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- **Delivering information, advice, tools and techniques**, by making appropriate products available to our policy and operations staff.

Steve Killeen

Head of Science

Executive summary

HR Wallingford and Halcrow have been commissioned by the Environment Agency to undertake a sensitivity analysis of the RASP HLM+ approach as applied within NaFRA 2005. The project aim is to establish the relative contribution of different input datasets to the variability in the RASP HLM+ outputs. The sensitivity testing is undertaken through a perturbation approach, whereby input data is varied within realistic ranges (based on knowledge of the associated field measurement techniques) and the sensitivity of outputs such as the probability of risk and economic damage are measured.

The sensitivity tests are undertaken for three sites, selected to include a fluvial, estuary and coastal location. The sites, which are well known by the project team and the Environment Agency, and in most instances have results available from more detailed RASP-type analyses, are:

- the Stour fluvial site in south-east England;
- the Thamesmead site on the Thames Estuary;
- the Skegness coastal site in Lincolnshire.

The perturbed input and model parameters include source terms (e.g. fluvial loading), pathway terms (e.g. crest levels, toe levels, valley shape etc), receptor terms (e.g. depth-damage curves) and model parameters (e.g. breach width).

The main findings from the sensitivity testing are:

- The calculated risk is very sensitive to loadings conditions.
- The calculated risk is very sensitive to the accuracy of the crest levels.
- For the chosen site toe level was not a critical model input – however, further exploration of sensitivity for a coastal site with measured toe level information is recommended.
- The calculated risk is sensitive to property floor space and hence the source of this data should be selected with care.
- The calculated risk is very sensitive to the number of events used to define the loading curve – with a minimum of 40 return periods recommended.
- The calculated risk is sensitive to the defence failure order, and it is recommended that the defence failure order is set equal to the number of defences within the defence system associated with a given impact zone.
- Although the coastal site results do provide some very useful conclusions regarding the importance of toe level data, more generic conclusions about the sensitivity of coastal sites cannot be derived from the existing pilot results and further exploration of sensitivity for a coastal site with measured toe level information is recommended.
- The coastal element of this study emphasises the importance of good quality data on toe levels as well as crest levels – this is clearly necessary in order to move to more probabilistic analysis of flood risk.
- If further work on sensitivity and uncertainty analysis is carried out, the choice of pilot sites should be based on an audit of data availability and quality at the pilot sites under consideration.
- The project has pointed the way to a rational approach to the value of data quality and model accuracy. Where the risks are high (e.g. large expected annual damage (EAD) values), data needs to be of high quality so that the band of uncertainty is reduced, as far as possible, to model uncertainty only. For lower risk areas, data quality may be less critical for risk-based decision-making.

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1 Introduction

1.1 Project aim

HR Wallingford and Halcrow have been commissioned by the Environment Agency to undertake a sensitivity analysis of the RASP HLM+ (Risk Assessment for Strategic Planning High Level Method *plus*) approach, as used for NaFRA (National Flood Risk Assessment) in 2005. The project aim is to establish the relative contribution of different input datasets to the variability in the RASP HLM+ outputs. The sensitivity testing is undertaken through a perturbation approach, whereby input data is varied within realistic ranges (based on knowledge of the associated field measurement techniques) and the sensitivity of outputs such as the probability of flooding and annual economic damage are measured. The results will provide key information on the significance and prioritisation of each dataset (for projects such as NaFRA 2006 as well as more detailed studies), helping to set priorities for future research into methodological improvements and data collection activities.

1.2 Approach

The RASP HLM+, which was used to support NaFRA 2005, has continued to be updated through the NaFRA development project (in support of NaFRA 2006). This study used the latest available versions of the NaFRA coding to maximise the benefit of the findings for the NaFRA 2006 project. The NaFRA tool relies on several national datasets, yet the sensitivity and uncertainties of the method to changes and quality of data are not well understood. Therefore, this project seeks to understand:

- the sensitivity and uncertainty of the method in relation to changes in and the quality of the datasets;
- the relative importance of the different dataset needs;
- the availability and quality of all existing dataset needs.

At the Project Board meeting on the18 January 2006, it was agreed that this project would focus on the first two of these three items. Although the original scope of work also discussed 'the availability and quality of all existing dataset needs', it was agreed that while this is an important area of research, it would require substantial resource and was outside the scope of the current work.

1.3 Layout of the report

This report is structured as follows:

Chapter 1 is this introduction.

Chapter 2 provides the site selection for the sensitivity tests.

Chapter 3 provides the adopted methodology, the sensitivity tests to be undertaken and the approach to analysing the results.

Chapter 4 provides the results and discussions of the sensitivity analysis for the three pilot sites.

Chapter 5 identifies the key conclusions and recommendations for taking forward to NaFRA 2006 as well as future related R&D work and data collection activities.

Appendix A:	Thamesmead site results (estuary)
Appendix B:	Skegness site results (coastal)
Appendix C:	Stour site results (fluvial)

2 Site selection

The sensitivity analysis was undertaken in the context of three sites where data from more detailed RASP-type analysis or good input data and knowledge was available either within the project team or the Environment Agency. These sites include estuary, coastal and fluvial locations as follows:

- The Thamesmead area of Thames Estuary, where more detailed analyses have taken place as under the Thames Estuary 2100 project.
- The Skegness coastline on the east coast of England. More detailed RASP analysis are continuing as part of the PAMS project.
- A fluvial site along the Stour River in the south-east of England, where more detailed analysis is under way as part of the NaFRA 2006 development project.

For these areas the more detailed results are considered as the reference datasets. The location of these sites is shown in Figure 2.1.

Figure 2.1: Map showing the three site locations

2.1 Thamesmead on the Thames

The Thamesmead embayment on the south side of the River Thames is located in Catchment Number 2804. The modelled extent is bounded on the north side by the River Thames and on the south side by the extent of the natural floodplain. The region extends from the River Poll upstream of the Thames Barrier, through to the River Derent, downstream of the Barrier. The input data and Ordnance Survey map are provided in Figure 1A, Appendix A. This includes information on the defence standard of protection (SoP), the defence condition grade (CG) and the defence class. The spatial distribution of the probability of risk and expected annual damages (EADs) are also provided. These are discussed in more detail in Chapters 3 and 4.

2.2 Skegness

This coastal site includes the Skegness coastline in Lincolnshire on the east coast of England and the area south of Skegness, bounded by the Steeping River. The input data and Ordnance Survey map are provided in Figure 1B, Appendix B. This includes information on the defence SoP, the defence CG and the defence class. These show that the Skegness Town, located in the north-east of the area, is protected to a 200 year SoP. The spatial distribution of the probability of risk and EADs are also provided. These are discussed in more detail in Chapters 3 and 4.

2.3 Stour

The Stour region is located in Catchment 4004 in the south-east of England. The input data and Ordnance Survey map are provided in Figure 1C, Appendix C. This includes information on the defence SoP, the defence CG and the defence class. The spatial distribution of the probability of risk and EADs are also provided. These are discussed in more detail in Chapters 3 and 4.

3 Methodology

3.1 Data sources

The adopted methodology is intended to illustrate the significance of the various data inputs to the outputs derived from the RASP HLM+ approach. This input data is based on national datasets, which have varying degrees of uncertainty typically related to the measurement approach or information source. For example, a defence crest level may be derived from a detailed survey or inferred from adjacent defence information. Table 3.1 provides a summary of the input datasets considered and the typical measurement techniques.

Table 3.1: Summary of datasets and associated measurement approaches

No.	Dataset	Measurement approach
1	Defence location	Offset from the river centreline
2	Crest level	LiDAR, SAR, detailed survey, inferred from SoP
3	Toe level	In situ measurement, remotely sensed
4	Condition grade	Visual assessment
5	Standard of protection	Subjective assessment
6	National Property Dataset 2005 (NPD 2005)	Derived from OS MasterMap Address and Building Layer, Valuation Office Commercial Property Valuation for Tax Purposes
7	Digital terrain model (DTM)	LiDAR, NextMAP, SAR
8	Demographic data	Population census
9	Input fluvial water levels	National broad-brush (Flood Zones), detailed calibrated models (Thames Estuary 2100)
10	Valley type	Derived from floodplain width and longitudinal defence slope
11	Floodplain width	Derived from defence location and Flood Zone 2 boundary

3.2 Sensitivity criteria

The sensitivity analysis is based on a perturbation approach, whereby input data is varied within realistic ranges drawn from the field measurement techniques (Table 3.1), and the sensitivity of outputs such as the probability of risk and economic damage are measured. For this, the reference case is based on the default parameters, i.e. the true national dataset information and model parameters within the evolved NaFRA 2006 approach. This reference case is only altered where the condition grade (CG) has a value of 3+. This indicates a large uncertainty associated with the data and hence the result, as the fragility curve is prescribed wider uncertainty bands. In this instance, the CG is reset to 3, enabling a clear interpretation of the results where the input CG is varied (Section 3.3).

To illustrate the sensitivity in output due to a perturbation in a given data input or model parameter relative to the reference case, the relative percentage change in output is assessed. This is undertaken for two output parameters:

- the probability of flooding over the modelled region;
- the expected annual damages (EADs) integrated over the modelled region.

Thus, the percentage difference ΔP (%) in probability of the reference case P_{ref} relative to the perturbed output probability P_{per} is given by:

$$\Delta P = \frac{P_{per} - P_{ref}}{P_{ref}} 100 \tag{1}$$

for a given impact zone. Similarly, the percentage difference in the EADs, Δ_{EAD} (%), is given by:

$$\Delta_{EAD} = \frac{EAD_{per} - EAD_{ref}}{EAD_{ref}} \tag{2}$$

where EAD_{ref} (£) and EAD_{per} (£) are the total EADs for the reference and perturbed cases respectively. These are evaluated from:

$$EAD_{ref} = \sum_{i=1}^{n} EAD_{ref\,i} \tag{3}$$

and

$$EAD_{per} = \sum_{i=1}^{n} EAD_{per\,i} \tag{4}$$

where n is the number of impact zones in the modelled region. For equation 1, if $P_{ref} = 0$ and $P_{per} > 0$, then ΔP is set as 99,999. Similarly, if $P_{ref} = 0$ and $P_{per} < 0$, then ΔP is set as -99,999.

For output (i), the spatial distribution of ΔP is given for each sensitivity test. Here, the percentage difference in probability, ΔP, has been categorised according to its significance (Table 3.2). For output (ii), the Δ_{EAD} (%) value is provided for each sensitivity test. These outputs are provided in Appendices A, B and C for the Thames, Skegness and Stour sites respectively.

Table 3.2: Categories for the percentage difference in probability at a given spatial location

ΔP (%)	Category name
-100 to -20	Sensitive
-20 to -5	Limited sensitivity
-5 to -0.0001	Insensitive
-0.0001 to 0.0001	No change
0.0001 to 5	Insensitive
5 to 20	Limited sensitivity
20 to 100	Sensitive
100 to 500	Very sensitive
>500	Extremely sensitive

3.3 Restricted probability banding

Review of the NaFRA 2005 outputs has indicated that in many instances the probability results are 'banded' in nature. For example, there will be a number of impact zones with a precise probability of say, 0.361. The reason for this is not clear and it may be related to the 'RP factor' where all the defences are on high ground and hence there is no breaching. To provide further insight, for each sensitivity test the identical probability values for the impact zones are counted and aggregated into a probability density function (e.g. Figure 3.1). These are then compared to ascertain whether the banded properties vary for different sites and conclusions are drawn.

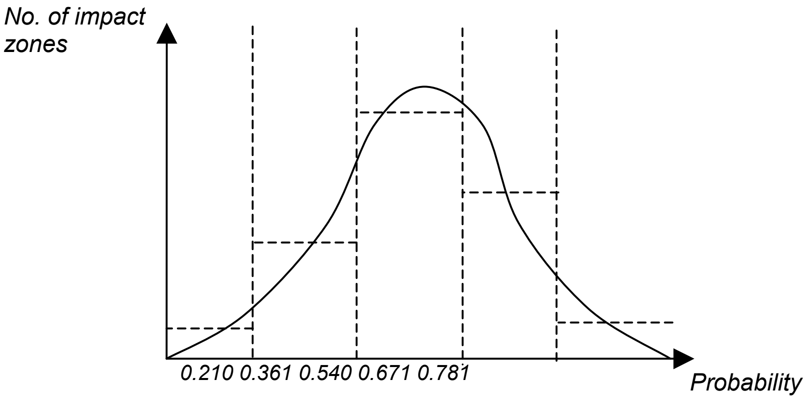


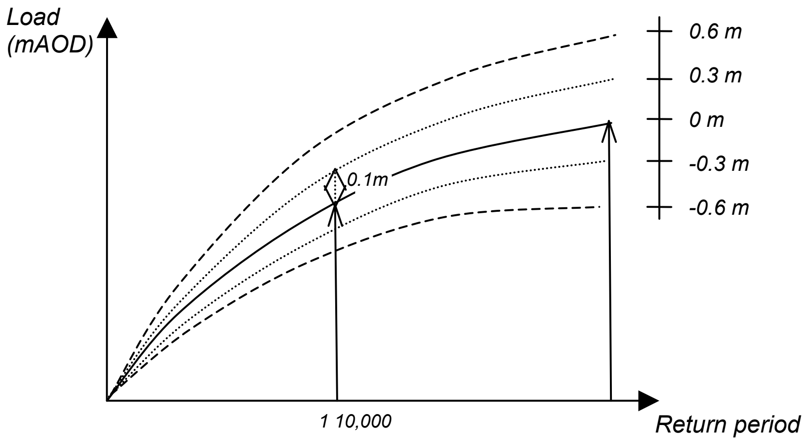
Figure 3.1: Example of banded probability

3.4 Perturbations to the input data

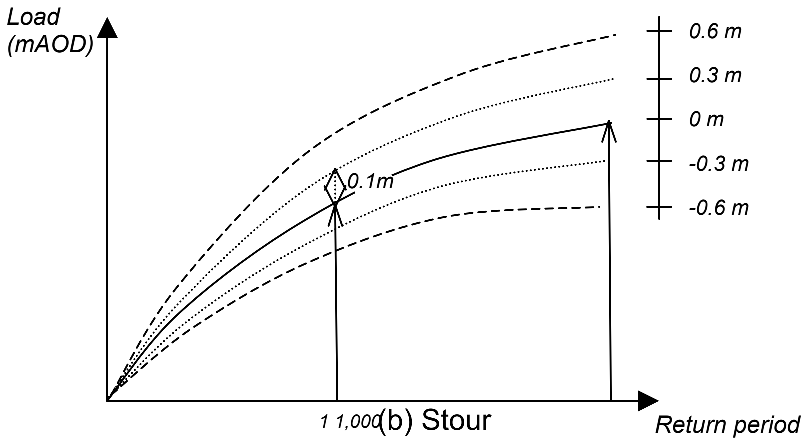
The sensitivity testing for the input data may be categorised according to the source, pathway and receptor terms as used within the RASP system analysis.

3.4.1 Source terms

For the source terms, the sensitivity test involves variation of the fluvial water levels in the fluvial and estuary sites. The NaFRA 2005 fluvial loading curve is based on 39 events, where the 100 year and 1000 year return period event are incorporated in deriving the curve shape. For the Thames case study, 65 events are available from the Thames Estuary 2100 project, allowing the event table to be extended by 26 events from the 1000 year event through to the 10,000 year event. The sensitivity test involves varying these fluvial levels to provide two upper and two lower estimate curves. For the Thames, there is information available regarding the typical ranges for the 1 and 10,000 year event, which are ± 0.1 m and ±0.3 m respectively. This information is used to derive the first upper and lower curve estimates for each event. These ranges are then doubled, i.e. ± 0.2 m and ±0.6 m for the 1 and 10,000 year event respectively, and similarly used to derive the perturbed loadings for the entire event curve (Figure 3.2a). As there is less available information for the Stour, the same ranges are adopted for the fluvial sensitivity test; however, the ranges are based on the 1 and 1000 year events to reflect this uncertainty (Figure 3.2b).



(a) Thames



(b) Stour

Figure 3.2: Fluvial level changes for the (a) River Thames and (b) the River Stour

The coastal water levels and wave conditions are not considered in this project.

3.4.2 Pathways terms

Defences – Crest levels
The variation of defence crest levels is applied at all three sites. The approach is to vary the crest levels by ± 50 cm, ± 20 cm and ± 10 cm to represent the possible error associated with the data measurement technique, for example, Light Detection and Ranging (LiDAR), Synthetic Aperture Radar (SAR) or detailed survey respectively. Where these perturbations result in the crest level dropping below the Ground or toe level, the crest level is set at that ground or toe level.

Defences – Standard of protection
Variation of the SoP is considered for the Stour site. The estimated crest level is based on the SoP, where the SoP is compared to the coastal or fluvial load for the SoP return period, and that load is then taken as the estimated crest level. Where the estimated crest level is greater than the ground level, it is set as the crest level. Where it is less than the ground level, it is set at the ground level. Thus, a perturbation in the SoP is effectively a perturbation in the estimated crest level. For the sensitivity testing the SoP is varied by ±20 and ±50 years. The impact of this change on the estimated crest levels is evaluated and hence the impact on the output probability and EADs is inferred from the aforementioned crest level tests.

For the Thamesmead site there is detailed crest level information available from the Thames Estuary 2100 project and the SoP is not used to determine the crest level.

Defences – Toe levels
The defence toe levels are varied along the Skegness coastline. There is a large uncertainty associated with two aspects:

- The measurement technique enables beach level (from the Environment Agency's ABMS for example) to be determined within ±1 m of the actual beach level.
- The toe level is difficult to determine in practice, e.g. where does the structure/beach end and the foreshore start?

The sensitivity test is therefore based on perturbing the toe levels through a range of ±1 m and ±2 m.

Defences – Condition grade
The condition grade (CG) is varied for all of the three sites. The CG is a value from 1 to 5 where 1 represents a good CG and 5 represents a poor CG. Where there is no information available, the CG is set at 3+. The implication is that within the NaFRA methodology, the uncertainty bands on the fragility curve are widened, providing a larger uncertainty range. For simplicity and to aid interpretation of the results in this study, where the CG is 3+ the reference case values are set to 3. The CG perturbations involve varying the CG by ±1 CG and ±2 CGs. This test is straightforward for the case where the reference CG is 3. Where it is not, the perturbation may result in a -1, 0, 6 or 7 value of the CG. The changes are therefore restricted to a minimum value of 1 and a maximum value of 5. The implication of this is that in areas where the CG is good there will be little change observed for an improvement in the CG, and vice versa for areas where the CG is poor.

Discharge calculations
The inflow hydrograph, which is used to determine the volume of water overtopping the defence or passing through the breach, is varied for the fluvial and estuary cases. The hydrograph shape is altered, by doubling the base, which effectively results in twice the overtopping volume that enters the floodplain. As there is a large uncertainty associated with the overtopping rate, only this one perturbation is considered.

Floodplain topology and topography
The valley type is assigned using a simple look-up table based on the defence type (coastal or fluvial), the floodplain width and the slope along the defence in the fluvial case. This look-up table (Table 3.3) is based on the RASP HLM Technical Report (Defra/Environment Agency, Report No W5b-030/TR1, 2002).

Table 3.3: Valley type look-up table for defences

	Fluvial (shallow <1/5000)	Fluvial (intermediate)	Fluvial (steep >1/1000)	Coastal all
Narrow (<250 m)	Unar	Wnar	Vnar	Cnar
Medium (250–500 m)	Umed	Wmed	Vmed	Cmed
Wide (>500 m)	Uwide	Wwide	Vwide	Cwide

Sensitivity tests are carried out with both the input variables, the floodplain width (narrow, medium, wide) in both fluvial and coastal cases and the floodplain shape (U, W, V) in the fluvial case.

The DTM is used to obtain the ground level in each impact zone and to obtain the landward ground level of the defence. For NaFRA to date, NextMap SAR data has been used. This dataset has a reported vertical accuracy of ±50 cm in the south of England and ±100 cm elsewhere in England and in Wales (Bluesky 2005). An alternative source for ground levels is LiDAR data, which has a reported vertical accuracy of ±25 cm.

(a) Floodplain shape
Floodplain shape is based in part on the valley slope. The accuracy of this information is a low priority as there are only three categories ($s < 1/5000$, $1/5000 \leq s \geq 1/1000$, $s > 1/1000$). To determine if a greater accuracy is required at the category boundaries, the following is tested:

- Shift each valley shape one category up: shallow to intermediate (U to W), and intermediate to steep (W to V).
- Shift each valley shape one category down: steep to intermediate (V to W) and intermediate to shallow (W to U).

(b) Floodplain width
Floodplain width is an input parameter used in two capacities:

- during data preparation to obtain a valley classification as in Table 3.1, expressed as narrow ($w < 250$ m) , medium (250 m $\geq w \leq$ 500 m), wide ($w >$ 500 m);
- during the actual modelling to determine the maximum lateral flood extent, based on the measured floodplain width during data preparation processes.

The sensitivity tests include:

(i) Substitute valley type 'wide' and 'narrow' with 'medium', leave floodplain width as per reference model.
(ii) Substitute valley type 'medium' with 'wide', leave floodplain width as per reference model.

(iii) Substitute valley type 'medium' with 'narrow', leave floodplain width as per reference model.
(iv) Leave valley type as per reference model, vary floodplain width by ±10% and ±20%.

(i) to (iii) aim to improve understanding of the influence of the data preparation process for calculating the floodplain width and (iv) is intended to assess the sensitivity of the model to the actual floodplain width.

(c) Ground levels
To reflect the reported accuracies of SAR and LiDAR-derived DTM data, the following tests are carried out for both the defence landward ground level and the impact zone ground level:

- vary ground level by ± 0.25 m;
- vary ground level by ± 0.5 m;
- vary ground level by ± 1.0 m.

Variation of the input ground level has effects on other model input parameters such as the estimated defence crest level, toe level and impact zone raw flood level curves and these have been recalculated. The crest level for the model is set to the actual crest level where this is available. Where the crest level is below ground level it is set to ground level. Toe levels are all set to the estimated toe level. Ground levels were varied by the same distance for each test.

3.4.3 Receptor terms

The HLMDamage routine as employed by NaFRA 2005 incorporates a post processing stage. This places a number of constraints on the calculation of damages and the following amendments had to be made to the reference model:

- The maximum scenario failure order is set to 2 and the parameter 'StoreDetailResults' is set to 'True' (value 1). This is needed to enable storage of detailed model results in order that the HLMDamage routine from NaFRA 2005 can be run without code modifications.

- After running the model, ***tblResults*** is updated such that where:
    - for Skegness: DefencesType = 1 it is set to 'F', where DefencesType = 2 it is set to 'C';
    - for Thamesmead: DefencesType are set to 'F' as it is an all-fluvial area.

Sensitivity tests are carried out with the following input variables:

(i) Using national average floor space as in NaFRA 2005 (which serves as the reference model).
(ii) Using floor space as identified in NPD 2005 (non-residential properties).
(iii) Vary NPD 2005 property floor space by ±5% and ±10%.
(iv) Damages are calculated where the flood depth ≥ 0.25 m.

Note: damages for residential properties are given per residential property and are not based on floor area in the Middlesex University depth-damage tables. Therefore, a variation of floor area is only applied to non-residential properties.

3.5 Perturbations to the model parameters

Within the RASP HLM+ model a number of model parameters are set that control the approach to the analysis. Perhaps the most important of these are:

- the maximum flood defence system size – for NaFRA 2002, 2004 and 2005 this has been set to 10;
- the maximum failure order (0) – for NaFRA 2002, 2004 and 2005 set to 2;
- the prescribed breach width parameters.

Flood defence system size

The flood defence system size is varied for all three sites. The default parameter within NaFRA 2005 is 10. This implies that the probability at any given impact zone is determined from a maximum of 10 defences, selected based on proximity to that impact zone. The sensitivity testing involves reducing this number to 5 and increasing it to 20, to ascertain any change in model performance or improvements in results. For example, if a system size of 5 provides the same results as a system size of 10, this may imply a reduction in required computational expenditure for NaFRA 2006.

Maximum defence failure order

The maximum defence failure order is varied for all three sites. The default for NaFRA 2005 was 2. The default for the evolved NaFRA 2006 code (Section 3.6) is 10. Thus, the reference case for the three pilots is based on a default value of 10. The sensitivity test involves setting this value at 2, 5 and prescribing a distribution where low return period events have a lower order, say 2, and high return period events have a higher order, say 10. An example of the intelligent distribution for the Thamesmead site is provided in Table 3.4.

Number of events required to establish the defence loading curve

The number of events required to define the rating is varied for all threes sites. For NaFRA 2005, the default number of events was 39. These events are derived from three curves based on the loading for the 100 and 1000 year event. The sensitivity perturbation involves reducing these numbers to 10 and 20 to ascertain whether there is any change in result. This reduction is distributed equally throughout the event range, for example, remove every second event for the reduction to 20 events. For the Thamesmead site, an additional test based on 60 events is also included as there are 65 events available from the Thames Estuary 2100 project. The intuitive result would be that for a greater number of events, the EADs asymptote to a given value.

Table 3.4: The selected distribution for the Thamesmead failure orders

RP number 1–20			RP number 21–30		
No.	**Return period**	**Order**	**No.**	**Return period**	**Order**
1	1	2	21	180	5
2	2	2	22	190	5
3	5	2	23	200	5
4	10	2	24	250	5
5	20	2	25	300	5
6	30	2	26	350	5
7	40	2	27	400	5
8	50	2	28	450	5
9	60	2	29	500	5
10	70	2	30	600	5
11	80	2	31	700	5
12	90	2	32	800	5
13	100	5	33	900	5
14	110	5	34	1000	10
15	120	5	35	1500	10
16	130	5	36	3000	10
17	140	5	37	4500	10
18	150	5	38	6000	10
19	160	5	39	8000	10
20	170	5	40	10,000	10

Note: In determining the EAD associated with each of the different failure order runs, the residual probability has been assumed to be associated with a flood depth of 0.3 m.

Breach width parameter for hard and soft defences

The breach width parameter is varied for all three sites. The defences are classified as 'hard' or 'soft' defences, where, for example, a concrete wall would be termed a hard defence and a natural embankment would be a soft defence. The breach width is linked to this classification, where soft defences breach more readily and have wider breach widths than hard defences. The default CB values for determining the widths for hard and soft defences are 0.1 and 0.2. The perturbation involves doubling and halving this parameter for each, which effectively doubles or halves the defence width, provided that the resulting width is not any larger than the actual defence. The final CB values are therefore 0.05 and 0.2 for hard defences and 0.1 and 0.4 for soft defences.

Number of scenarios

The number of scenarios for a given case is given by the system size 2^n (where n = 10 by default) multiplied by the number of events (default 39), giving a default number of scenarios of 39,936. For the sensitivity tests which provide a change in the system size, the number of scenarios is evaluated and provided on the result sheets in Appendices A to C.

Table 3.5 provides a summary of all the sensitivity tests.

Table 3.5: Summary of the sensitivity tests

Ref. No.	Sensitivity test	Term	Site(s)	Parameter perturbation
1	Variation of loading conditions, i.e. water levels	Source	Fluvial, estuary	2 upper and lower estimates. (i) based on the 1 and 10,000 year load at ±0.1 m and ± 0.3 m and (ii) based on 1 and 10,000 year load ± 0.2 m and ±0.6 m. For the Stour, the 10,000 year event is replaced by the 1000 year event.
2	Variation of defence crest levels	Pathway	All	± 50 cm, ± 20 cm, ± 10 cm
3	Standard of protection	Pathway	Fluvial, coastal	± 20 year and ± 50 year impact on results to be inferred from above test
4	Variation of toe levels	Pathway	Coastal	± 1 m, ± 2 m
5	Variation of defence condition grade (CG)	Pathway	All	± 1CG, ± 2CG (note: all 3+ condition grades set to 3)
6	Variation of inflow volume hydrograph	Pathway	Fluvial, estuary	2 x volume (i.e. 2 x base)
7	Variation of floodplain width	Pathway	All	Floodplain width: ±10%, ±20%
8	Variation of ground height	Pathway	Coastal	±0.25 m, ±0.5 m , ±1 m of both defence and impact zone ground level
9	Variation on damage calculation	Receptor	All	Compare using national average floor space values to actual floor space values (non-residential properties only)
10	Variation of defence system size	Model parameter	All	5, 10, 20
11	Variation in maximum defence failure order	Model parameter	All	2, 5 and a distribution based on return period
12	Variation in number of events required to establish the rating	Model parameter	All	10, 20, (60 for the Thames site only)
13	Variation of breach width parameter for hard and soft defences	Model parameter	All	Soft defence: half/double default width Hard defence: half/double default width
14	Variation of floodplain shape	Receptor	All	(i) Valley type: 'wide' and 'narrow' with 'medium', 'medium' with 'wide', 'medium' with 'narrow'; (ii) Valley type (a) shallow to intermediate (U to W), and intermediate to steep (W to V), (b) steep to intermediate (V to W) and intermediate to shallow (W to U).

3.6 Evolution of the NaFRA 2005/2006 code

During this project the NaFRA 2005 code has evolved under the NaFRA development project. The key changes which are relevant to the sensitivity testing are:

- it is now possible to run the model with the maximum defence failure order equal to the defence system size;
- the breach size equations have been improved.

For this project, it has been considered preferable to use the latest available code rather than preserve use of a single code. Although this increased the number of runs – demanding the need to rerun the reference case for each code change – this ensures the conclusions are relevant to NaFRA 2006. Two versions of the evolved code have been used:

- Version 1: Enabling order 10 to be considered.
- Version 2: Version 1 with an updated breach calculation.

The updated breach calculation has implications for certain tests, and these were therefore rerun with Version 2. Table 3.6 provides a summary of the tests, indicating for each site which version was used for the tests.

Table 3.6: Summary of code versions used

Ref. no.	Sensitivity test	Thamesmead	Skegness	Stour
1	Variation of loading conditions, i.e. water levels	Version 2		Version 2
2	Variation of defence crest levels	Version 1	Version 2	Version 2
3	Standard of protection	-	-	-
4	Variation of toe levels	-	-	
5	Variation of defence condition grade (CG)	Version 2	Version 2	Version 2
6	Variation of inflow volume hydrograph	Version 1	-	Version 2
7	Variation of floodplain width	Version 1	Version 1	-
8	Variation of ground height	Version 1	Version 1	-
9	Variation on damage calculation (failure order = 2)	Version 1	Version 1	-
10	Variation of defence system size	Version 1	Version 2	Version 2
11	Variation in maximum defence failure order	Version 1	Version 2	Version 2
12	Variation in number of events required to establish the rating	Version 1	Version 2	Version 2
13	Variation of breach width parameter for hard and soft defences	Version 2	Version 2	Version 2
14	Variation of floodplain shape	Version 1	Version 1	-

4 Results and discussion

4.1 Thamesmead estuary site

This section includes the results and discussion for the Thamesmead site on the River Thames. Figure 1A in Appendix A provides the information for the existing situation, including:

- The **spatial probability distribution**. These indicate a high probability of flooding upstream of the Thames Barrier and along the Derent River.
- The spatial distribution of the **expected annual damages** (EADs). The EAD values all fall within the lowest band, indicating an EAD in the range £0 to £10,000 for each impact zone.
- The defence **standard of protection** (SoP), which indicates that the River Thames has a 1000 year SoP, and its tributaries, the Derent and the Poll, have a 100 year SoP.
- The defence **condition grade** (CG), where a large proportion of the River Thames has defences of CG 1 and the Derent tributary defences are largely CG 3.
- The **defence class**, for example, high ground or other. A substantial portion of the defended area includes actual defences and the few high ground areas are located on the Poll and Derent River tributaries to the Thames. These tributaries have gates at the confluence with the Thames, which may be closed during flood events.
- An **Ordnance Survey** map of the site location.
- A table on the bottom left including the number and percentage of defences for a given CG. For the Thames, approximately 60% of the defences have CGs of 1, suggesting the defences are in reasonably good condition.

Note: for all the Thames sensitivity tests, the Thames Barrier is assumed not in operation (failed).

All figures for the Thamesmead site are provided in Appendix A.

4.1.1 Source terms

Test 1 – Fluvial loading
The fluvial loads for the River Thames were varied as described in Section 3.4.1. The result sheet for the two upper and lower test cases is provided in Appendix A, Figure 2A. These tests are labelled as follows:

- Reduction 1 (R1) which implies a reduction in the 1 and 10,000 year event of 0.1 m and 0.3 m respectively [Figure 2A(i)].
- Increase 1 (I1) which implies an increase in the 1 and 10,000 year event of 0.1 m and 0.3 m respectively [Figure 2A(ii)].
- Reduction 2 (R2) which implies a reduction in the 1 and 10,000 year event of 0.2 m and 0.6 m respectively [Figure 2A(iii)].
- Increase 2 (I2) which implies an increase in the 1 and 10,000 year event of 0.2 m and 0.6 m respectively [Figure 2A(iv)].

Figure 2A(i) shows that the results are Sensitive downstream of the barrier and there is Limited Sensitivity or zero change upstream of the barrier. The smaller change in sensitivity upstream of the barrier is explained by the high overtopping rates for the reference case, where the loading conditions already exceed the defences by some margin. Thus, reducing the loading in the first instance provides little change, but a further reduction (Figure 2A(iii)) shows a larger change.

Figure 2A(ii) shows that the probability output is Sensitive to a small increase in the loading and Figure 2A(iv) shows that for a large increase in the loading, the outputs are Very Sensitive downstream of the barrier. This large sensitivity is explained in that prior to this final increase in the water level the defences were not overtopped.

The percentage change in EAD is provided in the upper right hand corner of the Result Sheet for Thamesmead, Figure 2A. For the smaller reduction and increase, R1 and I1, the percentage change in EAD, Δ_{EAD}, is ~±20%, whereas, for the larger range (R2 and I2), Δ_{EAD}, is -30% and 55% respectively. The -30% is explained by the increase on sensitivity upstream of the barrier. The 55% is explained by the initiation of overtopping along the reach downstream of the barrier.

In general, the percentage change in probability is sensitive to the fluvial loading and the impact on the EAD is significant, highlighting the importance of the input loading conditions.

4.1.2 Pathway terms

Test 2 – Crest levels

The Thames crest levels were varied by ±0.1 m, ±0.2 m and ±0.5 m. The Result Sheet for Thamesmead is in Appendix A, Figure 3A. The spatial probabilities illustrate that a reduction in crest level increases the probability and an increase in crest level reduces the probability, as expected. For a small reduction of ±0.1 m, the output falls into the Sensitive range, i.e. ± 20 to 100%. Here, the distribution shows a larger percentage change along the River Thames compared with zero change along the tributaries. The reason for this may be that the tributaries are characterised by high ground, and the crest levels cannot fall below this ground level. Where the crest levels are lowered further, for example, -0.2 m and -0.5 m, the area upstream of the Thames Barrier shows a larger sensitivity to this change. The reason for this is that the defences and/or ground levels are lower, as the SoP is designed based on the Thames Barrier being operational. Where the crest levels are raised by +2 m and +0.5 m, the change in probability is less, as once the crest level is sufficiently high there is not change in the degree of overtopping.

The percentage change in EAD is provided in the upper right hand corner of the Result Sheet for Thamesmead in Figure 3A. A change in level of ±0.1 m results in a percentage change in EAD, Δ_{EAD}, of ~±20%. This is large, despite this perturbation range being associated with the uncertainty of a more detailed survey measurement. As the perturbation increases, the Δ_{EAD} increases, with a Δ_{EAD} of ~200% and -50% for ±0.5 m. This large change in EAD highlights the importance of crest level measurement in the data collection process. For the Thames site, the crest level information is not based on the SoP. For sites where the crest level is derived from the SoP, this large sensitivity highlights the importance of determining the SoP.

Test 5 – Condition grade

The condition grades for the Thames were varied by ± 1 CG and ±2 CGs. The Result Sheet for Thamesmead is in Appendix A, Figure 4A. Figure 4A(i) provides the percentage change in probability for a deterioration in CG of 1. Here, the results are zero for a large area and there are two bands immediately downstream of the barrier that indicate Sensitive and Very Sensitive regions. The reason for this banding is most likely related to the CG distribution (Figure 1A, Appendix A). Immediately downstream of the barrier, there are intermittent defences with CG 3, whereas for the vast majority of the defences, the CG is 1.

In Figure 4A(iii), where the condition grades are perturbed by -2CGs, the whole aforementioned banded region becomes Extremely Sensitive. The reason for this is that many more defences now have a CG of 3, and the dependence on the CG is non-linear and so related to the defence type, hence a substantially larger change in moving from CG 2 to 3 than the move from CG 1 to 2. In addition, further downstream there are defences with actual CG of 2, which have been increased to 4, providing a Very Sensitive change in output.

In Figure 4A(ii) and (iv), the improvements in CG show virtually no change in percentage probability. This is explained by the large percentage (~60%) of defences with CG 1, i.e. no improvement is possible.

The percentage change in EAD is negligible for all cases as expected in this case.

Test 6 – Hydrograph shape

The hydrograph shape has been altered to effectively double the overtopping volume. The sensitivity test results are provided in Figure 5A, Appendix A. Figure 5A(i) shows that the overall probability increases, as is intuitive, for a greater overtopping volume.

The EAD increases by 20%, highlighting the sensitivity to inflow volume. This increase may be related to the increased inundation extents.

Test 7 – Floodplain width

The tests with the actual floodplain width (±10% and ±20%) show that this parameter is sensitive in certain locations, but the results show no change for the majority of the test area. The floodplain widths for the defences in this test area are generally large (mean of 778 m). See Figure 6A in Appendix A.

Reducing or increasing the floodplain width by 10% has more of an effect on the average probability than reducing or increasing the floodplain width by 20%. The large Very Sensitive area mainly consists of changes from zero flood probability to a small flood probability (0.0001% or smaller) and is protected by defences with a large associated floodplain width.

Variation of the floodplain width has a spatially widespread impact on the reported flood probabilities (Figure 6A in Appendix A).

Table 4.1: Impact of floodplain width (FPW) on probabilities for Thamesmead

Test 7	Mean probability (%)[1]
Base case	1.3283 (2.3256)
FPW +20%	1.3390 (2.3295)
FPW +10%	1.3212 (2.2290)
FPW -10%	1.3565 (2.3748)
FPW -20%	1.3295 (2.3277)

Test 14 – Floodplain shape
The floodplain shape ((a) U to W, W to V and (b) V to W, W to U) is a limited sensitive parameter. The Thamesmead results show that for the whole area the influence of this parameter is medium, both resulting in relative increases and reductions in the flood probability. See Figure 7A in Appendix A for maps with the results.

Used as an indicator for the floodplain shape, the floodplain width ((i) wide and narrow to medium, (ii) medium to wide, and (iii) medium to narrow) is not a sensitive parameter. Changes in this parameter result in limited changes in the flood probabilities in this study area (Table 4.2).

Table 4.2: Mean probabilities for floodplain shape test for Thamesmead

Test 14	Mean probability (%)	Comment
Base case[2]	2.3256	
To medium	2.3258	322 defences amended to medium, 82 remained medium
Medium to wide	2.3253	82 defences amended from medium to wide
Medium to narrow	2.3254	82 defences amended from medium to narrow
U to W, W to V	2.3067	202 defences from U to W, 93 from W to V
V to W, W to U	2.3167	109 defences from V to W, 93 from W to U

4.1.3 Receptor terms

Test 9 – Depth-damage
Variation of floor space by 5% or 10% results in a variation of damages within 5% and 10%. This confirms the expected variation though there are some anomalies:

- For a number of properties the calculated damages from the HLMDamage tool using the actual floor area values do not fit within the expected range when compared against ±5% and ±10% variance models. The ± variance models behave normally and produce values that have the prescribed variance relative to all other results. This error seems to be restricted to the actual floor area model run only, which is anomalous as the variance models are based upon the actual floor area model. For the Thamesmead output, there were 892 non-residential properties (NRPs) that generated results using the model for the best-fit scenario. Of those

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[1] Note: the mean probability is not the same as test 14, due to excluding zero probabilities in the base model from test 14 but not from Test 7. The figures for test 7 excluding where the base probability is zero are given in parentheses.

[2] Note: the Mean probability is not the same as test 7, due to excluding zero probabilities in the base model from the above, but not from Test 7.

892 properties, 231 (26%) had the generated error while 662 (74%) showed no error.

- On examining this error no obvious pattern or relationship can be found to indicate the possible cause. There is no visible tendency for a particular property classification to produce the error as all the affected categories have both erroneous and non-erroneous outputs. Similarly, there is no spatial relationship for the error occurring as the distribution is shown to be random and share impact zones and co-ordinate locations with non-erroneous results. This also suggests that the look-up data tables used for the calculations are correct.

- The error is introduced through amendments in the RASP HLM model parameters. The Thamesmead site was prepared as a 'main–tributary' system, as opposed to the standard 'fluvial–coastal' system. This results in an inconsistent attribution of the source of flooding in impact zones. The damage calculations expect freshwater or saline and this is normally flagged with the defence system (F or C). As the Thamesmead test area is only fluvial, there are potentially two sources of freshwater flooding in the way this model is set up (main or tributary). The damage calculation routine from NaFRA 2005, which has not been adapted to cater for this new model parameter, then produces inconsistent results in these areas.

Substituting the national floor space for each NRP type with an estimated floor space based on OS MasterMap Building Layer varies the damages up or down, depending on the difference between the national and property-specific floor space.

The following reduction in £EAD occurs for each £EAD band (Lower, Best and Upper values from depth-damage tables) combined with respective flood probability values from Lower Bound, Best Estimate and Upper Bound (Table 4.3).

Table 4.3: Percentage change in EAD for depth-damage test for Thamesmead

Band	% change in £EAD
Lower	-30.93
Best	-47.71
Upper	-56.99

The overall change in floor area for NRP between using national floor area and property-specific floor area is a reduction of 64% in this site. When assuming a flood probability of 0.013 (1:75) and a flood depth of 0.25 m in all impact zones and the fluvial best estimate for 0.25 m from the depth-damage tables, this reduction in floor space results in a 72% reduction in the £EAD from £136 million to £39 million for the Thamesmead site.

4.1.4 Model parameters

Test 10 – Flood defence system size

The flood defence system size was varied from the default 10 to 5 and to 20. For the latter case, the array sizes were too large and the model was unable to run, i.e. the system had reached the upper extent of the computational limit. This is not unexpected since it involves an increase in scenario size from the reference Thames case of:

scenario size (reference case) = 2^{10} x 65 events = 66,560

to:

scenario size (for system size 20) = 2^{20} x 65 events = 68,157,440!

The result sheet for the change in system size from the default 10 to 5 is provided in Figure 8A in Appendix A. The area upstream of the barrier shows virtually no change in probability and the area downstream of the barrier is Sensitive.

The percentage change in EAD is only 8% for a significant reduction in scenario size from 39,936 to 1248 reflecting the stark difference in risk upstream and downstream of the barrier; upstream of the barrier the defences are overwhelmed and a reduction in system size has little influence on EAD; downstream the probability of defence failure is small and hence a modification to the system size has little influence.

Test 11 – Maximum defence failure order

The maximum defence failure order was varied from the default 10 to 2, 5 and a selected distribution that varies with the severity of the loading event (Table 4). In these tests the residual probability (i.e. the sum of the probabilities associated with scenarios not explicitly considered, this equals 0 when the maximum defence failure order is equal to the number of defences in the system) is assumed to give rise to a flood depth of 0.3 m and economic damage calculated accordingly.

The results are shown in Figure 9A in Appendix A. Figures 9A(i)–(iii) all indicate that a reduction in the order from 10 results in a Sensitive change upstream of the barrier and negligible changes downstream of the barrier. The reason for this is that the defences are in good condition and have a high SoP in the downstream region, and hence 5, 2 or even 1 breach is unlikely. In contrast, upstream of the barrier, the SoP is related to the barrier being in operation. As this is not the case, the defences are overtopped, and a change in the order will result in a different number of breaches occurring.

The percentage change in EAD for a defence failure order of 2 is large, >250%. This is reduced to 36% for a failure order of 5, which is not unexpected, since the area is characterised by strong defences and thus the likelihood of 5 or 10 breaches is low. For the selected distribution, the EAD is >250%. This is driven by the Order 2 which has been prescribed to the small events, which have a significant impact in the area upstream of the barrier.

Test 12 – Number of events to establish the rating

The number of events used to define the rating for the River Thames reference case is 40. This is varied to include 5, 10, 20 and 60 events. The resulting plots are shown in Figure 10A in Appendix A. The percentage change in probability shows an intuitive trend, in that the probability is Very Sensitive to a reduction to Order 5 (Figure 10A(i)), Sensitive to Very Sensitive to Order 10 (Figure 10A(ii)), Order 20 (Figure 10A(iii)) has Limited Sensitivity and Order 60 (Figure 10A(iv)) has Limited Sensitivity of the opposite sign. In general, the greatest sensitivity is downstream of the barrier.

The percentage change in EAD shows a large percentage difference for Order 10 (48%), whereas for Order 60 there is small percentage change (-0.04%). This suggests that the default value of 40 may be an adequate resolution to represent the curve, while reduction in this number is likely to significantly reduce the accuracy of the result.

Test 13 – Breach width parameter

The breach parameter for the hard and soft defences was doubled and halved, which has the effect of widening or narrowing the size of the breach within a given defence under a given load. The results for the sensitivity tests are available in Figure 11A, Appendix A. Figure 11A(i) shows that the reduction in breach width has negligible sensitivity upstream of the barrier, which, assuming the barrier has failed, can be explained by the high overtopping rates in this region regardless of the breach size. Downstream of the barrier, there is some increase in the probability when the breach width is doubled. This is because, although the probability of occurrence remains low, the 'zone of influence' of a breach increases reflecting the increased discharge into the floodplain. As the overall probability of the region is low, however, the change in breach width still has limited impact, i.e. moving from zero to some probability.

Figure 11A(ii) shows the results for the increase in breach width. These results are similar to those for the decrease in breach width, other than the change in sign.

For both cases the change in percentage EAD is low. The reason for this is that, although the change in probability relative to zero probability is large, the actual probability values are still close to zero. Thus, approximately zero probability results in a very small EAD, which is similar to the reference case.

4.2 Skegness coastal site

This section includes the results and discussion for the Skegness coastal site. Figure 1B in Appendix B provides the information for the existing situation, including:

- The **spatial probability distribution**. This indicates a low probability of flooding for the whole region other than immediately adjacent to the Steeping River tributary, where moderate probabilities are present.
- The spatial distribution of the **expected annual damages** (EADs). The EAD values largely fall within the lowest band (i.e. < £200) other than Skegness town, where the values in some impact zones are as high as £2000.
- The defence **standard of protection** (SoP), which indicates that the north and south coastline reaches have a SoP of 200 and 100 years respectively and the Steeping River and its upstream tributary have lower SoPs of 50 and 75 years respectively. In addition, there is a small reach at the confluence of the tributary and the Steeping River where the SoP is only 2.
- The defence **condition grade** (CG), where a large proportion area is surrounded by CG 2 and there are a few small stretches of CG 3, which most likely correspond to areas where there is no or uncertain information. Note that the aforementioned tributary confluence area, which has a SoP of 2, is also characterised by a CG of 3.
- The **defence class**, for example high ground or other. The defended area is protected by 'other' defences, except for the tributary to the Steeping River, which affords protection via high ground.
- A table on the bottom left including the number and percentage of defences for a given CG. 80% of the defences are CG 2 and 20% are CG 3.

Note that the Skegness toe level data contains erroneous information, suggesting that for a substantial portion of the coastline the toe levels are well above their actual level. The result is that the toe levels are, in most instances, higher than the coastal loading levels and breaching and/or overtopping is not possible. The impact of this on these results is that the probabilities for the entire coastal area are zero and for most of the sensitivity tests the percentage change in probability is zero. Thus, a key recommendation from this work is that the coastal sensitivity tests are rerun for a coastal site with measured toe level information.

The zero probability and zero percentage change in probability were initially attributed to the area being well defended and thus being insensitive to changes in input and model parameters. To this end, the condition grades for all the defences were altered by 2 CGs to reduce the perceived effectiveness of the defences and to simulate a system with some sensitivity in probability. This change was implemented for all the

Halcrow-led sensitivity testing, i.e. the DTM ground model tests and the receptor tests, as these were undertaken prior to the toe level data diagnosis.

All figures for the Skegness site are provided in Appendix B.

4.2.1 Pathway terms

Test 2 – Crest levels
The Skegness crest levels were varied by ±0.1 m, ±0.2 m and ±0.5 m. The result sheet for the Skegness crest level test is in Appendix B, Figure 2B. The spatial probabilities illustrate that a reduction in crest level increases the probability and an increase in crest level reduces the probability, as expected. These changes occur in the area adjacent to the Steeping River as well as a small coastal area that is only influenced by a reduction in the crest level. For a small increase in crest level (i.e. +0.1 m), the output falls into the Sensitive range (i.e. ± 20 to 100%), whereas for a corresponding decrease in crest level (i.e. -0.1 m), the percentage change is larger (up to 500% in some areas).

The percentage change in EAD is provided in the upper right hand corner of Figure 2B. The percentage change in EAD is negligible for all cases. The reason for this is that the area adjacent to the Steeping River, where the changes in probability occur, is not populated with property. The Skegness town is located alongside the coast in the north-east of the area and in this area the poor toe level data results in zero probabilities.

Test 4 – Toe levels
The Skegness toe levels were varied by ±1 m and ±2 m. The result sheet for the Skegness toe level test is in Appendix B, Figure 3B. For all four tests there was no percentage change in probability and similarly the percentage change in EAD was zero for each case. These results may be attributed to the poor toe level information.

Test 5 – Condition grade
The condition grades for the Skegness defences were varied by ± 1 CG and ±2 CGs. The result sheet for the Skegness site is in Appendix B, Figure 4B. Figures 4B(i) and (iii) provide the percentage change in probability for an increase (i.e. deterioration) in CG of 1 and 2, which give Sensitive and Extremely Sensitive results respectively in the area adjacent to the Steeping River. This is not unexpected since 80% of the defences are CG 2, and a deterioration of 2 CGs would therefore give a CG of 4. In contrast, an improvement in the CG results in most of the area being assigned a CG of 1, and being well protected (Figures 4B(ii) and (iv)).

The percentage change in EAD is negligible for all cases. This is most likely explained by the Skegness town being outside the region where any change in probability takes place.

Test 7 – Floodplain width
The tests with the actual floodplain width (±10% and ±20%) show that this parameter is sensitive in certain locations, but the results show no change for the majority of the test area. The floodplain widths for the defences in this test area are overall large (mean of 3272 m). Figure 5B in Appendix B shows the results.

Reducing or increasing the floodplain width by 10% has less of an effect than reducing or increasing it by 20%. An increase in the floodplain width results generally in a reduction of the flood probabilities and vice versa (Table 4.4).

Variation of the floodplain width has a localised impact on the reported flood probabilities where the floodplain widths are large (>500 m).

Table 4.4: Mean probabilities for floodplain width test for Skegness

	Mean probability (%)
Base case	0.1248
FPW +20%	0.1239
FPW +10%	0.1236
FPW -10%	0.1257
FPW -20%	0.1273

Test 8 – Ground level
Ground levels have been reduced for both defences and impact zones. Figure 6B in Appendix B shows these results.

Increasing the ground level results in zero probabilities for all impact zones, with two exceptions (see Table 4.5). This is caused by the impact zone flood depths being very low or zero when increasing the ground level and by the decrease in the defence loading. Flood depths and defence loads are derived from the fluvial JFLOW (2003) and coastal TIM (2003) flood levels and not amended (Table 4.5).

Table 4.5: Mean probabilities for ground level test for Skegness

Test 8	Mean probability (%)	Comment
Base case	0.0955	1200 impact zones with a probability
+ 1.00 m	0	All 0 probabilities
+ 0.50 m	0.0001	Only one impact zone with >0 probability
+ 0.25 m	0.0004	Only two impact zones with >0 probability
- 0.25 m	3.2228	3016 impact zones with probability
- 0.50 m	3.2312	3016 impact zones with probability
- 1.00 m	3.2377	3016 impact zones with probability

Reducing the ground level, even by a mere 0.25 m, doubles the number of impact zones with some flood probability (Table 4.5). However, as the flood depths will increase, the impact zone-based EAD increases in value (Table 4.6).

Table 4.6: Percentage difference in EAD for ground level test for Skegness

Test 8	EAD (£)	% difference from base
Base	254,344	
+0.25 m and above	253,443	-0.35
-0.25 m	262,284	+3.12
-0.50 m	265,093	+4.23
-1.00 m	267,824	+5.29

Test 14 – Floodplain shape
The floodplain shape ((a) U to W, W to V and (b) V to W, W to U) is a fairly sensitive parameter. The Skegness results show that there are a few areas where the influence of this parameter is significant, both resulting in relative increases and reductions in the flood probability. There is one area furthest away from defences where the influence is very strong and results in a large relative increase in the flood probabilities. See Figure 11B in Appendix B for maps with the results.

Used as an indicator for the floodplain shape, the floodplain width ((i) wide and narrow to medium, (ii) medium to wide, and (iii) medium to narrow) is not a sensitive parameter. Changes in this parameter result in no change in the flood probabilities in this study area (Table 4.7). It should be noted that in this area just four coastal defences are marked as medium and thus there is a limited influence on changing this parameter in this test area of tests (ii) and (iii).

Table 4.7: Mean probabilities for floodplain shape test for Skegness

Test 14	Mean probability (%)	Comment
Base case	0.1248	
To medium	0.1248	4 coastal defences not changed, all other defences have
Medium to wide	0.1248	4 coastal defences changed, no other defences changed
Medium to narrow	0.1248	4 coastal defences changed, no other defences changed
U to W, W to V	0.1352	Coastal defences not amended.
V to W, W to U	0.1386	Coastal defences not amended

4.2.2 Receptor terms

Test 9 – Depth-damage
Variation of floor space by 5% or 10% results in a variation of damages with 5% and 10%. This confirms that there is a linear relation between floor area and the expected variation of damages.

Substituting the national floor space for each non-residential property (NRP) type with an estimated floor space based on OS MasterMap Building Layer varies the damages up or down, depending on the difference between the national and property-specific floor space.

Table 4.8 shows the change in £EAD for the following bounds combinations: Lower, Best and Upper values from depth-damage tables combined with respective Lower bound, Best Estimate and Upper bound flood probabilities.

Table 4.8: Percentage change in EAD for depth-damage test for Skegness

Band	%change in £EAD
Lower	-0.17
Best Estimate	-17.97
Upper	-34.56

The reference model results are such that only 9 (Lower band) to 11 (Upper band and Best Estimate) individual NRP properties are considered at risk (flood probability at zero-depth >0 and flood depth ≥ 0.25 m) and thus the reduction in £EAD in Table 4.8 is not representative for the whole property dataset. This is due to the low probabilities and few occasions where the flood depth is ≥ 0.25 m

Excluded from the following analysis are 49 of 1207 NRP properties as these do not have an individual floor space in the NPD 2005. The NPD 2005 report can be referenced to obtain the reasons in detail, but broadly no floor space could be derived from OS MasterMap Boundary layer where there is no permanent building for the OS MasterMap Address (e.g. docks, caravan sites, industrial parks). In cases where no property-specific floor space is available, the national average floor space is used.

The overall change in floor area for NRP between using national floor area and property-specific floor area is a reduction of 69% in this site. When assuming a flood probability of 0.013 (1:75) and a flood depth of 0.25 m in all impact zones and the fluvial best estimate for 0.25 m from the depth-damage tables, this reduction in floor space results in a 49% reduction in the £EAD from £114 million to £58 million for the Skegness site.

4.2.3 Model parameters

Test 10 – Flood defence system size
The flood defence system size was varied from the default 10 to 5. This translates to a reduction in system size from the default:

scenario size (reference case) = 2^{10} x 40 events = 39,936

to:

scenario size (for system size 20) = 2^{5} x 40 events = 1248

The result sheet for the change in system size from the default 10 to 5 is provided in Figure 7B in Appendix B. The percentage change in probability is Sensitive for the area adjacent to the Steeping River, giving an overall reduction in probability.

The percentage change in EAD is zero and is attributed to the location of Skegness town being outside the area of influence.

Test 11 – Maximum defence failure order
The maximum defence failure order was varied from the default 10 to 2, 5 and a selected distribution that varies with the severity of the loading event. In these tests the residual probability (i.e. the sum of the probabilities associated with scenarios not explicitly considered, this equals 0 when the maximum defence failure order is equal to

the number of defences in the system) is assumed to give rise to a flood depth of 0.3 m and economic damage calculated accordingly.

The results are shown in Figure 8B in Appendix B. Figures 8B(i)–(iii) all show no sensitivity to defence failure order for the whole region. The reason for this is that 80% of the defences are CG 2 and offer a SoP of 50 or higher, and hence 5 or even 2 breaches are unlikely.

The corresponding percentage change in EAD is zero for all three cases.

Test 12 – Number of events to establish the rating

The number of events used to define the rating for the Skegness reference case is 40. This is reduced to include ratings with only 10 and 20 events. The resulting plots are shown in Figure 9B in Appendix B. The percentage change in probability shows that in both instances, the probability is reduced, and the whole area adjacent to the Steeping River is Sensitive. The reason for this is related to the combined shape effects of all the defence fragility curves as well as the depth-damage curve. These inform the relationship between the EAD and return period, and the bias of the sensitivity (i.e. reduction/increase in probability) is dependent on whether the relevant portion of the EAD–return period curve is concave or convex.

The percentage change in EAD for both cases is zero. This may be attributed to the Skegness town being located outside the region of influence.

Test 13 – Breach width parameter

The breach parameter for the hard and soft defences was doubled and halved, which has the effect of widening or narrowing the size of the breach within a given defence under a given load. The results for the sensitivity tests are shown in Figure 10B, Appendix B. Figure 10B(i) shows a Sensitive reduction in probability of 20–100% alongside the river, which is as expected. The area adjacent to the Steeping River tributary is Insensitive, and this may be explained by the nature of the defences, which are high ground.

Figure 10B(ii) shows the results for the increase in breach width. These results are Sensitive with increasing sensitivity away from the Steeping River, and the inland area shows Extremely Sensitive results. The reason for this is that the probability of occurrence remains low, the 'zone of influence' of a breach increases reflecting the increased discharge into the floodplain.

For both cases the change in percentage EAD is zero. This is, as before, attributed to the Skegness town being located outside the region of influence.

4.3 Stour fluvial site

This section includes the results and discussion for the Stour fluvial site. Figure 1C in Appendix C provides the information for the existing situation, including:

- The **spatial probability distribution**. This indicates a general low probability of flooding over the region with two distinct areas of significant risk, most likely related to the urban location coupled with the SoP.
- The spatial distribution of the **expected annual damages** (EADs). Here, the EAD values largely fall within the lowest band (i.e. < £200) other than two small areas where the EAD values are in the range £1000–2000.

- The defence **standard of protection** (SoP), which indicates a 150 year protection other than two inland areas with a lower SoP of 30 years.
- The defence **condition grade** (CG), where a large proportion (~70%) of the area has defences with a CG of 3 and the balance is CG 2. One small inland reach has CG 1.
- The **defence class**, for example, high ground or other. The coastal area and a few inland reaches are protected by raised or 'other' defences, while the bulk of the area is defended by high ground.
- A defence table on the bottom left includes the number and percentage of defences for a given CG. 70% of the defences are CG 3 and 30% are CG 2.

All figures for the Stour site are provided in Appendix C.

4.3.1 Source terms

Test 1 – Fluvial loading
The fluvial loads for the Stour site were varied as described in Section 3.1.1. The result sheet for the two upper and lower test cases is provided in Appendix C, Figure 2C. These tests are labelled as follows:

- Reduction 1 (R1), which implies a reduction in the 1 and 1000 year event of 0.1 m and 0.3 m respectively [Figure 2C(i)].
- Increase 1 (I1), which implies an increase in the 1 and 1000 year event of 0.1 m and 0.3 m respectively [Figure 2C(ii)].
- Reduction 2 (R2), which implies a reduction in the 1 and 1000 year event of 0.2 m and 0.6 m respectively [Figure 2C(iii)].
- Increase 2 (I2), which implies an increase in the 1 and 1000 year event of 0.2 m and 0.6 m respectively [Figure 2C(iv)].

Figures 2C(i) and (iii) show that the results are Sensitive for the whole area other than immediately adjacent to the coast and conversely Figures 2C(ii) and (iv) show Extreme Sensitivity for a similar coverage. The sign of the change is intuitive, i.e. increased loading effects increased probability, and the region is Sensitive as it is characterised by high ground with a CG of 3 rather than raised defences. The coastal strip is unaltered by the changes in fluvial load.

The percentage change in EAD is provided in the upper right hand corner of the result sheet in Figure 2C. For the smaller reduction and increase, R1 and I1, the percentage change in EAD, Δ_{EAD}, is -52% and +148% respectively, whereas for the larger range (R2 and I2) Δ_{EAD}, is -66% and +319% respectively. The smaller reductions are attributed to the area having a low default or base probability, and thus a reduction in loading does not result in a substantial reduction in the protection afforded. Conversely, an increase in loading may result in the initiation of overtopping. The percentage change in EAD does not appear to be linked to the location of built-up areas.

In general, the percentage change in probability is sensitive to the fluvial loading and the impact on the EAD is significant, advocating the importance of the input loading conditions. This is a similar finding to the Thamesmead site.

4.3.2 Pathway terms

Test 2 – Crest levels
The Stour crest levels were varied by ±0.1 m, ±0.2 m and ±0.5 m. The result sheet for the Stour site is in Appendix C, Figure 3C. The spatial probabilities illustrate that a reduction in crest level increases the probability and an increase in crest level reduces the probability, as expected. For all cases, regardless of the magnitude of the change,

the results are Sensitive and Extremely Sensitive for the whole area other than immediately adjacent to the coast. The reason for this is most likely related to the defence type, where the inland area is characterised by high ground whereas the coastal area has 'other' defences.

The percentage change in EAD is provided in the upper right hand corner of the result sheet in Figure 3C. A reduction in crest level has a substantial impact on the EAD, giving Δ_{EAD} values of 141%, 339% and 959%. The increase in crest level has a less significant impact, with an approximately 60% Δ_{EAD} value. These large changes in EAD highlight the importance of crest level data, which is inferred from the SoP for the Stour site.

Test 3 – Standard of protection

The SoP was varied by ±20, ±50 and ±100 years for 1035 defences in the Stour site. Table 4.9 provides a summary of the corresponding change in crest levels and the inferred significance of this for the EAD. For all SoP perturbations, including a 100 year change, the crest level changes by less than ±10 cm. This is similar to the uncertainty range associated with the most accurate measurement technique for crest levels, e.g. local survey. The crest level test results (Test 2 above) show a high sensitivity in probability and EAD, even for the small perturbation of ±10 cm. This information is used to infer the significance in the final column of Table 4.9, and hence the -9 cm change is considered high.

Table 4.9: Change in crest level due to a change in SoP

Change in SoP (years)	Change in crest level (m)	Significance for EAD
-100	-0.09	High
-50	-0.03	Low
-20	-0.01	Low
+20	+0.01	Low
+50	+0.02	Low
+100	+0.03	Medium

Test 5 – Condition grade

The condition grades for the Stour site were varied by ± 1CG and ±2 CGs. The result sheet is in Appendix C, Figure 4C. Figures 4C(i) and (iii) provide the percentage change in probability for deterioration in CG of 1 and 2 respectively. For a large part of the region there is no change. There are distinct areas where the change is notable. The reason for the larger increase in probability may be attributed to the change in the value of the CG having a more significant impact when it moves from 2 to 4 (in this region) than from 3 to 5 for the remainder of the region. These areas also coincide with 'other' defence types rather than the high ground, for which the change in CG has more influence on possible failure mechanisms, e.g. breaching.

Figures 4C(ii) and (iv) show a similar pattern to those described above, but with the opposite effect.

The percentage change in EAD is negligible for all cases. This may be attributed to any changes taking place in areas which are not built-up.

Test 6 – Hydrograph shape
The hydrograph shape has been altered to effectively double the overtopping volume. The sensitivity test results are provided in Figure 5C, Appendix C. Figure 5C(i) shows that the overall probability increases, as is intuitive, for a greater overtopping volume.

The EAD increases by 13%, highlighting the sensitivity to inflow volume. This increase may be related to the increased inundation extents.

Test 7 – Floodplain width
The tests with the actual floodplain width (±10% and ±20%) show that this parameter is sensitive in certain locations, but the results show no change for the majority of the test area. The floodplain widths for the defences in this test area are overall relatively small compared with the other sites (mean of 460 m). See Figure 6C in Appendix C.

Reducing/increasing the floodplain width by 10% has less of an effect than reducing/increasing it by 20%. An increase in the floodplain width generally results in a reduction of the flood probabilities and vice versa (Table 4.10).

Variation of the floodplain width has a localised impact on the reported flood probabilities where the floodplain widths are large (>500 m).

Table 4.10: Impact of floodplain width on probabilities for the Stour site

Test 7	Mean probability (%)
Base case	0.2767
FPW +20%	0.2789
FPW +10%	0.2780
FPW -10%	0.2767
FPW -20%	0.2770

Test 14 – Floodplain shape
The floodplain shape ((a) U to W, W to V) is a fairly sensitive parameter. The Stour results show that for the whole area the influence of this parameter is significant when shifting this parameter up (U to W and W to V), both resulting in relative increases, but largely in reductions in the flood probability. The sensitivity of shifting this parameter down (case (b) V to W, W to U) is limited and not as widespread as test (a). See Figure 7C in Appendix C.

Used as an indicator for the floodplain shape, the floodplain width ((i) wide and narrow to medium, (ii) medium to wide, and (iii) medium to narrow) is not a sensitive parameter. Changes in this parameter result in very limited changes in the flood probabilities (Table 4.11).

Table 4.11: Impact of floodplain width on probabilities for the Stour site

Test 14	Mean probability (%)	Comment
Base case	0.2767	
To medium	0.2767	2072 defences amended to medium, 460 remained medium
Medium to wide	0.2766	460 defences amended from medium to wide
Medium to narrow	0.2767	460 defences amended from medium to narrow
U to W, W to V	0.2645	1611 defences from U to W, 459 from W to V, 12 coastal defences unchanged
V to W, W to U	0.2790	450 defences from V to W, 459 from W to U, 12 coastal defences unchanged

4.3.3 Receptor terms

Test 9 – Depth-damage
Variation of floor space by 5% or 10% results in a variation of damages with 5% and 10%. This confirms that there is a linear relation between floor area and the expected variation of damages.

Substituting the national floor space for each non-residential property (NRP) type with an estimated floor space based on the OS MasterMap Building Layer varies the damages up or down, depending on the difference between the national and property-specific floor space.

Table 4.12 shows the change in £EAD for the following bounds combinations: Lower, Best and Upper values from depth-damage tables combined with respective Lower bound, Best Estimate and Upper bound flood probabilities.

Table 4.12: Percentage change in EAD for depth-damage test for the Stour site

Band	% change in £EAD
Lower	-5.98
Best Estimate	-18.25
Upper	-24.19

The reference model results show that only 152 (Lower band) to 257 (Upper band and Best Estimate) individual NRP properties are considered at risk (flood probability at zero-depth >0 and flood depth ≥ 0.25 m) and thus the reduction in £EAD in Table 4.12 is not entirely representative for the whole property dataset of 1170 NRP properties. This is due to the low probabilities and few occasions where the flood depth is ≥ 0.25 m.

This analysis excludes 68 of the 1170 NRP properties as these do not have an individual floor space in the NPD 2005. The reasons are detailed in the NPD 2005 report but, in brief, no floor space could be derived from the OS MasterMap Boundary layer where there is no permanent building for the OS MasterMap Address (e.g. docks, caravan sites, industrial parks). In cases where no property-specific floor space is available, the national average floor space is used.

The overall change in floor area for NRP from using national floor area and property-specific floor area is a reduction of 78%. When assuming a flood probability of 0.013 (1:75) and a flood depth of 0.25 m in all impact zones and the fluvial best estimate for 0.25 m from the depth-damage tables, this reduction in floor space results in a 70% reduction in the £EAD from £119 million to £37 million.

4.3.4 Model parameters

Test 10 – Flood defence system size
The flood defence system size was varied from the default 10 to 5. This translates to a reduction in system size from the default:

scenario size (reference case) = 2^{10} x 39 events = 39,936

to:

scenario size (for system size 20) = 2^5 x 39 events = 1248

The result sheet for the change in system size from the default 10 to 5 is provided in Figure 8C in Appendix C. The percentage change in probability is Sensitive in areas with 'other' defence types, giving an overall reduction in probability.

The percentage change in EAD is zero, which may be attributed to the area not being built-up.

Test 11 – Maximum defence failure order
The maximum defence failure order was varied from the default 10 to 2, 5 and a *selected distribution* that varies with the severity of the loading event. In these tests the residual probability (i.e. the sum of the probabilities associated with scenarios not explicitly considered, this equals 0 when the maximum defence failure order is equal to the number of defences in the system) is assumed to give rise to a flood depth of 0.3 m and economic damage calculated accordingly.

The results are shown in Figure 9C in Appendix C. Figures 9C(i)–(iii) all indicate that a reduction in the order from 10 results in no change or Limited Sensitivity in the on the northern edge of the coastal extent. The reason for this is that the area is characterised by high ground, where no breaching occurs, and the areas with 'other' defence types have a high SoP and a CG of 2 or 3, i.e. more than 2 breaches is unlikely.

The percentage change in EAD is zero for all cases. This reflects the small change in probability and that where the changes do occur, the areas are not built-up.

Test 12 – Number of events to establish the rating
The number of events used to define the rating for the Stour reference case is 39. This is reduced to include ratings with only 10 and 20 events. The resulting plots are shown in Figure 10C in Appendix C. The percentage change in probability shows that in both instances, the probability is reduced, and the whole area is Sensitive. The reason, as explained in Section 4.2.3, is related to the combined shape effects of all the defence fragility curves and the depth-damage curves, which inform the shape of the EAD versus return period curve.

The percentage change in EAD is significant (i.e. >2000%), highlighting the importance of the rating curve shape. The change from 10 to 20 to 39 does not appear to show convergence on the EAD value. Ideally, further testing with 30 and 50 events should be undertaken to determine whether 39 events suffice.

Test 13 – Breach width parameter
The breach parameter for the hard and soft defences was doubled and halved, which has the effect of widening or narrowing the size of the breach within a given defence under a given load. The results for the sensitivity tests are shown in Figure 11C,

Appendix C. Figure 11C(i) shows a reduction in probability that is relatively Insensitive in the areas with 'other' defence types, with a small area where the result is Sensitive. It should be noted that the reduction in breach width does not always cause a reduction in probability.

Figure 11C(ii) shows the results for the increase in breach width. These results have the opposite effect to a decrease in breach width, with similar coverage. The results are Insensitive or have Limited Sensitivity. As with the above case, there are areas where the increase in width causes a reduction in probability. This may be attributed to a given impact zone being influenced by more defences, as the 'area of influence' of the breach is larger reflecting the increased discharge.

For both cases the change in percentage EAD is zero. This is attributed to the changes taking place in areas that are not developed.

4.4 Probability banding

Probability banding has been observed in the NaFRA 2005 results, where there are a number of impact zones with a precise probability value (e.g. 0.361). To gain some insight into this, the number of impact zones versus prescribed probability bands is plotted for each site, Thamesmead (Figure 4.1), Skegness (Figure 4.2) and Stour (Figure 4.3).

The resulting histograms show a similar skewed pattern for all three sites, i.e. a large number of zero or small probabilities and few high probability values. The results do indicate the banded nature of the probabilities, for example, the Thamesmead site has a number of impact zones with probabilities 0.6325 and 0.3936. These values correspond to areas along the Thames tributaries, which have consistent defence types.

The Skegness site shows a smooth banded histogram shape, with a high percentage of the probability values (~80%) less than 0.001. This reflects the low base case probabilities (Figure 1B, Appendix B), which are largely a result of the poor toe level information.

The Stour site shows a smooth histogram, with one outlier on the far right. This corresponds to the most north-easterly coastal point of the Stour site (on the eastern coast stretch), which is influenced by a number of 'other' type defences with CG 3 and is located immediately behind the defence line.

The probability banding is not unexpected in that, for a given site, the defences along a reach have similar characteristics (e.g. SoP, CG, CL) and the defended area usually comprises a given land use (e.g. urban or rural). Thus, it is plausible that many impact zones may result in similar probability values and in most instances these are low values (0 to 0.001) as the sites chosen here are well defended. For areas that are less well defended, the shape of the histogram is likely to spread to the right. This trend is revealed for the three selected sites. For example, the Thamesmead site is the most well defended (SoP = 1000) and approximately 90% of the probabilities are in the range 0 to 0.0001 band, whereas at Skegness, which is less well defended (SoP = 50, 100, 200), approximately 80% of the probabilities are in the range 0 to 0.001, an order of magnitude larger.

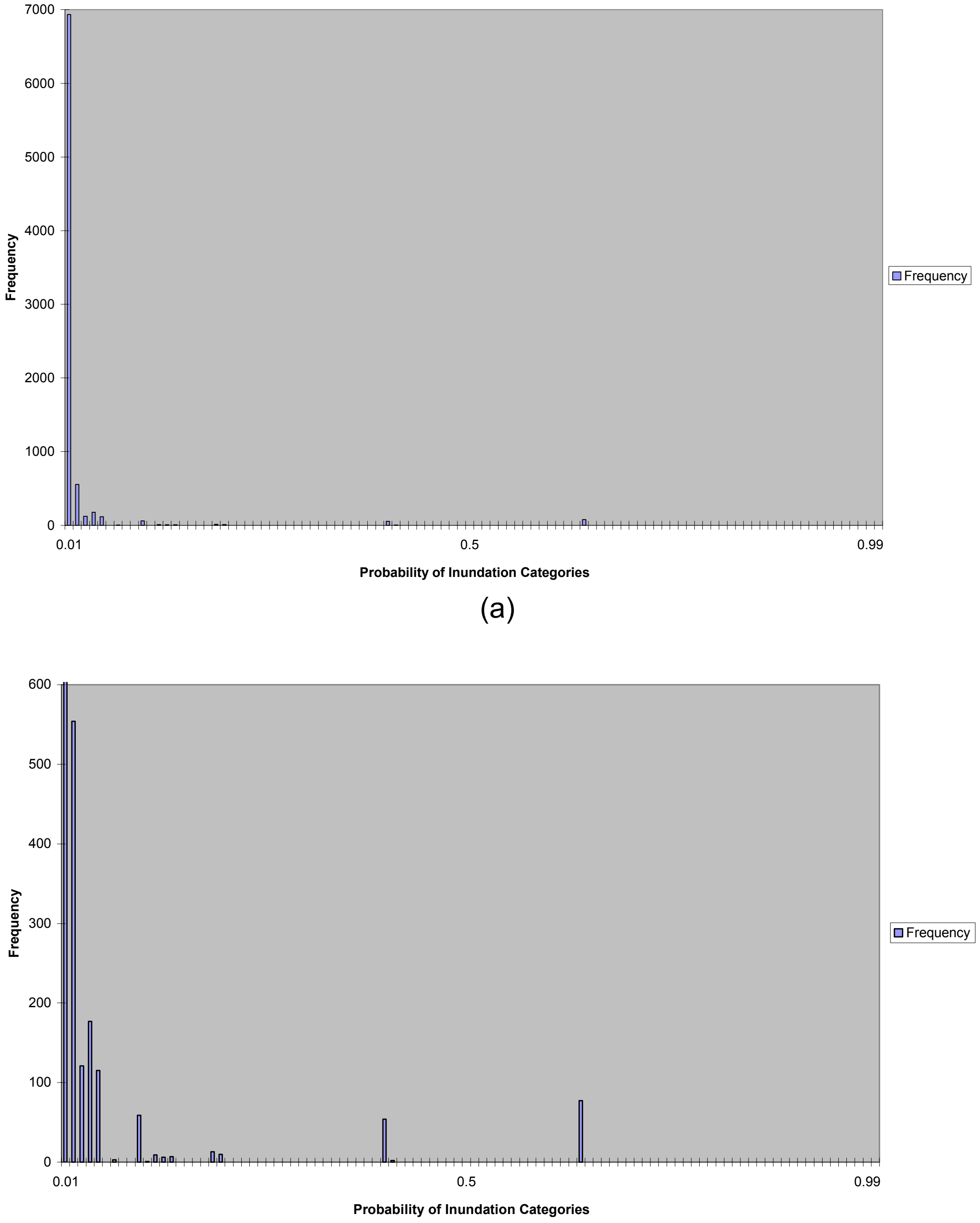
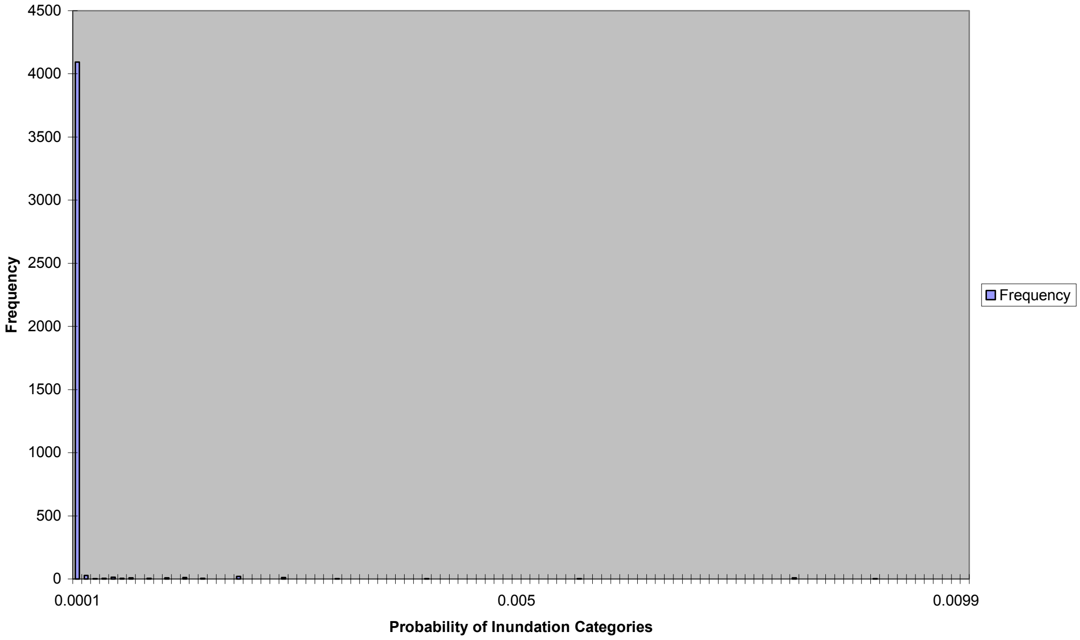
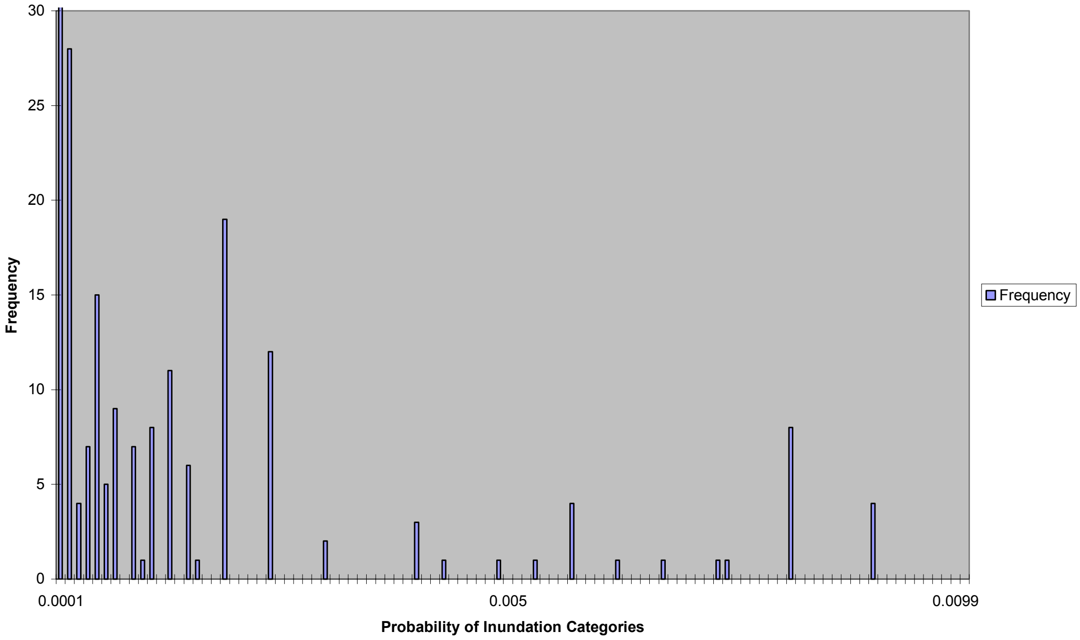


Figure 4.1: Probability of inundation versus frequency of occurrence (no. of impact zones) for the Thamesmead site, with (b) providing a scaled version of (a)

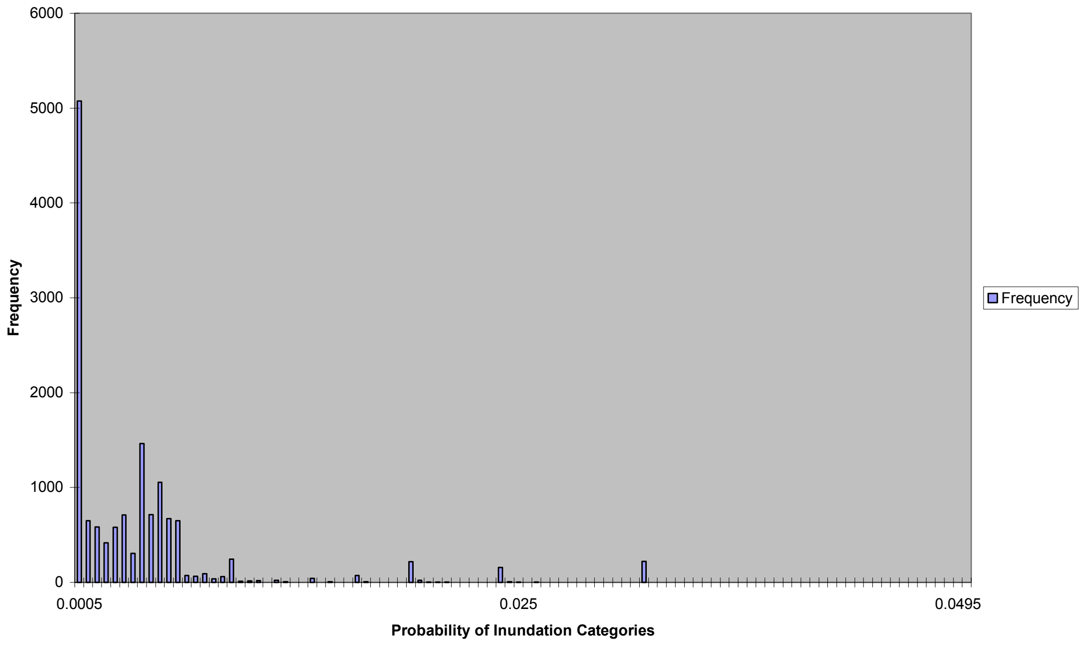


(a)

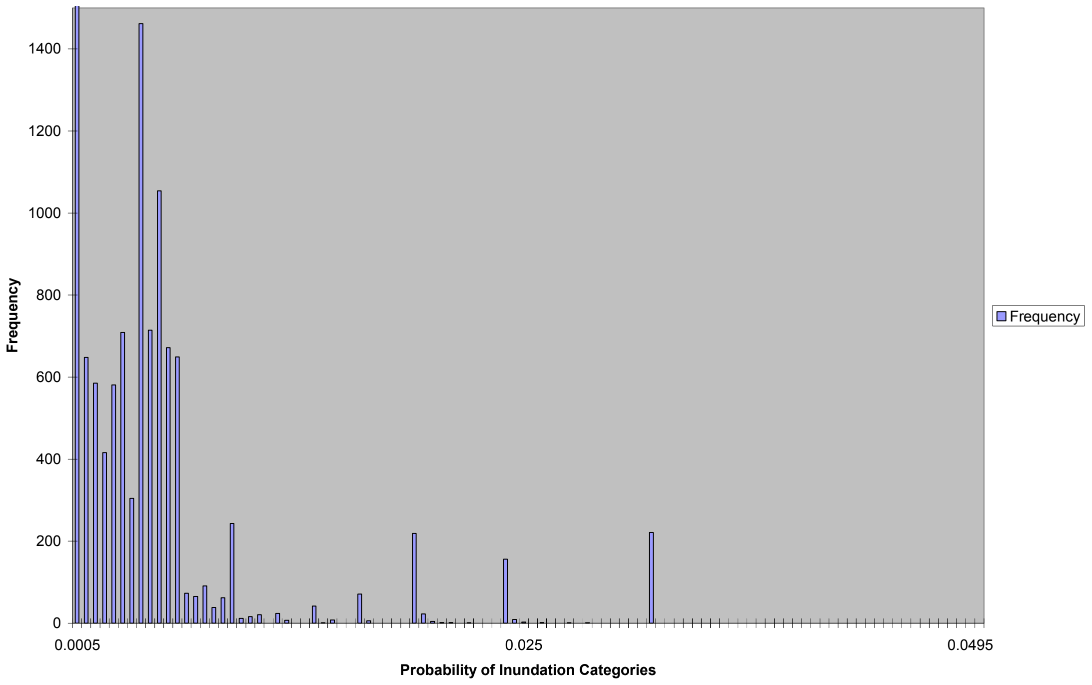


(b)

Figure 4.2: Probability of inundation versus frequency of occurrence (no. of impact zones) for the Skegness site, with (b) providing a scaled version of (a)



(a)



(b)

Figure 4.3: Probability of inundation versus frequency of occurrence (no. of impact zones) for the Stour site, with (b) providing a scaled version of (a)

5 Conclusions and recommendations

This section summarises the key findings, recommendations and lessons learnt based on the sensitivity testing for three sites:

- the Thamesmead site on the Thames Estuary;
- the Skegness coastal region in Lincolnshire;
- the Stour fluvial site in south-east England.

The tests are based on perturbing input data and model parameters to determine the influence on the resulting probabilities and expected annual damages (EADs). The results are presented as spatial distributions of the percentage change in probability, ΔP, and tabulated values of the percentage change in EAD, Δ_{EAD} (%). These detailed results are all provided in Appendix A (Thamesmead), Appendix B (Skegness) and Appendix C (Stour).

5.1 Key findings

Tables 5.1 and 5.2 provide summaries of the key findings, identifying parameters with Very high, High, Medium and Low sensitivities for each site. These categories are based on the absolute percentage difference in EAD, which are in the approximate range: >100%, 30–100%, 10–30% and 0–10% respectively. In some instances, these are modified to reflect local knowledge and/or expectation based on expert knowledge of the risk-based methods.

Thamesmead estuary site
The Thames Estuary site is largely urban and the EAD is therefore sensitive to small changes in the system. This is highlighted by the high sensitivity of the crest level parameter and the property floor space (i.e. depth-damage test). The area is well defended, with a SoP of 1000 along the main river. A reduction in the defence failure order from 5 to 2 shows a substantially larger change in EAD as, for these *strong* defences, there are unlikely to be more than 2 breaches. The CG is the least sensitive parameter, which may be attributed to the good condition of the defences in this area.

Skegness coastal site
The Skegness coastal site is well defended along the coastal portion (SoP of 100–200), and less well defended (SoP 50) along the Steeping River. As the urbanised area is adjacent to the coast, the sensitivity of the EAD is small. The probability maps provide a better interpretation of the changes due to perturbations. The Skegness toe level data is incorrect, and thus the probability data along the coastline for all tests is zero. This alters the results considerably as all changes occur along the Steeping River, and hence the coastal sensitivity testing requires further exploration. See Section 5.2 for further details.

Stour fluvial site
The Stour region includes coastal and fluvial influences with sparse urban developments. The inland region is defended by high ground and the coastal region is defended by other defence types. The site is most sensitive to the fluvial loading and crest level changes, which are reflected in the EAD and probability maps.

5.2 Lessons learnt

This project was intended as an exploration of the sensitivity of the NaFRA output to both data and model parameters. The pilot sites were not pre-selected on the basis of data quality or completeness, and were therefore felt to be a representative, if small, sample of areas to which NaFRA is applied.

During the study a series of internal reviews were held. At all sites the input data and the initial results were reviewed, which highlighted issues in the data for all sites. Revisions were made and the sites rerun. This process generally mirrored the area data reviews carried out within the NaFRA programme. In the case of the Thames pilot, HR Wallingford's local knowledge of the model data was extensive and the model reruns were few and undertaken with no major concerns concerning data. In the case of the Skegness coastal site, there were various issues with the data that had not been identified through previous project work. However, the poor toe level data for the Skegness site was not identified during these initial reviews. A key reason was that the data quality problem was not obvious even to the tried eye and it was initially believed that the small sensitivity in the results could be attributed to the high SoP and the methodology (i.e. step changes in inflow volumes to the floodplain). The selected coastal case study therefore failed to provide the detailed insight into the sensitivity of the outputs to perturbations in the input data and model parameters for the coastal frontage. However, even here we can learn lessons in that it highlights the importance of toe level data in the context of coastal sites, i.e. it is not enough to simply focus on crest level in coastal areas – reflecting the importance of depth limiting in determining overtopping and breach propensity. This pilot site also provides an additional fluvial reach, where the changes in probabilities *were* evident in the testing.

It is therefore recommended (Section 5.3) that, in future, a formal review of the issues and data quality would provide a more robust way of selecting the pilot site . This may lead to abortive work (i.e. those sites discarded) but would provide increased certainty that the selected pilot would satisfy the needs of the projects.

5.3 Recommendations

Based on the findings of the sensitivity testing, we make the following recommendations. These are the high priority areas for reducing uncertainty in the flood risk assessment:

- Appropriate resources and technology should be devoted to evaluating the fluvial loading and understanding the uncertainty bounds associated with these levels.

- The calculated risk is very sensitive to the accuracy of the crest levels – this should be a priority for data collection, particularly in 'high risk' areas.

- The calculated risk is sensitive to property floor space and hence the source of this data should be selected with care.

- The calculated risk is very sensitive to the number of events used to define the loading curve – a minimum of 40 return periods is recommended.

- The calculated risk is sensitive to the defence failure order, and it is recommended that the defence failure order is set equal to the number of defences within the defence system associated with a given impact zone.

- Although the coastal site results do provide some very useful conclusions regarding the importance of toe level data (Section 5.2), a detailed analysis of the sensitivity of coastal sites cannot be derived from the existing pilot results and further exploration of sensitivity for a coastal site with measured toe level information is recommended.

- Defence level parameters should be measured to an appropriate standard and linked to water level and wave information using a common datum.

- This study has developed a useful method for uncertainty and sensitivity analysis and has demonstrated its use at a small number of sites. It shows that the results are very dependent on the characteristics of the individual site. We should, therefore, be cautious and avoid over-interpreting the results. An extended study, based on the same method but carried out on a larger number of sample pilot sites, would enable us to explore the parameter spaced more fully and gain more insight into the significance of the uncertainties.

- Consideration should be given to whether this type of uncertainty and sensitivity analysis could or should be incorporated it the operational NaFRA analysis tools for probability and risk. This could help to highlight the areas of high, medium or low confidence in the results, depending on data quality and sensitivity to input parameters.

- The study has dealt with risk assessment and has not looked explicitly at the design process. But the findings do highlight the potential benefits of moving to probabilistic rather than deterministic design. In particular, where the risks are high (large EAD values), the data needs to be high quality so that the band of uncertainty is reduced as far as possible to model uncertainty only. For areas of less risk (in total numbers as opposed to risk per unit) some data uncertainty may be acceptable.

Table 5.1: Quantitative summary of sensitivity test results based on EAD[3]

Parameter	**Perturbation**	**Percentage difference in EAD**			
		Thamesmead (Estuary)	**Skegness (Coastal)**	**Stour (Fluvial)**	**Significance**
Fluvial loading	100 year level +0.1 1000 year level +0.3	23	-	148	***Very high***
	100 year level -0.1 1000 year level -0.3	-18	-	-52	
	100 year level +0.2 1000 year level +0.6	55	-	319	
	100 year level -0.2 1000 year level -0.6	-29	-	-66	
Crest level	+10 cm	23	0	141	***Very high***
	-10 cm	-17	0	-45	
	+20 cm	54	0	339	
	-20 cm	-28	1	-59	
	+50 cm	198	0	959	
	-50 cm	-50	3	-66	
Toe level	+1 m	-	0	-	***High***
	-1 m	-	0	-	
	+2 m	-	0	-	
	-2 m	-	0	-	
Condition grade	+1	0	0	0	***Very high***
	-1	0	0	1	
	+2	0	0	0	
	-2	1	0	6	
Inflow hydrograph	2 * volume	17	-	13	***High***
Floodplain width	+ 10%	-	-		***Low***
	- 10%	-	-		
	+ 20%	-	-		
	- 20%	-	-		
Ground level	+ 0.25	-	-0.35	-	***High***
	- 0.25	-	3.12	-	
	+ 0.5	-	-0.35	-	
	- 0.5	-	4.23	-	
	+ 1.0	-	-0.35	-	
	- 1.0	-	5.29	-	
Depth-damage	Lower	-30.93	-0.17	-5.98	***Very high***
	Best	-40.91	-17.97	-18.25	
	Upper	-56.99	-34.56	-24.19	
Defence system size	5	-8	0	0	***Low***
	20	Computationally too large			
Defence failure order	2	>250	0	0	***Very high***
	5	36	0	0	
	Based on return period	>250	0	0	
No. of events to establish rating	5	179	-	-	***Very high***
	10	48	0	2880	
	20	11	0	2181	
	60	-0.04	-	-	
Breach width	Half	0	0	0	***Low***
	Double	0	0	0	
Floodplain shape	Valley type 1	-	-		***Medium***
	Valley type 2	-	-		
Legend (approximate EAD ranges):				Very high	>100%
				High	>30%
				Medium	10–30%
				Low	0–10%

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[3] Note: these results are based on a limited number of sites and are intended to give a broad indication of the relative significance of different data and parameters. The significance will vary from site depending on the characteristics of the individual site.

Table 5.2: Qualitative summary of sensitivity findings[4]

No.	Parameter	Conclusion	Significance
1	Fluvial loading	The calculated flood risk is very sensitive to loadings conditions particularly where 'defence' standards are low (often the case for high ground) rather than raised defences are present. Appropriate resources and technology should be devoted to evaluating the fluvial loadings and understanding the uncertainty bounds associated with these levels. Resources are probably best deployed at more detailed levels than NaFRA, with NaFRA simply accessing results via NFCDD or another national database	Very high
2	Crest level	The calculated flood risk is very sensitive to crest levels. As for the fluvial loading, its importance is heightened where a low nominal standard of protection is afforded.	Very high
3	Standard of protection (SoP)	An error in SoP of greater than 50 years is likely to have a high significance in terms of the calculated EAD.	High
4	Toe level	Incident wave energy is highly dependent upon toe level along much of the coast. As the toe level data for the coastal site was incorrect (Section 5.2), the significance of this parameter is based on expert judgement and knowledge of the model.	High
5	Condition grade (CG)	The defence condition grade has a significant influence on the probabilities where the reference CG is 4 or 5. The differentiation between CG 1 and 2 is less significant. This reflects the nature of the difference between the likely fragility of defences.	Very high
6	Inflow hydrograph	The results are sensitive to the hydrograph shape and the trend is intuitive, i.e. an increase in volume results in an increase in probability and hence damage.	High
7	Floodplain width	The results show little change with floodplain width other than small isolated areas or a change from zero probability to a value – which appears sensitive.	Low
8	Ground level	The probabilities are very sensitive to a drop in the ground level, as the reference ground levels are marginally above the water levels. (The EAD shows negligible change, as the depths are small.)	High
9	Depth-damage	The calculated risk is sensitive to property floor space and hence the source of this data should be selected with care.	Very high
10	Defence system size	The defence system size influences the probabilities in locations with raised or 'other' defences but has negligible influence on EAD in the case examples. This conclusion may not be easily transferred to other sites.	Low
11	Defence failure order	The calculated risk is sensitive to the defence failure order, and it is recommended that the defence failure order is set equal to the number of defences within the defence system associated with a given impact zone.	Very high
12	No. of events to establish rating	The calculated risk is very sensitive to the number of events used to define the loading curve – with a minimum of 40 return periods recommended.	Very high
13	Breach width	The probabilities are insensitive to breach width other than where the zone of influence is altered and there are no changes in EAD. (This however reflects the relative insensitivity of the relatively crude parameterisation flood spreading model used within NaFRA 2006 and is likely to change with the introduction of a more representative spreading model.)	Low
14	Floodplain shape	The results indicate sensitivity to floodplain shape.	Medium

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[4] Note: these results are based on a limited number of sites and are intended to give a broad indication of the relative significance of different data and parameters. The significance will vary from site depending on the characteristics of the individual site.

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List of abbreviations

ABMS	Annual Beach Monitoring Survey
CG	condition grade
CL	crest level
DTM	digital terrain model
EAD	expected annual damages
FPW	floodplain width
GL	ground level
HLM+	High Level Method Plus
HRW	HR Wallingford
IZ	impact zone
LiDAR	Light Detection and Ranging
NaFRA	National Flood Risk Assessment
NPD	National Property Dataset
NRP	non-residential properties
PAMS	Performance-based Asset Management System
RASP	Risk Assessment of Flood and Coastal Defence for Strategic Planning
SAR	Synthetic Aperture Radar
SoP	standard of protection
TL	toe level

Appendices

Appendix A: Thamesmead summary and results

Appendix B: Skegness summary and results

Appendix C: Stour summary and results

We are The Environment Agency. It's our job to look after your environment and make it **a better place** – for you, and for future generations.

Your environment is the air you breathe, the water you drink and the ground you walk on. Working with business, Government and society as a whole, we are making your environment cleaner and healthier.

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Published by:

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www.environment-agency.gov.uk