Long term planning – Robust strategic decision making in the face of gross uncertainty (tools and application to the Thames)

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ABSTRACT: Robust long planning presents specific problems. Changing climate, changing socio-economic context as well as deterioration in defence assets all present the decision maker with complex policy choices with regard to what to do for the best. This paper presents research undertaken within FLOODsite to develop of next generation decision support tools that support the user in developing meaningful strategic alternatives (based on a pipeline of multi-staged actions) and assessing their performance through time using credible system risk models (based on the so-called RASP model) together with a structured assessment of their robustness that reflects their performance across a continuous space of climate and socio-economic futures. The science and tools developed through FLOODsite are shown through application to the Thames Estuary. This includes the development of strategic alternatives that include both structural and non-structural measures, climate change (that includes a wide range of possible change in both fluvial and surge conditions) and socio-economic (that includes a range of possible futures described through spatially varying population growth). The change in the defence infrastructure, deterioration and improvement, are also included together with more significant engineering interventions such as barriers and realignment. The selection of robust decisions in the context of these changes is then explored, including the identification of non-regret solutions and adaptable decision pathways.

1 INTRODUCTION

1.1 *The challenge of robust long-term planning*

Effective and efficient long-term planning is increasingly recognised as essential to the delivery of robust and sustainable flood risk management (FRM) policies in an uncertain future. Long term planning decisions require information on a range of metrics such as damages, casualties, environmental impacts and social equity, as well as a means to usefully interpret this information to support their choice of the best course of action. One important challenge underlying a more strategic approach to planning is the creation of meaningful future storylines, in that they reflect the plausible drivers of change and the potential management response to these. Typical difficulties include:

- *History teaches us less and less.* There is no certainty about what the future holds and increasingly a historical analogy provides limited guidance. Lack imagination in describing the possible future change can condition actions based on current knowledge and experience.
- *Multi-possible futures.* To be meaningful however all possible futures and possible strategies must be considered. To early judgment of the most likely strategic preference or possible future can precondition the answer in an undesirable and sub-optimal manner. Conversely over complication must be avoided, including unnecessary detail or very localized options.
- *Short-termism*. The planning and implementation of flood risk strategies is often bias towards quick wins. More progressive strategies that embed a longer term and progressive management are often difficult to develop and implement.
- *Lack of ownership*. Long term strategies demand action to take by many stakeholders over extended periods. Buy-in to such decisions can be difficult to achieve and require continual reinforcement and review. Often the ability to implement strategic management is undermined by local and independent actions.
- *Perception and value*. The past decades have seen an ever changing societal view as to what is and is not important. These criteria will continue to change into the future – these changing possible future value systems must feature within adaptable ‘no regret’ solutions.
- *Changing priorities*. Significant flood events can dramatically alter the perception of the risk floods poise. Collective memory is often short lived and

priorities can rapidly change. Implementing a long term plan requires long term commitment and continuity to be successful; a goal which is often difficult to secure in practice.
- *Radical solutions*. Engineers need to be brave enough to propose new or radical solutions such as land banking, integrated solutions (e.g. energy generation and flood defence, habitat creation and flood management etc), urban blue highways as well as ring dykes.
- *Sunk investment*. Much of the UK, like much of the developed world, has significant sums already invested in an aging defence portfolio. Incorporating and adapting this existing infrastructure in sustainable future plans presents a difficult challenge.
- *Multiple opportunities and constraints.* Increasingly flood management does not take place in isolation of other sustainable development goals. Achieving and understanding multiple (and changing) objectives presents many challenges; objectives often conflict both in the short term and perhaps fundamentally in terms of setting the long term direction of travel.
- *Uncertainty*. Gross uncertainties exist future land use and climate. These uncertainties are often irreducible and must be addressed through adaptable and flexible strategy design. Such gross uncertainties are in addition to the more normally considered model and data uncertainties.

Existing approaches to long-term planning (e.g. OST, 2004, Evans et al, 2004a and b) typically involve developing a range of possible options (portfolios of management measures through time) and evaluating these in the context of different socio-economic and climatic futures. This paper explores the development of integrated frameworks to assist in combining hazard, exposure and vulnerability information, as well as the effect of external and internal drivers, in support of identifying the preferred management strategies over the long term. A key element of the approach is the move to a more continuous representation of the climatic and socio-economic future – negating the need for evaluating select future scenarios and provide more robust guidance regarding the preferred course of action. Guidance is provided on developing both the socio-economic, climate scenarios and the management response strategies. Techniques for evaluating sustainability as well as up-and-coming measures such as robustness and adaptability are described. The methods are piloted on the Thames Estuary, illustrating the rich information available to decision makers in support of making robust choices. The Thames prototype Decision Support System (DSS) incorporates an innovative hierarchical variance-based sensitivity analysis to explore sources of uncertainty within the data and risk models (Gouldby et al, 2008).

1.2 *Decision Support Systems – constraints and opportunities*

Decision support systems (DSS) have been developed *ad infinitum.* Many have been useful and many more have been useless. The most pertinent questions that distinguish *useful* from *useless* have been distilled from a review of existing DSS tools (FLOODsite, 2007). The review covered 19 tools, predominantly from Germany, the Netherlands and the UK, consisting of long-term FRM tools as well as operational systems not specifically designed for long-term analyses, but considered useful additional sources of information. The review criteria included:
- *Contents* such as representation of the flood risk system, management measures, spatial and temporal scales, output metrics etc.
- *Data and methods*
- *Presentation* including target users and visualisation
- *Technology* e.g. software architecture;
- *Other* e.g. user/software support, application strengths and weaknesses

The most significant of the findings (FLOODsite, 2007) include:
- *Clarity of decision* being supported (not aim to solve too many things);
- Understanding the target user (*user engagement* throughout);
- Methods should reflect the *policy context* i.e. currently risk-based methods;
- *Uncertainty* should be explicitly recognised and appropriately disaggregated by source;
- Representation of output metrics should be clear whilst reflecting the complexity of the underlying analysis e.g. high level aggregation of data into *useable evidence*;
- Tools should be appropriately *modular and flexible*, limiting dependence on proprietary software where possible and independent of data source (e.g. user entered, external models);
- Ongoing *support*, training, maintenance releases etc are critical to user uptake.

It is worth bearing in mind that aside from their FRM decisions, decision makers also need to decide which DSS tool to use. DSSs may be an effective means of giving support provided they are broadly developed in accordance with these findings. A successful example is the UK Environment Agency's (EA) Modelling and Decision Support Framework (MDSF), which has been widely applied in support of Catchment Flood Management Plans and Shoreline Management Plans. This success is largely attributed to the flexible nature of the software which aggregates results from external models, reducing the complexity of use, and the ongoing user support and training. MDSF2 is currently being developed and the main drivers of this are the move to a more risk-based approach (based on the RASP methods, HR Wallingford, 2004, Gouldby *et al*, 2008) and the Environment Agency's desire for software which is as platform independent as possible - corroborating some of the findings of the review (Surendran et al, 2008).

2 FRAMEWORK FOR LONG-TERM PLANNING

2.1 *Aspects of integration*

Successful support to long term planning requires the following:

- A common *Conceptual Framework* which seeks to understand and formalise the full range of issues that stakeholders may pose (FLOODsite, 2008c).
- A supporting *Methodological Framework* which is a translation of the conceptual framework into an analysis process containing tangible algorithms, methods and model interactions. This framework is based on the Source-Pathway-Receptor-Consequence model tailored towards flooding (Sayers *et al*, 2002), which has been widely accepted throughout FLOODsite (Figure 1).
- An extendable and adaptable *Technological Framework* which considers the software and associated development protocols to be used to enact the methodology framework and crucially display the output risk metrics.

The Methodological Framework is the focus of this paper, and to this end, the modules in Figure 1 are briefly described below:

- *Source*. Traditionally the source module is used to derive the source terms which may be the precipitation, the catchment run-off, the inflows to the river system or the in-river or coastal water levels. The source terms are defined here as all elements upstream of the first management intervention.
- *Pathway*. This is used to describe the pathways including the important flood characteristics such as inundation depth, duration and velocity. The pathway module starts from the first management intervention and characterises the path through to the receptor terms, taking account of all upstream probabilities (e.g. precipitation, event, defence performance), to provide the probabilistic depth and velocity grid for the floodplain.

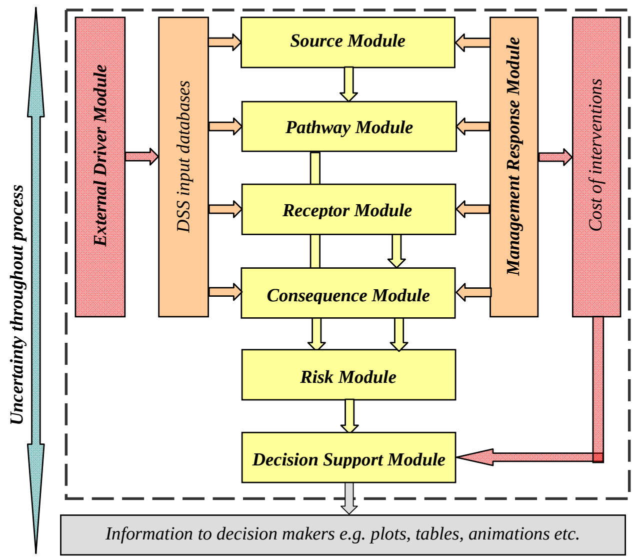

Figure 1: Outline of methodological framework supporting a general DSS tool

- *Receptor*. This is where the receptor information is collated i.e. the receptor exposure based on location, number and characteristics e.g. residential property, infrastructure, designated habitats.
- *Consequence*. This includes receptor damage and vulnerability information. More complex impacts such as social equity, environmental degradation, habitat reduction etc. are included qualitatively as the methods for quantifying these in terms of economic damage are still at an the embryonic stage.
- *Risk*. This integrates the outputs from the pathway consequences modules to provide the basic risk metrics. The outputs are expressed quantitatively (e.g. monetary value, expected economic damage), by category (e.g. high, medium, low) or descriptively.
- *External driver*. This is used to define the changes in the flood risk system due to autonomous events. These are implemented at different stages of the analysis as they affect different terms, for example, changes to the source may include altered loadings due to climate change.
- *Management response*. This allows for structural and non-structural intervention options to be described in simple terms reflecting physical change (e.g. a dyke crest level), or likely reduction in either receptor exposure or vulnerability. This module also includes option costs.
- *Decision support*. This integrates results from all previous modules into performance indicators for pre-specified criteria (e.g. robustness, adaptability) which can then be used in the evaluation of the preferred strategic alternative. These criteria will be used in the context of different analyses e.g. present value, risk reduction, benefit-cost to provide useful and credible guidance to decision makers.

A distinction is drawn between items which the flood risk manager has no influence over in the context of FRM and those which he has direct influence over. These are defined as (Floodsite Task 14):

- *Scenarios*. These include changes to the sources of risk (climate change, sea level rise, population growth, macro-economic developments), and to a lesser extent some features of the pathways and receptors of risk (e.g. societal resilience, attitudes, preparedness; ecological developments)
- *Strategic Alternatives*. This is the management response which includes actions to reduce the probability of flooding as well as the vulnerability of receptors. A strategic alternative typically consists of a sequence of portfolios of measures through time.

2.2 *Scenario development*

Scenario development involves moving from qualitative coherent storylines about the future, to the more detailed quantitative parameters which are explicitly represented in the risk models (e.g. RASP). A key element here is differentiating between global parameters such as climate change that have limited dependence on regional activities, and more localised parameters such as socioeconomic change, which may be driven by regional influences. These local and global aspects can be separated into two distinct axes:

- *climate change* represented in terms of the global emission scenario that in turn is characterised by a single continuous parameter of the rate of sea level rise (the rate of sea level rise increases as carbon emissions increase) and associated other climate changes; and
- *socioeconomic change* represented in terms of regional growth that in turn is characterised by a single continuous parameter of housing numbers and associated other changes (population, GDP, market forces etc.)

On these axes, a future space can then be bounded through identifying the "plausible" extremes of these ranges (Figure 2). Consider the Thames Estuary pilot application. For this, the range of climate emission scenarios is taken from three sources UKCIP02, Defra (2006) and HRW (2005). The extreme scenarios are the UKCIP02 'Low' and 'High++' (HRW, 2005), which are downscaled and designed specifically for the Thames Estuary region (FLOODsite, 2008a). Here, Medium corresponds to the Defra emission scenario. For the socioeconomic axis, a low, medium and high growth scenario can be defined, based on historic trends and expected projections (e.g. housing, population, GDP, market forces) to inform the likely growth through to 2100 (FLOODsite, 2008a).

Ideally the entire scenario space should be considered in the flood risk analysis to ascertain how a given strategic alternative performs regardless of reality of the future - a potentially exhaustive task. Two approaches to resolving this computational constraint have been explored in Floodsite; the so-called info-gap methods (Hall *et al* - see Floodsite Task 20) and structural response surface methods (described here in Section 3.4).

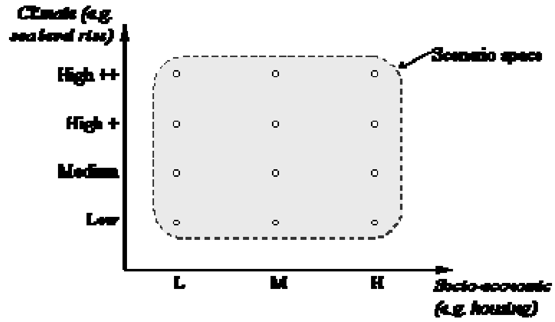

Figure 2: Plausible future climatic and socio-economic scenario space at time t

2.3 *Developing the management strategy*

Various approaches exist to support the construction of possible management responses through time (e.g. Middelkoop *et al*., 2004; OST, 2004; De Bruijn, 2005). These are typically either:

- *top-down* whereby a guiding philosophy is adopted to drive the nature of the management response; or
- *bottom-up* whereby the response is true to its definition - responsive to the anticipated change in risk compared to the perceived tolerable risk.

In FLOODsite a top-down approach has been adopted (FLOODsite, 2008a) based on extended concept of resilience-resistance (Figure 3). Different strategic alternatives reflect the preferred management paradigm - either resistant (e.g. heavily engineered solutions) and resilient (allowing for system to flood and then recover) – as well as the degree of influence the FRM decision maker has over people behaviour and spatial planning.

Top-down approaches applied in isolation can of course be impractical and unrealistic, rapidly losing buy-in. Hybrid methods that constraint the top-down methods with known bottom-up constraints regarding the timing and nature of large-scale external drivers in considering the response e.g. limits to Thames Barrier operation beyond 2070 or the hosting of 2012 Olympics, defence deterioration etc. In addition to these strategic management alternatives, the 'do nothing' or 'walk-away' case is essential to assess the baseline reference risk.

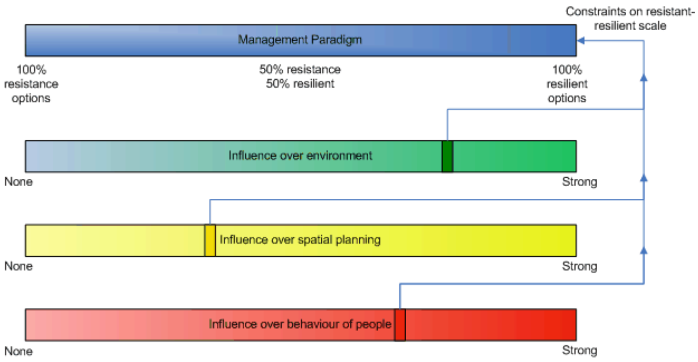

Figure 3: A structured approach to storyline development based on resilience-resistance concepts and influence of secondary guiding principles on these in developing strategic alternatives

2.4 *Evaluating performance*

The decision support system (or more appropriately referred to as a discussion support system) is intended to assist the decision maker in evaluating the:
- performance of a strategic alternative in the context of different socioeconomic and climatic futures
- performance of different aspects of valuing.

In FLOODsite, various measures have been identified as essential to this process (FLOODsite, 2008a&b):
- *Sustainability*: the ability of a strategic alternative to meet the needs of the present without compromising the ability of future generations to meet their own needs. This is typically linked to social, ecological and economic considerations as well as the two up-and-coming criteria: robustness and adaptability.
- *Robustness*: the ability of a given strategic alternative to perform well in the context of all possible future scenarios.
- *Adaptability*: the ability of a given strategic alternative to adapt following monitoring and observation of what actually does happen to ensure no regrets (e.g. heavy investments where the need is not realised).
- *Resilience*: the ability of the system to withstand hazards or extreme events (larger than the design criteria) or shocks i.e. performance under abnormal events.
- *Uncertainty*: recognition and representation of uncertainty due to data, methods and model structures as well as the gross uncertainty associated with future change.

These measures should be captured in so far as possible to provide a suitable evidence base for decision makers.

3 APPLICATION TO THE THAMES

3.1 *Developing the climatic and socio-economic scenario space*

3.1.1 *Climate scenarios*

UKCIP (2002) provides the most detailed future climate change projections for the UK, focusing on four (Low, Medium Low, Medium High and High) emission scenarios, broadly representing the range of conditions which may occur in the future. These are not intended as predictions, since there is no attempt to assign a probability of occurrence to any of these scenarios.

Defra (2006) provides simple numerical ‘adjustments’ for various commonly used parameters, so that all such studies can be assessed on a common basis. These ‘adjustments’ are neither predictions nor projections, but are usually referred to as appropriate ‘precautionary allowances’. This provides an additional climate change ‘scenario’ which is defined as ‘Medium’.

Two further worst-case scenarios for extreme sea level rise were developed by the Thames Estuary 2100 team, namely High+ and High++. These are loosely based on physically possible (but more extreme) changes.

For the Thames pilot study, the High++, High+, Medium (Defra, 2006) ‘precautionary allowance’ and the UKCIP02 Low emission scenarios are adopted to provide a wide range of possible futures (Table 1).

Table 1: Climate change scenarios

Emission Scenario	Year	MSL increase (m)	Fluvial flow increase (%)
Low (UKCIP02)	2050	0.00	0
	2100	0.00	0
Medium (Defra 2006)	2050	0.31	20
	2100	0.94	20
High+ (HRW 2005)	2050	0.64	16
	2100	1.60	40
High++ (HRW 2005)	2050	1.28	20
	2100	3.20	50

3.1.2 *Socioeconomic scenarios*

Numerous detailed studies have been undertaken for the London Boroughs in the Thames Estuary, covering past trends and medium-term predictions of housing, employment and population growth, including the spatial resolution of these changes (e.g. Mc Fadden *et al*., 2007). These take due cognisance of planned developments (e.g. Thames Gateway Project, 2012 Olympics) as well as spatial strategies and published plans from developers and different authorities which may go ahead.

For the Thames pilot, the socioeconomic scenarios are based on predictions through to 2030 for housing growth (Mc Fadden *et al*., 2007) and then three distinct growth scenarios - Low, Medium and High – are based on no further growth, direct extrapolation of the predicted curve and extrapolation of the prediction by a factor of two. The location of the new housing (e.g. Figure 4) is based on increasing the present day National Property Database properties, taking existing densities and housing types into account. These are used together with the predicted increases in inhabitants per house to inform the population growth by borough.

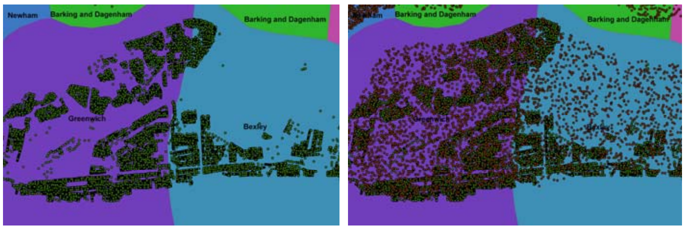

Figure 4: Representation of housing growth for the medium scenario in (a) present day and (b) 2040s in the Greenwich and Bexley Boroughs (within the undefended floodplain)

The 3 scenarios are further enhanced through altering the residential (household durables, susceptibility to damage, and spending power) and commercial (this additionally includes governance, advances in science and technology, legislation and regulation) damages (Table 2).

Table 2: Factor of change to damage curves by 2100

	Low	**Medium**	**High**
Residential – linked to market growth	No change	2 - all housing types	4 - all housing types
Commercial – linked to sector growth	8	15	20

The predicted Gross Domestic Product (GDP) directly impacts on affordability which is typically expressed in terms of Cost per GDP. For London, the predicted annual GDP growth until 2030 is 3.2 % compared with 2 to 2.5 % nationally. Thus for the Thames study, the low, medium and high growth scenarios are assumed to be associated with an annual GDP growth of 2.5 %, 3.2 % and 3.7 % respectively.

3.2 *Developing the management response*

Four strategic alternatives are considered for the Thames pilot (FLOODsite, 2008a):

- *Do nothing*. No active intervention including flood warning and maintenance. No work on defences and no operation of moveable structures. This is similar to the TE2100 P1 Policy.
- *Resistant*. This involves improving the existing system through defence raising and maintenance, over-rotating the barrier and introducing limited non-structural measures (flood forecast and warning).
- *Resilient*. This involves some improvements to the existing system such as limited defence raising, increased storage and managed realignment as well as introducing various non-structural measures (flood forecasting and warning, public awareness raising, emergency planning, business contingency planning and land-use planning/zoning). The aim is to improve the flood management benefit of the floodplains.
- *Highly resilient*. This is similar to the Resilient option; however, numerous non-structural measures are incorporated. These include during event measures such as individual and collective flood fighting activities (temporary defences, informal defence walls, diversion, removal of assets, evacuation, safe havens etc).

The strategic alternatives build on those adopted in the TE2100 High Level Option study (HRW 2007b), supplemented here with additional non-structural measures. The effect is simulated through modifications to the property damage curves and reduced public vulnerability taking due cognisance of likely effectiveness and uptake.

3.3 *Risk-based model*

The risk analysis is undertaken with the RASP flood risk model (Gouldby *et al*, 2008) which is based on the Source-Pathway-Receptor-Consequence concept and is an advancement of the RASP High Level Methodplus (HR Wallingford, Hall *et al*, 2003). This method involves the integration of a full range of loading conditions (extreme water levels) with the performance of defences, represented through fragility curves, allied to a flood spreading method, which enables economic consequences to be established. For a detailed description see HR Wallingford (2007a).

3.4 *Evaluating performance measures*

The approach adopted to evaluate performance measures in the UK and applied to the Thames (FLOODsite 2008a&b) is described below.

3.4.1 *Robustness*

Robustness requires that each strategic alternative is considered in the context all of the plausible future scenarios. For the Thames, the 12 unique combinations of climate and socioeconomic change have been defined. A description of the performance of the strategic alternative over the entire space may then be inferred from these 12 discrete points – providing a performance structure function. It is hence possible to evaluate the performance across all plausible futures through integrating the structure function for a single performance measure. Here, robustness is measured in terms of benefit-cost, where benefit is the reduction in risk (measured in Expected Annual Damages - £EAD) and cost is the capital and maintenance costs associated with implementing measures.

The Thames DSS tool additionally enables users to provide their own perception of how the future may pan out to influence the weighting of this integration (Figure 5). This is carried out computationally through adopting a Monte Carlo sampling of the surface based on user entered perception e.g. optimistic and pessimistic climate change, GDP etc.

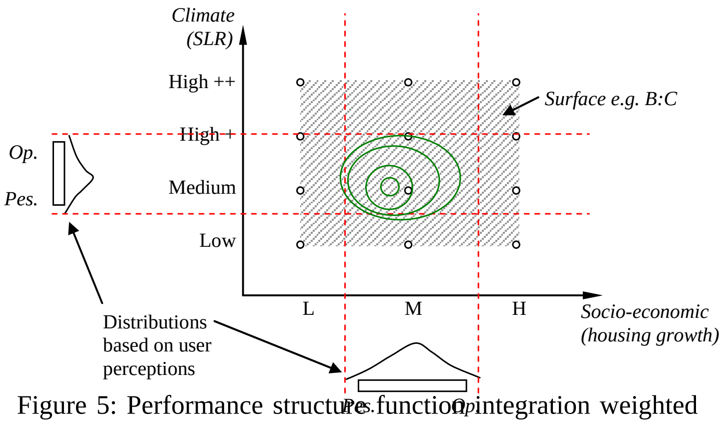

Figure 5: Performance structure function integration weighted in accordance with user entered perceptions (present day analysis)

3.4.2 *Adaptability*

This is based on a decision pathway analysis whereby at each decision point, the number of 'acceptable' solutions through the system from that decision point onwards is expressed relative to the total number of solutions from the initial decision point. This takes into account the decreasing uncertainty about the system at the time of the future decision as there will be some knowledge of what has actually occurred through monitoring e.g. has the predicted high sea level rise been realised?

3.4.3 *Sustainability*

The sustainability is measured through a range of indicators seeking to cover social equity, ecological aspects and long-term affordability, as well as robustness and adaptability. There is no limit on the number of indicators within these and where data are available, these are evaluated. However, the final outcome is a single measure for each of social, ecological and affordability aspects. The present day sustainability is based on a whole life costing approach whereby the greatest in year risk metric over the appraisal period is taken as the present day metric. This present day metric is evaluated for the given strategic alternative in the context of all scenarios and hence an overall performance measure is determined – in a similar manner to the robustness calculation. The following sustainability indicators have been derived for the Thames:

Social

- People risk 1: number of people exposed to 'frequent' flooding. This is defined as the number of people in an area with an annual probability of inundation of 1:75 of exceeding 0m depth
- People risk 2: expected annual deaths / serious injuries. This is defined as annual probability of inundation of exceeding 1m depth multiplied by the number of people at that location.

Ecological

- Area of habitat (derived from Land Cover Map 2000) with an annual probability of inundation of 1:75 of exceeding 0.5m depth (m^2). This includes 13 habitat categories.

Affordability

- Cost per GDP

3.4.4 *Resilience*

Extreme events are implicit within the risk-based methodology adopted in the UK, and thus this aspect is not independently evaluated.

3.4.5 *Uncertainty*

The gross uncertainty associated with modeling the future is handled through the use of scenarios covering all plausible futures. A hierarchical variance-based sensitivity analysis is being used to identify the key uncertainties and their contribution to the variance on estimated risk.

3.5 *Preliminary results*

The prototype tool development is currently underway and hence some of the preliminary results are summarised here. For these, the scenarios considered can be allied to the Foresight World views for ease of discussion:

- World Markets (WM) [high emissions, high growth]
- National Enterprise (NE) [med-high emissions, med-low growth]
- Local Stewardship (LS) [med-low emissions, low growth]
- Global Sustainability (GS) [low emissions, med-high growth]

3.5.1 *Benefit-costs*

Figure 6 provides the risk through time for each strategic alternative in the context of these four views. To aid readability, the uncertainty bands are not shown here. From these, it is apparent that the 'do nothing' option provides a substantially higher damage estimate than the three strategic alternatives - two orders of magnitude larger on the log normal axis. The total EAD values suggest that the resilient options tend to perform better than the resistant options across all future scenarios – and the highly resilient option performs better than the resilient option as expected. However, to truly understand the information, the detailed spatial descriptions of the probability of inundation and EAD need to be interrogated, as there may be local/spatial variations in the tolerable or acceptable level of risk, biasing the preference towards one particular strategic alternative.

Table 3 provides a summary of the present day benefits and costs (FLOODsite, 2008a), adopting the standard Defra discount rates. From this, it is apparent that the Resilient option is the most favourable in terms of Benefit and Cost (BC) for all futures. For a true understanding of these results, decision makers should consider the uncertainty distribution associated with the BC ratios. For example, it may be more favourable to adopt an option with a lower BC ratio if the uncertainty band is narrower, particularly if the entire uncertainty band falls above the tolerable/allowable BC ratio. For example, in Table 3, although the Resilient option is favoured in terms of the overall B:C, the Resistant option has a narrower B:C uncertainty band.

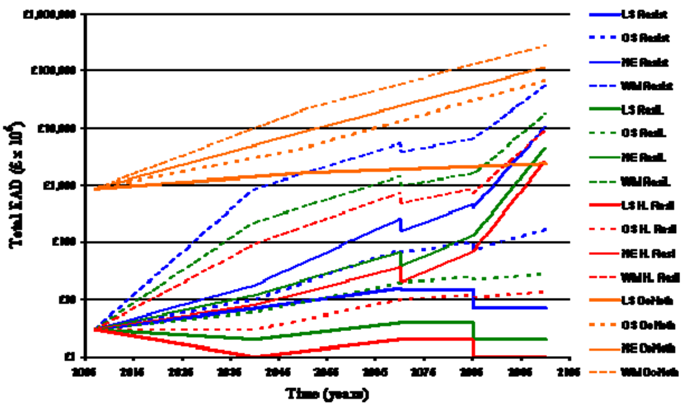

Figure 6: Total EAD for each strategic alternative in the context of each scenario

Table 3: Present day benefits and costs (£ x 106)

	PV Benefit	PV Cost Lower Bound	PV Cost	PV Cost Upper Bound	B:C Lower	B:C	B:C Upper	Uncertainty Band on B:C
Local Stewardship								
Resistant	£39,911	£3,031	£3,631	£4,231	9.4	11.0	13.2	3.7
Resilient	£40,016	£2,986	£3,586	£4,186	9.6	11.2	13.4	3.8
Highly Resilient	£40,035	£3,335	£3,935	£4,535	8.8	10.2	12.0	3.2
Global Sustainability								
Resistant	£271,714	£3,031	£3,631	£4,231	64.2	74.8	89.6	25.4
Resilient	£272,107	£2,986	£3,586	£4,186	65.0	75.9	91.1	26.1
Highly Resilient	£272,188	£3,335	£3,935	£4,535	60.0	69.2	81.8	21.8
National Enterprise								
Resistant	£451,339	£3,031	£3,631	£4,231	106.7	124.3	148.9	42.2
Resilient	£455,152	£2,986	£3,586	£4,186	108.7	126.9	152.4	43.7
Highly Resilient	£456,287	£3,335	£3,935	£4,535	100.6	115.9	138.8	38.2
World Markets								
Resistant	£1,029,228	£3,031	£3,631	£4,231	243.3	283.5	338.6	98.3
Resilient	£1,073,404	£2,986	£3,586	£4,186	256.4	299.3	359.5	103.1
Highly Resilient	£1,082,133	£3,335	£3,935	£4,535	238.8	275.0	324.4	85.6

3.5.2 *Social indicators*

Tables 3 and 4 provide the outputs for people risk 1 and people risk 2. For all cases, the number of people exposed to frequent flooding is high in 2100, with up to ~4 million at risk for three strategic alternatives in the worst case scenarios and just under 6 million at risk for the 'do nothing'. The resilient options show less people at risk of frequent flooding than the resistant option, which is explained by non-structural measures such as flood warning and evacuation planning reducing the floodplain population exposed during events. The expected annual deaths/serious injuries are substantially less for the strategic alternatives than for the do nothing and the resilient alternatives provide a lower expectation than the resistant alternative.

Table 4: Number of people exposed to frequent flooding

	GS	WM	NE	LS	Year
Existing Policy	839,438	839,438	839,438	839,438	2007
	2,620,806	5,895,616	2,328,352	859,323	2100
Resistant	863	863	863	863	2007
	5,817	128,570	9,180	5,053	2040
	85,046	4,404,114	1,210,516	1,267	2100
Resilient	863	863	863	863	2007
	5,838	91,901	5,015	1,225	2040
	42,424	3,947,645	983,858	779	2100
Highly Resilient	863	863	863	863	2007
	5,838	105,332	5,013	1,225	2040
	42,513	3,949,878	982,932	12,464	2100

Table 5: Expected annual deaths / serious injuries

	GS	WM	NE	LS	Year
Existing Policy	26,347	26,347	26,347	26,347	2007
	886,994	3,919,897	1,578,500	25,396	2100
Resistant	69	69	69	69	2007
	244	14,238	385	395	2040
	1,574	409,831	115,701	42	2100
Resilient	69	69	69	69	2007
	244	8,588	551	61	2040
	995	579,376	190,284	39	2100
Highly Resilient	69	69	69	69	2007
	245	13,757	551	62	2040
	995	579,079	108,723	213	2100

3.5.3 *Ecological indicators*

The ecological impacts are measured based on the area of habitat with an annual probability of inundation of 1:75 of exceeding 0.5 m depth (m^2). The habitat is derived from the Land Cover Map 2000. This was established for strategic alternative in context of each world view in 2040 and 2100 (FLOODsite, 2008a). Key observations include:

- the areas of barley, arable bare ground, intensive grassland, grass and rough grass are impacted in all cases;
- the Resilient option results in a lesser amount of heath and heath gorse being impacted;
- the Resistant option reduces the amount of swamp which is impacted.

3.5.4 *Unintended side affects*

The most dominant unintended side-effect of the strategic alternatives in the Thames Estuary is increased floodplain development as a result of improved defences, for example, defence raising or improvements to the Thames Barrier. These more heavily engineered solutions promote a sense of safety in the floodplain, resulting in increased development. This effect is largest for the Resistant strategic alternative – as would be expected. This effect should ideally be reduced within the overall management response, through for example, awareness raising with developers, planners and general public as well as changes in planning policy.

4 LONG TERM PLANNING SUPPORT - DSS TOOL

The Thames prototype DSS tool continues to be developed (Figure 7). This is based on the S-P-R-C model (Section 3.4) and incorporates an initial representation of the robustness calculation (Section 3.4.1) and whole life costing approach to the sustainability indicators (Section 3.4.3).

An important element of the technological development is what aspects of the Methodological Framework are incorporated in the actual tool, which is closely linked to the likely users. For example, in the Netherlands and Germany, the users tend to be high-level policy makers who require simple tools for rapid exploration of “what-if” scenarios. These tools are typically based on libraries of pre-cooked results for the source, pathway and receptor terms which are selected through a simple user interface. The advantage is that the tool is quick to operate and easy to understand, whilst this is offset with the limited flexibility in creating new user-defined what-ifs.

The Thames prototype tool is designed for the more expert user e.g. consultants and as such it has more flexibility to create user-designed what-ifs. The pre-cooked include in-river and coastal water levels, which may be modified in a simple manner to simulate change (e.g. scaled increases), and the pathway and receptor modelling is undertaken on-line. This is made possible as the RASP risk-based model (Section 3.3) has been modified to base the floodplain inflow volumes for each defence system state on expected volumes (rather than sampling the full probability distribution).

Figure 7: Example screen shots for the prototype DSS tool

5 CONCLUSIONS

A three-tiered framework for long-term (>50-100 years) flood risk management planning has been introduced to aid the challenges faced by decision makers. The methodological aspects of this framework have been explored in this paper. Methods for evaluating the performance of strategic alternatives (management response) in the context of different future climatic and socioeconomic scenarios have been described, including measures for robustness, adaptability and sustainability.

Four strategic alternatives were developed for the Thames pilot, the *Resistant*, *Resilient*, *Highly Resilient* and *Do Nothing* alternatives. The management intervention measures for these alternatives are planned for 2040, 2070 and 2085 and hence the model was evaluated before and after the planned interventions as well as in the present day and the year 2100. Preliminary results in terms of economic, social and ecological risks were derived in the context of four future scenarios, akin to the Foresight world views. The RASP-based model was adopted to simulate the flood risk system, including source, pathway and receptor, and providing the overall hazard (probability of inundation) and risk (e.g. Expected Annual Damages).

Through a formal robustness analysis the *Resilient* strategic alternative performs best.

The DSS continues to evolve with the inclusion of formal methods from assessing performance in terms of robustness, adaptability and sustainability in the context of all possible futures.

The study has highlighted a number of key findings:

- *Building strategic alternatives* for long-term flood risk management in the context of an uncertain future remains a challenging task. The structured framework trialled here provides a top-down approach to developing the alternatives, based on resilience and resistance-based principles. While these are useful in that a wide range of potential management interventions (structural and non-structural) is considered, they should not be applied without a fundamental understanding of the flood risk system and the existing infrastructure, e.g. main drivers of change (e.g. sea level rise), the likely timing of these (e.g. critical in year x), etc. Ideally, an initial, more general, study should be undertaken to ascertain these critical spatial and temporal points to aid design of the strategic alternatives.
- *Evaluating the ‘best’ option*. It is important to recognise that the results are intended to provide an evidence-base not a solution to decision makers and it is unlikely that one best solution exists. For example, consideration of the present value benefit cost suggests the Resilient strategic alternative is more favourable, whereas consideration

of the uncertainty bands suggests the Resistant strategic alternative may be more favourable as the bands are narrower. This highlights the needs for "discussion support systems" to aid stakeholder dialogue and concensus building.
- *Richness of information*. The shear volume of the available information (e.g. spatial/temporal resolution; consideration of all defence system states; risk attribution; uncertainty etc) can be overwhelming. A focus on rich and meaningful statements on risk and uncertainty that "aid" rather than "confuse" decision making is a vital components of the DSS presented here.
- *Multi-stage decisions*. The timing and nature of the interventions over the appraisal period is essential to FRM in the long term. A decision made today may impact what options are available at a future date. For example, the Resistant option may be favoured today if it performs well in all possible future scenarios; however, it may result in substantial infrastructure investments, the benefits of which may not be felt should the actual future be linked to low growth and climate change.

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