Towards the next generation of risk-based asset management tools

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h1 INTRODUCTION

Ensuring the acceptable performance of flood defence assets and the asset systems they compose is a considerable challenge. The wide variety in asset types (from natural channels to engineered walls, embankments, gates and pump systems) and the interaction between them and their physical setting further complicate the task. The concepts of system analysis, reliability and structured option searching all provide useful decision aids. These advanced tools and techniques enable critical assets and asset components to be identified and investment options to be compared and prioritised on a common footing (from data collection and further analysis through to actions to repair, renovate, replace or indeed remove assets).

Over recent years the principles, methods and tools to help support better asset management have significantly advanced (Environment Agency, 2002 & 2010, Sayers and Meadowcroft, 2005, Simm *et al*, 2005, USACE, 1993 & 2009). All of these approaches recognise the need to prioritise limited resources to best effect (maximising risk reduction and maximising beneficial opportunities) whilst taking account of present and future uncertainties.

To provide meaningful evidential support the underlying analysis must be:

- ***Systems-based*** - Recognising that the protection afforded to a given person, property or other valued feature in the floodplain (i.e. receptor) reflects the performance of the asset system as a whole and how it responds under a wide range of loads (and not the performance of an individual asset during a single design storm).

- ***Evidence-based*** – Recognising the need for transparent and auditable/challengeable evidence, whilst formally acknowledging that much of this evidence is uncertain.

- ***Hierarchical*** – Allowing for progressive refinement of the data and analysis to reflect the demands of the decision at hand (being *just* sufficient to ensure a robust choice and one that further refinement would not alter).

- ***Wide ranging*** – Enabling fixed and operational defence assets to be seen as only one, albeit important, component of a wider flood risk management strategy (where structural and non-structural measures act in concert to manage flood risk, allowing the advantages of one action to compensate for disadvantages of another).

This paper explores the state-of-the-art in assessing the performance of individual assets and asset systems. It provides a discussion of reliability analysis and system-based risk analysis tools. It also provides a forward look towards the practical application of formal optimisation tools that support the development of robust management strategies.

h1 OVERVIEW OF ASSET MANAGEMENT

An *asset* can be described as any feature that is actively managed to reduce the chance of flooding, including:

- A linear asset – e.g. a raised defence (levee or dyke)
- A point asset – e.g. a pump, gate or culvert trash screen
- The watercourse – e.g. the vegetation and sediment within a channel
- The coastline - e.g. a groyne, beach or backshore

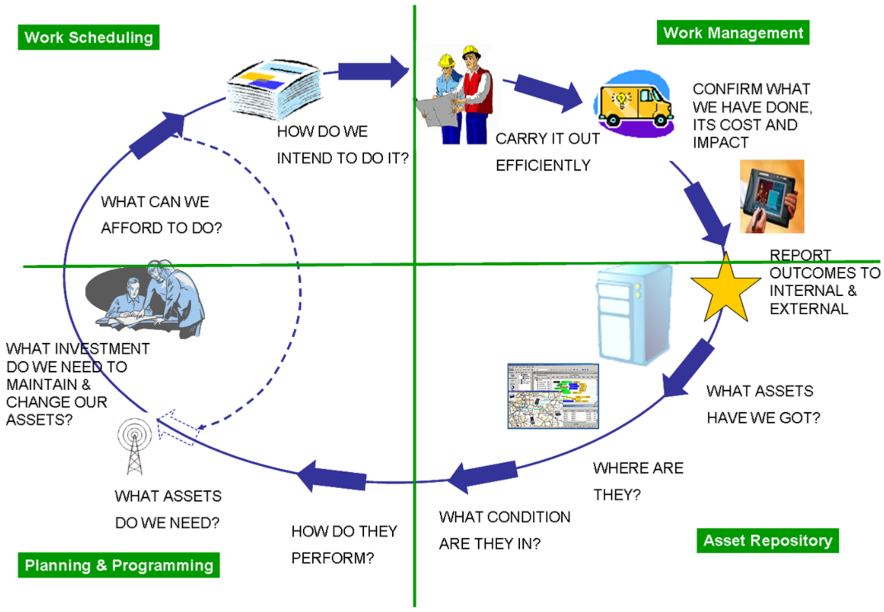

Figure 1 Asset management lifecycle (Environment Agency, 2010)

Delivering the whole life asset management in practice as outlined in Figure 1, presents a number of analytical challenges, including:

- ***Incomplete understanding of the asset base*** – The physical dimensions and engineering properties of the asset base is often unknown or poorly resolved (although significant effort has been devoted to improving the data in recent years – see for example Environment Agency, 2007a, USACE, 2008).

- ***Incomplete understanding of structural/operational performance*** – Assets are often a complex composite of structural components with spatially varying materials and profile. The physical processes that lead to failure are equally complex and often poorly understood and can be costly to analyse.

- ***Variability of impact*** – The potential impacts of failure can vary markedly in space and hence not all assets are equally important nor require a common standard or condition.

- ***Decision complexity*** – The invariable complexity of an asset system and the floodplains they protect make expert and engineering judgement difficult to apply. This often leaves asset managers with a rational doubt as to which action to take and when.

- ***Affordability*** - Budgets are limited and it is common to have insufficient resources (time and money) to undertake all "desirable" works. For example, in the US it has been estimated that *$2.2* trillion would be needed to raise all linear defences (levees) to the desired standard and condition (Stockton, 2009).

H1 BETTER ASSET MANAGEMENT – RISING TO THE CHALLENGE

Around the world innovative tools and techniques are being developed to better support asset managers in overcoming the challenges they face (Havinga and Kok, 2005, USACE, 2008, Environment Agency, 2010). This is in recognition that structural responses (including the on-going management of existing assets) will continue to play a major role in flood risk management into the future (e.g. *"A Safe Public and Reduced Economic Losses by means of Reliable Levees – part of an Integrated Solution to Flooding"* taken from the USACE, National Committee on Levee Safety, October 2008).

Common threads emerge from these activities including a drive for:

(a) Better evidence on individual assets

In England and Wales, the Environment Agency has stated that it will have succeeded in its asset management role when it knows exactly: "*what assets we have; where they are; what standard of protection they provide; how they were constructed; their current engineering integrity; and, how they work together to provide a flood defence system.*" (Tim Kersley – Head of Asset Management Environment Agency, 2008). Similar, seemingly basic requirements, can be seen to exist around the world and across sectoral disciplines (within rail, road etc) and are a central thrust of the USACE National Levee Safety Program (USACE, 2008).

Better evidence can be characterised as:

- *An improved understanding of the performance of the individual assets* **–** the importance of good quality data can not be underestimated, including direct access to basic parameters such as the location, condition and the standard of protection an asset affords as well as more accurate and useable information on probability of failure, dominant failure modes and critical uncertainties.
- *A better understanding of asset performance and their individual contribution to the residual risk* – including direct access to information on how an individual asset contributes to the overall performance of the system and its contribution residual risk. (see Figure 2).

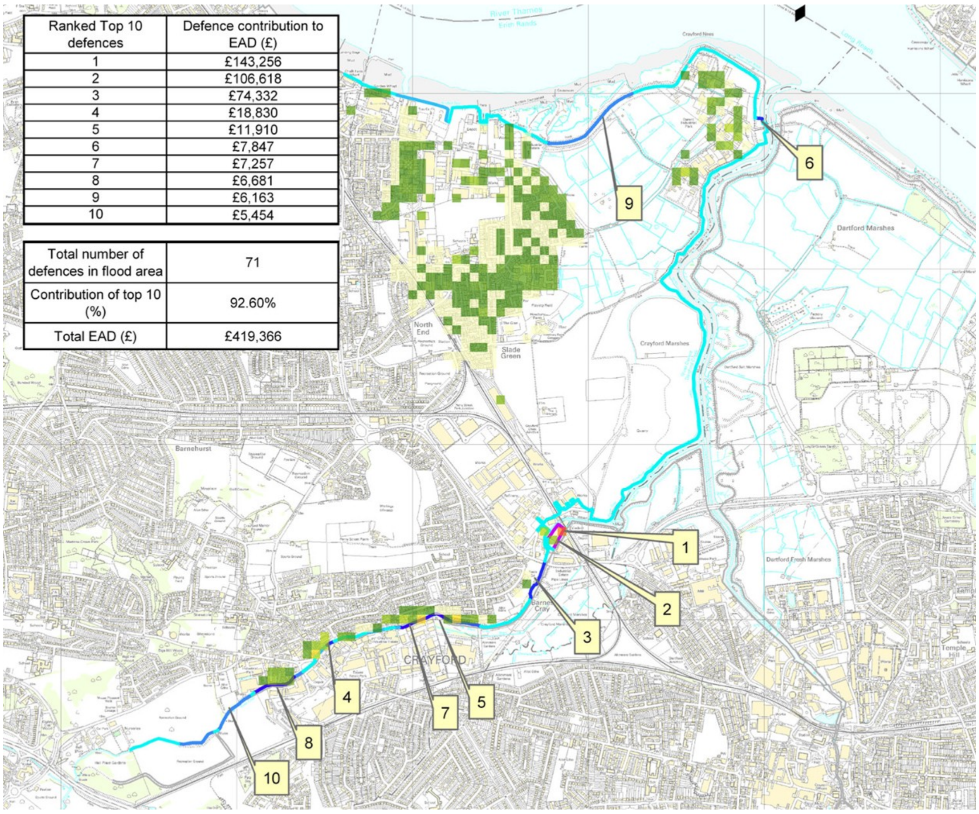

Figure 2 The expected annual damages attributed to individual defence assets with an asset system (as well as spatially within the floodplain)

(b) Better decision making

All asset managers seek to make *good* investment decisions; decisions that minimise whole life costs and maximise environmental gain whilst ensuring communities are appropriately protected from flooding now and in the future. Increasingly, consistent analysis techniques (Sayers and Meadowcroft, 2005, Gouldby *et al*, 2008, Gouldby *et al*, 2009a) and decision support tools (Surendran *et al*, 2008. McGahey and Sayers, 2008, Environment Agency, 2010) are available to support decision making. These tools and techniques provide a step change in the *"richness"* of the evidence provided to decision makers at all levels (across national, flood system and individual asset levels). In particular, they provide:

- *An improved understanding of the role that an individual asset plays within a larger asset system* – by highlighting those assets, within a system of assets, which contribute most to residual risk. Further disaggregation of the risk, to highlight the separate contributions from breach and overtopping, enables the asset manger to distinguish the relative importance of raising crest heights or improving asset strength.

- *A better understanding of the impact of uncertainty within the estimated risk* – by highlighting those assets that contribute most to the uncertainty in the estimates of risk the asset manager is able to prioritise the need for further data collection or engineering investigations on a common basis alongside structural measures. Structured sensitivity analysis (Gouldby *et al*, 2010) can help highlight critical epistemic uncertainties (such as within toe level, crest level, and asset condition as well as the modelling methods, Figure 3). (*Note*:

Model structure and local anomalies (reflecting the heterogeneity of the soil conditions) are not easily incorporated into such an analysis and continue to demand significant expert input.)

- *The ability progressively to refine the analysis detail* - Attributing risk to an asset, and an associated understanding of the critical contributors to the uncertainty in that estimate, enables the decision maker to target further analysis or data collection as appropriate for the decision in hand. Although, a tiered analysis is a well recognised concept (e.g. DETR, 2000) until recently it has been very difficult to achieve a hierarchical process whereby data and models evolve (rather than change) from one tier to the next (Sayers and Meadowcroft, 2005).

- *Support to develop optimal investment strategies* – Asset managers face difficult choices (i) *Where* to act? (ii) *When* to action, now or later? and (iii) *How* to act, collect more data, undertake more analysis or intervene? Increasingly it is not possible, or acceptable, to answer these question on intuition. The utility of formal optimisation methods, and their applicability and practicality for use in flood risk management, is now being explored and trialled with considerable promise (McGahey and Sayers, 2008, Philips *et al*, 2009, Woodward *et al*, 2010).

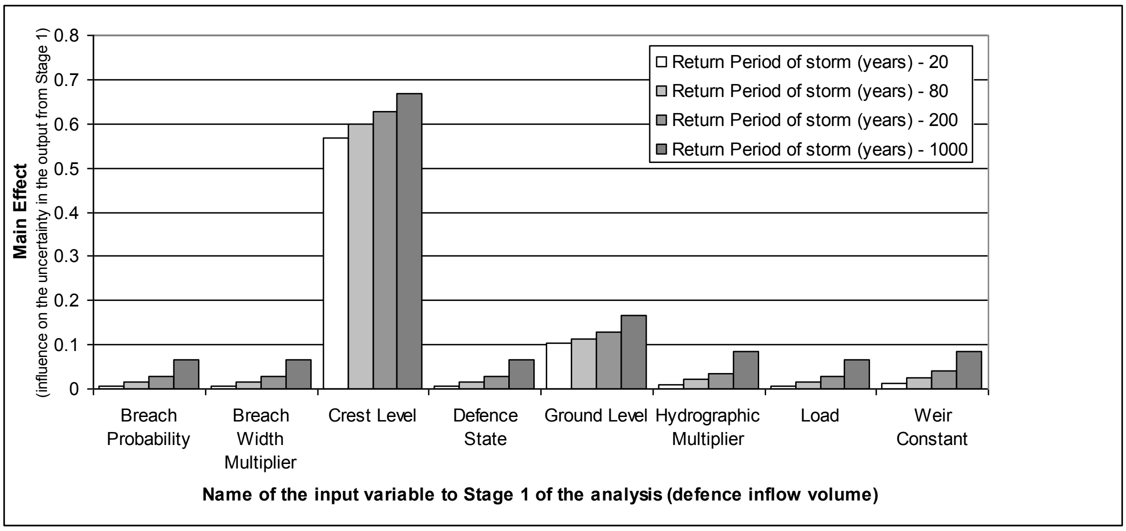

Figure 3 Relative importance of the uncertainties within asset descriptors and model parameters to the uncertainty within the risk attributed to a specific asset (Gouldby *et al*, 2010)

H1 ASSET MANAGEMENT TOOLS AND TECHNIQUES - KEY FEATURES

Good asset management decision aids share a number of good practice principles (Table 1).

Table 1 Best practice principles in support of asset management tools

Best practice principles in support of asset management tools	
Appropriateness	Appropriate level of data collection and analysis reflecting the level of risk associated with an asset and the uncertainty within the decision being made.
Understanding	Improving understanding of assets and their likely performance.
Transparency	Transparency of analysis enabling audit and justification
Structure	Structured knowledge capture encapsulated through fault tree, breach potential etc.
Tiered assessment and decision making	in terms of both data and modelling approaches.
Collect once use many times	Reusing data through the hierarchy of decision making stages and supporting tools – from national policy to local detail.
Simple use and practical	There is a significant challenge is converting good science in practical tools. Therefore, even though the underlying analysis may be complex, the user experience must be well-constructed and intuitive.

The translation of these *good practice principles* into practical tools (that provide the richness of evidence described in earlier sections) is receiving considerable attention world-wide (*e.g.* Infrastructure Management Theme of the Flood Risk Management Research Consortium, the Environment Agency R+D programme and USACE research agenda). Typically these tools have a number of common features as shown in Figure 4 and discussed below.

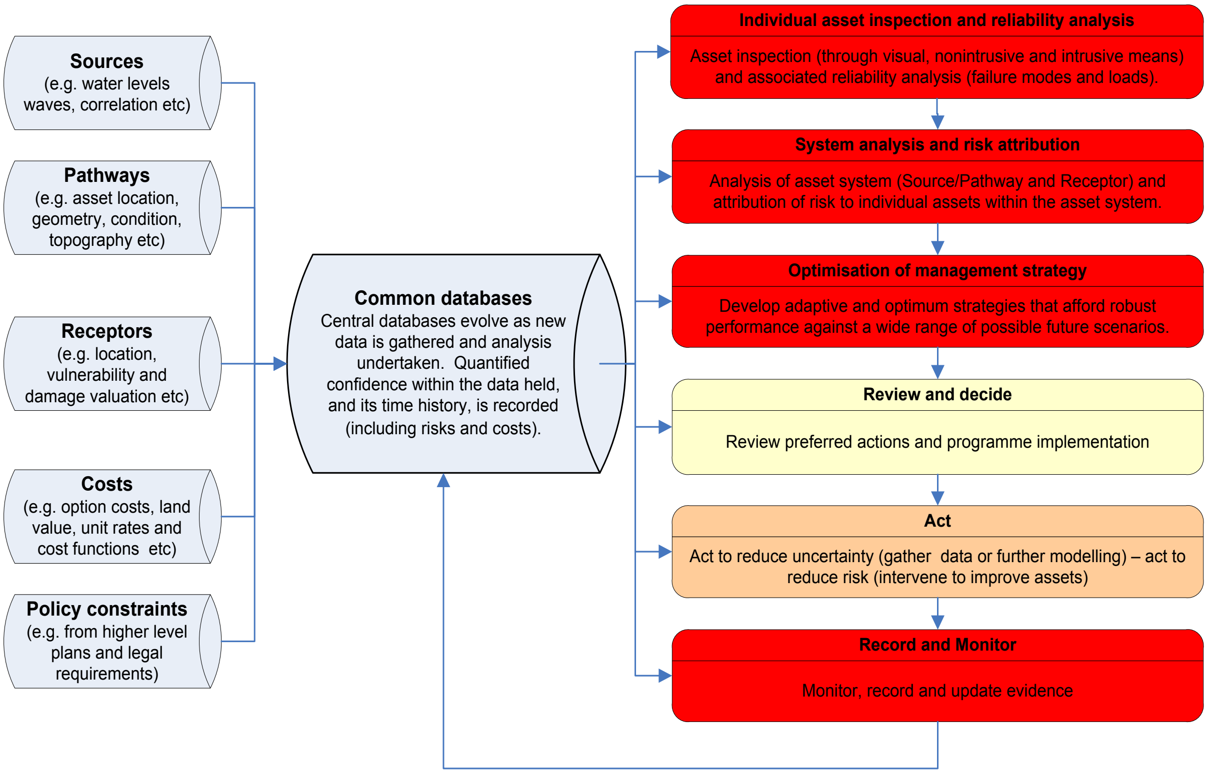

Figure 4 Asset management toolset - basic building blocks

H1 COMMON / CENTRAL DATABASES

Common databases provide a means of accessing data and progressively evolving data quality (supporting a 'collect once, use many times' policy). The importance of such a system, and the difficulty in achieving it in practice across multiple stakeholders, can not be under-estimated. Within England and Wales for example, the National Flood and Coastal Defence Database (NFCDD) provides a common home for asset data – regardless of ownership – but significant difficulties associated with access and data quality have been encountered. Similarly, in the US, a National Levee Database is currently under development. Although not without technical and organisational difficulties an *NFCDD* (or its equivalent) is a fundamental component of any asset management system without which, data collection and analysis activities are easily repeated and effort wasted.

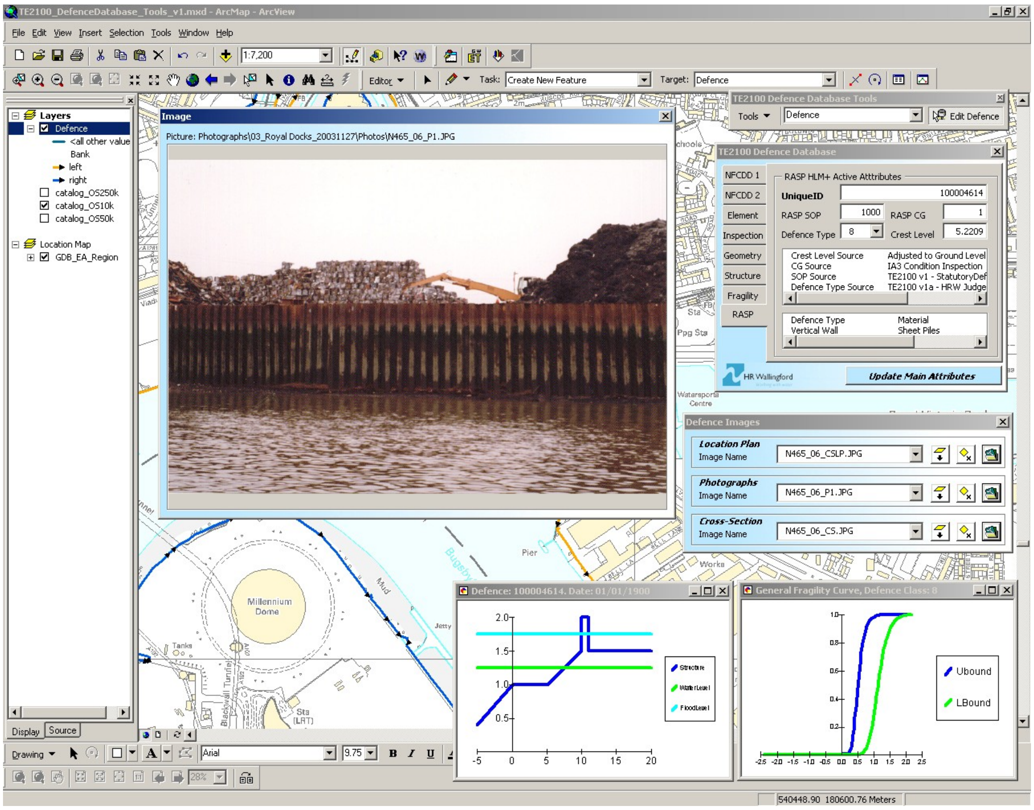

Figure 5 A common asset database as used and shared across the Thames Estuary Planning for Flood Risk Management 2100 (Sayers *et al*, 2006)

H1 UNDERSTANDING THE PERFORMANCE OF AN INDIVIDUAL ASSET

Understanding the performance of an individual asset under load is the first step towards understanding how best to manage it. The geometry and structural components of the asset together with the loading it experiences (e.g. waves, water levels etc) and the associated probability of failure are all important. Inspection methods (intrusive and non-intrusive, Long *et al*, 2008) and reliability analysis (see below) provide vital aids to the asset manager in developing this understanding.

h2 Asset reliability

The reliability of an individual asset can be expressed in a number of ways: *(i)* the probability of failure during a given time period (for example a year); *(ii)* the conditional probability of failure for a given load (Figure 6), referred to as a *fragility curve (*Casciati and Faravelli, 1991, Sayers *et al*, 2002).

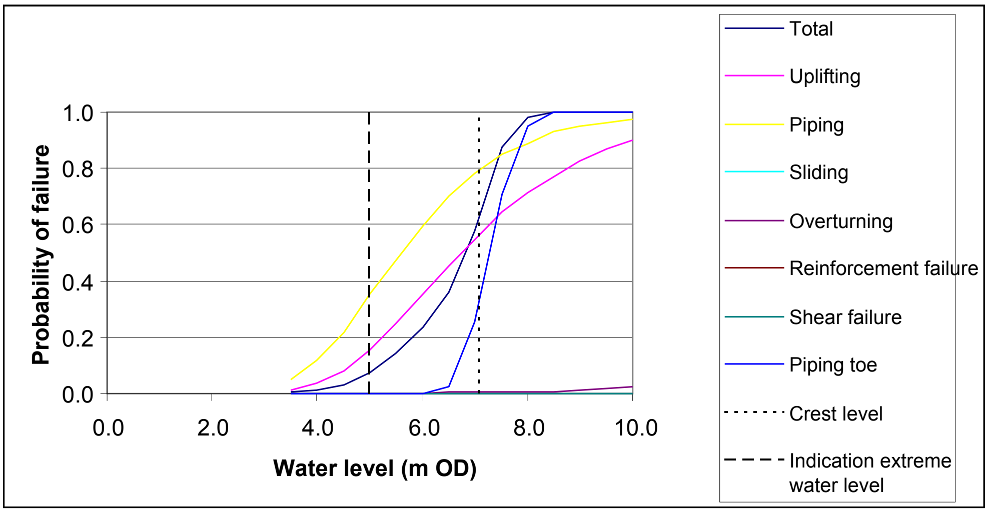

Figure 6 A typical fragility curve based on the reliability analysis for a defence in the Thames Estuary

Reliability methods can be used to derive either the annual probability of failure or a fragility curve (Melchers, 1999). This involves the specification and evaluation of a so-called Limit State Equation, in general form:

$$p(f) = P(R - S) < 0 \tag{1}$$

Where

P(f)	=	Probability of failure (typically defined as breach, blockage or failure of a pump)
S	=	Loading on the asset
R	=	Resistance of the asset to the loads

In traditional reliability analysis, the unconditional probability of failure (for example the annual probability of failure) is determined through integration of the joint density function (f_{RS}) of the loads and strengths over the region where the limit state is exceeded (i.e. *R-S<0*):

$$p(f) = P(R - S) < 0 = \int_{af} \int f_{RS}(r, s) \tag{2}$$

To derive a fragility curve, a similar process is followed. In this case, however, the *loads* are treated as known deterministic variables (hence the failure probabilities are conditional on the loads) and the probability of failure is assessed for specific loading events (by integrating the probability distributions assigned to variables and parameters that describe the *strengths (S)* of the asset over the failure region, i.e. the load exceeds the sampled strength).

A set of high level fragility curves that represent the typical assets found in the UK provide a common reference of asset fragility. These high level curves are based upon a limited number of readily available asset characteristics (e.g. from the NFCDD). The high level classification (so-called RASP types, Hall *et al,* 2002) differentiates the assets first by seven major types (fluvial – not exposed to wave action - or coastal – exposed to wave action, vertical or sloping) and then by their width (narrow, <6m crest, or wide, >6m crest) and the nature and extent of the surface cover protection. A restricted set of limit state equations are then used within a reliability analysis to develop the fragility curves for each RASP defence based on three indicator failure modes:

(i) Overtopping – periodic overflow of the defence due to wave action (coastal defences only);
(ii) Overflow – when the water level is above the defence (coastal and fluvial);
(iii) Piping – when the water level is below the crest level of the defence (fluvial only) (Environment Agency, 2007).

To determine an initial estimate of the fragility of a specific asset, the high level fragility curves can be combined with local scale data on asset condition (either measured or estimated), its crest level as well as the local loading conditions to which the asset is exposed. This allows the high level fragility curves to utilise available local data (without increasing analysis effort). (*Note:* for example, Gouldby *et al*, 2010 provides a full list of the local parameters used to complement the high level fragility curves as part of the National Flood Risk Assessment routinely undertaken for England and Wales.)

In many cases it is appropriate to refine the understanding of asset reliability beyond the high level fragility curves described above. This may be in response to the importance of a particular asset in terms of managing risk (e.g. a major structure such as the Thames Barrier) or where doubt remains as how best to intervene and further investigation is required. A structured procedure to derive more credible asset specific fragility curves is provided in Table 2.

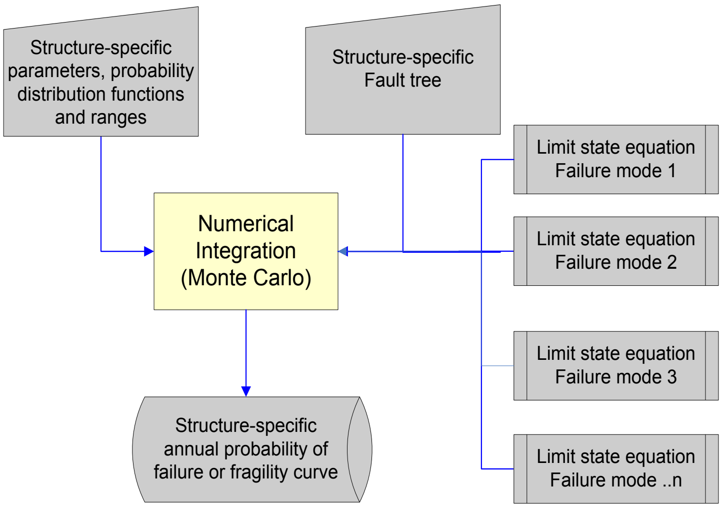

Figure 7 Building blocks of a structured Level III reliability analysis (as implemented within the RELIABLE software)

To support a detailed analysis of reliability, a flexible software tool (RELIABLE) has been developed based on a Level III reliability method. The basic building blocks of a Level III analysis and the way in which these have been enacted within RELIABLE are shown in Figure 7. In particular, RELIABLE contains:

- ***A fault tree drawing tool (OpenFTA)*** – enabling the user to construct an asset specific fault tree using failure mechanisms (and modes) linked with standard operators (AND, OR, NOT etc).

- ***A library of limit state equations*** - Limit state equations are made available to the user (currently describing 72 failure modes). These can be extended and made bespoke to specific assets through user defined LSEs (either based upon empirical formulae not yet coded within the Failure Mode Library or based on the emulation of more complex models).

- ***A database of parameters and variables*** - For a given flood defence structure, values must be supplied for each parameter and variable required by the relevant LSEs. A value may be fixed or specified as a statistical distribution with associated parameters.

- ***A Monte Carlo simulation*** - A large sample of input variables (strength and load) are generated and the annual probability of failure, conditional failure probability (where the hydraulic loading conditions are specified as fixed variables and then the strength variables systematically varied) and other related statistics calculated (van Gelder *et al*, 2008). The number of simulations required to achieve a converged estimate of the probability of failure, and thus the calculation time, depend on the chance of asset failure. Most structures in coastal and river engineering, for example, exhibit a relatively high probability of failure (i.e. a relatively low reliability – typically an annual probability of failure >0.005) compared to structures in other industries where reliability analysis is routinely applied (e.g. for the structural components of a nuclear power plant or mechanical components of an aeroplane the typical reliability will be much higher <0.0001). This presents Monte Carlo simulation as a viable and flexible numerical integration tool in the context of the majority of flood defence assets. In the case of a complex failure surfaces, where the response of the structure exhibits discontinuities, run times can increase to ensure such discontinuities are captured. In such cases, innovative sampling techniques (e.g. importance sampling) are techniques that could be usefully employed within RELIABLE to minimise run times (van Gelder, 2008a).

In generating the asset specific fragility information it is important to understand how these relate to more traditional assessment methods (based on partial factors of safety). An interesting comparison was completed as part of the Thames Estuary studies (Simm *et al*, 2008) which suggested that a 10% chance of failure can be expected at the design load (reflecting the various safety factors inherent within traditional design) and a 50% chance of geotechnical failure when the Factor of Safety is equal to 1. These figures are useful *rules of thumb* that can be used to give confidence in the results of the more complex full reliability analysis.

Table 2 A structured procedure for the assessment of asset fragility (adapted from Simm *et al*, 2008)

Step	**Description**
1. Define asset function	A flood defence asset rarely acts solely to protect from flooding; often functioning as a valuable environmental habitat, navigation or amenity asset. Understanding the multi-functionality of the asset is an important precursor to understanding how to manage it.
2. Establish incident loading	An asset may be subject to a range of loading conditions – joint wave and water levels, marginal high or low water levels, groundwater levels or perhaps a combination.
3. Identify failure modes	The *failure mechanisms* (processes that can lead to ultimate failure) and the *failure modes* (a process that defines ultimate failure) also need to be described. To avoid unnecessary effort, conventional deterministic approaches can be helpful to eliminate unrealistic failure mechanisms (i.e. relative low probability individual events in comparison with the likely overall reliability of the asset).  Wave impacts on cracks (Flood*site*) Surface erosion due to overtopping (Flood*site*) Internal cracking (Flood*site*) Fine fissuring – FRMRC WP 4.1 Mark Dyer Research into failure mechanisms continues to be vital to better understand asset performance (e.g. Allsop *et al*, 2007, Dyer *et al*, 2009, Sentenac *et al*, 2009)
4. Prepare a fault tree	Fault trees provide a useful visual, and formal, encapsulation of the failure mechanisms and their relationship to the failure modes.
5. Identify / establish appropriate Limit State Equations	An appropriate model needs to be selected to represent each failure mechanism\mode. In many cases empirical relationships will exist and these can be easily translated into the form of a Limit State Equation (utilised in the reliability analysis – see below). In some cases, the failure mechanisms are complex (e.g. slip failure) and demand the use of more sophisticated models (for example, traditional slope stability analysis or finite element model). It is possible to link such models within the reliability analysis (Lassing *et al,* 2003 Vrouwenvelder, 2001a&b) but this is often difficult and can incur an unacceptable runtime overhead. Emulation of these more complex models, through Artificial Neutral Networks for example, provide an efficient and effective means to enable such complete mechanisms to be incorporated into the reliability analysis (Kingston *et al,* 2007).
6. Document uncertainty in model variables and parameters	The engineering parameters, and the empirical variables, within the Limit State Equations will not be perfectly understood. Describing the uncertainty within these relationships and the supporting data on the asset of interest is an important task. In describing the uncertainty it is important that this process is comprehensive (ignoring uncertainty at this stage is to assume the data is perfectly known). Two groups of uncertainties can typically be distinguished (USACE, 1999, Environment Agency, 2002): • *Natural variability* (aleatory uncertainty) **-** Uncertainties that stem from known (or observable) populations and therefore represent randomness in samples. • *Knowledge uncertainty* (epistemic uncertainty) - Uncertainties that come from basic lack of knowledge of fundamental or measureable phenomena. Perhaps most critically, it is important to record the assumptions made regarding the uncertainty in the variables and parameters and the associated supporting evidence for these choices. This provides a vehicle for peer review and audit (Hall and Solomatine, 2008).
7. Undertake reliability analysis and display results	Once the above inputs have been established the reliability analyses can be undertaken. For each hydraulic loading condition a series of simulations (across the uncertainty bands for each input parameter) are resolved. Failure arises in a particular case when the combinations of parameter values in the limit state function (Z) yield a value for Z which is less than or equal to zero. The probability of failure for that given loading condition is then the number of times when the simulation gives Z as less than or equal to zero divided by the total number of simulations. Repeat for all hydraulic loads (Kortenhaus *et al*, 2002, Lassing *et al*, 2003, Simm *et al*, 2006, van Gelder *et al*, 2008a)
8. Display results	Present the results of interest (annual probability of failure, fragility curve etc).

h1 SYSTEM ANALYSIS AND ATTRIBUTING RISK TO INDIVIDUAL ASSETS

Risk based management requires a comprehensive consideration of the sources, pathways and receptor impacts. In the context of asset management, this implies that the asset manager must look beyond the performance of individual assets to understand the behaviour of the asset system, and the variation in loading and consequences. System risk analysis, based on the *Source-Pathway-Receptor* concept, (DETR, 2000, Sayers *et al*, 2002) and methods that sample multiple asset failure combinations (system states) and loading conditions together with the associated impact, are now well established (Hall *et al*, 2003, Sayers and Meadowcroft, 2005, Gouldby *et al*, 2008 Gouldby *et al,* 2009a). Within England and Wales the so-called 'RASP High Level Method' (HR Wallingford, 2009) is used in the National Flood Risk Analysis (NaFRA, Steel *et al*, 2009) and is currently being implemented within the Modelling Decision Support Framework (MDSF2, Surendran *et al,* 2008) Environment Agency, 2009) and the Performance-based Asset Management System (PAMS, Simm *et al*, 2006, Environment Agency, 2010) being developed by the Environment Agency. More detailed system analysis techniques that relax some of the assumptions within the RASP High Level Method are also being developed (for example within the Flood Risk Assessment under Climate change, FRACAS, Gouldby *et al*, 2009b).

Flood risk system models are typically used to provide a means of quantifying the spatial distribution of risk within the floodplain. For asset management purposes however, it is desirable to identify those defence sections that make a significant contribution to the risk. This aids the asset manager in targeting and prioritising resources to maximise risk reduction. Two distinct approaches have been developed to enable risk to be attributed to specific defence assets:

- A rigorous systems modelling approach
- A simplified field based approach

These two approaches are described below.

h2 A rigorous system modelling approach

The systems modelling approach described by Gouldby *et al* (2008) enables the contribution that an individual asset makes to the risk to be attributed to that asset. The method of *risk attribution* involves maintaining the relationship between the quantity of water discharged through each individual asset and the quantified impact of the resulting flood. This ability to trace the flow of water across the floodplain is provided by the Rapid Flood Spreading Method (RFSM, Lhomme *et al*, 2008) used within the system analysis tools, and enables the relationship between inflow and impact to be explicitly identified for every system state considered (Figure 8).

The attribution of risk to individual assets is achieved by first developing a relationship between the defence assets (*d*) and the *'adjacent Impact Zones'* (*Impact Zones* are topographic watersheds resolved within the RFSM) and then between *'adjacent'* and *'non-adjacent Impact Zones'* (i.e. those topographic watersheds remote from the river or coastal boundary).

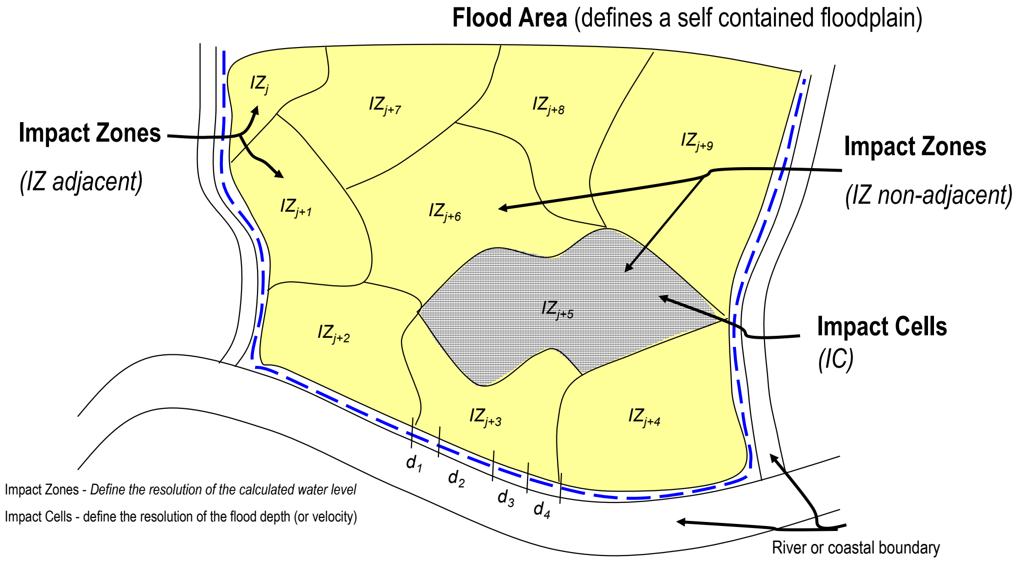

Figure 8 Conceptual diagram of the backdrop of the RASP system model for one Flood Area

Through the RFSM it is possible to associate the volume of water discharged into each *adjacent Impact Zone,* under each sampled system state, to the flood depth (hence consequential impact) in other non-adjacent Impact Zones by monitoring the flow of flood water as it propagates across the floodplain area. The quantified impacts associated with each (non-adjacent) Impact Zone are then apportioned to each of the adjacent Impact Zones accordingly (i.e. the total consequential impact for the whole Flood Area is expressed only in terms of the 'adjacent' Impact Zones). The defence contribution, for example for defence number d_1, to the damage (c_{d1}) is, for each flooding scenario, simply:

$$c_{d_1} = \frac{v_1}{v_{IZ\,i}} c_{IZ_i} \tag{3}$$

Where:

C_{IZ1} = Total economic damage associated with the i^{th} adjacent Impact Zone during the flood event (this equates to the damage within the Impact Zone itself and to those Impact zones that receive floodwater from the i^{th} adjacent Impact Zone).
v_1= The volume discharged into the i^{th} adjacent Impact Zone from defence d_1 during the flood event.
v_{IZi} = Total flood volume discharged into the i^{th} adjacent Impact Zone during the flood event.

The defence contribution to the residual risk conditional on the load (l) (based on all system states, *m,* sampled for load, l) can then be established simply for defence d_1 as follows:

$$\bar{c}_{d_1\,l} \approx \frac{1}{m_l} \sum_{j=1}^{m_l} c_{d_1\,j} \tag{4}$$

Where:

$\bar{c}_{d_1 l}$ = Mean consequence associated with the loading condition l for a specified defence (d_1).

The contribution of a given defence asset to the expected annual damage (EAD) is then calculated using the standard formula:

$$\mathrm{EAD}_{d_1} \approx \sum_{i=2}^{n} \left[p\left(l_i \geq \frac{l_i + l_{i+1}}{2} \right) - p\left(l_i \geq \frac{l_i + l_{i-1}}{2} \right) \bar{c}_{d_1 i} \right] \tag{5}$$

Where:

EAD = Expected Annual Damage
n = The number of load conditions considered

As the volume of water discharged into the floodplain is a function of the defence system state, the state of the defence assets (failed/not failed) is also monitored. The contribution to risk arising from a single defence asset can be further disaggregated into the contribution due to an ultimate limit state failure (i.e. breach in the case of a linear defence asset, or pump or gate failure) or serviceability failure (i.e. overtopping in the case of a linear defence asset, or capacity exceedence in terms a pump). See Figure 9.

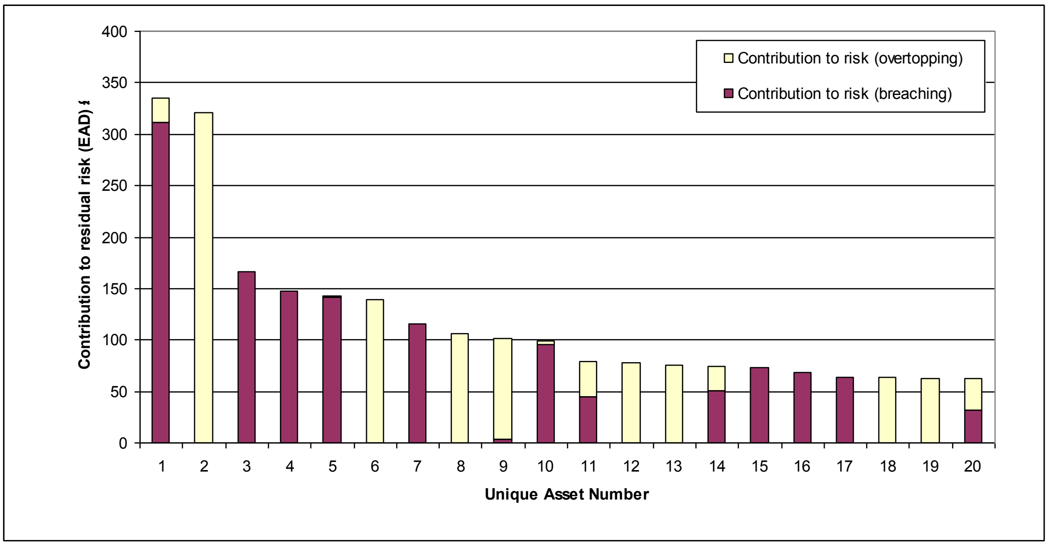

Figure 9 Risk attributed to individual assets can be further disaggregated into the contribution from ultimate (e.g. breach) and serviceability (e.g. overtopping) limit states (taken from the Thames Estuary)

h2 A simplified field based approach to risk attribution

As well as the rigorous approach to the attribution of risk there is often a requirement to provide a more simplified evaluation based on site inspections (without recourse to complex computational modelling). A simplified tool, 'RAFT – Risk Assessment field-based tool' (Environment Agency, 2009) can be used to provide a first estimate of:

- The annual probability of failure (breach) – taking account of geometry, structural condition and loading
- The consequential impacts should a given asset fail – taking into account a range of receptors.
- The risk (taking account of probability and consequence) attributed to an asset in its current condition and assuming improvement to its target condition.

RAFT provides the practitioner with an ability to assess the contribution of an individual asset to risk with a minimum of data and modelling. RAFT uses the physical characteristics of an asset – i.e. crest-level and materials of construction – to identify the most suitable high level RASP fragility curve. It then uses the fragility curve, alongside a user-specified asset length and extreme loading conditions, to estimate the annual probability of failure as follows:

$$P_{fi} = 1 - (1 - P_{fCg(i)})^n \qquad (6)$$

Where

$P_{fCg(i)}$ The annual probability of a single independent section of a given asset *i* failing (calculated by integrating the fragility curve over all loading conditions)

n The number of independent defence lengths within asset *i* that can be considered to be Condition Grade *j*

The number of independent lengths is simply calculated as the total length of the asset divided by either 300m (for hard defences such as walls and embankments) or 600m (for soft defences such as beaches and dunes).

In some instances however, the condition of a single asset may not be uniform. For example, a given asset may have localised problems over a short length with the remainder of the asset in a better condition. In this case, the annual probability of failure can be calculated based on the number of independent lengths considered to be in Condition Grade *i* and Condition Grade *j*.

By assuming independence between the part of the asset in Condition Grade *i* and that in Condition Grade *j,* a third estimate of annual probability of failure can be estimated:

$$P_{fc} = 1 - (1 - P_{fi}).(1 - P_{fj}) \qquad (7)$$

Where

P_{fi} and P_{fj} represents the annual probability of failure for the proportion of the asset in Condition Grade i and Condition Grade j respectively.

The annual probability of failure assigned to the asset as a whole is simply given as:

$$P_f = \max\lfloor P_{fi}, P_{fj}, P_{fc} \rfloor \quad (8)$$

This process ensures that the strength of the asset is not greater than its weakest link (regardless of length) whilst reconsidering that as the asset length increases, so will the chance of failure (assuming all other aspects remaining unchanged). Below a limiting length of 300m the annual probability of failure will be represented by the weakest link within the asset. The influence of asset length on the annual probability of failure is shown in Figure 10.

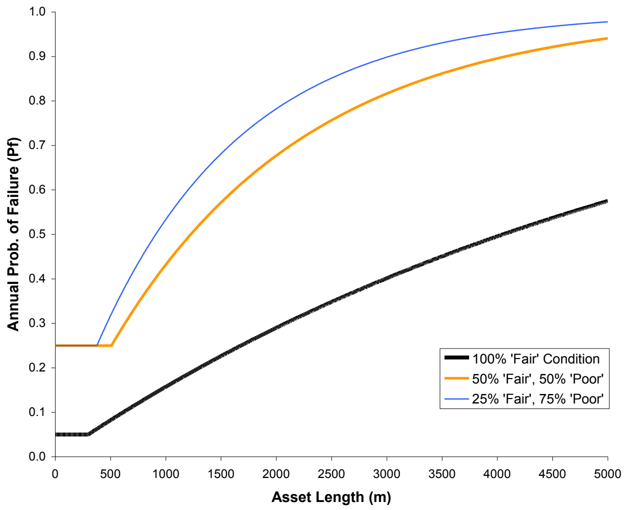

Figure 10 The influence of asset length with the simplified RAFT tool

A potential inundation extent is estimated based on the head of water above the floodplain during the event enabling the user to enter the number of properties that may be inundated in the event of a failure (either estimated or pre-calculated within a GIS) and the associated risk calculated taking account of both the probability of failure (i.e. breach) and the associated consequences.

H1 DEVELOPING ADAPTIVE AND OPTIMUM INTERVENTION STRATEGIES

Often, asset management consists of implementing a range of physical interventions and data improvements staged in time and space, and the asset manager is faced with many difficult questions:

- What is the existing flood risk? Where is it? What are the drivers?
- Which assets contribute the most to flood risk?
- How would an intervention change the risk?
- How much would a particular intervention cost?
- Is it better to intervene physically or should more data be collected / analysis undertaken? What level of confidence do I have in this decision?
- Which intervention strategy is best, given the future uncertainties?
- Which are the most important uncertainties in terms of their contribution to the doubt as to what to do for the best?

The foregoing sections outline the underlying risk analysis tools that can be used to explore the majority of these questions. More recently a number of projects have started to enact these methods within flexible decision support tools (Surendran *et al*, 2008, Mc Gahey and Sayers, 2008, Woodward *et al*, 2010). These decision support tools focus on providing the evidence to support the selection of a preferred investment action/strategy. Various considerations are essential to this process beyond the analysis of flood risk, including:

- *Robustness*: are the proposed actions robust? – *i.e.* will the strategy perform well in the context of a wide range of possible futures (resources, climate and socio-economic etc)

- *Flexibility*: are the proposed actions flexible? – i.e. are future choices compromised, or can alternative actions be taken at a future date with limited additional cost
- *Adaptability*: can the strategy be adapted to account for future change? - *i.e.* as the reality of the future unfolds can the asset designs be adapted (height/widened etc) with minimal cost
- *Uncertainty*: is the strategy robust to the uncertainty within the data, methods and model structures, as well as to the gross uncertainty associated with future change?

To use these criteria in assessing the likely impact of the investment, they must be considered not only in broad terms reflecting socio-economics and climate change, but also in terms of budgetary and legislative constraints and environmental impacts and opportunities. Understanding the robustness, flexibility and adaptability of an asset management strategy in quantifiable terms, however, remains the more elusive aim of sustainability in this context.

h2 Supporting tools and techniques in aiding robust option choices

In selecting the *best* investment strategy the decision maker is faced with choosing between many possible options of physical intervention, further data collection and analysis. Underlying this choice is a desire to maintain the flood risk system's ability to perform reasonably well in the context of all plausible futures that may be encountered throughout the appraisal period (i.e. funding changes and future affordability, climatic conditions, changes in anticipated performance).

In this context *performance* is typically measured in terms of efficiency (e.g. risk reduction, opportunity benefit) and effectiveness (e.g. benefit to cost ratio). Determining the preference ordering, assuming prefect information would be a straightforward ranking process. Both a multiple of aleatory and epistemic uncertainties combine to complicate this process.

Classical decision theory (e.g. French, 1988), discusses two widely considered approaches to deal with such uncertainty. One based upon Laplace's Principle of Indifference or Insufficient Reason, involves assigning an equal probability to uncertain quantities; and is therefore fundamentally probabilistic. The other, Wald's Maximin model, makes the assumption that the worst case of the uncertain quantity will always arise, and seeks to choose the option that maximises the reward given this assumption - the approach does not therefore involve assigning any likelihood to uncertain quantities.

'Info-Gap' approaches (Ben-Haim, 2006), that purport to be non probabilistic in nature, have also been applied in the context of flood risk management (for example by Hall and Harvey (2009). Many are critical of such approaches as they adopt a single description of the future and assume alternative futures become increasingly unlikely as they diverge from this initial description (Sniedovich, 2007). The method therefore assumes that the most likely future system state is known *a priori*. Given that the system state is subject to severe uncertainty, an approach that relies on this assumption as its basis appears paradoxical, and this is strongly questioned by Sniedovich (2007).

A more traditional method that involves Bayesian type probabilistic weighting for future scenarios and incorporating these into analysis of options has been explored through application to the Thames, including:

- *Intervention scenarios / decision pipelines* (Figure 11) – This includes analysis of a limited range of expert derived *decision pipelines* that describe a logical progression of management choices that are constrained by the preceding choices. Each decision point is constrained by previous actions and as such is more or less suited to different future states. Such analysis provides a pragmatic means of developing and exploring future asset management options (Mc Gahey and Sayers, 2008).

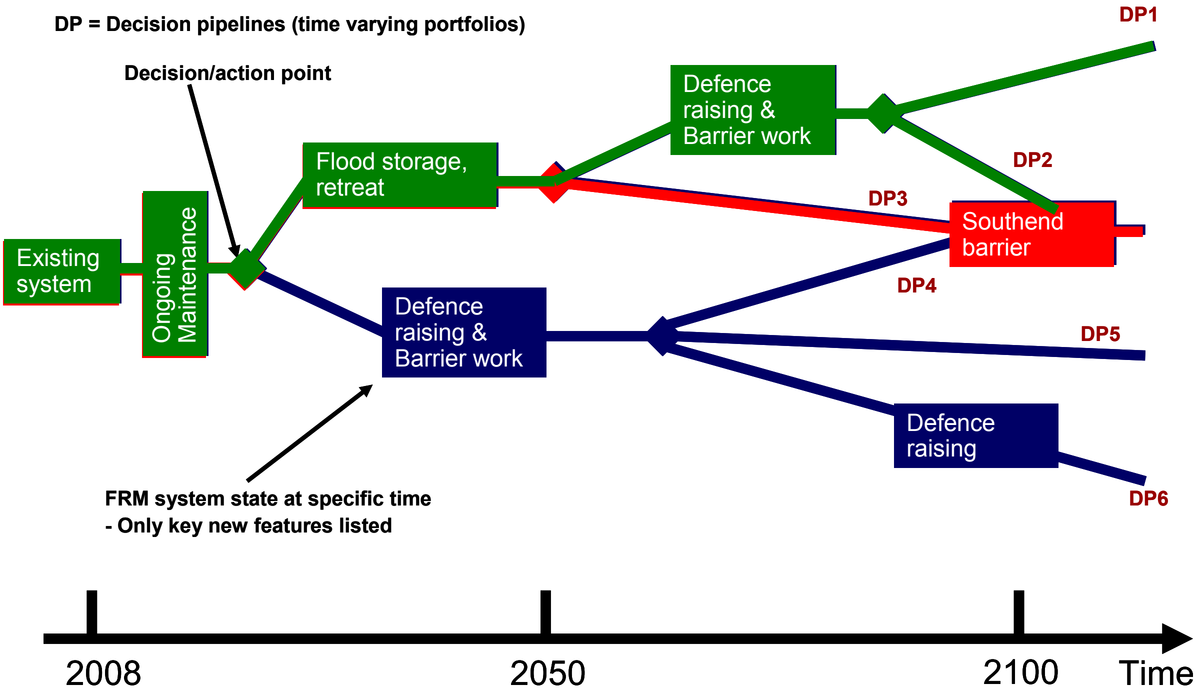

Figure 11 The performance of different strategic alternatives (represented by unique routes through the future decisions) enable adaptive strategies to be developed that reflect future uncertainty

- *Formal Optimisation of the asset intervention investment strategy* – More automated methods to optimise an asset management strategy have recently started to appear in the context of flood risk management (Philips *et al*, 2006, Woodward *et al*, 2010). These methods draw on various fields within civil engineering (including bridge maintenance, truss design and pipe network design) where optimisation methods are more widely used. The most promising methods are based around Genetic Algorithms (GAs); reflecting their ability to optimise performance across the many criteria of interest associated with flood risk management decisions.

  Genetic Algorithms work by seeking to combine the desirable qualities from solutions already found to create solutions that are even more desirable. In this way its search of the solution space is not as regimented as hill climbing techniques (allowing the search to be targeted in areas thought to be most favourable, whilst not restricting the search based on this bias) nor as random as Monte Carlo sampling. By combining the characteristics of two different 'parent' solutions a new solution is proposed. The best performing offspring are selected and recombined to develop (hopefully) ever *fitter* solutions. This process is repeated over several 'generations' (iterations) until the maximum utility (across multiple criteria) of the solution is reached.

  Tools to optimise basic interventions (crest level raising, condition grade improvements) have now been trialled on simple flood risk management studies (Philips *et al*, 2006, Woodward *et al*, 2010). The basic building blocks of these tools are shown in Figure 12 and include:

  - *A description of autonomous future changes:* The future is of course unknown and there are many uncertain influences outside of the asset manager's control. For example *(i) Climate change* (UKCP09 provides a probabilistic description of potential future climates than can be readily utilised within the optimisation process), *(ii) Asset Deterioration* (In the absence of management or reduced managed. Expert based deterioration curves are typically used to describe deterioration from one condition grade to the next (Simm *et al*, 2008). Process based statistical models are starting to emerge with the ability to model asset time-dependent processes using Markov processes, such as the Poisson or the gamma process (Buijs *et al*, 2005)) *(iii) Central budgetary change***,** and *(iv) Socio-economic change and floodplain development.*

  - *An ability to incorporate multiple (competing) objectives* **–** Flood risk management takes place in a world of many competing demands. Optimisation allows these to be explicitly described as objective functions, for example *(i)* Maximise economic benefits, *(ii)* Minimise whole life costs, *(iii)* Minimise loss of life, *(iv)* Maximise environmental enhancements etc whilst, for example, reflecting budgetary constraints.

- *An ability to explore real options*: Real options describe *"a choice that becomes available through an investment opportunity or action"* (HM Treasury, 2009). GAs enable the development of optimal, real options through time that take account of the constraints placed upon future choices by previous actions. This enables options to emerge that are appropriately adaptive and robust to future uncertainty - whilst achieving maximum utility when judged against the range of user defined objective functions. Practical working methods can also be reflected and included within the GA, such as an annual budgetary ceilings, or perhaps practical working constraints such as addressing multiple issues once the work force is mobilised. The progress of the GA in finding the best solutions (i.e. ones with higher net benefits) can be seen by plotting the best solution found for each generation (Figure 12). As shown in Figure 12 the same optimum strategy (in this case based on a single objective function of Nett Benefit) emerges after around 60 generations.

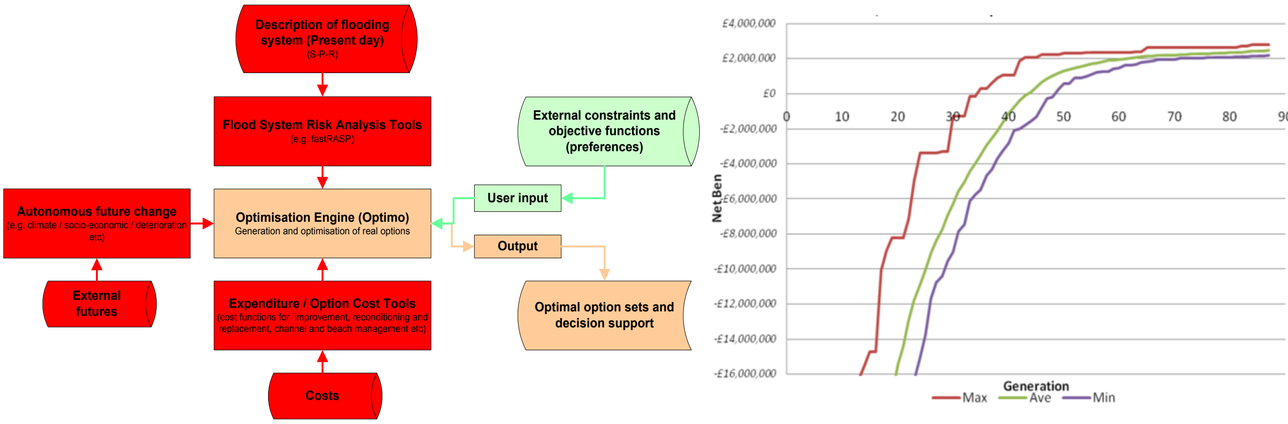

Figure 12 – *(right)* **Building blocks of an optimisation tool** (*left)* **Nett Benefit of the investment strategy proposed by each successive generation (Phillips, 2006)**

H1 REVIEW, DECIDE and ACT

Asset management tools seek to provide evidence in support of decisions and not, of course, make decisions. Expert judgement and engineering skill will continue to feature strongly throughout the asset management process – from the input data through to confirming the preferred course of action. Incorporating the expert judgement in an unbiased and transparent manner is problematic. Considerable progress has been made in recent years to integrate expert judgement and quantified analysis tools (Simm *et al*, 2008, Hall and Solomatine, 2008). In particular expert judgement can be used to validate model inputs and provide credibility to (and validation of) the outputs from the analysis. The decision maker also needs to be confident that the decision made is robust to the uncertainty in the data, the predicted impact of the action (e.g. reduced risk) and the associated cost (e.g. whole life costs and benefits). Quantified uncertainty propagation methods (Gouldby *et al*, 2010) together with multi-criteria decision making provide efficient methods to support the decision maker in identifying robust choices. Although these are interesting and important areas they are not discussed further in this paper.

h1 FUTURE UPTAKE – BARRIERS AND FACILITATORS

The introduction of formal and structured risk-based approaches to asset management challenges many traditional ideas and can be difficult to achieve in practice. Many of the barriers to the uptake of such methods reflect capacity to adopt new approaches, misconceptions around the complexities of risk based methods and the challenge of converting good science into practical useable tools. The science and practice of asset management need to go hand in hand – with one evolving from the other. The capacity for change is limited (in both skills and supporting infrastructure) and the scientific demand for change must be commensurate with the practical benefits afforded by that change. Simple illustrations and pilot studies that explain the complex scientific processes in practical terms are a vital aid in building understanding in the user community and avoiding mistrust and misconception.

h1 **CONCLUSIONS**

The implementation of risk based asset management reflecting whole life performance will demand close collaboration between the science community and engineering practice. To be successful there are a myriad of activities that will need to be integrated and co-ordinated within and outside of those organisations with a direct interest in managing flood defence assets. As this paper highlights, system analysis, reliability, risk attribution and optimisation techniques do, however, provide a number of important insights and aids to the decision maker.

The RELIABLE analysis tool provides a flexible and practical means to analyse the reliability of most structures. The results from RELIABLE have been shown to be credible and easy to apply, enabling high level generic fragility curves to be replaced (within the system analysis models) where the need is greatest.

An understanding of an asset's chance of failure (now and in the future) is an important contribution to understanding the risk and how best to manage it; but it is not the only consideration. Assets must be understood in the context of the asset system within which they reside. It is important to consider i) a full range of inundation scenarios (with and without one or more asset failures) across a wide range of storm events (from the frequent to rare), ii) evaluate the potential associated impacts (economic as well as other damages and importantly opportunities) and iii) integrate the results accordingly. Credible system analysis methods are now available and embedded within various tools. These tools are capable of attributing risk to individual assets which in turn provides a powerful support to the identification of critical defence assets.

The trial application of the more formal methods to optimise asset management strategies indicate that GAs are able to efficiently search the option space, and react appropriately to any constraints on the desired solution (e.g. budgetary, environmental, safety etc). Computational and complexity limitations continue to restrict the implementation of GAs more widely for practical decision support. At present expert led development of real options, through for example the use of decision pipelines, will continue to offer a very credible stop-gap.

Information technology is at the heart of an efficient approach to asset management (supporting the principles of good asset management). The USACE, Netherlands and Environment Agency have all undertaken similar initiatives to improve the underlying data and access to it.

All asset managers wish to be more efficient and more effective in their decision making. The advances outlined in this paper afford significant future opportunities for the asset manager to achieve this through a better understanding of the individual assets and the asset systems they compromise.

Acknowledgements

The work described in this publication was supported by the Performance-based Asset Management Project funded by the joint Defra/Environment Agency Programme, the European Community's Sixth Framework Programme through the grant to the budget of the Integrated Project FLOODsite, Contract GOCE-CT-2004-505420 and the Flood Risk Management Research consortium funded by the UK Engineering and Physical Sciences Research Council under grant GR/S76304/01, with co-funding from Environment Agency, Defra, Rivers Agency, SEPA and the Office of Public Works, Ireland.

The input of various staff at HR Wallingford is also gratefully including Ben Gouldby, Mike Panzeri, James Lanyon, Dr Caroline McGahey, Dr Julien Lhomme, Dr Marta Rocca and Dr Gordon Glasgow and many others. The contributions from Foekje Buijs whilst studying for her doctorate at Wallingford/Newcastle together with Jackie Banks, Dr Jim Barlow and David Denness of the Environment Agency together with the on-going direction of Dr Mervyn Bramley OBE (independent) throughout the various projects that underlie this paper are also gratefully acknowledged.

This paper reflects the authors' views and not those of the European Community, the Environment Agency or any other funder.

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