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Framework for assessing uncertainty in fluvial flood risk mapping

FRMRC flood risk management research consortium

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Framework for assessing uncertainty in fluvial flood risk mapping

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Summary

This guide provides a framework for good practice in the assessment of uncertainty in fluvial flood risk mapping. The starting point is the position that all uncertainty assessments involve subjective judgements because clarity and transparency in expressing and agreeing those judgements is imperative. The framework for doing so is a series of steps covering consideration of the range of uncertainties in data and modelling, together with the choices for presentation and visualisation of the resulting flood risk mapping. Ideally, the process of working through the steps should be undertaken as a joint exercise including the modeller/analyst and representatives of the end users of the flood risk mapping. The assumptions made in assessing the uncertainty should be agreed and recorded for future reference.

Although the focus is on fluvial flood risk mapping, similar approaches could be taken to good practice in assessing uncertainty in pluvial, coastal/tidal and groundwater flooding.

Many sources of uncertainty in flood risk mapping have been ignored or treated very simply in the past. They have also been managed implicitly by agreed protocols based on engineering judgement or limited research studies (eg 20 per cent increase in the 0.01 annual exceedance probability (AEP) flood discharge to allow for climate change, the use of zones based on the 0.001 AEP in PPS25 (CLG, 2006) etc). A more detailed consideration of the different sources of uncertainty, particularly in the estimation of design discharges, is likely to lead to identifying significant uncertainty in the risk map. However, this has two advantages. The first is that the resulting maps are much less likely to be wrong for any particular event. The second is that through providing a measure of confidence in the mapping of flood risk, such maps can inform a risk-based framework for decision making processes, with the mapped risk quantiles allowing both risk accepting and risk averse approaches to decisions within a single assessment.

It is important that any approach to assessing uncertainty in flood risk maps should be proportional in respect of the expected costs and benefits or disbenefits involved in any particular application. In this guide, the different levels of analysis that might be considered in being proportional are incorporated into a single framework of condition trees within which the assumptions made at each stage are recorded for later evaluation. Uncertainty estimates are conditional on the decisions made about those assumptions. The degree of detail involved might then vary from a qualitative expert judgement, through a sensitivity analysis to a detailed analysis involving many runs of a hydrodynamic model. Different types of project may require different approaches – conversely, a single project may involve more than one type of approach (starting with the simplest approach and, where necessary, progressing to more involved approaches only if the nature of the decision is shown to be sensitive to the uncertainty).

The guide is structured as follows:

Chapter 1 discusses why it might be worth considering uncertainty in flood risk mapping.

Chapter 2 is a summary of the conditional uncertainty framework.

Chapter 3 supports the material from Chapter 2 by a more detailed discussion of sources of uncertainty and of the decisions involved.

Chapter 4 demonstrates the implementation of those decisions (together with **Appendices A2** and **A3**) for two cases studies at Carlisle and Mexborough.

Appendix A1 discusses the representation of uncertainty and its use in decision making.

It is worth noting that this type of approach to acknowledging uncertainty in flood risk mapping is relatively new. Published research suggests that the uncertainties can be significant, but has given

only limited guidance about the importance of different sources of uncertainty, realistic ranges of effective parameters, and numerical issues with model implementations. However, this is not a good reason to neglect the uncertainty. In the same way that there is a wealth of practical experience among users in dealing with model implementation issues, over time the same type of experience will evolve in estimating the importance of different sources of uncertainty. What is important is that any estimate of uncertain flood risk should be on an agreed and appropriate basis, and explicitly recorded for later assessment.

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Abbreviations and acronyms

AEP	Annual exceedance probability
CES	Conveyance Estimation System
CFD	Computational fluid dynamics
DTM	Digital terrain model
EAD	Expected annual damages
FEH	Flood Estimation Handbook
FRMRC	Flood Risk Management Research Consortium
GEV	Generalised extreme value (distribution)
GL	Generalised logistic (distribution)
GP	Generalised Pareto (distribution)
GPU	Graphics processing unit
IPCC	Intergovernmental Panel on Climate Change
LHS	Latin hypercube sampling
LIDAR	Light Detection And Ranging
MCM	Multi Coloured Manual
MCMC	Markov Chain Monte Carlo Sampling
POT	Peaks over threshold
PPS25	Planning and Policy Statement 25 *Development and flood risk*
RASP	Risk assessment for system planning
RCM	Regional climate model
RMSE	Root mean squared error
ReFH	Revised flood hydrograph method in FEH
SPR	Standard percentage runoff in FEH
TAN15	Technical Advice Note 15 *Development and flood risk*
UKCP09	UK Climate Predictions 2009

Glossary

Aleatory uncertainty	The way in which a quantity varies in some random stochastic way in a system. Often used in contrast to epistemic uncertainty.
Annual exceedance probability (AEP)	Defined for independent random annual maximum values, the AEP is the probability that a value x will be equalled or exceeded in any one year. It is the inverse of the return period of the value x. So an AEP of 0.01 has a return period of 100 years.
Boundary conditions	Constraints and values of variables required to run a model for a particular flow domain and time period. May include input variables such as rainfalls and temperatures or constraints such as specifying a fixed head or specified flux rate.
Conditioning	The process of refining a model structure, or a distribution of parameter values of a model structure as more data become available.
Epistemic uncertainty	How the response of a system varies in ways that cannot be simply described by random stochastic variation. Often used in contrast to aleatory uncertainty. Also known as Knightian uncertainties. Knight (1921) referred to "true uncertainties" that could not be insured against, as opposed to risk that could be assessed probabilistically.
Exceedance probability	For a probabilistic variable the exceedance probability for a variable x is equal to 1–F(x) where F(x) is the cumulative density function of x.
Feasible range	Estimate of uncertainty defined in terms of maximum and minimum feasible range without any estimate of a probability or possibility distribution within the range. Projections might be made only at maximum and minimum values, or sampled randomly or discretely across the range (involving an implicit assumption about the distribution).
Floodplain infrastructure	Manmade features (bridges, embankments, culverts, walls, hedges, buildings) in the floodplain or channel that will have an effect on flood inundation.
Flood risk	Generally defined as the product of flood probability and consequence. See also *Risk*.
Forward uncertainty analysis	An assessment of uncertainty that depends only on the numerical propagation of prior assumptions about the nature of different sources of uncertainty and their interactions.
Freeboard	In the design of flood defences, an allowance for factors in addition to the estimate of discharge or water level at a given exceedance probability. A way of allowing for uncertainties that are not treated explicitly in a design analysis.
Fuzzy measure	A degree of membership of a quantity to a fuzzy set.
Fuzzy set	A set of quantities thought to have something in common. Membership of the set cannot be described precisely, but only through a degree or grade of membership or fuzzy measure.
Imprecise probability	An extension of probability concepts to allow for situations when a probability distribution is uncertain. Several schemes are available for manipulating imprecise probabilities.
Knowledge uncertainty	See *Epistemic uncertainty*.

Latin hypercube sampling	A method of choosing random samples from prior distributions of multiple variables. Correlation or co-variation between the variables can be taken into account.
Likelihood measure	A quantitative measure of the acceptability of a particular model or parameter set in reproducing the system response being modelled.
Monte Carlo Simulation	Simulation involving multiple runs of a model using different randomly chosen sets of parameter values.
Markov Chain Monte Carlo	A method of numerically integrating a probability or likelihood surface by iterative random sampling aimed at achieving a sample density dependent on the local probability or likelihood. Once convergence of the chain has been reached, each sample can be treated as having equal likelihood.
Pooling group method	An approach to estimating the flood statistics of an ungauged site by pooling the analyses from multiple 'similar' gauged sites in the *Flood Estimation Handbook* (FEH) (IoH, 1999).
Possibility	A subjective estimate of the weight allocated to a given projection consistent with fuzzy set theory as an alternative to probability theory. Operations of fuzzy set theory apply. Can be used in conditioning uncertainty given some observed variables using a wider range of operators than for probabilities.
Precautionary	An approach to decision making based on avoiding harmful effects, regardless of whether the risks can be properly assessed or not.
Proportionality	The concept that the effort required to carry out an analysis should be a function of the magnitude of the costs and potential benefits of a project.
Probability	Representation as a distribution (often of a mathematically defined form, eg normal, gamma, beta distributions) that conforms to the axioms of probability (probability of any feasible value of a variable must be non-negative; integral of probabilities over all feasible values should be equal to one; the frequency of all countable series of mutually exclusive feasible values must be equal to the sum of the probabilities of those values).
QMED	Median annual maxima flood, and has an annual exceedance probability of 0.5, and a return period of two years.
Rating curve	A function used to convert observations of water level at a river gauging station into estimates of discharge.
Return period	The inverse of AEP.
Risk	Uncertainty about responses of a real world system that can be characterised in terms of probabilities. BS ISO 31000:2009 on risk management terminology defines risk as the combination of the probability of an event and its consequence, but the term is often used more generally.
Scaling method	The estimation of flood discharges at an ungauged site by scaling the observations at a nearby gauged site in the FEH (IoH, 2009).
Scenario	Projections made conditional on specific assumptions but without any estimate of probability or possibility.
Sensitivity	Projections made according to assumed deviation of some variable away from its (a priori or calibrated) best estimate model. No estimate of the probability or possibility of such deviations available.
Stationarity	The assumption that statistics of a process are not changing over time.
Vulnerability	The expected consequences of an event. For some purposes vulnerability can be costed in terms of monetary damages, but other forms of vulnerability might also need to be considered.

1 Why worry about uncertainty in flood mapping?

1.1 INTRODUCTION

Flood risk is generally defined as the product of the probability of an event and the consequences of that event. Both components of risk are affected by multiple uncertainties but they can differentiate between assessing the uncertainty associated with probabilities of occurrence and uncertainty associated with the consequences. Both can be mapped individually, as well as the joint estimate of flood risk. Different types of mapping may be required to support different uses, for example, the requirements for making planning decisions might be different to the requirements for emergency planning, damage assessment or insurance purposes.

It is worth noting that the type of framework for good practice being proposed here is rather different from other guides to good practice that tend to be more definitive about what methodologies should be used (for example by IoH, 1999 or Kirby and Ash, 2000). This is because methods for estimating uncertainty in flood risk mapping are still relatively new and it is difficult to be definitive even about the dominant sources of uncertainty. To date, published research suggests that the uncertainties involved can be significant, but has given only limited guidance about the importance of different sources of uncertainty, realistic ranges of effective parameters, and numerical issues with model implementations. So it is difficult to provide a 'recipe' for the assumptions appropriate for different types of application. However, this is not a good reason to neglect the uncertainty. In the same way that there is a wealth of practical experience among users in dealing with model implementation issues, the same type of experience will evolve in estimating the importance of different sources of uncertainty.

The concept of proportionality is essential to the proposed framework. Many types of projects involving flood risk mapping will not justify a full analysis of uncertainty. Such an analysis might be considered a proportional response where there is a significant investment at stake and where the degree of confidence in the predictions of areas at risk of flooding might make a difference to the decision that is made (see Section 1.2).

This guide does not address the additional issues raised by pluvial, coastal or groundwater flooding, but similar approaches to those presented here could be used.

It is possible that in framing the problem for a particular application different stakeholders and users of uncertain flood risk information might have different impressions of the sources and nature of uncertainty in the assessment process. This will be expressed in terms of decisions about assumptions or conditions made in representing different sources of uncertainty (see Chapter 3). The resulting risk maps will always be conditional on these assumptions. So it is important that the assumptions are clear and agreed with stakeholders and potential users as part of the analysis. The explicit recording of the agreed decisions provides a suitable audit trail for the analysis for later evaluation. The framework provides a hierarchical structure to address the different types of uncertainty that will be encountered (see Section 1.4).

1.2 TYPES OF DECISION INFORMED BY FLOOD RISK MAPPING

1.2.1 Inundation mapping for flood risk assessment

Flood extent mapping, without consideration of vulnerability, underpins all flood risk assessments.

Useful website

Environment Agency flood map for planning (rivers and sea): http://tinyurl.com/czze35

Current practice is represented by the Environment Agency flood maps and underlying detailed mapping studies (see *Useful websites*). These represent the best estimate of areas of inundation for chosen probabilities of exceedance (AEP of 0.01 and 0.001) of flood magnitudes based on hydraulic model predictions without uncertainty. Flood extent maps are generally presented as crisp lines for the boundaries of inundation predicted for the different probabilities of exceedance. An estimate for the potential impact of climate change is also sometimes used in Environment Agency commissioned flood mapping, based on the AEP 0.01 event + 20 per cent, although this is now being reviewed following the availability of the UK Climate Predictions 2009 (UKCP09) ensemble climate projections (see Prudhomme and Reynard, 2009, and Prudhomme *et al*, 2010).

There are multiple sources of uncertainty in deriving these maps including:

- the estimated flood discharge for the chosen design event
- the definition of the floodplain topography and channel cross-sections
- the choice of effective hydraulic roughness coefficients
- the choice of a hydraulic model and its representation of the physics
- the treatment of floodplain infrastructure
- the consideration of the performance of flood defences
- and the potential for non-stationarity arising from both catchment change and climate variability and/or change.

1.2.2 Planning decisions

A major use for flood maps is in the planning process as defined by the National Planning Policy Framework (CLG, 2011) and TAN15 (Welsh Assembly, 2004). Current practice depends on the best estimate flood maps outlined in Section 1.2.1, with different zones dependent on the crisp outlines defined by the AEP 0.01 and 0.001 model simulations. These maps are subject to the same uncertainties as introduced in the previous section. Estimating the effects of such uncertainties will result in maps that are not crisp and will require changes to how flood maps feed in to the planning process. This could be as simple as defining a probability level to define the boundary for each zone. However, it could also allow for different levels of probability of inundation over some planning period for different types of development decision.

1.2.3 Emergency planning

Emergency planning is also dependent on flood mapping where both extent and hazard (implying a combination of flood depth and velocity) are important. In particular, access and evacuation routes will need to be assessed under different probabilities of exceedance. This type of application will be subject to the same types of uncertainty as the other uses of flood maps with more focus on uncertainties in flow velocity. Interpretation of the mapping in this case will also require assessment of key potential consequence locations (eg schools, hospitals) and safe evacuation routes.

1.2.4 Flood damage assessments

Flood damage assessments typically require both flood extent and depth maps and estimates of the economic consequences of flood events (eg a flood depth – damage relationship for different types of receptors). As well as the assessment of uncertainty in flood extent and depth, the estimated consequences will also be uncertain. Additional uncertainties are also present in the estimation of annualised consequences, eg expected annual damages (EAD), for example, due to assumptions related to the onset of flooding. All these sources of uncertainty should be taken into account when interpreting flood damage assessments.

1.3 WHEN MIGHT AN UNCERTAINTY ANALYSIS BE JUSTIFIED?

There are many sources of uncertainty that arise in producing fluvial flood risk maps. Some of these have to do with the natural variability in the occurrence of floods, and others more to do with the limited knowledge available about the nature of flood runoff and flood wave propagation including the geometry and infrastructure of channels and floodplains. So it is expected that the estimated extent of a 0.01 or 0.001 AEP flood to be uncertain even if current flood maps are presented in terms of crisp map boundaries based on deterministic model results. Published research confirms that there is significant uncertainty associated with flood extent predictions using hydraulic models (eg Aronica *et al*, 1998 and 2002, Bates *et al*, 2004, Pappenberger *et al*, 2005, 2006a and b, 2007a and b, Romanowicz and Beven, 2003). So the question is whether this difference between the expectation of uncertainty and current deterministic practice is important.

In a discussion paper from Water Resources Research (2006), Pappenberger and Beven considered "seven reasons not to use uncertainty analysis", which were:

1 Uncertainty analysis is not necessary given physically realistic models.
2 Uncertainty analysis is not useful in adding to process understanding.
3 Uncertainty (probability) distributions cannot be understood by policy makers and the public.
4 Uncertainty analysis cannot be incorporated into the decision making process.
5 Uncertainty analysis is too subjective.
6 Uncertainty analysis is too difficult to perform.
7 Uncertainty does not really matter in making the final decision.

All of these reasons are shown in their discussion not to be tenable, at least in principle when resources and computational feasibility allow (see also Beven, 2009). Perhaps the most important issue to consider here is item 7. It might be considered that the use of rare (0.01 AEP) or extremely rare (0.001 AEP) estimates of events, together with a 'freeboard' margin in the design of flood defences, is already an institutionalised way of dealing with uncertainties in the occurrence and magnitude of floods (acting essentially as a factor of safety argument).

However, it is suggested that an analysis of uncertainty will always be justified as a means of expressing confidence in model predictions but it is important that the effort required in making any assessment be proportional to the costs and potential benefits or disbenefits. This has been recognised, for example, in the procedures used in the Environment Assessment Agency (MNP) in the Netherlands, which provide for a staged approach from an initial qualitative assessment to a detailed quantitative analysis in applications that might justify the latter (eg van de Sluijs *et al*, 2005). Here it is suggested that such a hierarchical approach can be incorporated into a consistent decision framework. In this way, the issue of proportionality can be considered following a preliminary analysis based on expert judgement, and subsequent decisions can be recorded about the assumptions required to represent the various uncertainties in the risk mapping process (in sources, pathways and receptors).

The requirement for a detailed uncertainty assessment, as an expression of confidence in the model predictions, will be greatest when such an assessment might significantly change a decision (whether that decision is concerned with mitigating risk to life, expected annual damages, or some other measure). This depends critically on the nonlinearity of any consequence or vulnerability function on the (uncertainty in) predicted flow depths and velocities. There might be, for example, a critical piece of infrastructure either existing or proposed (for example a water treatment plant or electricity sub-station) that is outside the bounds of the 0.01 AEP flood extent as mapped deterministically, but which might be predicted as being flooded within the bounds of uncertainty associated with an 0.01 AEP event. Whether or not the level of confidence of being wrong in estimating the impacts of a 0.01 AEP event is sufficient to change the decision about a new project will then depend on the particular circumstances and their importance. However, the recognition of uncertainty is in itself an important component in the transparency of such decisions. Indeed, the Pitt Report following the summer 2007 floods, encouraged the recognition of uncertainty in flood risk assessment and forecasting (Pitt, 2008).

There is another aspect of proportionality that also needs to be considered within such a framework. It should be recognised that any assessment of uncertainty is conditional on a variety of assumptions as conditioned the information available. Further information might act to constrain the uncertainty and increase the confidence in the model predictions (or vice versa), and some pieces of information might be much more cost effective in constraining uncertainties than others.

1.4 AN OVERVIEW OF THE FRAMEWORK

This guide represents an outcome of the Flood Risk Management Research Consortium (FRMRC) second phase project. The proposed framework is not intended to be definitive, because research in this area continues to evolve. However, it is intended to provide a set of working procedures that can be considered to represent current good practice.

The guidelines that follow outline a procedure for making an uncertainty assessment in fluvial flood risk mapping within a source-pathway-receptor framework. The different uncertainties involved in the source of flooding, pathways of flood discharges and potential receptors are identified. This procedure is implemented in a very specific way, in terms of the conditions that are necessary to support an uncertainty assessment in different circumstances, taking account of the fact that the effort involved needs to be in proportion to the importance of the decision being made. Not all applications will justify a full uncertainty analysis. The decision could be made to consider only a qualitative assessment of uncertainty, or an analysis of the sensitivity of the mapping to ranges of particular inputs, particularly if there are no historical data available with which to constrain uncertainty estimates.

By allowing decisions about the conditional assumptions to be considered for different sources of uncertainty, there is a degree of flexibility in the type of analysis considered appropriate in different types of application. However, in doing so, and as part of good practice, it requires that the conditions are made explicit and (ideally) agreed between the relevant stakeholders so that they can be later be evaluated and modified as new information becomes available.

Underlying the development of the framework is the results from two FRMRC workshops held in Lancaster in January 2006 and in Sheffield in December 2009. The workshops brought together academics, Environment Agency and Defra staff, consultants and local authority staff, to discuss risk and uncertainty in flood risk management. The workshops led to framing this guide in terms of a condition process (rather than as a 'recipe') to allow flexibility for different types of application and decision processes. A condition tree for the whole process is provided in Chapter 2.

2 Condition-based framework for assessing uncertainty in fluvial flood risk mapping

2.1 A CONDITION-BASED FRAMEWORK

This guide provides a flexible framework that will allow users to determine how far uncertainties are important in using model predictions to inform robust decision making for particular applications. The framework covers the sources of uncertainty encountered in flood risk mapping within a source-pathway-receptor framework, how those sources might be represented, and methods for communicating the outcomes of an analysis to users. Probability theory provides a formal methodology for dealing with uncertainty (in the context of environmental modelling see, for example, Beven (2009) and Goldstein and Rougier, 2009) but not all uncertainties are easily evaluated as probabilities. In particular it is necessary to differentiate between uncertainties that arise from random variability and those that arise from lack of knowledge or understanding when a sensitivity analysis, scenario or possibilistic representation might be more appropriate. Some background to the representation of uncertainties and their use in decision making is given in Appendix A1 (see also Beven, 2009).

The condition-based framework is summarised in this section. This material is supported by more detailed generic discussion of sources and importance of uncertainty and of the decisions required in Chapter 3, including potential default options. By presenting the framework in this form it is intended that a conditional analysis might be defined at a range of levels of detail, from a simple sensitivity analysis to a full quantitative analysis where the nature of the uncertainties and the outcomes that depend upon the risk mapping justify the additional resources required. The implementation of sets of conditions for two cases studies (Carlisle and Mexborough) is introduced in Chapter 4 with full details in Appendices A2 and A3.

It is important to remember in what follows that any quantitative estimate of probability is necessarily dependent on the assumptions made in developing the quantification. In applications such as flood risk mapping it is not possible to be completely sure about what assumptions should be used. This means that in any report, as in the case studies presented here, good practice requires that the assumptions used should be stated explicitly so that they can be reviewed and reassessed as necessary. It also means that all quantitative estimates of probability should be considered as conditional on those assumptions. So, this is a condition-based framework.

2.2 SOURCES OF UNCERTAINTY

Flood risk mapping involves many sources of uncertainty in the source-pathway-receptor system but is a type of application where some attempt can be made to try and quantify the effects of the different sources of uncertainty on flood risk maps (and consequent decision making). These sources of uncertainty can be summarised as follows:

- uncertainty in fluvial flood sources (Section 3.1)
    - uncertainty in fluvial design flood magnitude
    - uncertainty in assessing effects of future climate change
    - uncertainty in assessing effects of future catchment change

- uncertainty in pathways (Section 3.2)
    - uncertainty in hydrodynamic model structure
    - uncertainty in channel morphology/conveyance/rating curve
    - uncertainty in effects of floodplain infrastructure
    - uncertainty in performance of defences
- uncertainty in receptors (Section 3.3)
    - uncertainty in consequences/vulnerability
- decisions in implementing an uncertainty analysis (Section 3.4)
    - defining interactions between sources of uncertainty
    - defining an uncertainty propagation process (including sensitivity analysis)
- decisions in conditioning uncertainty using observational data (Section 3.5)
    - uncertainty in observational data
    - defining a conditioning process
- defining a presentation method (Section 3.6)

A flow diagram for this framework is shown in Figure 2.1. It is worth emphasising at this point that within the condition-based uncertainty estimation framework, it should be part of good practice and the audit trail for any application that the conditions made are recorded explicitly. In any particular application, not all of these uncertainties will be relevant nor will a detailed quantitative analysis be proportional to the decision to be made. The framework is, however, common to these different levels of analysis.

2.3 HOW TO USE THE CONDITION TREE FRAMEWORK

Each of the sources of uncertainty in the source-pathway-receptor structure outlined in the previous section is explored in more detail in Chapter 3. For each source a condition tree is provided to guide the user through an application. The response at each decision point will depend on the nature of the application and the information available and the resources available to support the decision making process. Effectively each condition will define the assumptions upon which the consequent analysis depends. Decisions about these assumptions should be recorded for later evaluation. In some cases, the assumptions might define a simple qualitative analysis based on expert judgement as a way of assessing whether a more detailed analysis is justified or not. In some cases default options will be available as an extension of existing guidelines (such as the use of FEH methods in estimating the magnitude of a chosen design flood). In the future, further default options might be defined as part of standardised procedures for specific purposes (such as assessing the impact of future climate change). The two case studies that follow in Chapter 4 demonstrate the application of this framework for cases where a quantitative flood risk map is the result of the analysis, including conditioning on past flood extent observations.

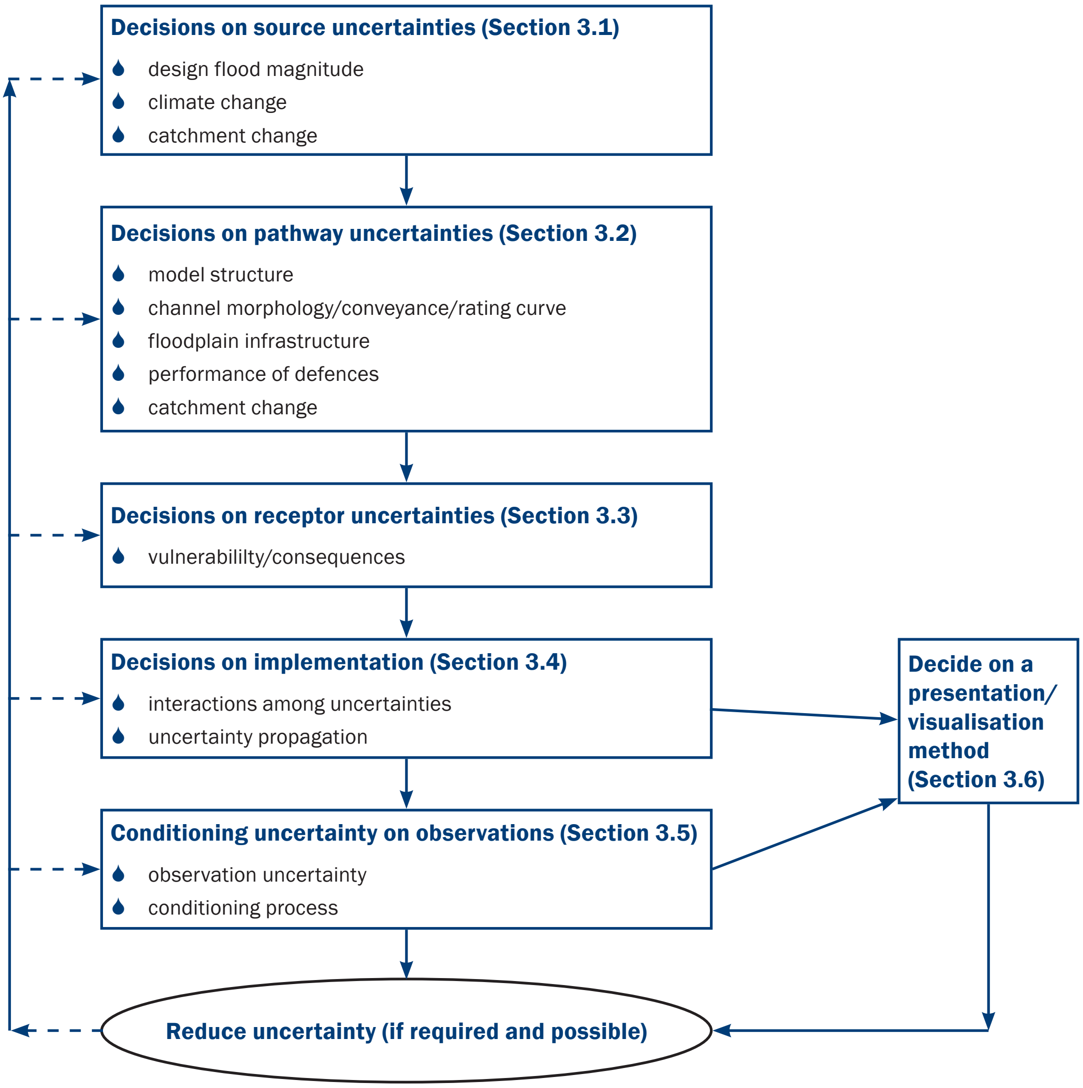


Figure 2.1 Flow diagram for the condition framework

3 Uncertainties in fluvial flood risk mapping

3.1 UNCERTAINTY IN FLUVIAL FLOOD SOURCES

3.1.1 Uncertainty in fluvial design event magnitude

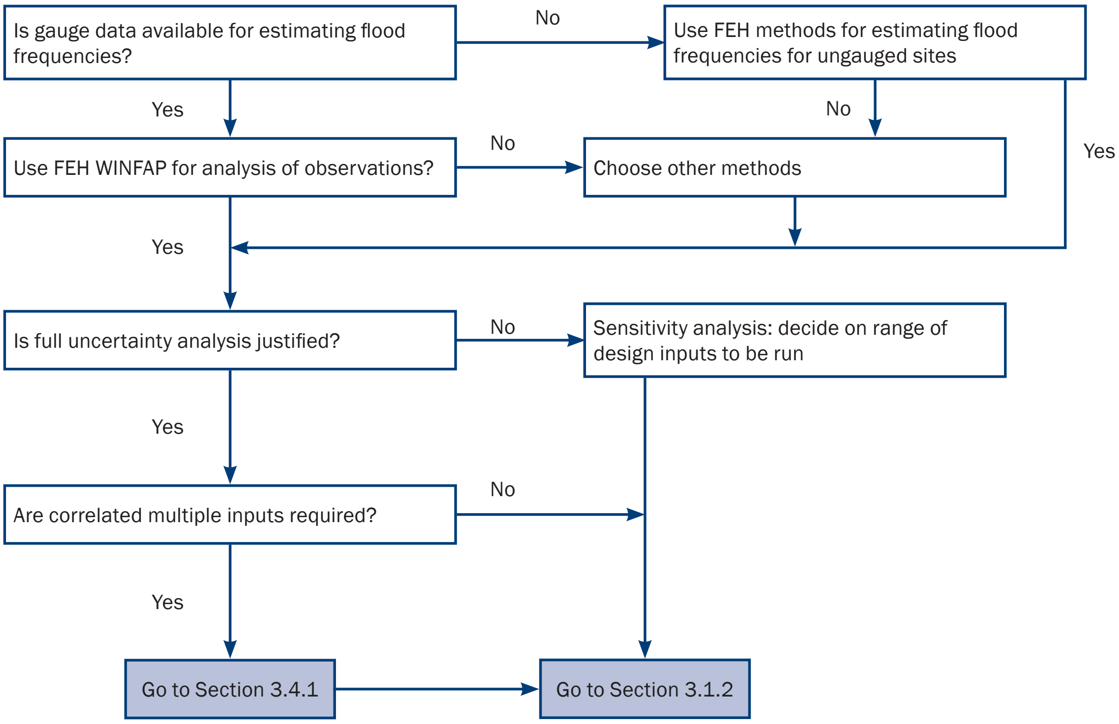


Figure 3.1 Condition tree for assessing uncertainty in fluvial design event magnitude

Uncertainty in design event magnitude is generally considered to be a statistical problem, conditional on the choice of a particular distribution for the probabilities of exceedance. As in fitting any statistical distribution to a set of sample data, the resulting uncertainty estimates reflect uncertainty due to sampling variability under the assumption that the chosen distribution is the correct model. This is rather important in the case of extreme values, since the characteristics of different statistical distributions will vary most in their tail behaviour. In fact, statistical theory suggests that the extremes for block maxima for an underlying distribution should asymptotically (as sample size increases) conform to the generalised extreme value (GEV) distribution, assuming that the blocks are long enough and the data is stationary. This was the chosen distribution that flood probabilities in guidance by NERC (1975) were based upon. Despite this theoretical advantage, however, the GEV was replaced by the generalised logistic distribution (GLD) in the *Flood Estimation Handbook* (FEH) (IoH, 1999) because, when fitted to actual data, fewer catchments showed a distribution with an apparent upper limit to flood magnitude than when fitting the GEV. This reveals that even where data are available the sample sizes are generally too short to be sure of an appropriate distribution, although there are further statistical arguments that can be used in selecting an appropriate distribution for block maxima in the presence of a non-stationary process (eg Eastoe and Tawn, 2009).

Within the prevailing methodologies used in practice for flood risk management the choice of distribution tends to be fixed, or limited to a small number of candidate distributions, which suggests that uncertainty estimates based on sampling variability conditional on the choice of particular distributions might underestimate the uncertainty in design event magnitude. So, the choice of a particular distributional form should only be considered as the starting point. Current best practice in fitting a distribution to observed peaks at a single site follows the recommended procedures in the FEH and includes the use of the WinFAP software, which allows for the direct estimation of uncertainties at different AEP. However, current best practice introduces further uncertainties associated with estimating design event magnitudes at single sites for events with low probabilities of occurrence (eg an AEP 0.01 design event) as the recommended procedures require the use of additional observed peaks from remote yet hydrologically similar sites, ie the pooling group method.

The uncertainty in estimated flood discharges is also generally neglected in fitting frequency distributions in this way but can be significant (see also Section 3.5). Flood discharges, by definition involving overbank flows, provide challenges to field measurement. First estimates are generally based on existing site rating curves but for more extreme events these can involve significant inaccuracies. In the past, post-event analysis has led to significant modifications of discharge estimates. For example, after the Carlisle flood in January 2005, a post-event analysis suggested that the peak discharge was 60 per cent higher that estimated using the previous rating curve. A comprehensive re-evaluation of significant floods in the USA by Costa and Jarrett (2008) revealed similar discrepancies. So, this is a source of knowledge uncertainty that feeds into the probabilistic estimation of flood frequency and design magnitudes.

There is, for most sites of interest, the additional uncertainty associated with estimating a design event magnitude without local gauging site data being available. Some form of extrapolation from remote gauged sites is then required. In addition to the FEH statistical methods for ungauged catchments (ie the application of the pooling group method using observed peaks at hydrologically similar sites), other research has made some suggestions for estimating the uncertainty in flood magnitudes at ungauged sites, including approaches based on the uncertain extrapolation of:

- parameters of flood distributions (McIntyre *et al*, 2005)
- parameters of rainfall runoff models (Lamb and Kay, 2004)
- hydrograph characteristics to constrain runoff model parameters (Yadav *et al*, 2007, Bulygina *et al*, 2009).

As with the FEH statistical methods, it is not guaranteed that any of these methods will always give flood frequencies close to those derived from observed floods at all test sites. So, there is significant knowledge uncertainty associated with estimating the design flood magnitude for an arbitrary site.

The discharge estimate for any chosen AEP will be uncertain. As noted earlier the uncertainty arises both from lack of knowledge about the true discharges at gauging sites, the true statistical distribution, the sampling uncertainty of a small dataset and extrapolation uncertainties through use of remote gauged sites.

More broadly, a variety of methods are defined in the FEH methodology for estimating the frequency characteristics of a site depending on the situation of the site with respect to gauged record length. These include event hydrograph methods (derived from regressions against catchment characteristics) and scaling methods. In each case, the FEH methodology is based on the transfer of information about the median annual peak flow and associated growth curves, without explicit account being taken of uncertainty in the estimates.

Also, uncertainty associated with fluvial flood sources is inherent where event hydrograph methods or scaling methods are used to estimate design event hydrograph shape and timing. Where local data is used to parameterise event hydrograph methods the overall uncertainty is typically constrained but may be less transparent unless uncertainty in model parameterisation is recorded and applied during the estimation of design event hydrographs.

The overall uncertainty in design event magnitude, shape and timing is also typically constrained where multiple complementary methods are used, for example, statistical distribution fitting and event hydrograph methods. In such cases, the uncertainty associated with the individual methods should be identified and combined to provide a single overall assessment of uncertainty.

UK standard methods for estimating design event magnitudes are based on the FEH methodology, so it is proposed that these methods – fitting statistical distributions, event hydrograph and scaling – should be extended by taking account of appropriate uncertainties for both gauged and ungauged sites.

3.1.2 Gauged catchments

The FEH methodology typically recommends fitting a statistical distribution for estimating frequency characteristics of a gauged catchment, typically the generalised logistic (GL) distribution for annual maximum flood series or the generalised Pareto (GP) distribution for peaks over threshold series. The WinFAP software provided as part of FEH does allow the fitting of a wider range of distributions if an alternative choice would seem to be appropriate for a site. In WinFAP, statistical estimates of the uncertainties at a single site, conditional on assuming that the chosen distribution is correct, can be output for any chosen AEP. However, such uncertainties cannot be currently output for a pooling group analysis.

A special case arises when there are inputs from multiple gauged mainstream and tributary inputs to a flood risk area. In this case the frequency characteristics of the individual inputs are expected to be correlated. Keef *et al* (2009b) provide a methodology for assessing the frequency characteristics of co-varying flood sites. These can also be used to generate correlated Monte Carlo realisations of, for example, the AEP 0.01 flood (see Carlisle case study in Chapter 4, which involves discharges from the multiple tributaries). This method provides estimates of and samples from the joint distribution of flood peaks. However, the prediction of flood inundation might also be dependent on assumptions about the timing of flood peaks, which will depend on several variables including the pattern of rainfall, the relative size and position of the catchment areas. In this situation some assumption will be necessary about the nature of the hydrograph, consistent with any peak flow estimate. A simple solution is to scale historical hydrographs to the estimated peaks but this is likely to underestimate the knowledge uncertainty associated with the relative timing of the different sources. A more complete future solution would be to investigate the joint distribution of both peak magnitudes and relative timing, at least for cases where sufficient data is available for such an analysis.

3.1.3 Ungauged catchments

A variety of methods are recommended in the FEH methodology for estimating the frequency characteristics of an ungauged site depending on the situation of the site with respect to gauged sites.

In the pooling group method, estimates of uncertainties in the median flood are readily available. As previously noted, estimates of growth curve uncertainties are less accessible. However, uncertainty estimates can be calculated for each of the individual (gauged) pooling group sites and these could be weighted to form a joint distributional estimate for the target site.

Any event hydrograph method, based on catchment characteristic regressions, should in principle have uncertainty associated with them based on the samples used to develop the regression, although these will be conditional on the validity of the statistical assumptions being made in the regression analysis (generally that the variables are multi-variate normal distributed with stationary variance and covariance's). For example, the Revitalised Flood Hydrograph (ReFH) report provides a discussion of the uncertainty associated with the estimation of ReFH model parameters and as such uncertainty estimates of design event magnitude, as well as event hydrograph shape and timing can be obtained (Kjeldsen, 2007).

In the scaling method, using one or more local gauged sites, if uncertain estimates were made available for the gauged sites then the uncertainties could also be scaled as a first approximation to estimate uncertainty at the target site.

A fuller implementation of these methods for estimating design event magnitude uncertainty and both gauged and ungauged target sites will need to await a review of the FEH methodologies in the light of the increasing interest in uncertainty in flood mapping.

3.1.4 Uncertainty in effects of future climate change

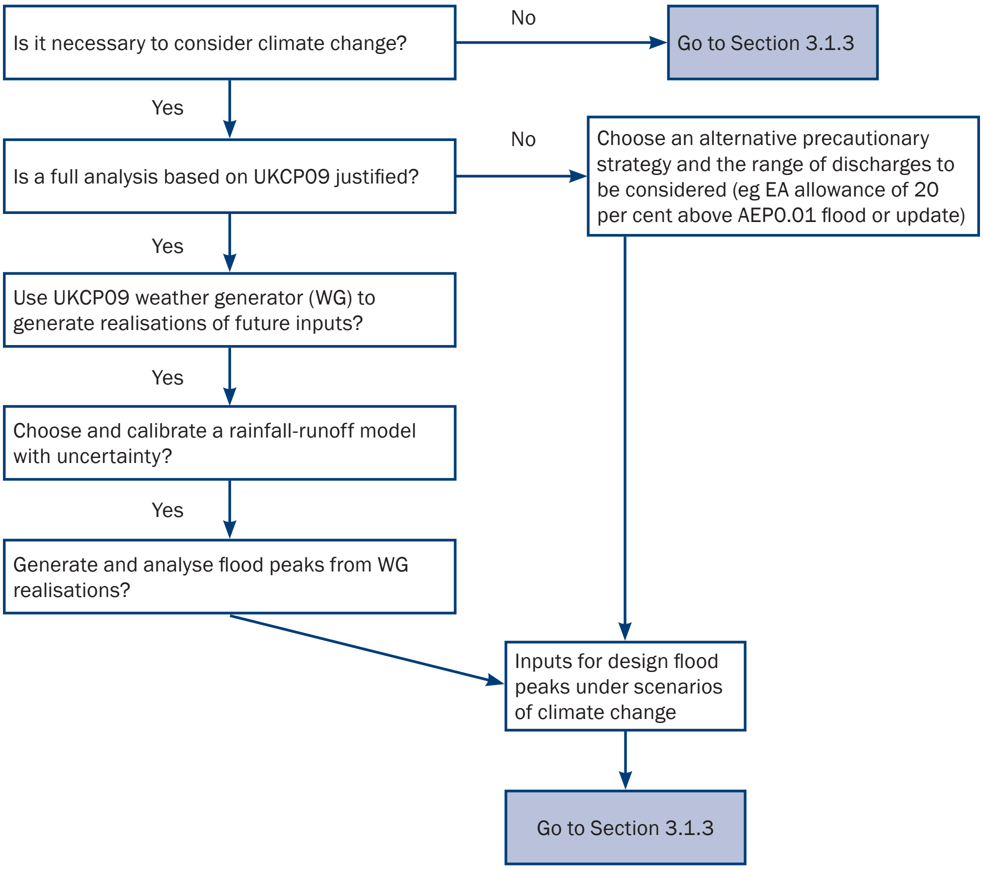


Figure 3.2 Condition tree for assessing uncertainty in effects of climate change

Classical frequency analysis is carried out as if the discharge frequency characteristics of a catchment are stationary (although FEH does include an adjustment for QMED estimates from short records in an attempt to account for variability owing to clustering of flood-prone years). Now that the Intergovernmental Panel on Climate Change (IPCC) has concluded that it is very likely that recent changes in global climate are due to anthropogenic impacts on the earth system, it is difficult to sustain an assumption of future stationarity in flood frequency (Milly *et al*, 2008). The nature of future climate change, and how it might modify the frequency of extreme events, remains, however, uncertain. In the UK, in some applications, the Environment Agency has required that as well as modelling the AEP 0.01 discharge, an additional simulation of the AEP 0.01 discharge + 20 per cent to represent the potential impact of future climate change. This figure represents the average change in the AEP 0.01 flood magnitude in the simulation studies of the Thames and Severn catchments by Reynard *et al* (1998 and 2001). Those studies did not consider uncertainty in the models used to represent the catchments, or any uncertainty in the future climate predictions that were available at the time.

Since the studies of Reynard *et al* the UKCP09 predictions of future climates have been released. These predictions are based on two ensembles of model runs for each of three different emissions scenarios:

1 A small number of runs of a high resolution regional climate model.
2 A larger number of a lower resolution model.

A statistical methodology is used to combine the two ensembles into a best estimate of the probabilities of change for different climate variables under each of the three scenarios. Probabilities are here being used to represent uncertainty in the predicted changes even though not all sources of uncertainty in the modelling can easily be represented probabilistically (in this respect the climate change prediction problem is a more extreme case of the importance of knowledge uncertainties than modelling flood risk). The UKCP09 predictions do not assign a probability to the different emissions scenarios. These are conditional on the emission scenario assumptions (about which there is significant knowledge uncertainty) but represent credible potential futures to inform the development of adaptation strategies. The probabilistic predictions for each scenario should be taken as potential futures in the same way.

The question then arises as to how best to incorporate those potential futures into an analysis of potential future change in flood frequency. Most attempts to do so have involved several steps as follows:

- calibrate a rainfall-runoff model for a catchment of interest using historical data
- modify the inputs to that catchment using the change factors from the climate predictions. This can be either by modifying historical data series or using a weather generator. In UKCP09, a weather generator is provided to produce realisations of rainfall and other variables for 5 km grid squares in the UK for each decade into the future up to 2100 in a way consistent with monthly probabilistic change factors (see Kilsby *et al*, 2007)
- run the rainfall-runoff model to produce scenarios of future flood peak discharges based on the modified input series.

There have been many such studies in the past but few have taken any account of uncertainty in the rainfall-runoff model (but there are exceptions, for example Cameron *et al*, 2000, Lamb and Kay, 2004, and Wilby and Harris, 2006). The first study of this type to use the UKCP09 probabilistic futures as inputs is that of Prudhomme and Reynard (2009). Their study has used the 11 member UKCP09 ensemble of high resolution regional climate model (RCM) projections in an exploration of the sensitivity of 150 catchments in the UK to potential changes. However, there is a general issue with this type of study of how well even the RCM projections can represent the potential changes in extremes.

There are many limitations of this approach. Firstly, rainfall-runoff models are not always calibrated to optimise the accuracy of flood peaks, nor does the calibration often take account of the uncertainty in the flood peaks. It is known, for example, that when rainfall-runoff models are used to reproduce a series of annual maximum peaks, the annual maximum peaks simulated are not always the same as those in the historical period (eg Lamb, 1999). The UKCP09 probabilities also cannot be taken as true expected probabilities of future change. They are empirical probabilities of the outcomes from the ensemble predictions for each emission scenario, which may or may not represent future climate conditions well. So in both the climate change predictions and the use of those predictions in continuous simulation to estimate change in flood frequency characteristics, important knowledge uncertainties arise. UKCP09 probabilities are a way of dealing with those knowledge uncertainties by assumptions about appropriate scenarios. Other assumptions might be considered and it is not actually necessary to invoke climate predictions in being precautionary against future change (eg Wilby and Dessai, 2010, and Beven, 2011). The major decisions to be made in dealing with the potential effects of climate change on flood discharge relate to which approach to being precautionary should be taken and what range of possible future discharges should be considered.

3.1.5 Uncertainty in effects of future catchment change

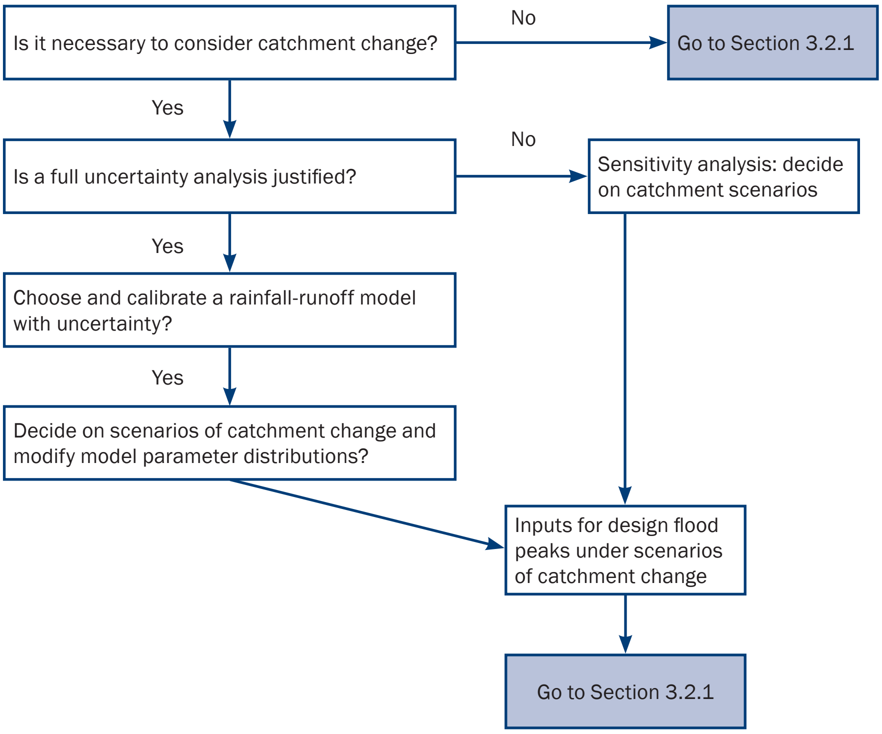


Figure 3.3 Condition tree for assessing uncertainty in effects of catchment change

Another aspect of catchment change is that associated with land management. Agricultural intensification, urbanisation and other land management effects are expected to affect runoff generation and have an impact on flood runoff in both the past and future. However, except at small catchment scales where a change in vegetation cover or urbanisation has affected a large proportion of the catchment area, it has been very difficult to prove significant change in catchment response due to past catchment change by the analysis of historical observations (eg O'Connell *et al*, 2005, and Beven *et al*, 2008). It does not mean that there has not been such an effect in the past, only that it is not detectable given the uncertainties in hydrological observations. It also does not mean that there will not be an effect in the future but unless very significant change is expected then this is unlikely to be a major cause of uncertainty in flood risk.

If there is a specific requirement to assess the potential effects of catchment change on flood runoff generation then any such predictions will be necessarily uncertain. The FEH provides methods for estimating the effects of urbanisation on the median annual flood but without an associated estimate of uncertainty, while Defra/Environment Agency (2005) project FD2014 provided estimates of changes to standard percentage runoff (SPR) values for use in the ReFH method. However, these changes were based purely on engineering judgment and no associated uncertainties are given (O'Connell *et al*, 2004).

This is a case where a scenario or sensitivity analysis approach to uncertainty evaluation might be taken, with any assumptions about the nature and implementation of change recorded.

3.2 UNCERTAINTY IN FLOOD PATHWAYS

3.2.1 Uncertainty in hydraulic model structure

The inundation models used in practice vary from single cross-section models applied under normal flow assumptions, to 1D and 2D depth averaged dynamic models of different degrees of approximation

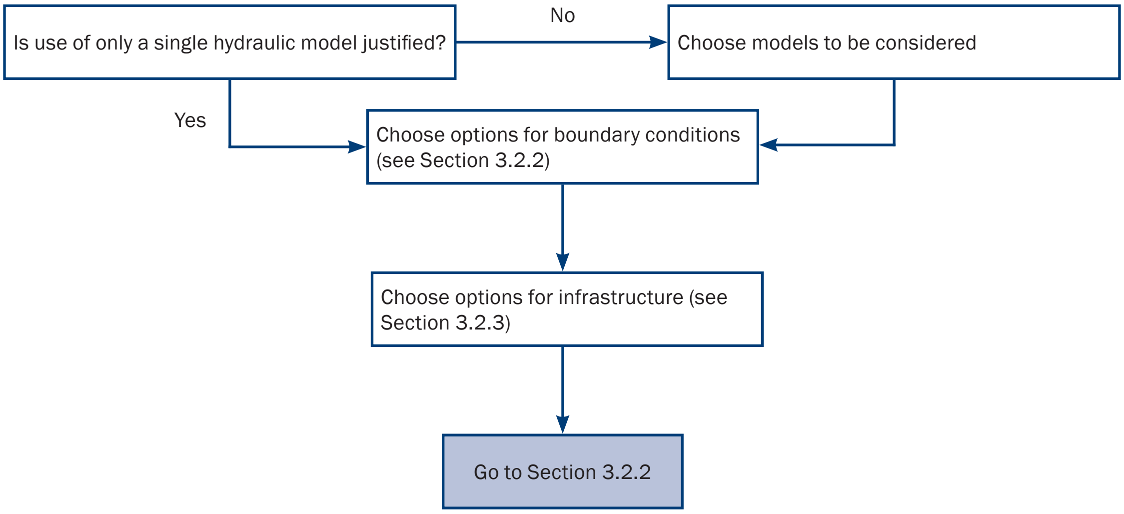


Figure 3.4 *Condition tree for assessing uncertainty in choice of hydraulic model*

to the fully dynamic equations. Only for very limited reaches are 3D computational fluid dynamics (CFD) models used (eg in checking the rating curve under flood conditions for a specific site). Each type of model could provide different inundation predictions (eg ISIS, TUFLOW, MIKE 11, HEC-RAS, LISFLOOD, JFLOW). In fact, many modelling packages provide several implementation options (eg about how to handle boundaries or bridge or weir structures or link 1D and 2D representations) and different implementations of the same generic model type can provide different inundation predictions (eg Neelz and Pender, 2010, and Pappenberger *et al*, 2006a). Also, the use of reduced complexity or coarser grid models to speed up run-times when multiple simulations are required will necessarily result in further uncertainty. These are also forms of knowledge uncertainty in predicting flood inundation. Chapter 7 of guidance by the Environment Agency (2009) summarises the different types of 1D and 2D models and discusses the relative merits of each model type.

Kirby and Ash (2000), in their guidance for estimating freeboard, also recognise a number of other factors that can affect flooding that may not be recognised in many modelling studies. These included the effects of wind set-up, waves and super-elevation of the water surface at bends in overtopping of defences, as well as the effects of settlement, sedimentation and deterioration relative to the original design of defences.

3.2.2 Uncertainty in parameterisation of channel and floodplain conveyance and rating curves

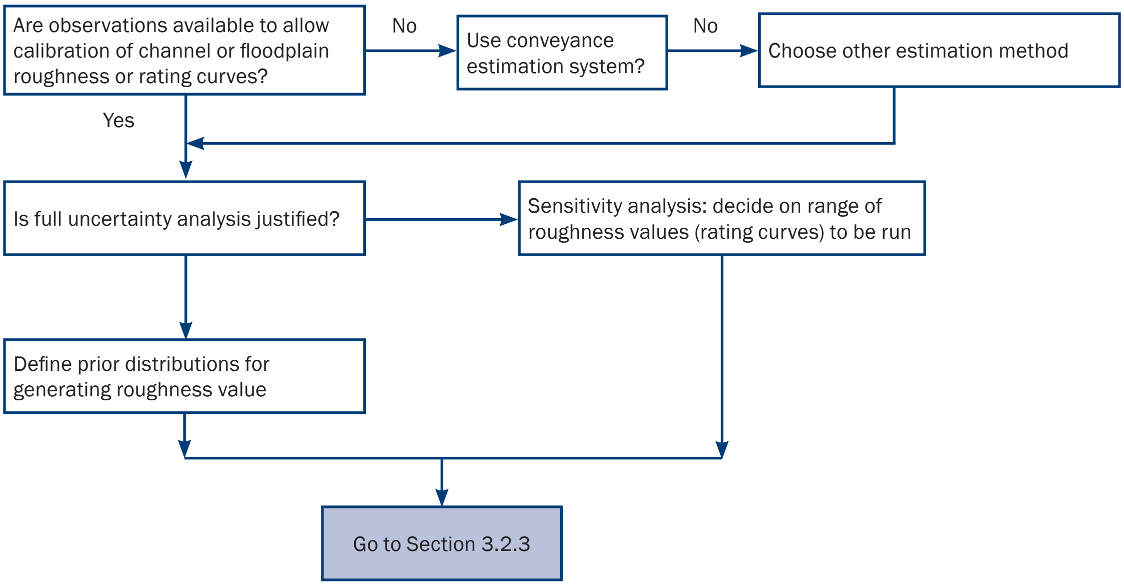


Figure 3.5 *Condition tree for assessing uncertainty in choice of channel and floodplain roughness and rating curves*

Estimating channel and floodplain conveyance raises a number of issues. Current practice allows for the estimation of appropriate roughness coefficients from hydraulic considerations, as tabulated in many texts, and engineering experience. In many practical applications, sensitivity of model predictions to estimated roughness coefficients is assessed by varying values from previous best estimates. Generally, however, more detailed studies of uncertainty in roughness coefficients and conveyance values have been neglected because it tends to be assumed that uncertainty in roughness values is dominated by other sources of uncertainty in the modelling process, because roughness has some physical basis. However, studies have shown that when hydraulic models of different types are compared against observed inundation data with a view to estimating effective roughness coefficients, the resulting estimates often show poorly constrained marginal distributions and large uncertainty (eg Aronica *et al*, 2002, Bates *et al*, 2004, and Pappenberger *et al*, 2007a). Part of the reason for these variations in roughness is that the roughness parameter is model dependent and related to the degree to which known physical behaviour is represented in the model; so as physical representation is increased (eg through use of a full 2D solution of the shallow water equation) the variation in the 'optimum' roughness value is expected to reduce. Another reason is due to the way in which derived roughness is compensating for other sources of uncertainty (floodplain topography, channel form, floodplain infrastructure, model numerics, uncertain boundary conditions etc). So the 'effective' roughness values (and their associated uncertainty) that will be required to give good predictions of flood inundation will depend on the choice and implementation of a particular inundation model as well as the available data.

The estimation of roughness and conveyance parameters has been grouped together with the estimation of rating curves in this section because they are often intrinsically linked in model implementation. At sites where gauging measurements are available, BS ISO 1100-2:1998 and BS ISO 5168:2005 procedures exist for generating rating curves. However, the extrapolation of rating curves with a limited range of measurements to flood depths (whether by statistical regression or hydraulic calculation) may be uncertain and needs to be evaluated carefully (Environment Agency, 2003, provides further guidance). Care is also often required to ensure that models are implemented with boundaries far enough away from the reach of interest so as to have no detrimental effect on the predicted inundation in that reach. Hydraulic models (1D, 2D and even 3D) have also been used to construct or verify rating curves for overbank flows. Such predictions will be dependent on how effective roughness (or turbulent energy transfers) is assumed to vary at higher flood levels (as well as uncertainty associated with the physical representation of the gauged site).

There is also the issue of spatial patterns of effective roughness or conveyance functions and their dependence on cross-sectional and surface characteristics. Recently, the Environment Agency introduced the Conveyance Estimation System (CES) (Knight *et al*, 2010, and HR Wallingford, 2009) which, based on laboratory and field data, takes account of river-floodplain interactions in estimating total conveyance in overbank flows. CES allows a somewhat more sophisticated approach to estimating a cross-section conveyance function and also, in its *Uncertainty Estimator*, provides upper and lower credible bounds for conveyance, derived from the upper and lower roughness estimates from the CES *Roughness Advisor* (see Knight *et al*, 2009, and Section 3.3). This provides some allowance for the uncertainty in estimating conveyance (and consequent predicted water level for a given design discharge), though without any associated estimate of probability. It is also recommended in CES that such values should be superseded by calibrated roughness values where this is possible. CES provides estimates only for rural situations and assumes the validity of the normal-depth relationship.

The situation is more complex for 2D inundation models in which effective roughness values can vary more widely. In practice it is common to vary estimates of effective roughness values by river reach or vegetation type and explore the sensitivity of results to these estimates by one-at-a-time variation of values.

It is clear that knowledge uncertainty is an issue in the estimation of effective roughness coefficients, conveyance functions and rating curves. Roughness does, however, have an important impact on the predicted depths and pattern of inundation. So some prior assumptions will have to be made about the expected nature of the uncertainty. Generally, this uncertainty is constrained by calibration against observed inundation values both at point locations and spatially using, for example, aerial photography, although this does not necessarily guarantee that good predictions of inundation will be possible throughout the entirety of a simulated reach (eg Pappenberger *et al*, 2007b).

3.2.3 Uncertainty in effects of infrastructure

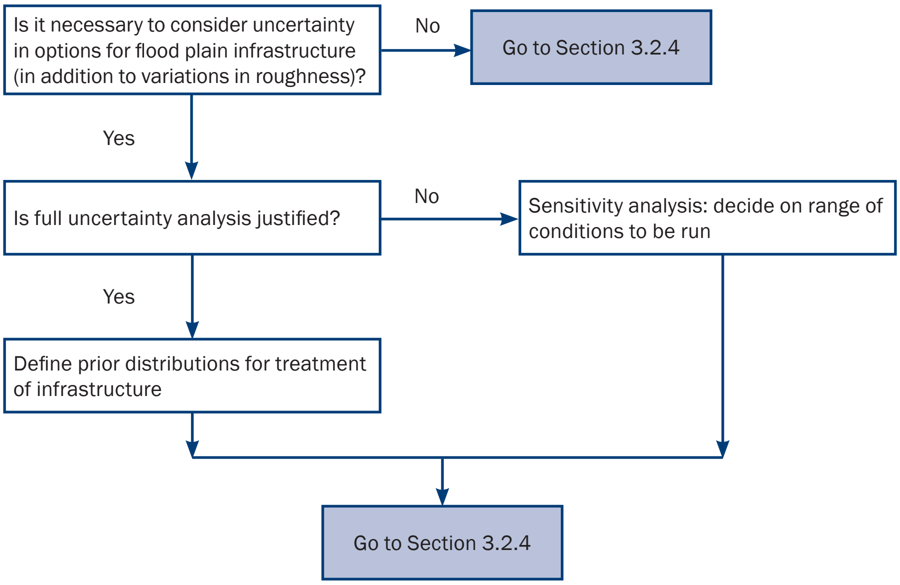


Figure 3.6 Condition tree for assessing uncertainty in effects of infrastructure

There are many types of within-channel and floodplain infrastructure that will affect flood inundation predictions. These include weirs, bridges, embankments for roads and railways, buildings, walls, hedges, and culverts (and flood defences, which are the subject of Section 3.2.4). Not all of the infrastructure that might affect patterns of inundation are always detectable from topographic imaging or easily represented within hydraulic models (eg culverts, narrow flood defences, walls and hedges) while the effects might be dynamic during any particular event, for example, due to the possibility of bridges and culverts being blocked by debris. In some cases, it might be necessary to represent the effects implicitly rather than explicitly (eg representing the effect of a wall or hedge as an effective roughness coefficient for the floodplain). Again, there are knowledge uncertainties about the representation of infrastructure that might be difficult to represent explicitly so that any assessment of uncertainty in the inundation predictions will be conditional on the way in which the infrastructure is treated.

There are two ways in which floodplain infrastructure can affect the uncertainty in inundation predictions:

1. Whether infrastructure that will have an effect on inundation in a particular reach is properly identified. For example, filtered and unfiltered LIDAR topography can be used to examine the sensitivity of inundation predictions as a way of evaluating the effects of structures on the floodplain on model predictions.
2. How that infrastructure can be represented within a particular modelling package.

Modelling packages typically provide options about how the effects of infrastructure, such as the energy losses associated with bridges, can be implemented. In-channel structures, such as weirs, are generally easier to implement than out-of-bank structures. An Environment Agency scoping study into the calculation of afflux at bridges and culverts found that this was one of the most important sources of uncertainty in urban areas (Benn *et al*, 2004). Sensitivity to different choices of implementation should be investigated as forms of knowledge uncertainty treated in terms of scenarios or possibilities.

3.2.4 Uncertainty in performance of flood defences

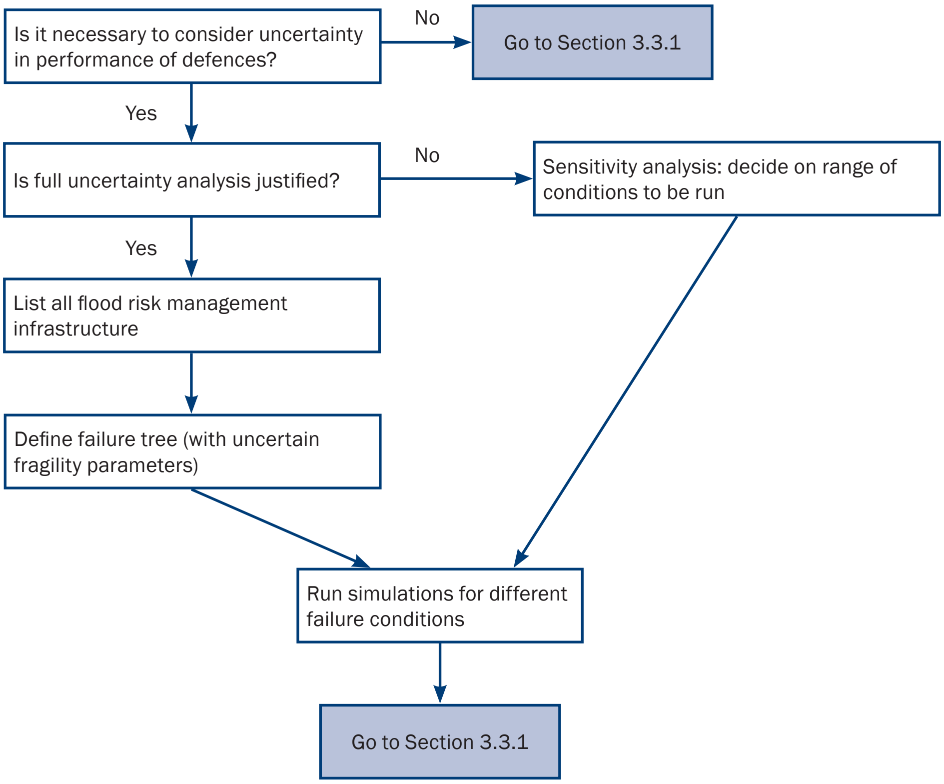


Figure 3.7 Condition tree for assessing uncertainty in performance of flood defences

In assessing the performance of flood defences, it is first necessary to list all the potential effects of flood risk management infrastructure that might affect water levels during flood conditions, including fault trees for potential failures. This will include flood embankments, flood control gates and pumping stations.

The failure of flood defences is generally treated deterministically, although modelling tools are available to treat defence failure in a probabilistic way, with the changing probability of failure with flood magnitude being represented as a fragility curve, for example, the risk assessment for system planning (RASP) methodology (Sayers and Meadowcroft, 2005) and the RELIABLE software (Gouldby, 2008). These allow different sources of uncertainty to be taken into account in formulating the fragility curve. There is very rarely any local data available on which to base estimates of failure parameters or condition local failure probabilities for different potential modes of failure, so such estimates are normally the result of a forward uncertainty analysis based on prior estimates for failure parameters and the role of inspection and maintenance regime. Estimates of the probability distributions for different inputs to the failure models are propagated to estimate the output probabilities for different sections of flood defence (forward uncertainty propagation).

For fluvial flooding, the resulting failure probabilities depend on a condition assessment and an estimate of the in-channel water level that affects the defence relative to crest level. Normally such assessments are made independent of the sequence of events over which the defences age with no coupling of failure in one or more sections of defence and probabilities of failure at other sites. This independence allows failure probabilities at a particular site to be directly related to probabilities or possibilities of uncertain water levels, but does not then consider the potentials for one failure to affect the probability of failure elsewhere.

In principle, joint failures for embankments, control structures and other infrastructure can be handled within a failure tree framework. This will also require a set of assumptions about the failure tree to be agreed for a particular analysis.

3.3 UNCERTAINTY IN RECEPTORS

3.3.1 Uncertainty in consequences/vulnerability

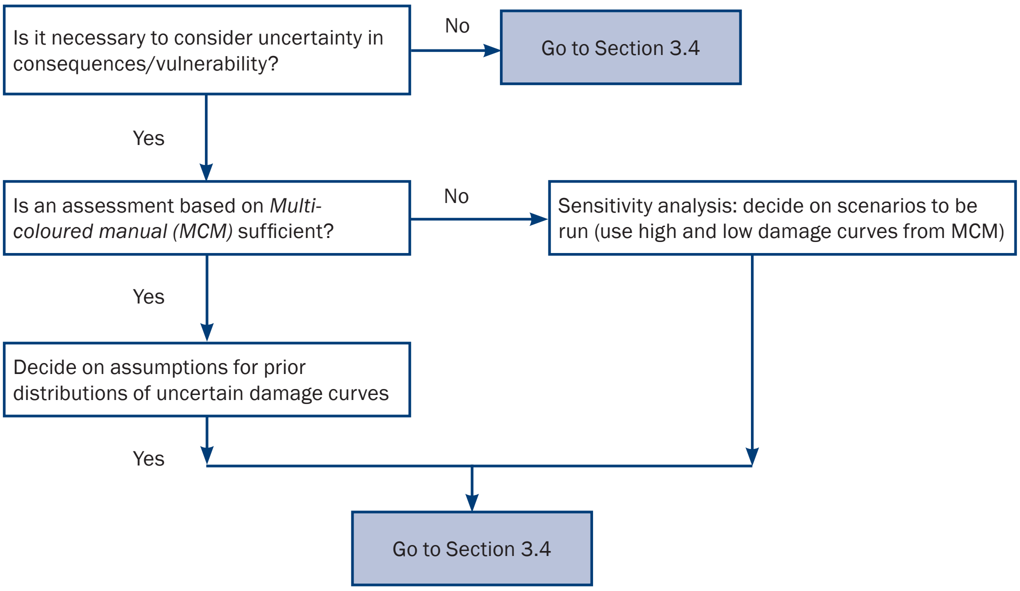


Figure 3.8 Condition tree for assessing uncertainty in consequences/vulnerability

In assessing flood risk in terms of the potential damages from a flood event or sequence of flood events it is necessary to estimate both the probabilities and the resultant consequences. The consequences of flooding are typically considered as direct, indirect or intangible. These consequences can be further categorised as:

- direct property damage
- risk to life
- other economic damage
- infrastructure damage
- health and social damage
- institutional damage
- other damage.

In the UK, the established process of estimating flood consequences follows the methodology for assessing potential direct property damages in what is commonly known as the Multi-Coloured Manual (MCM) developed by the Flood Hazard Research Centre at Middlesex University (Penning-Rowsell *et al*, 2005 and 2013). This currently provides a deterministic estimate of potential direct property damages within an area defined by the modelled flood extent, together with high and low damage scenarios, not associated with any estimate of probabilities.

Beyond the uncertainties in flood extent discussed earlier, the damage calculations are prone to knowledge uncertainties in the reference data that informs the depth damage calculations. These are from three sources:

1. Property location and type data provides information on the types of property within the flood extent and their exposure to the calculated flood depths. The data might not be correctly defined on the current property that has been built, its use, doorstop elevation, presence of basements, floor level voids and barriers to flows within properties.
2. Current value inventories: these are possible damages set against property types. Here current values may not reflect market values or inventories of possessions or items lost may not completely match property types.

3 Depth damage curves: the link between the flood extent, the properties inundated and the costs of losses calculated. Here the curve may not reflect the flood characteristics for the full flood extent where velocities and duration of flooding that affect property may vary.

The MCM highlights such uncertainties alluding to their possible impact. An early edition of the Blue Manual (Penning-Rowsell and Chatterton, 1986) provided 95 per cent confidence intervals for the residential depth damage calculations but these were not produced for later editions. Set within the context that the MCM provides a consistent evaluative approach informing cost-benefit analysis between different FRM options the precise matching of reality of costs, although pursued, is not viewed as a significant issue:

> *"We suggest that uncertainty is only important if its resolution would make a difference to what option is chosen: that is, whether the preferred option is 'robust' to the remaining uncertainty." "At each stage it is necessary to decide whether any reductions in the uncertainty concerning the estimates of the benefits of the options justify the cost of the work necessary to improve those estimates."*
>
> Penning-Rowsell *et al* (2005)

However, if these deterministic estimates of damages are combined with the uncertain estimates of flood inundation extent, then an uncertain damage estimate will result. Decisions could then be made robust to uncertainties in damage estimates given that for any cost-benefit analysis it would be necessary to assess some expected annual damage (EAD) value by integrating over the uncertainty in both depths and damages (see also the approach based on InfoGap methods for dealing with some of the sources of uncertainty in design calculations in Hine and Hall, 2010).

Where a vulnerability assessment considers the broader range of consequence categories, additional uncertainty is included related to both similar considerations as those for direct property damage and to the relative lack of supporting evidence to guide their enumeration.

3.4 IMPLEMENTING AN UNCERTAINTY ANALYSIS

Many of the uncertainties already discussed involve decisions about the sources of uncertainty in implementing a flood risk modelling exercise at a particular site. Here, the decisions in implementing the uncertainty analysis itself are considered. There are two important aspects of such an implementation:

- the assessment of the interactions between sources of uncertainty
- the choice of method of propagating the assumptions about the sources of uncertainty through to an uncertain flood risk map.

Any estimate of uncertainty will be conditional on the assumptions made in each case. The constraint of uncertainty using additional observational data will be considered in Section 3.5.

It is worth noting that in the past, assumptions about different sources of uncertainty have been dealt with implicitly within flood defence design using the concept of 'freeboard'. Details of this approach are provided by Kirby and Ash (2000). It is also common practice to explore the sensitivity of flood maps to variations in assumptions by making a (generally small) number of sensitivity analysis runs of an inundation model (see, for example, Pappenberger *et al*, 2008). Here the aim is to provide a more complete analysis of how uncertainties propagate through a model.

3.4.1 Assessing interaction between sources of uncertainty

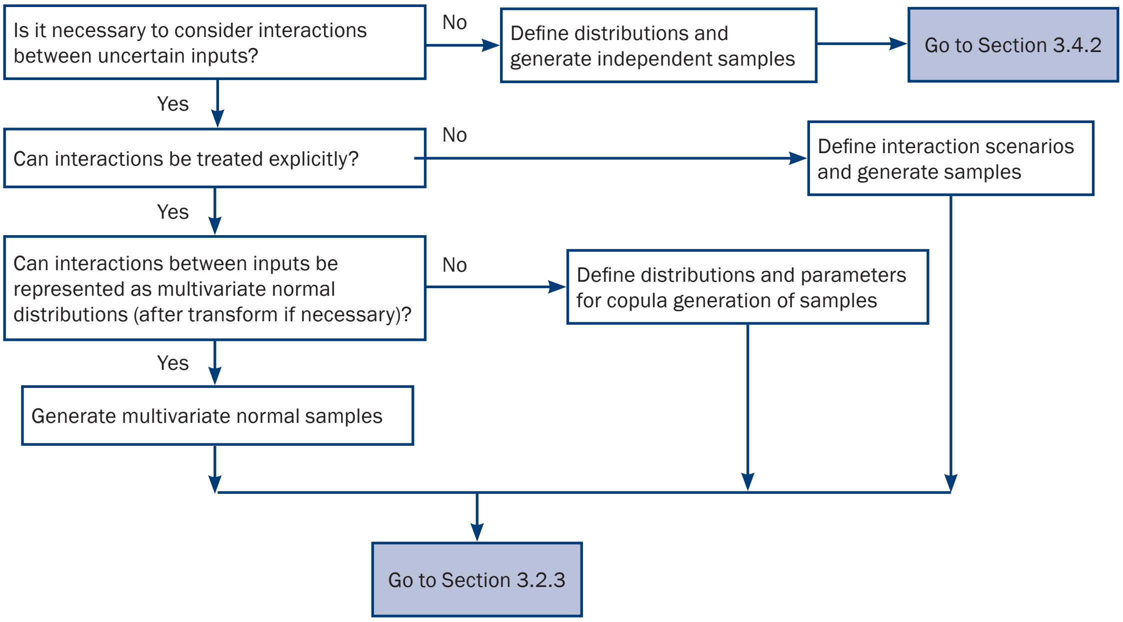


Figure 3.9 Condition tree for assessing interactions between uncertain inputs

There are two forms of assumptions that can be made about the interactions between different sources of assumptions:

1. **Explicit interactions** are most appropriate in dealing with variables that have obvious interactions (such as the uncertainties in the design flood for a chosen AEP that occur at nearby sites). In this case, the nature of the interaction between sites can be analysed (when there are data available) or specified by assumption. Techniques such as copula transformations can be used to specify interactions amongst multiple variables of arbitrary distributions (see Beven, 2009, Kurowicka and Cooke, 2006, and Keef *et al*, 2009a). An explicit treatment of interactions will generally result in probabilistic (or possibilistic) predictions that are conditional on the assumptions made.

   There are many other cases where it is expected that there will be interactions between uncertain variables in an analysis but which may be much more difficult to specify a priori (but which might be revealed implicitly in the conditioning process where there are observations available for evaluating model representations, see Section 3.5). Examples would be the interactions between channel and floodplain roughness in different parts of a flood risk zone, or between model grid scale and effective roughness values.

2. **Scenario interactions**, without any attempt to specify probabilities or possibilities associated with each scenario, can be used to deal with such interactions by specifying particular conditions in a flood risk assessment in a way similar to the use of failure trees in the use of joint failures. This is most appropriate where it is unclear how to specify a form of interaction because of knowledge uncertainties. A special case of this is where different sources of uncertainty are assumed to be independent because of lack of knowledge. So, for example, channel and floodplain roughness values might be assumed to be constant over a flood risk zone. This is unlikely to be true, but represents an acceptable simplification. Rather than treating this as a form of perfect explicit correlation in space, it is better to treat this as a scenario assumption. An obvious example of scenario assumptions is the use of a particular UKCP09 emissions ensemble in assessing the potential for future change in flood risk, independent of any other sources of uncertainty.

3.4.2 Defining an uncertainty propagation process

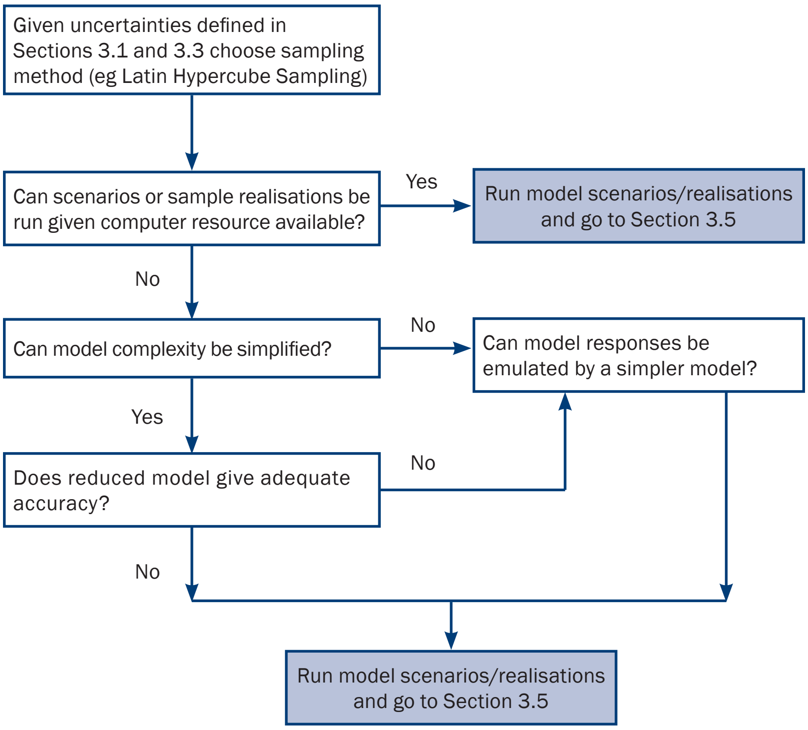


Figure 3.10 Condition tree for assessing an uncertainty propagation process

With some exceptions, existing hydraulic inundation modelling packages have not been designed to run multiple realisations for uncertainty estimation. As these models are nonlinear in their predictions in space and time, analytical methods for the propagation of uncertainties are not generally applicable. The simplest method for propagating the effects of different sources of uncertainty in such models is through Monte Carlo simulation.

Monte Carlo simulation is based on taking samples from a set of uncertain inputs to a model (parameters, boundary conditions etc) and propagating the results for that realisation of a model to produce an ensemble of the required outputs. Monte Carlo simulation raises the issue of computability. Given all the different sources of uncertainty, a very large number of runs might be required to define the output distribution of inundation maps. Also, for a complex floodplain configuration, even a single run of a model might take significant computer time.

This type of Monte Carlo simulation is, however, ideally suited to cheap parallel computing solutions, including the use of multiple PCs, multi-core PCs or GPU (graphics processing unit) systems that, for the right type of application, can have run times two orders of magnitude less than a single sequential processor (eg Lamb *et al*, 2009). The use of parallel computing systems will assist the runs required to make the production of uncertain flood risk maps more routine.

However, it is likely that computability will continue to remain a constraint in terms of specifying the number of runs required to undertake uncertainty estimation. While techniques are available to sample the requisite distributions as efficiently as possible, or to interpolate results between a smaller number of runs in the output space (eg Conti and O'Hagan, 2010, and Rougier, 2008), other approaches might sometimes be justified, including trading model complexity for the possibility of running a larger ensemble of models, or simpler methods analogous to the use of the 'freeboard' or factor of safety concept to allow for uncertainty in engineering design (see Kirby and Ash, 2000). Care should be taken however to ensure that such approaches do not result in unrealistic inference in decision making due to their simplification. Again, the way in which the conditioning framework provides an audit trail for the decisions made in an analysis should encourage the use of realistic assumptions.

It is well known that crude Monte Carlo sampling (sampling randomly across the range of variability of one or more variables) is not an efficient way of propagating uncertainty for well-behaved problems. It becomes increasingly inefficient with a higher number of uncertain inputs, especially where those inputs have well-defined distributions or are known to interact. A number of techniques have been developed to choose realisations as efficiently as possible in deriving the distribution of required outputs, for example, Latin hypercube sampling (LHS).

In LHS the probabilistic distribution of each input variable is divided into a number of increments of equal probability. The number of increments is generally the same as the number of realisations required. Samples are then generated, taking account of any specified interactions between variables, by non-replacement sampling, so that each increment is only used once. This ensures a reasonable coverage of the sampled space while reflecting the specified distributions of each input in the realisations. Each model realisation can then be run to produce an ensemble of outputs (eg flood inundation maps), which will have equal probability.

Efficient sampling methods, such as LHS, are recommended for forward uncertainty propagation where the input distributions are simple in nature. Methods for cases where observations are available for conditioning initial uncertainty estimates are discussed in the next section.

3.5 CONDITIONING UNCERTAINTY USING OBSERVATIONAL DATA

This chapter has considered whether the different sources of uncertainty in the flood mapping process can be quantified in probabilistic or other terms. In all cases, the outputs from the process will be conditional on the assumptions made and it cannot be stressed too strongly that those assumptions, embodied in the condition tree boxes, should be listed explicitly in any study (see the case studies examples in Chapter 4).

In some studies, however, it will be possible to condition the original uncertainty estimates by the use of historical observations, albeit that there is uncertainty in those observations and that historical events will (generally) have a higher AEP than the design levels used in flood risk mapping. However, such observations should be informative in assessing inundation at a lower AEP, relative to only using a forward uncertainty analysis based on prior assumptions about the nature of the sources of uncertainty. The use of this information is best achieved by associating the likelihood for different model realisations generated in a way consistent with the earlier assumptions about different sources of uncertainty. Although the way that likelihood should be assessed is not necessarily clear.

Within a probabilistic framework, the likelihood should be defined based on a model of the errors. In assessing the error in flood inundation predictions, however, the space-time nature of the modelling errors may be complex and is not simply statistical but depends on different sources of knowledge error that (together with the uncertainty intrinsic to the observations with which the model is being compared) reduces the effective information content of the space-time error series. In such a situation, to use statistical theory it is necessary to make strong assumptions about the nature of the errors (which then define the likelihood function) under the assumption that the model structure is correct and the errors are random. This can lead to over-conditioning of the model parameters when it is then used to predict other conditions.

Concern about knowledge uncertainties has led to alternative approaches to evaluating model likelihoods, based on fuzzy measures, informal likelihoods or limits of acceptability (Beven, 2006 and 2009). Such methods require subjective choices to be made about the knowledge uncertainties. Consequently, they do not purport to predict the probability of a future observed water level or inundation extent. Rather, they provide empirical distributions of model outcomes, weighted by some measure that reflects how well they fit the data. So, they might be better described as possibilistic methods. Such methods will be useful where the more formal probabilistic assumptions are subject to doubt.

However, the principle in both probabilistic and possibilistic cases is the same. A model realisation is evaluated and a weighted distribution of outcomes (in this case flood maps) produced. In both cases, a similar issue arises of how best to sample the range of potential models to most efficiently produce the posterior weighted distribution of models. This is still the subject of ongoing research but some guiding principles can be given here.

3.5.1 Uncertainty of observations used in model calibration/ conditioning

There are a number of different types of observations that might be used in model calibration or conditioning of uncertainty estimates. In particular, level records at a site over time (when these are not used for specifying model boundary conditions) provide local conditioning information that is often used in model calibration. More distributed information can be obtained from post-flood surveys of maximum inundation extent or depth data or photographic or radar imaging of water extent at the time of an overflight (eg Romanowicz and Beven, 2003, Bates *et al*, 2004, and Leedal *et al*, 2010). These calibration data can in itself be subject to both random and knowledge uncertainties. Random effects might arise because of fluctuations in water level or the precision with which the height of a trash line indicates an actual water level. Knowledge uncertainties can arise in relating a point maximum level measurement to the cross-sectional or element average elevation predicted by a hydraulic model in space and time, or in the registration of an image of water extent on to the representation of floodplain topography used in a model. Experience suggests that there can also be issues of observer or survey error that leads to anomalous or inconsistent values of water levels. These considerations suggest that where observations are available for model calibration or conditioning some assessment of uncertainty associated with those observations should be made. Studies where this has been done include Romanowicz and Beven, 2003, and Pappenberger *et al* (2007a).

Direct observations of flood water levels in both space and time are a useful constraint on prediction uncertainty through calibration or conditioning of the prior ranges of roughness and other sources of uncertainty. The question of how best to use those observations is considered later. Here only the assessment of uncertainty in the observations is considered.

3.5.2 Define observational error or limits of uncertainty for level/ discharge time series

Water levels can usually be measured relatively accurately and precisely at gauging stations, except where specific uncertainties related to gauge referencing occur (eg change in gauge location over time). Such data then provide a time series for comparison with model predictions all the time that a gauge continues to operate properly. The limited uncertainty associated with such level measurements can reasonably be considered as random and represented as a (Normal) statistical distribution. However, there is scope for failure of gauges and consequent loss of data during major flood events, limiting the value of the time series in model calibration or conditioning of uncertainty estimates. Conversion of water level data into discharges (where required) will be more uncertain and has already been addressed in Section 3.2.2. Hydraulic models will normally be implemented so that a calculation point can be related directly to such a gauge measurement. A single site will, however, provide only limited information for conditioning inundation predictions over a whole reach. There may also be some ad hoc level observations recorded by individuals during an event that might be of value.

3.5.3 Define observational error or limits of uncertainty for post-flood survey points

Post-event surveys can provide useful information of patterns of inundation over whole reaches, albeit limited in time to the maximum inundation (which might be at different times in different parts of a modelled reach). There may also be uncertainty in referencing a point measurement to the water level predicted in the closest model calculation element. The uncertainty in such measurements, if properly surveyed, will also likely to be relatively small but will vary depending on the width of trash marks, fuzziness in staining on walls, referencing to model topography etc. Accordingly, once gross and obvious errors have been eliminated, post-event survey information could be represented by a (normal) statistical distribution or a fuzzy measure within local minimum and maximum feasible values to account for such uncertainty (eg Parkes *et al*, 2013).

3.5.4 Define observational error or limits of acceptability for airborne/satellite image inundation extent

Several studies have used airborne or satellite sensing data to determine patterns of inundation (eg Romanowicz and Beven, 2003, Di Baldassarre *et al*, 2009, Mason *et al*, 2009, Schumann *et al*, 2009). The major issues in using such information are the type of sensor, the method of determining the flood outline, and the registration of the outline back to the model topography and level predictions. Certain sensors, such as air photo surveys during flood conditions may provide rather accurate flood outlines under good conditions. Others, such as satellite SAR images may provide rather uncertain flood outlines. In all such cases, the information content of the images in constraining the estimated uncertainty in flood mapping will be dependent on the timing of the overpass and the registration of the images to the model topography. Although providing wider spatial coverage than ground-based information, these data are likely to have a higher associated level of uncertainty and may not easily be represented statistically.

3.5.5 Defining a conditioning methodology

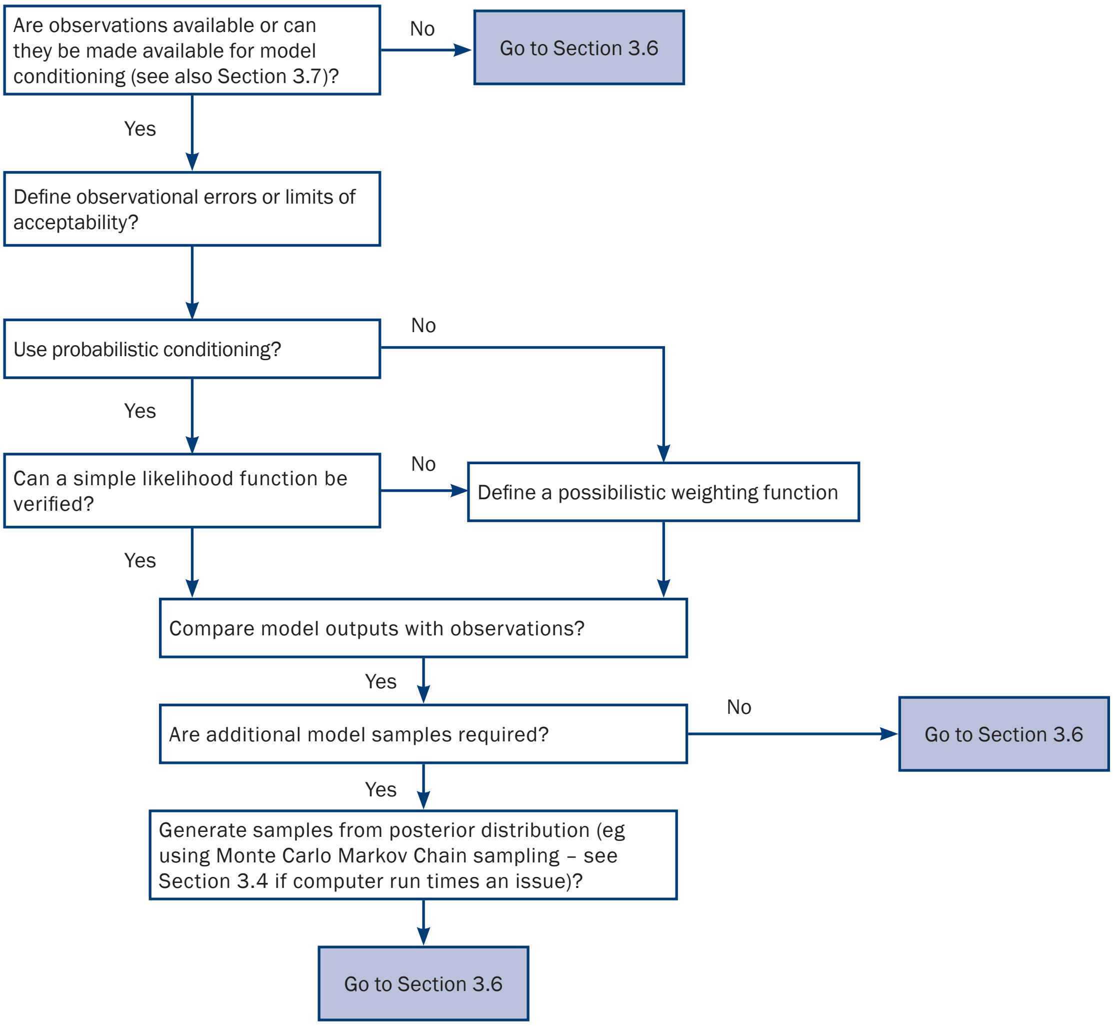


Figure 3.11 Condition tree for defining a conditioning methodology

Possibilistic conditioning

Many different possibility measures have been used with flood inundation models. These include the fuzzy measures used by, for example, Romanowicz and Beven (2003) and Pappenberger *et al* (2007a), and the *F-measures* based on cell inundation prediction performance used by, for example, Horritt and Bates (2001), Bates *et al* (2004) and Di Baldassarre *et al* (2009 and 2010). Such measures reflect the performance of a model in fitting any conditioning data without any explicit consideration of the error at any individual point. The measures can serve as weighting functions in predicting new sets of conditions using an ensemble of models under the assumption that performance in the future will be similar to performance on the historical events (a similar assumption is needed for probabilistic error models). The approach will work best where the ensemble of models shows no local bias in its predictions but rather brackets all the observed values (allowing for their observation uncertainty). Because of knowledge errors (eg in defining floodplain topography or the representation of floodplain infrastructure or error in the observations themselves) this may not always be the case (eg Romanowicz and Beven, 2003, and Pappenberger *et al*, 2007b) and model runs should be checked for adequacy across all observations.

Probabilistic conditioning

There have been relatively few attempts to use formal likelihood methods in assessing the space-time predictions of hydraulic models. An early attempt was by Romanowicz *et al* (1996) who evaluated the predictions of a 1D hydraulic model for a 12 km reach of the River Culm in Devon under the assumption that the errors would be additive, normally distributed, with a first order autoregressive correlation structure in time. The 'observations' used in this study were taken from a single simulation of a 2D RMA-2 model of the same reach. Errors at each of the six 'observed' cross-section water levels were treated as independent. In this case the availability of multiple time series at different stations in the reach also allowed updating of the likelihoods as the event progressed. Such datasets are rarely available in practice. There may be a very small number of stations recording water levels over time (that are not used in setting up the model boundary conditions) while a very small number of inundation patterns might also be available (when any errors might be expected to be correlated in space, and in time if multiple patterns are available). It is much more difficult to formulate an appropriate likelihood function for these more realistic cases (but see Hall *et al*, 2011, for a recent attempt to do so).

Defining a method of sampling posterior distributions

For either possibilistic or probabilistic conditioning, there is interest in finding a posterior likelihood or possibility measure distribution over all the dimensions of the sources of uncertainty considered. As in the case of forward uncertainty propagation it is much more efficient to sample in a way that reflects the density of likelihood or possibility in this model space. The difference from the forward uncertainty propagation case is that the regions of high density are not known beforehand, although earlier assumptions can be used to guide the initial search.

Statisticians have developed a range of posterior sampling techniques of which the most widely used are Markov Chain Monte Carlo (MCMC) algorithms (eg Gamerman and Lopes, 1997, and Robert and Casella, 2004). MCMC iteratively samples the model space to gradually home in on the density distribution in the model space. The method works best where there are a small number of dimensions, and where the likelihood function is well-defined in the model space. Even then a relatively large number of runs may be required to obtain sample realisation that properly reflect the posterior density.

With the more relaxed assumptions of possibility measures, it has been more usual to use either gridded sampling (with a small number of dimensions, eg Werner *et al* (2005) who evaluated only channel and floodplain roughness dimensions) or random uniform sampling (eg in Romanowicz *et al*, 1996, and Pappenberger *et al*, 2006a and b, and 2007a and b) where there is little information available on which to base previous distributions. Random uniform sampling is not at all efficient when the posterior density is concentrated in a small part of the model space, but experience with the application of different possibilistic measures has suggested that this is rarely the case (almost certainly because of the knowledge and interacting nature of different sources of error).

3.6 DEFINING A PRESENTATION METHOD

Considering a presentation method for uncertainty as previously described, it is assumed that the condition tree procedures have been followed to determine a set of predictions of inundated area (and/or depths and velocities) for the required at-risk areas. These predictions will depend directly on the choices made in allowing for and representing different sources of uncertainty. It is expected, as part of good practice, that these have been agreed with potential users of the information before the predictions of uncertainty are made.

Each prediction will be associated with a probability or possibility weight and (in the case of probabilistic methods) a representation of the model error. Flood probability and consequence estimates may then be combined in formulating uncertainty in patterns of flood risk. Different types of application might require different types of presentation of the resulting risk maps. The following guidelines represent the results of a consultation process with potential producers and users of uncertain flood risk information.

There are, in fact, two important components of the presentation and communication process (Faulkner *et al*, 2007). These are the effective communication of the assumptions on which the uncertain predictions are based and the effective visualisation of the resulting outcomes of those assumptions. In effect, the assessments and decisions listed in this guide are intended as a mechanism for communicating the nature of the assumptions of an analysis. This section concentrates on methods of visualisation of the outcomes.

3.6.1 Visualisation of uncertain flood mapping

As part of the work within the FRMRC a visualisation tool has been developed that allows flood information to be visualised in many different ways (see the case studies in Chapter 4). The tool is interactive so that different users might choose to visualise and use the underlying information in different ways.

This tool provided the basis for discussion at an end user FRMRC workshop, which highlighted that the framework would need to support a variety of end user activities. The workshop discussions generated four key principles for the development of uncertainty visualisations:

1 Visualisations should support end user decision making. Depending on the end user activities, responsibilities and the need for further communication to other stakeholders, the degree of manipulation and information required in flood risk visualisations will vary. End users concerned with planning evacuation routes, dry areas to locate emergency equipment and prioritisation of warning and emergency activities may require more facilities for manipulation and uncertainty visualisation in assessing risks. However, end users associated with development planning enforcement in relation to PPS25 (CLG, 2006) require limited uncertainty information, in fact a crisp line, in an enforcement map. The crisp line need not be the deterministic prediction, but could be chosen to be more risk averse. In cases that are challenged they may require further information to ensure transparency in allowing for the uncertainty associated with that line.

2 Visualisations should build on current approaches to end user decision making. Discussions in the end user workshops suggested that uncertainty is already considered qualitatively in end user decision making. Examples were given of ‘uncertainty’ bands defining mapped boundaries, the control of calculations and data through map scaling to suppress the effects of larger uncertainties and also individual interpretation of mapping results. However, the breadth and depth of understanding of the uncertainties involved vary across end users depending on their knowledge, experience and responsibilities. Consistency with existing approaches and tools will help engagement with uncertainty information.

3 Visualisations should be consistent in content and approach. Methods of communicating confidence through colour scales and worded scales are already used in a variety of domains. It is useful to build on existing practice but, where practical, the format decided on should remain consistent between flood risk management activities. Uncertainty communication should become integral to the risk assessment and management process or become familiar to a wide range of

practitioners and users to ensure the uncertainty information is not 'separated' from the data it informs. The mapping information provided should also be consistent.

4 Visualisations should use language that supports end user decision making. The language used within visualisations should be sympathetic to supporting evidence for decision making and help to engage appropriately with stakeholders such as developers, the public and the media. Rather than the term uncertainty it has been suggested to use more positive and supporting terms such as 'confidence' and 'best estimate'. Language should be understandable, limiting misinterpretation appropriate to the receptors of that information. The issue of colour blindness is an important aspect here, together with general perceptions of the meanings of colours and words.

3.6.2 An initial assessment of different forms of visualisation

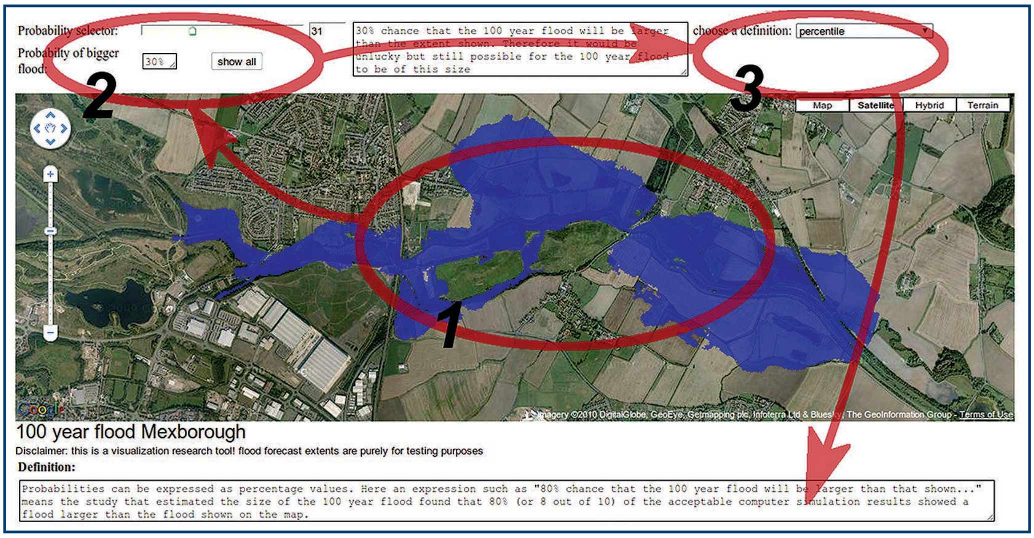
The full implications of the issues outlined in Section 3.6.1 for different flood risk management applications have not been fully explored in formulating the framework. Instead several different visualisation methods are presented here for consideration of particular applications. Each are based on ensemble predictions of hydraulic inundation models, with or without conditioning on historical data, with each ensemble member being associated with a possibilistic or probabilistic weight. The accumulated weights over all ensemble members are used to produce the maps of potential inundation for different AEP levels.

The FRMRC2 visualisation tool

The FRMRC2 flood mapping tool has been developed to allow a variety of different visualisation methods to be explored, tailored to different end user audiences. The tool is available in two versions:

- a stand-alone viewer written in the Matlab™ language
- an online web-based viewer incorporating Google Maps™ and dynamic HTML technologies (see Figure 3.12).

Both tools provide a dynamic, interactive interface between the user and the underlying database of ensemble inundation predictions. At present only AEP 0.01 event simulations are incorporated into the tool but other event magnitudes could easily be added.



30% chance that the 100 year flood will be larger than the extent shown. Therefore it would be unlucky but still possible for the 100 year flood to be of this size

100 year flood Mexborough

Disclaimer: this is a visualization research tool! flood forecast extents are purely for testing purposes

Probabilities can be expressed as percentage values. Here an expression such as "80% chance that the 100 year flood will be larger than that shown..." means the study that estimated the size of the 100 year flood found that 80% (or 8 out of 10) of the acceptable computer simulation results showed a flood larger than the flood shown on the map.

Figure 3.12 The FRMRC2 probabilistic flood inundation visualisation tool and interactive GUI (web-based viewer)

Note

The red circles and arrows have been added to the image to show the groupings and attention flow anticipated of the user.

1 Indicates the main map pane and initial user focus.
2 Shows the user control centre where inundation exceedance probability can be selected using an interactive slider or text input field.
3 Shows additional tools to help the user. In this case, a drop-down menu of definitions for the small number of specialist terms used on the website.

Threshold probability maps

The FRMRC2 visualisation tool provides the user with the facility to generate threshold probability maps. A slider control allows the level of probability of inundation to be changed while the resulting predicted inundated area consistent with that probability is displayed (see Figure 3.13).

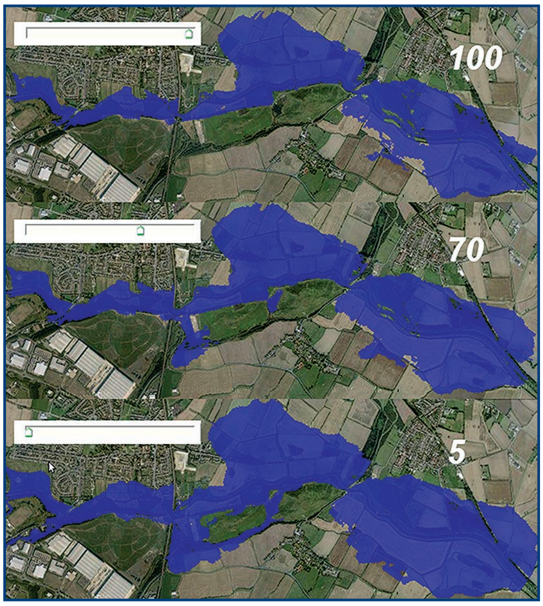


Figure 3.13 Mosaic image of inundation extents (web-based viewer)

Note: the mosaic illustrates the dynamic linking between the slider user input widget and the map overlay .The numbers (100, 75, 5) have been added to the figure to indicate the percentage probability of exceedance selected by the slider in each panel.

Colour coded inundation probabilities

Alternatively, the full range of predicted inundations can be displayed, colour coded by levels of probability (eg Figure 3.14). The assumptions that underlie the results of the figure are discussed in full in the Mexborough case study (Section 4.2).

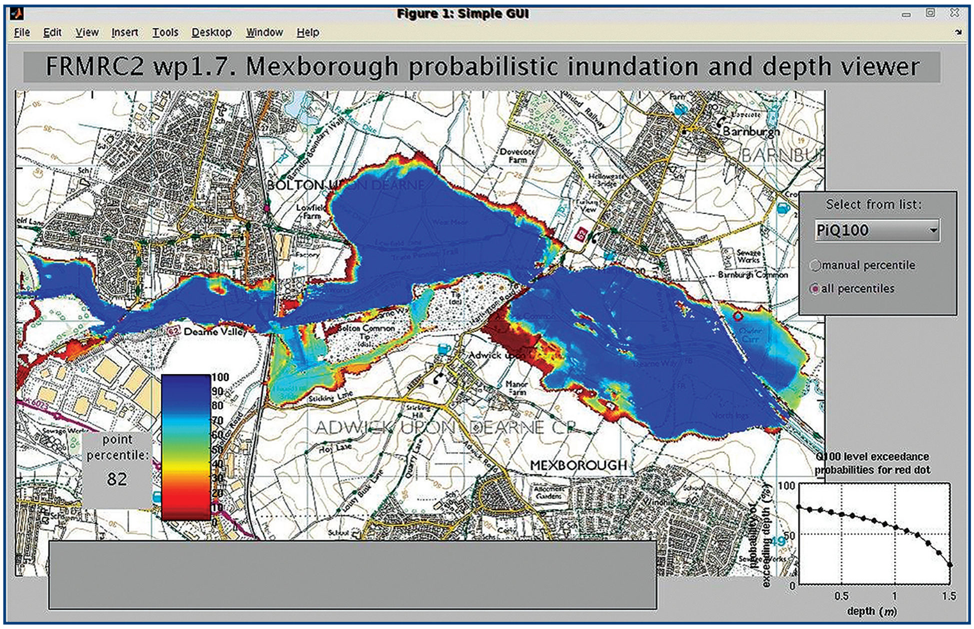


Figure 1: Simple GUI

FRMRC2 wp1.7. Mexborough probabilistic inundation and depth viewer

Select from list: PiQ100

○ manual percentile

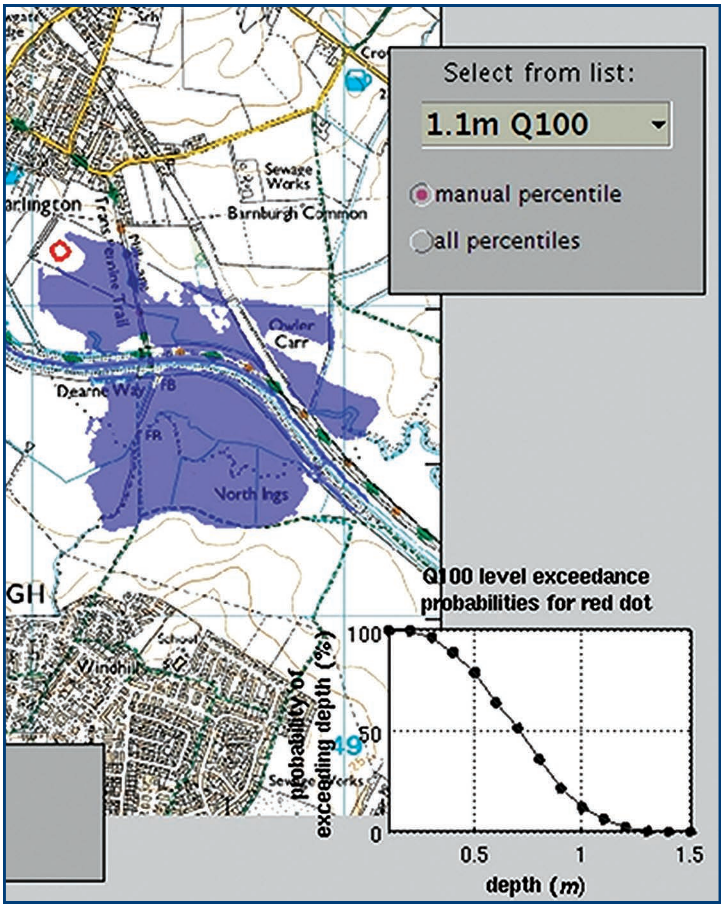
● all percentiles

point percentile: 82

Figure 3.14 Colour coded inundation extents (Matlab viewer)

Threshold depth probability maps and point specific information

Some users might be interested in the probability that flooding will reach a certain depth in certain locations. The Matlab tool provides information for inundation and depth probability at individual pixels of the model domain chosen by the user (using a mouse click on the map). Figure 3.15 shows how the area predicted as exceeding a certain depth with a chosen probability can be displayed. Also, the graphical output in Figure 3.15 shows, for the red circled point, the probability of depths at the AEP 0.01 event for that point.



Select from list: 1.1m Q100

● manual percentile

○ all percentiles

Note

The red circle is a movable point that interrogates individual pixels within the results database. The probability (y axis in per cent) of exceeding depths (x axis ranging from 0.1 m to 1.5 m) for the chosen pixel is shown in a separate figure at the bottom right of the GUI.

Figure 3.15 Threshold-depth probabilities (Matlab viewer)

Solid/dashed/dotted outline maps – confidence range mapping

A method of presenting uncertainty over multiple AEPs has been developed as part of an uncertain flood risk mapping project carried out by Halcrow for the Office of Public Works in Eire. The main features of the Halcrow visualisation method include (Wicks *et al*, 2008, and Borthwick *et al*, 2013):

1. Multiple mapping scales are presented: the 1:5k scale are used for urban areas and at 1:25k with background mapping at 1:50k for rural areas.
2. Fluvial flood events are shown for AEP 0.1, 0.01 and 0.001 events, coloured using a transparent fill from dark blue to light blue. Points along the river centreline with a table on the map showing the flow for the AEP 0.01 event and water level at each point and for each AEP shown for the existing situations. Where ‘all’ is stated in the table this means outputs for the AEP 0.5, 0.2, 0.1, 0.04, 0.02, 0.01, 0.002, 0.001 events.

3 Tidal flood events are shown for AEP 0.1, 0.005 and 0.001 events, coloured using a transparent fill from dark green to light green. Points along the edge of the flood extent at key locations, with a table on the map showing the water level at each point and for each AEP shown for the existing situations.

4 Fluvial and tidal maps are shown separately so that it is possible to see the source of flood risk. Areas benefiting from defences are shown by a grey hatched area.

This type of visualisation provides a form of confidence range mapping. Uncertainty is shown by a changing flood extent outline: solid = high confidence, dashed = moderate confidence, dotted = low confidence. In this case, the level of confidence is defined by the width of the predicted inundation uncertainties (<30 m, 30 m to 50m and >50 m). Outlines are blue, except for the AEP 0.01 event, which is in red to make it more visible (see Figure 3.16).

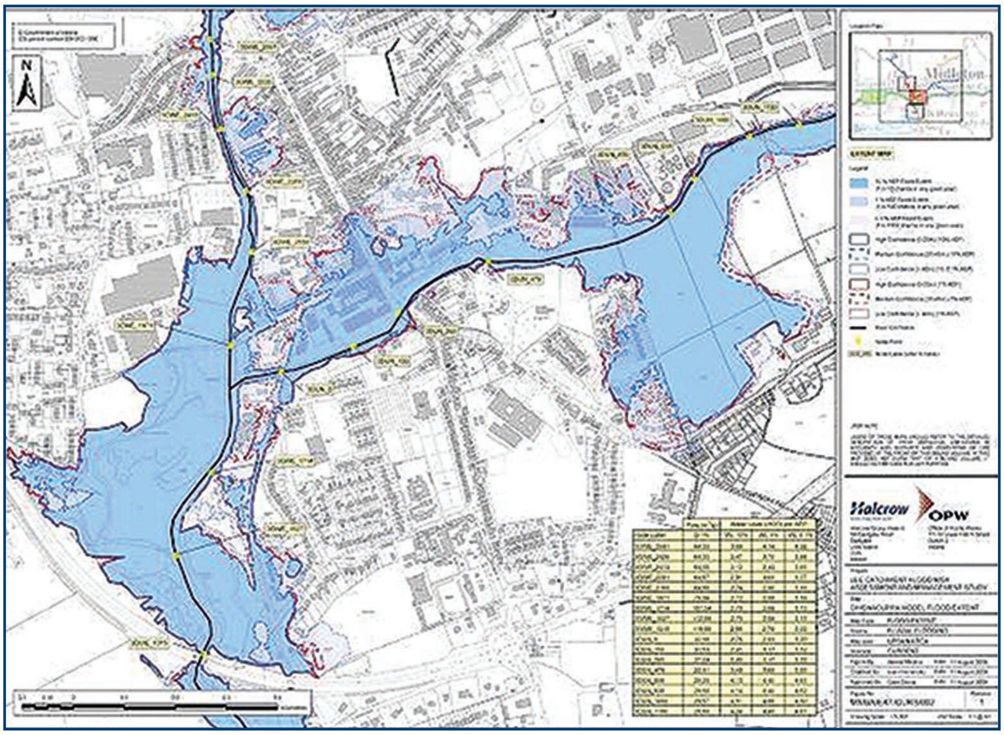


Figure 3.16 Visualisation approach developed by Halcrow. Figure shows map for River Owenacurra in Eire (after Berry et al, 2008)

4 Case studies

This chapter provides a brief introduction to the application of the framework for assessing uncertainty to two case studies, in Carlisle and Mexborough. In each case study not all components of the framework have been applied, for example, climate change and catchment change uncertainties were not considered in either study.

Appendices A2 and A3 set out a record of how the framework has been applied through explicit reference to the Conditions in the Carlisle and Mexborough case studies respectively, and as such acts as an important reference with which to interpret the resultant flood risk mapping outputs.

4.1 CASE STUDY 1: CARLISLE

Carlisle provides an example location of elevated flood risk in the UK with over 4500 residential properties, 1000 non-residential properties and large swathes of agricultural land at risk from an AEP 0.01 event. Significant flooding occurred in January 2005 in which about 2700 properties were affected by flooding. The cost of the January 2005 flooding has been estimated at over £400m.

The Carlisle case study serves as a generic exercise in the production of a model-driven probabilistic flood inundation map documented according to the framework. The particular interest of this application is the need to take account of the co-variation of the mainstream Eden and the Caldew and Petteril tributaries in contributing to the fluvial flooding at Carlisle. Figure A2.1 shows the location, topography and transportation infrastructure within the Eden catchment.

Appendix A2 provides a full record of the condition tree analysis made for the Carlisle case study using the framework of Chapter 3.

4.2 CASE STUDY 2: MEXBOROUGH

Mexborough provides an example location of an area deeply affected by the June 2007 flooding. It is an area in the River Don catchment that is low lying, tidally affected and heavily urbanised, with steep sided valleys in the upper catchment.

The Mexborough case study is of particular interest due to the high level of end user interest in the output of the case study uncertainty framework application.

Appendix A3 provides a full record of the decisions made for the Mexborough case study using the framework of Chapter 3.

5 Summary and conclusions

This guide provides a framework for good practice in assessment of uncertainty in fluvial flood risk mapping. The starting point is the position that all uncertainty assessments necessarily involve subjective judgements so that clarity and transparency in expressing and agreeing those judgements is essential. The framework for doing so is a series of decisions concerning the conditional assumptions about the range of uncertainties in data and modelling, together with the choices for presentation and visualisation of the resulting flood risk mapping. Ideally, the process of working through the condition tree should be undertaken as a consultative exercise including the modeller/analyst and representatives of the end users of the flood risk mapping. This might take place during the development of a tender document for a typical application. The decisions on how to assess the uncertainty should be agreed and recorded for future reference. The framework then serves as a tool for communication for both the assumptions and methods that underlie an assessment of uncertainty, and the meaning of the outcomes.

It is clearly important that any approach to assessing uncertainty in flood risk maps should be proportional in respect of the costs and expected benefits or disbenefits involved in any particular application. Within the framework the different levels of analysis that might be considered in being proportional are incorporated into a framework of mutually linked and sequential condition trees within which the assumptions made at each stage are recorded for later evaluation. The degree of detail involved might then vary from a qualitative expert judgement, through a sensitivity analysis, to a detailed analysis involving many runs of a hydrodynamic model. As such, different types of project may require different approaches. Conversely, a single project may involve more than one type of approach, typically starting with the simplest approach and, where necessary, progressing to more involved approaches if the type of decision informed by the flood risk assessment is shown to be sensitive to the uncertainty analysis, or thought to be potentially sensitive to the residual uncertainty not considered by simpler approaches.

This type of approach to acknowledging uncertainty in flood risk mapping is relatively new. Published research suggests that the uncertainties can be significant, but has given only limited guidance about the importance of different sources of uncertainty, realistic ranges of effective parameters, and numerical issues with model implementations. However, this is not a good reason to neglect the uncertainty. In the same way that there is a wealth of practical experience among users in dealing with model implementation issues, the same type of experience will, over time, evolve in estimating the importance of different sources of uncertainty. What is important is that any estimate of uncertain flood risk should be on an agreed and appropriate basis, and explicitly recorded for later assessment.

Details of two case study applications of the framework have been included in this guide. These provide a record of the decisions taken at each stage in the conditioning framework, including sources of uncertainty that have been neglected as well as the assumptions made about those considered to be important.

Although the focus is on fluvial flood risk mapping, similar approaches could be taken to good practice in assessing uncertainty in pluvial, coastal/tidal and groundwater flooding.

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STATUTES

Directives

Directive 2007/60/EC of the European Parliament and of the Council of 23 October 2007 on the assessment and management of flood risks

Standards

BS ISO 1100-2:1998 *Measurement of liquid flow in open channels. Determination of the stage-discharge relation*

BS ISO 5168:2005 *Measurement of fluid flow. Procedures for the evaluation of uncertainties*

ISO Guide 73:2009 *Risk management – vocabulary*

A1 Representation of uncertainty

A1.1 TYPES OF UNCERTAINTY

There are various ways of classifying different types of uncertainty. At the most fundamental level is to distinguish between those that could be reduced given further knowledge or measurements, and those that cannot and should be treated as random. Knowledge uncertainties, which could be reduced, are often called epistemic uncertainties. Irreducible random uncertainties are often called aleatory uncertainties. This distinction was made by Knight (1921) who called knowledge uncertainties the real uncertainties. Random probabilistic representations of uncertainty are used more widely than for strictly irreducible random variables, especially when a reduction in uncertainty might be feasible in principle but where it is limited by cost or technical constraints.

Aleatory uncertainties are often described as those due to 'natural variability'. Aleatory uncertainties can be treated in the form of probabilities (see Table A1.1). Epistemic uncertainties are often treated as if they can be represented as probabilities, even imprecise probabilities, but this might lead to overconfidence in uncertainty estimation if the structure of the epistemic uncertainty is non-stationary in space or time (as it often will be). Model structural error, for example, is an epistemic uncertainty that will generally have non-stationary characteristics. It might then be better to choose to represent knowledge uncertainties as possibilistic or as scenarios (see definitions in the Glossary). Possibility theory, as developed in Fuzzy Set Theory, allows associating weights to different possible outcomes. It also allows more flexible ways of manipulating those variables (for example, Beven, 2009).

Random variability is generally treated in probabilistic terms. In the current context an example would be the assumption of a standard statistical distribution for the frequency of floods of a given magnitude, such as the GLD recommended for the annual maximum series in the FEH (IoH, 1999). Other types of uncertainty are less obviously probabilistic in nature. An example would be the uncertainty in a rating curve when extrapolated beyond the range for which observations are available and where a statistical regression-type extrapolation (such as defined using standard BS ISO 1100-2:1998 and BS ISO 5168:2005 methods) might be wrong. This is an example of a knowledge or epistemic uncertainty. Other examples would be the possibility of another distribution being chosen to represent flood frequency (such as the GEV distribution), or the different errors that might be associated with the spatial estimation of rainfalls for different types of events. Table A1.1 gives examples of random and knowledge uncertainties in flood risk mapping problems. A similar analysis of the types of uncertainties that arise in rainfall-runoff modelling may be found in Beven and Young (2013).

Table A1.1 Examples of random and knowledge uncertainties in flood risk mapping

Source of uncertainty	Uncertainty often treated as random	Knowledge uncertainty that might not be random
Design flood magnitude	Floods occur randomly	Are floods generated by different types of events? What frequency distribution should be used for each type of event? Are frequencies stationary? Will frequencies be stationary into the future?
Conveyance estimates	Based on observations with random error, or statistical estimation based on random assumptions	Is channel geometry stationary over time? Do conveyance estimates properly represent momentum losses and scour at high discharges? Seasonal changes in channel/floodplain vegetation? Is floodplain infrastructure, walls, hedges, culverts etc taken into account?
Rating curve extrapolation	Often based on statistical extrapolation of observations at lower flows	Is channel geometry stationary over time? Does extrapolation properly represent changes in momentum losses and scour at high discharges?
Floodplain topography	Random survey errors	Correction algorithms in preparing digital terrain map?
Model structure		Results depend on choice of model structure, dimensions, discretisation, and numerical approximations
Floodplain infrastructure	Random errors in specifying positions of elements, including elevations of flood defences	How to treat storage characteristics of buildings, tall vegetation, walls and hedges in geometry Missing features in DEM (eg walls, culverts)
Observations used in model calibration	Random survey errors	Misinterpretation of wrack marks Systematic survey errors
Future catchment change		Scenario errors
Future climate change	Realisations of weather generators for given scenario	Scenario errors
Fragility of defences	Random nature of failures	Expectations about failure modes and parameters
Consequences/ vulnerability	Random natures of losses in loss classes	Knowledge about loss classes and vulnerability Link between vulnerability and warnings

While not all natural variability is simply random, the distinction between aleatory uncertainties, which can be treated as probabilities, and epistemic uncertainties, which should not, will still hold, albeit that there may be epistemic uncertainty about the properties of aleatory uncertainties. So, there is a danger of confusion when model predictions subject to epistemic uncertainty are presented as if they are probabilities. An example here is the outputs of the UKCP09 ensemble climate predictions. These are presented as probability quantiles about potential future climate when in fact they represent an interpolation of the probability surface of the outputs of a sparse sample of model predictions for a particular emission scenario. The probabilities are of the distribution of model outputs, not of future climate, under that emission scenario. This does not properly reflect the total (epistemic) uncertainty about future climate. The difference is important when there are significant differences between model predictions and actual climate in the recent past.

In fact, for epistemic uncertainties, it is never certain that the full range of possibilities has been considered, because there is a lack of knowledge about what that range might be. This reinforces the point that it is important to convey to decision makers the assumptions on which a model uncertainty assessment is based whether that be on probabilities or possibilities.

Uncertainty and making decisions

There are important links between the way in which models are evaluated, the communication of uncertainty, and decision making methodologies. All decision makers regularly deal with uncertainty, but it is probably not sufficiently appreciated in many decision making contexts that a consideration of robustness to uncertainty in potential futures might make a difference to the decision made. It is possible to evaluate sensitivity to model uncertainty in many different ways (eg Pappenberger *et al*, 2008).

For example, classical techniques for risk-based decision making require that all sources of uncertainty are treated in probabilistic form so that ranking of options can be achieved by integrating a cost function over the probabilities of predicted outcomes (eg Bedford and Cooke, 2001). This implies both completeness of the uncertainties considered, including the cost function and a probabilistic treatment of recognised knowledge uncertainties. The effects of epistemic uncertainties in this context, particularly the estimation of conditional exceedance probabilities of risk in decision making are discussed by Rougier and Beven (2013).

There are other methods of decision making under certainty that are less dependent on treating all uncertainties probabilistically (see Chapter 6 of Beven, 2009 for a summary). The InfoGap methodology of Ben-Haim (2006), for example, looks at the robustness of a model-based decision in achieving defined minimum requirements to the potential for some best estimate model to be wrong (for an environmental application see Hine and Hall, 2010).

A decision maker might also, when facing severe uncertainty, revert to being risk-averse or precautionary (see Beven, 2011). The important point here is that deciding on a response to model uncertainty in formulating a decision will depend on two important inputs. The first is a realistic assessment of the uncertainty associated with a model. The second is conveying to a decision maker the assumptions on which that assessment is based particularly where a decision might depend on cascades of model components in a driver-source-pathway-impact-response system (see also Beven and Alcock, 2012). A clear understanding of these assumptions might guide the decision making strategy and provide insight into where uncertainty might be reduced by the collection of additional information.

A2 Carlisle case study

Carlisle provides a good example of a location with elevated flood risk in the UK: with over 4500 residential properties, 1000 non-residential properties and large swathes of agricultural land at risk from an AEP 0.01 event. Significant flooding occurred in January 2005 and about 2700 properties were affected by flooding. The cost of the 2005 flooding has been estimated at over £400m.

This case study serves as an exercise in the production of a model-driven probabilistic flood inundation map documented according to the condition-based framework for assessing uncertainty in fluvial flood risk mapping. Of particular interest in this application is the need to take account of the co-variation of the mainstream Eden, and the Caldew and Petteril tributaries in contributing to fluvial flooding at Carlisle.

Figure A2.1 shows the location, topography and transportation infrastructure within the Eden catchment.

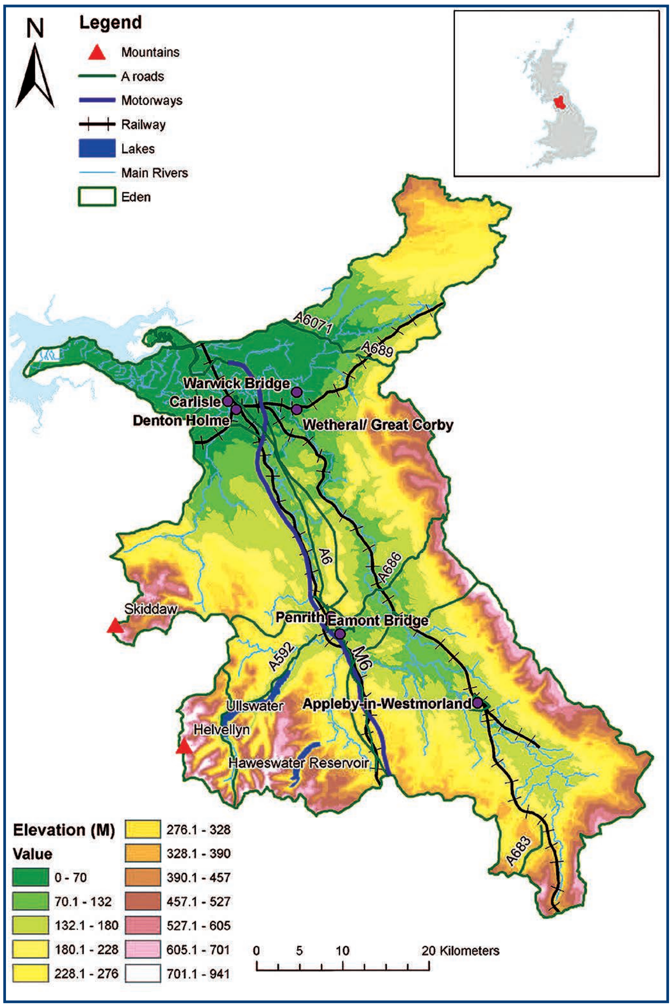


Figure A2.1 The Eden catchment (courtesy Environment Agency)

The following summary provides an overview of the methods for producing the AEP 0.01 probabilistic inundation map for Carlisle, including a treatment of co-variation of the mainstream Eden, Caldew, and Petteril tributaries in contributing to the fluvial flooding at Carlisle.

1 Statistical methods were applied using observations of river level together with Environment Agency rating curves to form a joint distribution function for extreme events at the Sheepmount, Cummersdale, Harraby Green, Linstock, Great Corby, and Greenholme gauge sites. The resulting model provided the joint distribution function from which samples of inflow into Carlisle could be drawn. These samples provided a representation of the combined statistical properties of flows for the Caldew, Petteril and Eden river confluence at Carlisle.

2 A Monte Carlo sampling procedure was then used to draw a large number of events from the joint distribution function representing the range of flood events (above a chosen threshold) that could be expected to occur within a AEP 0.01 event.

3 The samples of level and flow generated by Step 2 were then used as the boundary conditions for a LISFLOOD-FP (distributed water balance) hydraulic model of the Carlisle floodplain. This model incorporated a digital terrain model (DTM) with a 10 m resolution. In-channel and floodplain roughness parameters for the LISFLOOD-FP model had been previously calibrated using estimated flows and inundation extent incorporating wrack mark data from the December 2004 and January 2005 flood events.

4 The boundary condition ensemble applied to the LISFLOOD-FP model was then evaluated using a parallel processing computation environment and the frequency of inundation for each model cell was calculated. This value formed the probability of inundation for a given 10 m × 10 m region of the floodplain for a 100-year period given the statistical and physical assumptions of the various modelling components.

The implementation of this analysis within the framework of the condition-based framework for assessing uncertainty in fluvial flood risk mapping is given as follows.

A2.1 RECORD OF DECISIONS

Condition 3.1.1: assessing uncertainty in fluvial design event magnitude

Is gauge data available for estimating flood frequencies?

Yes, data is available from a number of Environment Agency gauge sites on both the main Eden channel leading into/through Carlisle as well as the Caldew and Petteril tributaries. Table A2.1 shows the specific stations used and the begin/end date for the data used in the study.

Table A2.1 List of Environment Agency river gauge stations used for the Carlisle probabilistic inundation mapping study together with the start and end dates of the data used

Station	Start date	End date
Sheepmount	31 December 1975	30 November 2007
Cummersdale	16 September 1997	30 November 2007
Harraby Green	31 December 1975	30 November 2007
Linstock	17 December 1998	30 November 2007
Great Corby	11 December 1996	30 November 2007
Greenholme	31 December 1975	30 November 2007

Use FEH WinFAP for analysis of observations?

No. A peaks over threshold (POT) analysis was carried out for the three input sites using the software described in Keef *et al* (2009a and b) (see Condition 3.4.1).One of the unique features of this case study is its treatment of multiple inflows into the model domain. The estimation of a statistical event generator model was necessary to achieve this. The WinFAP approach is not able to produce estimates for design events in situations where more than one inflow channel needs to be modelled.

Is full uncertainty analysis justified?

Analysis was confined to the effects of uncertainty in the spatial distribution of extreme events across the three main river reaches leading into Carlisle. It was felt to be too computationally demanding to incorporate uncertainty in the rating curve. This would have required sampling from a high dimensional distribution in order to generate a reasonable Monte Carlo ensemble. In effect the uncertainty in the transformation from level to flow is aggregated into the joint level distribution function.

Are correlated multiple inputs required?

Yes. It was decided that this case study would focus on estimating the magnitude of a AEP 0.01 event, plus uncertainty, where the magnitude of the event was estimated from gauge data at three inflow sites (main Eden channel, Caldew, and the Petteril). The estimation of the magnitude of the AEP 0.01 event would also take into consideration the covariance of the inflow values for the three channels. The LISFLOOD-FP model that was used in this case study is configured to accept inflow boundary conditions at the three locations previously described. Using the correlated multiple input event generator it is possible to sample inputs from a joint distribution function and run the model with these inflows. Continue to Condition 3.4.1.

Condition 3.4.1: assessing interactions between uncertain inputs

Can interactions be treated explicitly?

Yes. The spatially correlated extreme event theory of Heffernan and Tawn (2004) was applied to produce a non-parametric statistical model. This will go some way towards representing the joint probability distribution function of river levels at the three sites that are then used as the inflow boundary conditions to the LISFLOOD-FP hydraulic model.

Can interactions among inputs be treated as multivariate normal distributions?

No. A more complex non-parametric model was used as described by Heffernan and Tawn (2004) and Keef *et al* (2009a and b). A brief non-technical summary of the process follows:

1. The station stage data was filtered to find daily maximum stage values.
2. The distribution of daily maximum stage data was transformed to a suitable set of marginal distributions. In this case the generalised Pareto distribution was chosen for stage data above a specific threshold (0.99 probability) and the empirical distribution used for values below the threshold. The fit procedure was focused on values in the upper tail of the distribution. A visual inspection of Q-Q plots and the diagnostic tests described in Coles (2001) were used to assess the ability of the statistical models to represent the properties of the data at the gauge sites.
3. The distributions were then transformed to Gumbel marginal distributions.
4. The number of events (ie the number of times any of the stations exceed the 0.99 probability threshold) that can be expected to occur in a 100-year period was then calculated by first breaking the data into five day blocks and fitting a Poisson distribution to the number of blocks containing an event. Simulating from the resulting Poisson distribution provides an estimate of the number of events expected in a 100 year period.
5. The assumption was made that the correlation between each pair of gauging stations is equal. The ability of the models to simulate the observation sites including dependence was assessed by visual inspection as shown in Figure A1.1.
6. The Heffernan and Tawn (2004) model was fitted to the data by conditioning on each gauge site in turn.
7. Samples from the fitted models were drawn and used as boundary conditions for the LISFLOOD-FP model.
8. Steps 1–7 performed on the observed data provided an estimate of the set of events expected

within a 100-year period. Repeating these steps on 99 bootstrapped samples provided the uncertainty in the event set. In total this process resulted in 47 724 flood events that exceed the 0.99 probability threshold on any of the three rivers in the Carlisle system. Each of these events was then simulated in a dynamic realisation of the LISFLOOD-FP model. The maximum water depth resulting in each cell during each model run was stored.

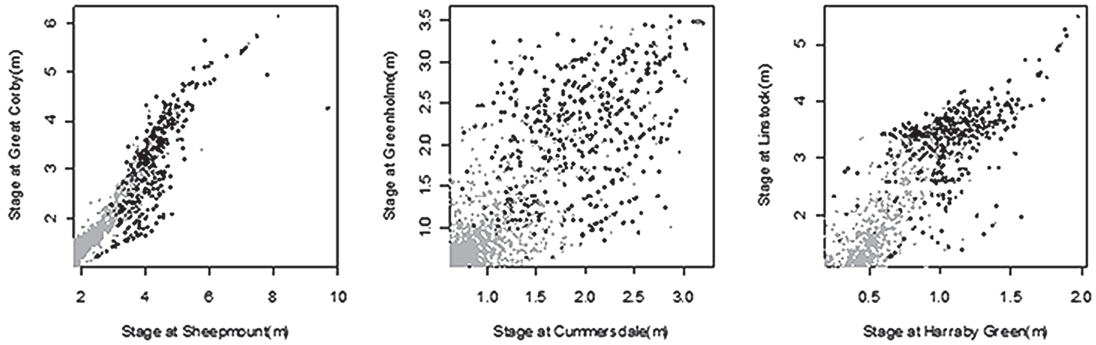


Figure A2.2 Observed (grey) and simulated (black) values for stage at Sheepmount, Cummersdale and Harraby Green gauge sites

The full process outlined in Steps 1 to 8 is described in detail in a paper by Neal *et al* (2012) and its references.

Condition 3.1.4: assessing uncertainty in effects of climate change

Is it necessary to consider climate change?

For the scope of this study it was not necessary to include uncertainties or impacts attributable to forecast climate change.

Condition 3.1.5: assessing uncertainty in effects of catchment change

Is it necessary to consider catchment change?

No. For the scope of this study it was not necessary to include uncertainties or impacts resulting from any change (land use, urbanisation etc) to the characteristics of the Eden catchment. The statistical properties of flow rate and return period (which are clearly a function of land use to some degree) were assumed to be stationary.

Condition 3.2.1: assessing uncertainty in choice of hydrodynamic model

Is use of only a single hydraulic model justified?

Yes, for the purpose of this study. While an inter-comparison of two or more model types would be wise, it cannot justify the necessary resources. A further justification for using a single model is that the time (human and computer) needed to set up and run the alternate formulations can be better used by increasing the size of a Monte Carlo ensemble. One of the authors has experience with additional model representations and inter-comparisons (see Neal *et al*, 2009).

During the design phase of the modelling exercise alternate model cell resolutions where tested for the LISFLOOD-FP model. After trying 5 m, 10 m and 25 m cells, the 10 m × 10 m resolution was selected as it demonstrated very little degradation in calibration performance over the 5 m version but provided a considerable increase in processing speed. The 10 m cell size also avoided issues with mass blocking effects found in the larger cell set-up.

Choose options for boundary conditions

It was decided to define three inflow locations and one outflow location as the model boundary conditions. These correspond to the location of Environment Agency gauges. The boundary conditions comprised a flow and level state. The level was supplied from the joint probability distribution function, which was then converted to flow via deterministic Environment Agency rating curves.

Choose options for infrastructure

All infrastructure was simply represented by the elevation and roughness of the model topographic grid domain. The empirical representations of bridges or weirs have not been included within the floodplain.

Condition 3.2.2: assessing uncertainty in choice of channel and floodplain roughness and rating curves

Are observations available to allow calibration of channel or floodplain roughness or rating curves?

Yes. Usefully, a large amount of data was available describing the inundation outline in the form of wrack mark locations. Environment Agency level data and rating curves were available for estimating model inflows.

Is full uncertainty analysis justified?

No. It was not possible to commit the resources to investigate uncertainty in channel and floodplain roughness coefficients (let alone to introduce spatial variation in these parameters). It would also have been very difficult to interpret the uncertainty from any additional parameters given the expected uncertainties arising from the input discharges. Instead it was decided to select uniform channel and floodplain Manning's roughness coefficients conditioned on 2005 flood extent wrack mark data. Values of 0.06 and 0.07 were chosen respectively.

The uncertainty analysis focused on developing a joint distribution function for flood event stage at the gauge sites corresponding to the LISFLOOD-FP model boundary condition locations. The conversion of stage to flow was performed deterministically using the standard Environment Agency rating curves.

Condition 3.2.3: assessing uncertainty in effects of infrastructure

Is it necessary to consider uncertainty in options for floodplain infrastructure (in addition to variations in roughness)?

No. It was not possible to model the effects of uncertainty of infrastructure. The case study focused on generating a very general inundation extent map rather than attempting to optimise or modify infrastructure characteristics. The processing time and power was not available to investigate the large number of scenarios required when investigating the effects of infrastructure using Monte Carlo methods.

Condition 3.2.4: assessing uncertainty in performance of flood defences

Is it necessary to consider uncertainty in performance of defences?

The new Carlisle flood defence structures built since the January 2005 floods have been included in the floodplain topography but these have been assumed to be fixed structures with zero probability of failure. Analysing the effect of defence failure would require multiple ensembles, one for each failure scenario. This was not feasible within the constraints of the project.

Condition 3.3.1: assessing uncertainty in consequences/vulnerability

Is it necessary to consider uncertainty in consequences/vulnerability?

Yes. This case study made a simple estimate of consequences in the form of a damage curve with associated percentiles. The location of buildings was identified from OS MasterMap GIS data and an associated cost was calculated using the depth-damage relationship from Penning-Rowsell *et al* (2005).

Condition 3.4.2: assessing uncertainty propagation process

Given uncertainty defined in above sections choose sampling method.

The sampling for jointly distributed inflow boundary conditions was carried out using the event simulator as described in Keef *et al* (2009a and b). Condition 3.4 Section A3.4.1.1 provides an outline of these methods.

Can scenarios or sampling realisations be run given computing resources available?

Yes. A parallel computing infrastructure was employed to perform ~47 000 realisations of the model with samples taken from the AEP 0.01 inflow joint distribution event simulator model.

Condition 3.5.5: defining a conditioning methodology

Are observations available or can they be made available for model conditioning?

Yes. There are two distinct model conditioning processes where data is available:

1. Wrack mark and approximate stage/flow data is available from the 2005 flood event (estimated to be a AEP 0.0067 event).
2. Stage observation data is available from the gauge sites listed in Table A1.1 from which the joint distribution function for the extreme event stages is identified.

Define observational errors or limits of acceptability?

Yes. For the conditioning of the LISFLOOD-FP channel and floodplain roughness parameters, an estimate of uncertainty of about +/- 0.05 m was established by referencing rack marks with observed water level at the Botcherby Bridge gauge site on the River Petteril.

Missing data in the observation record of stage was accounted for using the missing data extension to the Heffernan and Tawn model described by Keef *et al* (2009b).

Can a simple likelihood function be verified?

Yes. For the LISFLOOD-FP roughness conditioning a RMSE cost function described by Neal *et al* (2009) was used.

For the event simulator, a maximum likelihood scheme assuming Gaussian residuals was used to estimate the model parameters. This assumption is not ideal; future research should provide either greater support for making this simplification or provide an alternative.

Compare model output with observations?

Yes. This was carried out for both the LISFLOOD-FP roughness calibration using 2005 wrack marks, and at several steps during the identification of the joint probability distribution event generator model. An example of the later is shown in Figure A1.1. for the final model ensembles, and an example of a comparison of the probabilistic AEP 0.001 inundation ensemble to the January 2005 AEP 0.0067 event is shown in Figure A2.3.

Are additional model samples required?

No. The large ensemble (~47 000 members) should be sufficient to explore the joint probability distribution space of the stage event generator. Further research should focus on refinements to the method rather than generating larger ensembles.

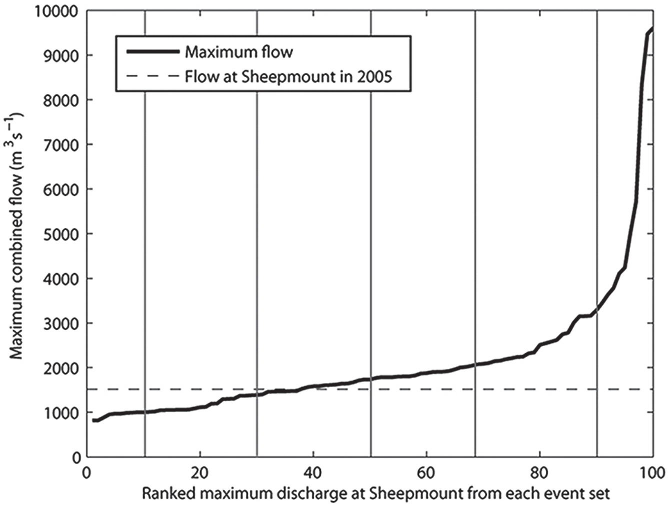


Figure A2.3
Comparison of AEP 0.01 ranked inundation ensembles expressed as maximum flow at Sheepmount (solid line) together with the estimated maximum flow for the January 2005 event (dashed line)

Visualisation methods

The Monte Carlo methods described in this case study generated large datasets. The frequency with which a cell within the model domain reached or exceeded a specific criterion were calculated by summing the number of times the criterion was met during the ensemble realisations (and dividing by the number of realisations). This process was carried out to calculate the frequency at which each cell was being inundated, and the frequency of each cell exceeding a set of specific depth thresholds. This resulted in a series of arrays covering the model domain, where each entry in the array is a probability between 0 and 1 that the cell will meet the chosen criterion (either ‘be inundated’ or ‘experience a depth above a specific value’). The arrays of probabilities were georeferenced and superimposed on a background map. Either all probabilities could be displayed as a colour continuum or specific thresholds could be shown as a single-colour patch.

Traditional maps with overlays have been produced to communicate the model results.

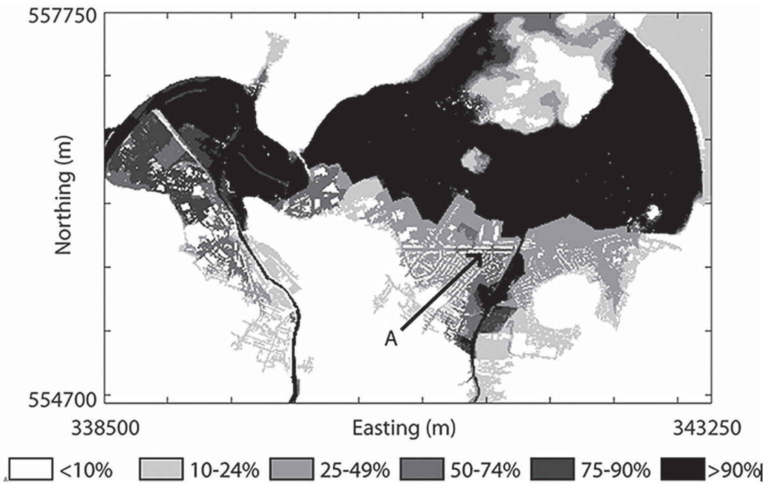
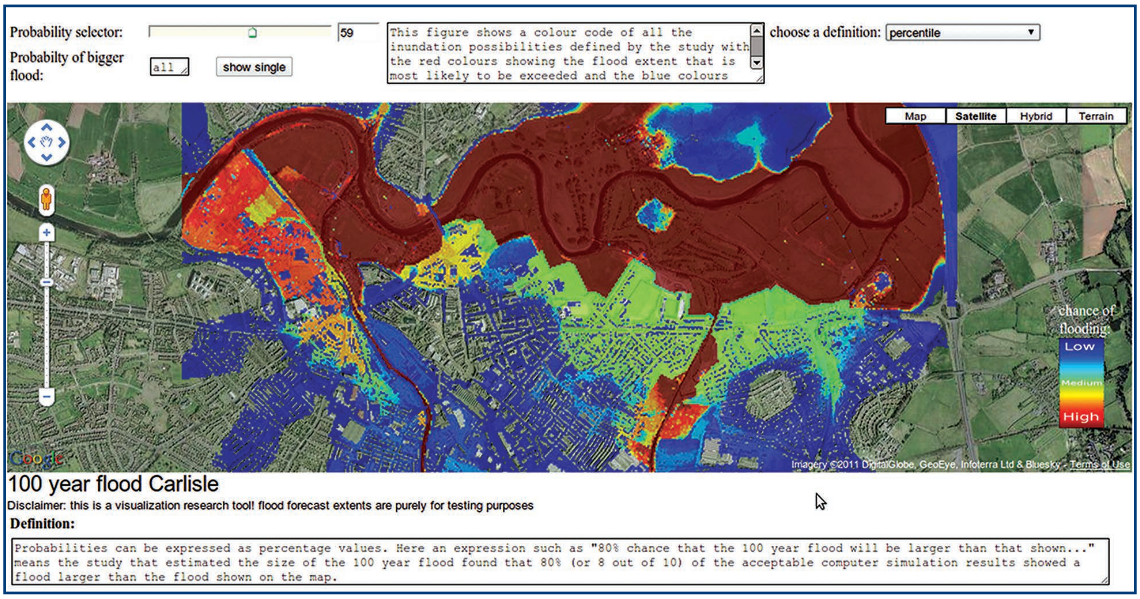


Figure A2.4 Probabilistic inundation map showing regions of inundation at specific levels of exceedance probability

An alternative to the static map types shown in Figure A2.4 is to take advantage of Dynamic HTML (DHTML) technologies that allow for the dynamic interaction of an overlay with Google™ maps (or other map base layer providers). The FRMRC2 web visualisation tool was employed here to provide an intuitive interface for querying the ensemble data. The tool is shown in Figure A2.5.


Probability selector: 59

Probabilty of bigger flood: all

This figure shows a colour code of all the inundation possibilities defined by the study with the red colours showing the flood extent that is most likely to be exceeded and the blue colours

choose a definition: percentile

100 year flood Carlisle

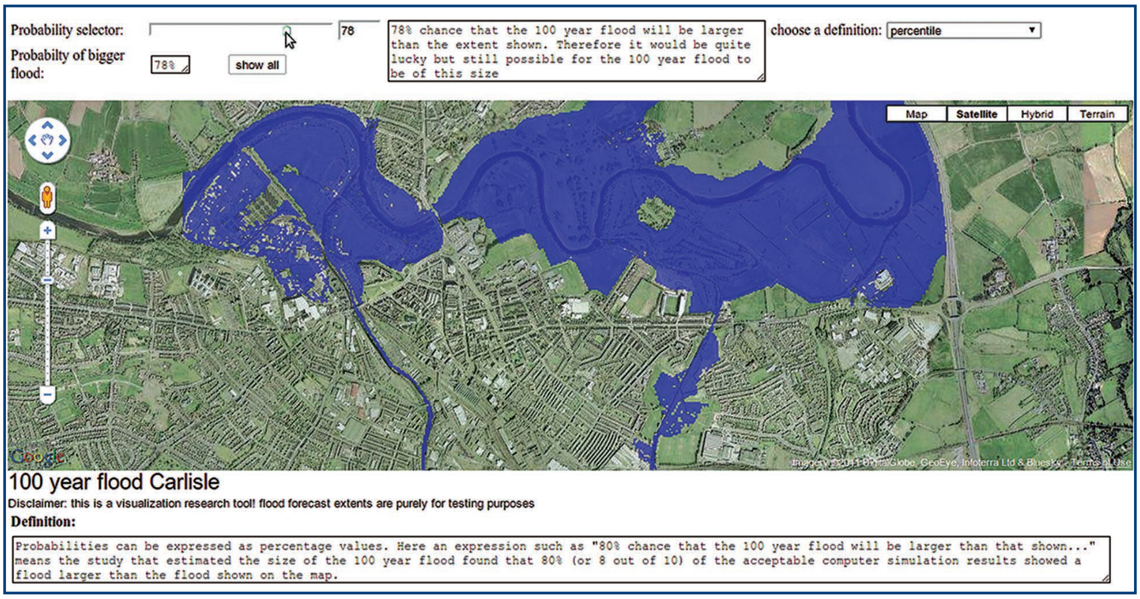
Disclaimer: this is a visualization research tool! flood forecast extents are purely for testing purposes

Definition:

Probabilities can be expressed as percentage values. Here an expression such as "80% chance that the 100 year flood will be larger than that shown..." means the study that estimated the size of the 100 year flood found that 80% (or 8 out of 10) of the acceptable computer simulation results showed a flood larger than the flood shown on the map.

Figure A2.5 FRMRC2 web-based interactive visualisation tool. Here the 'show all probabilities' option is selected

Figure A2.6 shows a zoomed-in selection with a threshold of inundation exceedance selected (using the interactive slider tool).


Probability selector: 78

Probabilty of bigger flood: 78%

78% chance that the 100 year flood will be larger than the extent shown. Therefore it would be quite lucky but still possible for the 100 year flood to be of this size

choose a definition: percentile

100 year flood Carlisle

Disclaimer: this is a visualization research tool! flood forecast extents are purely for testing purposes

Definition:

Probabilities can be expressed as percentage values. Here an expression such as "80% chance that the 100 year flood will be larger than that shown..." means the study that estimated the size of the 100 year flood found that 80% (or 8 out of 10) of the acceptable computer simulation results showed a flood larger than the flood shown on the map.

Figure A2.6 The FRMRC2 web-based interactive visualisation tool showing a single overlay selected interactively by the user using the slider tool. The overlay shows the extent of inundation for the AEP 0.01 event that has a 78 per cent chance of being exceeded

A3 Mexborough case study

Mexborough provides an example of a region at risk from flooding. The area was deeply affected by the June 2007 flooding. It is in the River Don catchment, is low lying, tidally affected, and heavily urbanised, with steep sided valleys in the upper catchment.

Figure A3.1 shows the location of the main urban areas in the Don and Rother catchments.

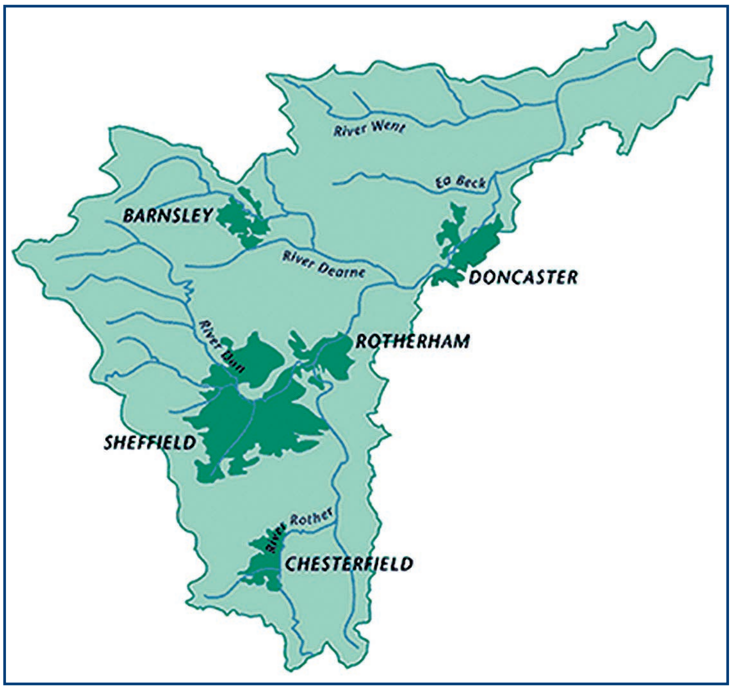


Figure A3.1 The Don and Rother catchments. Mexborough is about 10 km upstream of Doncaster

The probabilistic inundation case study for the AEP 0.01 event for Mexborough can be summarised as follows:

1. Standard FEH methods were used on data from the Environment Agency's Adwick gauge site to identify a normal random variable describing the range of the AEP 0.01 design flood event.
2. The median annual maximum flood (QMED) value was used as an empirical proxy to define a uniform random variable describing the range of the channel capacity for the model domain reach.
3. A uniform random variable was estimated to define a global Manning's *n* roughness coefficient for the model domain.
4. The one normal and two uniform random variables described here were considered independent. 500 runs of the JFLOW 2D model were made where the three uncertain parameter values were drawn at random from their respective probability distribution functions. After completing the model runs, the probability that inundation would be observed in any one of the 10 m × 10 m model cells within the model domain was calculated. For example, if a cell became inundated in all 500 model runs then that 10 m × 10 m region of the floodplain was ascribed a 100 per cent probability of being flooded during a flood of magnitude equal to the design event. If a cell was inundated in half of the ensemble members then the corresponding region of the floodplain was ascribed a 50 per cent probability of flooding and so on.
5. The results from the study were processed for visualisation in both Matlab™ and web-based tools.

The implementation of this analysis within the framework of the condition-based framework for assessing uncertainty in fluvial flood risk mapping is given as follows.

A3.1 RECORD OF DECISIONS

Condition 3.1.1: assessing uncertainty in fluvial design event magnitude

Is gauge data available for estimating flood frequencies?

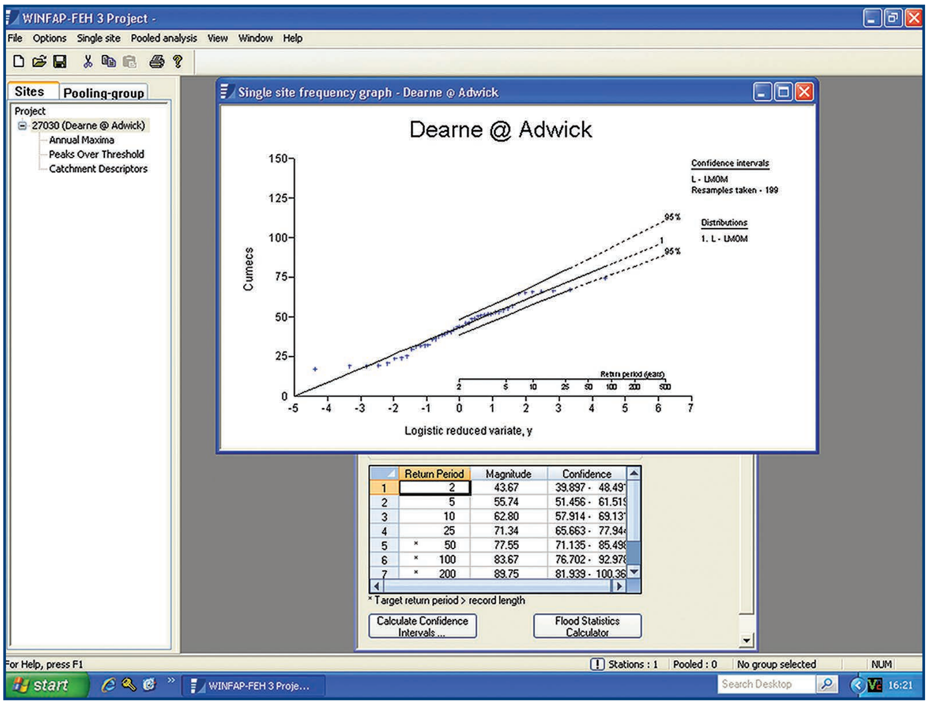
Yes. Data is available from the Adwick Environment Agency gauge site.

Use FEH WinFAP™for analysis of observations?

Yes. FEH WinFAP software was used to define the flood frequency curve and uncertainty for the Adwick Environment Agency gauge site based on a GLD.

Is full uncertainty analysis justified?

Yes. It was decided that one of the uncertain elements to investigate in the study would be the magnitude of the AEP 0.01 flow. Figure A3.2 shows a screenshot of the WinFAP software.



	Return Period	Magnitude	Confidence
1	2	43.67	39.897 - 48.49
2	5	55.74	51.456 - 61.51
3	10	62.80	57.914 - 69.13
4	25	71.34	65.663 - 77.94
5	× 50	77.55	71.135 - 85.49
6	× 100	83.67	76.702 - 92.97
7	× 200	89.75	81.939 - 100.36

× Target return period > record length

Figure A3.2 FEH WinFAP™ software calculating the expected flood frequency curve for Adwick together with uncertainty range

By following the WinFAP analysis, a normally distributed random variable was defined for the AEP 0.01 flow with a 95 per cent confidence interval of 76.7 m^3s^{-1} to 92.9 m^3s^{-1}.

Are correlated multiple inputs required?

No. The model domain only represents inflow from the main upstream channel. This is justified as there are no significant tributaries in this section of the river.

Condition 3.1.4: assessing uncertainty in effects of climate change

Is it necessary to consider climate change?

No. For the scope of this study, uncertainties or impacts attributable to climate change were not included. The remit of this case study was to investigate the effect on inundation extent of uncertainties in the AEP 0.01 event inflow, floodplain roughness coefficient, and channel capacity. It is common practice to include a +20 per cent adjustment for climate effects. This could be added as a post process step if necessary.

Condition 3.1.5: assessing uncertainty in effects of catchment change

Is it necessary to consider catchment change?

No. For the scope of this study it was not necessary to include uncertainties or impacts resulting from any change (land use, urbanisation etc) to the characteristics of the Don catchment. Apart from the previously mentioned model parameters, all other factors were considered to be stationary over time.

Condition 3.2.1: assessing uncertainty in choice of hydrodynamic model

Is use of only a single hydraulic model justified?

Yes, for the purpose of this study. Comparing multiple models could increase confidence in the uncertainty estimation results, but it was not possible to commit the necessary resources.

Choose options for boundary conditions

The Adwick gauge site was chosen as the upstream inflow boundary condition.

Choose options for infrastructure

All infrastructure is simply represented by the elevation and roughness of the model topographic grid domain. Empirical representations of the effect of bridges or weirs within the floodplain have not been included. Again, while it is possible to achieve this (for example, Fewtrell *et al*, 2011) there were no resources available to explore these options. Also, the addition of more parameters to include into the Monte Carlo approach presents the 'curse of dimensionality' problem whereby very large ensembles, with their associated processing demands, would have been required.

Condition 3.2.2: assessing uncertainty in choice of channel and floodplain roughness and rating curves

Are observations available to allow calibration of channel or floodplain roughness or rating curves?

Yes. Usefully, a reasonable amount of data exists for the Adwick gauge and inundation on the Mexborough floodplain including a large event in 2007 where flows were estimated to be within the range 71.1 m^3s^{-1} to 73.5 m^3s^{-1} with 95 per cent confidence.

Wrack marks are available to define the extent of the 2007 inundation event.

Is full uncertainty analysis justified?

Yes. FEH WinFAP was used to define a rating curve incorporating uncertainty. This was then used to define a normal distribution for the AEP 0.001 flow. The estimated 95 per cent confidence interval for the AEP 0.001 flow is 76.7 m^3s^{-1} to 92.9 m^3s^{-1}.

Manning's roughness coefficients were defined using a uniform random variable with a range of 0.05 to 0.2. These values were selected only with reference to the experience of the model designer.

Channel capacity was calculated using QMED as a proxy. QMED was calculated using empirical catchment descriptors. The formula (Equation A3.1) and descriptors are shown here:

$$\mathrm{QMED} = 8.3062\ \mathrm{AREA}^{0.8510}\ 0.1536^{\frac{1000}{\mathrm{SAAR}}}\ \mathrm{FARL}^{3.4451}\ \ 0.0460^{\mathrm{BFIHOST}^{2}} \qquad \text{A3.1}$$

Table A3.1 Catchment descriptors used with Equation A3.1 to estimate QMED

AREA	310.96	LDP	45.47	URBCONC1990	0.717	F	2.37178
ALTBAR	105	PROPWET	0.32	URBEXT1990	0.0971	C(1 km)	-0.024
ASPBAR	86	RMED-1H	10.3	URBLOC1990	0.822	D1(1 km)	0.327
ASPVAR	0.2	RMED-1D	33.8	C	-0.02499	D2(1 km)	0.405
BFIHOST	0.533	RMED-2D	45.7	D1	0.36318	D3(1 km)	0.226
DPLBAR	21.46	SAAR	696	D2	0.44402	E(1 km)	0.298
DPSBAR	61.5	SAAR4170	707	D3	0.24994	F(1 km)	2.401
FARL	0.952	SPRHOST	25.42	E	0.29957		

A uniform random variable with range 12 m^3s^{-1} to 54 m^3s^{-1} was estimated for channel capacity. Flows above the channel capacity were assumed to spill onto the floodplain for storage and/or conveyance downslope.

Condition 3.2.3: assessing uncertainty in effects of infrastructure

Is it necessary to consider uncertainty in options for floodplain infrastructure (in addition to variations in roughness)?

No. For this study the effects of uncertainty in floodplain infrastructure beyond a distribution of values for the floodplain roughness coefficient were not considered. It was not possible to commit the resources necessary to collect or process data pertaining to infrastructure and its alternate configurations.

Condition 3.2.4: assessing uncertainty in performance of flood defences

Is it necessary to consider uncertainty in performance of defences?

No. The performance of flood defences was not considered in this study. Information describing fragility curves etc. was not available. To keep the analysis tractable, it was decided to focus on the effect on inundation extent of uncertainty in the three key model parameters described previously.

Condition 3.3.1: assessing uncertainty in consequences/vulnerability

Is it necessary to consider uncertainty in consequences/vulnerability?

No. This study was concerned only with the extent of inundation to the floodplain and not the consequent damages.

Condition 3.4.1: assessing interactions between uncertain inputs

Can interactions be treated explicitly?

No. Each random variable was considered to be independent.

Define distributions and generate independent samples

A normal distribution for AEP 0.001 flows, a uniform distribution for global Manning's roughness coefficient, and channel capacity (see Section A3.2.2) were chosen. 500 samples were then generated from these distributions to use for Monte Carlo analysis simulated with the Mexborough JFLOW hydrodynamic model.

Condition 3.4.2: assessing uncertainty propagation process

Given uncertainty defined above, choose sampling method

A Monte Carlo forward propagation of uncertainty method with uncertain parameters sampled from independent distributions was used. The three uncertain parameters were:

1. The AEP 0.001 inflow (normal distribution).
2. Global Manning's roughness coefficient (uniform distribution).
3. The channel capacity (uniform distribution).

Can scenarios or sampling realisations be run given computing resources available?

Yes. A high performance computing infrastructure was used to perform 500 realisations of the model with model parameters sampled from the identified AEP 0.01 inflow, Manning's roughness uniform distribution, and channel capacity.

Condition 3.5.5: defining a conditioning methodology

Are observations available or can they be made available for model conditioning?

Yes. Wrack mark and approximate stage/flow data is available for the 2007 flood event. A record of stage at Aldwick is available for use with WinFAP.

Define observational errors or limits of acceptability?

Yes. Uncertainty of level for the maximum inundation extent was assumed to be 0.1 m.

Can a simple likelihood function be verified?

Yes. The 2007 event provided a reasonable inundation outline from which to form a cost function.

Compare model output with observations?

Yes. A posterior likelihood function was formed for the model parameter space conditioned on the fit of the inundation outline of a single large flood event (June 2007) to observed wrack marks. Due to the complex interaction between model parameters input data, and calibration data uncertainty, the model performs within an acceptable range over a considerable subset of the parameter space. The resulting parameter space and inflow distribution can then be interrogated using MCS to produce a range of inundation extents at specified design flood AEPs and levels of likelihood conditioned on the model calibration exercise.

Are additional model samples required?

Probably, even with only three degrees of freedom the use of 500 samples provided a relatively sparse sampling of the parameter space. However, extra computing resources were not available for this study.

Visualisation methods

The Monte Carlo methods described in this case study generate large datasets. The frequency with which a cell within the model domain reaches or exceeds a specific criterion was calculated by summing the number of times the criteria was met during the ensemble realisations (and dividing by the number of realisations). This process was carried out to calculate the frequency of inundation for each cell, and frequency of each cell exceeding specific depths. This resulted in a series of arrays covering the model domain where each entry in the array is a probability between 0 and 1 that the cell will meet the chosen criteria (either 'be inundated' or 'experience a depth above a specific value'). The arrays of probabilities were georeferenced and superimposed on a background map. Either all probabilities were colour-coded or the extent of a flood exceeding a specific depth threshold was shown with a single coloured patch.

To communicate the results of this study both the Matlab™ and web-based FRMRC2 visualisation tools were used. Results from the Matlab™ tool are shown in Figure A2.3.

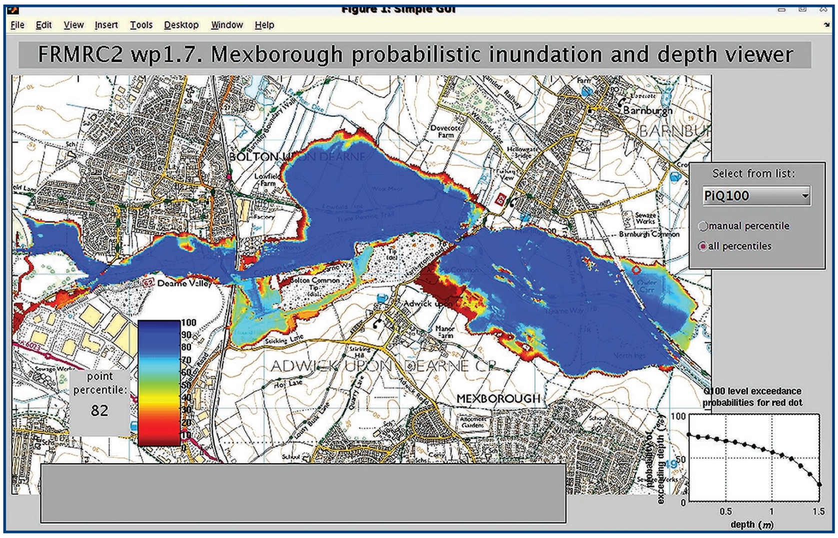


Figure 1: Simple GUI

FRMRC2 wp1.7. Mexborough probabilistic inundation and depth viewer

Select from list: PiQ100

○ manual percentile

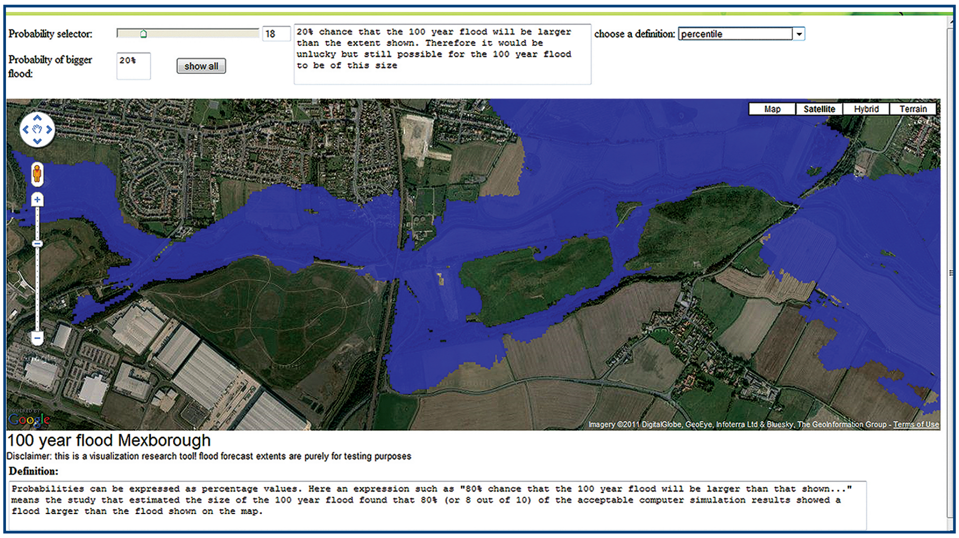
● all percentiles

point percentile: 82

Q100 level exceedance probabilities for red dot

Figure A3.3 *Matlab™ FRMRC2 probabilistic inundation map visualisation tool showing all uncertainty range together with depth exceedance at a user-specified individual point (the red circle in the far right of the map)*

The Dynamic HTML (DHTML) FRMRC2 web visualisation tool incorporating Google maps™ is shown in Figure A3.4. Both tools allow the user to interact dynamically with the inundation data produced by the study. The interaction interface is designed to be as intuitive as possible.


Probability selector: 18

Probabilty of bigger flood: 20%

```
20% chance that the 100 year flood will be larger
than the extent shown. Therefore it would be
unlucky but still possible for the 100 year flood
to be of this size
```

choose a definition: percentile

100 year flood Mexborough

Disclaimer: this is a visualization research tool! flood forecast extents are purely for testing purposes

Definition:

```
Probabilities can be expressed as percentage values. Here an expression such as "80% chance that the 100 year flood will be larger than that shown..."
means the study that estimated the size of the 100 year flood found that 80% (or 8 out of 10) of the acceptable computer simulation results showed a
flood larger than the flood shown on the map.
```

Figure A3.4 *FRMRC2 web-based interactive visualisation tool. Here the user has selected the 20 per cent probability of exceedance overlay, and has zoomed the map to a subset of the model domain*

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This guide provides a framework for good practice in assessment of uncertainty in fluvial flood risk mapping. The starting point is the position that all uncertainty assessments needs to involve subjective judgements because clarity and transparency in expressing and agreeing those judgements is imperative. The framework for doing so is a series of steps covering consideration of the range of uncertainties in data and modelling, together with the choices for presentation and visualisation of the resulting flood risk mapping. Ideally, the process of working through the steps should be undertaken as a joint exercise including the modeller/analyst and representatives of the end users of the flood risk mapping. The decisions on how to assess the uncertainty should be agreed and recorded for future reference.

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