertainty, design, appraisal, development planning, freeboard, residual uncertainty

**Research Contractor:**
Royal HaskoningDHV, Rightwell House, Bretton, Peterborough, Cambridgeshire PE3 8DW
01733 334455.

**Environment Agency's Project Manager:**
Owen Tarrant, Evidence Directorate

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Doug Wilson

**Director of Research, Analysis and Evaluation**

# Executive Summary

Evidence supporting flood risk management decisions will always have some degree of uncertainty associated with it because flooding mechanisms might be poorly understood or flood information is incomplete or inaccurate. Some of these uncertainties will have been addressed through standard design and appraisal procedures; others will not. Those uncertainties that remain are called residual uncertainties.

This guide provides a structured approach to assessing, recording and addressing the residual uncertainties associated with flood risk management decisions. It aims to supersede the Environment Agency's Fluvial Freeboard Guidance Note published in 2000, hereafter referred to as W187. Through the summer and autumn of 2017 The Environment Agency and Natural Resource Wales will how to adopt this research in their work.

W187 promoted freeboard allowances as a single response of additional depth to be added to the design water level to determine the crest level of a fluvial defence. However, this approach is no longer appropriate for 3 main reasons.

- W187 focused only on fluvial flood risk management. Guidance on the management of uncertainty is required for other sources of flood risk, such as coastal, estuarine and tidal. A new guide provides the opportunity to widen the scope from existing and new fluvial assets to other sources of flood risk and for development planning purposes.
- Modern flood and coastal risk management uses a range of measures. Following guidance in W187 results in a single response of defence crest level raising, but this is only one of many possible responses. Response at the defence or pathway may take other forms different to raising crest level (for example, designing for safe overtopping). Response could also be provided at the source or the receptor of flooding, or through a combination of different measures.
- Supporting analysis and data have improved significantly. Flood risk data and information, such as model outputs, are presented in ever more complex ways, rather than simply still water level. Many of the traditional considerations in the assessment of freeboard are routinely included in the analysis of flood risk. Databases increasingly provide information on data provenance and associated statements of accuracy. New guidance that enables the flexibility to deal with the increasing complexity and forms of data output was therefore required.

The extension of the scope of the guidance from fluvial to multiple sources and from a single dimensional defence raising response to a wide range of measures means that the terms 'fluvial' and 'freeboard' were no longer appropriate for its title. It is therefore a guide that helps to determine an allowance to account for residual uncertainty.

For this guide, the residual uncertainty allowance is defined as:

> An allowance that seeks to assure the present day performance of the chosen means of managing flood risk by accounting for uncertainties that have not been explicitly addressed elsewhere in the planning, appraisal, design, or implementation process; whether qualitatively or quantitatively.

The residual uncertainty allowance is underpinned by 5 principles as described and illustrated below.

**Principles of residual uncertainty allowance**

1. Challenge the credibility of system components
2. Consider the reality of the present day
3. Explore a range of measures to manage uncertainty
4. Ensure a proportional response
5. Effective management of uncertainty is a continuous process

To challenge the credibility of the system components as required by Principle 1, the guide provides clear methods, processes and templates to help identify all the uncertainties associated with a flood risk management activity. It then supports a process of identifying and quantifying those which remain unaccounted for.

Principle 2 seeks to remove significant inconsistencies and double counting associated with accounting for future changes as part of this process. Future changes such as climate change or development are omitted from residual uncertainty considerations. Dealing with future change often involves trade-offs between acting now, in the future or employing managed adaptive approaches. Such decisions should be properly considered as part of an appraisal process rather than just using a single precautionary approach such as freeboard. Principle 2 is also relevant for the assessment of the performance of existing assets, moving you away from back-casting to previous assessments or designs and trying to estimate how much of the previous allowance is still valid. This principle encourages you to assess the performance of your asset based on best available knowledge.

The guide supports the move to multiple ways of accounting for residual uncertainty advocated by Principle 3 through the provision of clear examples and illustrations. It separates the stage for assessing the size of the residual uncertainty from that for determining how to account for it. Due to Principle 3's multiple approaches for addressing residual uncertainty, the concept of standard of protection and threshold of overtopping as currently used were found to no longer be relevant. Two forms of standard of protection, the ultimate limit state standard of protection (uSoP) and the serviceability limit state standard of protection (sSoP) are identified to better address the separate issues of standard of some desired service and structural limits of performance.

A proportionate response is required with Principle 4. The guide provides a tiered and staged method of determining an appropriate residual uncertainty allowance. This methodology distinguishes between the following applications:

- development planning and control
- developing a strategy, appraising options, assessing the performance of an existing defence or designing a new scheme

The methodologies allow the particular local context and risk levels of each assessment to be considered ensure the effort is proportionate and the outcomes are realistic.

Principle 5 recognises that the process of assessing and accounting for uncertainty within the development of a flood risk management solution is an evolutionary process through the lifetime of a project. Guidance and methods are provided to support the continuous assessment of uncertainty, recording the actions to manage it and identify the residual uncertainties as you follow a project though its from the strategic to detailed design stages. This process is supported by case studies that cover different stages of the project and planning lifecycles.

# Acknowledgements

We would like to thank those who have been involved in the development of this guide through their involvement on the Project Board and Project Advisory Group:

| | |
|---|---|
| Paul Bates | Bristol University |
| Johnathan Austin | Environment Agency (up to April 2015) |
| Andrew Eden | Environment Agency (from April 2015) |
| Tim Hunt | Environment Agency |
| Nick Haigh | Defra (Corresponding) |
| Paul Stainer | Environment Agency |
| Russell Stead | Environment Agency |
| Nick Steele | Natural Resources Wales |
| Owen Tarrant | Environment Agency |
| Anne Thurston | Environment Agency |
| Mike Wood | Torbay Council |

We would also like to thank all those who attended the user testing workshops in March and December 2014, and all who contributed to the pilots during the summer of 2015.

Additionally, we would like to thank all those who have provided information, case studies and photographs for inclusion in this guide.

# Contents

# 1 Introduction

This guide aims to supersede the Environment Agency's Fluvial Freeboard Guidance Note from 2000, referred to throughout this document as 'W187'. The Environment Agency and Natural Resources Wales are currently (summer 2017) undertaking pilot testing of this new guide to better understand how this research may affect the provision of flood risk management and planning advice as well as during the delivery of flood risk management projects.

## 1.1 Why read this guide

Inevitably, all evidence supporting flood risk management decisions have a degree of uncertainty. This is because flooding mechanisms might be poorly understood or flood information is incomplete or inaccurate. For example, extreme water levels used in development planning or design contain uncertainty. Some of these uncertainties will have been addressed through standard design and appraisal procedures, but others will not. Those uncertainties that remain are called 'residual uncertainties'.

This guide will help you to:

- identify the individual drivers of residual uncertainty
- take appropriate measures to quantify and manage them

## 1.2 Who should use this guide

This guide is intended to support those involved in the management of fluvial, tidal and coastal risks, in particular those engaged in:

- **Planning and approval of development on the floodplain** – planners, architects, developers and Risk Management Authorities (such as the Environment Agency, Lead Local Flood Authorities and Internal Drainage Boards) to establish a common understanding of the credibility of supporting flood analysis and take action to ensure developments are appropriately safe in terms of flood risk
- **Appraising and designing flood risk management options –** enabling Risk Management Authorities and their consultants to:
  - identify sources of uncertainty
  - record how they have been accounted for
  - choose an appropriate response to residual uncertainties when developing a strategy (such as catchment flood management plans, shoreline management plans or local flood risk management strategies), selecting a preferred option or designing a scheme
- **Managing existing flood defences –** assisting Risk Management Authorities and their consultants to assess the protection offered by existing defences while taking account of residual uncertainties

This guide presents detailed guidance and methods for accounting for residual uncertainty for flooding from fluvial, tidal and coastal sources and for development planning. Although the guide does not provide detailed guidance for land drainage or other forms of flooding such as surface or groundwater flooding, the principles presented in this guide are generally applicable to them.

This guide may also provide useful information for others such as local community and regulatory bodies that may have interest in, or are affected by, flood risk management activities.

## 1.3 The problems with the W187 guidance

Freeboard allowances have traditionally been derived based on the assessed uncertainty in the design water level and applied to the crest level of the defence (Environment Agency 2000). This approach is no longer appropriate for the following 3 main reasons.

- **Guidance focused only on fluvial flood risk management.** The management of uncertainty in other sources of flood risk, such as coastal, requires guidance. In addition, there was not a consistent approach for dealing with flood risk uncertainty in development planning.
- **Modern flood and coastal risk management uses a range of measures.** The W187 guidance results in a single response of defence crest level raising; however, this is only one of many possible responses. It may be more appropriate to respond at the source or the receptor of flooding. Also, response at the defence or pathway may take other forms different to raising crest level. In some cases, a combination of different forms of responses may be appropriate.
- **Supporting analysis and data have improved significantly.** Flood risk data and information such as model outputs are presented in more complex ways rather than simply still water level. Many of the traditional considerations in the assessment of freeboard are routinely included in the analysis of flood risk (for example, estimates of waves or culvert blockages). Databases increasingly provide information on data provenance and associated statements of accuracy. The databases also provide an opportunity to record and, with time, develop a shared understanding of important uncertainties at a particular location.

These issues, allied with the development of risk-based and adaptive approaches, mean that a new approach is needed. The approach promoted in this guide centres on the residual uncertainties (those that have not been accounted for elsewhere). Table 1.1 presents some important differences between W187 and this guide.

**Table 1.1 Differences in philosophies between W187 and this guide**

| Topic | W187 (Environment Agency 2000) | This guide |
|---|---|---|
| Approach to identifying relevant uncertainties | A combination of user-driven and prescriptive approaches – largely unstructured but useful checklists provided | A structured hierarchy – primary, components and sub-components. See Section 3.3.2. |
| Climate change | Ambiguous whether included as ‘freeboard’ or through a precautionary allowance when appraising options. This ambiguity has sometimes led to inefficiencies and/or double counting. | Excluded from the residual uncertainty allowance. Allowance for climate change is an appraisal matter requiring choices on timing of response or investment. It is more appropriately dealt with during land use planning, adaptive approaches, appraisal or design processes. See Section 2.3.3 for further details. |

| Topic | W187 (Environment Agency 2000) | This guide |
|---|---|---|
| Factors of safety | Relationship between freeboard and factors of safety is unclear. This ambiguity has sometimes led to inefficiencies and/or double counting. | This guide does not seek to duplicate factors of safety that may already be included in design standards/ procedures. See Section 2.3.3 for examples. |
| Focus of response | A prescribed single management response – raising the defence crest level | Not prescribed – the focus is on taking appropriate actions (single or multiple) to manage it at the source, pathway or receptor. Indicative allowances are provided for development planning only. |
| Links between detailed design and appraisal | Ambiguous – there is considerable scope for double counting. | Explicit recognition of detailed design usually leading on from an appraisal. Principle 5 sets this out and the importance of documenting. See Section 2.3.6. |
| Most simple method | Quick method using a multi-attribute technique, consisting of an 'open' weighting and scoring approach | A guided multi-criteria assessment specifically targeted at development planning; see Section 3.2. |
| More detailed method | First order error analysis | First order error analysis – now called a Tier 1 method (see Section 3.3.4) |
| Most complex method | Composite exceedance probability analysis and Monte Carlo simulation | Sampling and simulation approaches, but now called Tier 2 methods (see Section 3.3.4) |
| Philosophy | Freeboard included physical processes that affect crest level and had not been allowed for in the design water level, for example waves, defence settlement, consolidation and super elevation at bends. | Physical processes and temporal changes are now routinely appraised as part of the option development and design process (for example, settlement, defence consolidation, wave run-up and super elevation at bends). The onus is on the decision maker/designer to identify and record important physical processes and to decide when to incorporate. If uncertainties in physical processes are not accounted for, then they should be managed as residual uncertainty. |
| Scope | The defence and the loads upon it | The whole source–pathway–receptor system, as appropriate to the decision at hand. |
| Scope of uncertainties | Ambiguous | Only those present day ones that have **not** been considered elsewhere in the design or appraisal process; these are referred to as 'unaccounted for uncertainties'. |
| Standard of protection | A conservative assessment of the chance that a storm event overflows the crest of a defence – expressed as a single return period value in years<br>Applicable only to fluvial linear defences. | A conservative assessment of the chance that the overtopping or overflow rate across a defence may exceed an acceptable value (expressed as a range of annual exceedance probability values). Applicable to both fluvial and coastal defences and to serviceability and ultimate limit state criteria. See Section 3.4.4. |
| Terminology | Freeboard | Residual uncertainty allowance – see Chapter 2 for explanation. |

## 1.4 Structure of this guide

This guide is structured as follows (Figure 1.1):

- Chapter 2 presents the definition of the residual uncertainty allowance and the supporting principles that underpin the guidance provided. It includes how the residual uncertainty allowance fits with economic appraisal and standard of protection.
- Chapter 3 describes the approach to assessing the residual uncertainty allowance in the context of (i) development planning, (ii) appraising flood risk management options and scheme design and (iii) managing existing flood defences. It also outlines how to identify and combine uncertainties that may be relevant to your decisions. This chapter contains some worked examples of specific methods.

The appendices include further information on the sources of uncertainty, example templates for assessment, and examples of application in development planning, appraisal of new works and strategy including the assessment of existing assets.

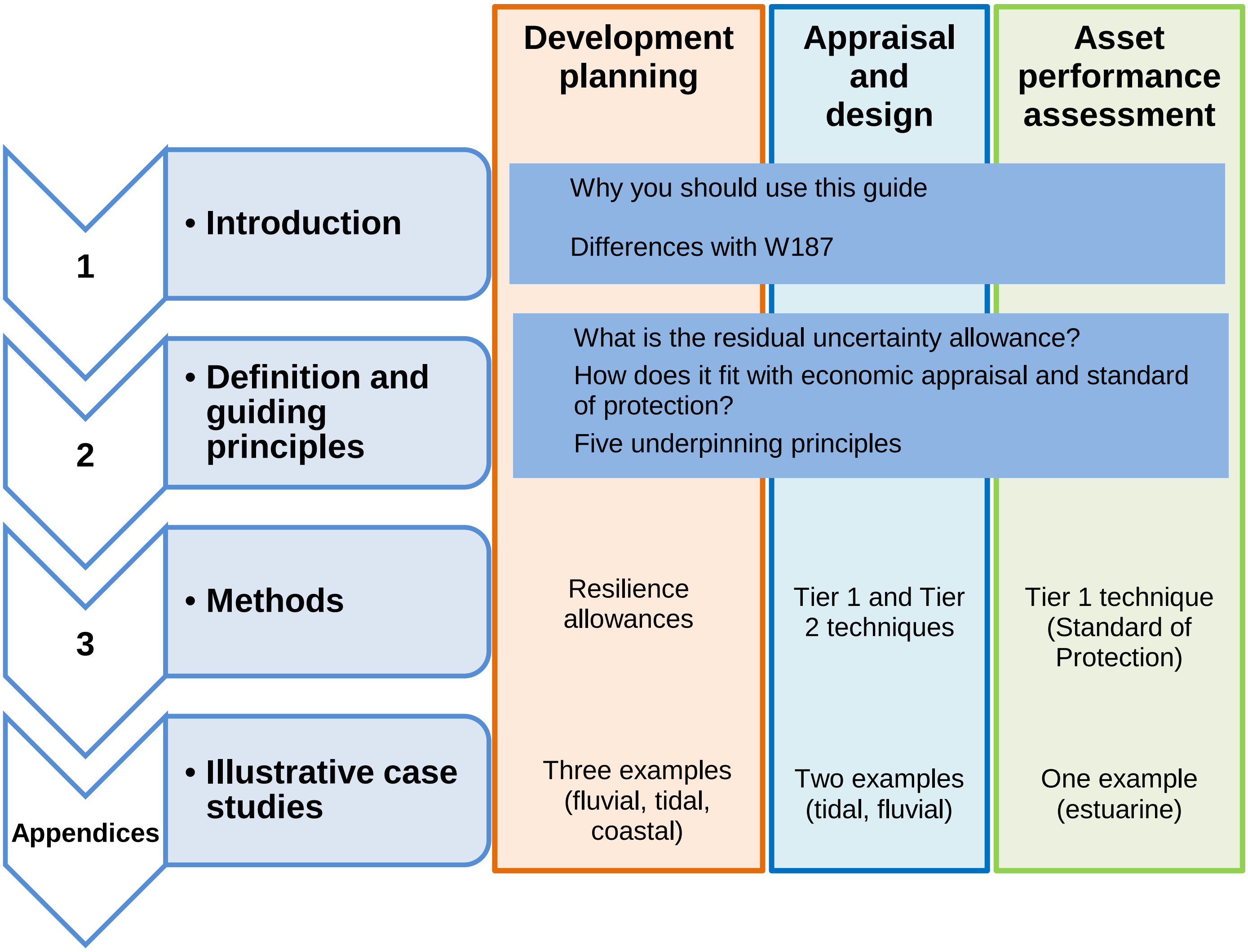



**Figure 1.1 Overview of the structure of this guide**

# 2 Definition and guiding principles

## 2.1 Introduction

This chapter sets out:

- the definition of residual uncertainty allowance and how it relates to economic appraisal and standard of protection
- the principles that underpin the assessment of the residual uncertainty allowance

## 2.2 Defining the residual uncertainty allowance and its context

A residual uncertainty allowance is defined as:

> An allowance that seeks to assure the present day performance of the chosen means of managing flood risk by accounting for uncertainties that have not been explicitly addressed elsewhere in the planning, appraisal, design, or implementation process; whether qualitatively or quantitatively.

### 2.2.1 Residual uncertainty allowance in relation to economic appraisal

The Environment Agency's Flood and Coastal Erosion Risk Management Appraisal Guidance (FCERM-AG) calls for proper consideration of uncertainty in appraisal decisions (Environment Agency 2010).

The cost associated with providing the residual uncertainty allowance must be included within the strategy or scheme appraisal costs as part of the business case development. This is because the residual uncertainty allowance forms part of what gets delivered. However, the benefit associated with the scheme should not be altered to account for the impact of the residual uncertainty allowance. This is because the inclusion of residual uncertainty allowance does not provide any new benefit. It simply increases the confidence that a minimum level of performance will be provided. In other words, if the residual uncertainty allowance had not been applied, the likelihood of realising the full benefit would be low. Illustration 2.1 explains this rule.

**Illustration 2.1 – Residual Uncertainty Allowance only adds cost**

Bristol City centre is predominantly affected by tidal floods via the Floating Harbour. If the Council wants to provide protection against the tidal flood with a 0.5% annual chance of occurring, they need confidence that defences will perform despite data/ knowledge gaps. The present day flood level with a 0.5% annual chance of occurring is 9.11m AOD. Analysis shows that the uncertainty unaccounted for in this value is 0.3m. Therefore a peak water level of 9.41m AOD would be used to design a tidal flood risk management scheme; the option cost would include the associated costs to protect against a 9.41m AOD water level. However, the economic appraisal would use 9.11m AOD to determine the damages.

### 2.2.2 Accounting for uncertainty in the standard of protection

The standard of protection indicates the design event that a structure defends against with a high degree of confidence, normally expressed as an annual exceedance probability (AEP). The degree of confidence is defined by uncertainty.

There are 2 situations where you may choose to define the standard of protection and need to account for uncertainty:

1. **When designing a new flood risk management scheme**. You seek to achieve a reasonable level of confidence that the asset will achieve (as a minimum) the agreed design requirements. For example, in the storm event with a 1% annual chance of occurring, you may require a high degree of confidence that overtopping will be limited and the defence remains structurally intact. Section 3.3 explains how the residual uncertainty allowance gives you this confidence. The principles described in Section 2.3 will help you manage it.
2. **When assessing the performance of an existing defence**. Section 3.4 explains how this works. The rules for this are outlined below and differ from the W187 guidance.

Traditionally (with the W187 guidance) an allowance for uncertainty and physical processes was deducted from the existing defence level and that revised (lower) level was used to define the standard of protection. The practice has now changed and instead you appraise the reality of what is in place today – the design water level and an assessment of unaccounted for uncertainties within it. Further details are found in Section 3.4.

## 2.3 Five underpinning principles

### 2.3.1 Summary

The residual uncertainty allowance is underpinned by 5 principles, which are applicable to all sources of flood risk. Figure 2.1 presents the underlying principles of the Residual Uncertainty Allowance. Sections 2.3.2 to 2.3.6 describe and explain each principle. They will help you to use sound and consistent approaches to account for residual uncertainty.

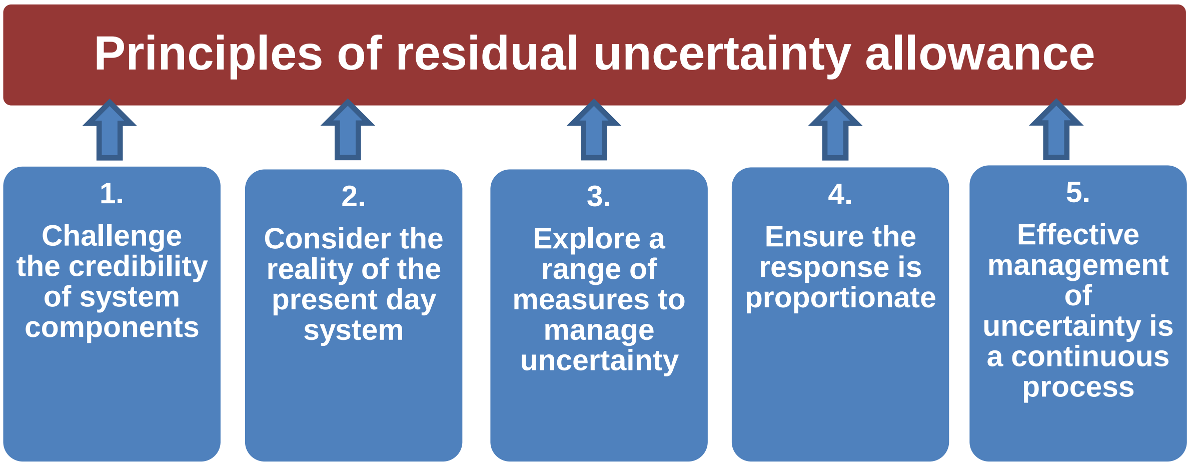
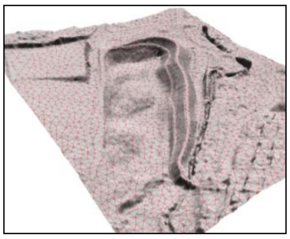



**Figure 2.1 Principles underlying the residual uncertainty allowance**

## 2.3.2 Principle 1: Challenge the credibility of system components

Uncertainty is pervasive in all data and information. To make well-informed choices about how best to respond to this uncertainty, it must first be understood. This includes considering how the uncertainty may be generated and, in particular, the uncertainty introduced through the following.



- **Data and models.** Data uncertainty arises through multiple sources; for example, errors in the topographic data through to the errors introduced through the extrapolation of short observational records. Model uncertainties also have multiple sources; for example, errors in the statistical model used to interpolate the extreme values or the ability of the inundation model to represent important physical processes.

- **Analysis completeness (or lack of).** An analysis approach that fails to represent the important aspects of the real system can be said to be 'incomplete'. When significant elements of the flood risk system are excluded, uncertainty is introduced. For example, excluding a bridge that controls water levels or the potential for boat swash can undermine confidence in the analysis. The structure of the analysis may also introduce uncertainty. For example, the analysis may be limited to a small number of AEP events and exclude design events that exceed crest levels, or the analysis may treat tidal and fluvial loads as independent and ignore joint probability issues.

- **Design and decision choices.** Choices made by the designer can, in some instances, affect the ability of the scheme to perform as desired. For example, the future use of a promenade may be unclear. The assumed use, such as being closed to pedestrians during all storm events, may influence the acceptable overtopping rate and hence the design.

The categories above are not exhaustive, but aim to stimulate the consideration of uncertainty and encourage flood risk managers to think broadly about all potential sources.

Box 2.1 shows how this principle relates to a flood risk assessment for a development application. Considering the source–pathway–receptor zones will help (Figure 2.2 and Figure 2.3).

**Box 2.1: Credibility of system components**

In flood risk assessments (FRAs), good practice such as setting the finished floor levels at a safe height is encouraged. This means that the development or internal floors within them should be dry during particular flood events. This height includes an allowance for uncertainties in the analysis. Below are some useful prompts to help challenge components of the FRA.

- Does modelling contain recent changes, such as upgrades to a flood wall or culvert?
- How have coastal/ tidal/ estuarine threats been represented?
- Have any flood defence failures been represented?
- How have ground levels been measured and represented?
- What method has been used to calculate hydrology?
- How have nearshore waves and sea levels been derived?
- How has surface run-off been represented?
- How have groundwater threats been represented?

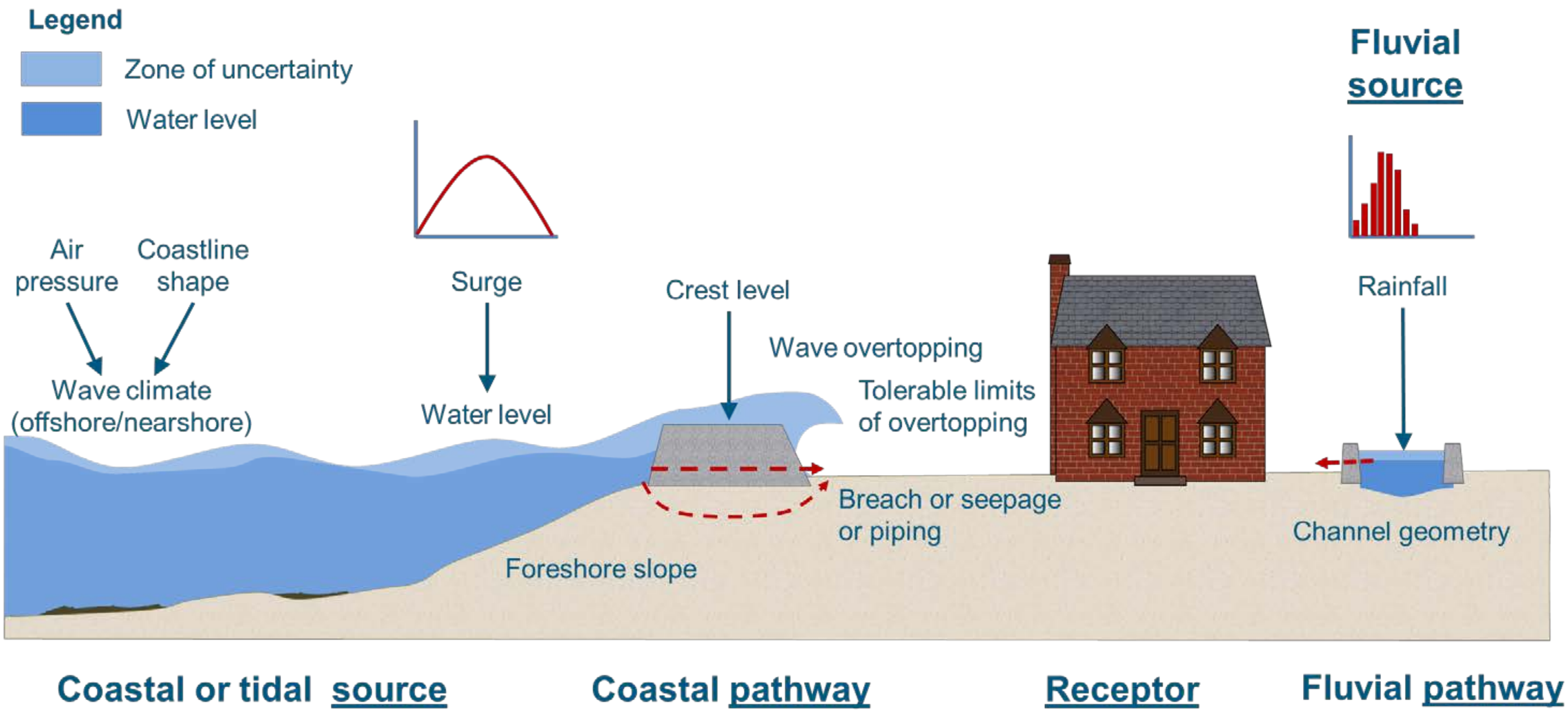



**Figure 2.2 Uncertainties existing in our understanding across the source and pathway**

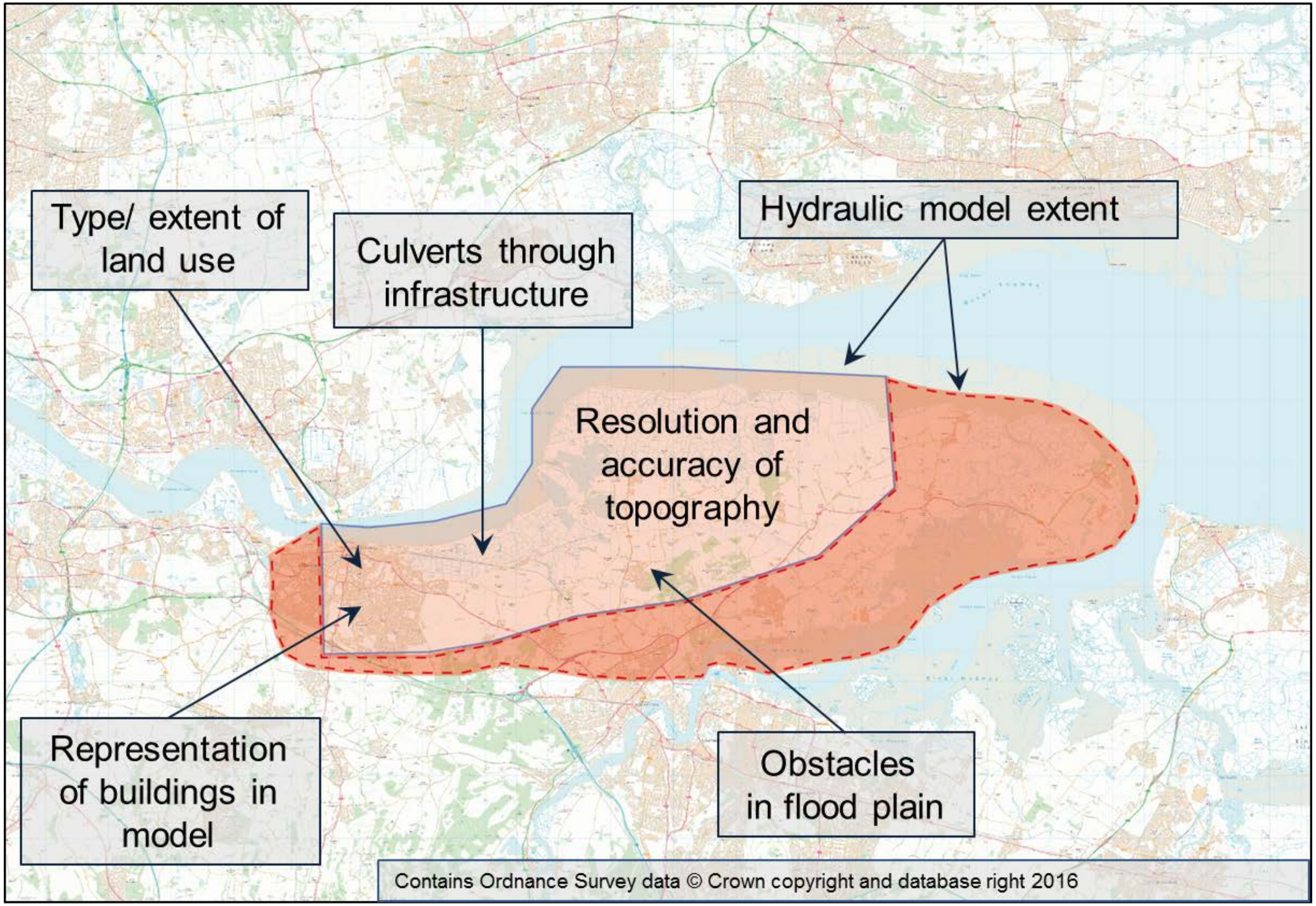



**Figure 2.3 Typical uncertainties in pathways and receptors**

### 2.3.3 Principle 2: Consider the reality of the present day system

The residual uncertainty allowance described in this guide only addresses the uncertainty in present day parameters, for example, the loadings from waves and water levels currently experienced by a flood defence. Future uncertainties are better addressed through precautionary allowances, for example, for climate change. The appraisal process is the point at which to agree the amount of adaptive capacity that should be embedded into the present day actions to account for future risks and uncertainties. Box 2.2 lists some future uncertainties and suggests further reading about dealing with future change.

This principle emphasises that the residual uncertainty allowance only addresses the existing system. You should only appraise the asset or system as it presently is. It is not necessary to carry out reverse calculations to remove freeboard from a previous assessment to define the existing defence performance.

Although the scale of the uncertainties and the approach to their management should be recorded all through analyses and design, the residual uncertainty allowance should only be assessed **after** the end of the relevant project development phase, for example, appraisal or design. This means that the analysis or design is based on the reality of the system with no attempt, for example, to remove an allowance for uncertainty from the measured crest levels or artificially introduce bias into how the system is represented.

Partial safety factors are already used in the design process and account for some uncertainties. For example, BS EN 1997-1:2004 (BSI 2004a and 2004b) contains factors of safety for slope stability when designing walls, so the residual uncertainty allowance does not need to address uncertainty in slope stability assessment as it is already accounted for. Principle 2 therefore focuses on unaccounted for present day uncertainties and avoids double counting.

**Box 2.2: Future change excluded from the residual uncertainty allowance**

Uncertainties associated with future change are excluded such as:

- climate change – affecting sea levels, rainfall and wind climate
- socio-economic changes – population growth and changes in funding
- changes in design parameters – deterioration, defence performance and settlement.

Future uncertainties must be directly accounted for as part of the decision-making appraisal processes; this avoids double counting. The allowances are often decided through a trade-off in the benefits and costs.

Scenario analyses can help to understand the effects of gross future uncertainties. These uncertainties could be managed through agreed precautionary allowances, some of which are agreed at a national or regional level.

Adaptive approaches can also be used, enabling strategies and designs to be more readily modified as the reality of the future becomes better known; see Appendix A of the Supplementary Green Book Guidance (HM Treasury 2009).

Further reading includes:

- 'Practical guidance on determining asset deterioration and the use of condition grade deterioration curves' (Environment Agency 2013a)
- 'Accounting for adaptive capacity in options appraisal' (Environment Agency 2016a)
- 'Adapting to climate change: advice for flood and coastal erosion risk management authorities' (Environment Agency 2016b)
- 'Flood risk assessments: climate change allowances' (Environment Agency 2016c)
- 'Accounting for the effects of climate change. Supplementary Green Book Guidance' (HM Treasury 2009)

### 2.3.4 Principle 3: Explore a range of measures to manage uncertainty

The raising of crest levels is only one of several available ways to manage uncertainty. In some situations, crest raising may not be appropriate, for example, in coastal locations or where visual impacts place a constraint on defence thresholds. An appropriate way to manage residual uncertainty can be through intervention at source, pathway or receptor, or through a combination of measures, see Illustration 2.2.

Principle 3 encourages you to think and use your expertise and local knowledge to manage uncertainty. Figure 2.4 illustrates some examples of appropriate responses.

**Illustration 2.2: Implementing measures to manage uncertainty**

An existing fluvial flood embankment is in an environmentally sensitive location with a narrow corridor of land owned by the Environment Agency. The designers seek to achieve an appropriate degree of sureness that the asset will be resilient, as a minimum, against a storm event with a 1% annual probability. There are uncertainties in the duration and magnitude of waves at the embankment. In this situation, legitimate responses to managing these uncertainties include:

- performing a sensitivity analysis of larger waves and longer durations of overtopping
- armouring the rear slope to resist higher rates of overtopping
- limiting wave overtopping rates by adding a margin of safety to crest levels, increasing the crest width or slackening the rear slope

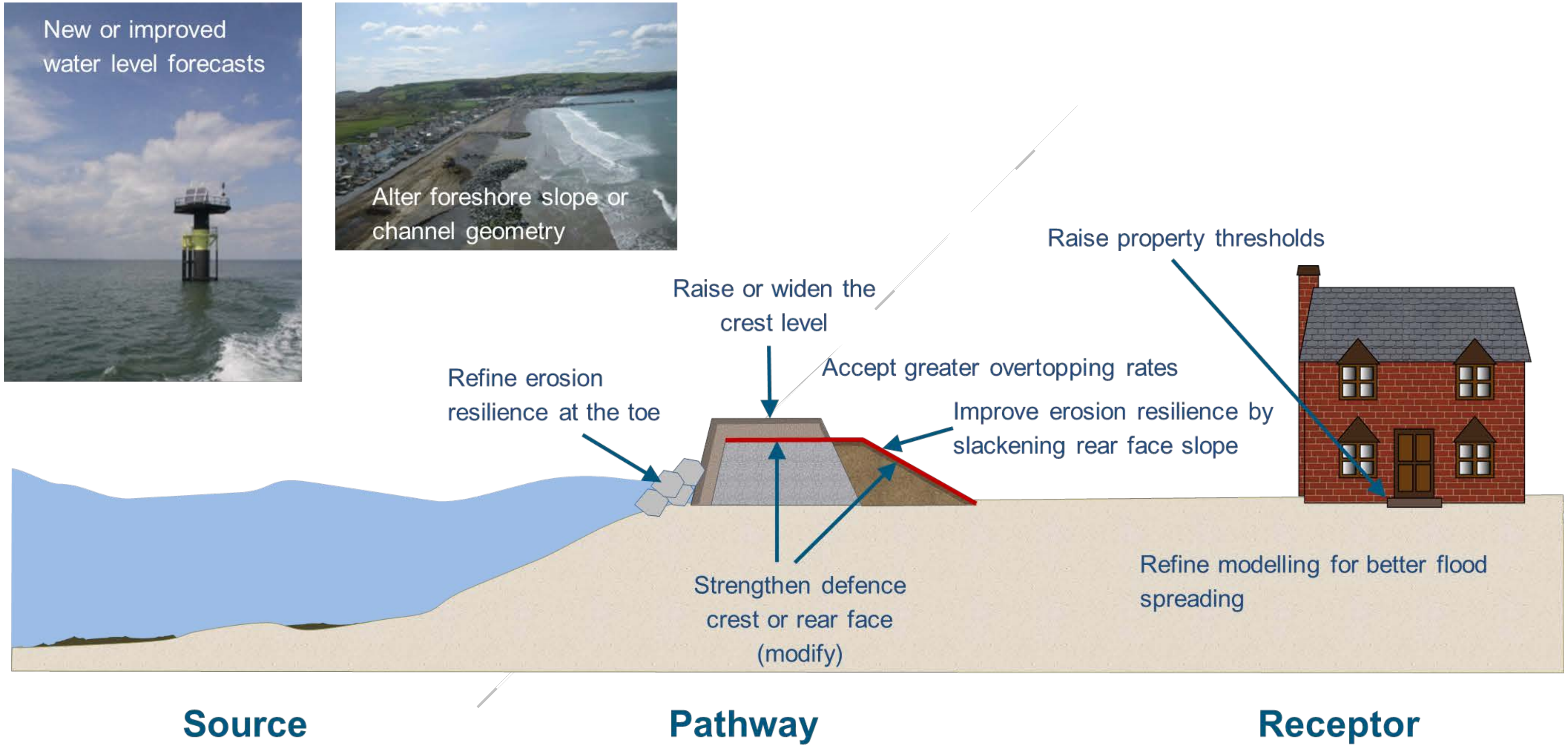



**Figure 2.4 Examples of appropriate measures to manage residual uncertainties**

### 2.3.5 Principle 4: Ensure the response is proportionate

Depending on the context in which the decision is being taken, some residual uncertainties may be easily addressed through reasoned argument and/or minor cost additions to the final project. In other cases, addressing the residual uncertainties may add significantly to the cost of the strategy, scheme or development and careful consideration of the most appropriate response is required.

You can choose to respond to these residual uncertainties in one of 4 ways:

1. Conduct further analysis to refine the supporting knowledge and therefore reduce the uncertainty.
2. Accept the uncertainty as a residual uncertainty and its associated costs, but act to reduce its impact via adding to the final project.
3. Accept the uncertainty as a residual uncertainty. Record it, but choose not to act to reduce its impact.
4. Go back to the appraisal of other options.

When deciding which of these 4 options to choose, you need to consider the significance of the risk associated with the uncertainty compared with the costs of managing that uncertainty. In making this choice, consider the following questions.

- Is further analysis likely to significantly change the identification of the preferred option/preferred course of action or its cost?
- Does choosing to manage the residual uncertainty by adding to the final scheme significantly change the cost benefit case for the preferred option?

If the answer to both these questions is 'no', then the residual uncertainty should be accepted and action taken to reduce its impact. Section 3.3 explains this further. Determining the effort to make a design 'adaptive' (through stronger foundations, wider crests, and so on) is more appropriately considered through the appraisal process.

### 2.3.6 Principle 5: Effective management of uncertainty is a continuous process

Uncertainties should be identified and managed progressively across all stages in the project life cycle (Figure 2.5). There may be occasions when residual uncertainties passed down the chain need to be passed back up for strategic decisions. This principle also emphasises the importance of recording uncertainties and their management; this will help to improve knowledge on previous unknowns. It is likely that the implementation of building information modelling (BIM) will be an important vehicle for this principle. This is because data will be more accessible across different stages of a project and development application.

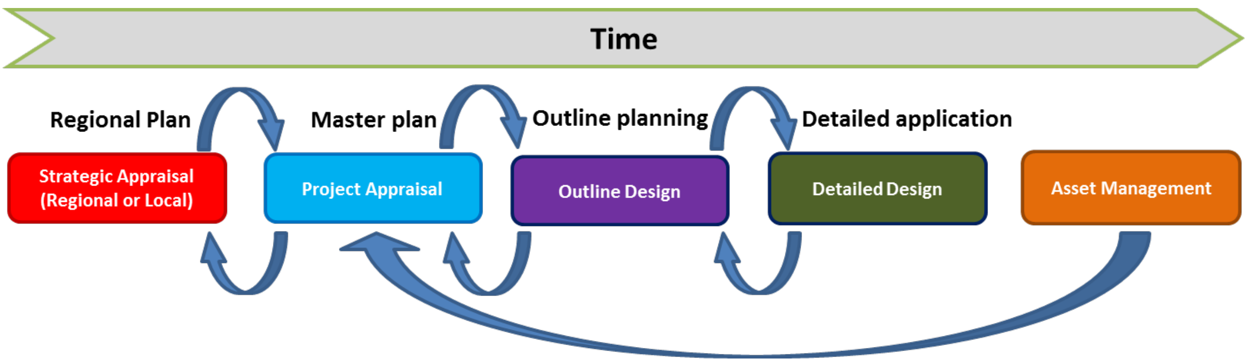



**Figure 2.5 When to consider the residual uncertainties**

## 2.4 Summary

This chapter has set out:

- the definition of the residual uncertainty allowance and how it relates to economic appraisal and standard of protection
- the five principles that underpin the assessment of the residual uncertainty allowance:
  1. Challenge the credibility of system components
  2. Consider the reality of the present day system
  3. Explore a range of measures to manage uncertainty
  4. Ensure the response is proportionate
  5. Effective management of uncertainty is a continuous process.

This chapter has highlighted that the analysis must be proportionate. To facilitate this, the next chapter introduces the tiered and staged assessment method of determining an appropriate residual uncertainty allowance.

# 3 Methods

## 3.1 Introduction

This chapter explains how to determine an appropriate residual uncertainty allowance.

If you are providing advice and making decisions relevant to development planning go to Section 3.2.

If you are developing a strategy, appraising options, assessing the performance of an existing defence or designing a new scheme go to Section 3.4.

## 3.2 Detailed stages for development planning

### 3.2.1 Overview

The approach to determining the residual uncertainty allowance in the context of development planning is designed to be quick and easy, yet thorough. It involves assigning confidence scores to different aspects of the evidence and combining these estimates into an overall confidence rating. The confidence rating is then used to inform a recommended residual uncertainty allowance.

There are 3 important stages for the assessment:

- Stage 1 – Identify and record all primary sources of uncertainty
- Stage 2 – Estimate the magnitude of the residual uncertainties
- Stage 3 – Determine the appropriate response

An important aspect of the approach is to record your decisions at each stage. This will help you engage and communicate the important uncertainties with all project partners. A template for documenting this evidence is provided in Appendix A and illustrated in Case Studies 1 to 3 in Appendix D.

### 3.2.2 Stage 1 – Identify and record all primary sources of uncertainty

Table 3.1 lists the primary sources of uncertainty to consider.

In some cases these may not be relevant and can be excluded from the assessment. However, the reason(s) for exclusion must be recorded. For example, if there are no flood defences present, the scoring of breaches can be excluded.

**Table 3.1 Considerations for identifying primary sources of uncertainties in development planning**

| Consideration | Description |
|---|---|
| **How appropriate is the flood risk analysis?** | Does it contain the important local features such as culverts or de facto defences (that is, structures acting as but not designed as defences)? Is the analysis up-to-date? For example, does it incorporate local land use change or a new flood wall? The age of the analysis can be a factor. |
| **How well is the floodplain modelled?** | The type and resolution of the floodplain topography data are important as the floodplain could have important pathways or |

| | |
|---|---|
| | features such as drainage channels and road embankments which need to be resolvable. Examples of topographic survey include: synthetic aperture radar (SAR), light detection and ranging (LIDAR) and fast laser imaging mapping and profiling (FLI-MAP). Each survey and survey technique will have a different resolution. Selecting the right resolution is important. |
| **How well has the potential for defence failure been modelled?** | If flood defences or assets influence residual water levels at the site, the number and type of breaches will affect the confidence in the flood risk analysis. See Box 3.1 for exceptions when credible failures might not be considered. |
| **What is the confidence in the hydrology?** | This is the basis for deriving inflows for fluvial, surface run-off or groundwater sources (for example, length of records). Has a considered approach to the use of data and hydrological analysis been followed? |
| **How good are the coastal/ estuarine/ tidal boundaries?** | The boundaries form the basis for deriving nearshore conditions such as waves and sea level. Has a considered approach to the use to the selection of the boundary conditions been followed? |
| **How have the fluvial threats been represented?** | Assess the appropriateness of the modelling technique. |
| **How have coastal threats been represented?** | Assess the detail of wave overtopping and tidal inundation in comparison to the complexity of the site. |
| **How has surface run-off been represented?** | Assess the detail of the modelling in comparison to the complexity of the site. |
| **How have groundwater hazards been represented?** | Assess the detail of the modelling in comparison to the complexity of the site. Local policy may indicate when analysis is required. |
| **What is the strength of the evidence?** | How strongly does the evidence support/ validate flooding representation (for example, calibration of modelling against observed events)? |

**Box 3.1: When is it credible not to consider failure of a defence/ asset?**

If a flood defence or asset is influencing the probability of flooding, it is good practice to consider the consequences of failure. There is always a chance of failure when loaded to levels at or near the design level. The **only** credible exception is when you know the probability of failure is very low or an asset is highly resilient, such as in the following examples.

- According to local Environment Agency policy, flood risk assessments upstream of the Thames Barrier need not account for failure to close the barrier.
- Certain Nationally Significant Infrastructure Projects (NSIPs) have defences designed to withstand extremely rare flood events.

### 3.2.3 Stage 2 – Estimate the scale of the residual uncertainty

For each relevant consideration, determine the scale of residual uncertainty. Use Table 3.2 to assess the confidence score. You should record the score as well as the reasons.

**Table 3.2 Development planning confidence assessment (adapted from Environment Agency 2013 b)**

| **Topic** | **Confidence (level of representation for the current situation)** | | | | |
|---|---|---|---|---|---|
| | **Very unlikely to be locally reliable (scores 10)**<br>**Poor representation** | **Unlikely to be locally reliable (scores 5)** | **Likely to be locally reliable (scores 3**<br>**Basic local representation)** | **Very likely to be locally reliable (scores 2)**<br>**Good local representation** | **Highly likely to be locally reliable (scores 1)**<br>**Very good representation** |
| **How appropriate is the flood risk analysis?** | There have been significant changes since the model or evidence was created (for example, a new defence) or applicability has not been assessed or compared against changes in the system. | n/a | There have been minor changes in the source–pathway–receptor, but the model or evidence has not been updated or created and minor issues are known about, for example, defence schematisation. | There have been changes in the source–pathway–receptor and the model or evidence has been updated or created for a selection of features. Still some known minor issues. | There have been no changes, or the model or evidence has been updated or created to represent the current situation well (for example, new defences, changes in land use, boundaries updated). |
| **How well is the floodplain modelled?** | Data type or resolution does not reflect the variation in floodplain topography, such as use of SAR or low resolution methods applied to represent complex topography. Flood flow routes not represented or omitted and in-channel features not represented. | n/a | Data type or resolution gives a basic representation of variation in floodplain topography. Represents the main flood flow routes in out-of-bank areas. Out-of-bank and in-channel features are omitted or simplified due to low resolution of topographical survey. | Data type or resolution gives a fair representation of variation in floodplain topography and all flood flow routes are represented in out-of-bank areas. A few topographical features are not picked up due to the resolution of topographical survey or LIDAR. | Data type or resolution reflects the variation in the floodplain topography. For example, using very detailed high resolution (<5m resolution) LIDAR to represent complex floodplain features and in-channel survey at very frequent intervals with linear features identified along bank tops and in the out-of-bank areas. |
| **How well has the potential for defence** | No evidence that the potential for a structure or defence failure has been incorporated. | Evidence that failure has been identified and one breach/failure have been tested. | Evidence that failure has been considered and multiple individual breaches/failures have | Evidence that multiple individual breaches/failures have been tested and a sensitivity analysis performed. | A credible assessment of multiple individual failures and combination failures. Evidence of using local historical breach data |

| Topic | Confidence (level of representation for the current situation) | | | | |
|---|---|---|---|---|---|
| | Very unlikely to be locally reliable (scores 10) Poor representation | Unlikely to be locally reliable (scores 5) | Likely to be locally reliable (scores 3 Basic local representation) | Very likely to be locally reliable (scores 2) Good local representation | Highly likely to be locally reliable (scores 1) Very good representation |
| **failure been modelled?** | | | been tested. Simple methods from FD2320 (Defra and Environment Agency 2005) used. | | to inform conditions. Complex methods from FD2320 used. |
| **What is the confidence in the hydrology?** | For example, Flood Studies Report (FSR) prediction, records are short or only of low flows/ levels | For example, Flood Estimation Handbook (FEH) analysis using catchment descriptors | For example, FEH analysis using donor catchment and pooling group, some use of FEH guidelines | For example detailed gauging station analysis, moderate record of high flows and levels where one flow is at least as high as the design flow | For example, detailed gauging station analysis, long record of high flows and levels where more than one flow is at least as high as the design flow, use of FEH guidelines |
| **How good is the coastal/ estuarine/ tidal boundary?** | No local records and no evidence that uncertainty has been considered in the design storm conditions. | For example short records of tide levels/waves with few storm events, simple calculations | Locally credible information of sea levels and waves with longer records. For example, 50 percentile sea level extremes taken from Environment Agency guidance on coastal flood boundary conditions for UK mainland and islands (Environment Agency 2011) | More locally credible information of sea levels and waves with longer records. For example, 50 percentile sea level extremes taken from Environment Agency guidance on Coastal flood boundary conditions for UK mainland and islands (Environment Agency 2011) and some local analysis or assessment of uncertainty. | Very good local records and/or specific statistical analysis, historical understanding of key process included and good evidence that uncertainty has been considered in the design storm conditions. For example, considered uncertainty in nearshore waves. Tested range of uncertainty in water levels from the 5th to the 95th percentile for sensitivity and either insensitive or highly sensitive with a precautionary 95th percentile adopted. Joint probability for waves and water levels |
| **How have fluvial threats been represented?** | For example, simple calculations, | | For example, simple 1D or linked 1D–2D model simulating only 2 annual likelihoods | | For example, 1D or linked 1D-2D model simulating 5 or more annual likelihoods covering ones |

| Topic | Confidence (level of representation for the current situation) | | | | |
|---|---|---|---|---|---|
| | Very unlikely to be locally reliable (scores 10) Poor representation | Unlikely to be locally reliable (scores 5) | Likely to be locally reliable (scores 3 Basic local representation) | Very likely to be locally reliable (scores 2) Good local representation | Highly likely to be locally reliable (scores 1) Very good representation |
| | generalised modelling or obsolete methods | | as stated by planning policy guidance. Simple calculations might be appropriate with sufficient evidence or justification. | | stated by planning policy and associated guidance. |
| **How have coastal threats been represented?** | Simple calculations, simplified (no) breach consideration, use of obsolete methods | | For example, local application of overtopping methods (for example, EurOtop) with no or limited toe level information. 1D or 1D–2D model simulating only 2 annual likelihoods stated by planning policy guidance. Simple calculations might be appropriate with sufficient evidence or justification. | | Local application of overtopping methods including toe level with recently surveyed bathymetry, 1D or 1D–2D model simulating 5 or more annual likelihoods covering ones stated by planning policy and associated guidance. |
| **How has surface run-off been represented?** | For example, simple calculations, use of obsolete methods | | For example, 1D or 1D–2D model simulating only2 annual likelihoods stated by planning policy guidance. Simple calculations might be appropriate | | For example 1D or 1D–2D model simulating 5 or more annual likelihoods covering ones stated by planning policy and associated guidance. |

| Topic | Confidence (level of representation for the current situation) | | | | |
|---|---|---|---|---|---|
| | **Very unlikely to be locally reliable (scores 10)**<br>**Poor representation** | **Unlikely to be locally reliable (scores 5)** | **Likely to be locally reliable (scores 3**<br>**Basic local representation)** | **Very likely to be locally reliable (scores 2)**<br>**Good local representation** | **Highly likely to be locally reliable (scores 1)**<br>**Very good representation** |
| | | | with sufficient evidence or justification. | | |
| **How have groundwater hazards been represented?** | For example, use of commercially available national scale groundwater hazard/emergence mapping or an assessment by a non-specialist. | For example, basic assessment by a competent groundwater specialist using publicly available data (such as 1:50,000 scale geological mapping), without site–site specific data or local groundwater level | For example, basic assessment by a competent groundwater specialist using publicly available data (such as 1:50,000 scale geological mapping) and local, long-term groundwater level records, without site–site specific data. | For example, detailed assessment by a competent groundwater specialist using all publicly available geological data, local long-term groundwater level records and site-specific hydrogeological data | For example, detailed assessment by a competent groundwater specialist using all publicly available geological data, local long-term groundwater level records and site-specific hydrogeological data, combined with statistical analysis or numerical modelling |
| **What is the strength of evidence?** | No evidence that the models used have been calibrated or validated. | Validated/calibrated against one flood event more frequent than design event | Validated/calibrated against one flood event less frequent than design event or multiple events more frequent than the design event. Performed some sensitivity analysis. | Validated/calibrated against multiple flood events with at least one less frequent than design event | Validated/calibrated against multiple flood events less frequent than design event |

## 3.2.4 Stage 3 – Determine the appropriate response

The appropriate response for dealing with uncertainty in development planning is derived by completing the steps below. Illustration 3.1 provides a worked example of Stage 3.

(a) Take the 2 highest scores – in other words, the 2 topics with the least confidence – and use Table 3.3 to determine the confidence rating. The overall confidence and accuracy in the assessment are heavily influenced by the weakest links, which are the parameters with the worst confidence. Here it is assumed that their influence is equal. The matrix is based on the approach taken by the Environment Agency to measure confidence in the National Flood Risk Assessment (NaFRA) outputs.[1]

**Table 3.3 Scoring matrix to derive confidence rating**

<table>
<tr><th colspan="2"></th><th colspan="5">Worst topic 1 score</th></tr>
<tr><th colspan="2"></th><th>10</th><th>5</th><th>3</th><th>2</th><th>1</th></tr>
<tr><th rowspan="5">Worst topic 2 score</th><th>10</th><td colspan="3">1 star</td><td>2 star</td><td>3 star</td></tr>
<tr><th>5</th><td colspan="2">1 star</td><td>2 star</td><td>3 star</td><td>4 star</td></tr>
<tr><th>3</th><td>1 star</td><td>2 star</td><td>3 star</td><td colspan="2">4 star</td></tr>
<tr><th>2</th><td>2 star</td><td>3 star</td><td colspan="2">4 star</td><td>5 star</td></tr>
<tr><th>1</th><td>3 star</td><td colspan="2">4 star</td><td colspan="2">5 star</td></tr>
</table>

(b) Use the confidence rating and Table 3.4 to determine the residual uncertainty allowance; select the higher depth. The minimum depths in Table 3.4 range from 300mm to 900mm, and are based on a review of best practices from across Europe. The intervals between the values are distributed evenly.

**Table 3.4 Residual uncertainty allowance in development planning**

| Confidence rating | Confidence description | Proportion of design flood depth [1] | Minimum depth (mm) |
|---|---|---|---|
| 1 star | Very unlikely to be locally reliable | 40% | 900 |
| 2 star | Unlikely to be locally reliable | 30% | 750 |
| 3 star | Likely to be locally reliable | 20% | 600 |
| 4 star | Very likely to be locally reliable | 10% | 450 |
| 5 star | Highly likely to be locally reliable | 5% | 300 |

Notes: [1] Using the appropriate design water level criteria according to national planning policy (DCLG 2012a and b). If the site is defended, use the residual water depth from breaching.

(c) An appropriate response for development planning is to raise the floor level (property threshold). The level is calculated by adding the residual uncertainty allowance to the design water level at the site. The choice of confidence percentile for the coastal extreme water level is governed by local policy. This guide does not provide advice on this matter as it is influenced by local social, economic and political situations. There are some instances where the property threshold cannot be achieved, for example, in change of use applications, disabled access and where there are roof height

[1] Measuring Confidence in NaFRA Outputs, FCPIF00151B00/R

restrictions. In such situations, some alternative appropriate responses are outlined below – explore the first before the second:

i. Recommend action to improve the confidence score, such as improving topography quality, 1D or 2D representation, breach or sensitivity assessment.

ii. The property threshold should be raised as high as is reasonably practicable. The remaining minimum allowance should be comprised of flood resistant and resilient construction measures. Useful advice can be found in BS 85500:2015 (BSI 2015).

**Illustration 3.1: Stage 3 example for development planning**

According to the Local Plan, a council has decided that residential dwellings can be located on a greenfield site in the fluvial Flood Zone 3. The council has received an FRA and completed stages 1 and 2 of the residual uncertainty allowance method; see the assessment table below.

| Consideration | Applicability | Score | Reasons |
|---|---|---|---|
| How appropriate is the flood risk analysis? | Yes | **3** | Basic local representation – a private flood defence built for a new supermarket upstream of the site has not been included in the model but the greenfield site does not have a flood embankment. |
| How well is the floodplain modelled? | Yes | 2 | Good local representation of floodplain pathways. The 5m grid using LIDAR and detailed topographic survey reasonably represents the variation in the local ground levels but upstream is flood embankment missing. |
| How well has the potential for defence failure been modelled? | n/a | - | No defences of note at the site. |
| What is the confidence in the hydrology? | Yes | **3** | Basic local representation, for example, FEH analysis using donor catchment and pooling group |
| How good is the coastal/ estuarine/ tidal boundary? | n/a | - | Not applicable – inland location |
| How have the fluvial threats been represented? | Yes | **3** | Good local representation – 1D–2D linked model used to define the 1% and 5% annual probability flood events for the present day and with 100 years climate change |
| How have coastal threats been represented? | n/a | - | Not applicable – inland location |
| How has surface run-off been represented? | n/a | - | Not applicable – will be considered in the drainage assessment |
| How have groundwater hazards been represented? | n/a | - | Not applicable – no history of groundwater flooding |
| What is the strength of evidence? | Yes | **5** | Model validated against a flood event that had a 20% annual probability and which did not reach the new private flood defence. |

**Stage 3a**: Using Table 3.3, the resultant confidence rating is 2 star.

**Stage 3b:** The maximum design flood depth (1% annual probability) is 900mm. Using Table 3.4, the proportion of design flood depth is 270mm. As this is less than the minimum required allowance, 750mm will be recommended when setting the finished floor level of the dwellings.

The council requires climate change to be included. The 1% design water level with climate change at the site is 3.78m AOD. Hence the target floor level (property threshold) is 4.53m AOD, but with the caveat that flood risk is not increased elsewhere. The developer has indicated that it is possible to raise thresholds up to 4.10m AOD. The council recommends that the 1D–2D model is updated with details of the private flood defence. This would result in a 3 star confidence rating and a 600mm allowance for residual uncertainty, which would lower the target threshold level. The developer is requested to use flood resilient measures to protect dwellings above 4.10m AOD up to the new target threshold level.

### 3.2.5 Inclusion of climate change

As per Principle 2, the allowance for climate change is excluded from the residual uncertainty allowance. However, it is common practice to consider an appropriate climate change allowance when making a development safe during its lifetime. In these cases, the residual uncertainty allowance should be added to the site design water level that includes an appropriate allowance for climate change.

If the site is defended, the residual uncertainty allowance should be added to the water level that has taken account of the existing flood defence, such as overtopping or failure. This would give a precautionary allowance when setting the finished floor levels.

### 3.2.6 Summary

Figure 3.1 summaries the approach for development planning.

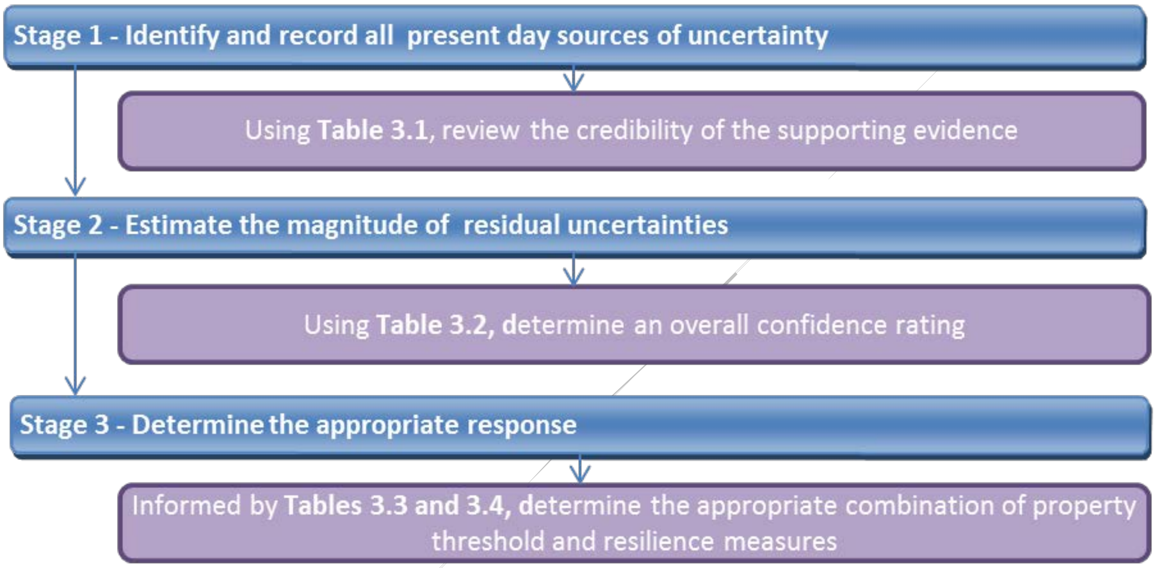



**Figure 3.1 Stages of assessment for development planning**

## 3.3 Detailed stages in flood risk management strategy or scheme

### 3.3.1 Overview

There are 4 stages to reach the residual uncertainty allowance in the context of strategies, appraisals and detailed design (Figure 3.2). The technique used to combine all of the remaining residual uncertainties to arrive at a residual uncertainty allowance requires more thought than is required for develop planning.

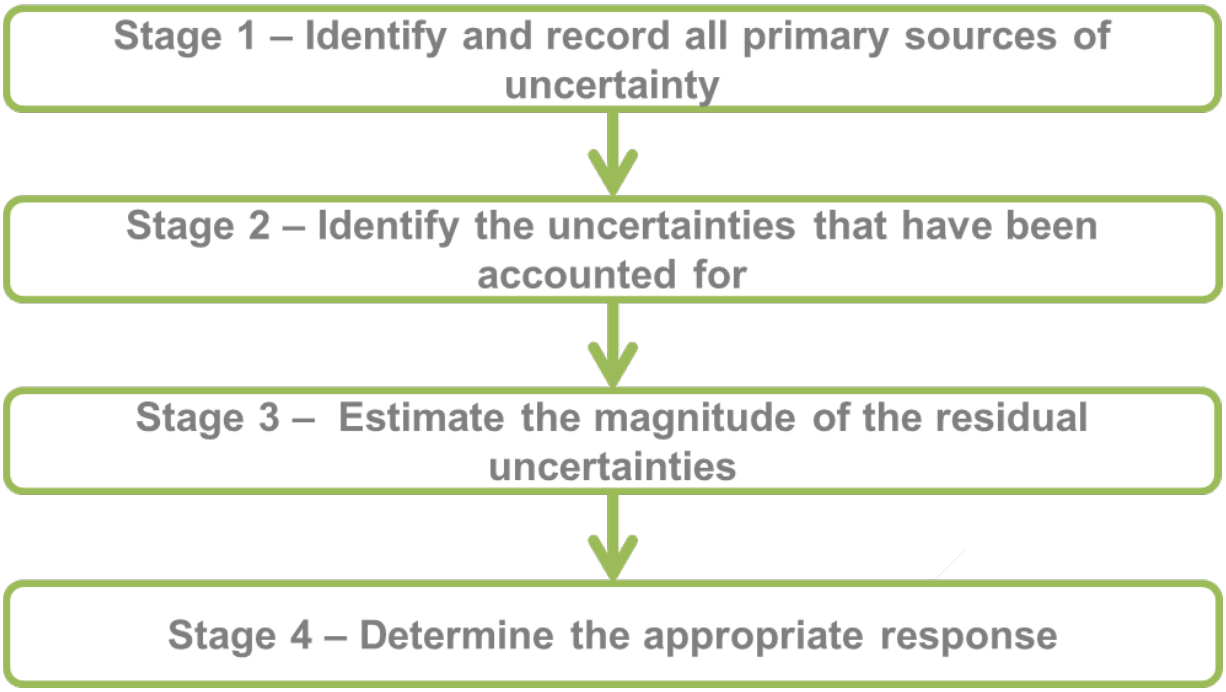



**Figure 3.2 Stages of assessment in relation to strategies, appraisals and design**

### 3.3.2 Stage 1 – Identify and record all primary sources of uncertainty

This stage enables you to develop an understanding of all relevant sources of uncertainties.

Using the categories of uncertainty in Principle 1, identify and record all primary sources of uncertainty. Appendix B contains some examples of these under each of the following categories:

- **Data and model uncertainties** – reflecting the uncertainties in the input data and models used
- **Analysis completeness** – reflecting the potential uncertainties that may be introduced by making simplifying assumptions or excluding important physical processes
- **Design and decision choices** – reflecting the choices made regarding the approach to the design or decision-making

Primary sources of uncertainty should not be confused with the components of each uncertainty. The components of uncertainty contribute to each primary source. For example, Figure 3.3 illustrates some of the components of uncertainty in the primary source of ‘watercourse water level’ uncertainties and Figure 3.4 shows components of uncertainty in the primary source of coastal overtopping rates.

You should only consider present day uncertainties that are relevant to your decision. This could be something that influences the assessment of risk or the performance of the asset.

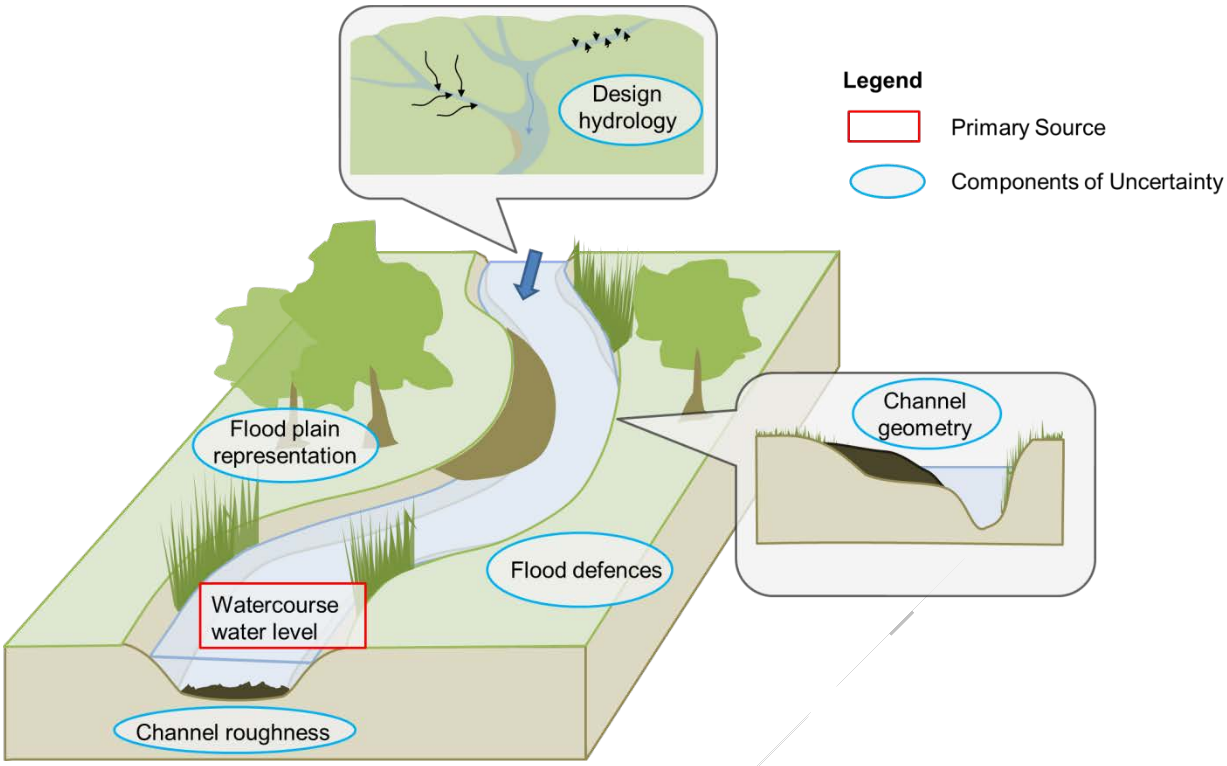



**Figure 3.3 A fluvial example of a primary source of uncertainty and its components**

It can be useful to use engineering systems[2] to identify the primary sources of uncertainty; the ones that control functions of a particular system. Section 3.4 provides a selection of techniques to consider weighting and significance of uncertainty components.

To ensure that uncertainties are not dealt with at multiple points in the project life in appraisal and design leading to double counting, it is important to indicate and record which uncertainties have already been accounted for. Usually this means that the uncertainty does not require further management action. If further knowledge emerges on the uncertainty that improves confidence, it is useful to reconsider the uncertainty especially if it offers an opportunity to reduce costs or increase efficiency of project delivery.

Use the template in Appendix C to record uncertainties and their associated management actions, and if it is likely that the uncertainty would need to be reconsidered in the future.

[2] For further information go to the Massachusetts Institute of Technology, Engineering Systems Division's website (https://esd.mit.edu/research/uncertainty.html).

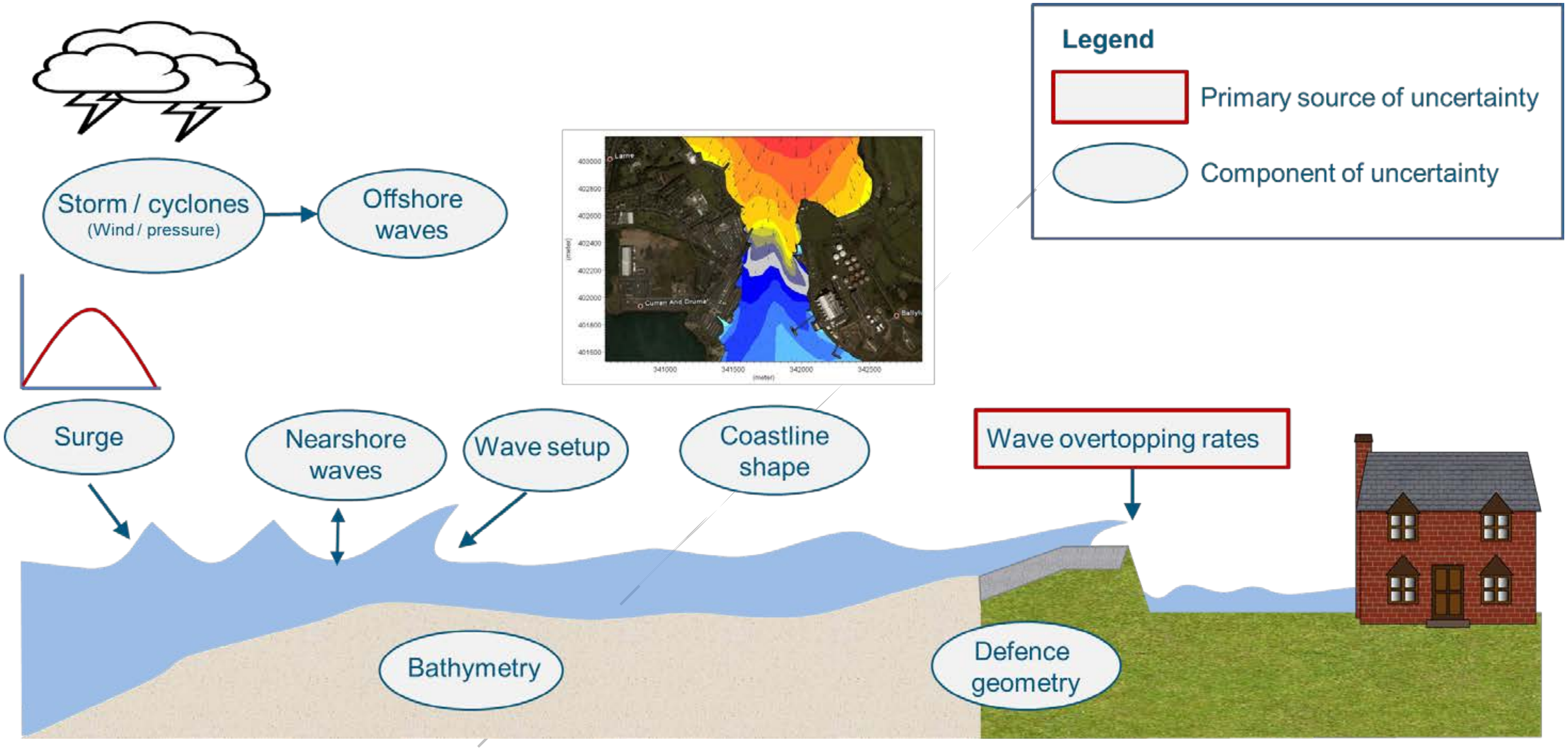



**Figure 3.4 A coastal example of a primary source of uncertainty and its components**

### 3.3.3 Stage 2 – Identify the uncertainties that have been accounted for

After all uncertainties have been identified, the next stage is to record those that have already been addressed. Here 'addressed' means they have been accounted for in the strategy, appraisal or design process. The uncertainties that have not yet been addressed should be assessed in Stage 3. Illustration 3.2 provides an example of when an uncertainty has been accounted for.

**Illustration 3.2: Example of an accounted for uncertainty**

There were concerns in the Lewisham and Catford Project Appraisal about the accuracy of the urban hydrology model as it was 14 years old and was undergoing a review that would report after the appraisal had been submitted. The critical cases used in the appraisal hydrology were for short duration storms and the designers knew from previous projects that longer durations with a greater volume are more critical for flood storage reservoirs. Changes in the hydrological method or storm duration could mean that a lower standard of protection is offered by the reservoir. This would have a significant impact on the decision to invest in the scheme. The designers increased the volume to be stored to account for the longer duration and other uncertainties in the hydrology. This illustrates that the uncertainty on the urban hydrology has been accounted for.

### 3.3.4 Stage 3 – Estimate the magnitude of the residual uncertainties

Stage 3 involves appropriately quantifying the uncertainties not already accounted for, that is, the residual uncertainty.

Depending on available information, the estimation can be based on expert judgement or more detailed analysis. Stage 4 will help you to decide if you require further evidence.

There are 2 techniques for estimating uncertainty and determining the most important sources of uncertainty as discussed:

- Tier 1 – First order error analysis
- Tier 2 – Sampling and simulation

The methods for tiers 1 and 2 differ in complexity and the analysis effort required.

The selection of the most appropriate method will depend on:

- magnitude of potential consequences
- cost of proposed management measures
- nature of available data and analysis tools
- time available

#### *Tier 1 – First order error analysis*

The assumption behind first order error analysis is that flood systems behave non-linearly but that the change in primary variables (such as in-river water level or flood depth) is small for a small change in the input variables (for example, roughness).

This allows the first order error analysis to be used to quantify the primary uncertainty (for example, in in-river water level) by a simple weighted summation of the contributory uncertainties (for example, channel roughness and hydrological record).

A simple application of the first order error analysis proceeds as follows.

**a. List the secondary variables that contribute to the primary variable of interest.** Table 3.5 gives examples that are likely to contribute to the uncertainty in the in-river water level.

**Table 3.5 Components of uncertainty in watercourse water levels**

| Components of uncertainty in watercourse water levels | |
|---|---|
| Accuracy of hydrological response | Understanding of hydrological conditions throughout catchment |
| | Reliability of gauging records |
| | Availability/length of gauging records |
| | Performance of rainfall run-off method |
| | Storm patterns |
| | Statistical model to derive extreme water level |
| Accuracy of hydraulic response | Information of channel geometry |
| | Floodplain flow interactions |
| | Model parameters (transient, steady state, simple backwater analysis) |
| | Weir coefficients |
| | Variation in channel roughness |

b. **Estimate the change in the primary variable for a small change in each secondary variable.** This can be done using judgement or scenario testing (by perturbing the secondary variable and observing the change in primary variable). For example, an increase in Manning's n of 0.01 may lead to an increase in the design water level of 0.2m. Where sensitivity testing has been carried out to test the impact of variables, this can usefully feed into this assessment.

c. **Estimate the uncertainty in the secondary variables.** Where possible this should be based on testable evidence. In many cases, however, judgement will be needed to determine this range. Regardless of the approach taken the evidence/reasoning should be recorded.

   Note: The notional confidence interval of this range is not prescribed here but should be considered in the context of the decision being taken and the same level of confidence applied to all secondary variables. When assessing the uncertainty in each secondary variable, however, the same confidence interval must be considered, such as the 90% 95% percentile. The appropriate value is likely to change given the context of the decision; Box 3.2 offers some assistance. It is vital that the user records the value chosen.

d. **Estimate the total uncertainty in the primary variable through a simple weighted summation of independent contributions.** This can be done using the following equation:

$$R = f(x, y, z)$$

   where:

   R represents the primary variable of interest x, y, and z are the components (secondary variables) upon which R depends

This relationship is straightforward to evaluate if we assume:

- each secondary variable acts independently of the others – the first step above tries to ensure this is the case; if they are not, they should be subdivided further and the steps (a) to (c) repeated
- the uncertainty in primary variable is at the same level of confidence as the secondary variables and is normally distributed

Making these assumptions simplifies the analysis and supports the following practical method to estimate the primary uncertainty ($R_{unc}$):

$$R_{unc} = \sqrt{\left[\left(\frac{\partial R}{\partial x}\right) x_{unc}\right]^2 + \left[\left(\frac{\partial R}{\partial y}\right) y_{unc}\right]^2 + \left[\left(\frac{\partial R}{\partial z}\right) z_{unc}\right]^2}$$

where:

R is the total uncertainty in the primary source interest (at the same level of confidence as the secondary uncertainties)

$\left(\frac{\partial R}{\partial x,y,z}\right)$ are partial derivatives that represent the relationship between a small change in the components and the resulting change in the primary uncertainty; the relative size of the partial derivative 'weights' the contribution for each component

Illustration 3.3 provides a simple worked example of the Tier 1 approach.

### Illustration 3.3: Worked example of first order analysis

The Floating Harbour at Bristol is predominantly affected by tidal flooding and uncertainty in the extreme tidal water level has been identified as a primary uncertainty ($R_{unc}$). Prior analysis and judgement suggests three sources of uncertainty have an important influence on the tidal level:

- cross sectional area of tidal River Avon, x
- wave setup, y
- boundary surge, z

Scenario testing suggestions that:

- A 20% change in cross-sectional area ($\partial x = 0.2$) can change water level by 0.1m ($\partial R = 0.1$m). Therefore $\partial R / \partial x = 0.5$. The estimated uncertainty in cross-sectional area (at plausible upper bound assumed to be equivalent to a 90% confidence interval), given by a relatively recent bathymetry and channel survey in 2010, is 10% ($x_{unc} = 0.1$).

- An additional wave setup of 0.1m ($\partial y = 0.1$) increases water level in the Floating Harbour by 0.1m ($\partial R = 0.1$). Therefore $\partial R / \partial y = 1$. The estimated uncertainty in wave setup (at plausible upper bound assumed to be equivalent to a 90% confidence interval) is 0.25m ($y_{unc} = 0.25$).

- The surge conditions at the mouth of the estuary directly affect the water levels in the estuary. An additional 0.5m of surge height ($\partial z = 0.5$) increases water levels in the harbour by 0.5m ($\partial R = 0.5$). Therefore $\partial R / \partial z = 1$. The estimated uncertainty in surge boundary conditions (at a 90% confidence interval) is 0.5m ($z_{unc} = 0.5$).

By substituting these values into the equation, the uncertainty in the estimated water level in the floating harbour ($R_{unc}$) can be assessed as:

$$R_{unc} = \sqrt{\left[\left(\frac{0.1}{0.2}\right) 0.1\right]^2 + \left[\left(\frac{0.1}{0.1}\right) 0.25\right]^2 + \left[\left(\frac{0.5}{0.5}\right) 0.5\right]^2} = 0.6$$

**Box 3.2: Composite exceedance probability**
**Credibility of system components**

W187 sets out an alternative manual approach for determining the uncertainty within the output variable of interest (for example, in-river water level or flood depth) based upon an assessment of the composite exceedance probability. The composite exceedance probability method recognises that the AEP of an in-river water level is not a single value, but is more accurately represented by a probability distribution (a probability density function). Each water level can then be represented by a probability density function and a family of curves can be built up.

In recent years, the use of computation simulation models as part of flood risk assessment studies has significantly increased and these are available to support a simulation-based assessment as introduced above. The composite exceedance probability approach is not described in this guide.

In flood risk assessments (FRAs), good practice is encouraged such as setting the finished floor levels at a safe height so that the development or internal floors within them should be dry during particular flood events. This height includes an allowance for uncertainties in the analysis.

Below are some useful prompts to help challenge components of the FRA.

- Does modelling contain recent changes such as upgrades to a flood wall or culvert?
- How have coastal/tidal/estuarine threats been represented?
- Have any flood defence failures been represented?
- How have ground levels been measured and represented?
- What method has been used to calculate hydrology?
- How have nearshore waves and sea levels been derived?
- How has surface run-off been represented?
- How have groundwater threats been represented?

### *Tier 2 –Scenario and simulation approaches*

Scenario and simulation approaches are 2 of the most commonly applied approaches to uncertainty and sensitivity analysis (see, for example, Hamby 1994, Saltelli et al. 2004).

Uncertainty and sensitivity analysis seeks to support the decision-maker in understanding:

- the uncertainty in primary variables of interest (for example, flood depth)
- the extent to which the uncertainty in a given input variable and model parameters influence that uncertainty

Scenario and simulation approaches can be defined as follows.

- **Scenario approaches** involve the permutation of a limited set of individual input values (or combinations) through a range of plausible estimates, calculating the change in the output.
- **Simulation approaches** typically involve assigning probability distributions to input variables and model parameters. Single values of each variable and model parameter are then drawn from the input distribution functions (for example, using a Monte Carlo sampling scheme) and passed through the analysis model to yield an uncertain estimate of the output variable of interest. The additional objective of the sensitivity analysis is to determine the relative importance (or

not) of individual input variables in terms of their contribution to the uncertainty in the output of a model.

**Note**: When presented with an estimate of uncertainty and the associated sensitivities (however calculated), it is often assumed that the estimate is a complete representation of all uncertainty (Penning-Rowsell et al. 2014). This is always not the case. The analysis may be 'incomplete' and fail to represent important processes or interactions. However, understanding whether or not the uncertainty is under- or overestimated is problematic. As for example, Beven (2009) points out, we often do not actually know. Expert review and logical discussion of the results are therefore vital to ensure that the results as well as how they have been generated are well understood and credible.

### 3.3.5 Scenario-based sensitivity analysis

Scenario-based sensitivity analysis usually involves varying each input variable and model parameter considered to be important, either individually or in combination through a plausible range of values. Other parameters are held at their 'best estimate' value. This relatively simple approach, if done carefully, can provide very useful insights. It can also highlight the relative importance of different sources of uncertainty (without quantification in absolute terms) and help guide further effort to reduce uncertainty (if necessary).

Scenario testing does not provide an objective means of characterising uncertainty. It relies on subjective judgement to select a plausible combination of inputs to illustrate the notional range of uncertainty in the outcomes. As such, it is often appropriate to conduct some form of scenario-based sensitivity tests before embarking on more computationally demanding simulation approaches discussed later.

Where the cost of taking action to address the most important uncertainties is low, sensitivity analysis also provides a valid means of directly determining an appropriate residual uncertainty allowance.

*Simulation-based uncertainty and sensitivity analysis*

Simulation-based approaches typically involve randomly selecting a single value of each input variable and model parameter from their associated probability distribution. This combination of values is then passed through a simulation model (for example, channel–floodplain hydraulic model) to obtain one realisation of the output variable of interest (for example, flood depth).

This sequence of events is then repeated many times (sometimes in the region of 10,000) and the results used to generate a probability distribution of the output variable. This type of approach is particularly useful when the uncertainty associated with the input variables can be described by a probability density function – a function that describes the relative likelihood that a random variable will take a given value.

Monte Carlo analysis provides a convenient tool for sampling the input values and passing the values through a response function to obtain the output in terms of a probability distribution. This widely used process (Pappenberger et al. 2006) is summarised in Figure 3.5.

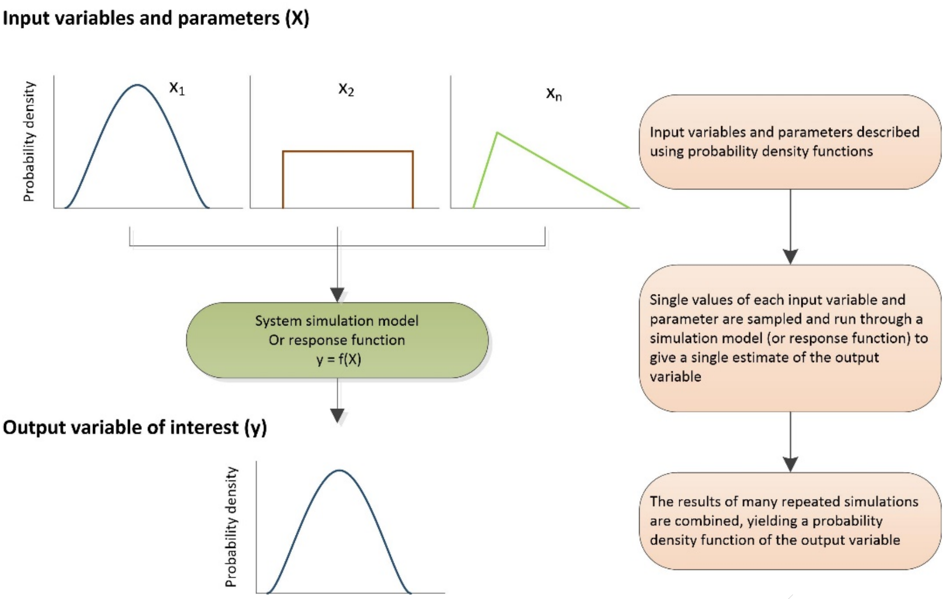



**Figure 3.5 Schematic showing the steps involved in a Monte Carlo modelling approach**

Source: Sayers et al. (2002)

**Note**: When using this approach, it is important to assess any dependencies between the input variables and include these in the modelling process. Making the assumption of independence between partially correlated variables, for example, can result in significant bias in the output.

By building on this framework of uncertainty analysis, simulation-based sensitivity analysis extends it to enable those input variables and model parameters that contribute most to the uncertainty in the output variable of interest to be identified.

To implement a simulation-based sensitivity analysis, 1 of 2 approaches is often used.

### Local sensitivity analysis

A local sensitivity analysis records the change in the output of interest while varying each input parameter, one-at-a-time, according to its probability density function. By formalising the simplified scenario testing approach introduced above, a local sensitivity analysis is able to provide useful insights into the source of the most important uncertainties, including:

- a **sensitivity measure** such as the ‘sensitivity index’ that reflects the percentage difference in the output value of interest when varying one input parameter from its minimum value to its maximum value (Hoffman and Gardner 1983)
- an **importance measure**, given 2 model input distributions, one narrow and one wide, producing identical variations in the output; the output can be seen to be more sensitive to the input variable of the narrow distribution, and hence this variable can be said to have a greater ‘importance index’

A local sensitivity approach is conceptually simple and outputs are easily understood. However, there are some significant limitations. For example it cannot detect important combinations of parameter variations – a simplification overcome in the ‘global sensitivity analysis’ outlined below.

## Global sensitivity analysis

A simulation approach based on a 'global sensitivity analysis' examines the sensitivity of the output to uncertainty to input variables and model parameter both individually and in-combination.

A technique for global sensitivity analysis that has been widely used is variance-based sensitivity analysis (Saltelli et al. 2004). As with the local sensitivity analysis, variance-based sensitivity analysis builds on underlying uncertainty analysis, but enables the output variance to be deconstructed by allowing one input variable to vary across its range while all other input variables remain fixed.

Two important insights are provided as a result.

- **Main effect**. The reduction in uncertainty in the output variable of interest that would be achieved if it is possible to learn the true value of a given input variable or model parameter.
- **Total effect.** The importance of a given variable that is correlated with others. By progressively fixing combinations of correlated variables, the total effect of a single variable can be determined. A variable with a low total effect can be frozen to any value within its range without significant impact on the output.

A global sensitivity analysis can give significant insights into which input uncertainties are most important and hence where to target effort in addressing residual uncertainties. However, it comes with a high computational demand and is likely to be appropriate in only the most complex and high value studies. Despite this, some useful attempts have been made within flood risk management, including an application of a staged variance-based sensitivity analysis (Gouldby et al. 2010).

## Example application

An example application of sensitivity analysis (undertaken in association with a dam risk assessment by Rory Nathan, Australia) is shown in Figure 3.6. The closer the red line is to the edge of the circle in Figure 3.6, the greater the uncertainty in that variable influences the uncertainty in the output.

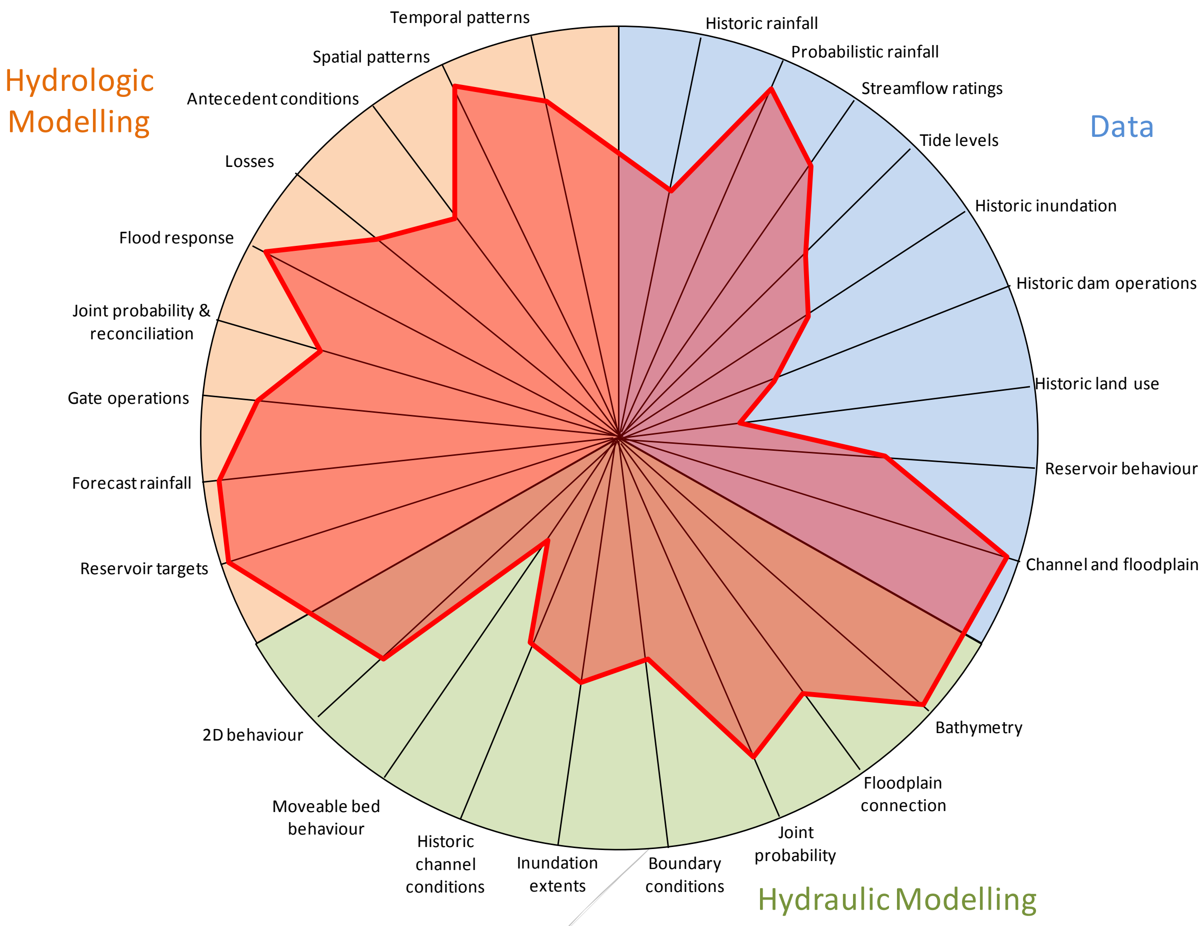



**Figure 3.6 Relative importance of different sources of uncertainty on a selected project objective determined through scenario testing**

Source: Sayers et al. (2012)

### 3.3.6 Stage 4 – Determine the appropriate response

There are 2 main elements in Stage 4:

- to decide how to respond
- where to implement measures

You can choose to respond to the residual uncertainties in one of 4 ways:

- undertake further analysis to refine the supporting knowledge and therefore reduce the uncertainty
- accept the uncertainty as a residual uncertainty and its associated costs, but act to reduce its impact and add costs to the final project
- accept the uncertainty as a residual uncertainty, record it, but choose not to act to reduce its impact
- go back to the appraisal of other options

Your response to managing the residual uncertainties should be risk-based. It should also be proportionate to the cost of a scheme and the impact on receptors such as people, infrastructure, the environment and the economy. Following the steps in Figure 3.7 will help you to achieve this (Principle 4).

It is important that the response is clearly recorded so that it can easily be referred to in each stage of the flood risk management scheme development. Use the template in Appendix C.

When acting to reduce the impacts you should consider a range of mitigation measures (Principle 3). Figure 3.8 provides some examples, while Illustration 3.4 offers some suggestions and prompts to help you decide when your action is enough.

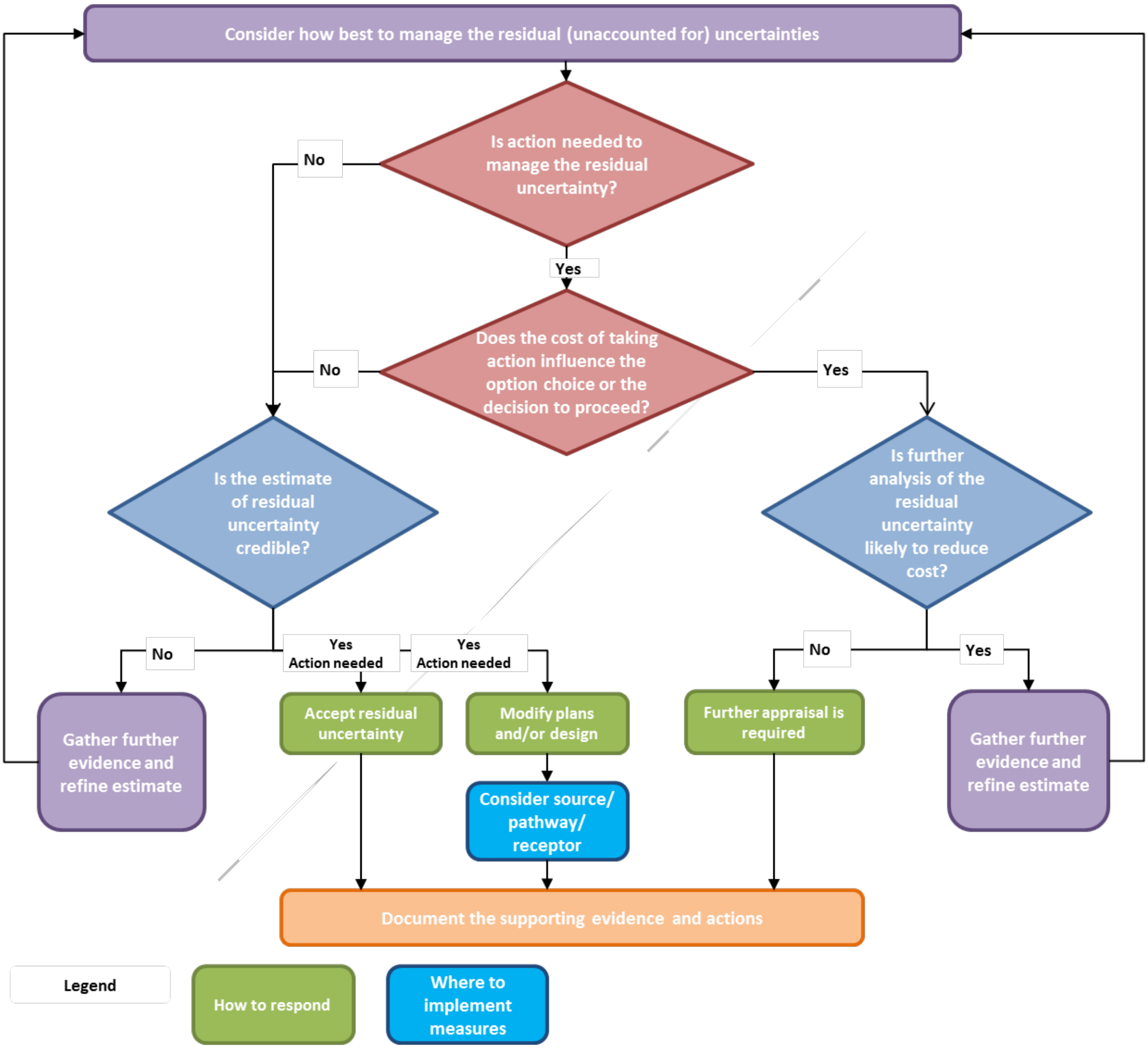



**Figure 3.7 Steps to determine the proportionate response and mitigation measures**

## Illustration 3.4: When to take the decision to stop analysing?

Only a practitioner or a regulator can decide and understand when enough is enough based on the particular context. However, the residual uncertainty allowance pilot with the Thames Estuary Asset Management 2100 (TEAM2100) project identified some questions that will help:

- What does the additional work give you information that you don't already know or have?
- Is the additional cost worth it?
- Does the additional cost of taking action influence any important decisions?
- Is further analysis likely to significantly change your course of action or the construction cost?

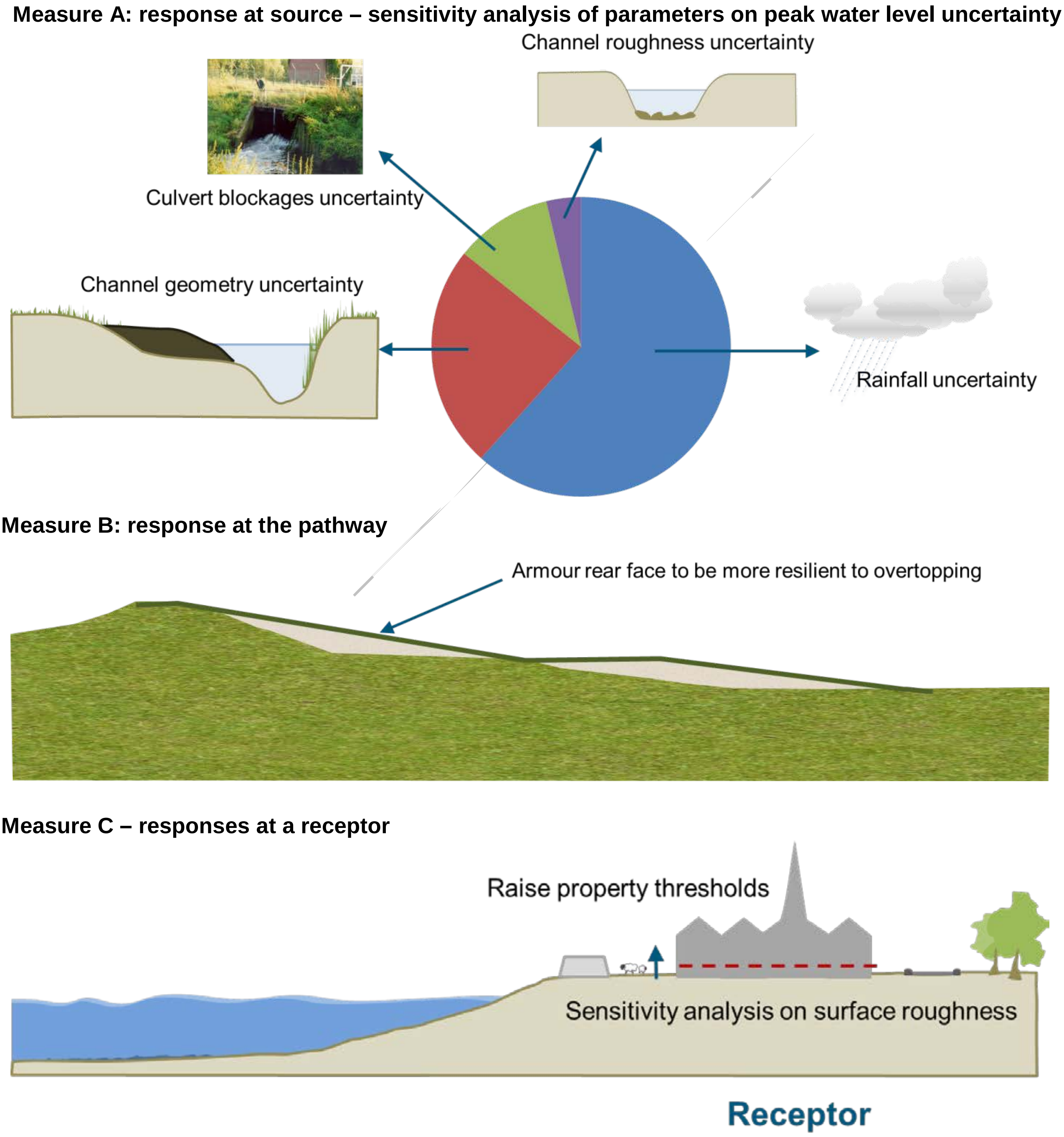



**Figure 3.8 A range of measures to mitigate uncertainty in water level**

## 3.4 Assessing performance of existing defence assets

### 3.4.1 Introduction

The same framework for the appraisal and design of new schemes can be applied when appraising investment decisions involving existing flood defence assets. Principle 2 forms the platform, whereby the flood risk assessment and appraisal should consider the existing system as it is today. This sub-section focuses on 2 facets:

- Appraising the reality of the present day system
- Communicating the standard of protection of a defence based on uncertain information

### 3.4.2 Appraising the reality of the present day system

Achieving an unbiased assessment of both risk and a credible estimate of the cost of the option is important to any appraisal. Decision-makers require a ‘true’ representation of the likely benefit and costs of action or in-action. The evidence provided must reflect the behaviour of the existing system as appropriately as possible.

The appraiser should not make judgements regarding the ‘correctness’ of previous assumptions from the design of existing defences. Instead the appraisal of existing defences should be based on an assessing the system as it is today. This is explained further in Illustration 3.5 in relation to a coastal sea defence; it also explains the difference with optimism bias.

**Illustration 3.5: Avoiding bias or double counting in appraisal and design**

If all uncertainties are known and represented in the appraisal, all uncertainties would be accounted for at the appraisal stage and no further allowances would be needed during design. It is not, however, always possible to incorporate all uncertainties into the appraisal process. In this case, the cost associated with dealing with these residual uncertainties should be included in the estimated option cost but not the associated benefits.

For example, consider an option that suggests raising the crest level of a defence to 7.1m AOD to provide an expected standard of protection of 0.5% annual probability. However, there are uncertainties that have not been formally included in this assessment, such as a limited record length and limited calibration of the supporting models. Residual uncertainties suggest that the crest level may need to be 0.3m higher to give a high confidence that a 0.5% annual probability standard of protection will be provided. The cost of raising the defence a further 0.3m adds to the option cost (and consultations with local communities are based on a finished crest level of 7.4m AOD). The associated benefits remain unchanged.

This approach helps ensure that the more detailed assessment of the residual uncertainties at the design stage will yield a design that is equivalent to preferred options identified during the appraisal. Hence the final ‘as built’ design will be very similar to the appraised option (in form and cost). This is not the same as optimism bias; optimism bias does not seek to account for uncertainty in performance (the focus of the residual uncertainty allowance). Optimism bias simply recognises that engineers systematically underestimate the cost of works.

Similarly, when appraising present day risks no attempt should be made to subtract historical allowances that may or may not have been made. To avoid undue bias in the appraisal, the reality of the present day system must be represented. For example, consider an existing defence that has a crest level of 7.1m AOD; this crest level is used without subtracting an allowance of any ‘inbuilt’ freeboard. Instead, uncertainties in the system, such as measurement in crest level or water levels, should be explicitly recorded and addressed, either within the appraisal or, where appropriate, through the residual uncertainty allowance.

### 3.4.3 Accounting for uncertainty when communicating the defence standard of protection

W187 used 2 terms to describe the performance of a defence:

- **Threshold of overtopping** is an estimate of annual probability (percentage) of the extreme water level that can be expected to overtop the crest level of a fluvial defence.
- **Standard of protection** is the maximum annual probability (percentage) of the extreme water level that, given the various uncertainties, is unlikely to overtop the defence. To determine this annual probability, the residual freeboard[3] is deducted from the defence crest level to give a notional crest level that can then be compared with the extreme water levels.

However, these definitions are misleading and are no longer relevant for 3 main reasons.

- **They fail to recognise the significance of the overtopping.** Would overtopping lead to very minor flooding that local drainage could cope with? Or would it compromise the stability of the defence and, for example, lead to a breach?
- **They are meaningless in the context of coastal defences**. Overtopping rates increase with the severity of the storm load (a combination of waves and water levels). As such, the notion of step change between overflowing and not overflowing at a given water level (the assumption underpinning the above definitions) is meaningless.
- **They convey a false impression of confidence**. Communication of the standard of protection as a single unique value is misleading.

### 3.4.4 Limit state of standards of protection

Building on the more explicit consideration of uncertainty that this guide promotes, more meaningful definitions are introduced as follows.

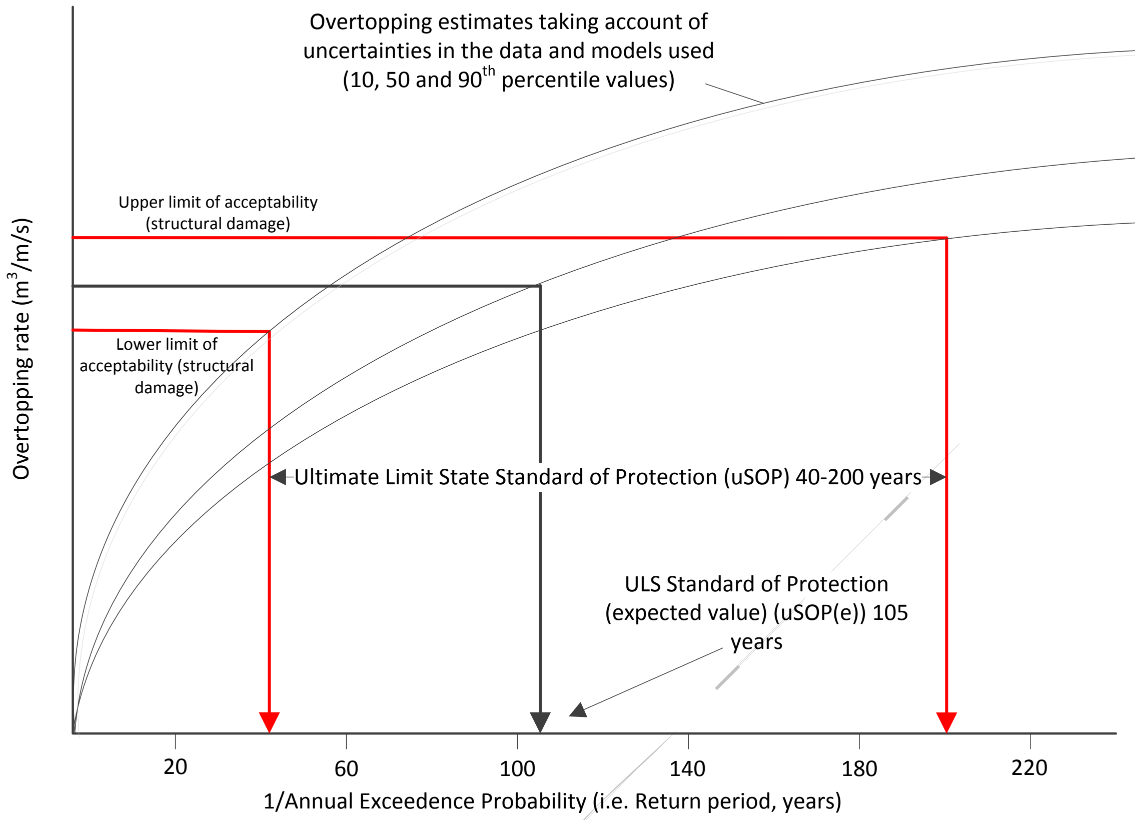
- **Ultimate limit state standard of protection (uSoP)** – the annual probability of exceedance associated with the minimum overtopping or overflow rate that is likely to compromise the structural integrity of a defence or significantly undermines its ability to perform a flood defence function
- **Serviceability limit state standard of protection (sSoP)** – the annual probability of exceedance associated with the minimum overtopping or overflow rate that is likely lead to disruption of a service of interest (for example, requiring a road to be closed to vehicles or a promenade to be closed to pedestrians)

To communicate the standard of protection provided by a defence, uncertainty in both the estimate of overtopping/overflow and the acceptable rates needs to be used. This means that the uSoP and sSoP should be conveyed as a plausible range – including a notional upper bound and lower bound estimate as well as an expected value.

All 3 of these terms are shown graphically for the uSoP of a coastal defence in Figure 3.9a and a fluvial defence in Figure 3.9b.

[3] The freeboard applied to the original design, less any reduction in freeboard that may have occurred since construction, for example, settlement of the crest.

(a)


Overtopping estimates taking account of uncertainties in the data and models used (10, 50 and 90th percentile values)
Upper limit of acceptability (structural damage)
Lower limit of acceptability (structural damage)
Ultimate Limit State Standard of Protection (uSOP) 40-200 years
ULS Standard of Protection (expected value) (uSOP(e)) 105 years
Overtopping rate (m3/m/s)
20
60
100
140
180
220
1/Annual Exceedence Probability (i.e. Return period, years)

(b)

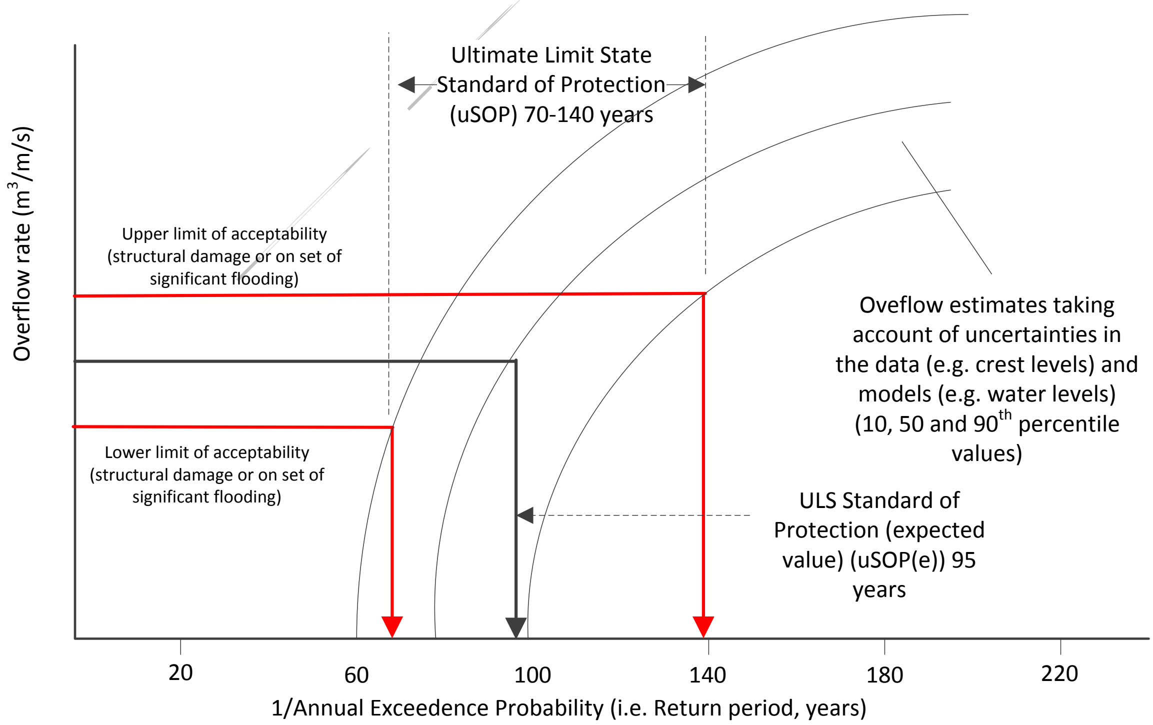

Ultimate Limit State Standard of Protection (uSOP) 70-140 years
Upper limit of acceptability (structural damage or on set of significant flooding)
Oveflow estimates taking account of uncertainties in the data (e.g. crest levels) and models (e.g. water levels) (10, 50 and 90th percentile values)
Lower limit of acceptability (structural damage or on set of significant flooding)
ULS Standard of Protection (expected value) (uSOP(e)) 95 years
Overflow rate (m3/m/s)
20
60
100
140
180
220
1/Annual Exceedence Probability (i.e. Return period, years)

**Figure 3.9 Redefinition of standard of protection accounts for uncertainty in the assessment of overtopping or overflow and the definition of what is acceptable: (a) a coastal defence and (b) a fluvial example**

Notes: ULS = ultimate limit state

By using alternative definitions of 'acceptability' in terms of the overtopping or overflow rate, equivalent statements for the sSoP can be determined.

This approach has a number of advantages.

- **It applies equally to coastal and fluvial defences**. The revised definition is based on estimated overtopping or overflow rate – not water level.
- **It distinguishes the significance of the overflow/overtopping**. The revised definition differentiates the acceptability in terms of minor (serviceability limit states – access constraints and minor local flooding) and more severe (ultimate limit states – structural integrity and significant flooding) overtopping/overflow rates.
- **It recognises uncertainty appropriately**. The revised definition expresses the standard of protection as a range rather than as a single value, acknowledging uncertainty in both the estimate of the overtopping/ overflow rate and the definition of the acceptable overtopping/overflow rates.

An example is shown in Illustration 3.6.

**Illustration 3.6: Standard of protection of a single defence Illustration 2.1: Residual uncertainty allowance only adds cost**

The uSoP and the sSoP are replacements for the current definition of the standard of protection. The range of values for each should be described and based on estimated overtopping or overflow rate (not water level), while taking account of uncertainty in both the estimated rate and the definition of what is acceptable.

For example, using the values in the table below, the revised standard of protection should be expressed as follows.

The defence offers a uSoP against significant flooding that is expected to be 1:200 years on average (0.5% AEP) but this could be as low as 1:100 years (1% AEP) and as high as 1:300 years (0.33% AEP). The sSoP against more minor overtopping is expected with 1:15 years on average (6.67% AEP) but this could be as low as 1:10 years (10% AEP) and as high as 1:20 years (0.33% AEP).

| Standard of protection | Return period (years) and equivalent (AEP) | | |
|---|---|---|---|
| | **Lower (10th percentile)** | **Expected (50th percentile)** | **Upper (90th percentile)** |
| Ultimate limit state | 1:100 (1% AEP) | 1:200 (0.5% AEP) | 1:300 (0.33% AEP) |
| Serviceability limit state | 1:10 (10% AEP) | 1:15 (6.67% AEP) | 1:20 (5% AEP) |

For example, Bristol city centre is predominantly affected by tidal floods via the floating harbour. If Bristol City Council wants to provide protection against the tidal flood with a 0.5% annual chance of occurring, they need confidence that defences will perform despite data/ knowledge gaps. The present day flood level with a 0.5% annual chance of occurring is 9.11m AOD. Analysis shows that the uncertainty unaccounted for in this value is 0.3m. Therefore a peak water level of 9.41m AOD would be used to design a tidal flood risk management scheme; the option cost would include the associated costs to protect against a 9.41m AOD water level. However, the economic appraisal would use 9.11m AOD to determine the damages.

## 3.5 Summary

This chapter sets out a staged approach to determining an appropriate residual uncertainty allowance.

The details differ in accordance with the contexts and situations of flood and coastal risk management. Thus there are different methods for:

- development planning (Section 3.2):
  - Stage 1 – Identify and record all primary sources of uncertainty
  - Stage 2 – Estimate the magnitude of the residual uncertainties
  - Stage 3 – Determine the appropriate response.
- appraisal and design of new flood risk management strategies or schemes (Section 3.3):
  - Stage 1 – Identify and record all primary sources of uncertainty
  - Stage 2 – Identify the uncertainties that have been accounted for
  - Stage 3 – Estimate the magnitude of the residual uncertainties
  - Stage 4 – Determine the appropriate response
- appraising investment decisions involving existing schemes and assets (Section 3.4):
  - Appraising the reality of the present day system
  - Communicating the standard of protection of a defence based on uncertain information

To support your assessment of the residual uncertainty allowance, templates and supporting information are provided in Appendices A, B and C.

Illustrative case studies for a range of situations in development planning, strategy development and appraisal, including asset performance management, are provided in Appendix D to showcase example application of the methods to different use scenarios.

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# List of abbreviations

| | |
|---|---|
| AEP | Annual Exceedance Probability |
| AOD | above Ordnance Datum |
| CAFRA | Central Area Flood Risk Assessment [Bristol] |
| Defra | Department for Environment, Food and Rural Affairs |
| FCDPAG | Flood and Coastal Defence Project Appraisal Guidance |
| FEH | Flood Estimation Handbook |
| FRA | flood risk assessment (site-specific) |
| ICE | Institution of Civil Engineers |
| LIDAR | light detection and ranging |
| MCM | Multi-coloured Manual |
| NaFRA | National Flood Risk Assessment |
| SAR | synthetic aperture radar |
| SLR | sea level rise |
| sSoP | serviceability limit state Standard of Protection |
| uSoP | ultimate limit state Standard of Protection |

# Glossary

| Terminology | Description |
|---|---|
| Annual exceedance probability | The estimated probability of a flood of given magnitude occurring or being exceeded in any year. Expressed as, for example, 1 in 100 chance or 1%. |
| Climate change | Long-term variations in global temperatures and weather patterns, both natural and as a result of human activity |
| Climate change adaptation | Adjustments to natural or human systems in response to actual or expected climatic factors or their effects, including from changes in rainfall and rising temperatures, which moderate harm or exploit beneficial opportunities. |
| Cumulative impact | Impact in combination with other development. That includes:<br>• existing developments of the kind proposed<br>• those which have permission<br>• valid applications that have not been determined<br>The weight attached to undetermined applications should reflect their position in the application process. |
| De facto defence | A structure, such as a road embankment, rail embankment or wall, that was not designed to provide a flood risk management function but which provides a level of protection to a vulnerable receptor. |
| Design event | A historic or notional flood event of a given annual flood probability, against which the suitability of a proposed development is assessed and mitigation measures, if any, are designed. |
| Design event exceedance | Flooding resulting from an event which exceeds the magnitude for which the defences protecting a development were designed – see also residual risk |
| Design flood level | The maximum estimated water level during the design event. |
| Flexible design | Where future demand and relative prices are uncertain, it may be worth choosing a flexible design adaptable to future changes, rather than a design suited to only one particular outcome – see also managed adaptive approach. See Annex 4 of 'The Green Book' (HM Treasury2003) for further information. |
| Flood defence | Flood defence infrastructure, such as flood walls and embankments, intended to protect an area against flooding to a specified standard of protection. |

| Terminology | Description |
|---|---|
| Floodplain | Area of land that borders a watercourse, an estuary or the sea, over which water flows in time of flood, or would flow but for the presence of flood defences where they exist. |
| Flood risk | The combination of the probability of a flood and the potential adverse consequences associated with a flood, for human health, the environment, cultural heritage and economic activity. |
| Flood risk management measure | Any measure which reduces flood risk such as flood defences. |
| Freeboard allowance | An allowance that takes account of adverse uncertainty in the prediction of physical processes that affect the defence level and physical processes which affect the defence level, which have not been allowed for in the design water level. |
| Fluvial flooding | Flooding caused by rivers. |
| Functional floodplain | The areas of land where water flows in times of flood which should be safeguarded from further development because of their function as flood water storage areas. For planning purposes the functional floodplain will generally have a 5% (1:20) probability of flooding in any year. |
| LIDAR (light detection and ranging) | LIDARA remote sensing technology that measures distance by illuminating a target with a laser and analysing the reflected light. |
| Local Planning Authority | The public authority whose duty it is to carry out specific planning functions for a particular area. All references to local planning authority apply to the district council, London borough council, county council, Broads Authority, unitary authority, National Park Authority and the Greater London Authority to the extent appropriate to their responsibilities. |
| Local Plan | The plan for the future development of the local area drawn up by the local planning authority in consultation with the community. |
| Managed adaptive approach | When considering climate change (or other uncertain future change), it is not possible to predict exactly how much change will happen or when. Instead of designing an asset or building now to withstand the upper end of change for its expected life, it is possible to design it to be resilient to a lower change and then be altered at a later stage in the future when there is more confidence and resources to increase the resilience. This approach requires involvement from the Local Planning Authority and developer to agree how the development can be adapted over its lifetime, including how and when to review assumptions about climate change used when granting planning permission. |

| Terminology | Description |
|---|---|
| NaFRA | The National Flood Risk Assessment provides an indication of flood risk at a national level. |
| Pluvial flooding | Flooding as a result of rainfall run-off flowing or ponding over the ground before it enters a natural (for example, watercourse) or artificial (for example, sewer) drainage system or when it cannot enter a drainage system (for example, because the system is already full to capacity or the drainage inlets have a limited capacity). |
| Precautionary principle/ approach | Where there are threats of serious or irreversible damage, lack of full scientific certainty must not be used as a reason for postponing cost-effective measures to prevent environmental degradation. |
| Residual flood risk | The risk which remains after all risk avoidance, reduction and mitigation measures have been implemented. |
| Residual uncertainty allowance | An allowance that seeks to assure the present day performance of the chosen means of managing flood risk by accounting for uncertainties that have not been explicitly addressed elsewhere in the planning, appraisal, design, or implementation process; whether qualitatively or quantitatively. See Section 2 for further information. |
| Property level resilience | Constructing a building in such a way that, although flood water may enter the building, its impact is minimised, structural integrity is maintained and repair, drying and cleaning are facilitated. |
| Property level resistance | Constructing a building in such a way as to prevent flood water entering the building or damaging its fabric. |
| Serviceability limit state standard of protection (sSoP) | The annual probability of exceedance associated with the minimum overtopping or overflow rate that is likely lead to disruption of a service of interest (for example, requiring a road to be closed to vehicles or a promenade to be closed to pedestrians). |
| Standard of protection | The maximum annual probability (percentage) of the extreme water level that, given the various uncertainties, is unlikely to overtop the defence. |
| Sustainable drainage system | A sequence of management practices and control structures, often referred to as SuDS, designed to drain water in a more sustainable manner than some conventional techniques. Typically these are used to attenuate run-off from development sites. |
| Ultimate limit state standard of protection (uSoP) | The annual probability of exceedance associated with the minimum overtopping or overflow rate that is likely to compromise the structural integrity of a defence or significantly undermines its ability to performance a flood defence function. |

| Consideration | Description | Applicable | Score | Reason(s) |
|---|---|---|---|---|
| **How appropriate is the flood risk analysis?** | How appropriate is the analysis/ modelling. Does it contain the relevant features? Is it up-to-date? | Y/N | | Reason for score/why criterion is not pertinent |
| **How good is the floodplain topography?** | Type/resolution of floodplain pathways | Y/N | | Reason for score/why criterion is not pertinent |
| **How well has the potential for defence failure been modelled?** | Evidence that credible failures have been considered | Y/N | | Reason for score/why failures are not credible |
| **What is the confidence in the hydrology?** | Basis for deriving inflows for fluvial, surface run-off or groundwater sources | Y/N | | Reason for score/why criterion is not pertinent |
| **How good is the coastal/ estuarine/ tidal boundary?** | Basis for deriving nearshore conditions that is, waves, sea level | Y/N | | Reason for score/why criterion is not pertinent |
| **How has the fluvial threats been represented?** | How has the fluvial system been represented? | Y/N | | Reason for score/why criterion is not pertinent |
| **How have coastal threats been represented?** | How have coastal threats been represented that is, wave overtopping and tidal inundation? | Y/N | | Reason for score/why criterion is not pertinent |
| **How has surface run-off been represented?** | How has surface run-off been represented? | Y/N | | Reason for score/why criterion is not pertinent |
| **How have groundwater hazards been represented?** | How have groundwater hazards been represented? | Y/N | | Reason for score/why criterion is not pertinent |
| **What is the strength of evidence?** | Strength of evidence to support/validate flooding representation | Y/N | | Reason for score/why criterion is not pertinent |
| **Overall rating (stars)** | | | | |
| **Residual uncertainty allowance (mm)** | | | | |

**Further advice**

1. If one criteria scores poorly (that is, is high) and becomes a factor in the overall score, consider taking action to improve the confidence for example, improve topography quality, improve 1D and 2D representation, model more than 2 AEPs.
2. When raising finished floor levels, consider local policy and flood management strategies on providing compensatory storage.
3. If the minimum allowance is unfeasible for developers or conflicts with other planning requirements, you should recommend that the property threshold is raised as high as is reasonably practicable. The remaining minimum allowance should consist of flood resilient construction measures.

**Notes:**

**Table B1 Uncertainties in data and models**

| | Variable | Source of uncertainty |
|---|---|---|
| Source | Rainfall | Observations, data quality and method |
| | Channel water level | Observations, data and models |
| | Coastal/estuarine water level | Observations, data and models |
| | Surface water depth | Observations, data and models |
| | Offshore/nearshore wave climate | Observations, data and models |
| | Joint probability | Observations, data and models |
| | Flows | Observations, data and models |
| Pathway | Foreshore bathymetry | Survey method and spatial representation |
| | Topography, such as channel geometry | Survey method and spatial representation |
| | Linear asset geometry, such as flood wall height | Measurement history and methods |
| | Point asset operational, such as sluice opening rules | Operational manual |
| | Condition of asset | Inspection method and deterioration |
| | Floodplain inflow, such as overtopping an asset or failure of an asset | Overtopping calculations, blockage potential, breach width/ base/ duration |
| Receptor | Location of buildings/ critical infrastructure | Quality of data sources and coordinates |
| | Infrastructure networks/ dependencies | Data sources and network connections |
| | Property thresholds | Survey method and spatial representation |
| | Ground levels | Survey method, coverage |
| | Damage estimation of contents | Quality of data sources, estimation method |
| | Land use | Quality of data sources, poor coverage |

**Table B2 Uncertainties in analysis completeness**

| | Variable | Source of uncertainty |
|---|---|---|
| Source | Rainfall | Missing extremes |
| | Channel water level | Missing extremes, processes and geometric features |
| | Coastal/estuarine water level | Missing extremes, processes and geometric features |
| | Surface water depth | Missing extremes, processes and geometric features |
| | Offshore/nearshore wave climate | Missing extremes, processes and geometric features |
| | Joint probability | Missed correlations |
| Pathway | Foreshore bathymetry | Biased (too high/ too low) or missed features due to poor horizontal resolution |
| | Topography | Biased (too high/ too low) or missed features due to poor horizontal resolution |
| | Linear asset | Missing assets or features, such as new flood wall or de facto defence |
| | Point asset | Missing assets or features, such as outfalls or gates |
| | Condition of asset | Missed significant issues, such as cracks, vermin damage or excessive vegetation |
| | Inundation depth/ velocity | Missing floodplain features, such as drainage channel or hill due to poor horizontal resolution |
| | Floodplain inflow, such as overtopping an asset or failure of an asset | Missing features or processes, such as failure modes |
| Receptor | Location of buildings/ critical infrastructure | Quality of data sources, missing properties |
| | Infrastructure networks/ dependencies | Data sources and network connections |
| | Ground levels | Biased (too high/ too low) or missed features due to poor horizontal resolution |
| | Ability to respond to an event or recover from | Biased (too high/ too low) or missed features |
| | Land use | Gross error in assigned value |

**Table B3 Uncertainties in design and decision choices**

| Variable | Source of uncertainty |
|---|---|
| Design life | Assumptions made to establish design life, such as deterioration rates of new defences |
| Ultimate performance limit | Incorrect/ incomplete definition of the ultimate limit of the performance criteria, such as acceptable overtopping rates |
| Serviceability limit | Incorrect/incomplete definition of serviceability limit criteria, such as acceptable overtopping rates for access |
| Human operations to operate defences | Assumptions regarding probability of humans deploying or operating defence elements, such as flood gates |
| Functionality | Incorrect/incomplete definition of purpose |
| Evacuation potential | Incorrect assumption that evacuation is possible or poor assumptions of efficiency, such as capacity of road network or public transport |

## Pro forma – First order analysis template

| Primary uncertainty: | | | | | |
|---|---|---|---|---|---|
| **Components of primary uncertainty** | | | | | |
| | **Absolute error (native parameter)** | | **Relative error (m)** | **Weighting** | **Comment** |
| | **Distribution** | **SD** | **SD** | | |
| For example, fluvial calibration | | | | | |
| | | | | | |
| | | | | | |
| | | | | | |
| | | | | | |
| | | | | | |
| **Total** | | | | | **(assuming independence of errors)** |

## Pro forma – Assessment template

| Variable or model parameter | Applicable to setting (Y/N) | Type of uncertainty category | Uncertainty (quantitative ± error or qualitative) | Unit | Dealt with as part of regional/ local strategy (Y/N) | Comments and nature of error/ response | Dealt with as part of appraisal (Y/N) | Comments | Dealt with as part of design (Y/N) | Comments | Summary of the approach to dealing with residual uncertainty | Status of action |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Source** | | | | | | | | | | | | |
| In-river water level | | | | | | | | | | | | |
| Estuarine water level | | | | | | | | | | | | |
| Surface water depth | | | | | | | | | | | | |
| Nearshore local waves | | | | | | | | | | | | |
| Groundwater | | | | | | | | | | | | |
| **Add others from each category and consider joint probability** | | | | | | | | | | | | |
| **Pathway** | | | | | | | | | | | | |
| **System representation and applicability** | | | | | | | | | | | | |
| Foreshore bathymetry | | | | | | | | | | | | |
| Topography | | | | | | | | | | | | |
| **Linear assets** | | | | | | | | | | | | |
| Geometry (location and shape) | | | | | | | | | | | | |
| Condition (surface and internal)) | | | | | | | | | | | | |
| **Point assets** | | | | | | | | | | | | |
| Geometry (location, shape and capacity) | | | | | | | | | | | | |
| Condition | | | | | | | | | | | | |
| Operational arrangement (how used) | | | | | | | | | | | | |
| **Performance of models and applicability** | | | | | | | | | | | | |
| **Linear assets** | | | | | | | | | | | | |
| Non-failed performance: Inflow into floodplain | | | | | | | | | | | | |
| Failed performance: Inflow into floodplain | | | | | | | | | | | | |
| **Add others from each category, for example, chance of failure, interdependencies between assets** | | | | | | | | | | | | |

## Pro forma – Assessment template

| Variable or model parameter | Applicable to setting (Y/N) | Type of uncertainty category | Uncertainty (quantitative ± error or qualitative) | Unit | Dealt with as part of regional/ local strategy (Y/N) | Comments and nature of error/ response | Dealt with as part of appraisal (Y/N) | Comments | Dealt with as part of design (Y/N) | Comments | Summary of the approach to dealing with residual uncertainty | Status of action |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Point assets** | | | | | | | | | | | | |
| Inflow into floodplain (asset not failed) | | | | | | | | | | | | |
| Inflow into floodplain (asset failed) | | | | | | | | | | | | |
| **Inundation** | | | | | | | | | | | | |
| Inundation depth | | | | | | | | | | | | |
| Inundation velocity | | | | | | | | | | | | |
| **Receptors** | | | | | | | | | | | | |
| **System representation and applicability** | | | | | | | | | | | | |
| Location of buildings and critical infrastructure | | | | | | | | | | | | |
| Network dependencies | | | | | | | | | | | | |
| Threshold levels | | | | | | | | | | | | |
| Buildings and contents | | | | | | | | | | | | |
| Ability to respond to flood event | | | | | | | | | | | | |
| Ability to recover from flooding | | | | | | | | | | | | |

This appendix presents 6 case study applications:

- Planning development
  - Case study 1 – Fluvial and undefended
  - Case study 2 – Tidal and undefended
  - Case study 3 – Coastal and defended
- Appraisal and design
  - Case study 4 – Strategic (tidal Bristol)
  - Case study 5 – Design (fluvial Lewisham)
- Asset performance assessment
  - Case study 6 – Appraising existing defences to develop a strategy (estuarine Thames)

These examples will help you understand how to apply the approaches in practice.

## Case Study 1: Nene Valley

**Planning development summary**
Title: Nene Valley
Location: River Nene, Northamptonshire
***Type of situation:*** Fluvial and undefended

**Case study details**
The River Nene has an overall length of about 160km from Daventry in Northamptonshire to the Wash near Sutton Bridge in Lincolnshire. The Nene Valley is located in the middle reach in Northamptonshire.

The area is covered by a catchment scale strategic model (1D) which provides a suite of flood levels for 11 different probabilities and scenarios. The hydrology is calibrated using a range of gauging stations. The model is validated against 2 incidents.

The floodplain is large and flat with no raised defences. There is no influence from the sea. There are no known issues of surface water or groundwater flooding.

**Record of assessment**

| Consideration | Stage 1 Y/N | Stage 2 Score | Reason |
|---|---|---|---|
| How appropriate is the flood risk analysis? | Y | 1 | Good local representation at a catchment scale. Assessment is applicable. |
| How good is the floodplain topography? | Y | 3 | Reasonable representation for a strategic scale model. Some minor digital terrain model issues are known. |
| How well has the potential for defence failure been modelled? | N | - | No defences of note. |
| What is the confidence in the hydrology? | Y | 1 | Very good representation. Calibrated hydrology using a range of gauging stations. |
| How good is the coastal/ estuarine / tidal boundary? | N | - | Not applicable |
| How has the fluvial threats been represented? | Y | 1 | 1D model with more than 3 annual likelihoods |
| How have coastal threats been represented? | N | - | Not applicable |
| How has surface run-off been represented? | N | - | Not applicable |
| How have groundwater hazards been represented? | N | - | Not applicable |
| What is the strength of evidence? | Y | 2 | Model validated by 2 incidents of varying magnitude but more frequent than 1% AEP |

**Stage 3**

**(a)**

| Worst topic 2 score | Worst topic 1 score: 10 | 5 | 3 | 2 | 1 |
|---|---|---|---|---|---|
| 10 | 1 star | | | 2 star | 3 star |
| 5 | 1 star | | 2 star | 3 star | 4 star |
| 3 | 1 star | 2 star | 3 star | 4 star | |
| 2 | 2 star | 3 star | 4 star | | 5 star |
| 1 | 3 star | 4 star | | 5 star | |

**(b)**

| Confidence rating | Confidence description | Minimum depth |
|---|---|---|
| 1 star | Very unlikely to be locally reliable | 0.90m |
| 2 star | Unlikely to be locally reliable | 0.75m |
| 3 star | Likely to be locally reliable | 0.60m |
| 4 star | Very likely to be locally reliable | 0.45m |
| 5 star | Highly likely to be locally reliable | 0.30m |

**(c)**

**Residual uncertainty allowance**
The worst considerations give a 4 star confidence and a recommended residual uncertainty allowance of 0.45m.

The minimum threshold may not be achievable everywhere. Where this is the case, the property threshold should be raised as high as is reasonably practicable in liaison with the Environment Agency and planning authority. The remaining minimum allowance should consist of flood resilient construction.

# Case Study 2: Jacks Pill

**Planning development summary**
Title: Jacks Pill (car park)
Location: Newport, Wales
Type of situation: Tidal and undefended

**Case study details**
A developer wishes to create 18 dwellings and 76 apartments adjacent to the tidal River Usk. The site is partially within the 0.5% and entirely within the 0.1% annual probability tidal flood outlines (undefended).

The River Usk tidal model (2012) incorporates the nationally available coastal flood boundary conditions (Environment Agency 2011), LiDAR data and changes to landforms (5m grid resolution), including the new riverside tidal flood defences (located upstream on the other bank). The site is flooded in the defended scenarios.

There are no known issues of surface water or groundwater flooding.


**Record of assessment**

| Consideration | Stage 1 Y/N | Stage 2 Score | Reason |
|---|---|---|---|
| How appropriate is the flood risk analysis? | Y | 1 | Model represents changes in floodplain. |
| How good is the floodplain topography? | Y | 1 | High resolution LiDAR. |
| How well has the potential for defence failure been modelled? | N | - | No defences present. |
| What is the confidence in the hydrology? | N | - | Tidally dominated. |
| How good is the coastal/ estuarine / tidal boundary? | Y | 1 | Chosen the 95% extreme water level. QMED for fluvial inflows |
| How has the fluvial threats been represented? | N | - | Not applicable |
| How have coastal threats been represented? | Y | 1 | 1D–2D model simulating at least three annual likelihoods |
| How has surface run-off been represented? | N | - | Not applicable |
| How have groundwater hazards been represented? | N | - | Not applicable |
| What is the strength of evidence? | Y | 5 | Newport is near a Class A gauge and the model has been calibrated for one event, (January 2014) where it performed well. |

**Stage 3**

**(a)**

| Worst topic 2 score | Worst topic 1 score: 10 | 5 | 3 | 2 | 1 |
|---|---|---|---|---|---|
| 10 | 1 star | | | 2 star | 3 star |
| 5 | 1 star | | 2 star | 3 star | 4 star |
| 3 | 1 star | 2 star | 3 star | 4 star | |
| 2 | 2 star | 3 star | 4 star | | 5 star |
| 1 | 3 star | 4 star | | 5 star | |

**(b)**

| Confidence rating | Confidence description | Minimum depth |
|---|---|---|
| 1 star | Very unlikely to be locally reliable | 0.90m |
| 2 star | Unlikely to be locally reliable | 0.75m |
| 3 star | Likely to be locally reliable | 0.60m |
| 4 star | Very likely to be locally reliable | 0.45m |
| 5 star | Highly likely to be locally reliable | 0.30m |

**(c)**

**Residual uncertainty allowance**
The worst considerations give a 4 star confidence rating and a recommended residual uncertainty allowance of 0.45m minimum. Considering the 0.5% annual probability event with 95% confidence bound, the predicted flood level is 9.94m AOD. So the minimum finished floor level should be 10.39m AOD; 9.54m AOD is the water level with a 50% confidence bound. So discussions with the developer should start with 9.99m AOD and consider resilience.

## Case Study 3: Chalet development

**Planning development summary**
Title: Chalet development
Location: Winthorpe, Lincolnshire
Type of situation: Coastal and defended

**Case study details**
The Lincolnshire coastline consists of hard sea defences, dunes and extensive artificially nourished beaches. The hinterland is generally flat and has a large proportion of seasonal properties. A developer wished to change occupancy from seasonal to permanent and construct new chalets. The predominant threat of flooding is from the sea. There are no known issues of surface water or groundwater flooding.

The Environment Agency has produced flood maps based on wave overtopping and several breach locations along the coastline. Without climate change, the site is not affected by wave overtopping during the 0.5% AEP but flooded by up to 0.25m during the 0.1% AEP. In 2115 (with climate change), the entire site is inundated by both the 0.5% AEP and the 0.1% AEP events with depths of up to1.25m and 1.75m respectively. The terrain in the 2D model (2010) is LiDAR and SAR; LiDAR covers ±0.15m. The model grid resolution is 20m.

**Record of assessment**

| Consideration | Y/N (Stage 1) | Score (Stage 2) | Reason |
|---|---|---|---|
| How appropriate is the flood risk analysis? | Y | 3 | 2010 model. Minor defence schematisation issues known about. Assessment is applicable. |
| How good is the floodplain topography? | Y | 3 | Reasonable representation using a 20m grid. Some minor digital terrain model issues are known about <focus on what makes it a 3–20m grid and so on |
| How well has the potential for defence failure been modelled? | Y | 3 | Multiple individual breaches have been modelled, not in combination |
| What is the confidence in the hydrology? | N | - | Tidally dominated site |
| How good is the coastal/ estuarine / tidal boundary? | Y | 3 | Good quality local dataset used, consistent with national coastal flood boundary dataset. |
| How has the fluvial threats been represented? | N | - | Tidally dominated site |
| How have coastal threats been represented? | Y | 2 | 2D model. Locally credible geometry of defences. Two annual likelihoods modelled. |
| How has surface run-off been represented? | N | - | Not applicable |
| How have groundwater hazards been represented? | N | - | Not applicable |
| What is the strength of evidence? | Y | 2 | Extents validated against December 2013 storm, less frequent than design flood |

**Stage 3**

**(a)**

| Worst topic 2 score | Worst topic 1 score: 10 | 5 | 3 | 2 | 1 |
|---|---|---|---|---|---|
| 10 | 1 star | | | 2 star | 3 star |
| 5 | 1 star | | 2 star | 3 star | 4 star |
| 3 | 1 star | 2 star | 3 star | 4 star | |
| 2 | 2 star | 3 star | 4 star | | 5 star |
| 1 | 3 star | 4 star | | 5 star | |

**(b)**

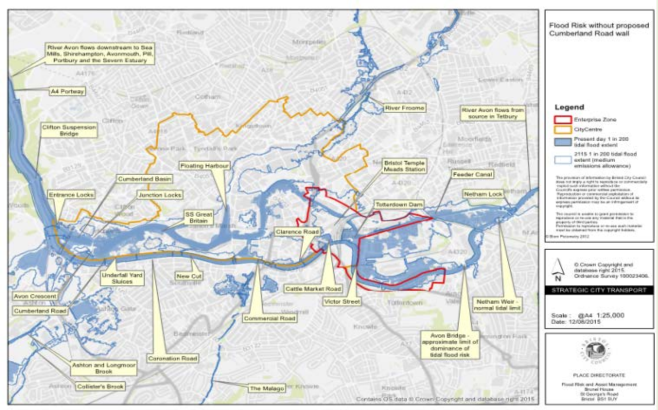
| Confidence rating | Confidence description | Minimum depth |
|---|---|---|
| 1 star | Very unlikely to be locally reliable | 0.90m |
| 2 star | Unlikely to be locally reliable | 0.75m |
| 3 star | Likely to be locally reliable | 0.60m |
| 4 star | Very likely to be locally reliable | 0.45m |
| 5 star | Highly likely to be locally reliable | 0.30m |

**(c)**

**Residual uncertainty allowance**
The worst considerations give a 3 star confidence rating and a recommended residual uncertainty allowance of 20% of the flood depth or 0.6m minimum. Therefore finished floor levels should be at least 0.6m above the residual water level.

The above residual uncertainty allowance aims to provide confidence of achieving the required flood protection. It assumes the strategic decision has been taken to allow change to permanent occupancy.

## Case Study 4: Tidal flood risk management strategy for Bristol




**Situation:** Tidal, defended, asset performance management

**Context:** Bristol city centre is exposed to a number of sources of flooding. The most severe, however, is tidal flooding. The Floating Harbour has some capacity to store water when low spots along the River Avon are overtopped at times of high tide. The Floating Harbour provides a route for tidal flood waters to enter the city and disrupt infrastructure. The highest recorded tide occurred in 1981 when an unexceptional spring tide partially coincided with a storm surge, increasing the peak level by 1.6m. A low flood wall, proposed as part of a parallel transport project, will reduce the chance of overtopping further.

Future predictions of high tidal flood risk constrain the scale and form of development in central Bristol today. Bristol City Council, working in partnership with the Environment Agency, is developing a tidal flood risk management strategy for Bristol. The strategy will appraise various flood risk management intervention options and also how soon they would be required, recommending an adaptive flood risk management strategic approach. This is being informed by the Bristol Central Area Flood Risk Assessment (CAFRA), a modelling study completed in 2013.

**Record of assessment**

The residual uncertainty allowance framework was applied at a pre-strategy phase to help define the scope of the strategy. The table overleaf shows the assessment. This box gives 2 examples of employing the 3 stages.

| Stage | Uncertainty A | Uncertainty B |
|---|---|---|
| 1. Identify and record present day sources of uncertainty | Long term climate change – not present day uncertainty but has a significant potential impact on the strategy outcome | Water level (tidal) |
| 2. Estimate the magnitude of residual uncertainties | CAFRA 2015 used upper end medium emission 95th percentile and high emission 95%ile UKCP09 scenarios. Tidal boundary varies by 0.4m depending on scenario. | 0.3m based on first order analysis (see Illustration 3.2 in Chapter 3) |
| 3. Determine the appropriate response | **Is action needed to manage the residual uncertainty?** Yes<br>**Does the cost of action influence the strategy choice?** Yes<br>**Is further analysis of the residual uncertainty likely to reduce cost?** No<br>**Outcome:** Further appraisal is required | **Is action needed to manage the residual uncertainty?** Yes<br>**Does the cost of action influence the strategy choice?** No<br>**Is the estimate of residual uncertainty credible?** Yes, action needed<br>**Outcome:** Modify plans. Some examples included better forecasting (source), demountable defences or adding multi-functional detention areas like rain gardens, (source), add resilience measures to buildings (receptor). |

**Outcome:**

The process has helped identify where there are residual uncertainties that have not been accounted for and so help refine the scope of the strategy to include:

- identification of assumptions, exclusions and residual uncertainties
- an assessment of what is there, the real height and the real chance of failing (no back analysis of the uncertainties used in the original design is necessary)
- identification of residual uncertainties and agreement of the process of progressive refinement – to include defining the strategy's approach to external variables
- review of the existing model to ensure that its suitability for intended use or impact of limitations are quantified
- use of proportionate sensitivity analysis to explore the residual uncertainty of predictions

| Variable or model parameter | Type of uncertainty category | Uncertainty (quantitative ± error or qualitative) | Unit | Comments and nature of error | Potential impact of uncertainty on strategy outcome? | Dealt with as part of appraisal (Y/N) | Comments | Dealt with as part of design (Y/N) | Comments | Summary of the approach to dealing with residual uncertainty | Status of action |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Source** | | | | | | | | | | | |
| In-river water level | Data | 0.4 | m | See components table below. | Low – downstream of Avon Bridge, River Avon levels are tidally dominated | N | n/a | N | n/a | CAFRA WS3 flood risk predictions and model limitations discussed in detail within CAFRA reporting. Catchment-wide WS3 model suitable for strategic decision-making but should be revisited during appraisal. | Live |
| Estuarine water level | Data | 0.3 | m | **Tidal validation.** WS3 calibrated at Netham for 3 tidally dominated events. Model showed good match for timing and level for observed tidal peaks (+0.0m to +0.23m). WS4 extreme value analysis of recorded levels at Cumberland Basin found 'good agreement with the modelled results approximately 0.1m greater than statistical analysis'. CAFRA 2015 validation against 2014 tidal event found 'generally capable of matching in-channel levels' to ±0.2m.<br>**Run substitution.** CAFRA 2015 update used substitution approach based on common downstream boundary conditions within +-0.05m, larger medium emissions ±0.1m and larger upper end estimate events ±0.25m<br>**Tidal boundary**. Avonmouth tidal gauge available to provide high-quality local level information. Return period tidal levels from coastal boundary guidance (Environment Agency 2011) did not calculate 95th percentile confidence bounds since statistical smoothing had been employed.<br>**Vertical land movement.** WS3 excluded allowance for vertical land movement (0.08m by 2115). This was noted in | High – tidally dominated tidal flood risk | N | n/a | N | n/a | Information available to test model sensitivity in strategy | Live |

| Variable or model parameter | Type of uncertainty category | Uncertainty (quantitative ± error or qualitative) | Unit | Comments and nature of error | Potential impact of uncertainty on strategy outcome? | Dealt with as part of appraisal (Y/N) | Comments | Dealt with as part of design (Y/N) | Comments | Summary of the approach to dealing with residual uncertainty | Status of action |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | CAFRA 2015 update equivalent event substitution.<br>**Tidal/surge phase shift.** WS4 found strong correlation between tidal/surge AEP and peak water levels. WS4 used 6.21 hours. | | | | | | | |
| Mid-term climate change | Data/model | 0.1 | m | **Tidal.** CAFRA 2015 update provided substitutions for upper end medium emission and high emission 95th percentile scenarios. Tidal boundary +0.09 (±0.01m depending on scenario) by 2030 and 0.24 (±0.06m depending on scenario) by 2050. Concurs with projected/observed - relative mean sea level trend of 2.4 mm/year based on 1993 to 2007 observations and projected+0.37m by 2050 (Phillips and Crisp 2010). Analysis of 1961-2012 mean sea level rise of 2 mm/year (Haig et al. 2015).f<br>**Fluvial.** CAFRA 2015 update +10% peak river flows 2030 – follows guidance in Environment Agency (2011). | Low – relative convergence of evidence although actual response to climate change unlikely to be linear | N | n/a | N | n/a | | Closed |
| Long-term climate change | Data/ Model | 0.4 | m | **Tidal.** WS3 used upper end seal level rise (SLR) allowance (equivalent to planning). WS4 used UKCP09 medium emissions 95th percentile (0.74m to 2110). CAFRA 2015 update provided substitutions for upper end medium emission and high emission 95th percentile scenarios. Tidal boundary varies by 0.4m depending on scenario.<br>**Fluvial.** CAFRA 2015 update +20% to 2065, +25% to 2115 – follows guidance in Environment Agency (2011). | High – divergence of evidence | N | n/a | N | n/a | CAFRA WS3 used a precautionary SLR allowance. 2015 CAFRA update allows for range of scenarios to be used. Information available to test sensitivity in the strategy | Live |
| Inland waves | Data | 0.2 | m | Anecdotal records suggest westerly wind can create waves on New Cut upstream (2014 event estimated at 0.2m). | Medium | N | n/a | N | n/a | Note: Propose considered during detailed design/option appraisal as localised issue. | |
| **Pathway** | | | | | | | | | | | |

| Variable or model parameter | Type of uncertainty category | Uncertainty (quantitative ± error or qualitative) | Unit | Comments and nature of error | Potential impact of uncertainty on strategy outcome? | Dealt with as part of appraisal (Y/N) | Comments | Dealt with as part of design (Y/N) | Comments | Summary of the approach to dealing with residual uncertainty | Status of action |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **System representation and applicability** | | | | | | | | | | | |
| Topography | Data | 0.25 | m | **Survey.** CAFRA WS3 collated historic and new watercourse survey with spot check comparisons on Brislington Brook (good agreement), River Malago and Pigeonhouse Stream.<br>**LIDAR.** Error in LIDAR derived digital terrain model due to filtering average (standard ±0.25m confidence). | Medium – while captured in fluvial/tidal calibration, significant impact on property threshold sensitivity | N | n/a | N | n/a | Consider damage sensitivity to property threshold test and sample review of suitability using StreetView. | Live |
| **Linear assets** | | | | | | | | | | | |
| Geometry (location and shape) | Data | 0.02 | m | There are limited formal raised defences in the area of interest.<br>**Formal defences.** CAFRA WS3 used topography (River Avon) and Halcrow (January 2005). CAFRA WS3 excluded downstream defences in Shirehampton and Pill as in 1D area.<br>**Informal defences.** Linear features, including third party de facto defence walls missing from the topography used in the inundation model. Unconstrained extent of lower return period events. Buildings represented with 0.3 Manning's n roughness. Hyder and JBA peer review consider acceptable. Note research into representing buildings in floodplain that found differences between using n values of 0.3 and 1.0 was relatively minor (Syme 2008). Higher return period events wall risk breach/collapse (WS4 surveyed Underfall Yard and concluded walls could retain hydrostatic depth of 1.3m with no allowance for debris or local turbulence around gate openings).<br>**Proposed raised defence options.** Construction tolerance ±0.01m | High – observed extent during low AEP events significantly less than predicted due to informal raised structures | N | n/a | N | n/a | Survey of de facto defences ongoing. Consider approach to model representation. Note risk of breach/collapse prior to overtopping and risk from lack of formal management unless designated. | Live |

| Variable or model parameter | Type of uncertainty category | Uncertainty (quantitative ± error or qualitative) | Unit | Comments and nature of error | Potential impact of uncertainty on strategy outcome? | Dealt with as part of appraisal (Y/N) | Comments | Dealt with as part of design (Y/N) | Comments | Summary of the approach to dealing with residual uncertainty | Status of action |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Condition (surface and internal) | Data | | | Formal defences – visually inspected annually<br>Informal defences – condition and maintenance unknown | High – observed extent during low AEP events significantly less than predicted due to informal raised structures | N | n/a | N | n/a | Survey of de facto defences ongoing. Consider approach to model representation. Note risk of breach/ collapse prior to overtopping and risk from lack of formal management unless designated. | Live |
| **Performance of models and applicability** | | | | | | | | | | | |
| Geometry and operational arrangement (point assets) | Model | unknown | | **Floating Harbour.** Complex assets. Represented in WS3 in 2D using bathymetry data with initial water level controlled by Netham Weir; lock gates in Cumberland Basin area are assumed to be permanently closed and Underfall Yard sluices are assumed to operate using their standard operational rules. | High – operation of Floating Harbour affects extent and duration of tidal flood | N | n/a | N | n/a | Investigate operational protocol drawing on recent City Docks' failure mode, effects and criticality analysis. | Live |
| Condition (point assets) | Data | unknown | | **Floating Harbour.** Condition varies, if known. | High – Floating Harbour asset condition presents risk of unimpeded tidal inundation into Floating Harbour, post-event rapid drawdown (risk of dockside structure collapse) or post-event impoundment | N | n/a | N | n/a | Floating Harbour emerging asset management – inspection regime and residual life of some key assets to be established | |
| Inflow into floodplain (linear assets - not failed) | | | | A 1D–2D linked model has been used.<br>**Roughness.** WS3 P111 – roughness +20% show small change in flow/depth. Roughness -20% shows small change in flow/depth except upstream of Chapel | Low – limited raised defences and limited roughness impact on tidally dominated areas | N | n/a | N | n/a | No further consideration | Closed |

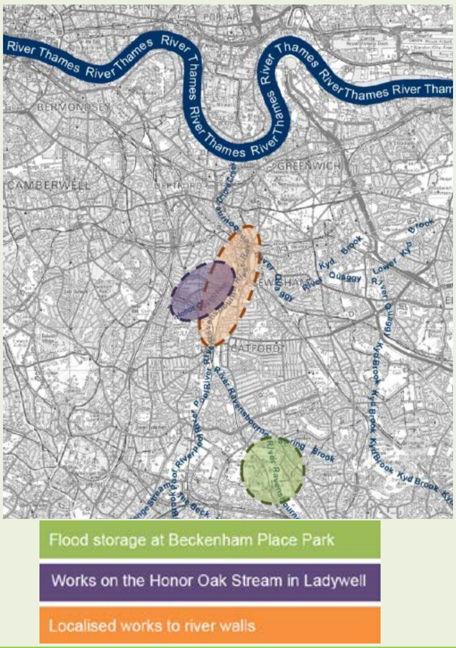
| Variable or model parameter | Type of uncertainty category | Uncertainty (quantitative ± error or qualitative) | Unit | Comments and nature of error | Potential impact of uncertainty on strategy outcome? | Dealt with as part of appraisal (Y/N) | Comments | Dealt with as part of design (Y/N) | Comments | Summary of the approach to dealing with residual uncertainty | Status of action |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Way, Brislington Brook with flow +20%. No change in tidally dominated areas.<br>**Domain resolution.** CAFRA WS3 2D domain used 4m cells –- representation of raised defence options with z-shape. Hyder concluded will result in conservative model predictions. | | | | | | | |
| Inflow into floodplain (linear assets – failed) | | | | Limited raised defences so limited applicability. | n/a | N | n/a | N | n/a | No further consideration | Closed |
| Inflow into floodplain (point assets – not failed) | | | | **Floating Harbour.** Represented in WS3 in 2D using bathymetry data with initial water level controlled by Netham Weir - 6.2mOD, Cumberland Basin lock gates permanently closed and Underfall Yard sluices using their operational roles.<br>**Floating Harbour operation.** Relies on manual operational protocols. WS4 results underscored the importance of Underfall Yard discharging water before onset of second tidal peak. | High – Operation of Floating Harbour affects extent and duration of tidal flood | | | | | Catchment-wide WS3 model suitable for strategic decision-making but should be revisited during appraisal | |
| Inflow into floodplain (point assets – failed) | | | | **Fluvial watercourse blockages** assessed in WS3 P116. Largely no new pathways or increases in properties at risk as model assumed tide-lock. Brislington Brook railway culvert 0.9m increase of Q100 flows. | Low – limited impact on tidally dominate area and also locations subject to tide-lock. | N | n/a | N | n/a | No further consideration | Closed |
| Inundation depth | | | | TUFLOW 1D–2D linked model | n/a | N | n/a | N | n/a | No further consideration | Closed |
| Inundation velocity | | | | TUFLOW 1D–2D linked model | n/a | N | n/a | N | n/a | No further consideration | Closed |
| **Receptor** | | | | | | | | | | | |
| **System representation and applicability** | | | | | | | | | | | |
| Location of buildings and critical infrastructure | | | | National Receptor Database used – excludes properties constructed 2012 onwards | High | N | n/a | N | n/a | Proportionate analysis with infrastructure providers. Residual uncertainty considered | Live |

| Variable or model parameter | Type of uncertainty category | Uncertainty (quantitative ± error or qualitative) | Unit | Comments and nature of error | Potential impact of uncertainty on strategy outcome? | Dealt with as part of appraisal (Y/N) | Comments | Dealt with as part of design (Y/N) | Comments | Summary of the approach to dealing with residual uncertainty | Status of action |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | high for highway network. | |
| Network dependency | | | | Regional impact of damage/disruption to city centre | Medium | N | n/a | N | n/a | Proportionate analysis with infrastructure providers. Residual uncertainty considered high for highway network. | Live |
| Threshold levels | | | | No direct measurements. WS4 and prefeasibility study assumed nominal threshold height of 0.1m. 2015 initial economics assessment assumed 0.3m. | Medium | N | n/a | N | n/a | Approach to be agreed as part of Local Plan refresh discussions – could consider through planning with new buildings to make appropriate allowances, but will constrain form/scale of city centre development. | Live |
| Buildings and contents | | | | Multi-coloured Manual (MCM) used to estimate property contents/fabric damage. No consideration of abnormal costs with listed heritage properties or cultural amenities such as SS Great Britain or M Shed. | High | N | n/a | N | n/a | Proportionate investigation into special damage items not addressed in MCM approach.<br>Participation in UCL research into flood vulnerability/damage of heritage.<br>Best estimates to be used in appraisal with some sensitivity testing to confirm chosen option as robust. | Live |
| Ability to respond to flood event | | | | **Response disruption.** Risk of inundation of emergency service centres such as Central Fire Station on Temple Slip. Increasing risk of disruption to transportation through/within the city centre with north–south movements prevented except for St Philips Causeway. | Medium | N | n/a | N | n/a | Best estimates to be used in appraisal with no sensitivity testing. | Live |

| Variable or model parameter | Type of uncertainty category | Uncertainty (quantitative ± error or qualitative) | Unit | Comments and nature of error | Potential impact of uncertainty on strategy outcome? | Dealt with as part of appraisal (Y/N) | Comments | Dealt with as part of design (Y/N) | Comments | Summary of the approach to dealing with residual uncertainty | Status of action |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | **Inundation duration.** CAFRA predicted flooding spanning multiple tidal cycles due to limited draw-down capacity of Floating Harbour. WS3 1 in 100 AEP event spanned 3 tidal cycles, WS4 spanned 5. | | | | | | | |
| Ability to recover from flooding | | | | Methods and data used to explore recovery | Medium | N | n/a | N | n/a | Best estimates to be used in appraisal with no sensitivity testing | Live |

| **Primary uncertainty:** In-river water level | | | | | |
|---|---|---|---|---|---|
| **Components of primary uncertainty** | | | | | |
| | **Absolute error (native parameter)** | | **Relative error (m)** | **Weighting** | **Comment** |
| | **Distribution** | **SD** | **SD** | | |
| Fluvial calibration | | | -0.4m to +0.3m | 1.0 | WS3 (P100) calibration considered 3 fluvially dominated events. Less effective calibration (-0.4m to +0.3m). Noted manually scaled observed flow at Bathford to derive model inflow at Saltford and confidence lower in areas where more than one fluvial mechanism dominates and interacts with tide. Model overestimated levels upstream of Netham during low tide. Good correlation with previous studies on River Frome. CAFRA recommended prioritised tributary gauging to improve confidence. |
| Hydrology | | | 0.1 | 1.0 | FEH using Revitalised Flood Hydrograph (ReFH) and Modified Rational Method – low confidence in use of rainfall–run-off so scaled flows to statistical peaks. WS3 P111 – flow sensitivity assessed to +-20% Q100 average 0.5m change in water level. Almost no change in tidal-dominated areas. WS4 tested T200 combined with F2, F5 or F10 and found harbour levels only change 0.1m with very weak relationship between Avon/Frome return period and harbour levels. WS4 validation against recorded levels at Cumberland Basin proved tidal dominance. |
| TUFLOW software revisions | | | 0 | 1.0 | CAFRA 2015 update used updated TUFLOW resulting in 'minor changes in results in areas… which have no interaction with the Floating Harbour' |
| TUFLOW parameters | | | 0.002 | 1.0 | WS3 model runs required adjustment of modelling parameters to accommodate result instabilities |
| Fluvial storm duration | | | 0.002 | 1.0 | WS3 conservatively used catchment-specific tributary critical storm durations phased to coincide with River Avon peak at Bathurst Basin. |
| Fluvial–tidal phase | | | 0.2m | 1.0 | WS4 found tidal/fluvial phase shift to be of equal if not greater importance than joint probability combinations. WS3 conservatively phased peak tide to coincide with fluvial peak at Bathurst and peak surge centred on the preceding low tide to the tidal peak, increasing duration of tide-lock. WS3 noted daily dependence between river flow and surge in River Avon as 'strongly correlated and conservatively applied the dependency value to the Frome'. |
| Total (assuming independence of errors) | | | 0.4m | | |

## Case Study 5: Lewisham and Catford Flood Risk Management Scheme – outline design in the Project Appraisal Report




**Situation:** Fluvial, defended, preferred option outline design
**Context:** The River Ravensbourne, with River Quaggy and River Pool as tributaries, runs through the London Borough of Lewisham and discharges into the River Thames upstream of the Thames Barrier. A third of the flows originate from a chalk catchment. The existing system consists of a concrete channel showing signs of ageing. Repairs are needed to maintain the 4.8km of channel and a 1.5km culvert over the next 50 years.

The main issue is that blockages lead to flooding if defences are abandoned (Do Nothing) or when the minimum maintenance is performed (Do Minimum). The current standard of protection is around 3% AEP.

The preferred scheme involves providing a 1.33% AEP protection with a flood storage reservoir at Beckenham Place Park (upper reach) and local defences within the channel. The flood storage reservoir requires excavation of World War II rubble, an embankment next to a railway line and a sluice including a coarse debris screen. Improved trash screens are proposed for the culvert intakes to reduce blockage and health risks.

**Record of assessment**
The residual uncertainty allowance framework was applied to help understand and account for residual uncertainties in the outline design. The table overleaf shows the assessment. This box gives 2 examples of employing the 3 stages.

| Stage | Uncertainty A | Uncertainty B |
|---|---|---|
| 1. Identify and record present day sources of uncertainty | Local waves – waves have been considered for the flood storage reservoir. | Operation of penstocks – to maximise the hydraulic deficiency of the reservoir an automated penstock with level sensors has been incorporated. |
| 2. Estimate the magnitude of residual uncertainties | Followed ICE reservoir safety guidance (3rd edition) (ICE 1996) to calculate waves. No wave data to verify calculations. Selected location where worst arrangements exist. | Not been estimated. |
| 3. Determine the appropriate response | **Is action needed to manage the residual uncertainty?** No<br>**Is the estimate of residual uncertainty credible?** Yes<br>**Outcome:** Accept residual uncertainty and document. | **Is action needed to manage the residual uncertainty?** Yes<br>**Does the cost of action influence the option choice?** No<br>**Is the estimate of residual uncertainty credible?** No<br>**Outcome:** Gather further evidence and refine estimate. Scenarios will be tested in the model. |

**Outcome**
The process has helped identify where there are unaccounted for uncertainties. Some have been accepted, others will be investigated further.

| Variable or model parameter | Type of uncertainty category | Uncertainty (quantitative ± error or qualitative) | Unit | Dealt with as part of strategy (Y/N) | Comments | Dealt with as part of appraisal (Y/N) | Comments and nature of error | Dealt with as part of detailed design (Y/N) | Comments | Summary of the approach to dealing with residual uncertainty | Status of action |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Source** | | | | | | | | | | | |
| In-river water level | Data | 150 | mm | N | – | N | Hydrology incorrect, hydraulics incorrect.<br>Hydrology based only on urban run-off; only excludes chalk.<br>Reasonable data for calibration from last 40 years<br>Hydrology based on FRQSIM specifically designed for London's urban rivers.<br>Extensive river level data at a number of points and coincident flow records from 1968 approximately onwards<br>1D–2D ISIS TUFLOW model based on cross section survey. Model calibrated at very few gauge locations. Losses at structures not calibrated.<br>Minor improvements were made to the hydraulic model. Suspicion that losses at structures are over estimated. If these were reduced then the model would need to be recalibrated which would increase losses in the channel. | n/a | n/a | Adopted the strategic hydraulic model provided to the project and added 150mm to new defence crest level. Best to revisit in detailed design when there will be a new hydraulic model and assess the cost of changing the design if the uncertainty has reduced. | Live |
| Estuarine water level | n/a | n/a | n/a | n/a | n/a | n/a | Fluvial location | n/a | n/a | n/a | n/a |
| Local waves | Design/ decision | n/a | n/a | N | n/a | Y | No wave data to verify calculations.<br>Calculations based on worst arrangements at Molesworth Street.<br>Waves only considered an issue for local embankments as local walls are non-erodible. (No estimate made of wave overtopping quantities.)<br>Waves considered for reservoir using ICE reservoir safety guidance (ICE 1996) | n/a | n/a | Accept the uncertainty from the ICE reservoirs safety guidance. | Closed |
| **Pathway** | | | | | | | | | | | |
| **System representation and applicability** | | | | | | | | | | | |

| Variable or model parameter | Type of uncertainty category | Uncertainty (quantitative ± error or qualitative) | Unit | Dealt with as part of strategy (Y/N) | Comments | Dealt with as part of appraisal (Y/N) | Comments and nature of error | Dealt with as part of detailed design (Y/N) | Comments | Summary of the approach to dealing with residual uncertainty | Status of action |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Topography | Data | 150 | mm | N | – | N | Some of the topographic survey may be quite old and so bed levels may changed | n/a | n/a | Topography based on LIDAR and topographic cross-sections. | Closed |
| Topography | Analysis completeness | 0 | m | N | – | Y | Analysis includes 2D. | n/a | n/a | No response as consider residual uncertainty is negligible. | Closed |
| **Linear assets** | | | | | | | | | | | |
| Geometry | Data | 50 | mm | N | – | Y | The majority of defence crest levels with the system have been taken from either the model or from LIDAR. | n/a | n/a | Has been taken at face value may contain errors. Have accepted the uncertainty. | Closed |
| Condition (surface and internal) | Data | 1/2 | CG | N | – | N | Condition of existing assets overestimated. Only cursory visual inspection by project team. Environment Agency condition inspections undertaken. | n/a | n/a | Repairs included in scheme. Accept the higher cost. Broad estimate of remedial works included in scheme following consultation with Environment Agency Asset Systems Management team. | Closed |
| Condition (surface and internal) | Analysis completeness | 5 | % of wall distance | N | – | N | More could be done to assess services condition in the reservoir. Wall condition in the channel. | n/a | n/a | Not used for design of walls as a conservative approach using the river water levels has been taken. | Closed |
| **Points assets** | | | | | | | | | | | |
| Geometry and operational arrangement (point assets) | Model | 0.1 | $m^3/s$ | N | – | N | Performance overestimated. | n/a | n/a | Flap valves are passive, no backup measure provided. Risk of flooding accepted. Penstocks are automated; both stop logs and manual closing provided, Twin penstocks to provide further redundancy. Penstocks vastly oversized for flow capacity. | Closed |
| Condition (point assets) | Data | n/a | n/a | n/a | – | n/a | Flap Valves, Penstocks and Screens all being added however all are new so condition not relevant. | n/a | n/a | n/a | Closed |
| **Performance of models and applicability** | | | | | | | | | | | |
| **Linear assets** | | | | | | | | | | | |
| Non-failed performance | Model | – | – | N | – | Y | A 1D-2D linked model has been used to assess the inflow hydrograph. | n/a | n/a | This is the assumption for the scheme. Measures included in | Closed |

| Variable or model parameter | Type of uncertainty category | Uncertainty (quantitative ± error or qualitative) | Unit | Dealt with as part of strategy (Y/N) | Comments | Dealt with as part of appraisal (Y/N) | Comments and nature of error | Dealt with as part of detailed design (Y/N) | Comments | Summary of the approach to dealing with residual uncertainty | Status of action |
|---|---|---|---|---|---|---|---|---|---|---|---|
| : inflow into floodplain | | | | | | | | | | the design to improve condition and design new elements to reduce this likelihood. | |
| Non-failed performance : inflow into floodplain | Analysis completeness | – | – | N | – | Y | Analysed in model. | n/a | n/a | Included using standard ISIS parameters. | Closed |
| Failed performance : inflow into floodplain | Model | | | N | – | Y | A very simple breach model (given failure) has been used. Very few assets are above ground. Those that are below ground level could not fail in a way that would increase flood risk. | n/a | n/a | Assume that failed assets are repaired. The exception is Armoury Road, which is in poor condition; however, this is to be repaired as part of the scheme. | Closed |
| **Point assets** | | | | | | | | | | | |
| Non-failed performance : inflow into floodplain | Analysis completeness | -200 | mm | N | – | Y | No losses included. | n/a | n/a | Included using standard ISIS parameters. | Closed |
| Failed performance : inflow into floodplain | Model | – | – | N | – | Y | The design assumes that flap vales do not fail. | n/a | n/a | The design assumes that flap vales do not fail. | Closed |
| **Inundation** | | | | | | | | | | | |
| Inundation depth | Analysis completeness | – | – | N | – | Y | 2D model so analysis complete although not actually used. | n/a | n/a | Water levels from river channel used which are higher than floodplain. | Closed |
| Inundation velocity | Model | – | – | N | – | Y | Output from TUFLOW. Concrete walls – few earth embankments. Expert judgement used. | n/a | n/a | Residual uncertainty on erosion of structures still applies. Design undertaken to address typical velocity induced scour. | Closed |
| **Receptor** | | | | | | | | | | | |
| **System representation and applicability** | | | | | | | | | | | |
| uSoP | Design | Overestimate | % AP | N | – | Y | – | – | – | Many elements designed by eye taking a conservative choice. | Closed |
| Human operations - to operate defences | Decision | 20 | % | | | N | Only a broad principle on operation of penstocks established. This has not been properly tested in the model. | | | This will be tested in the model. | Live |

| Variable or model parameter | Type of uncertainty category | Uncertainty (quantitative ± error or qualitative) | Unit | Dealt with as part of strategy (Y/N) | Comments | Dealt with as part of appraisal (Y/N) | Comments and nature of error | Dealt with as part of detailed design (Y/N) | Comments | Summary of the approach to dealing with residual uncertainty | Status of action |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Functionality | Decision | Low | | | | Y | Incorrect/incomplete definition of usage | | | Landscaping for local defences not fully developed. Changes highly likely; plenty included in the costs. | Closed |

# Asset performance assessment

## Case Study 6: Thames Estuary Asset Management 2100 programme (TEAM2100) – North Kent Marshes Policy Management Unit


**Situation:** Estuarine, defended, strategy with asset performance management

**Context:** The Thames Barrier was inaugurated by the Queen in 1983, 30 years on from the 1953 floods. The Barrier, its associated gates and defences were designed to protect London from the 0.1% annual probability combined tidal/fluvial flood event in the year 2030. This design standard included an allowance for sea level rise and local subsidence.

Today the flood risk is managed in the estuary using a wider portfolio of approaches, although the most obvious being the formal flood defence system consisting of barriers, tidal gates and flood walls and embankments (see map above).

At the start of 2000 the Environment Agency embarked on a major study to plan how best to manage tidal flood risk in the Thames estuary through to the year 2100. The resulting Thames Estuary 2100 Plan, also called TE2100, (Environment Agency 2012) identifies preferred policy options for a series of Policy Management Units. Through the Thames Estuary Asset Management (TEAM) 2100 initiative, the Environment Agency is working on how to deliver the first 10 years of TE2100, mainly consisting of the refurbishment and improvement of tidal flood defences.

This case study covers the North Kent Marshes Policy Management Unit, where the preferred policy is:

> 'Policy 3: To continue with existing or alternative actions to manage flood risk. We will continue to maintain flood defences at their current level, accepting that the likelihood and/ or consequences of a flood will increase because of climate change'.

The TEAM2100 project is currently in the process of identifying how best to implement this policy. The findings of this local strategy will then be used to inform a full appraisal of options. The Flood Defence Grant-in-Aid (FDGiA) score is only 6%, so there is currently no funding for the reach. There is also an urban portion that has been designated as Policy 4 due to the railway. There are locations for potential managed realignment (for example, Lower Hope Point and St Mary Marshes) and flood storage (western area north of the railway line).

**Record of assessment**

The residual uncertainty allowance framework was applied at a post-strategy, but pre- detailed appraisal stage to:

- help identify all uncertainties considered relevant to the assessment of flood risk within the North Kent Marshes Policy Management Unit
- identify those uncertainties that have already been addressed within the TE2100 studies (and elsewhere) together with a summary explanation of how they have been addressed
- determine the magnitude of the remaining (residual) uncertainties and recording the evidence used in support of this estimate
- consider the general responses that are likely to be taken in managing these residual uncertainties
- understand the current level of protection offered by the existing flood defence

The assessment table below gives a record of the findings.

**Outcome**

The exercise of using the process defined by this guide to identify and assess the scale of the residual uncertainties has been a very valuable exercise. It has allowed proper records of the uncertainties already addressed, and enabled understanding of the scale of the residual uncertainties and initial exploration of how they may be accounted for during the next stage of the project.

The assessment showed that components of uncertainty in resilience to overtopping velocities will be an important aspect for appraisal of options. The proportionality principle will be applied at the next stage to determine how best to respond.

Note: No effort at this stage has been made to considering the cost of a potential response and hence a decision on the final approach to the residual uncertainty allowance has not been made.

| Variable or model parameter | Type of uncertainty category | Uncertainty (quantitative ± error or qualitative) | Unit | Dealt with as part of regional/ local strategy (Y/N) | Comments and nature of error/response | Dealt with as part of policy unit appraisal (Y/N) | Comments | Dealt with as part of design (Y/N) | Comments | Summary of the approach to dealing with residual uncertainty | Status of action |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Source** | | | | | | | | | | | |
| Estuarine water level | Data uncertainties | 0.45 | m | N | 1. Length of record<br>2. Tide gauge accuracy<br>3. Suitability of tide gauge location for making representative decisions at a policy unit level<br>4. Accuracy of historical understanding of coincidence of surge and tide<br>5. Effect of barrier closures on water middle estuary water levels<br>6. Effect of potential breaches elsewhere in the estuary on water levels<br>7. Effect of planned future re-alignment on estuary water levels | Y | | Y | | Will take value from TE2100 as defined within the Standards of Protection and Freeboard Paper in defining water level uncertainty. Value to be added to water level. Response to manage will be considered in how asset can be resilient to overtopping velocities. | Closed |
| Estuarine water level | Analysis completeness | 0.58 | m | N | Policy unit is exposed to wind and boat generated wave action. Changing its orientation makes it difficult to define the precise effect across it. Current assumptions likely to be conservative. | N | | N | | | Active |
| Surface water depth | – | – | – | – | – | – | – | – | – | – | – |
| Nearshore local waves | Data uncertainties | 0.15 | m | N | Potential inaccuracy in assessment of wind generated waves within TE2100. Related to: | Y | | Y | | Ways to deal with uncertainty include:<br>1. Early Warning Meeting with TE2100 team members to documents key assumptions | Live |

| Variable or model parameter | Type of uncertainty category | Uncertainty (quantitative ± error or qualitative) | Unit | Dealt with as part of regional/ local strategy (Y/N) | Comments and nature of error/response | Dealt with as part of policy unit appraisal (Y/N) | Comments | Dealt with as part of design (Y/N) | Comments | Summary of the approach to dealing with residual uncertainty | Status of action |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | 1. Uncertainty in assumptions made for TE2100 analysis<br>2. Length of record<br>3. Proximity of wave gauge to relevant location<br>4. Accuracy of gauge<br>5. Relevance to whole policy unit, given changes its geography | | | | | 2. Review of TE2100 existing data and models to establish approach to deterring asset performance requirements<br>3. Establish policy unit performance requirements<br>4. At detail design identify local options for sustain asset performance requirements over the whole life of the asset | |
| **Pathway** | | | | | | | | | | | |
| **System representation and applicability** | | | | | | | | | | | |
| Foreshore bathymetry | Data uncertainties and analysis completeness | Medium | | N | High level analysis was undertaken as part of the TE2100 strategy. Increased loss of foreshore has been noted since completion of the TE2100, specifically around Lower Hope. | Y | | Y | | Estuary geomorphic study to determine the impact and potential need for further monitoring | Live |
| Topography | Data uncertainties | 0.78 | m | Y | The bare-earth topography derived from Ordnance Survey dataset has been used. This dataset has known limitations in this area.<br>Linear features, such as walls missing from the topography used in the inundation model. | Y | | Y | | LiDAR survey of floodplain undertaken as part of TE2100 | Closed |
| **Linear assets** | | | | | | | | | | | |
| Geometry (location and shape) | Data uncertainties | 0.15 | m | Y | The majority of defence crest levels with the | N/A | | N/A | | Defence level topographic survey undertaken as part of TE2100. Data now *c*.8 years | live |

| Variable or model parameter | Type of uncertainty category | Uncertainty (quantitative ± error or qualitative) | Unit | Dealt with as part of regional/ local strategy (Y/N) | Comments and nature of error/response | Dealt with as part of policy unit appraisal (Y/N) | Comments | Dealt with as part of design (Y/N) | Comments | Summary of the approach to dealing with residual uncertainty | Status of action |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | system have been measured from LIDAR. | | | | | old and will need updating within the next 2–3 years. | |
| Condition (surface and internal) | Data uncertainties | ±1 | CG | Y | Condition Assessment Manual condition grade. Visual inspection. | Y | N/A | | | Site visit by specialist engineer as part of TE2100. This assessment has been refined as part of the TEAM2100 Part A studies. Consider endemic failure modes and perform site investigation to change condition grade. | closed |
| **Point assets** | | | | | | | | | | | |
| Geometry and operational arrangement (point assets) | Model uncertainties | 0.1 | m | Y | Analysis reasonably complete – ignore | Y | | Y | | Broad geometrical arrangements were picked up as part of TE2100, but the policy unit reviews and Part A appraisal will identify operational arrangements. | live |
| Condition (point assets) | Model uncertainties | High | | Y | Analysis reasonably complete – ignore | Y | | Y | | Note: Classically defined condition grade is well understood. The completeness of condition grade assessment as a proxy for performance is debatable. | live |
| **Performance of models and applicability** | | | | | | | | | | | |
| **Linear assets** | | | | | | | | | | | |
| Inflow into floodplain (linear assets – not failed) | Analysis completeness | Low | m3/s | Y | Fully hydrodynamic TUFLOW 2D modelling of floodplain flow (dynamically linked to the 1D model of the river) Insufficient level of detail to assess the risk at an asset level | Y | | N | | Improved asset level modelling will be undertaken at policy unit level. | Live |
| Inflow into floodplain | Analysis completeness | Medium | | Y | Treatment of breaching through a combination of | Y | | N | | High quality mode for strategic assessment, but | Live |

| Variable or model parameter | Type of uncertainty category | Uncertainty (quantitative ± error or qualitative) | Unit | Dealt with as part of regional/ local strategy (Y/N) | Comments and nature of error/response | Dealt with as part of policy unit appraisal (Y/N) | Comments | Dealt with as part of design (Y/N) | Comments | Summary of the approach to dealing with residual uncertainty | Status of action |
|---|---|---|---|---|---|---|---|---|---|---|---|
| (linear assets – failed) | and model uncertainties | | | | breach factors and embayment scale TUFLOW 2D breach models. Insufficient level of detail to assess the risk at an asset level | | | | | breach assumptions simplistic for operational decision-making.<br>TE2100 modelling undertook strategic modelling to a very high standard, to the extent that it can support strong tactical decision-making. Current limitations of the model include the inability to understand the relative importance of each asset within a Policy Unit. This will be addressed through delivery of the risk at asset level project. | |
| **Point assets** | | | | | | | | | | | |
| Inundation velocity | | 0.5 | m | N | Missing – lack of physical process representation within the chosen hydraulic model | N | | N | | Actions taken to manage an emergency (evacuation routes and so on) or develop the floodplain should not rely on the modelling carried out for the appraisal or design. Additional analysis will be required. However, this lack of information is not considered material in the assessment of the preferred option or design detailing. | Live |
| **Receptor** | | | | | | | | | | | |
| **System representation and applicability** | | | | | | | | | | | |
| Location of buildings and critical infrastructure | Data uncertainties | Moderate | | Y | Well modelled through TE2100; any errors likely to occur due to age of data set in a dynamic environment | Y | – | – | – | – | – |

| Variable or model parameter | Type of uncertainty category | Uncertainty (quantitative ± error or qualitative) | Unit | Dealt with as part of regional/ local strategy (Y/N) | Comments and nature of error/response | Dealt with as part of policy unit appraisal (Y/N) | Comments | Dealt with as part of design (Y/N) | Comments | Summary of the approach to dealing with residual uncertainty | Status of action |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Network dependencies | | Moderate | | | Well modelled through TE2100; any errors likely to occur due to age of data set in a dynamic environment. | Y | – | – | – | – | – |
| Threshold levels | | 0.5 | m | Y | Well modelled through TE2100; any errors likely to occur due to age of data set in a dynamic environment. | Y | – | – | – | – | – |
| uSoP | | Moderate | – | | Conservatism within the limits of acceptable overflow rates at uSoP | | | | | In determining the strengthen of the rear face protection and slope the allowable overflow rates have been increased by 10% – this is based on X | |
| sSoP | | Moderate | – | | Conservatism within the limits of acceptable overflow rates at sSoP | | | | | In determining the strengthen of the rear face protection and slope the allowable overflow rates have been increased by 10% – this is based on X | |
| Human operations – to operate defences | | 20.0 | % | | The human element of operating certain parts of a flood defence system can hold significant uncertainties. | | | | | | |

| Variable or model parameter | Type of uncertainty category | Uncertainty (quantitative ± error or qualitative) | Unit | Dealt with as part of regional/ local strategy (Y/N) | Comments and nature of error/response | Dealt with as part of policy unit appraisal (Y/N) | Comments | Dealt with as part of design (Y/N) | Comments | Summary of the approach to dealing with residual uncertainty | Status of action |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Functionality | | Low | - | | Incorrect / incomplete definition of usage | | | | | The embankment may be crossed by cattle. Specific crossing points have been encouraged with strengthen crests. Operational guidance is also provided to ensure crest levels and surface cover materials are well managed. This has added an additional £50k to the option of the preferred option. Combined with the other additional costs the benefits to cost ratio remains 3.5. It is unclear if these additional costs would have changed the preferred option. | |
| Evacuation potential | | 15.0 | % | | Incorrect assumption that evacuation is possible or poor assumptions of efficiency | | | | | | |

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