THAMES ESTUARY – ESTABLISHING A ROBUST FLOOD SYSTEM MODEL TO SUPPORT ENGINEERING INVESTMENT DECISIONS

Eur Ing PAUL SAYERS BEng CEng MICE, HR Wallingford Ltd
Owen Tarrant BSc, Environment Agency
Ben Gouldby BSc, HR Wallingford Ltd
David Kavanagh, BSc Environment Agency
Mike Panzeri BSc MSc, HR Wallingford Ltd

KEYWORDS: Flood risk, Thames Estuary, System modelling

ABSTRACT
The Environment Agency is currently planning its long-term approach to Flood Risk Management within the Thames Estuary. This is a significant and multi-dimensional challenge. Adapting and managing existing defences, barriers, gates and pumps as well as building new ones are likely to have a significant role as part of this future. This paper explores the initial development and first application of a system model capable of supporting a risk-based targeting of investment.

The paper demonstrates how a regional system analysis tool – based on the RASP High Level analysis framework - can be used to provide an assessment of both flood risk and the performance of different response strategies under future scenarios. The practical issues explored in this paper include:

- Data gathering – including hierarchical approaches to the use of data and the attribution of data uncertainties.
- Defence performance analysis – how national scale and local analysis of defence failure can be integrated.
- Quantifying the individual defence contribution to risk (within the context of over 480km of defences within the tidal Thames)

The paper concludes with a practical insight to the use and utility of system models in the context of an active and complex decision making process.

INTRODUCTION
The study area within the Thames Estuary includes approximately 470 km^2 of flood plain between Teddington and Foulness Point / Whitstable that would be liable to tidal flooding in the absence of the existing defences (Figure 1). Most of these defences were constructed or improved in the late 1970s and early 1980s as part of the Thames Estuary Flood Prevention Scheme. The defences were generally designed to last until about 2030 and the Environment Agency has recently started the process of planning their future strategy for managing flood risk in the Thames Estuary (the so-called Thames Estuary 2100 project) to ensure any works required are in place in a timely and well-considered manner.

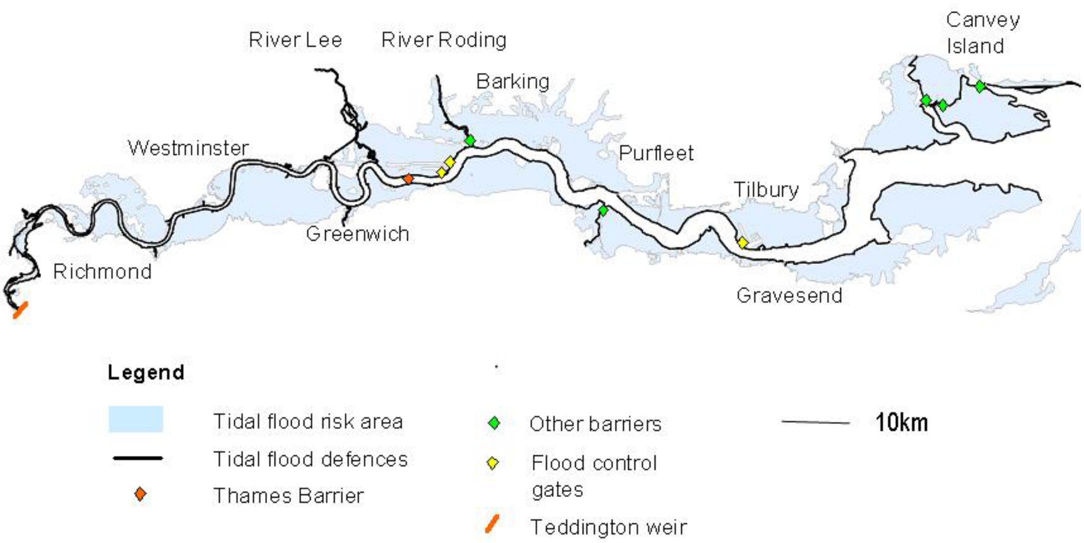


Figure 1 The study area

Flood risk within the Thames Estuary is influenced by a complex combination of meteorological factors (including fluvial flow, local and remotely generated waves and surge), estuary morphology and the performance of a range of active defences (such as barriers and gates) and passive defences (such as embankments and vertical walls). Due to the size and importance of the estuary the development of a flood risk strategy is a difficult undertaking; demanding a good understanding of a wide range of physical processes, engineering issues and stakeholder views.

PURPOSE OF THIS PAPER

This paper deals with the development of a flood system model to support the "intelligent" risk-based prioritisation of maintenance and capital investment with the Thames Estuary over the next 100 years.

The model (so-called IA System Model) was developed as part of the Interventions and Assets (IA) Theme of the TE 2100 project and is capable of:

- Attributing risk – both managed and residual risk – to specific assets (linear defences, barriers and gates).
- Attributing risk to specific receptors in the floodplain - providing a spatially differentiated picture of risk.
- Exploring future changes in risk driven by changes in climate and defence deterioration as well as socio-economic change.
- Exploring future changes in risk as a function of management interventions – both structural and non-structural.
- Deriving present value whole life benefits and costs.
- Explicitly quantifying uncertainty and how it changes as new / improved data becomes available and our understanding of sources, pathways and receptors improves.

Given that the TE 2100 project is in its early stages, the IA System Model has been established to evolve and improve as new data becomes available. In particular, embedded within the approach is a positive feedback between the assessment of risk and the focus of future data collection and specific analysis.

This paper does not set-out to provide definitive results for the Thames, but rather show the direction (and methods) being adopted by the IA Theme within the TE 2100 Project.

WHAT IS A SYSTEM MODEL

A system model describes all those aspects of the physical and management process that define our understanding of risk and inform our choices as what to do, where and when (see Figure 2).

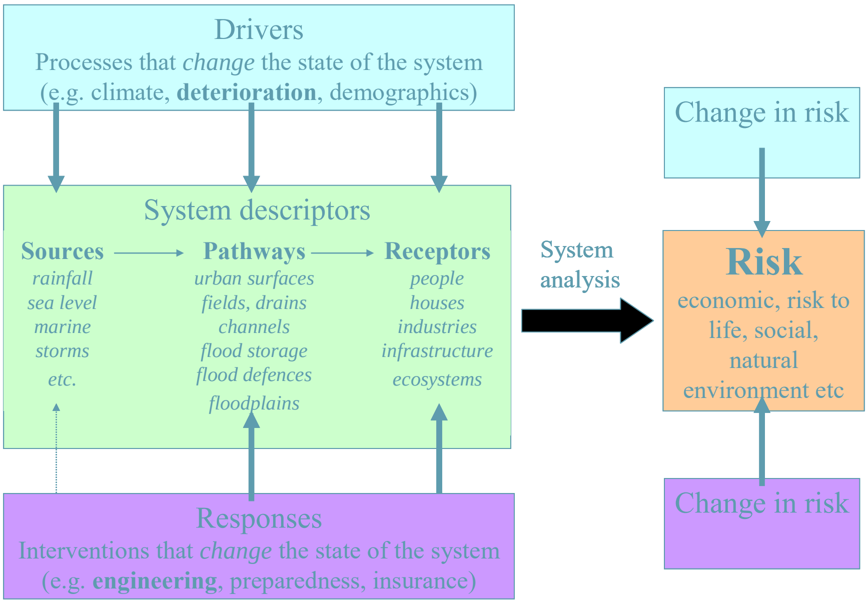


Figure 2 A system model provides a coherent and integrated framework for the analysis and management of risk (adapted from Evans et al, 2004)

WHY DEVELOP A SYSTEM MODEL

Developing an effective and efficient investment strategy is, even for the simplest of asset systems, often a difficult and subjective process. The particular difficulties faced within TE 2100 include:

- the complexity of the flood defence system – with many different components, all of which contribute to the state of the system and the way it performs in a flood event (See Box 1);
- difficulties in achieving a meaningful assessment of asset condition (including the effects of deterioration of components) of flood defence assets using visual inspection data and monitoring data;
- the potential complexity of the relationship between the condition of individual asset and the overall system performance during an extreme event (the Thames is characterised by extensive interconnected flood plains);
- difficulties in assessing the improvement in performance (or reliability) that will result from management interventions – which could range from routine maintenance (e.g.

replacement of sheet piles) to a major remodelling of individual assets (e.g. the heightening of a waterfront wall).

- ensuring that not only flood defence requirements are met but also other performance objectives (e.g. Safety; amenity; environmental) are also met.

Box 1 Overview of flood defence assets within the study area

There are approximately 280km of defences on the Thames with approximately 200km of tributary defences. These include (see also Figure 4.1):

- ***The Thames Barrier:*** This barrier is closed during extreme tidal events to prevent high tidal water levels upriver of the Barrier. It can also be used to reduce fluvial flood risk in West London by closing at low tide and preventing tidal water levels causing fluvial flows to 'back-up' in West London.

- ***Other moveable barriers:*** There are moveable barriers on the River Roding (Barking Barrier), River Darent (Dartford Barrier) and three barriers in the tidal creeks around Canvey Island (Fobbing Horse, East Haven and Benfleet Barriers). These barriers are closed during extreme tidal events.

- ***Fixed flood defences downriver of the barriers***: These provide protection against tidal flooding from the tidal Thames and the associated tidal creeks.

- ***Fixed flood defences upriver of the barriers***: These also provide protection against flooding, but the defence levels are lower than the downriver defences because maximum water levels are reduced by barrier operation. Maximum levels are affected by fluvial flows, particularly on the Thames and Roding.

- ***Flood control gates:*** There are three flood control gates that provide flood protection at dock entrances (Tilbury lock, King George V lock and Gallions lock).

- ***Drainage outfalls:*** There are a large number of outfalls for land drainage that pass through the fixed flood defences. The majority of these consist of tide flaps with penstocks, that allow water to discharge but prevent reverse flow during periods of high tides. There are also some pumping stations. The outfalls include Combined Storm Overflows (CSOs) and outfalls from Sewage Treatment Works (STWs).

- ***Frontage flood gates:*** These are gates in the fixed defences that provide access to wharves and other riverside facilities. They are closed when a flood warning is received.

Note: Further details on how the flood system behaves and how the flood defences are operated within the tidal Thames are provided in Ramsbottom *et al*, 2006.

DEVELOPING A ROBUST RASP BASED SYSTEM MODEL

Overview of the modelling approach

The IA System Model is based on the so-called RASP methods. RASP was originally developed under the joint defra/Environment Agency Programme (as previously reported at this conference, Sayers *et al* 2002, 2003, 2005). RASP consists of a hierarchy of methods ranging from High Level to Detailed. The specific approach used here is based on the RASP High Level Method (HLM). This approach was initially designed to support national scale analysis of flood risk and the application of the RASP HLM (and more recently HLM*plus*) under the National Flood Risk Assessment (NaFRA) Programme has been on-going since 2002 (HR Wallingford, 2002, Deakin *et al*, 2004 and 2005). Application of this approach to the Thames Estuary has however, provided an opportunity to develop a robust 'local' system model based upon site specific reliable data and process models. For ease, an overview of the system model set-up is provided in Box 1.

Box 1 Overview of the system model set up ***(adapted from HR Wallingford, 2004 and Hall et al, 2004)***

The method used within the TE 2100 IA System Model is based on the Source-Pathway-Receptor approach (HR Wallingford, 2002) and is an advancement of the RASP High Level Method*plus (*HR Wallingford, 2004). As with all RASP methods, a full range of loading conditions are integrated with the performance of defences, represented through fragility curves, and allied to an appropriate flood spreading and damage module. The conceptual building blocks for the RASP High Level Method are shown in the Figure B1.1 and discussed below.

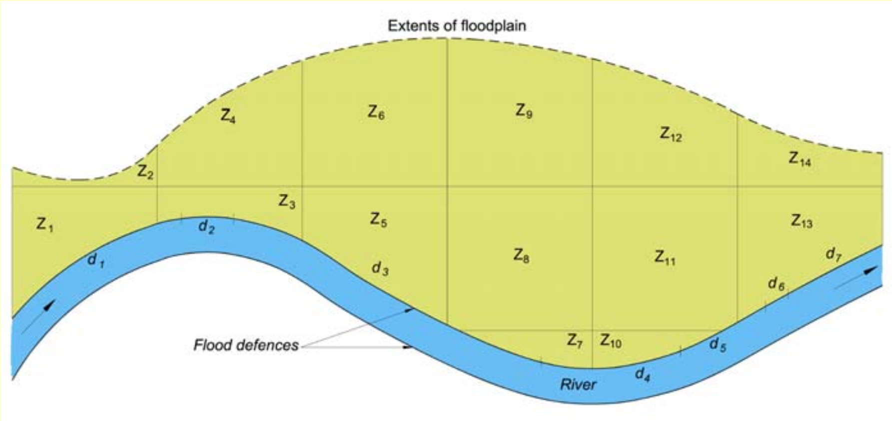


Figure B1.1 Conceptual diagram of the RASP building blocks

Figure B1.1, depicts a fluvial flood system by a series of discrete (raised or non-raised) flood hereby defences (d_1, d_2,…, d_n). Each defence section has an independent and different resistance to hydraulic loading as described by its specific structural characteristics. The floodplain be described by a series of Impact Zones (z_1, z_2,…, z_m) that can be influenced by any one or more defence(s) within the system of (n) defences. Flood water discharged into the floodplain over one or more of the defence(s) will inundate one or more, but not necessarily all, Impact Zones.

For any given hydraulic loading condition any individual defence section is assumed to have two possible states: failed or not failed (d, $\overline{d}$); where the behaviour of defences are considered to be independent of one another. The potential number of defence system states, for any specified hydraulic load, is therefore 2^n.

Given the assumption of independent defence strengths, the probability associated with any given defence system state (defined by a combination of defences that have failed/not failed) being realised during a specified storm loading (l) is straightforward to calculate. For example, for a defence system state where only d_2 has failed, the probability of the defence system state occurring, given the load l is:

$$\Pr\{\overline{d_1} \cap d2 \cap \overline{d_3}.....\overline{d_n}|l\} = \Pr\{\overline{d_1}|l\}\ \Pr\{d_2|l\}\ \Pr\{\overline{d_3}|l\}\ ...\Pr\{\overline{d_n}|l\} \qquad (1)$$

The integration of loading across all defence system states (and onto flood risk) is handled through discretisation of the loading variable into m bands (see Hall et al for further details). The probability of any particular flooding scenario (defence system state and loading event) is therefore given, for the i^{th} loading band, by (using the defence system state example detailed in 1):

$$\Pr\{\overline{d_1} \cap d_2 \cap \overline{d_3}......\overline{d_n}\} = \left[\Pr\left(L \geq \frac{l_i + l_{i+1}}{2}\right) - \Pr\left(L \geq \frac{l_i + l_{i-1}}{2}\right)\right] \Pr\{\overline{d_1} \mid l_i\}\Pr\{d_2|l_i\}\Pr\{\overline{d_3}\}.....\Pr\{\overline{d_n}\} \qquad (2)$$

Box 1 Overview of the System model – continued

For each flooding scenario, the associated flooding within an Impact Zone is then calculated. This is done by first calculating the volume of water discharged into the floodplain through each defence section.
For defences that have failed, an inflow volume that takes account of the breach is used. The spatial distribution of flood depth is then calculated using a parametric inundation model and used to calculate a range of quantified flood risk indicators. For example, the calculation of economic damage is straightforward based on knowledge of the type, floor area and number of properties within each Impact Zone (Flood Hazard Research Centre – Multi-coloured Manual).

Example calculation of a quantified risk indicator - Expected Annual Damage (EAD)

The expected risk associated with any particular loading event (R_e)(typically these are associated with discrete Return Periods) and any specified Impact Zone can then be obtained by linking equation 2 with the associated damage, for all possible defence system states (D) under the same loading condition (eg. i^{th}):

$$R_e = \sum_{j=1}^{2^n} \left[\Pr\left(L \geq \frac{l_i + l_{i+1}}{2} \right) - \Pr\left(L \geq \frac{l_i + l_{i+1}}{2} \right) \right] \Pr\{D_j\}\, c_j \qquad (3)$$

Where c_j is the economic consequence associated with the jth defence system state. This approach can then be extended over the full range of loading conditions (m bands) and all Impact Zones to determine an overall risk (R_{EAD}(Expected Annual Damage (EAD)).

$$R_{EAD} = \sum_{i=1}^{m} \left\{ \sum_{j=1}^{2^n} \left[\Pr\left(L \geq \frac{l_i + l_{i+1}}{2} \right) - \Pr\left(L \geq \frac{l_i + l_{i+1}}{2} \right) \right] \Pr\{D_j\}\, c_j \right\}$$

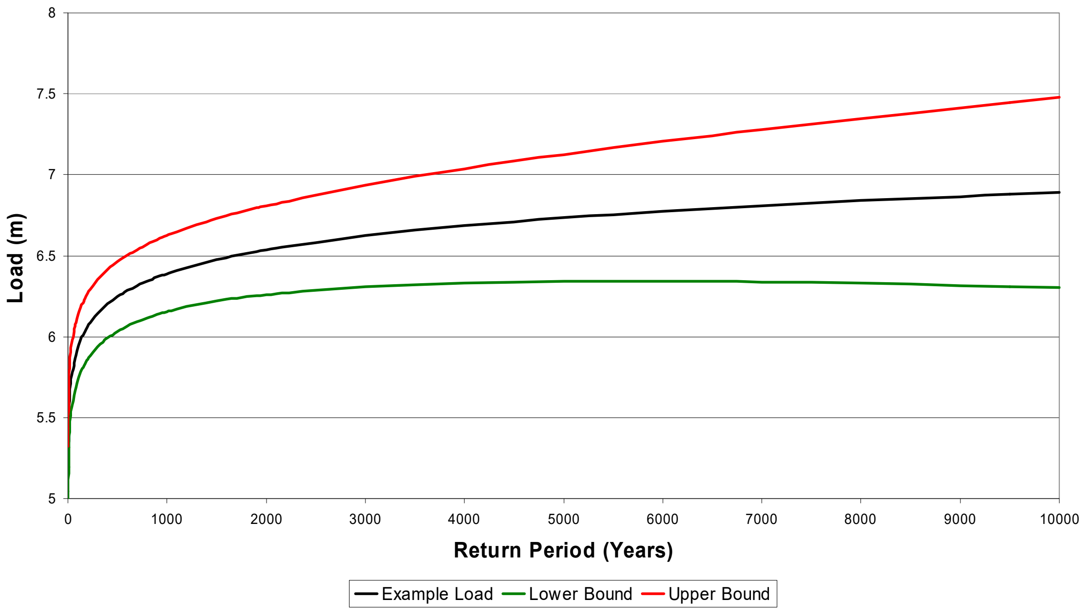
Any other risk indicator – with an associated quantified relationship between flood depth / velocity and damage / harm can be calculated in a similar way.

Sources of risk – Developing a local understanding of asset loading conditions

Extensive studies of the estuary behaviour, joint probability and river flows have been commissioned under the Estuary Processes theme of the TE Project. The results from these studies have been used to derive the two primary load parameters used by the IA System Model:

- Water level extreme value distributions within the estuary based on fluvial/tidal joint probabilities.
- Water level extreme value distributions within the tributaries from site specific modelling, including barrier failed and working states.

A particular strength of the RASP methods is that they enable uncertainty to be explicitly recognised and propagated through the analysis of risk. Therefore, through a combination of statistical analysis and expert judgement initial estimates of the uncertainty in these extremes have been developed (Figure 3) and used to support the calculation of defence overtopping that is subsequently used within the IA System Model.



Note: the extremes are controlled so that the lower bound values always increase with return period.

Figure 3 Estimated uncertainties in the extreme water level loading conditions (Present day)

Pathways – Asset performance

To supplement data currently in NFCDD and available from other national databases, a number of specific data gathering studies have been commissioned as part of the TE 2100 Project to establish asset location, type, geometry and condition. These include:

- Low level LIDAR survey of the outer Thames defence line (see Kavanagh et al, 2006)
- Targeted asset condition inspection surveys – using the methods emerging from the joint defra/Agency R+D programme via the Performance-based Asset Management System Project (see for an update Simm *et al*, 2006)
- Localised GPS survey data
- Targeted extraction of asset parameters from 'as constructed drawings'

Given the size of the study area, however, it has not been possible, or appropriate, to establish detailed data everywhere and for a number of defences it has been necessary to rely upon existing data sources of varying quality to establish the geometry, type and condition of the defences. It has therefore been important to reflect the uncertainty in the data within the IA System Model. For example, the uncertainties within the various sources of data have been quantified and fed into the calculation of overtopping (see Tables 1 and 2). As can be seen from Table 2, inclusion of the data uncertainties has a dramatic impact on the estimated overtopping volume; in particular when the mean estimate of water level is below the mean estimate of crest level.

Table 1 Sources of data and model uncertainty used in the estimate of defence overtopping

<table>
<tr><th colspan="2"></th><th>Lower Bound – 10th percentile (Relative to Best Estimate/Mean Value)</th><th>Upper Bound – 90th percentile (Relative to Best Estimate/Mean Value)</th><th>Standard Deviation</th><th>Distribution Type</th></tr>
<tr><td rowspan="9">Crest Level</td><td colspan="4">Source</td><td rowspan="9">Normal</td></tr>
<tr><td>Local GPS survey</td><td>-0.05m</td><td>+0.05m</td><td>0.039m</td></tr>
<tr><td>Low Level LIDAR</td><td>-0.269m</td><td>+0.269m</td><td>0.21m</td></tr>
<tr><td>Land Charge Register Drawings 1997</td><td>-0.45m</td><td>+0.45m</td><td>0.35m</td></tr>
<tr><td>Statutory Defence Levels</td><td>-0.475m</td><td>+0.475m</td><td>0.37m</td></tr>
<tr><td>As built drawings</td><td>-0.50m</td><td>+0.50m</td><td>0.39</td></tr>
<tr><td>Visual Inspection</td><td>-0.525m</td><td>+0.525m</td><td>0.41m</td></tr>
<tr><td>Thames Tidal Database (Embayment Strategy Volume 3)</td><td>-0.575m</td><td>+0.575m</td><td>0.45m</td></tr>
<tr><td>Estimation from SOP</td><td>-0.60m</td><td>+0.60m</td><td>0.47m</td></tr>
<tr><td rowspan="6">Load (values apply to loadings in estuarial areas and in tributaries)</td><td colspan="4">Return Period (years)</td><td rowspan="6">Normal</td></tr>
<tr><td>1</td><td>-0.10m</td><td>+0.10m</td><td>0.08m</td></tr>
<tr><td>10</td><td>-0.10m</td><td>+0.10m</td><td>0.08m</td></tr>
<tr><td>100</td><td>-0.10m</td><td>+0.10m</td><td>0.08m</td></tr>
<tr><td>1000</td><td>-0.12m</td><td>+0.12m</td><td>0.09m</td></tr>
<tr><td>10000</td><td>-0.30m</td><td>+0.30m</td><td>0.23m</td></tr>
<tr><td rowspan="2">Ground Level</td><td colspan="4">Source</td><td rowspan="2">Normal</td></tr>
<tr><td>High Level LIDAR</td><td>-0.54m</td><td>+0.54m</td><td>0.42m</td></tr>
<tr><td rowspan="2">Weir Equation Constant</td><td colspan="4">Source</td><td rowspan="2">Normal</td></tr>
<tr><td>Physical model studies reported in the literature</td><td>-0.2</td><td>+0.2</td><td>0.16</td></tr>
<tr><td rowspan="2">Breach Width Multiplier</td><td colspan="4">Source</td><td rowspan="2">Triangular</td></tr>
<tr><td>Literature/Experience</td><td>-0.5 * Best Estimate Value</td><td>+0.5 * Best Estimate Value</td><td>NA</td></tr>
<tr><td rowspan="3">Duration of overflow / overtopping</td><td colspan="4">Source</td><td rowspan="3">Normal</td></tr>
<tr><td>Model studies and expert judgement.</td><td></td><td></td><td></td></tr>
<tr><td>Estimated T (hours)</td><td>-1 Hour</td><td>+1 Hour</td><td>0.78 Hours (47 minutes)</td></tr>
<tr><td>Defence Length</td><td>NA</td><td>NA</td><td>NA</td><td>Assumed Certain</td><td>NA</td></tr>
</table>

Table 2 Variation in estimated overtopping volumes after taking account uncertainties

<table>
<tr><th colspan="4">Defence Unique Number 200000001</th></tr>
<tr><td rowspan="2">Return period (years)</td><td colspan="2">Overtopping Volume (m3)</td><td rowspan="2">% difference between upper and lower bounds</td></tr>
<tr><td>Ub</td><td>Lb</td></tr>
<tr><td>1</td><td>1,233</td><td>0</td><td>Infinity</td></tr>
<tr><td>10</td><td>117,977</td><td>0</td><td>Infinity</td></tr>
<tr><td>100</td><td>578,427</td><td>0</td><td>Infinity</td></tr>
<tr><td>200</td><td>745,655</td><td>0</td><td>Infinity</td></tr>
<tr><td>1000</td><td>1,159,240</td><td>21,966</td><td>5,278</td></tr>
<tr><td>5000</td><td>2,017,033</td><td>332,630</td><td>606</td></tr>
<tr><td>10000</td><td>2,283,926</td><td>275,374</td><td>829</td></tr>
</table>

The data on geometry and condition have been supplemented with data on defence reliability to support the RASP analysis within the IA System Model. Nationally available data has been combined with site specific reliability analysis (such as the detailed reliability analysis undertaken as part of the on-going Thames Estuary Barriers and Associated Gates (TEBAG) project) to provide an initial best estimate. As with crest level, the estimates of defence fragility – relating the probability of failure to a given loading – are provided to the system model as uncertain estimates depending upon the nature of the defence and the rigour of the inspection and reliability analysis (Figure 4).

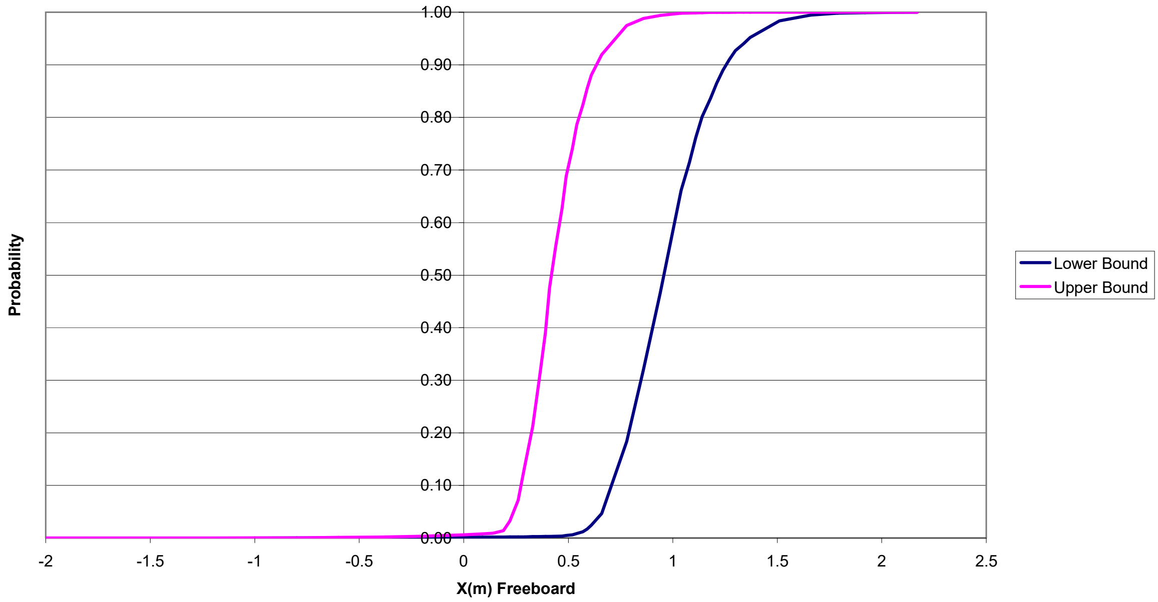


Figure 4 Defence fragility – initial estimates taken from NaFRA 2005 are being replaced with defence specific analysis on an as required basis.

The defence data is stored in a PAMS (Performance Based Asset Management) type database developed by HR Wallingford. The database is based on, and compatible with, NFCDD but enables additional defence data and parameters, that are potentially useful for flood risk analysis (such as defence specific fragility curves and loading conditions), to be stored. Typical screen shots of the database, are shown in Figures 5a and 5b.

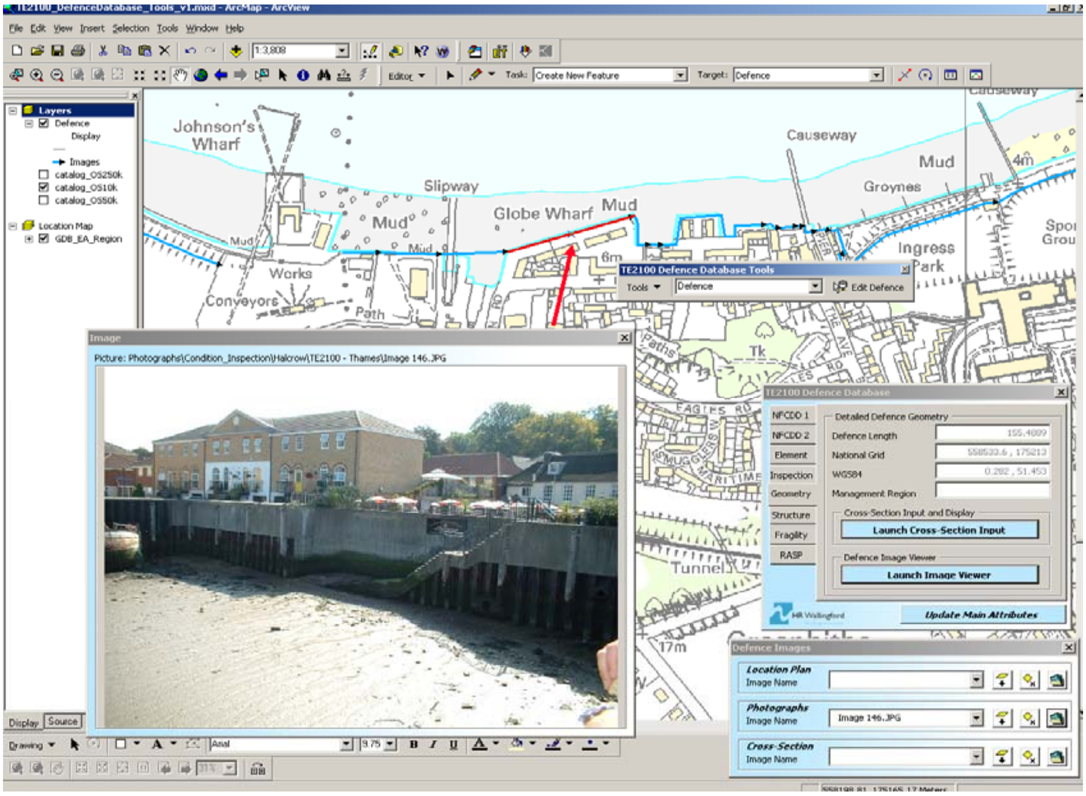


Figure 5b Example screenshot from the Asset Database – based on the NFCDD XML schema

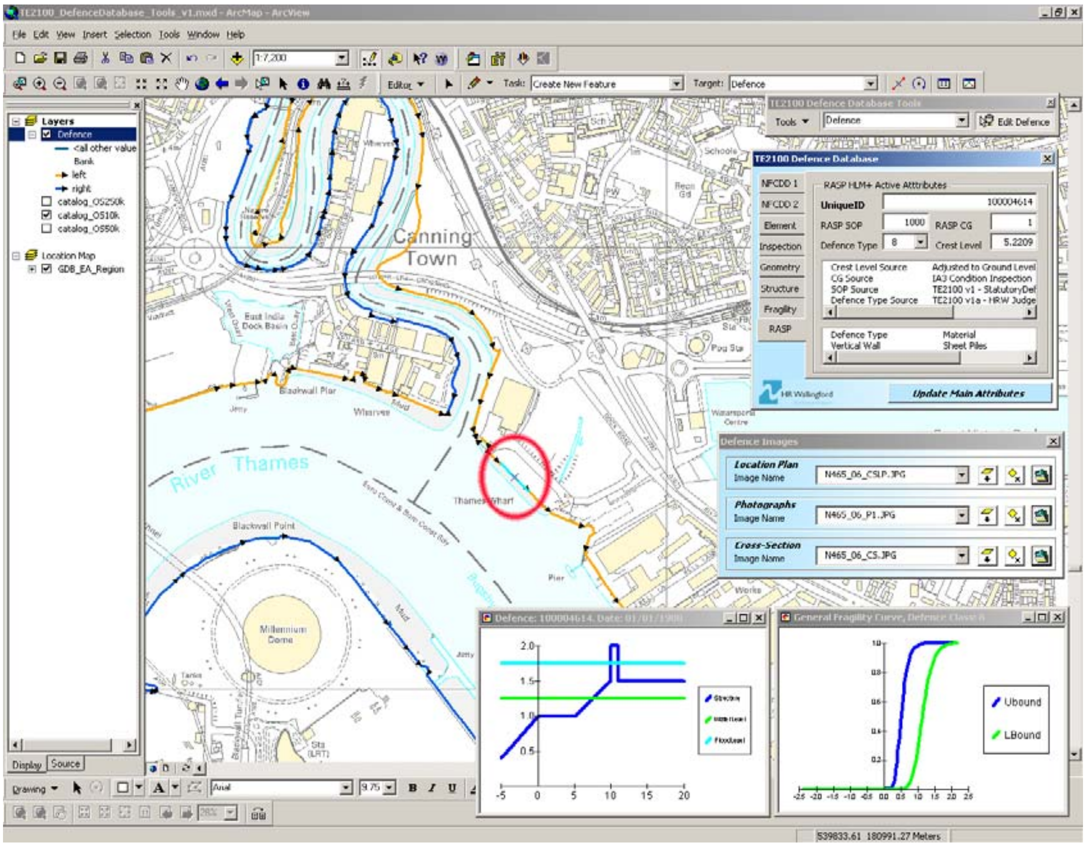


Figure 5b Example screenshot from the Asset Database showing additional fields holding defence specific loading conditions and fragility curves.

SOME INITIAL RESULTS

To date the flood system model has been run for a small number of selected policy options and time horizons. For the purposes of this paper only two are considered as shown in Table 3.

Table 3 P1 and P3 Policy descriptions

Policy P3 (Present Day):	Continue with existing or alternative actions to maintain the current flood risk management regime (accepting that flood risk will increase over time from this baseline). Defences maintained at current levels and condition. Moveable structures operated.
Policy P1 (2030):	No active intervention (including flood warning and maintenance). The 'do-nothing' policy. Cessation of all work on the defences and cessation of barrier/gate operation. Defences deteriorate.

The policies have been represented within the model by modifying model input data, primarily the extreme in-river water levels and the defence condition grade taking account of defence deterioration. Example results for each of the above are shown in Figures 6 and 7 for P3 and P1 respectively.

As shown in Figure 6a, present day risk within the Thames Estuary is limited by the current asset system. Figure 6b shows the attribution of risk to individual assets in an area upstream of the Thames Barrier. This type of analysis enables the intervention of defences to be prioritised and appropriate action taken.

Assuming a Policy of P1 (i.e. adaptation of a do nothing and abandment of the barriers) or the next ~~Following~~ thirty years of a "do nothing" ~~policy and abandonment of the barriers, however,~~ flood risk within the estuary would~~has~~ radically changed.

Unsurprisingly, if the Barrier fails to operate significant areas of floodplain can be expected to be inundated. Downstream of the barrier the annual probability of inundation increases as defences become more likely to breach; resulting in the risk being 'transferred' from overtopping to breaching cases. Upstream of the barrier, when the barrier is non-operational, the combination of high water levels, low crest levels and lower condition grades results in significant annual probabilities up to approximately 0.1 (or 10%). It is also the case that the economic risk is dominated by these upstream areas (representing >95% of the risk). This is almost solely attributable to overtopping (due to the high water levels relative to crest level in this area) with little contribution from breaching.

Influence of the barriers and moveable structures on risk
Comparison of the P1 and P3 EAD present day estimates can be used to provide an indication of the contribution that the barriers makes to risk reduction. Initial indications suggest that approximately £80m is saved annually (on average) as result of the operation of the active defences; a figure that confirms the importance of the Barrier and associated gates.

This assessment has only been possible by integrating the barrier fragility curves for the barriers into the system model and attributing risk in a structured manner that isolates the influence of each barrier and gate.

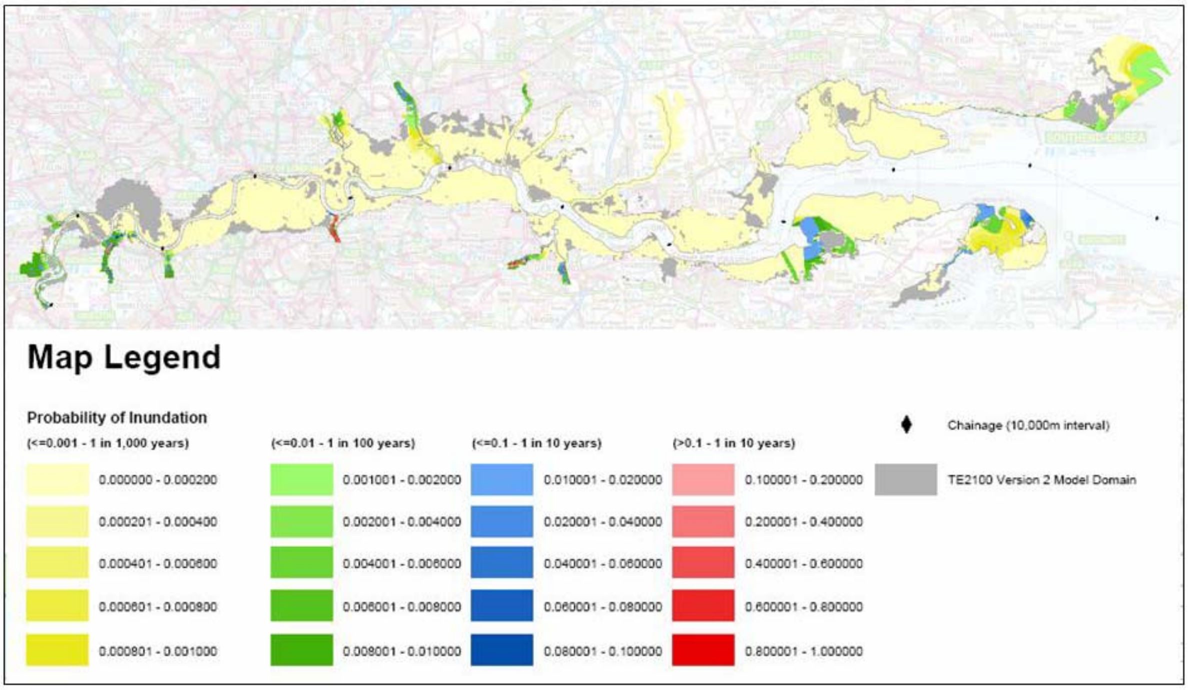
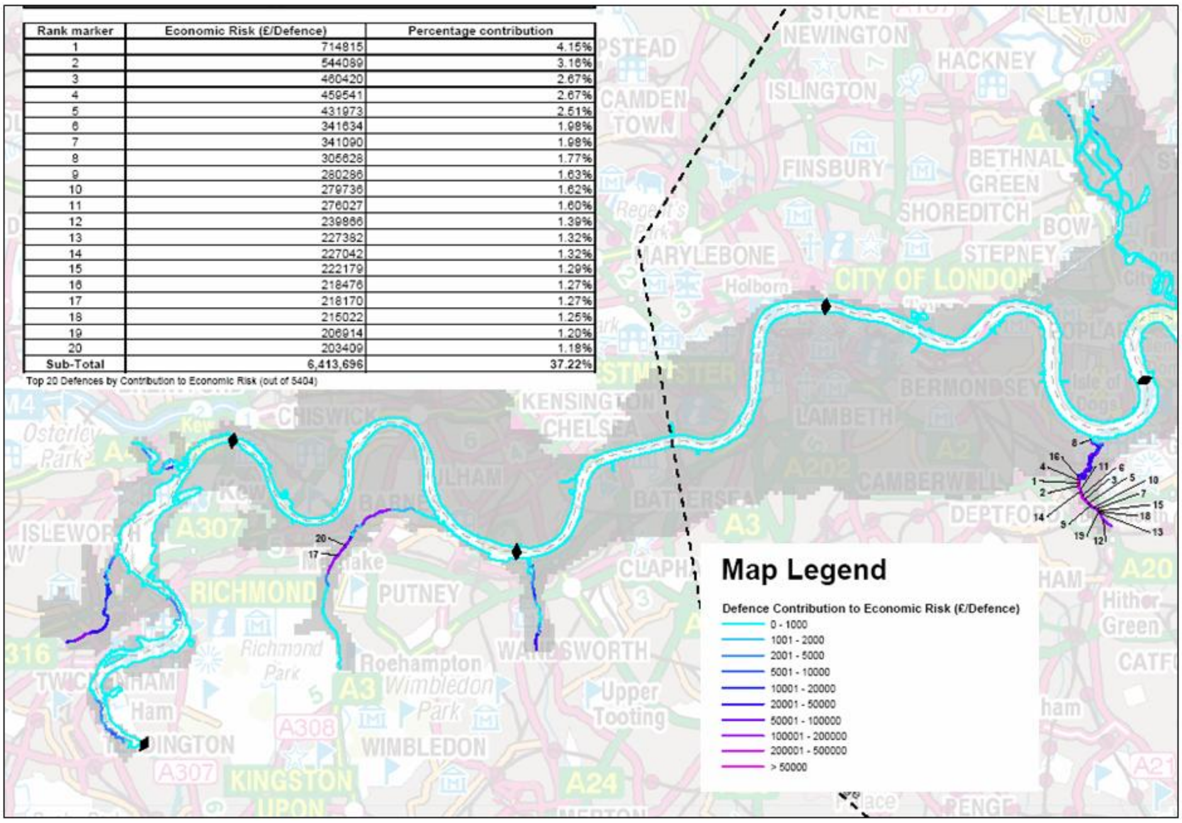


Figure 6a Present day spatial distribution of inundation probability – results of the initial version of the IA System Model



Rank marker	Economic Risk (£/Defence)	Percentage contribution
1	714815	4.15%
2	544089	3.16%
3	460420	2.67%
4	459541	2.67%
5	431973	2.51%
6	341634	1.98%
7	341090	1.98%
8	305628	1.77%
9	280286	1.63%
10	279736	1.62%
11	276027	1.60%
12	239866	1.39%
13	227382	1.32%
14	227042	1.32%
15	222179	1.29%
16	218476	1.27%
17	218170	1.27%
18	215022	1.25%
19	206914	1.20%
20	203409	1.18%
Sub-Total	6,413,696	37.22%

Top 20 Defences by Contribution to Economic Risk (out of 5404)

Figure 6b Attribution of risk to individual assets – example Map and tabular output

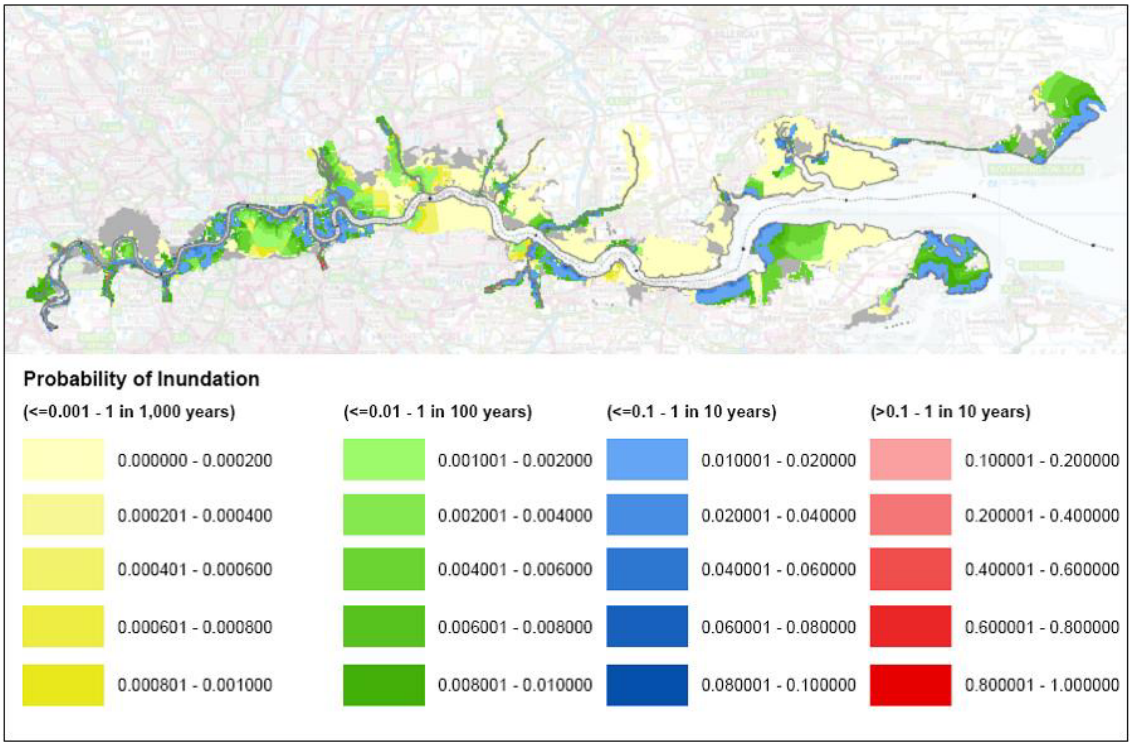


Figure 7 Future spatial distribution of inundation probability (P1 2030) – results of the initial version of the IA System Model

CONCLUSIONS

A model that utilises the conceptual *Source/Pathway/Receptor* model to undertake structured flood risk assessment has been developed and applied on the Thames Estuary and tributaries. The model includes analysis of extreme value distributions of water levels together with a probabilistic description of defence failure (structural failure/breaching), hydraulic spreading of flood inundation and subsequent economic damages to properties.

The model has proved capable of providing a range of outputs that are useful for supporting decisions on the planning of asset management and flood risk management strategies, these include:

- Spatial floodplain distribution of the likelihood of inundation
- Spatial floodplain distribution on the Expected Annual Damage (EAD)
- Annual probability of defence failures.
- Contribution to residual risk (EAD) from each defence
- Contribution to residual risk (EAD) from each overtopping of each defence
- Contribution to residual risk (EAD) from breaching of each defence

Given the current status of the TE 2100 Project it is not yet appropriate to report specific risk figures and distributions. It is however hoped to provide a more detailed paper on the results from the System Model in the coming years.

Next steps
The development of next version of the IA System Model has already commenced. Some of these are summarised below.

Input Data
Defence data collection activities are ongoing and include:

- Prioritised visual condition inspections and extract of data from archives
- Additional information on active structures (gates and barriers)
- Additional consideration of defence

Methodology improvements changes

- Flood spreading – a new flood spreading method that provides a rapid, but accurate representation of floodplain flood depths, has been developed by HR Wallingford and will be used to replace the simplified spreading currently within the RASP HLM.
- Defence specific discharge volumes – wave driven overtopping will be incorporated.
- A benefit/cost capability will be added to the model. This will be capable of analysing and deriving benefit cost ratios for each of the policies considered.

ACKNOWLEDGEMENTS

In addition to funding from the TE 2100 Team, HR Wallingford work for the Interventions and Asset Theme of the TE 2100 Project is supported by the joint defra/Environment Agency Research and Development Programme (Sustainable Asset Management Theme) via the Performance-based Asset management System Project (PAMS), the EC funded Floodsite Project led by HR Wallingford and the Flood Risk Management Research Consortium – RPA 4 led by Paul Sayers.

REFERENCES

Evans, E.P., Ashley, R., Hall, J.W., Penning-Rowsell, E.P., Saul, A., Sayers, P.B., Thorne, C.R. and Watkinson, A (2006). The Foresight Future Flooding Project – Drivers, Responses And Choices For Future Flood Risk Management. Proceeding the ICE *Journal of Water Management*.

Hall J, Dawson R, Sayers P, Rosu C, Chatterton J and Deakin R (2003) 'A Methodology for National-Scale Flood Risk Assessment' Proceedings of the Institute of Civil Engineers, Water and Maritime Engineering 156, September.

Scott et al (2006). Capturing and abstracting flood defence data from low level LiDAR. . Proceeding of the 41th Defra Conf. of River and Coastal Management.

HR Wallingford (2002) 'Risk Performance and Uncertainty in Flood and Coastal Defence: A defining review', HR Wallingford Report SR587, Report FD2302/TR1

HR Wallingford (2004a) National Flood Risk Assessment 2004: Supported by the RASP HLM*plus* methodology' HR Wallingford Report SR659.

Sayers P B, Hall J W and Meadowcroft I C (2002). Towards risk-based flood hazard management in the UK. Proceedings of ICE, Civil Engineering 150 May 2002 pp. 36-42

HR Wallingford..(2004b). RASP – Risk Assessment for Strategic Planning – A summary. Environment Agency Report R&D Technical Report W5B-030/TR

Sayers PB and Meadowcroft IC., (2005) RASP - A hierarchy of risk-based methods and their application. Proceeding of the 40th Defra Conf. of River and Coastal Management

Simm, Wallis, Sayers, Gouldby, Buijs, Flikweert, Hamer (2006) Developing A Performance - Based Management System Tool For Flood And Coastal Defence Assets. Proceeding of the 41th Defra Conf. Of River and Coastal Management – Short Paper

Penning-Rowsell E, Johnson C, Tunstall S, Tapsell S, Morris J, Chatterton J, Coker A and Green C (2003) 'The Benefits of Flood and Coastal Defence: Techniques and data for 2003' Middlesex Univarsity Flood Hazard Research Centre, 2003.