Technical Note - Internal

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Project Title: **Understanding and communicating uncertainty and confidence in flood maps**

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Author: Paul Sayers

Contact: Paul Sayers
+44 1865 600039, +44 7711 798786
paul.sayers@sayersandpartners.co.uk

Contributors: Jaap Flikweert - Royal HaskoningDHV and Netherlands Water Partnership

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Executive Summary

This note has been prepared following a workshop in Queensland and subsequent review of the note: 'Reliability and Utility of "Fit for Purpose" Flood Investigations and Hazard Products'. This document is not meant as a definitive guide but rather to provide some background that might be useful in developing the specific approach to be adopted in Queensland in the coming months.

Contents

1 Introduction

The 'purpose', and the reliance that governments and others place upon the resulting data from flood models has significantly increased in recent years, and so too has the need for a more structured and consistent assessment of the uncertainties. In particular, users of the flood risk information ask how confident they should be in the results at any given location or scale of aggregation.

Communicating confidence in flood mapping, either based on qualified scoring methods (describing high to low confidence, e.g Sayers et al 2012) or through quantified forward propagation methods (describing distributions, e.g. Gouldby et al, 2010), is difficult but significant progress has been made in recent years.

It has been, and always will be, necessary to make decisions in the absence of perfect information. In the past, uncertainty has been implicitly accounted for in flood risk management decisions through safety factors and allowances rather than with explicit analysis of uncertainties. Recognizing uncertainty does not however prevent decisions from being made. In fact, recognizing uncertainty is a key requirement for appropriately designing adaptive capacity and resilience into flood risk management choices. Only by quantifying and acknowledging uncertainty are we better placed to decide how best to manage it.

In this context it should not be the goal of the analysis to eliminate uncertainty, a practical and philosophical impossibility, but to understand its importance in terms of the decision being made. If the decision would remain the same, despite the recognized uncertainty in the evidence upon which it is based, then no further refinement of the analysis is required.

2 Forms of uncertainty

Typically three forms of uncertainty are distinguished and each presents its own challenges, namely:

- **Natural variability** (often called aleatory uncertainty) - this refers to randomness observed in nature. Such uncertainties are routinely dealt with through consideration of a range of different AEP storm events. This enables probabilities of inundation to be determined whilst accepting that it is not possible to determine when or where the next major event will be. Uncertainty generated through natural variability is generally regarded as irreducible.

Figure Uncertainty arising from the natural randomness in nature is routinely addressed when making decisions - but can not be reduced

- **Knowledge uncertainty** (or epistemic uncertainty) - this refers to our state of knowledge of a system and our ability to measure and model it and predict how it might change in the future. Increasingly it is recognised that all uncertainties should be explicitly stated and their importance determined in the context of the specific decision being made. By doing so, this presents significant opportunities to target data improvements, research and future analysis as required.

Figure Epistemic uncertainty arising from our lack of knowledge reflects our ability to measure and model it and predict how it might change in the future

- ***Decision uncertainty*** - is a state of rational doubt as to what to do. Uncertainty is natural. This should be recognised as wholly acceptable. Understanding and communicating uncertainty is therefore fundamental.

3 Thoughts on a framework for uncertainty and sensitivity analysis

Uncertainty and sensitivity analysis are closely related, but not the same, and both are useful. Uncertainty seeks to enable the decision maker to better understand the confidence within the evidence presented. Sensitivity analysis seeks to highlight to the decision maker those aspects of the analysis that contribute greatest to the uncertainty in the output.

A general framework for handling both **routine uncertainties -** those associated with input data (crest levels, topography, damage functions etc.) and **severe uncertainties** - those associated with future change in socio-economics and climate - is given in the Figure below.

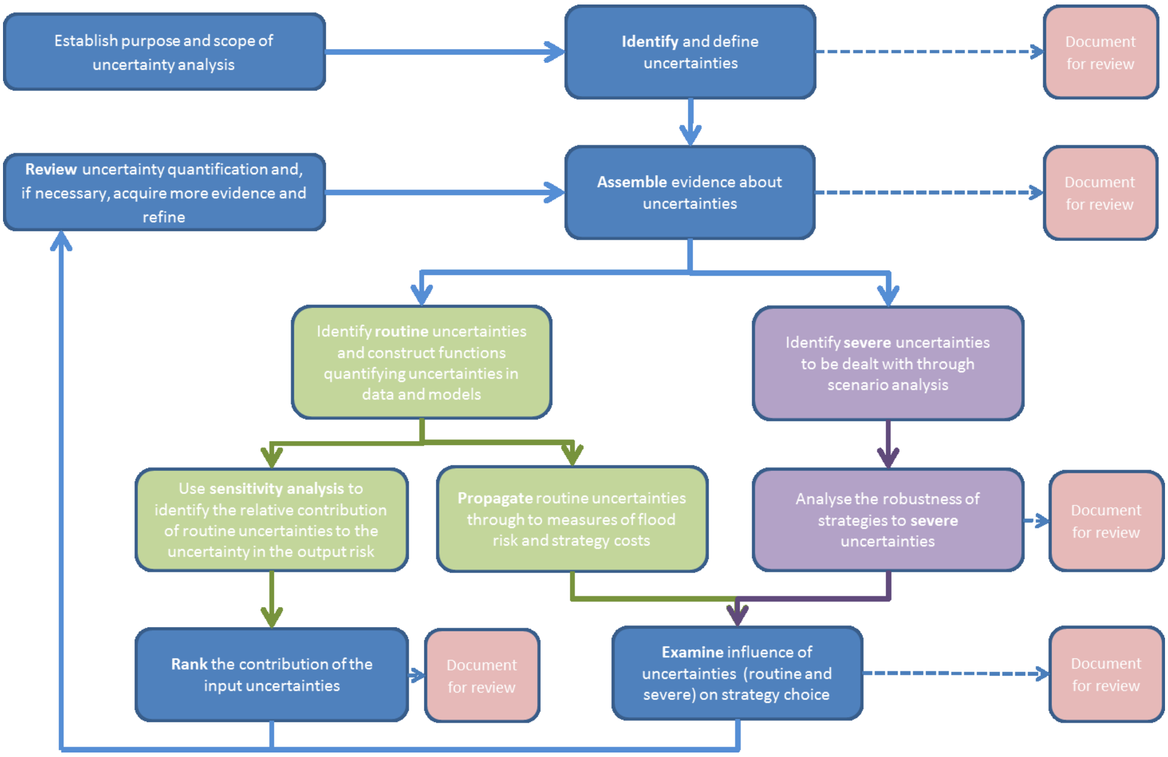


Figure Framework for uncertainty analysis and structured recording of the uncertainties within the risk analysis (Sayers et al, 2012).

4 Supporting approaches to uncertainty analysis

Various approaches available to estimate uncertainty in the output of flood models exist. Together with associated sensitivity analysis these can be used to target effort towards reducing the most important uncertainties. For example, is it better to invest in research, perhaps to improve the representation of the flood physics within the model components (for example the representation of breach size or flood propagation), or data collection (perhaps to improve topography or river channel data); which would reduce the uncertainty more?

Two basic approaches exist, a scoring and weighting approach or forward propagation methods.

4.1 Scoring and weighting

An approach based on a Confidence Index is currently being developed in the UK by the Environment Agency (Sayers et al, 2012).

This is has the aim of being:

- based on evidence and a readily understood methodology
- credible
- accepted
- clearly presented

The approach is being developed through a collaboration of local teams, expert reviewers and the consultant teams working together. This has included both 'challenge workshops' (where stakeholders where given the opportunity to challenge the method) and reviews. This led to an approach that includes a series of steps that can be undertaken centrally, to provide an estimate of the confidence in the probability of flooding presented through the Environment Agency's website.

Doing so presents a number of challenges of course and these are presented below together with a short statement outlining the approach adopted to overcome them.

Lack of observations: In a probabilistic assessment, the probability of inundation can only ever be estimated, rather than measured directly. This reflects:

- The non-stationarity within the flood systems (not only climate but condition and nature of the defences, land use etc).
- The inclusion of rare physical circumstances that may never have been observed (but are plausible and - significantly – can be modelled). As such, the probability of inundation and risk outputs cannot typically be compared directly to an objective measurement of the same quantities (at the extreme end of the AEP range).

To overcome this difficulty: The approach to scoring confidence is therefore based on implementing a consistent process – that appropriately uses expert argument/judgement and, wherever possible, observational evidence is used to support the scoring process.

Heterogeneity of real flood systems: The physical characteristics of flood risk management systems (FRMS) vary significantly, together with the quality of the data that is available (both from one FRMS to another and within a single FRMS). It is therefore difficult to assess probabilistic model performance across all physical settings (catchment types, defence systems, receptors etc) and data quality combinations. This will be an issue in Queensland too, reflecting the significant variation in nature of the flood risk across the large and diverse catchments.

To overcome this difficulty: The likely confidence of the NaFRA outputs is assessed in the context of different Flood Area typologies – identified to reflect the different aspects of the physical setting that are likely to impact the model performance. A similar approach could be followed for Queensland, based on the knowledge developed in the course of the mapping work in recent months.

The variation in the weakest link: The quality of the results is governed by the weakest component of the model, be that a specific model component, model structure or data aspect. For example, replacing the Rapid Flood Spreading Model (RFSM) with a state-of-the-art inundation model will have limited impact if inflows are provided by a poor/incorrect description of the boundary conditions. Equally, focusing on the hydraulic representation across the floodplain whilst ignoring the need to accurately represent defence performance will limit model utility in defended areas. Identifying the weakest link is therefore difficult; as all aspects must be fit-for-purpose if a credible answer is to be provided. The "critical aspects" will vary depending on the nature of the floodplain but some useful work has been done to identify these (see previous studies discussed below).

To overcome this difficulty: The weakest link(s) within the critical data or model components, for each Flood Area type as introduced earlier, is used to determine the overall confidence index. The confidence will be communicated through the addition of an overall 'confidence index' associated with each grid of the flood map. This will reflect both a Data Quality Indicator and a Model Performance Indicator. In the UK context, the format of the mapping remains in discussion but various options have been put forward.

4.2 Simulation approaches to assessing the impact of uncertainty

The simulation approach involves representing uncertainties by probability distributions. These probability distributions are then combined to provide a probability distribution of the response variable (e.g. probability of a levee failure and associated consequences), which incorporates the uncertainties in the parameters, variables and model relationships. Where few observations or very limited data are available with which to 'condition' a model, forward propagating uncertainty techniques are the most viable approach for the analysis of routine uncertainties (Gouldby et al, 2010).

Of the options available, Monte-Carlo procedures are the most flexible, robust and therefore prevalent (Pappenberger *et al.* 2008). These methods involve assigning probability distributions to input variables. Samples are drawn at random from the input distribution functions and passed through the model. Model structural uncertainties can be included by specifying error terms associated with different functions, or the overall model, and assigning distributions. If there are many different types of uncertainty, involving many different parameters and variables, this approach can become complex. This is particularly so where there are dependencies between separate parameters and variables. To avoid over complicating the process, it is worthwhile considering the sensitivity of the response variable to each of the parameters, together with the associated uncertainty. If a parameter has a narrow confidence interval (small uncertainty) and has a minor effect on the response it is acceptable to consider the parameter as perfectly known. Additionally, it may be necessary to consider the different sources of uncertainty as separate elements and structure the analysis to calculate specific uncertainty sources before combining these analyses in an overall simulation.

Such an approach supports a range of formal sensitivity analysis techniques including Variance Based Sensitivity Analysis, a generic method for establishing the relative importance of variables contributing to the output of interest (Figure below). For a further description see Saltelli *et al.* (2004).

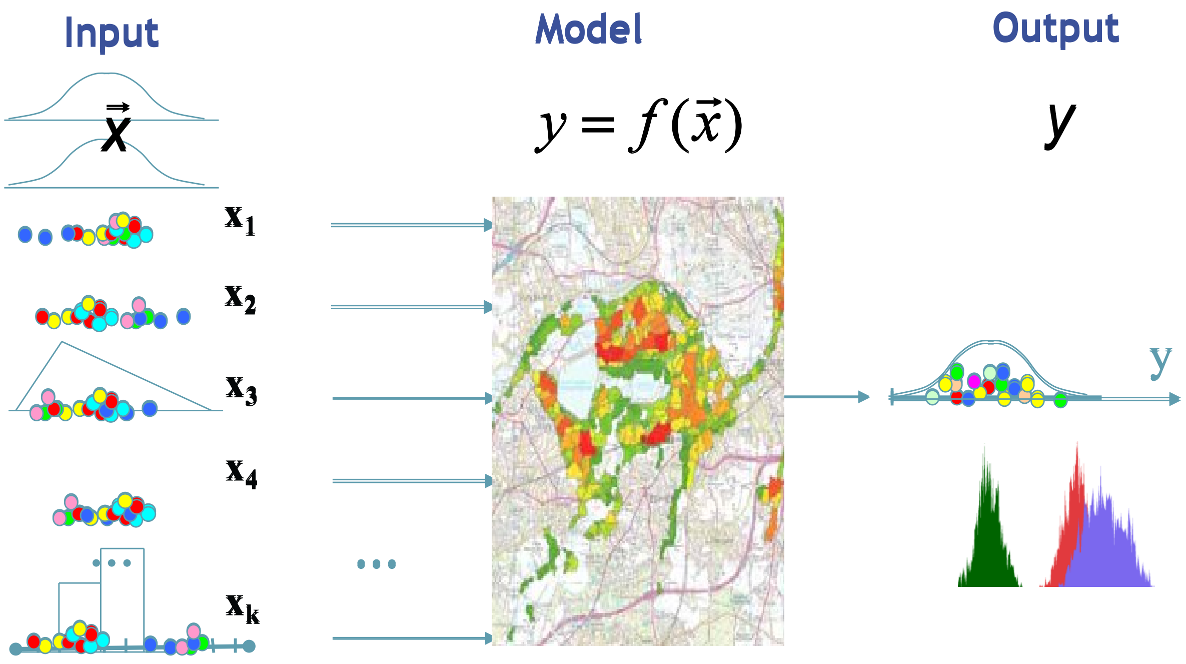


Figure Forward propagation of uncertainty through the RASP risk analysis model (Sayers et al, 2004) and associated sensitivity analysis (courtesy: Zhengfu Rao, 2009)

Such an analysis provides the decision maker with a much richer understanding of the level of confidence in the risk estimates and which uncertainties are most important in terms of their contribution to uncertainty in the risk. Examples of the type of additional outputs are given below.

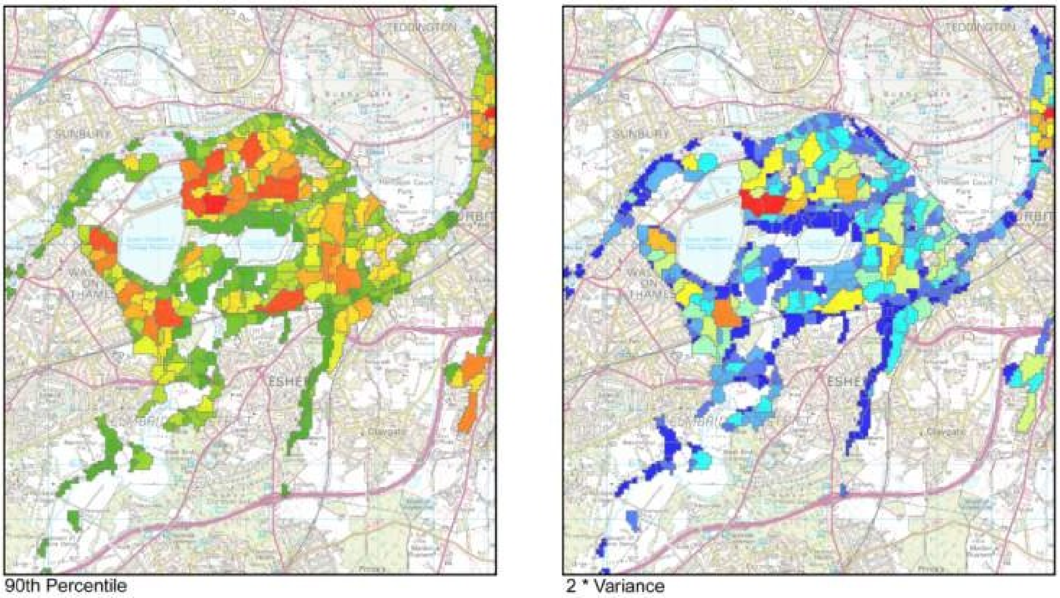
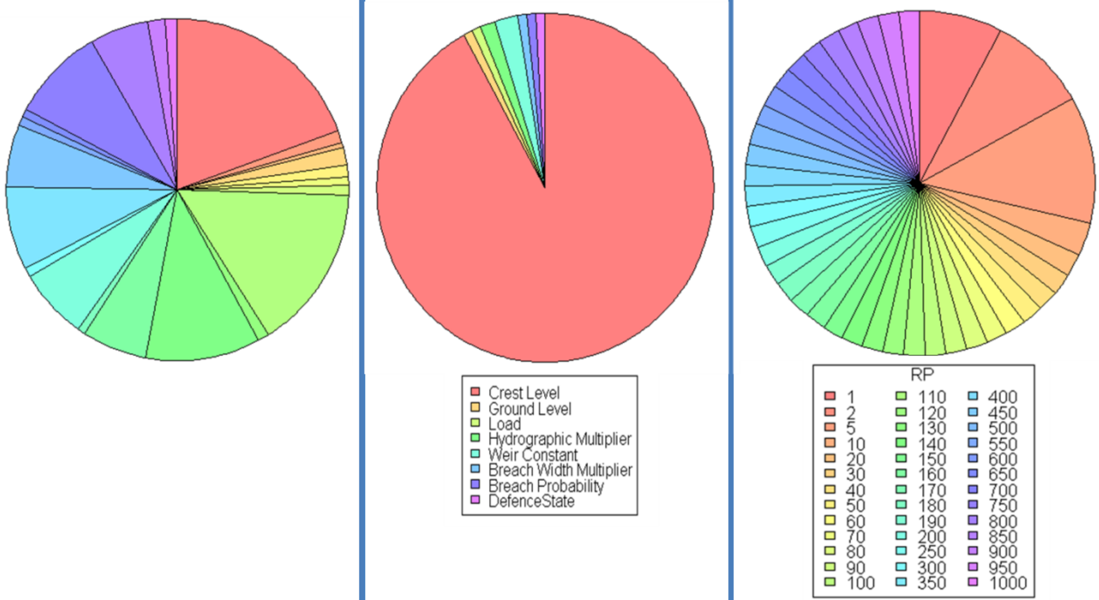


*Figure Spatially disaggregating the level of confidence in the mapped risk (Environment Agency, 2009). Left –The estimated expected annual damage Right – the confidence in the estimate of risk expressed by plotting the value of 2*variance in the risk estimate*



The contribution of each defence to uncertainty in the estimate of risk

The contribution of each parameter of a given defence to uncertainty in the estimate of risk

The contribution of each storm event to uncertainty in the estimate of risk (by return period, years)

Figure Disaggregating the driving sources of uncertainty (Environment Agency, 2009)

5 The importance of a tiered approach

Perhaps the most important lesson from the UK is that tiered approaches can be used to drive improvement of data / analysis in relation to the significance of the uncertainty. For example, within the UK the RASP methods (Sayers and Meadowcroft, 2005, Environment Agency, 2002) that are based on a progressive hierarchical approach to the analysis of risk and uncertainty enable quantification of uncertainties within the risk and give a clear (even economic) justification for further investment in analysis or data collation. In the Netherlands, the legal safety assessment also follows a tiered approach (basic, detailed or advanced); if a higher tier is needed but data or methods are unavailable, the assessment score is 'uncertain' (rather than conservatively assuming in that case that it's non-compliant), which in turn drives further analysis and research budgets.

6 Developing a credible, but practical, approach in Queensland

This short note has highlighted some of the recent activities in the UK and elsewhere. A number of important lessons have emerged from these applications that could be very useful in developing a framework of analysis and means of communicating uncertainty (or more general confidence) in the flood maps currently being developed for Queensland.

Perhaps the most important lessons are associated with developing an approach that is suitably comprehensive (influence all important uncertainties not simply those that are easily captured within a Monte Carlo framework for example) and communicating this in a meaningful and accessible way.   The first step on this journey is to develop a 'framework of analysis and communication' that sets out the approach (the assumptions, the input uncertainties (associated with data and model structure) and the means of communication) and establishes a broad buy-in to the process.

References

The contents of the note draws upon various studies Paul Sayers and Jaap Flikweert have undertaken within the Environment Agency and internationally in recent years, and in particularly draws upon three reports:

Beven et al, 2010. Uncertainties in fluvial flood modeling. FRMRC publication

Environment Agency. (2002). Risk, Performance and Uncertainty in Flood and Coastal Defence: A review. Environment Agency: Authors: Sayers PB, Meadowcroft, IC, Gouldby, B, Simm J, and Hall JW.

Environment Agency. (2009). Understanding the confidence in the national flood risk assessment 2008. Authors: Sayers, Meadowcroft, Panzeri. London: Environment Agency. (Currently being updated by Sayers, JBA, HRW, Halcrow and the Environment Agency)

Gouldby, B., Sayers, P., Mulet-Marti, J., Hassan, M., & Benwell, D. (2008). A Methodology for Regional Scale Flood Risk Assessment. Proceedings of the Institution of Civil Engineers: Water Engineering, June.

Gouldby, B., Sayers, P., Panzeri, M., & Lanyon, J. (2010). Development of application of efficient methods for the forward propagation of epistemic uncertainty and sensitivity analysis within complex broad-scale flood risk system models. Canadian Journal of Civil Engineering. Vol., 37.

Sayers, P. B., Hall, J. W., & Meadowcroft, I. C. (2002). Towards risk-based flood hazard management in the UK. ICE Journal of Civil Engineering 2002, 150(5), 36-42.

Sayers, P., & Meadowcroft, I. (2005). RASP - A hierarchy of risk-based methods and their application. Proceedings of the 40th Defra Conf. of River and Coastal Management.

Sayers, P., Galloway, G., Penning-Rowsell, E., Shen, F., Wen, K., Chen, Y., et al. (2012). Flood Risk Management: A strategic approach. UNESCO on behalf of WWF and GIWP, China.

Paul Sayers is currently also involved in a project to 'benchmark probabilistic models' for the Environment Agency (together with JBA, Royal HaskoningDHV and HRW) - an important step to establishing greater understanding of uncertainties.

Appendix 1 Background to the motivation to understand uncertainty in the UK

The need to understand and manage uncertainty has been recognised within UK government guidance for some time and continues to be recognised as a prerequisite for good decision making. To provide a context for the current need to both benchmark the NaFRA process and the support a better understanding of uncertainty (through a separate but associated initiative) it is useful to reflect upon the areas of current or past Government policy where uncertainty is reflected, including for example:

Flood Risk Regulations 2009 – Although not explicitly mentioned, there is an implied requirement for the Environment Agency to publish hazard maps for rivers and coasts that are fit for purpose and in a way that helps users to understand the associated uncertainties.

Government Departmental Guidance – The Defra Flood and Coastal Defence Project Appraisal Guidance repeatedly calls for proper consideration of uncertainty in appraisal decisions. For example in Flood and Coastal Defence Project Appraisal Guidance (Defra, 2001) on “good decision making” (p5) it states good decisions are most likely to result from considering all economic, environmental and technical issues for a full range of options, together with a proper consideration of risk and uncertainty. FCDPAG3 (Defra, 2000a) has a section on “sensitivity analysis and robustness testing” and highlights the importance of identifying options whose benefits are robust to uncertainty. FCDPAG4 (Defra, 2000b) calls for a more explicit treatment of uncertainty in risk analysis (p8): All risk assessments are predictive and, therefore, the results are inherently uncertain. In undertaking risk assessment work, it is important to acknowledge explicitly the degree of uncertainty.

Flood and Water Management Act 2010 – Following the severe UK floods in 2002, and 2004, Defra through the publication of Making Space for Water (Defra, 2005) reiterated that “decisions will reflect the uncertainty surrounding a number of key drivers…” (p14). The glossary (p41) defines appraisal as “The process of defining objectives, examining options and weighing up the costs, benefits, risks, and uncertainties before a decision is made”. This underlying thinking is now embedded within the Flood and Water Management Act 2010.

UK Treasury Guidance – The HM Treasury Green Book (HM Treasury, 2003) has uncertainty at the heart of decision making. Chapter 5 on appraising options has numerous references to uncertainty and a specific annex, Annex 4, devoted to "risk and uncertainty". The following statement is made in the section on "presenting results" (p6): The results of sensitivity and scenario analyses should also generally be included in presentations and summary reports to decision makers, rather than just single point estimates of expected values. Decision makers need to understand that there are ranges of potential outcomes, and hence to judge the capacity of proposals to withstand future uncertainty. In the overview of the appraisal process (p4) it is stated that “… as options are developed, it will usually be important to review more than once the impact of risks, uncertainties and inherent biases.” The need to consider a range of values is reiterated on p28, “appraisers should calculate an expected value of all risks for each option, and consider how exposed each option is to future uncertainty.”

The section on "assessing uncertainty" (p32-33) dwells upon sensitivity analysis. It opens with these words: An expected value is a useful starting point for understanding the impact of risk between different options. But however well risks are identified and analysed, the future is inherently uncertain. So it is also essential to consider how future uncertainties can affect the choice between options.

Annex C of the Supplementary Guidance to the Green Book, highlights the important of taking into account future uncertainty within the selection of the preferred management options: an issue that is related but outside of the current project focus.

Strategic Environmental Assessment – The Environment Agency report published in 2004 on Good Practice Guidelines on Strategic Environmental Assessment (SEA) gives "report uncertainties, limitations and assumptions" as one of the good practice principles for assessment and states that "a particular strength of risk assessment is its ability to explicitly recognise uncertainty surrounding future predictions." Uncertainties are identified in the use of expert judgement and in scenarios analysis and are mentioned in several of the case studies.

National Audit Office Review (2011) – The recent NAO report highlighted the need to better communicate the uncertainty within the NaFRA outputs and in particular how it might vary between locations reflecting the model performance and input data quality.

Drivers from within the Environment Agency – The Environment Agency recognises that understanding uncertainty is a prerequisite for good decision making. By understanding uncertainty, levels of confidence can be communicated, and allow staff, partners and customers to make better decisions informed by, rather than in spite of, uncertainty.

The Environment Agency want to understand to what extent uncertainty affects a decision. When uncertainty prevents sound decision making, either the uncertainty should be reduced, a precautionary approach taken, or the affects of a wrong decision mitigated against. So this understanding supports a "yes, if" approach, integral to the Environment Agency's ways of working, as opposed to an overly precautionary approach, to risk management.

By describing the levels of confidence in the Environment Agency's risk information (even just qualitatively at first – i.e. using words rather than numbers), this makes their information more open and transparent. This then enables data to be shared more openly and allows partners and customers to make their own decisions based on it and the confidence associated with it.

Ultimately, describing levels of confidence in NaFRA results will enable users to decide if they are fit for the purpose they intend, and make decisions appropriate to the level of confidence in the risk information.

There are a set of strategic drivers within the Environment Agency for providing information about uncertainty or confidence.

The National Flood and Coastal Erosion Risk Management (FCERM) Strategy[1] (Section 3.3.1) states that "Flood and coastal erosion risks can only be managed effectively if they are properly understood. Key to this is estimating the risks through assessing data, information and modelling and understanding the uncertainty in the predicted levels of risk."

FCERM Modelling Strategy[2] (Principle 3) states that "We will understand and communicate uncertainty in modelling outputs to assist decision-making by ourselves, our partners and our customers. We will reduce any uncertainty that prevents us from making sound decisions."

1 http://www.official-documents.gov.uk/document/other/9780108510366/9780108510366.pdf
2 http://publications.environment-agency.gov.uk/pdf/GEHO0310BSBT-e-e.pdf

FCERM Risk Mapping Strategy[3] (A3.1 & A3.2) states that "We will use uncertainty in a positive way as part of the way we communicate flood and coastal erosion risk and make decisions; work with our partners and customers to ensure we display uncertainty in ways that make it most understandable to them."

[3] http://publications.environment-agency.gov.uk/pdf/GEHO0310BSBS-e-e.pdf