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FLOODS—A NEW APPROACH

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Towards risk-based flood hazard management in the UK

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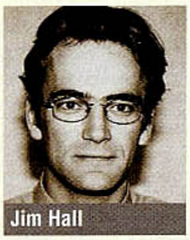

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Flood engineering in Britain is evolving from traditional approaches based on design standards to the development of risk-based decision-making, which involves taking account of a range of loads, defence system responses and impacts of flooding. Adopting such a 'whole systems' approach enables combinations of structural and non-structural approaches to be assessed and compared so resources can be targeted to best effect. Building on methods and know-how already in widespread use in river and coastal engineering, risk-analysis techniques are now being adopted in all areas—from high-level planning based on outline analysis to detailed designs using high-resolution simulation models. This paper explores some of the new techniques of this emerging approach to flood risk management.

Management of risk is a topic that received increasing attention in the latter half of the twentieth century and is set to be a dominant issue in the twenty-first century. Indeed, it has been suggested that risk will be the primary issue that occupies our modern societies[1]—an assertion that often seems to be borne out in the media. Specific areas of attention that will be familiar to all civil engineers are the management of health and safety risk,[2–4] construction risk,[5,6] environmental risk[7] and business risk.[8] Moreover, because river and coastal engineering has traditionally been less codified than other sectors of the civil engineering industry, risks have always had to be addressed in a fairly explicit way. For example, it has always been acknowledged that however extreme the design loading, more severe conditions could be encountered.

This paper explores the concept of 'risk' and related issues such as 'performance' and 'uncertainty' as key components of decision making in flood management and planning. The authors discuss current best practice and look to the future when risk will form a central part of a more integrated 'whole system' approach to flood management.

Risk in the flooding context

It has long been recognised that 'risk' is a central consideration in providing appropriate flood defences. The Waverley report following the devastating east coast floods of 1953 recommended that flood defence standards should reflect the land use of the protected area, noting that urban areas could expect higher levels of protection than sparsely populated rural areas. Today, the term 'flood risk' is used in a number of ways. A range of meanings, derived from either common language or the technical terminology of risk analysis, are in use. These different meanings often reflect the needs of particular decision-makers—there is no unique specific definition for flood risk and any attempt to develop one would inevitably satisfy only a proportion of risk managers. Indeed, this very adaptability of the concept of risk is one of its strengths.

In all of these instances, however, risk is thought of as a combination of the chance of a particular event, with the impact that the event would cause if it occurred. Risk therefore has two components—the chance (or probability) of an event occurring and the impact (or consequence) associated with that event. Intuitively, it may be assumed that risks with the same numerical value have equal 'significance' but this is often not the case. In some cases, the significance of a risk can be assessed by multiplying the probability by the consequences. In other cases it is important to understand the nature of the risk, distinguishing between rare, catastrophic events and more frequent, less severe events. For example, risk methods adopted to support the targeting and management of flood warning represent risk in terms of probability and consequence, but low probability/high consequence events are treated very differently to high probability/low consequence events. Other factors include how society or individuals perceive a risk (a perception that is

> "The potential exists for an integrated description of the whole flooding system from causes to consequences, including risk management measures"

influenced by many factors including, for example, the availability and affordability of insurance) and uncertainty in the assessment.

Benefits of a risk-based approach

The benefit of a risk-based approach, and perhaps what above all distinguishes it from other approaches to design or decision making, is that it deals with outcomes. Thus, in the context of flooding it enables intervention options to be compared on the basis of the impact that they are expected to have on the frequency and severity of flooding in a specified area. A risk-based approach therefore enables informed choices to be made based on comparison of the expected outcomes and costs of alternative courses of action. This is distinct from, for example, a standards-based approach that focuses on the severity of the load that a particular flood defence is expected to withstand.

The focus on outcomes coincides with the move towards performance-based engineering that has taken hold in the seismic engineering community in the US[9] and which is increasingly recognised as a model for efficient provision of infrastructure. In performance-based engineering, the range of demands that may be placed on a system are explicitly recognised and targets are set for the performance of the system under each of these demands. For example, in a moderate earthquake the performance target may be that structures suffer only superficial damage, whereas in a very severe earthquake it is recognised that some buildings will be rendered uninhabitable but essential emergency facilities, such as hospitals, must continue to function. This represents a much more subtle approach than the conventional crude engineering classification of a system as either 'failed' or 'not failed', or indeed the conventional extension to consider two performance criteria: 'serviceability' and 'ultimate' limit states. This conventional engineering distinction between failure and non-failure has, for many years, been translated to the design of flood defences by way of the concept of a 'design load', and is almost always expressed in terms of a return period (in years). Within this rather simplistic engineering paradigm, design is proceeded by

- establishing the appropriate standard for the defence (e.g. the '100 year return period' river level), based on land use of the area protected, consistency and tradition
- estimating the design load, such as the water level or wave height with the specified return period
- designing (that is, determining the primary physical characteristics such as crest level or revetment thickness) to withstand that load
- incorporating safety factors, such as a freeboard allowance, based on individual circumstances.

Over the last decade the limitations of such an approach in delivering efficient and sustainable flood defence solutions have become clear and act as a barrier to the large scale, long-term planning of flood defence that is now desired. In addition, there has recently been much more emphasis on the process of appraisal in order to make choices between options (Fig. 1). These options can be quite diverse and offer quite different approaches for managing flood risk and, again, the simple paradigm of 'design loads' is rather limiting. Consideration of loads above a design standard encourages development of robust designs that have appropriate levels of residual strength and that do not fail in catastrophic modes.

The challenge of flood risk management

Modern flood risk management is aimed at managing whole flooding systems, be they catchments or coastlines, in an integrated way that accounts for all of the potential interventions that may alter flood risk. In support of this aim, the science and technology of flood management has made tremendous progress in the last half century. Process-based, parametric and statistical models describing key elements of the flooding system (loads, defence response, inundation and impacts) are now available and are continuing to be developed. The potential exists for an integrated description of the whole flooding system from causes to consequences, including risk management measures.

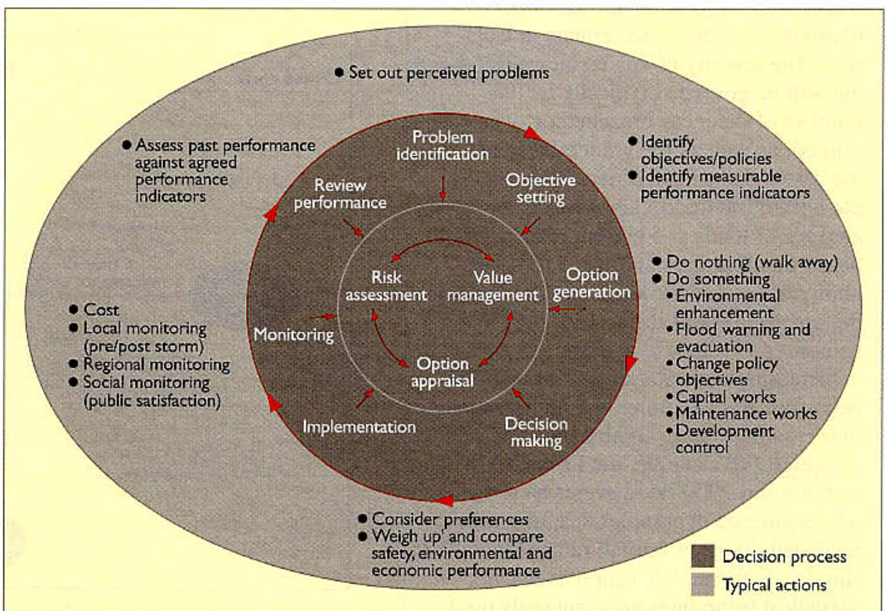

Fig. 1. The cyclic option appraisal process—problems are identified, objectives set, options generated and appraised, decisions made, implemented and monitored, leading to improved understanding and better decisions. The outer oval gives an indication of issues considered at each stage; the centre circle reflects the weighting-up of risk and value in appraising options

Without appropriate decision support tools, however, 'flood risk managers' understandably struggle to handle the complexities inherent in integrated management of the flooding system and the hazard it represents. Some of the challenges faced by modern day flood risk managers are set out below.

Loading is naturally variable

The loads such as rainfall and marine waves and surges on flood defence systems are not forecastable beyond, at the most, a few days into the future. For design purposes, loads have to be described in statistical terms. Extreme loads that may never have been observed in practice form the basis for design and risk assessment. Extrapolating loads to these extremes is fundamentally uncertain, particularly when based on limited historical data and in a climate that may be changing.

Load and response combinations are important

The severity of flooding is usually a consequence of a combination of conditions. So, for example, overtopping or breach of a sea defence is usually a consequence of a combination of high waves and surge water levels, rather than either of these two effects in isolation. The severity of any resultant flooding will be governed typically by the number of defences breached or overtopped, as well as the vulnerability of the assets and preparedness of the people within the floodplain. Therefore, analysis of loads and system response is based on an understanding of the probability of combinations of random loading conditions and the system responses.

Increasing understanding of system behaviour has illustrated the importance of increasingly large combinations of variables. For example, the Easter 1998 and autumn 2000 flood events were both a consequence of complex spatial/temporal distributions of rainfall rather than a simple, single rainfall–runoff event.[10,11] Statistical techniques are commonly used to address joint loading and response conditions[12] and research into this area continues.

Complex and uncertain responses must be accommodated

The response of river, coastal and man-made defences to loading is highly uncertain. Research into topics such as embankment stability and overtopping has provided engineers with some tools for addressing specific aspects of system response. However, experimental results that these tools are based upon often show that a great deal of scatter and field verification is scarce. Whilst research in the UK and Europe is addressing the breaching process, predictive models will always be limited by the availability of data on the condition and performance of defences that may have been modified over hundreds of years.

Spatial interactions are important

River and coastal systems show a great deal of spatial interactivity. It is well recognised that construction of flood defences upstream may increase the water levels downstream in a severe flood event. Similarly, construction of coastal structures to trap sediment and improve the resistance of coasts to erosion and breaching in one area may deplete beaches down-drift. These interactions can be represented in system models, but engineering understanding of the relevant processes, particularly sedimentary processes over long-time scales, is limited. Even where we have a detailed understanding of the physical processes, there may be fundamental limits to our ability to predict behaviour due to the chaotic nature of some of the relevant processes and loading.

Flooding systems are dynamic over a range of time-scales

River and coastal systems are subject to change. Change may impact upon the loads on the system, the response to loads or the potential impacts of flooding. It may be due to natural environmental processes, for example, long-term geomorphological processes, evolution in ecosystems, or intentional and unintentional human interventions in the flooding system. Social and economic change will have a profound influence on the potential impacts of flooding and the way they are valued. All of these futures are difficult to predict. Fig. 2 illustrates how various changes may influence the consequences

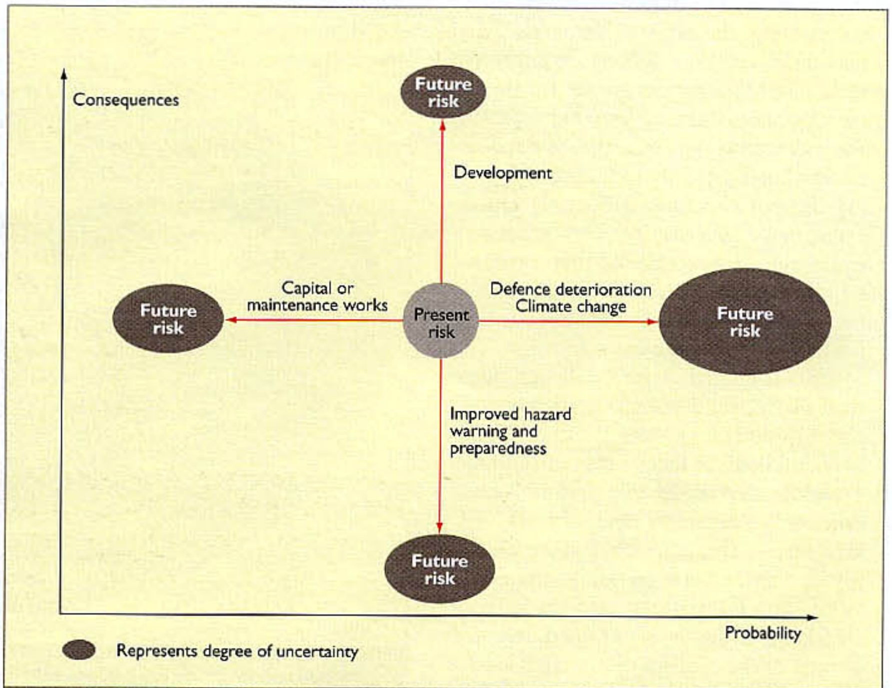

Fig. 2. Some factors that can change flood risk[19]

and/or probability of flooding, with an indication of their associated uncertainties.

Rivers and coasts are valued in different ways by a range of stakeholders

The aim of risk reduction is central to the UK government's Department for Environment, Food and Rural Affairs (DEFRA). Environment Agency and DEFRA guidance on appraisal of projects identifies the economic, environmental and social dimensions as relevant to decision making, but there are no well-established criteria for what might represent 'acceptable' risks from flooding.[13–15]

Risk-based approaches provide a subtle and adaptable framework for supporting decision makers in addressing these uncertainties. The aim is not to replace the judgement and expertise of decision makers by prescribing preferred options, but to make sense of some of the complexities and uncertainties outlined above, in appropriate ways, that reflect the needs of specific decision problems. The concept of appropriateness—finding the balance between uninformed decision-making and paralysis by analysis, depending on the circumstances and consequences of any particular decision—is well established in risk management. Within flood management, this concept is being translated into a tiered risk assessment methodology. The remainder of this paper explores how this range of appropriate risk assessment methods is being used in practice.

Applying risk-based techniques to flood hazard management

Analysis of flood risk involves consideration of the whole flooding system and acknowledgement of the uncertainties within predictions. Within this process it is necessary to consider each of the stages that lead from the extreme climatic conditions that initiate a flood to the individuals and assets in the floodplain who suffer the consequences. The discipline of this procedure provides tremendous insight into the way flooding occurs and how flood risk may be efficiently reduced (Figs 3 and 4). Unlike a standards-based approach, schemes can be assessed and compared in cases where factors other than geometry affect the effectiveness of the defence—such as

> "Analysis of flood risk involves consideration of the whole flooding system and acknowledgement of the uncertainties within predictions"

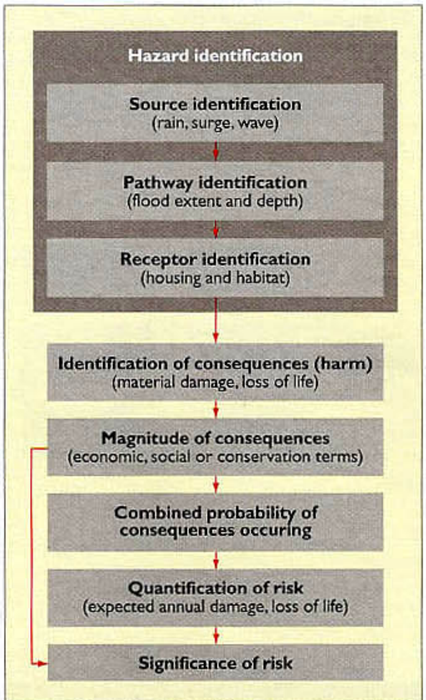

Fig. 3. The flood risk assessment process

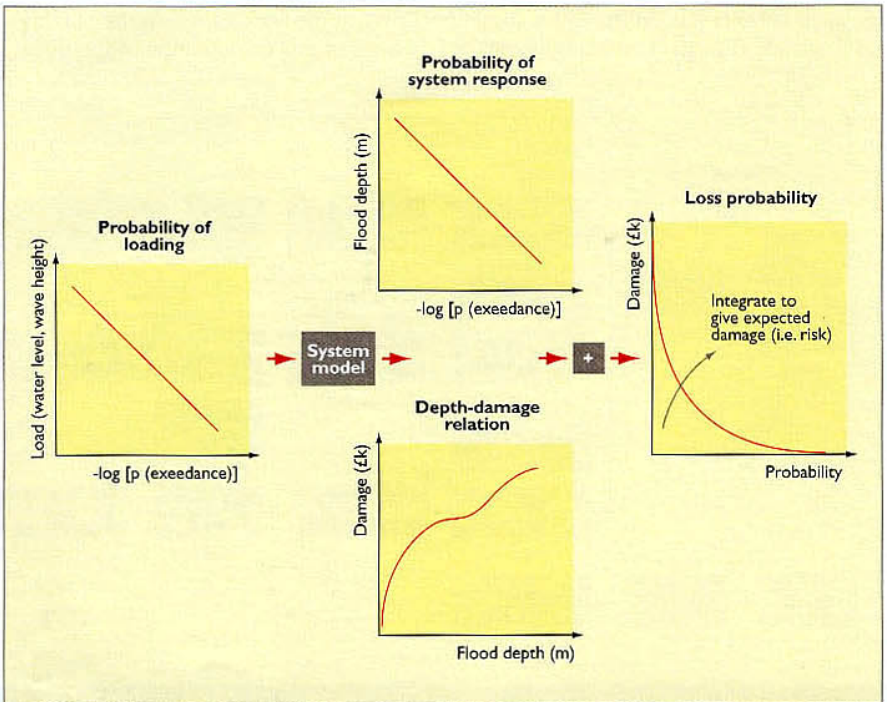

Fig. 4. How economic flood losses are calculated using risk-based techniques

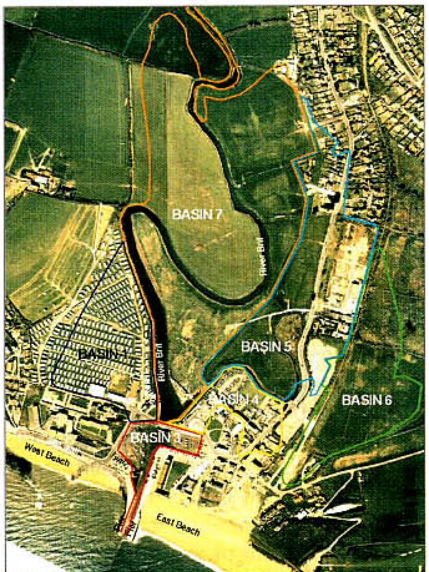

Fig. 5. Aerial photograph of West Bay on the south coast of England, indicating low-lying areas or 'basins' at risk from flooding

flood gates, which depend on accurate, timely flood warnings and operational response.

Figures 5 and 6 illustrate a risk assessment undertaken by HR Wallingford in partnership with West Dorset District Council at West Bay on the south coast of England. The site is small, but complex from the point of view of a systems analysis. The low-lying areas at the site have been labelled as basins 1–6 in Fig. 5. These are also the areas that are occupied by people and economic assets at risk from flooding. These basins may be flooded by the sea and/or fluvial water in the River Brit. Other uncertain events, such as failure to open the sluice gates, will modify the flooding process. Fig. 6 provides a cause–consequence chart, which illustrates the ways in which flooding can occur. The arrows denote the direction from cause to consequence. Note that a cause will only result in a given consequence if the cause is sufficiently severe. Thus, for example, lowering of East Beach will only result in overtopping of the beach and flooding if the beach lowering and marine storm are sufficiently severe.

Figure 6 has been further subdivided based on the commonly used source–pathway–receptor model.[7] For a 'risk' to be present there must be a source of the hazard (atmospheric storms), a receptor (people and properties) and a pathway between the source and the receptor. As shown in Fig. 6, a particular atmospheric storm may cause heavy rainfall and hence high fluvial flows, surge water levels in the sea, high waves, or any combination of the three. Therefore, to analyse the flooding system, a joint probability analysis of all of the load conditions was required. This was then combined with numerical modelling of all of the pathways (system responses) to generate probability distributions for the depth of flooding in basins 1–6. Flood depth was then used in an economic analysis of the risk of flooding.

Once a risk model had been established, it was then possible to test and optimise a range of potential designs and management strategies (provided the model could resolve their influence on the system behaviour). Thus, it was possible to examine the relative merits of investing in new capital works or improving the maintenance of existing defences. Scenarios of future land use could also be tested in order to inform the planning process.

Alternative designs and management strategies can be compared on the basis of their cost and risk profiles. There are many reasons for different options to have different risk profiles, including higher sensitivity to extreme loads as well as different degrees of uncertainty about future performance. Risk-based analysis can help differentiate between options with similar expected benefit–cost ratios, for example. As

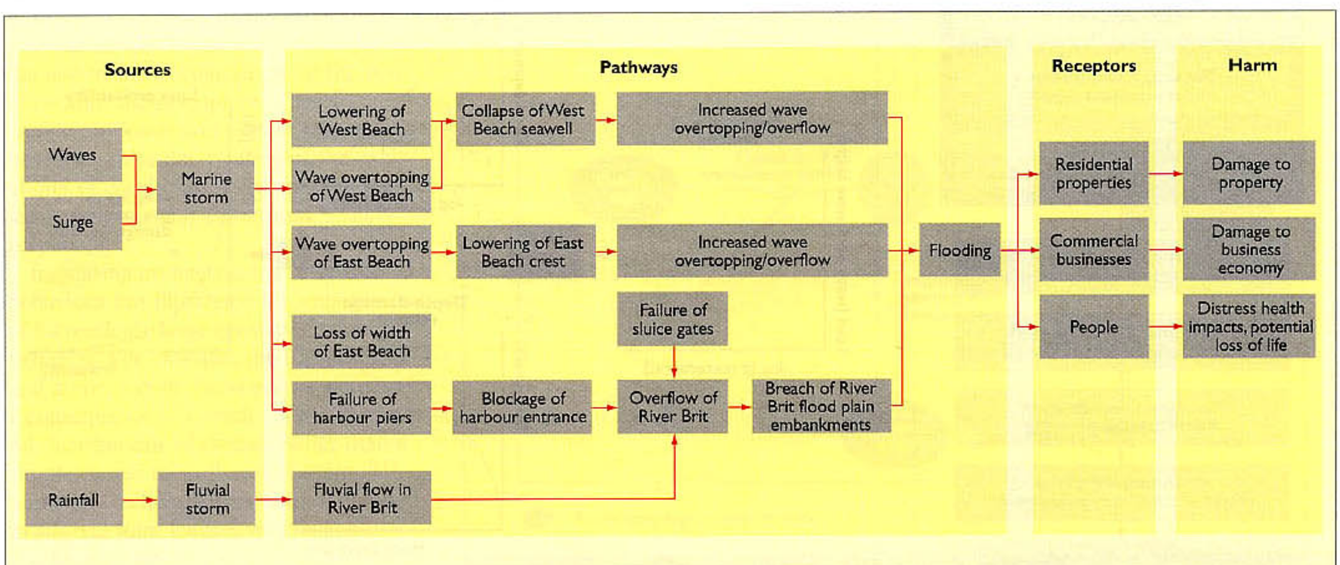

Fig. 6. Cause–consequence diagram for flooding in West Bay—a probability analysis of sources was combined with numerical modelling of pathways to generate probability distributions of flood depth in each basin

> Integrated flood risk management is a complex endeavour, which will need to be supported by computer-based tools

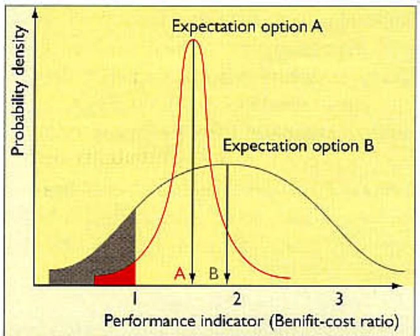

Fig. 7. Risk profiles for different options—option B has a greater expected benefit–cost ratio than option A but is more likely to fail to achieve a minimum benefit cost ratio of unity[22]

shown in Fig. 7, option B has a greater expected benefit–cost ratio than option A. However, given the greater spread of uncertainty of the expected value, it is more likely to fail to achieve a minimum benefit–cost ratio of unity if pursued.

Development of hierarchical risk assessment and decision making

Table 1 provides an overview of a tiered assessment methodology being developed in the UK. The principle is to provide consistent approaches at each level but with increasing detail of analysis and reducing uncertainties. For each tier of analysis, the appropriate level of detail is based on consideration of the type of decision in hand and the availability of the required data and analysis, or its expected cost if it is not available. Thus, if high-resolution data and analysis are available at little or no cost, then it is appropriate that it is used in the high-level methodologies to reduce uncertainty. Insights into the uncertainty associated with a given level of analysis can then be obtained by comparing the results of the analysis from progressively more detailed levels.

The high-level method in Table 1 is based on the minimum information that is currently available from national datasets (including the Environment Agency's new national flood and coastal defence database). Topographical, land use and property data are now available at quite high resolutions on a national basis. Information on flood defences includes an inventory of assets, a visual characterisation of the defence condition and an estimate of the return period of the flood event in which the defence is expected to be overtopped. Based on this limited dataset, the high-level method aims to provide a national estimate of flood risk that can be used to monitor changing risk from year to year, building on methods used in the recent assessment of national economic assets at risk.[16,17]

More site-specific decisions are informed by progressively more detailed analysis. At the intermediate level, a modelling and decision support framework is currently being developed for DEFRA and the Environment Agency to support the new catchment flood management plan process.[18] At the most detailed level are high-resolution simulation models that combine simulated time series of loads (for example, rainfall) with high-resolution models of runoff, channel conveyance and floodplain inundation. Both the intermediate and detailed level analysis have recourse to high-resolution topographic data and each considers multiple defence failure mechanisms.

Table 1. The tiered risk assessment methodology being developed in the UK

Level	Decisions to inform	Data sources	Methodologies
High	• national assessment of economic risk, risk to life or environmental risk • prioritisation of expenditure • regional planning • planning of flood warning	• defence type • condition grades • standard of service • indicative floodplain maps • socio-economic data (including Ordnance Survey Address Point/Focus datasets, aggregated agricultural and transportation datasets) • land use mapping	• generic probabilities of defence failure based on condition assessment and crest freeboard • assumed dependency between defence sections • empirical methods to determine likely flood extent
Intermediate	As above plus • flood defence strategy planning • regulation of development • maintenance management	As above plus • defence crest level and other dimensions where available • joint probability load distributions • floodplain topography • detailed socio-economic data	• probabilities of defence failure from reliability analysis • systems reliability analysis using joint loading conditions • modelling of limited number of inundation scenarios
Detailed	As above plus • scheme appraisal and optimisation	As above plus • all parameters required describing defence strength • synthetic time series of loading conditions	• simulation-based reliability analysis of system • simulation modelling of inundation

A look to the future

The techniques and application of flood risk assessment and management in the UK are in the midst of a period of significant change. This paper represents a snapshot taken at an instant when the direction of change has been clearly established and some of the components of future techniques are in place but the full systems approach has yet to be implemented in practice. At the moment, aspects of UK practice that represent best practice internationally, for example multivariate statistics, are being disseminated more widely to practitioners.[19]

Meanwhile, best international practice, for example recent Dutch work on reliability assessment of dyke rings,[20,21] is being identified and adapted for the particular conditions in the UK. New data acquisition, analysis, communication and presentation techniques are being tested and applied. Emerging issues, such as the impact of climatic and other long-term change, are being assimilated into the risk assessment framework. This work is being conducted with the overall aim of integrated risk assessment and continuous active management of whole river catchments and coastal flooding systems.

Integrated flood risk management is a complex endeavour, which will need to be supported by computer-based tools that enable analysis of the whole system, evaluation of the consequences of strategic intervention and coordination of intervention activities. A flood risk management decision support system will include

- an inventory of data, distributed databases and metadata to enable users to judge the pedigree of data
- knowledge bases that guide decision makers through key processes, such as selecting risk assessment methodologies

- tiered risk assessment methods, from broadly applicable high-level methods to powerful simulation tools, which enable a wide range of possible risk management actions to be evaluated
- techniques for representing uncertainty in data, models and predictions, and accounting for it in decision making
- open architecture modelling support systems that help decision makers apply best practice methodologies
- a geographical information systems (GIS) interface that presents risk information to a range of decision makers and stakeholders, including the public, in an appropriate format.

Technology on its own will not result in integrated flood risk management. It needs to be accompanied by continued evolution of existing expertise and experience. It will require organisational change and the building of capabilities within the flood risk management industry, and some changed behaviours on the part of the general public. Finally, if integrated flood risk management is to be a product of complementary actions of many individuals and organisations, then the general understanding of the objective, process and best practice of risk management among those individuals and organisations will have to be enhanced. It is hoped that this paper will contribute to that aim.

Acknowledgements

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References

1. BECK U. *Risk Society: Towards a New Modernity*. Sage, London, 1992
2. INSTITUTION OF CIVIL ENGINEERS. *The Management of Health and Safety in Civil Engineering*. Thomas Telford Publishing, London, 1995.
3. BARNARD M. *Health and Safety for Engineers*. Thomas Telford Publishing, London, 1998.
4. FINK S. E. *Health and Safety Law for the Construction Industry*. Thomas Telford Publishing, London, 1997.
5. GODFREY P.S. *Control of Risk: a Guide to the Systematic Management of Risk from Construction*. CIRIA, London, 1996, Special Publication 125
6. HALL J. W., CRUICKSHANK I. C. and GODFREY P. S. Software-supported risk management for the construction industry. *Proceedings of the Institution of Civil Engineers Civil Engineering*, 2001, **144**, 42–48.
7. DEPARTMENT OF THE ENVIRONMENT, TRANSPORT AND THE REGIONS, ENVIRONMENT AGENCY AND INSTITUTE OF ENVIRONMENTAL HEALTH. *Guidelines for Environmental Risk Assessment and Management*, 2nd edition. The Stationery Office, London, 2000.
8. INSTITUTE OF CHARTERED ACCOUNTANTS IN ENGLAND AND WALES. *Internal control: guidance for directors on the combined code*. Institute of Chartered Accountants in England and Wales, London, 1999.
9. STRUCTURAL ENGINEERS ASSOCIATION OF CALIFORNIA. *Vision 2000—a framework for performance based design*. SEAOC, Vision 2000 Committee, Sacramento, California, 1995.
10. BYE P. AND HORNER M. *Easter 1998 Floods: Report by the Independent Review Team to the Board of the Environment Agency*, volumes 1 and 2. Environment Agency, Bristol, 1998.
11. ENVIRONMENT AGENCY. *Lessons Learned: Autumn 2000 Foods*. Environment Agency, Bristol, 2001.
12. HR WALLINGFORD. *The joint probability of waves and water levels JOIN-SEA: a rigorous but practical new approach*. HR Wallingford, Wallingford, 1998, HR Report SR 537.
13. DEPARTMENT FOR ENVIRONMENT, FOOD AND RURAL AFFAIRS. *Flood and Coastal Defence Project Appraisal Guidance—Approaches to Risk*. The Stationery Office, London, 2000, Report FCDPAG4.
14. ENVIRONMENT AGENCY. *An Environmental Vision*. Environment Agency, Bristol, 2000.
15. ENVIRONMENT AGENCY. *Framework for Change—Reducing Flood Risk*. Environment Agency, Bristol, 2001.
16. DEPARTMENT FOR ENVIRONMENT, FOOD AND RURAL AFFAIRS. *National appraisal of assets at risk from flooding and coastal erosion*. The Stationery Office, London, 2000, HR Wallingford Report.
17. DEPARTMENT FOR ENVIRONMENT, FOOD AND RURAL AFFAIRS. *National appraisal of assets at risk from flooding and coastal erosion, including the influence of climate change*. The Stationery Office, London, 2001, Halcrow Report.
18. HR WALLINGFORD. *Catchment flood management plans—a best practice approach*. HR Wallingford, Wallingford, 2001, HR Report.
19. HR WALLINGFORD. *Risk, performance and uncertainty in flood and coastal defence, a review*. HR Wallingford, Wallingford, 2002, HR Report SR 587 (second draft).
20. TECHNICAL ADVISORY COMMITTEE FOR WATER DEFENCE. *From Exceedance Probability to Flooding Probability*. TAW, Den Haag, 2000 (in Dutch).
21. VRIJLING AND VAN GELDER. Policy implications for uncertainty integration in design. *Proceedings of the 8th International Symposium on Stochastic Hydraulics*, 2000.
22. MEADOWCROFT I. C., HALL J. W. AND RAMSBOTTOM D. M. *Application of risk methods in flood and coastal defence—a scoping report*. HR Wallingford, Wallingford, 1997, HR Report SR 483.

Bibliography

1. INSTITUTION OF CIVIL ENGINEERS. *Learning to live with rivers*. ICE, London, 2001, Final Report of the ICE's presidential commission to review the technical aspects of flood risk management in England and Wales.
2. MORRIS M. AND SIMM J. *Construction Risk in River and Estuary Engineering*. Thomas Telford Publishing, London, 2000.
3. SAYERS P. B., GOULDBY B. P. AND SIMM J. *Risk, performance and uncertainty in flood and coastal defence—a review*. HR Wallingford, Wallingford, 2001, HR Report SR 587.
4. SIMM J. AND CRUICKSHANK I. *Construction Risk in Coastal Engineering*. Thomas Telford Publishing, London, 2000.