Ecological impact assessment tools for fluvial flooding and coastal inundation

Technical Report – XXXXXX/TR (SC060062)

The Environment Agency is the leading public body protecting and improving the environment in England and Wales.

It's our job to make sure that air, land and water are looked after by everyone in today's society, so that tomorrow's generations inherit a cleaner, healthier world.

Our work includes tackling flooding and pollution incidents, reducing industry's impacts on the environment, cleaning up rivers, coastal waters and contaminated land, and improving wildlife habitats.

This report is the result of research commissioned and funded by the Environment Agency's Science Programme.

Published by:
Environment Agency, Rio House, Waterside Drive, Aztec West, Almondsbury, Bristol, BS32 4UD
Tel: 01454 624400 Fax: 01454 624409
www.environment-agency.gov.uk

ISBN: XXXXXXXXXX

Further copies of this report are available from:
The Environment Agency's National Customer Contact Centre by emailing:
enquiries@environment-agency.gov.uk
or by telephoning 08708 506506.

Author(s):
Old, Gareth; Acreman, Michael; Laize, Cedric; Nottage, Albert; Overton, Ian; Mountford, Owen; Packman, John; Walton, Sam; Cowx, Ian; Thorne, Colin; Thompson, Julian; Newman, Jonathan; Ramsbottom, David; Gouldby, Ben; Lumbroso, Darren; Gowing, David

Dissemination Status:
Publicly available / Restricted

Keywords:
Flooding, inundation, ecological, coastal, fluvial, ecological impact assessment

Research Contractor:
Centre for Ecology and Hydrology
Maclean Building
Wallingford
Tel. 01491 838800

Environment Agency's Project Manager:
Adam Baylis and office

Collaborator(s):
In alphabetical order (refer to guidance document)

Science Project Number:
SC060062

Product Code:
XXXXXXXXXXXX-E-P

Science at the Environment Agency

Science underpins the work of the Environment Agency. It provides an up-to-date understanding of the world about us and helps us to develop monitoring tools and techniques to manage our environment as efficiently and effectively as possible.

The work of the Environment Agency's Science Group is a key ingredient in the partnership between research, policy and operations that enables the Environment Agency to protect and restore our environment.

The science programme focuses on five main areas of activity:

- **Setting the agenda**, by identifying where strategic science can inform our evidence-based policies, advisory and regulatory roles;
- **Funding science**, by supporting programmes, projects and people in response to long-term strategic needs, medium-term policy priorities and shorter-term operational requirements;
- **Managing science**, by ensuring that our programmes and projects are fit for purpose and executed according to international scientific standards;
- **Carrying out science**, by undertaking research – either by contracting it out to research organisations and consultancies or by doing it ourselves;
- **Delivering information, advice, tools and techniques**, by making appropriate products available to our policy and operations staff.

Steve Killeen

Head of Science

Executive Summary

Background

This report presents the scientific basis and development of the ecological impact assessment (EIA) tools for fluvial flooding (EIA F tool) and coastal inundation (EIA C tool). These tools have been developed within the *Ecological Consequences of Flooding* (ECF) project and may be used to support an environmental risk assessment.

When developing plans to manage flood risk, economic, social and environmental impacts are considered. There are many tools to estimate the economic impacts. However, there is currently no standard approach for evaluating the impacts on the natural environment within a flood risk assessment. Impacts of floods on the natural environment are often complex and include benefits and disbenefits. The Broad-Scale Ecosystem Assessment (BSEA) toolkit is based on existing or producible GIS datasets that have an apparent relationship with ecological characteristics. It is largely left to experts to interpret the ecological implications of these data. The project reported here builds on this work by introducing more scientific knowledge and objectivity to the assessment of ecological impact by developing prototype GIS-based tools to support decision making.

The prototype tools developed here will be used to make an initial assessment of environmental assets at risk of fluvial flooding and coastal inundation. In this way they will help Flood and Coastal Risk Management (FCRM) authorities fulfil their duties under the EU Floods Directive, Habitats Directive, Bird's Directive and Water Framework Directive. In the future it is envisioned that the tool will be embedded within software and made available to general users through an application like the Modelling Decision Support Framework used by the Environment Agency in the preparation of catchment flood management plans (CFMPs). The tools will thus support environmental impact assessments and strategic environmental assessments for flood risk management activities.

The scoping study that underpins this project (Ramsbottom *et al*., 2005) concluded that although gaps exist in our scientific understanding of ecological impacts and data coverage and resolution, it was feasible to integrate the available information within a Geographical Information System (GIS), and to produce prototype tools.

Aim and objectives

The overall aim of the project was to develop, test and disseminate prototype methods for assessing and mapping the environmental risk, including harmful and beneficial effects, of flooding.

The aim was achieved through the following objectives:

- reviewing literature and consulting experts to identify current requirements, tools and knowledge;
- defining the scope of the tool and ecologically significant hydrological indices;
- deciding on the resolution of impact assessment;
- specifying the methodology;

- defining ecological sensitivities to flooding using scientific literature, empirical assessment and expert opinion;
- preparing scorecards as frameworks for impact assessment;
- producing guidance for the prototype tools;
- pilot testing: calibrating, verifying and assessing applicability of the proposed methods;
- disseminating findings including a scientific paper and good practice guidance.

The prototype tools and their application

The prototype tools described in this report guide the user in making an objective and quantitative (where appropriate) assessment of the impacts of floods on the environment using ARC GIS 9.3 with its standard toolbox supplemented with Spatial Analyst. Although GIS-based, they are spreadsheet tools that assess the environmental impact of a given hydrological scenario by comparing this to the sensitivities of mapped environmental assets. The tools would support anyone undertaking an ecological flood risk assessment. They represent a tiered approach (comparable to the BSEA) to environmental impact assessment which is necessary to ensure that the right level of analysis is adopted to match the importance of the decision.

Step-by-step guidance in using the tools is available (in the guidance report). The environmental assessment is made using spreadsheet-based scorecards. The ecological sensitivities mentioned above for environmental impact assessment are captured on the scorecards. The user must define the current flooding/relative sea level rise scenario and undertake a series of defined spatial data queries before assessing the impacts of flooding. The user must specify the impact assessment criteria as these are likely to change with time and with the specific objectives of a given assessment (for example, what is an allowable loss of bird habitat?). The impacts of flooding are then evaluated by comparing the sensitivities of flooding to the flood characteristics.

Given that the prototype tools use many spatial datasets of varying resolution, accuracy, age and completeness, several areas of uncertainty are identified and discussed. These must be acknowledged in any environmental assessment and a decision must be made as to which need quantifying in a given study.

The prototype tools have been tested in two fluvial and two coastal regions. Tests of both tools were successful and demonstrated the applicability of the tools. A degree of verification was made by expert assessment of the results of the pilot tests.

Relevance to strategy and legislation

The ECF method supports activities throughout the tiered approach to fluvial flood risk management planning.

In particular, it supports Catchment Flood Management Plans (CFMPs), shoreline management plans (SMPs), strategy planning and Preliminary Flood Risk

Assessments (PFRAs), required under the Flood Risk Regulations 2009. The tools could also support the assessment of outcome measures, spatial planning and appraisal. They provide a framework for assessment, although the level of detail would change from the more general CFMP/SMP to the more detailed strategy plan. The application of the tools at the more detailed scheme level requires further consideration and would need to include site-specific information. The way the ECF tool link to existing tools and methods is considered here, as this is key to its successful integration with flood risk management.

Conclusions and recommendations

The prototype tools successfully integrate current scientific knowledge, expert opinion and available data in a framework that allows a more objective assessment of the environmental impacts of flooding. However, our ability to assess the impacts of flooding on the environment would be greatly enhanced by the following:

- Developing National Flood Risk Assessment (NaFRA) data to include more ecologically relevant data (frequent floods, seasonality and duration).
- Increasing coverage of up-to-date high resolution habitat mapping (such as national vegetation classification data).
- Increasing scientific understanding of the sensitivities of environmental assets to flooding/inundation.

The relevance of the methods to current strategy and legislation has been demonstrated by considering specific activities within flood risk management.

Acknowledgements

We would like to acknowledge the expertise and advice received from a range of project partners and people including:

- **The project board** – comprising Duncan Huggett, Suresh Surrendran and Adam Baylis (Client Project Manager).
- **Workshop attendees** – whose names are too numerous to mention here, but who represented key organisations (such as Natural England, Environment Agency).
- **Input to hydraulic modelling** – Mike Panzeri, Stephen Wade and Hubert Bast (HR Wallingford) are thanked.
- **Individual technical experts: external to the project team** – who provided useful guidance and contributed as a source of technical information, including Nigel Holmes (Alconbury Consultants), Robin Welcomme and Richard Noble (University of Hull).
- **Commenting on results of pilot testing the coastal tool:** Robin Crawshaw (Environment Agency) is thanked.
- **Providing scores of river channel modification:** Ian Vaughan (Cardiff University) is thanked.
- **Estimating the return periods of the July 2007 floods used in the pilot test cases:** Thomas Kjeldsen (CEH Wallingford) is thanked.
- **Provision of biodiversity action plan habitat data:** Countryside Council for Wales and Natural England are thanked.
- **Provision of flood and topographic data:** the Environment Agency is thanked.

Contents

1 Introduction

There is currently no standard approach for evaluating the consequences of flooding on the natural environment within a flood risk assessment (Old, 2008). Conlan *et al.* (2002) concluded that there is no systematic understanding of the cause and effect relationships between ecosystems and fluvial flooding, and no integrated methods for assessing potential impacts. They concluded that there is a pressing need to develop a comprehensive dataset of existing knowledge, from which suitable modelling tools can be developed into an integrated impact assessment approach. The scoping study that underpins this project (Ramsbottom *et al*., 2005) concluded that although gaps in data coverage and resolution exist, it was feasible to integrate the available information within a Geographical Information System (GIS), to produce prototype tools.

The scoping study (Ramsbottom *et al.,* 2005) and subsequent literature review (Old, 2008) identified the various tools and information relevant to the assessment of the environmental consequences of flooding. Of particular relevance is the Broad-Scale Ecosystem Assessment (BSEA) approach (Conlan *et al*., 2006). Where appropriate, methods following this approach were developed here. In particular, quantitative rules were specified, where possible, to provide an objective assessment of impact. A similar philosophy to BSEA was adopted in our project where impacts are evidence-based, spatial datasets are used for broad-scale assessments and a modular framework is used to facilitate future updates.

In summary, the spreadsheet-based prototype tools developed here use GIS to assess the environmental impact of given hydrological scenarios by comparing these to the sensitivities of mapped environmental assets. The tools would support anyone undertaking an ecological flood risk assessment. They represent a tiered approach (comparable to the BSEA) to environmental impact assessment which is necessary to ensure that the right level of analysis is adopted to match the importance of the decision.

This report documents the decisions made during each stage of the development of the prototype tools to assess, model and map the environmental consequences of flooding.

The development of the fluvial and coastal tools is documented in Sections 2 and 3, respectively.

The use of spreadsheet-based scorecards to assess the impact of flooding is described in Section 4 before the ability to produce user-defined maps is considered in Section 5. Results of fluvial and coastal pilot testing are presented in Sections 6 and 7 respectively.

Relating outputs to social and economic risks of flooding is considered in Section 8 whilst support from the tools for strategy and legislation is discussed in Section 9. In Section 10 the requirements of a detailed fluvial analysis are discussed for each environmental asset. Concluding remarks are made in Section 11 before future research needs are summarised in Section 12.

Summary of key stages in method development:

- literature review and expert consultation to identify current requirements, tools and knowledge;
- definition of scope of tool and ecologically significant hydrological indices;
- decision on resolution of impact assessment;
- specification of methodology;

- definition of ecological sensitivities to flooding using scientific literature, empirical assessment and expert opinion;
- preparation of a scorecard as a framework for impact assessment;
- production of guidance for prototype tool;
- pilot testing.

Step-by-step guidance on how to use the prototype tools can be found in Old *et al*. (2011).

2 Development of the fluvial tool

2.1 Scope of the tool and available knowledge

Although flooding of terrestrial ecosystems can result from a number of processes (Old and Thompson, 2008), including groundwater flooding and direct precipitation, only fluvial flooding is considered here.

A detailed literature review was carried out to consider the sensitivities to flooding of key aspects of the environment (Old, 2008). Knowledge was collated from scientific literature and by consulting experts at workshops. This process led to the identification of many gaps in knowledge. The particular aspects of the environment addressed reflects those specified in the project scoping study (Ramsbottom *et al.,* 2005), BSEA approach (Conlan *et al.,* 2006) and those requested by professionals to meet current legislative obligations. A project workshop held in May 2008 evaluated the completeness of the environmental aspects considered and their sensitivities to flooding were discussed. Following this workshop the literature review was finalised (Old, 2008). Participants in project workshops included the Environment Agency, Natural England and several consultants.

In September 2008 a teleconference was held with the project board on the proposed methodology developed in collaboration with Ian Overton (CSIRO, Australia). At this conference the appropriateness of the environmental aspects was revisited and in-stream impacts were added to support Water Framework Directive obligations at the request of Environment Agency staff. In March 2009, a second workshop was organised where the agreed method was presented to a wider group and sensitivities to flooding were discussed in detail. In particular, this workshop discussed the most appropriate habitat data. The method was presented using land use classes from the Centre for Ecology and Hydrology (CEH) Land Cover Map 2000 to identify habitats. It was clear that this was too broad a classification and national vegetation community (NVC) scale would be far more appropriate. However, as NVC maps are not available for all habitats across much of England and Wales, priority biodiversity action plan (BAP) habitats were agreed to be a good compromise. Questionnaires were circulated and these confirmed general support for the methodology. Following this workshop, a long period of data collation and analysis was necessary. In August 2010 Ian Overton (CSIRO) worked at CEH to produce the final method which is presented in here. The final method involved defining tolerances and benefits of agreed environmental assets to inundation and inputs of sediment-associated nutrients. These were presented in a spreadsheet in terms of quantifiable hydrological indices allowing an impact assessment to be made.

A. River - floodplain ecosystem impact

B. Terrestrial BAP priority habitats

C. In-stream ecology

  i. Fish

  ii. Macrophytes

  iii. Invertebrates

D. Wetland birds

Impacts of flooding on sediments were not considered in their own right but sediments were included as a mechanism by which floods affect the environmental aspects. The impacts of floods on sediments were considered in the literature review, subsequent indicator report and discussed in detail via a teleconference in July 2009. An indicator document was then prepared that considered how these sediment impacts should be used within the current project (Appendix A). The key impacts of floods on ecology via sediments that are included here are: (1) transport and deposition of nutrient-rich agriculturally derived sediment and (2) channel geomorphic instability. The selection of these elements for inclusion in the project reflects their environmental significance in addition to data availability.

Although an important environmental asset, it was agreed that mammals were beyond the scope of this project.

2.2 Ecologically significant flood indices

The literature review combined with expert consultation at both project workshops identified the ecologically significant flood indices presented in Table 2.1. The data that may be used to derive these indices are also summarised.

Table 2.1 Summary of ecologically significant indices and data used to define them

Ecologically significant Index	Dataset	Resolution	Source
Frequency of flooding exceeding specific depths	NAFRA data (0, 25 and 50 cm depths).	50 m x 50 m grid	Environment Agency
Duration of flooding	Typical flood duration based on CEH assessment of mean daily flow data. Estimate given for catchments with a base flow index of <0.75.	Upstream catchment	CEH
Seasonality of flooding	Ratios of spring: summer: winter flooding based on CEH assessment of mean daily flow data.	N/A	CEH
Degree of channel modification	Bank reinforcement and channel re-sectioning indices.	500-m reaches	Derived from Environment Agency River Habitat Survey data w. published equations (Vaughan, 2010)
Degree of channel-floodplain connectivity in upstream catchment	Area of 0.2 probability of inundation derived from NAFRA data.	Upstream catchment	Environment Agency
Degree of channel-floodplain connectivity at a site	Area of 0.2 probability of inundation within a 500-m radius circle. Derived from NAFRA data.	500-m radius circle	Environment Agency
Constrained channel-floodplain at a site	Area of 0.2 probability of inundation within a 500-m radius circle less than 7%. Derived from NAFRA data.	Upstream catchment	CEH Land Cover Map

Frequency and ***depth*** of flooding are given in the National Flood Risk Assessment (NAFRA) dataset. The project team had anticipated using the original Modelling and Decision Support Framework (MDSF) flood outlines but owing to technical problems the project was instructed to use NAFRA data as an intermediate between MDSF and the future enhanced MDSF2. Significant delays in the project work resulted from obtaining NAFRA data, assessing its suitability and then scoping the work needed to increase its resolution for frequent events and introduce seasonality. NAFRA can be used to provide annual probabilities of inundation exceeding specific depths (for example 0, 25 and 45 cm). As NAFRA is designed to assess social and economic impacts of flooding, it is most suited to assessing infrequent extreme events and detail for frequent events is coarse. The coarse resolution of inundation values reported in NAFRA is clear from Figure 2.1. The wide probability limits (0.5, 0.8, 0.9…) used in NAFRA for frequent events (T=2, 5, 10…), the largely uniform setting of bankfull flow (usually at T=2 all along undefended rivers), and the neglect of local topography in defining flood elevation within a flood zone mean that the risks of frequent flooding are not adequately resolved over undefended flood plains. Inundation probability estimates tend to band closely to loading probabilities (T=2, 5, 10…). In this project it became clear that ecology is likely to respond to frequent events and the impact of flooding will be strongly influenced by the time of year.

Cell depth probability data (NAFRA 2008) reclassification

The NAFRA data were supplied as flood probabilities ranging from zero to one. Although theoretically continuous, the data presents distinct steps (Figure 2.1). Thus, it is possible to reclassify the data as discrete probability ranges to significantly lower computational burden and in doing so only loose minimal information. After close inspection of the data distribution, we identified the probability ranges shown in Table 2.2; for convenience and readability, we used rounded probability values (representing commonly used return periods) for the class names (such as 0.01 rather than 0.008; see third column in Table 2.2).

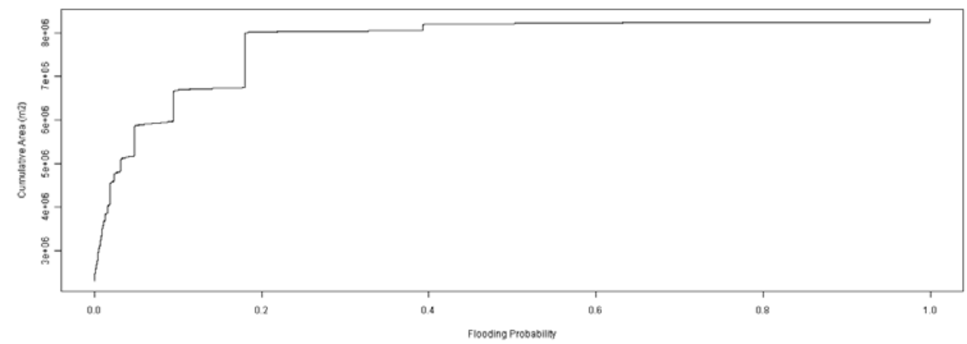

Figure 2.1 Cumulative area of cell depth probability

Table 2.2 Reclassification of cell depth probabilities (p)

Step in inundation probability	Reclassification probability range	Inundation class name
0.39	$0.39 \le p$	05
0.18	$0.18 \le p < 0.39$	02
0.09	$0.09 \le p < 0.18$	01
0.047	$0.047 \le p < 0.09$	0.05
0.018	$0.018 \le p < 0.09$	0.02
0.008	$0.008 \le p < 0.018$	0.01
	$p < 0.008$	<0.01

NAFRA 2006 data were used initially before being replaced by the improved dataset of NAFRA 2008. Although beyond the scope of the resources available to our project, the team showed that NAFRA could be run to improve the resolution of more frequent events and introduce seasonality.

Significant effort was invested in a pilot study to predict ***duration*** and ***seasonality*** of flooding across England and Wales (Appendix B). Although broad associations were found on a national basis, sufficiently strong relationships to predict flood duration and/or seasonality for individual catchments could not easily be defined and as a result, national factors were used. Typical flood durations were defined for low and high base flow index (BFI) catchments. Similarly, factors that describe the seasonality of flooding across all of England and Wales were defined that could be applied to annual probabilities.

Measures of ***channel modification*** are given by bank reinforcement and channel resectioning indices calculated from River Habitat Survey (RHS) data (Vaughan, 2010). Both indices range from low (zero per cent) to high (100 per cent) intensity of modification. In this project we used the upper quartile of all sites with modification indices to identify the most heavily impacted reaches. Therefore, where the combined modification index is above100 per cent (bank reinforcement plus channel resectioning) the reach is identified as being heavily impacted.

Channel-floodplain connectivity of the upstream catchment was assessed by considering the area inundated (specific event or 0.2 probability of inundation).

Channel-floodplain connectivity at a site was assessed by calculating the area of a 500-m radius circle around the site with 0.2 probability of inundation.

Sites with constrained channel-floodplains may be identified as those where the area of 0.2 probability of inundation within a 500-m circle of a site is less than seven per cent.

The BSEA provides guidance on how ***sediment*** supply may be estimated by analysing spatial datasets (including land use, runoff and gradient). McHugh *et al.* (2002) followed a similar approach and produced maps of sediment erosion risk. We planned to use the maps from McHugh's work in our project but after exhaustive, but ultimately unsuccessful, attempts to acquire the necessary data we adopted an alternative approach. We used a simplified approach to estimating the nutrient-rich sediment load of flood water by identifying areas of erosive agricultural land use classes within the catchment. The agricultural land use classes included coniferous woodland, arable cereals, arable horticulture, arable non-rotational, and improved grassland from the CEH Land Cover Map 2000. An average value for the percentage land area of

England and Wales covered by erosive agricultural land use was determined as 61 per cent and this was used to assess specific catchments as being either high or low.

Although water quality is an important hydrological index that clearly has an impact on ecosystems, it was beyond the scope of the project (excepting fine sediment).

2.3 Resolution of impact assessment

The current tool represents a tiered risk-based approach (varied levels of detail) to impact assessment which is consistent with the BSEA. The focus here is on the broad scale but the importance of a more detailed level of analysis is acknowledged and considered later in the report (see Chapter 11). National datasets are used but where appropriate more detailed information on areas may be included. The functionality of the tool with respect to broad-scale impact assessment is particularly relevant to the Environment Agency as this is the scale at which it manages the environment. Furthermore, it was necessary to use nationally consistent and readily available data and these were only available at the broad scale. The scale at which the impact of flooding on each ecological asset is assessed is defined in the sections below.

2.3.1 Impact via sediment

Several ecological impacts of floods are mediated through sediments. Sediment impacts are assessed for the whole upstream catchment. Indices of channel modification (bank reinforcement and re-sectioning; Vaughan (2010)) and fine sediment supply from agricultural land are used.

2.3.2 River-floodplain ecosystem impact

The general impact on the river-floodplain system is assessed by considering the extent of flooding, its duration and whether the channel is heavily modified. This is assessed for the whole upstream catchment.

2.3.3 Terrestrial habitats

The impact of flooding on the terrestrial environment is primarily assessed in relation to the priority biodiversity action plan (BAP) habitats given in Table 2.3 throughout the catchment. The selection of habitat type as the appropriate level of ecological resolution was agreed at the first project workshop (May 2008) in recognition of the fact that the current policy framework focuses heavily on habitats and that, given existing knowledge and understanding, adequate evaluation of species-specific impacts on a broad scale is not feasible at present. Furthermore, the literature review showed that many species requirements were contradictory and one species may depend on another with different flood tolerance. If the project focussed on species, many crucial dependencies might be missed. The assumption made in this selection was essentially the one implicit in the Habitats Directive, that by ensuring that the condition of habitats is maintained in, or restored to, favourable condition the characteristic communities of plants and animals associated with those habitats will be conserved. This is consistent with the Broad Scale Ecosystem Assessment (BSEA) approach (Conlan *et al.,* 2006).

Table 2.3 Priority biodiversity action plan habitats included in the fluvial method

Biodiversity action plan habitat (England)	Biodiversity action plan habitat (Wales)	Biodiversity action plan habitat (England and Wales)	Data source
Blanket bog	Blanket bog	Blanket bog	CCW/NE
Coastal and floodplain grazing marsh	Coastal and floodplain grazing marsh	Coastal and floodplain grazing marsh	CCW/NE
Lowland calcareous grassland	Lowland calcareous grassland	Lowland calcareous grassland	CCW/NE
Lowland dry acid grassland	Lowland dry acid grassland	Lowland dry acid grassland	CCW/NE
Lowland meadows	Lowland meadows (points converted to 50-m cells)	Lowland meadows	CCW/NE
Lowland raised bog	Lowland raised bog	Lowland raised bog	CCW/NE
Purple moorgrass and rush pastures	Purple moorgrass and rush pastures	Purple moorgrass and rush pastures	CCW/NE
Upland calcareous grassland	Upland calcareous grassland	Upland calcareous grassland	CCW/NE
Wet woodland	Wet woodland (points converted to 50-m cells)	Wet woodland	CCW/NE
Upland hay meadow		Upland hay meadow	NE
	Arable land	Arable land	CCW
Deciduous woodland	Broadleaved woodland	Deciduous broadleaved woodland	CCW/NE
Lowland mixed deciduous woodland			CCW/NE
Fens	Fen (all components) and reedbed	Fens and reedbeds	CCW/NE
Reedbeds	Fen (flush and spring component)		CCW/NE
	Fen (swamp component) and reedbad		CCW/NE
	Reedbeds (points so not used)		CCW/NE
Lowland heathland	Lowland dry heathland	Low heathland	CCW/NE
	Lowland wet heathland		
Upland heathland	Upland dry heathland	Upland heathland	CCW/NE
	Upland wet heathland		

2.3.4 In-stream ecology

Fish

The impact of flooding on fish is assessed at the assemblage level using a subset of nationally distributed sites (n=3,790), with each site representing the immediate location at which a fish sample was taken and a 500-m radius of its surrounding catchment. A fish community typology was developed based on the method used in the CAMS project (Noble and Cowx, 2007) and the FAME project (FAME 2004, Pont *et al*. 2006, Reyjol *et al.* 2007). In these projects, fish community types were identified by separating a subset of Environment Agency monitoring sites in England and Wales into categories based on their species structure using multivariate hierarchical cluster analysis. The resulting classification consisted of eight fish types (see Table 2.4). From the literature review and subsequent flood indicator report (Appendix F) it became clear that fish assemblages have contrasting tolerances to flooding, so it would be impossible to define generic sensitivities.

Table 2.4 Fish community typology

Fish Type (1-8)	Description
1 Salmon/Trout	*S. salar* zone, *S. trutta fario* may be present
2 Trout/Salmon	Very high abundance of *S.trutta fario*. High abundance of *S.salar*.
3 Trout/Cyprinid	High abundance of *S. trutta fario* with rheophilic cyprinids (L. leucius, L. cephalus, *C. gobio*) as next most common guild. Rheophilic minor species (*B. Barbatula, P. Phoxinus*) also present.
4 Trout	Trout-dominated community, usually found above the salmon limit in upland streams. Rheophilic minor species are absent.
5 Rheophilic cyprinid	High abundance of *L.cephalus, B.barbus* present and also relatively high in abundance. *E.lucius* and *T.thymallus* also present. Represents upper barbel zone of very large river systems, in particular sampling sites on the main river stem (note barbel are not present in every river system in UK).
6 Eurytopic a	Lowland coarse fish type characterised by *L.cephalus*, *L.leuciscus, G.gobio, R.rutilus, A. Brama and E. Lucius*.
7 Eurytopic b	Generally low overall abundance, *R.rutilus* dominate, *E.lucius* and *A.alburnus* are relatively abundant. Representative of large lowland rivers, in particular the main river stem, characterised by water depth (generally boat-based survey data)
8 Chalk rivers	Characterised by *S.salar*, *E.lucius* and *T.thymallus* and specifically representative of the chalk rivers of the south coast of England, in particular the rivers of Hampshire.

Macrophytes and invertebrates

A general assessment was made using generalised rules and not specifying species. In both cases, the assessments undertaken relate to the whole upstream catchment.

2.3.5 Wetland birds

A general assessment was made for the upstream catchment using rules that capture the requirements of wetland birds. Although the needs of individual species were assessed (including Common Snipe, Redshank, Lapwing, Curlew and Mallard), generalised flood requirements were derived. This was appropriate given the common habitat use, breeding and feeding requirements of several wetland birds.

2.4 Defining environmental tolerances to inundation

To assess the impacts of flooding, knowledge on the tolerances of each aspect of the environment documented in the literature review were used. Where scientific understanding was unavailable and appropriate data existed, tolerances were derived empirically but for other aspects of the environment it was necessary to use expert judgement. Knowledge was summarised in flooding impact indicator reports for sediments (Appendix C), fish (Appendix F) and birds (Appendix G). These indicator reports were written to distil the vast amounts of information into rules that could be quantified in the current study.

River - floodplain ecosystem impact

Area of flooding demonstrates the extent of river and floodplain connectivity which is widely accepted as being beneficial to the environment. However, if flooding is prolonged this may have negative impacts. The typical duration of floods in catchments with low and high BFI values were assessed (Table 2.5). This empirical analysis is described in detail in Appendix E. In low-BFI catchments three-quarters of flood events have durations of up to three days. Therefore, events lasting 10 days or more in these catchments are classed as having a long duration. In high-BFI catchments longer durations may be expected and habitats may be less sensitive to them.

Highly modified channels will be geomorphologically unstable during floods. They may be deposition- or erosion-led depending on the balance between sediment input, hydraulics and channel dimensions. They are likely to be poor ecological habitats. A channel modification score was derived from River Habitat Survey baseline data (based on extent of bank reinforcement and channel resectioning; Vaughan (2010)). The length of heavily modified upstream channel was assessed (Section 3) in relation to the total surveyed length. Flooding pressures on the river-floodplain ecosystem, their impact and metrics for assessment are summarised in Table 2.6.

Table 2.5 Empirically defined flood durations

Catchment base flow index (BFI)	Mean duration of flooding (days)	Standard deviation of duration of flooding (days)	Durations of flooding (Mean days +/- 2sd)
Low (<0.75)	1.46	0.72	0.01 to 2.90
High (>0.75)	18.90	18.89	0.00 to 56.67

Table 2.6 Summary of impacts of flooding on river-floodplain ecosystem impact

Pressure	Impact on habitat	Reference for impact	Metric
Flooding	Benefit (river floodplain connectivity is good for a healthy river-floodplain system)	Ramsbottom *et al*. (2005)	Area flooded
Prolonged flooding	Disbenefit (bad for soil biogeochemical processes, birds, fish, and many terrestrial habitats)	Ramsbottom *et al.* (2005)	Area flooded for more than 10 days in low-BFI catchments
Flooding modified river channels by large event (<0.2 probability)	Disbenefit (high flow velocities, geomorphic instability and limited refuge)	Old and Acreman (2006) Appendix C	If flooded: Length (%) of river channel that is heavily modified and length (%) of river channel surveyed

Terrestrial habitats

Empirical analysis of the inundation frequency of all priority BAP habitats throughout England and Wales shows that all exist within the NAFRA inundation frequency bands of 0.5 to below 0.01 (Appendix H). Therefore, all habitats can tolerate a wide range of inundation. The main reason for this is that our focus is at the broad scale as this is the management scale and also the scale at which nationally consistent data are available. It is clear that within each broad habitat there are communities with very different hydrological requirements/tolerances. This means that the same broad habitat types may exist in areas with a wide range of inundation frequencies, but they could have very different community structures, because of the wide definition of the broad habitat types. For example, the species composition varies considerably within the type lowland meadows, from flower-rich meadows to those dominated by a few herbs and grasses. Furthermore, the range of mechanisms that determine the wetness of floodplains, including direct rainfall, local runoff from side-streams and shallow and deep groundwater exchange, may explain why we did not find such strong dependence of such habitats on surface inundation. In Australia, where a similar system has been developed, dependencies on river flood water are strong. During the early stages of method development (September 2008) we planned to only assess good examples of each habitat as defined by SSSI (Sites of Special Scientific Interest) designation. Following discussions it was decided that SSSI status may not necessarily mean the habitat is in a good condition. Furthermore, this screening considerably reduced the size of the dataset. Thus all habitat data were included in the analysis, but if a better metric of habitat quality becomes available in the future this analysis could be repeated.

Consideration of the correspondence of habitats and inundation resulted in several hypotheses being proposed. Firstly, many habitat patterns may reflect management practices. Catchments in England and Wales are heavily managed. For example, arable, horticultural and forestry land use accounts for on average 61 per cent of catchments (CEH Land Cover Map 2000). It is likely that riparian areas with high inundation frequencies have high concentrations of many broad habitats because they are not actively managed for agriculture. This does not mean that these habitats are well suited to these areas but that they can tolerate inundation. Secondly, some unexpected patterns emerged that led us to question whether habitats had been accurately classified (see Appendix I).

Thresholds of inundation are defined here as the bands where the habitats occur with a greater likelihood than would be expected taking into account the areas of each band (Appendix H). This should not be interpreted as the band that each habitat requires. The threshold identifies areas where we have many examples of the given habitat surviving. The link between hydrology and habitat may be indirect. For example, areas that are inundated with a probability of 0.2 may not be cultivated so they are available for broad habitats. The inundation thresholds for each habitat given in Table 2.8 are discussed in Appendix F.

The sensitivities of habitats to flood duration are known to be strongly dependent on season. Expert knowledge was combined with published data to populate the tolerated durations of flooding for each habitat for each season in Table 2.7.

The sensitivities of each habitat to receiving inputs of nutrient rich-agriculturally derived sediment were defined by experts and included in Table 2.7.

In Table 2.8 thresholds for the impact of flooding on priority broad habitats are given.

Table 2.7 Tolerances of floodplain priority BAP habitats to flooding in different seasons, nutrient inputs and their concentrations within areas of specific inundation probabilities

BAP priority habitat	Tolerated (fluvial) flood duration			Impact of nutrient-rich sediment input	Inundation band with greatest concentration of each habitat
	Spring (mid March-May)	**Summer (June-October)**	**Winter (November - mid-March)**		
Blanket bog (*NVC* types **M17** and **M19**)	Maximum one day (see note for winter).	Less than one day.	Possibly five days, though this ombrotrophic habitat rarely occurs where there is flooding OTHER than that temporarily caused by heavy rainfall events, ponding on the surface.	Negative under all circumstances.	0.2
Coastal and floodplain grazing marsh (landscape type rather than habitat *per se*)	Ten days - especially if in early spring and assuming that botanical aspects are not the key value.	Five days.	Flooding of a month or even more should not be a problem.	Some benefit from cation deposition but species diversity will decline with increased loading of nitrogen and phosphorus.	0.5 to 0.1
Lowland calcareous grassland (*NVC* communities **CG1-CG8**)	Less than one day	Under one day - assuming calcareous grassland comprises one of the listed *NVC* types, which are typical of freely-drained situations (even summer-arid).	Although not likely to occur in any site prone to regular or frequent flooding, this habitat would probably tolerate a total of 10 days through the winter, with no flood event lasting more than two days.	Negative under all circumstances.	0.5 to 0.2
Lowland dry acid grassland (*NVC* types **U1-U4**)	Probably as lowland calcareous grassland with U4 being slightly more tolerant than U1-3.	Probably as lowland calcareous grassland with U4 being slightly more tolerant than U1-3.	Probably as lowland calcareous grassland with U4 being slightly more tolerant than U1-3.	Negative under all circumstances.	0.5 to 0.2
Lowland meadows (*NVC* types **MG4-5, MG8-9** and **MG11-13**)	From Gowing (2004) over18 days likely to be damaging (seven days in any one event) and 30 days (12 days per event) will destroy **MG4** meadows. **MG5** is less tolerant than this, but data are limited, so quantification not available. **MG8-9** are more	Equivalent Gowing figures for **MG4** are nine days (three days per event) and 14 days (seven days per event) - see comments under spring for other communities.	Equivalent Gowing figures for **MG4** are 35 days (10 days per event) and 45 days (18 days per event) - see comments under spring for other communities.	Benefit from cation deposition and from moderate nitrogen and phosphorus additions, but damaging if loading is high or frequent.	0.5

BAP priority habitat	Tolerated (fluvial) flood duration			Impact of nutrient-rich sediment input	Inundation band with greatest concentration of each habitat
	Spring (mid March-May)	**Summer (June-October)**	**Winter (November - mid-March)**		
	tolerant than **MG4** and **MG11-13** more so.				
Lowland raised bog (*NVC* **M20**)	As blanket bog	As blanket bog	As blanket bog	Negative under all circumstances	0.5
Purple moorgrass and rush pastures (*NVC* types **MG10** and **M22-26**)	MG24 can only tolerate brief episodes (under three days), whilst other types may tolerate slightly longer flood events.	MG24 can only tolerate brief episodes (under three days), whilst other types may tolerate slightly longer summer flooding.	MG24 may tolerate a few days flooding, whilst other types (especially MG10 and rush pastures) could tolerate up to 40 days winter flooding.	Some benefit from cation deposition and some limited tolerance of nitrogen and phosphorus addition where managed for hay (especially MG10), but diversity will fall if substantial nitrogen and phosphorus are added in sediment.	0.5 to 0.2
Upland calcareous grassland (*NVC* communities **CG9-CG14**)	Probably as lowland calcareous grassland.	Probably as lowland calcareous grassland.	Probably as lowland calcareous grassland.	Negative under all circumstances.	0.5 to 0.02
Upland hay meadow (*NVC* communities **MG2-MG3**)	Most such meadows occur on sloping sites, with little likelihood of flooding. Tolerance might be up to two days.	See spring - probable maximum duration one day or less.	See spring - probable maximum duration up to five days.	Benefit from cation deposition and from moderate nitrogen and phosphorus additions, but damaging if loading is high or frequent.	0.05
Wet woodland (*NVC* communities **W1-W7**)	Very variable from floodplain situation to gallery woodlands along streams (possibly influence by springlines) - see Barsoum *et al*. (2005). Suggest maximum of 10 days in **W5**, other types less.	Under five days.	Possibly up to 30 days, but not all as one event - standing water in winter and late spring frequent, but normally patchy.	Neutral at moderate levels – with benefits to understorey of cation deposition but nitrogen and phosphorus deposition likely to reduce diversity.	0.05 to 0.02
Deciduous broadleaved woodland (*NVC* communities **W8-W12** and **W14-W17**)	Two to three days maximum.	Under one day.	Absolute maximum of five days, otherwise transition to wet woodland.	Ground flora likely to be damaged by anything more than minor deposition.	0.2

BAP priority habitat	Tolerated (fluvial) flood duration			Impact of nutrient-rich sediment input	Inundation band with greatest concentration of each habitat
	Spring (mid March-May)	**Summer (June-October)**	**Winter (November - mid-March)**		
Fens and reedbeds (*NVC* **S4** and **S24-S25**, but "fen" may include a wider range of types)	For reedbeds see Mountford (2004) - indicating that such habitats can have (continuous) surface water throughout year. Tall-herb fen (*fide* Wheeler & Shaw 2004) have well below five days surface water in spring.	See spring for reedbed - tall-herb fen normally has no surface water in summer, will tolerate up to five days exceptionally.	See spring for reedbed - for tall herb fen, prolonged inundation tolerated (30 days or more).	Benefit from cation deposition and tolerant of some nitrogen and phosphorus addition where reed is cut, but diversity in fen communities will fall where substantial nitrogen and phosphorus are delivered in sediment.	0.5 to 0.1
Lowland heathland (wet heaths *NVC* types **H3-H5** and **M14-16** and **M21;** dry heaths H1, H2 and **H6-H11**)	For dry heath as acid grassland - for wet heath (see Mountford *et al.* 2005) possibly up to two or three days, with no event above one day.	See spring for dry heath - wet heath up to one day.	See spring for dry heath - wet heath may be up to three to five days, with no event above two days.	Negative under all circumstances.	0.5 to 0.2
Upland heathland (*NVC* types **H12-H22**)	As with other upland habitats - hardly likely to undergo any flooding, and probably tolerant of no more than one day inundation.	As spring.	As spring.	Negative under all circumstances.	0.2

Table 2.8 Summarised thresholds for impact of floods on priority BAP habitats

Pressure	Impact on habitat	Reference for impact	Metric
1. Flooding of habitats within thresholds of inundation probability	Benefit to all	Empirically defined (Table 2.7)	Area and percentage of each priority habitat flooded within empirically defined inundation probability thresholds
2. Flooding of habitats within thresholds of tolerated duration	Benefit to all	Expert judgement and literature (Table 2.7)	Area and percentage of priority habitats inundated within their season specific tolerated duration
3. Flooding of habitats with water containing a high load of agriculturally derived nutrient-rich sediment	Disbenefit for most but some benefits for some habitats: See Table 5.3.	Expert judgement and literature (Table 2.7)	Area and percentage of each habitat flooded where catchment is classed as having high agricultural soil erosion potential?
4. Winter flooding	Benefit to wet woodland (good for dispersing vegetative fragments and depositing them in wet conditions where they are less likely to dry out)	Expert judgement	Total area of winter (October to March) flood?
5. Spring/early summer flooding	Benefit to wet woodland (good for dispersing seeds e.g. willow)	Expert judgement	Total area of spring early summer (March – June) flood?
6. Summer flooding – second half of growing season (July to September)	Disbenefit to wet woodland (may destroy seedlings)	Hughes (2003)	Total area of summer flood (July to September)?
7. Summer flooding (May to September)	Disbenefit to woodland (increased chance of waterlogged ground and treefall)	Expert judegement	Area and percentage of woodland flooded in summer (May to September)
8. Extreme floods	Benefit to wet woodland (good for creating regeneration sites)	Hughes (2003)	Total area of flooding with <0.2 probability of inundation
9. Short duration flooding	Disbenefit to wet woodland (deposits seeds and vegetative fragments and as waters quickly recede they dry out before they can establish themselves)	Hughes (2003)	Total area flooded by short duration event (under one day)
10. April/May flooding	Disbenefit to grassland (reduces species diversity)	Gowing *et al.* (1997, 2002); Mountford (2003)	Area and percentage of grassland flooded in April/May

11.Area flooded	Area potentially exposed to alien plant species	Total area flooded

Thresholds for fish

The impact of flooding on the eight fish types (Table 2.4) was assessed using a combination of empirical analysis, knowledge from the literature and expert opinion.

Assessing association of fish types with extents of floodplain (0.2 probability of inundation)

An empirical assessment was undertaken of the relation between the extent of inundation at a site and the fish types present. The extent of inundation was quantified as the area with a 0.2 probability of inundation within a 500-m radius circle around each fish site as a percentage of the total area of the circle (Table 2.9). The empirical analysis shows that some fish types are associated with sites with greater extents of flooding than others. For example, Type 7 is associated with sites with more extensive inundation than Types 1, 2, 3, 4, 5 and 8. This result is plausible given that Type 7 is typical of large lowland rivers where good connectivity with floodplains is a common feature. Furthermore, Type 4 is associated with sites with very small extents of floodplain. This is plausible as it is a trout-dominated community that is usually found in upland areas with little floodplain.

The suitability of any site with new inundation probability data could be assessed by comparing results with these data. If the inundation extents are within the 25th and 75th percentile the habitat may be considered suitable. If the extent is outside the 25th to 75th percentile range but within the observed range of values, a warning could be given that this site may be close to the limits of suitability for this fish type. If the extent is beyond the observed range of values, it is possible that the site is unsuitable for a given fish type. Further investigation would be needed to assess whether suitable sites exist in close proximity.

Assessing whether the floodplain is narrow

It is likely that fish sites with narrower floodplains are more impacted by extreme events as refuge will be limited. A narrow floodplain is defined here as a site where the 0.2 probability of inundation accounts for less than seven per cent of the total area of a 500-m radius circle draw around a fish site. A straight river through the centre of a 500-m circle with a 25-m floodplain either side of the channel gives a percentage of 6.4.

Table 2.9 Percentiles of areas with 0.2 probability of inundation within a 500-m radius circle around each fish site as a percentage of the total area of the circle

Fish Type (1-8) and name	Per cent area of 0.2 probability of inundation within a 500-m radius circle around each fish site	
	25th to 75th percentile	Observed Range
1 Salmon/Trout	0.00 - 14.38	0.00 - 87.74
2 Trout/Salmon	0.00 - 10.40	0.00 - 80.45
3 Trout/Cyprinid	0.00 -13.83	0.00 - 58.45
4 Trout	0.00 - 6.68	0.00 - 53.94
5 Rheophilic cyprinid	0.00 - 21.76	0.00 - 92.21
6 Eurytopic a	0.00 - 37.57	0.00 - 93.55
7 Eurytopic b	24.58 - 63.13	0.00 - 88.64
8 Chalk rivers	0.00 - 4.31	0.00 - 68.78

Based on the above empirical assessment, knowledge collated through the literature review and the flooding impact indicator report (see Appendix C), rules for specific fish types were identified. These rules are assessed using the criteria in Table 2.10.

Table 2.10 Summarised thresholds for impact of floods on fish

Flood characteristic	Pressure	Impact on fish	Reference	Metric
Timing	Flooding between July and September	Some benefit to Types 5, 6 and 7 for spawning/feeding.	Bischoff and Wolter 2001, Clark 1950, Kwak 1998, Masse *et al.* 1991	Fish sites flooded (July to September)
		Disbenefit to Types 1 to 8 (bad – especially for juveniles). Could cause displacement if channelised (check extent of channel modification) or loss of fish over flood banks.	Bradford 1997, Bradford *et al.* 1995, Nunn *et al.* 2003	
	Flooding between August and October	Benefit to Types 1,2,3,4 and 8 (support pre-spawning movements and preparation of substrates for spawning).	Cowx et al. 2004, Crisp 2000, Hendry *et al*. 2003, Lucas and Baras 2001, Sambrook and Cowx 2000	Fish sites flooded (August to October)
	Flooding between October and March	Benefit to Types 5, 6 and 7. (access to overwinter habitat).	Garner 1997, Masters *et al.* 2002	Fish sites flooded (October to March)
		Disbenefit for Types 1 to 4 (peak floods during incubation period could wash out from gravels, but this may be considered a natural event).	Carline and McCullough 2003, Elwood and Waters 1969, Lapointe *et al.* 2000, Phillips *et al.* 1975, Seegrist and Gard 1972	
	Flooding between March and June	Benefit to Types 1-8 (access to floodplain and migration).	Bischoff and Wolter 2001, Clark 1950, Cowx *et al.* 2004, Crisp 2000, Hendry *et al.* 2003, Kwak 1998, Lucas and Baras 2001, Masse *et al.* 1991, Sambrook and Cowx 2000	Fish sites flooded (March to June)
		Disbenefit for Type 2 (spring floods may be bad for fish - especially the young. Could cause gravel washout or displacement if channelised).	Carline and McCullough 2003, Elwood and Waters 1969, Lapointe *et al.* 2000, Phillips *et al.* 1975, Seegrist and Gard 1972	
Magnitude	Extreme event	Benefit (may increase species diversity).	Bischoff and Wolter 2001	Sites flooded with probability of inundation <0.2.
Duration	Flooding of less than a day	Disbenefit		Sites flooded for under one day
Nature of catchment/site	Extent of 0.2 probability flooding within a 500-m radius of the site	Benefit: Suitable site	Empirically derived (see also: Amoros and Bornette 2002, Junk *et al.* 1989, Poff *et al.* 1997, Ward and Stanford 1995a and b, Welcomme and Halls 2001)	Extent of 0.2 probability flooding is between 25th - 75th percentile of empirically observed range.
		Possible disbenefit: may be close to limits of suitability		Extent of 0.2 probability flooding is within empirically observed range.
		Probable disbenefit: may be unsuitable		Extent of 0.2 probability flooding is outside empirically

Flood characteristic	Pressure	Impact on fish	Reference	Metric
				observed range.
	Large flood (<0.2 prob. of inundation) at site with narrow floodplains	Disbenefit (fish at sites with narrow floodplains may be impacted by extreme events).	Empirically derived	Number and per cent of fish sites flooded with narrow floodplains. Narrow floodplains: Area of 0.2 inundation probability as percentage of total area of a 500-m radius circle around the fish observation site. Narrow floodplains are defined as those with an area below seven per cent.
	Large flood (<0.2 probability of inundation) in a highly modified river	Disbenefit (risk to fish of high velocities and limited refuge if channel is modified).	Baras and Lucas 2001, Grift *et al.* 2003	If flooded by large event: (<0.2 probability of inundation) calculate length and per cent of river channel that is highly modified. Must report length and per cent surveyed.
	Flooding with water containing a high load of agriculturally derived nutrient-rich sediment	Disbenefit for Types 1-8 (deposition of fine sediment may reduce spawning and feeding success and lead to eutrophication and low dissolved oxygen – fish kills in extreme cases).	Phillips *et al.* 1975	Is catchment classed as having high agricultural soil erosion potential?

Thresholds for macrophytes

Based on the knowledge collated through the detailed literature review and additional contributions from CEH experts, general rules were produced for impacts of floods on macrophytes. These rules are assessed using the criteria in Table 2.11. The impacts of floods on macrophytes are often short term and/or marginal. During high flows they are often washed flat and are minimally impacted. Where flood flows remove macrophytes there is a short-term loss but root structures and marginal stands will often remain to enable regrowth. Furthermore, broken fragments carried by flood water may then aid dispersal. Indeed, the impact of macrophytes on floods is often a greater concern.

Table 2.11 Thresholds for impact of floods on macrophytes

Pressure	Impact on macrophytes	Reference	Metric
Flooding between October and February	Benefit (clean macrophytes of old growth and remove algae and floating weed)	Expert judgement	Is flood between October and February?
Flooding with water containing a high load of agriculturally derived nutrient-rich sediment	Disbenefit (sediment deposition on submerged and marginal vegetation can lead to extinction or changes in community structure. Turbid water may reduce photosynthesis. Nutrient inputs can lead to eutrophication. Enhanced epythitic growth damages macrophytes).	Mountford, 2008	Is catchment classed as having high agricultural soil erosion potential?
Large flood (annual inundation probability of <0.2) between March and September	Disbenefit (large summer floods may remove reproductive structures of plants and seeds as well as erode sediment structures and marginal habitats).	Scientific literature (e.g. Riis and Biggs, 2003; Madsen *et al.* 2001)	Is large flood between March and September (annual probability of inundation <0.2)?
Large flood (<0.2 annual inundation probability) of modified river channel between March and September	Disbenefit (extreme velocities in modified channels bad for macrophytes).		Length and percentage of river that is highly modified and flooded by large event (annual probability of inundation <0.2) between March and September. Must report length and percentage of river surveyed.

Based on the knowledge collated through the detailed literature review and additional contributions from experts general rules were produced for impacts of floods on invertebrates. These rules are assessed using the criteria in Table 2.12

Table 2.12 Thresholds for impact of floods on invertebrates

Pressure	Impact on invertebrates	Reference	Metric
Flooding with water containing a high load of agriculturally derived nutrient-rich sediment	Disbenefit (deposition of fine sediment can alter invertebrate assemblages. May also increase drift).	Armitage and Ladle (1991)	Proportion of agricultural land with high erosion in catchment relative to average for England & Wales. Classed as high if above 61 per cent.
Large flood (<0.2 annual inundation probability)	Disbenefit (loss of invertebrate food source; species with greater tolerance for high flows will thrive and other may decline. Rapid flow changes are bad. Downstream migration of invertebrates may be a problem in headwaters).	Cortes *et al.* (2002), Fleituch (2003), Rempel *et al.* (1999)	Is it a large flood (annual probability of inundation <0.2)?
Large flood (<0.2 annual inundation probability) in a highly modified river channel	Disbenefit (enhanced loss of invertebrate food source; species with greater tolerance for high flows will thrive and other may decline. Rapid flow changes are bad. Downstream migration of invertebrates may be a problem in headwaters. Refugia are limited.).	Cortes *et al.* (2002), Fleituch (2003), Rempel *et al.* (1999)	Length and percentage of highly modified river flooded (<0.2 annual probability of inundation). Must report total length and percentage of river channel surveyed.

Bird thresholds

Thresholds were defined for wetland birds (waders and waterfowl) using knowledge published in the scientific literature. This information was used to define key indicators of the impacts of flooding (summarised in Appendix D). The indicators were used to define the thresholds presented in Table 2.14. To assess the impacts of flooding using these rules, the habitats on which the birds depend must first be identified. A list of bird-favourable habitats is presented below:

- arable land
- blanket bog
- coastal and floodplain grazing marsh

- lowland calcareous grassland
- lowland dry acid grassland
- lowland meadows
- lowland raised bog
- purple moorgrass and rush pastures
- upland calcareous grassland
- upland hay meadow
- fens and reedbeds
- lowland heathland
- upland heathland

Table 2.13 Thresholds for impact of floods on wetland birds

Pressure	Impact on birds	Reference	Metric
Flooding of 0-50 cm depth for under 10 days in winter	Benefit (waterfowl are attracted to standing water and can feed in water depths up to 50 cm. High water tables adjacent to flooded areas force invertebrates closer to the soil surface and increase the penetrability of the soil to wading birds)	Literature review (e.g. Thomas, 1982 and Green, 1986)	Area of bird-favourable habitat with flooding depth 0-50 cm in winter. Flooded for less than 10 days.
Flooding of over 50 cm depth for over 10 days in winter	Disbenefit (loss of suitable feeding habitat)	Literature review (e.g. Thomas, 1976)	Area of bird-favourable habitat with flooding over 50 cm deep in winter for a duration of over10 days.
Area of grassland flooded in winter	Benefit (species of conservation concern)	Scientific literature (Ausden and Hirons, 2002)	
Flooding in late winter up to end of March.	Benefit (good for bird feeding when water table is high (20-30 cm below ground) in spring and early summer)		Area of bird-favourable habitat flooded in late winter to March.
Flooding (over 25 cm depth) in spring (1 April to 30 June)	Disbenefit (destroys nests)	Expert opinion and scientific literature (Appendix G)	Area of bird-favourable area flooded (over depth) in spring (1 April to 30 June).
Summer flooding under 30 cm	Benefit (dabbling ducks feed in water depths of less than 30 cm. Other birds can fly to dry sites)	Literature review (e.g. Thomas, 1981)	Area of summer flooding under 30 cm in bird-favourable areas.
Prolonged flooding any time of year	Disbenefit: Reduction of food source in soil	Literature review (Ausden *et al.* 2001)	Flooding for >10 days in bird-favourable areas.

3 Development of the Ecological Impact Assessment Coastal Tool (EIA C Tool)

3.1 Scope of the EIA C Tool

The literature review undertaken at the start of this project identified various tools and information relevant to the assessment of the ecological impact of inundation of the coastal zone by the sea. Thus, although gaps in data coverage and resolution were found, it was deemed feasible to integrate the available information within a Geographical Information System (GIS) format, to assess, model and map the ecological impact of progressive inundation by the sea on biodiversity in the coastal zone (the area currently subject to tidal inundation together with that area immediately landward of the current tidal zone on unconstrained coasts that is inundated under future tidal levels). Subsequent to this project being commissioned, another study was initiated by the Department for Environment, Food and Rural Affairs (Defra) and Natural England (CR0422) to investigate the consequences of tidal flooding of terrestrial (especially freshwater) habitats behind sea defence works and landward of the tidal zone on unconstrained coastlines. The two projects are complementary and, jointly, encompass the entirety of the coastal zone.

3.2 Habitat type as the level of resolution

In essence, our approach presents the baseline situation, for each site, in terms of current location of the various coastal habitat types and tidal levels in a GIS. The area of interest is the current (and future) inter-tidal zone, that is, the area subject to tidal inundation by the sea. The particular aspect of the environment addressed is the vegetation and associated animal communities (biodiversity) of this zone as defined by the various habitat types present. The selection of habitat type as the appropriate level of ecological resolution was made in recognition of the fact that the current policy framework focuses heavily on habitats and that, given existing knowledge and understanding, adequate evaluation of species-specific impacts in the coastal zone on a broad scale is not feasible at present. The assumption made in this selection was essentially the one implicit in the Habitats Directive, that by ensuring that the condition of coastal habitats is maintained in, or restored to, favourable condition the characteristic communities of plants and animals associated with those habitats will be conserved. This is consistent with the approach adopted in the Broad-Scale Ecosystem Assessment (BSEA) approach (Conlan *et al*., 2006).

3.3 General indicators of habitat quality employed

Clearly, locating the position of the various habitat types in a GIS fulfilled the mapping requirement of this study. The modelling requirement was, in the first instance, addressed by applying generally accepted predicative scenarios for sea level rise and subsequent shoreline migration (Defra, 2006) to the baseline situation for each site at two example points in the future (2025 and 2050). In order to assess the impact(s) of inundation under these different scenarios, it was necessary to derive general indicators of habitat quality that could be readily quantified from mapped data

The total area and surface elevation of the coastal habitats relative to the local tidal frame were employed in this regard. The basic concept underpinning this approach is illustrated by reference to saltmarsh. The relationship between saltmarsh community structure and available tidal levels is sufficiently well established to divide British saltmarsh into two broad zones based on tidal height; low-middle saltmarsh and high (or upper) saltmarsh. Low-middle zone saltmarsh generally occurs between mean high water neap (MHWN) tide and mean high water spring (MHWS) while high zone saltmarsh is typically found above this level. Each zone is characterised by a particular vegetation type and the most biologically diverse saltmarsh communities are those which have low, middle and high marsh zones.

Given information on the local tidal range and the surface elevation profile of a saltmarsh, frequency distributions can be constructed of those areas of the saltmarsh that fall within defined surface elevation bands relative to the local tidal range. For any given saltmarsh, such actual frequency distributions can then be compared to optimal distributions of the characteristic saltmarsh community types (as defined, for example, by reference to a comparable marsh recognised as exhibiting favourable conservation status) to obtain an indication of the quality of the saltmarsh being studied in terms of its dynamic state (eroding, accreting or stable) and the diversity of its vegetation community structure. The likely pattern of saltmarsh habitat development at sites created by man through coastal realignment could also be investigated using this technique.

3.4 Habitat types considered in the development of the EIA C Tool

Other BAP priority coastal habitats such as mudflats, vegetated shingle, sand dunes and saline lagoons can also be usefully assessed in relation to surface elevations and tidal levels (see Table 2.1). Saline lagoons are atypical in that they are transient features which eventually fill in. They may be natural or manmade, but there are not many in England and Wales. Each one is unique, however, and the impact of inundation by the sea would need to be assessed with this in mind.

Maritime cliff and slope habitats are located well above and outside the inter-tidal zone and coastal and floodplain grazing marsh habitats are usually found behind sea defences above the MHWS tide level. Consequently, these habitats are not considered here although some grazing marsh might be included within the general saltmarsh category that is applied.

The various habitat types considered during the development of the coastal tool are presented in Table 3.1

Table 3.1 Locations of various inter-tidal and coastal shoreline habitats in relation to tidal frame (based on expert judgement and values derived from scientific literature such as Carter, 1988; Packham and Willis, 1997)

Inter-tidal/shoreline habitat type	Typical location in relation to tidal frame
Sand dunes	Above MHWS
Vegetated shingle	Above MHWS
Saline lagoons	Mostly as above, but some may lie within the inter-tidal zone.
Saltmarsh: Low (pioneer) - Mid zone saltmarsh – can include grazing marsh High zone (upper) saltmarsh – can include grazing marsh	 Between MHWN and MHWS Above MHWS
Mudflats	In areas sufficiently sheltered for saltmarsh to develop, mudflats will typically occur below the level of low marsh (MHWN). Elsewhere, sedimentary substrate may occupy the entire inter-tidal area with the particle size of material becoming coarser as the degree of exposure increases.

Progressive inundation of freshwater habitats by a rising MHWS tidal level may be assumed to be detrimental in all cases. Saline flooding of habitats above MHWS is dealt with in the related project CR0422.

4 Assessing ecological impacts of flooding/inundation using the scorecards

The prototype tools described in this report guide the user in making an objective and quantitative (where appropriate) assessment of the impacts of floods on the environment using Arc GIS 9.3 with its standard toolbox supplemented with Spatial Analyst. Step-by-step guidance in using the tools is available (Old *et al*., 2011) but the tools should only be used by qualified individuals (it may be necessary to contact the Environment Agency's National Environment Assessment Service for support in interpreting the results). The Environment Agency currently has licences to use the data required to run the tool (an important requirement raised at workshops). The assessments are made using spreadsheet-based scorecards. The sensitivities presented above (Chapters 2 and 3) for environmental impact assessment are captured on the SCORE and THRESHOLD tabs of the scorecard. The user must define the current flooding scenario on the SCENARIO tab and undertake a series of defined spatial data queries (listed on the SCORE DATA tab) before assessing impacts of flooding/inundation. The assessment may involve the impact of a new fluvial flood regime (EIA F Tool regime functionality), a specific fluvial flood event (EIA F Tool event functionality) or the impact of progressive relative sea level rise to a specified future date (EIA C Tool). When assessing the impact of relative sea level rise, it may be particularly useful to undertake assessments at a series of moments in time to enable the prioritisation of mitigation efforts. When using the scorecards, the user must specify the impact assessment criteria on the SCORE tab as these are likely to change with time and with the specific objectives of a given assessment (for example, what is an allowable loss of bird habitat?). The impacts of flooding are then evaluated using the SCORE tab by comparing the sensitivities of flooding to the flood characteristics (see OUTCOME cells).

5 Mapping the environmental impacts of flooding

At project workshops, the value of being able to generate maps of possible environmental impacts of flooding was emphasised. As the prototype tools are GIS-based, impacts can be presented using a wide range of user-defined maps. The GIS operations used to fulfil the data queries can be used to produce map outputs. Examples of possible maps are listed below.

- Priority broad habitats inundated.
    - Export a map of the catchment outline with habitats included and extent of inundation.
- Bird nesting areas inundated.
    - Export a map of the catchment outline with bird-favourable habitats included and extent of inundation.
- Priority broad habitats receiving inputs of nutrient-rich sediment.
    - If catchment has a high proportion of agricultural land with a high erosion risk export a map of the catchment outline, habitats and inundation extent.
- Extent of saltmarsh erosion at specified future dates.
    - Export a map of the coastal region being investigated with current and future saltmarsh extents mapped.

6 Fluvial pilot testing

6.1 Chosen pilot test regions and objectives of testing

Following consultation of the project team two pilot trial regions were chosen: 1) Upper Trent (NAFRA catchment 2804) and 2) Wye (NAFRA catchment 5502). The Upper Trent was selected as it includes a wide variety of habitats from relict flood meadows to a range of woodland types. The Wye catchment was selected as it has a diverse range of Welsh habitats from limestone woodland to mixed agricultural land, and broadleaved woodland to upland/moorland. Both catchments have populations of wading birds and are acceptable sites to assess impacts on fish.

The aims of pilot trials were to help calibrate/verify and assess the applicability of the proposed method.

The **applicability** of the method was assessed in two ways:

i. Assessing the environmental impact of a future hydrological situation defined by scenario-based NAFRA data.Given that future scenario-based NAFRA data were unavailable, we shifted the inundation probability by one class to simulate more frequent floods (polygons with probability classes <0.01, 0.01, 0.02, 0.05, 0.1, and 0.2 became 0.01, 0.02, 0.05, 0.1, 0.2, and 0.5, respectively; polygons with probability 0.5 remained 0.5).

ii. Assessing the environmental impact of a present day specific event (user-defined season, duration and extent). For this, the July 2007 flood events in both catchments were used with durations of one week.

Calibration/verification of the regime and event functionality of the prototype tool was undertaken through expert review of results from the applicability tests described above.

As the tool was developed using national data, it was decided to assess the correspondence of current environmental assets with baseline regime data.

Further verification is given by the assessment of results from the hypothetical regime shift and the estimated July event.

We did not have alternative input datasets to undertake a detailed uncertainty analysis. For instance, we had one NAFRA layer and a complex mix of habitat data collected over varying time periods. It would have been a huge task (far beyond the resources available for this work) to assess the impacts of uncertainty in each input variable on the final results in a rigorous way. If we had done this on a selected input variable such as NAFRA, the results would likely have been misleading. It was more appropriate for the project team to identify and discuss the areas where uncertainty should be acknowledged (see guidance report). This usefully highlighted areas that should be a priority for further research/data improvement. When the tool is used, our discussion of uncertainty could be used to define a detailed uncertainty analysis.

In Chapter 8 we explain how the outputs from our fluvial and coastal tools are closely aligned with MDSF2.

6.2 Applicability and calibration/verification of the EIA F tool

6.2.1 Assessing the ecological impact of a new hydrological regime (regime functionality of the tool)

To assess the applicability of the regime functionality of the tool (Chapter 4) baseline and future regime results were considered. Current environmental assets were assessed against current baseline hydrological conditions and the hypothetical regime in each test catchment. The results are summarised and discussed below.

Completing the scorecard

The SCENARIO, SCOREDATA REGIME CHANGE and SCOREDATA BASELINE tabs were successfully completed with data obtained from basic GIS analysis using standard tools. Data in the REGIME SCORE tab were automatically evaluated.

Summary report on baseline regime in the Upper Trent catchment

Upper Trent (NAFRA catchment 2804): baseline regime assessment

Approximately one per cent (1,797 ha) of the catchment is flooded with a >0.2 inundation probability.

The flood water in the catchment is estimated as having a low concentration of agriculturally derived nutrient rich sediment. Total proportion of agricultural sediment sources is 57 per cent.

Significant lengths of the surveyed river channel are highly modified.

All surveyed fish sites have narrow floodplains.

All fish type sites are within the 25th to 75th percentile range for the proportion of 0.2 inundation probability within a 500-m circle.

Large areas of BAP priority habitats are outside the empirically defined range of greatest concentration.

Summary report on baseline regime in the Wye catchment

Wye (NAFRA catchment 5502): baseline assessment

Approximately five per cent (10,119 ha) of the catchment is flooded with a >0.2 inundation probability.

The flood water in the catchment is estimated as having a high concentration of agriculturally derived nutrient rich sediment. Total proportion of agricultural sediment sources is 64 per cent.

Significant lengths of the surveyed river channel are highly modified.

Approximately 60 per cent of surveyed fish sites have narrow floodplains.

All but one fish type sites are within the 25th to 75th percentile range for the proportion of 0.2 inundation probability within a 500-m circle; the other is within the observed range.

Large areas of BAP priority habitats are outside the empirically defined range of greatest concentration.

Assessing the results of the baseline regime

The large areas of both catchments that are flooded with >0.2 inundation probability clearly illustrate good river channel floodplain connectivity.

The high concentration of sediment-associated agricultural nutrients in flood waters in the River Wye is confirmed by SSSI reports produced by the Countryside Council for Wales. Although the Upper Trent is classed as low in this respect, problems with sediment are acknowledged in Environment Agency CFMP reports. Our empirically defined median threshold value to differentiate between likely high and low concentrations may be too simplistic. There is only a seven per cent difference in proportions of agricultural sediment sources in the Wye and Upper Trent catchments but they are classed as having high and low proportions of agricultural sediment sources, respectively. A continuous index from low to high likely sediment-associated nutrient input may be more appropriate. As a check on the utility of the current measure of likely impacts of nutrient inputs via sediment, use could be made of maps prepared for FEPs (Farm Environment Plans) and the extent of feature N01 (land at risk of generating diffuse pollution) within a catchment or water-management area.

The impact is higher than expected in the Upper Trent. The reason for this may be the extent of anthropogenic changes along this river that have disrupted natural geomorphological processes and exacerbated sediment transport (especially in areas where gravel extraction and mining have taken place). Furthermore, significant amounts of sediment enter the Upper Trent from steep tributary channels and are deposited in low gradient reaches. Our assessment of low and high sediment concentrations is not sensitive to such local affects. A more accurate estimate of sediment impact might have been possible if data from McHugh *et al.* (2002) had been available to the project.

It is reasonable to conclude that significant lengths of both rivers are heavily modified. In this context, the CFMP for the Upper Trent emphasises the many anthropomorphic changes to the river.

Fish types in both catchments are all within the empirically defined percentile ranges with one exception that was still within the range of observed data.

The large areas of priority BAP habitats lying outside the empirically defined areas of greatest habitat concentration were expected. This reflects the fact that all habitats are found in all inundation probability bands and the areas inundated with specific probabilities are often small. A given inundation probability area may have a high concentration of a habitat, but because of its limited areal extent, it may only account for a small proportion of the total habitat area in the catchment. Furthermore, NAFRA data may be too coarse to capture hydrological conditions produced by microtopography that may support vegetation.

Summary report on scenario-based future regime in the Upper Trent catchment

Upper Trent

NAFRA Catchment 2804

Pilot test of the fluvial tool

A future scenario was defined by shifting NAFRA inundation probability bands one class. For example, the 0.1 probability class becomes the 0.2 probability class. This can be assumed to reflect an extreme climate change scenario.

River-floodplain ecosystem impact
Under the scenario the increased area (+1,600 ha) of river-floodplain connectivity (with a >0.2 inundation probability) is beneficial.

Priority BAP habitats
Increased flood frequencies appear to be beneficial to affected priority BAP habitats within this catchment.

No reductions in areal extents of habitats within areas of ‘greater than expected likelihood’ were observed. Furthermore, small increases in proportions (up to one per cent) of deciduous woodland (+40.7 ha), fens and reed beds (+4.9 ha), lowland heathland (+4.3 ha), and wet woodland (+17.7 ha) in areas of ‘greater than expected likelihood’ were observed.

Possible impacts from high inputs of sediment-associated nutrient are low in this catchment.

In-stream ecology
Four fish types have been observed in this catchment and under the future scenario all fish type sites (n=19) have 0.2 probability floodplain extents within their empirically defined 25th to 75th percentiles.

However, fish may be adversely affected by the new hydrological regime as all sites have narrow floodplains and almost half of the surveyed length of the channel is highly modified (NOTE: the surveyed reach constitutes only 1.7 per cent of the Upper Trent).

The wide extent of highly modified channels in this catchment may result in negative impacts on macrophytes and invertebrates.

Possible impacts from high inputs of sediment-associated nutrient are low in this catchment.

Wye

NAFRA Catchment 5502

Pilot test of the fluvial tool

A future scenario was defined by shifting NAFRA inundation probability bands one class. For example, the 0.1 probability class becomes the 0.2 probability class.

River-floodplain ecosystem impact
Under the scenario the larger area (+2,179 ha) of river-floodplain connectivity (with a >0.2 inundation probability) is beneficial.

Priority BAP habitats
Small gains and losses in proportions (under five per cent) of priority BAP habitats within areas of 'greater than expected likelihood' were observed.

Small gains occurred in extents of fens and reed beds (+8.7ha), lowland heathland (+14.8ha), purple moorgrass and rush pastures (+52.5ha), and upland calcareous grassland (+2.6ha). Small losses occurred in extents of blanket bogs (-7.3ha), deciduous broadleaved woodland (-1852ha), upland heathland (-43.6ha) and wet woodland (-2.6ha).

Possible high sediment-associated nutrient inputs may result in negative impacts in all priority BAP habitats (note: some benefits may result from cation deposition).

In-stream ecology
Four fish types have been observed in this catchment and under the tested scenario all fish type sites (n=37) have 0.2 probability floodplain extents within their empirically defined 25th to 75th percentiles. This is an improvement on the baseline situation where one Type 2 site was outside the empirically defined percentile range although within the observed range.

However, fish may be adversely affected by the new hydrological regime as almost 60 per cent of sites have narrow floodplains and one-third of the surveyed channel is highly modified (NOTE: only 1.2 per cent of the overall length of the river has been surveyed).

The extent of highly modified channels in this catchment may result in negative impacts on macrophytes and invertebrates.

Fish, macrophytes and invertebrates may be affected by high inputs of sediment-associated nutrients.

Assessing the results of the scenario-based regime

An increase in flooded area was expected and the tool clearly illustrates the increased extent of river floodplain connectivity under the new regime.

Reasonable changes in the areas of priority BAP habitats within the empirically defined thresholds are identified in each catchment. Increases in areas of many priority BAP habitats under the new regime are likely to be due to the total area flooded, with given probabilities changing as the NAFRA data are shifted. Equally, increases may reflect concentrations of habitats outside the empirically defined inundation band that are counted as data are shifted. This may represent a real benefit to those habitats.

In the Wye catchment the small losses that occurred in the areas of blanket bogs, deciduous broadleaved woodland and upland heathland may be explained by their concentrations in the riparian corridor (area of 0.2 inundation probability) becoming too frequently inundated (probability of 0.5).

Under the new regime all observed fish types are within the empirically defined 25th to 75th percentile range for the extent of their 0.2 probability of inundation floodplain. In the Wye catchment this is a slight improvement from the baseline condition.

However, as sections of the channels in both catchments are narrow and heavily modified, the hydrological, sediment and morphologic impacts of the new flood regime are likely to generate negative consequences for fish, invertebrates and macrophytes.

Flood waters in the River Wye are likely to have high sediment and nutrient loads, leading to negative impacts on all priority BAP habitats, fish and macrophytes in the catchment. Although sediment and nutrient concentrations in the Upper Trent are currently classed as low, similar impacts may exist for the same reasons.

6.2.2 Assessing the event functionality

Ideally, the event functionality of the tool would have been verified by making detailed field observations of the impacts of a series of different flood events. However, field observations were beyond the scope of this project. Hence, the event functionality of the tool was verified for each catchment by assessing the results of the impacts of the July 2007 floods.

To estimate the annual probability of the July 2007 flood in both catchments, a Generalised Logistic (GLO) distribution was fitted to the at-site series of annual maximum peak flow as made available by the Environment Agency through the HiFlows-UK dataset. Estimates were made in both catchments using data from the most downstream gauging stations (Station 28019 Trent at Drakelow Park and 55023 Wye at Redbrook).

Trent at Drakelow Park (Station 28019)

On the Trent, the summer 2007 flood was the largest event recorded in Water Year 2006/2007 (October 2006 – September 2007). The largest flood on record (at this station) is 384.95 m^3s^{-1} recorded 7 November 2000. On 22 July 2007: Qpeak = 310.98 m^3s^{-1}. Using the 47 years of data available in HiFlows-UK, the return period of the 2007 summer flood is around 35 years. This return period was rounded up to the NAFRA inundation probability band of 0.02.

Wye at Redbrook (Station 55023)

In contrast, the July, 2007 flood was not the largest event recorded in the River Wye during Water Year 2006/2007. On the 23 July 2007, a peak flow of 618.5 m^3s^{-1} was recorded, but this was surpassed by a flood peak of 702.1 m^3s^{-1} recorded on the 6 March 2007. The highest flood recorded at this gauging station occurred on 3 February 2002, when 904.4 m^3s^{-1} was recorded. Using the 38 years of data available in HiFlows-UK, the return period of the 2007 summer flood (Qpeak = 618.5 m^3s^{-1}) is around three years. This return period was rounded up to the NAFRA inundation probability band of 0.2.

Duration

The inundation duration in both catchments was assumed to be seven days.

Completing the scorecard

The SCENARIO and EVENTSCORE DATA tabs were successfully completed with data obtained from basic GIS analysis using standard tools. Data in the EVENTSCORE tab were automatically evaluated with some requirement for the user to consult thresholds on the THRESHOLD tab.

Summary report on results of the July 2007 flood event in the Upper Trent catchment

Event assessment: Upper Trent

NAFRA catchment 2804

Event: July 2007

Duration: seven days

Event probability

This flood was an extreme event in the Upper Trent catchment. The seasonally adjusted inundation probability for this summer event is 0.001 (one in 1,000 years), rounded up to the nearest NAFRA probability band to enable assessment. Negative impacts on many aspects of the environment from rare flood events are natural and should not be mitigated. Whether or not the impacts are an issue will depend on whether the return period of the event being investigated remains constant or whether it is changing. Most environmental assets gain longer term benefit from extreme events that inevitably have short-term adverse impacts.

River floodplain ecosystem

A large area of floodplain was inundated (18,291 ha; 5.9 per cent of the catchment). In general there are many benefits associated with extensive areas of river floodplain connectivity. However, this is a simplistic assessment and there are likely to be many other impacts that will depend on the timing and duration of the event. These are considered below.

As almost half of the surveyed river channel is heavily modified (although only 1.7 per cent of the overall length of the channel was surveyed, sample reaches were selected to be representative of the river as a whole) it is likely to be geomorphologically unnatural, to exhibit adverse sediment and morphological responses to large floods and to provide a low range of predominantly poor ecological habitats. Given the available data this is a reasonable conclusion because although only a small amount of the river has been surveyed the sites are selected to be representative. Confidence in this conclusion would increase with the length of surveyed river.

Priority BAP habitats

A worst case habitat assessment is made on the EVENTSCORE tab of the scorecard as the most sensitive component community threshold within each habitat is used. A more detailed understanding of the impact of a given flood duration on specific component of a habitat may be gained by consulting the information given in the threshold table (the last tab of the scorecard).

Season-specific flood duration thresholds were exceeded for areas of the following priority BAP habitats: deciduous and broadleaved woodland (216.9 ha; 3%), fens and reedbeds (110.2 ha; 22%), lowland heathland (21.4 ha; 1%), lowland meadows (16.6 ha; 3%), purple moorgrass and rush pasture (1.2 ha; 2%), and wet woodland (22.1 ha; 1%).

It is significant that almost a quarter of the fen and reed bed habitat in this catchment is flooded for longer than its tolerable, seasonal duration.

Event assessment: Upper Trent – (continued)

As this is an extreme event it is beneficial to wet woodland in that it may produce regeneration sites. However, this habitat may be adversely affected because this event was a summer flood that occurred in the second half of the growing season, meaning that seedlings may be destroyed.

Treefall may be a problem as the flood will result in waterlogged ground at a time when trees are in leaf.

Impacts from high inputs of sediment-associated nutrient are likely to be low in this catchment.

The large flooded area means that there is potential for widespread colonisation by alien species.

In-stream ecology

Fish
This event may be bad for all four observed fish types (Types 2,4,5 and 6). High summer floods can cause displacement of fish downstream and over flood banks – especially a problem for fry and juvenile fish. Risks to fish are likely to be amplified given that almost half of the surveyed channel is heavily modified and all 19 fish type-sites have narrow floodplains. Given the available data this is a reasonable conclusion because although only a small amount of the river has been surveyed the sites are selected to be representative. Confidence in this conclusion would increase with the length of surveyed river.

The event is likely to be of some benefit to the spawning success of Types 5 & 6.

Furthermore, as it is a large flood it may increase species diversity.

The risk of the river experiencing high levels of siltation and/or eutrophication from this event is low.

Invertebrates
Large events can remove food sources and change species composition. The heavily modified condition of almost half of the surveyed channel is likely to exacerbate the adverse impacts of this flood on invertebrates.

Macrophytes
Large flood events may rip out in-stream vegetation and the likelihood of this happening is increased by the heavily modified condition of nearly half the length of the surveyed channel. There is, however, a low risk of negative impacts on plant growth or eutrophication due to the inputs of nutrient-rich sediment in this catchment.

Wetland birds
Approximately one per cent of the bird-favourable area is flooded to a depth of less than 30 cm, which suits dabbling ducks. No negative impacts on wetland birds are identified.

Event assessment: Wye

NAFRA catchment 5502

Event: July 2007

Duration: seven days

Event probability
This flood was large for a summer event in the Wye catchment. Its three-year annual return period was approximated to the 0.2 annual NAFRA probability. The probability was adjusted for season by multiplying by the summer factor of 0.065. The seasonally adjusted inundation probability for this event is 0.01 (one in 100 years), rounded up to the nearest NAFRA probability band to enable assessment. Negative impacts on many aspects of the environment from rare flood events are natural and should not be mitigated. Whether or not the impacts are an issue will depend on whether the return period of the event being investigated remains constant or whether this is changing. Most environmental assets gain longer term benefit from extreme events that inevitably have short-term adverse impacts.

River floodplain ecosystem
A large area of floodplain was inundated (10,119 ha; 4.6 per cent of the catchment). In general there are many benefits associated with extensive areas of river floodplain connectivity. However, this is a simplistic assessment and there are likely to be many other impacts that will depend on the timing and duration of the event. These are considered below.

As a third of the surveyed river channel is heavily modified (although only 1.2 per centof the overall length of the channel was surveyed, sample reaches were selected to be representative of the river as a whole) it is likely to be geomorphologically unnatural, to exhibit adverse sediment and morphological responses to large floods and to provide a low range of predominantly poor ecological habitats. Confidence in this conclusion would increase with the length of surveyed river.

Priority BAP habitats

A worst case habitat assessment is made on the EVENTSCORE tab of the scorecard as the most sensitive component community threshold within each habitat is used. A more detailed understanding of the impact of a given flood duration on specific components of a habitat may be made by consulting the information given in the threshold table (the last tab of the scorecard).

Season specific flood duration thresholds were exceeded for areas of the following priority BAP habitats: blanket bog (14.3 ha; 0.3%), deciduous and broadleaved woodland (3571.1 ha; 4.9%), fens and reedbeds (248.7 ha; 7.6%), lowland heathland (77.4 ha; 1.6%), lowland meadows (8.9 ha; 10.2%), purple moorgrass and rush pasture (215.2 ha; 2.3%), upland calcareous grassland (10.3 ha; 1%), upland heathland (86.3 ha; 1%), and wet woodland (45.6 ha; 1%).

As this is an extreme event it is beneficial to wet woodland in that it may produce regeneration sites. However, this habitat may be adversely affected by this summer flood as it occurs in the second half of the growing season when seedlings may be destroyed.

Event assessment: Wye – continued

Treefall may be a problem as the flood will result in waterlogged ground at a time when trees are in leaf.

Possible high sediment-associated nutrient inputs may result in negative impacts in all priority BAP habitats (conversely, some benefits may result from cation deposition).

The large flooded area means that there is potential for widespread colonisation by alien species.

In-stream ecology

Fish
This event may be bad for all four fish types observed (Types 1, 2, 4 and 5). High summer flows can cause displacement of fish downstream and over flood banks – especially a problem for fry and juvenile fish. Fish may be especially at risk given that a third of the surveyed channel is heavily modified and that around 60 per cent of the 37 fish type-sites have narrow floodplains.

The event is likely to be of some benefit to the spawning success of Type 5.

Furthermore, as it is a large flood it may increase species diversity.

There is a risk that the river may experience high levels of siltation and/or eutrophication from this event.

Invertebrates
Large events can remove food sources and change species composition. The heavily modified condition of approximately a third of the surveyed channel is likely to exacerbate the adverse impacts of this flood on invertebrates.

Macrophytes
Large flood events like this may rip out in-stream vegetation and the likelihood of this happening is increased by the heavily modified condition of approximately a third of the length of the surveyed channel. There is also a substantial risk of negative impacts on plant growth or eutrophication due to the inputs of nutrient-rich sediment in this catchment.

Wetland birds
Approximately 1,233 ha (0.8 per cent) of the bird-favourable area is flooded to a depth of less than 30 cm, which suits dabbling ducks. No negative impacts on wetland birds are identified.

Discussion of the results of the event-based assessment

A reasonable assessment is made of the benefit of a large extent of river floodplain connectivity. Caution is raised in relation to the likelihood that unnatural sediment and morphological responses to floods in the heavily modified reaches limit the range and quality of ecological habitat available.

The tool successfully provides further information on the consequences of the flood for specific ecological assets. For instance, areas of specific habitats that are inundated for longer than their tolerable thresholds are given and are reasonable. The proportions of the total area of each habitat in the catchment that are adversely affected in this way are also given. In this respect it may be significant that in the Upper Trent almost a quarter of fen and reedbed habitat is likely to be damaged by the seven-day flood event. This is a plausible finding as fens and reedbeds in the Upper Trent may have a greater proportion of soligenous types located close to the river and thus affected by the flood. Local conservation specialists should be able to verify the impact on these habitats. In the Wye more of the fens and reedbeds may be topogenous and thus be located further from the river and be less affected by the flood.

The finding that negative impacts of sediment/nutrient-rich flood water on all priority BAP habitats inundated in the Wye catchment is reasonable. Similar impacts are likely in the Upper Trent, even though the proportion of agricultural sediment sources was classed as low and reasons for this have been discussed above.

Credible negative and positive effects of the flood are highlighted for specific fish types in both catchments. The negative impact on macrophytes in both catchments due to this summer flooding is also reasonable.

The lack of negative effects on wetland birds is to be expected with a July flood event, as most young birds will have fledged and left the nest at this time of year.

Therefore, it may be concluded that the event functionality of the ECF tool is sensitive to the ecologically critical duration and timing of flood events.

An important consideration when evaluating the impact of an event is whether or not the return period of the event has changed or is likely to change in the near future. Many of the negative impacts associated with the July 2007 flood (as highlighted above) are acceptable (and may be even desirable) provided such events occur rarely. They would, however, be flagged as damaging if the frequency of occurrence of events of this magnitude were increasing.

6.2.3 Summary of applicability and verification of the EIA F Tool

Pilot testing has clearly demonstrated how the tool can be used to undertake a regime and/or event-based ecological flood impact assessment. The scorecard has proven to be an effective way of capturing scenario information and storing score data. Functions within the scorecard then successfully calculated the score data and allowed an assessment of the impacts for key environmental assets.

The baseline regime assessment of the tool illustrated how current data in both test catchments are adequately explained. However, results illustrate the weak dependence of priority BAP habitats on the probability of inundation. Assessing a hypothetical future flood regime and the July 2007 flood event in both pilot test catchments allowed an expert evaluation of the results. Results for impacts on BAP priority habitats, fish, birds, macrophytes and invertebrates were reasonable. In particular, the sensitivity of the event functionality of the tool to the ecologically critical timing and duration of flood events is a great benefit.

6.3 Principal limitations and sources of uncertainty

The principal limitations and sources of uncertainty are discussed in detail in the guidance report (TR2c).

The main issues include:

- limited knowledge of the sensitivities of environmental assets to flooding;
- suitability of NAFRA data to support environmental impact assessment (need for information on flood duration, seasonality and frequent return periods);
- high level habitat classification (BAP habitat) encompassing species with very different tolerances to flooding;
- accuracy of BAP habitat mapping (date of last survey, resolution of mapping, possible misclassification);
- classification of fish into eight types which may be insensitive to specific requirements of some species;
- assessment of fish habitat on a site basis rather than a whole catchment;
- generalised requirements for macrophytes, wetland birds and invertebrates.

7 Coastal pilot testing

7.1 Coastal pilot test regions and objectives of testing

Two pilot studies were implemented; the North Norfolk coast and the Blackwater and Crouch estuaries (jointly part of the Essex Estuaries System) respectively (Figure 7.1). Whereas the former is a relatively natural coastline that possesses a variety of habitat types, the latter contains major sea defence works throughout fronted by mudflat and saltmarsh habitat subject to coastal squeeze. Thus, the proposed methodology was trialled against varied ambient conditions.

The purpose of the pilot trials was threefold:

- To assist in calibration/verification and to assess the applicability of the approach proposed.
- To assess the confidence in the method and its sensitivity to uncertainty in input data.
- To explore how outputs can be related to social and economic risks of flooding.

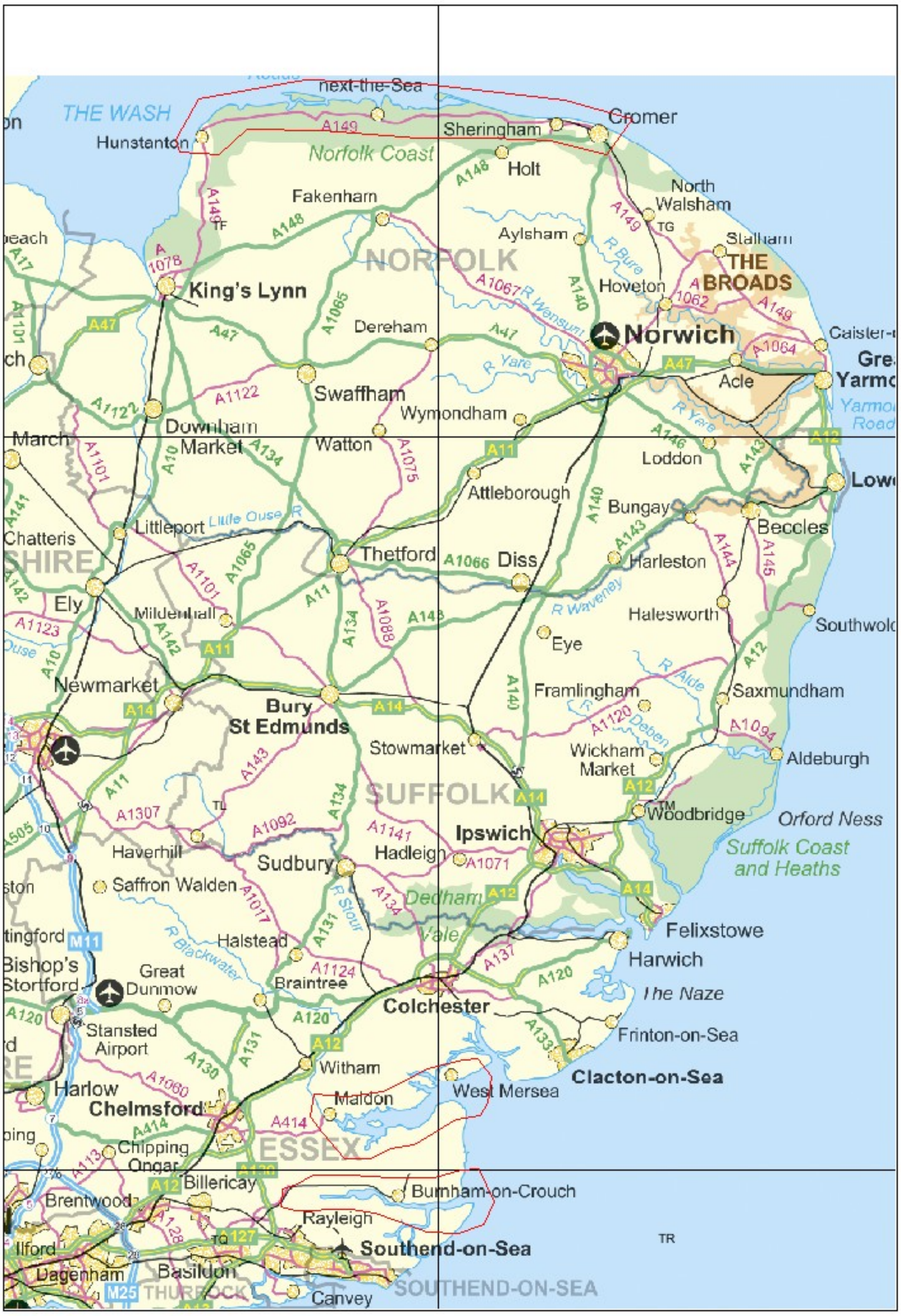

Figure 7.1 Map illustrating the locations of the two pilot regions (delineated in red). North Norfolk coast can be seen at the top whereas the Blackwater and Crouch estuaries can be seen at the bottom of the map, respectively.

7.2 Calibration data employed by the EIA C Tool

7.2.1 Habitat data

For both coastal pilot regions (North Norfolk, and Crouch and Blackwater estuaries: Figure 7.1) selected BAP priority habitats for England were sourced from Natural England and obtained as polygon shapefiles. There is one shapefile per habitat but there is some overlap between shapefiles where different communities co-exist. Data were downloaded from the Natural England website (http://www.gis.naturalengland.org.uk/pubs/gis/GIS_register.asp; accessed August 2008-March 2009) or provided directly by NE (May 2009; June 2010 for saltmarsh). See summary in Table 7.1.

Only the coastal habitats included in Table 7.1 were assessed in the pilot trials. The impact of a transgressing MHWS tidal level on freshwater habitats (negative impact in all cases) was not quantified here.

Table 7.1 Coastal BAP Habitat data used in this study

BAP priority habitat	Versioning	Source habitat information	Habitat survey period	Source mapping	Pilot areas
Coastal sand dunes (sand dunes)	v 1.3 2002-04	Radley (1994)	Mostly 1987-1990	OS 1:50,000	North Norfolk
Coastal vegetated shingle (vegetated shingle)	v 1.1 2004	Various e.g. Sneddon and Randall (1994	Mostly 1987-1996	OS Land-Line (1:1,250/1:2,500; 2003) Habitat surveys	North Norfolk Blackwater
Mudflats	v 1.2 2003-2004	Environment Agency (2002)	n/a	OS Mastermap (2003) OS 1:10,000	North Norfolk Blackwater Crouch
Saline lagoons	2004	Smith and Laffoley (1992) & various	n/a	OS Land-Line (1:1,250/1:2,500)	North Norfolk
Saltmarsh	n/a	n/a	n/a	n/a	North Norfolk Blackwater Crouch

7.2.2 Surface elevation data

LiDAR data for the two pilot regions were provided by the Environment Agency as ASCII files. LiDAR coverage is split in tiles with data available with different resolutions depending on tile (0.25, 0.5, one and/or two-metre grids). In order to keep the LiDAR retrieval manageable size-wise, the lowest resolution available for each tile was requested (two-metre grid, then one-metre, 0.5-m and 0.25-m grids). ASCII files for each tile were converted to rasters and merged as one two-metre resolution in ArcGIS. To select data, the LIDAR tiles were laid over the OS maps and tiles selected visually so that coverage extended far enough offshore and inland.

All tiles were surveyed between 1999 and 2008, with most done in the 2006-2008 period. Each LIDAR tile is not necessarily 100 per cent surveyed. The median percentage coverage was 63, 83 and 62 per cent for North Norfolk, Blackwater, and Crouch sites, respectively.

7.2.3 Tidal level data

Tidal level data obtained from the from Admiralty Tide Tables (UKHO, 2009) included (from lowest to highest): mean low water spring (MLWS), mean low water neap (MLWN), mean high water neap (MHWN), and mean high water spring (MHWS).

Levels (metres) relative to the Ordnance Datum were derived at specific locations following the standard procedure described in the volume. Depending on the pilot site and on the tidal level, tidal data were available for two to five locations along the coast. Table 7.2 summarises which ports were used.

Table 7.2 Summary of tidal ports used

Pilot site	Standard Port		Secondary Ports	
	ID	**Name**	**ID**	**Name**
North Norfolk	173	Immingham	154	Cromer
			155	Blakeney Bar
			155a	Blakeney
			157	Wells Bar
			157a	Wells
			158	Burnham (Overy Staithe)
			161	Hunstanton
Blackwater	129	Walton-on-the-Naze	123	Bradwell Waterside
			123a	Osea Island
			123b	Maldon
			124	West Mersea
Crouch	129	Walton-on-the-Naze	122	Burham-on-Crouch
			122a	North Fambridge
			122b	Hullbridge
			122c	Battlebridge

Tidal limits were then obtained by averaging values for available ports for each pilot area, then reclassifying the LiDAR elevation dataset. For Blackwater and Crouch, there were two to three ports available depending on tidal level, with very close values so that averaging would be adequate; for North Norfolk, more ports were available but with greater differences between values so that averaging would likely be a cruder approach.

Projected relative sea level rise data were obtained from DefrA (2006; “Table 1: Regional net sea level rise allowances 1”). For the East of England, where all three pilot areas are located, the following rates are projected: for 1990-2025, +4 mm/year; for 2025-2055, +8 mm/year. The current tidal levels being based on the latest edition of the Admiralty Tide Tables (UKHO, 2009) were taken as the starting year so that the projected rates of sea level changes are: for year 2025, 16 years (2009–2025) at 4 mm/year, thus +64 mm from current levels; for 2050, 25 years (2026–2050) at 8 mm/year + 64 mm = +264 mm (from current levels).

7.3 Incorporation of baseline data into the Geographic Information System (GIS)

The GIS analysis was done using a standard off-the-shelf GIS package and scripted batch processing (ArcGIS 9.3 and Python).

7.3.1 LiDAR data reclassification

LiDAR rasters were re-classified using ArcGIS Spatial Analyst. For technical reasons, values -99,999 and 99,999 had to be used as extreme low and high thresholds (no data below -99,999 or above 99,999); this can cut the zones below MLWS or above MHWS. The actual thresholds used are presented in Tables 7.3 a-c.

Table 7.3a Reclassification of LiDAR elevation according to current levels

Code	Intertidal zone	Elevation range (mm) North Norfolk	Blackwater	Crouch
1	< MLWS	-99,999 to -2,401	-9,999 to -2,256	-9,999 to -2,084
2	MLWS - MLWN	-2,400 to -951	-2,255 to -1,406	-2,083 to -1,284
3	MLWN - MHWN	-950 to 1,430	-1,405 to 1,866	-1,283 to 1,850
4	MHWN - MHWS	1,431 to 2,870	1,867 to 2,733	1,851 to 2,862
5	> MHWS	2,871 to 99,999	2,734 to 99,999	2,863 to 99,999

Table 7.3b Reclassification of LiDAR elevation according to current levels

Code	Intertidal zone	Elevation range (mm) North Norfolk	Blackwater	Crouch
1	< MLWS	-99,999 to -2,337	-9,999 to -2,192	-9,999 to -2,020
2	MLWS - MLWN	-2,336 to -887	-2,191 to -1,342	-2,019 to -1,220
3	MLWN - MHWN	-886 to 1,494	-1,341 to 1,930	-1,219 to 1,914
4	MHWN - MHWS	1,495 to 2,934	1,931 to 2,797	1,915 to 2,926
5	> MHWS	2,935 to 99,999	2,798 to 99,999	2,927 to 99,999

Table 7.3c Reclassification of LiDAR elevation according to current levels

Code	Intertidal zone	Elevation range (mm) North Norfolk	Blackwater	Crouch
1	< MLWS	-99,999 to -2,137	-9,999 to -1,992	-9,999 to -1,820
2	MLWS – MLWN	-2,136 to -687	-1,991 to -1,142	-1,819 to -1,020
3	MLWN - MHWN	-686 to 1,694	-1,141 to 2,130	-1,019 to 2,114
4	MHWN - MHWS	1,695 to 3,134	2,131 to 2,997	2,115 to 3,126
5	> MHWS	3,135 to 99,999	2,998 to 99,999	3,127 to 99,999

7.3.2 Combination of data for habitat and intertidal zones

For each habitat and each reclassified LiDAR file, reclassified LiDAR were cropped using the habitat shapefile. Attribute tables were exported. These were then post-processed in the R statistical package (http://www.r-project.org/) to calculate the extent (km^2) and percentages of each habitat within each intertidal zone for the three pilot areas and three reference periods (current, 2025, 2050). Technical difficulties made it impractical to generate a 2050 projection for the Blackwater estuary and hence, only the current and 2025 periods are featured for this pilot area.

7.4 Comment on pilot test results

7.4.1 Extent of habitats in each case study region

The extents of each habitat for present day (2010) conditions are presented in Table 7.4. Total areas above MLWS are presented in hectares to enable a regional assessment of the magnitude of each habitat. In addition, the areas of the habitats within specified tidal ranges are presented in hectares and as percentages of the total habitat area. The correspondence of habitats with their expected tidal ranges may be used to provide an initial evaluation of the method being tested here, to characterise habitat structure (such as saltmarsh and saline lagoons), and to infer habitat condition. The correspondence of mudflats and saltmarsh with tidal levels along part of the North Norfolk coastal pilot area is shown in Figure 7.2. Where areas of habitats lie inside expected tidal limits, they are assumed to be in good condition. Where habitats lie outside expected tidal limits, this could reflect inadequate data accuracy and/or habitats that are in a degraded state. Detailed groundtruthing would be needed to resolve this issue. When assessing impacts of relative sea level changes, areas of habitats outside expected ranges are interpreted as lost or degraded. All habitats below MLWS are assumed lost.

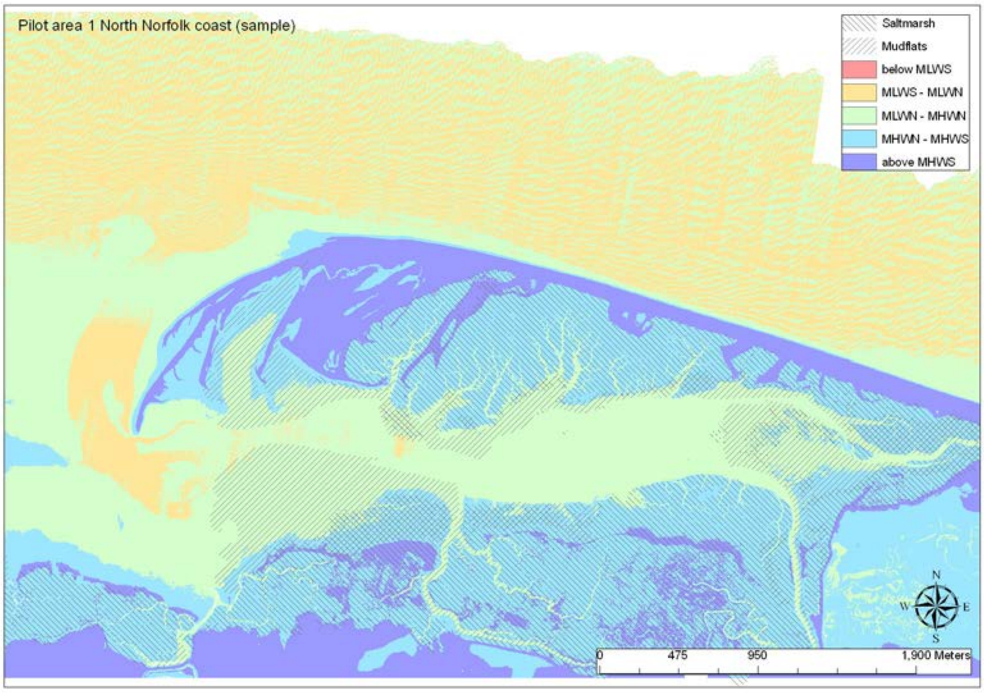

Figure 7.2 Areas of mudflat and saltmarsh overlain by tidal levels along part of the North Norfolk coastal pilot area

In the Crouch estuary there are areas of saltmarsh (243 hectares) and mudflats (476 hectares).

In the Blackwater estuary there are areas of saltmarsh (391 hectares), mudflats (2,004 hectares) and vegetated shingle (two hectares).

The North Norfolk coast contains a wide range of coastal habitats. There are large areas of saltmarsh (1,794 hectares), mudflats (508 hectares), sand dunes (300 hectares), vegetated shingle (52 hectares) and saline lagoons (13 hectares).

7.4.2 Correspondence with tidal limits

Saltmarsh closely corresponds to the expected tidal range (above MHWN) in the Crouch estuary (70%) and the North Norfolk coast (99%: Figure 2). However, in the Blackwater estuary correspondence is poor (38%).

Areas of mudflats closely correspond to the expected tidal range (MLWS to MHWS) in the Crouch estuary (100%), Blackwater estuary (100%) and the North Norfolk coast (95%: Figure 7.2). Large percentages of mudflats occur below the level of saltmarsh habitat (below MHWN) as expected.

Vegetated shingle corresponds reasonably well with its expected tidal limit (above MHWS) in the North Norfolk coast region (67%). However, the small extent (two hectares) that occurs in the Blackwater estuary is outside its expected tidal range.

Sand dunes only occur in the North Norfolk coast region where they correspond closely (96%) to their expected tidal limit (above MHWS).

Saline lagoons only occur in the North Norfolk coast region and 95% occur within the intertidal zone. This is a plausible distribution as saline lagoons are diverse and can exist in a wide range of coastal positions.

Reasons that may account for the areas of habitats observed outside their expected tidal limits include:

1) use of average tidal levels;

2) resolution of habitat mapping;

3) correspondence of the date of habitat mapping and relative sea level data;

4) season of habitat mapping (for example, saltmarsh extent varies seasonally).

The poor correspondence of saltmarsh and tidal limits in the Blackwater estuary (38%) may be explained by recent high rates of erosion in this region. These high rates have been attributed to relative sea level rise in addition to changes in the direction of the prevailing wind and increased storminess.

7.4.3 Assessing habitat structure

Intertidal habitats commonly exhibit clear ecological zonation at different levels reflecting their frequency of inundation. Different zones of saltmarsh habitat are associated with specific elevation ranges with respect to tidal levels. Although each zone is likely to be of ecological importance, the greatest diversity of plant species is usually found in the upper fringes of saltmarsh. A good quality saltmarsh should have areas of low/middle and upper saltmarsh. At present (2010) in the pilot test regions low/middle saltmarsh (MHWN-MHWS) accounted for 31 to 68 per cent whilst upper saltmarsh (>MHWS) accounted for seven to 31 per cent of total saltmarsh. The proportions of saltmarsh in the pilot test regions illustrate the impact of coastal squeeze. Along the unconstrained coastline of North Norfolk the upper saltmarsh accounted for 31 per cent of the total area, whereas along the constrained coastlines of the Crouch and Blackwater estuaries it only accounts for 14 and seven per cent, respectively. The nature of saline lagoons is also dependent on their frequency of inundation. Along the North Norfolk coast two-thirds of the saline lagoon area occurs between MLWN and MHWN whilst one-third occurs between MHWN and MHWS.

Table 7.4   Areal extent of priority habitats in the Crouch estuary, Blackwater estuary and North Norfolk coast (data for 2010)

Region	Priority habitat	Area between given limits in hectares Percentage of total habitat area (>MLWS) in brackets					
		Total (MLWS to inland limit)	**<MLWS**	**MLWS-MLWN**	**MLWN-MHWN**	**MHWN-MHWS**	**>MHWS**
Crouch estuary	Saltmarsh	242.839	0.000 (0)	0.034 (0)	72.473 (30)	136.688 (56)	33.644 (14)
	Mudflats	476.374	0.005 (0)	40.965 (9)	407.719 (86)	27.148 (6)	0.542(0)
Blackwater estuary	Saltmarsh	390.771	0(0)	0(0)	243.512 (62)	120.317 (31)	26.942 (7)
	Mudflats	2004.225	2.946(0)	191.500 (10)	1790.578 (89)	18.469 (1)	3.678(0)
	Vegetated shingle	2.057	0(0)	0(0)	2.034(99)	0.024 (1)	0(0)
North Norfolk coast	Saltmarsh	1794.309	0 (0)	0.001 (0)	29.043 (2)	1213.784 (68)	551.481 (31)
	Mudflats	507.712	0(0)	0.816 (0)	220.726 (43)	264.588 (52)	21.581 (4)
	Vegetated shingle	52.174	0(0)	0(0)	5.821(11)	11.559 (22)	34.794 (67)
	Sand dunes	300.417	0(0)	0(0)	0.045 (0)	10.717 (4)	289.655 (96)
	Saline lagoons	12.944	0(0)	0(0)	8.440 (65)	4.439 (34)	0.064 (0)

7.4.4 Assessing impacts of changes in relative sea level

Changes in relative sea level may affect the areal extents and proportional distribution of habitats throughout the tidal range. The current baseline data can be used to assess the changes that are likely to occur under predicted relative sea levels for 2025 and 2050, as considered when formulating shoreline management plans (SMPs – Defra, 2006). As static habitat data were used in the pilot trials, the results reflect the common situation where habitats are constrained on their landward side by infrastructure such as a sea defence or road. It is possible that along unconstrained coastlines habitats may migrate inland. The potential for this landward migration should be investigated by studying each site in detail. The changes in area of each habitat under each sea level scenario are presented in Table 7.5 in hectares and as percentage changes.

7.4.5 Assessing changes in habitat size

With sea level rise there are significant reductions in the area of upper saltmarsh in all study regions. Along the North Norfolk coast the change in relative sea level from 2010 to 2050 is likely to reduce the area of upper saltmarsh by around280 hectares. In each region there is an increase in the area of low-middle saltmarsh. However, some marsh lies in the tidal range of mudflats below the level of saltmarsh. This habitat is likely to be eroded or be in a degraded state. Therefore, along constrained coasts the total area of saltmarsh is reduced with greatest reductions occurring in the extent of upper saltmarsh.

The area of sand dunes along the North Norfolk coast changes with relative sea level rise from 2010 to 2050. The area of good condition sand dunes above the MHWS tide level is likely to decrease by around nine hectares as the intertidal area migrates inland and erodes them. The dunes may migrate landward if they are not constrained, but this needs to be assessed by detailed site study.

The total area of mudflats in the Crouch estuary and North Norfolk coast decreases by 2050. Mudflat area is lost as the MLWS tide level rises and floods this habitat. Overall the area in the intertidal zone decreases as the tidal levels rise. It may be possible for mudflat habitat to migrate landwards with sea level rise at the expense of lower saltmarsh but this would need to be investigated.

Good condition vegetated shingle occurs above the MHWS tide level. Along the North Norfolk coast the area of good condition vegetated shingle is shown to decrease as a result of rising sea levels unless it can migrate landwards.

7.4.6 Assessing changes in habitat structure

By 2050 the area of upper saltmarsh in both the Crouch estuary and along the North Norfolk coast is reduced to about half of the current amount. Data were not available for 2050 in the Blackwater estuary. Parallel reductions in extent were not observed in the mid and lower saltmarsh areas. In fact, areas of mid-lower saltmarsh actually increase in the Crouch estuary and the North Norfolk Coast. These contrasting changes in area result in the proportions of low-mid to upper saltmarsh changing.

Coincident with the changes in areas of low-middle and upper zone marsh, the areas of saltmarsh increase in the tidal range of mudflats where it cannot survive. This most likely reflects the erosion of saltmarsh and transition to mudflats.

Saline lagoons become located in areas of greater inundation as tidal levels rise. This may change their characteristics. Along the North Norfolk coast from 2010 to 2050 the area of saline lagoons between MHWN and MHWS decrease by around 30 per cent while the area between MLWN and MHWN increases by around 17 per cent.

Table 7.5 Changes in areal extent (hectares and percentage) of priority habitats in the Crouch estuary, Blackwater estuary and North Norfolk coast under predicted relative sea levels for 2025 and 2050

Region	Priority habitat	Relative sea level (Year)	Area between given limits in hectares Percentage of total habitat area (>MLWS) in brackets					
			Total (MLWS to inland limit)	<MLWS	MLWS-MLWN	MLWN-MHWN	MHWN-MHWS	>MHWS
Crouch estuary	Saltmarsh	2010-2025	0.000	0.000 (/)	0.012 (34)	3.954 (5)	2.440 (2)	-6.405 (-19)
		2010-2050	-0.003	0.003 (/)	0.069 (200)	16.573 (23)	0.675 (0)	-17.320 (-51)
	Mudflats	2010-2025	-1.049 (0)	1.055 (/)	11.873 (29)	-9.696 (-2)	-3.075 (-11)	-0.150 (-28)
		2025-2050	-3.922 (-1)	3.927 (/)	30.704 (75)	-21.528 (-5)	-12.749 (-47)	-0.348 (-64)
Blackwater estuary	Saltmarsh	2010-2025	0.000	0 (0)	0 (0)	7.146 (3)	-1.377 (-1)	-5.770 (-21)
	Mudflats	2010-2025	0.000	1.802 (61)	67.368 (35)	-66.402 (-4)	-1.977 (-11)	-0.790 (-21)
	Coastal vegetated shingle	2010-2025	0 (0)			0.003 (0)	-0.003 (-15)	0 (0)
North Norfolk coast	Saltmarsh	2010-2025	-0.026	/	0.002 (169)	8.491 (29)	73.767 (6)	-82.285 (-15)
		2010-2050	-0.018	/	0.018 (1544)	43.826 (151)	235.464 (19)	-279.326 (-51)
	Mudflats	2010-2025	-0.013 (0)	0(0)	1.216 (149)	15.306 (7)	-12.549 (-5)	-3.986 (-18)
		2010-2050	-0.012 (0)	0(0)	4.188 (513)	61.453 (28)	-54.294 (-21)	-11.359 (-53)
	Sand dunes	2010-2025	0.013	0(0)	0(0)	0.070 (156)	1.562 (15)	-1.619 (-1)
		2025-2050	0.013	0(0)	0(0)	0.268 (601)	8.525 (80)	-8.780 (-2)
	Coastal vegetated shingle	2010-2025	0	0(0)	0(0)	0.309 (5)	0.424 (4)	-0.732 (-2)
		2025-2050	0	0(0)	0(0)	0.942 (16)	1.885 (16)	-2.827 (-8.13)
	Saline lagoons	2010-2025	0(0)	0(0)	0(0)	0.320 (4)	-3.01 (-7)	-0.019 (-30)
		2025-2050	0(0)	0(0)	0(0)	1.409 (17)	-1.364 (-31)	-0.045 (-71)

7.4.7 Evaluating impact of habitat change in relation to changes in relative sea level

Quantifying the areas of specific habitats that will be lost under future sea level change scenarios enables us to estimate the need for and extent of offsetting habitat creation. Furthermore, if a financial or social value is placed on a given habitat per unit area, this can easily be reported.

Because habitats are extremely complex, dynamic features, the number of indicators of structure and function potentially available to define them tends to be large. Moreover, most of them are resource- and time-intensive (hence expensive) to measure and difficult to specify with precision as they exhibit substantial levels of inherent variation. As a result habitat indicatords are, at present, not directly useful for management purposes. However, given greater knowledge of the relationships between surface elevation and local tidal frame (frequency and duration of tidal inundation) and the diversity and abundance of the flora and fauna of inter-tidal areas, it might prove possible to construct generalised distribution patterns for the inter-tidal biota in relation to the tidal regime at different shore levels. These could then be employed to more accurately assess the significance of likely changes in the biota as a result of inundation from the sea.

7.4.8 Scoping the potential for habitat creation

Given that we know the tidal ranges that support specific coastal habitats, we can assess the likely success of a proposed habitat creation scheme. To do this, we need to combine the outline of a proposed site with topographic data and tidal levels.

The information on timelines that this approach provides is valuable not only in terms of estimating the level of risk attached to any given situation, but in scheduling any mitigation and/or compensation measures proposed. Any programme seeking to relocate and/or replace habitats which are in danger of being lost should aim to schedule the work so that comparable replacement habitat becomes available before, or at the same rate as, the existing habitat disappears. Scheduling habitat replacement in this way needs to take account of the fact that the new habitat will take time to develop.

As well as identifying habitats at risk of loss or change as a result of flooding from the sea, the approach proposed is able to investigate the suitability of inter-tidal sites as areas for habitat creation/restoration. By highlighting areas under threat and identifying relatively stable, potential mitigation/compensation sites over, say, a one hundred-year timeframe, the GIS approach facilitates the compilation of a quantitative national potential profit and loss account for habitats in the coastal zone over various spatial and temporal scales, thereby extending the work already undertaken, in this context, by coastal habitat management plans. Such a potential profit and loss account will, by providing a temporal dimension, be extremely valuable for focusing response measures and scheduling management actions in the most timely, cost-effective manner.

7.5 Principal limitations and sources of uncertainty

This method for the broad-scale assessment of the impact of progressive tidal inundation relies on a wide range of datasets with varying levels of resolution and collected over different time periods. The sources of uncertainty have been highlighted throughout this section under each part of the methodology and are summarised below. They are discussed in detail in the guidance report.

- Current habitat data reflects data collected since 1987.
- Tidal levels are derived by averaging levels of nearest ports.
- Scenario assessment assumes there are no changes to the coastal elevations. However, this is highly unlikely when dealing with dynamic coastal environments. The interaction of various coastal processes at any given site will be one of the biggest uncertainties in any assessment of this sort.
- Habitat data are cropped with LiDAR data. Where LiDAR data are missing areas of habitat are not lost from the assessment.

7.6 Concluding remarks on pilot testing

The approach trialled here builds upon and complements the Broad-Scale Ecosystem Assessment (BSEA) approach set out by Defra. As demonstrated by the investigation of saltmarsh and mudflat habitats at two case study regions, the approach provides a fast and effective way of mapping and assessing the ecological impacts of inundation by the sea, generating output that can be used by existing Environment Agency modelling tools and/or employed in qualitative risk assessment procedures.

The use of a standard, commercially available GIS framework facilitates the import and manipulation of existing data already in a GIS format and provides a means of readily integrating output with multi-criteria evaluation techniques such as those employed in the Modelling Decision Support Framework (MDSF) that is currently used for fluvial studies.

Incorporating the key information into a series of GIS overlays also provides a straightforward means of identifying and prioritising areas subject to potential change, as a result of flooding from the sea due to progressive increases in relative sea level over short, medium and long-term timescales. Different levels of risk (high, medium and low) can be colour-coded in traffic light style (red, amber and green) to show the vulnerability of different lengths of coastline at a glance, in both spatial and temporal contexts.

Following successful completion of the coastal pilot trials, the procedure was demonstrated to an Environment Agency specialist (Robin Crawshaw) who confirmed that it provided the basis for a readily understandable assessment tool that he thought would be of considerable use in the work he undertakes.

When management responses are being formulated for specific sites or localities, however, more detailed information will be required for a full assessment of the relevant issues and the likely outcome of different management options might need to be investigated by means of suitable modelling techniques.

A substantial amount of professional knowledge and judgement will invariably be required to interpret the outcome(s) of this approach and the interpretation(s) will often have a high degree of uncertainty associated with them. The uncertainty in predictions pertaining to the effect(s) of physical processes on habitats and species could be greatly reduced if more precise indicators of ecological quality were available against which the likely significance of potential impacts could be assessed.

Further assessments could be made as to the condition of vegetated shingle and sand dune habitats using surface elevation. Changes in the cross-sectional profile of a shingle shore or the variability of surface elevation within a sand dune system, for example, might reasonably be expected to correlate with consequent changes in biotic community structure. Any assessment along these lines, however, requires improvements in our understanding of the relationships involved.

8 Relating outputs to social and economic risks of flooding

We developed a GIS framework through which monetary values could be assigned to environmental assets and used within the MDSF2 framework for coastal or fluvial assessments. Spatial layers of costs associated with flooding environmental assets could be overlaid with estimated annual damage (EAD) costs currently used by the Environment Agency. The EAD costs could be assessed via their component parts (residential (ResRiskBest) and non-residential (NRPRiskBest) costs). These data have been investigated and are available at the same resolution as NAFRA inundation probabilities so could be easily combined with EIA tool outputs.

Furthermore, CEH have contributed to the National Ecosystem Assessment which aims to quantify the economic value of freshwater ecosystem services, including rivers and floodplains. The ecosystem services include landscape values such as recreational and aesthetic qualities.

Valuation of coastal ecosystem services is a relatively new approach and the information that exists is either very site-specific or highly generic in nature. Consequently, any attempt to assign monetary values, or social benefits, to ecological assets identified in the EIA C Tool is likely to require focused studies in these areas. Of particular interest is the degree to which the perceived quality of any given habitat is reflected in any monetary and/or social values assigned to it, as the measurement of habitat quality needs to be better defined before any such values can be really meaningful. Furthermore, any monetary/social benefits assigned now would need to be reassessed in the future as priorities change.

9 Relevance to strategy and legislation

The relevance of the proposed ecological impact assessment method to strategy and legislation is considered in detail in the guidance report (REF).

In summary, the method supports activities throughout the tiered approach to fluvial and coastal flood risk management planning. In particular, it supports catchment flood management planning/shoreline management planning, strategy planning, and scheme development. The methods could also support the assessment of outcome measures, spatial planning and appraisal. Together they provide a framework for assessment, although the level of detail would change from the more general CFMP/SMP to the more detailed strategy plan. The way the method links to existing tools and methods is considered in the guidance report, as this is key to its successful integration with flood risk management.

10 Towards a detailed level of assessment

10.1 Fluvial studies

In this section the issues that may need to be considered, the data required and tools available for a detailed level assessment of the impacts of fluvial flooding on the environment are discussed. In many instances, a detailed analysis is constrained by data availability and our knowledge of environmental tolerances of flooding. Given current research efforts directed at the WFD and understanding ecosystem responses to climate change, our knowledge on sensitivities to flooding should increase.

10.1.1 River-floodplain ecosystem impact

A more detailed level of analysis would need to take into account the continuity of river floodplain connection. It is critical for us to know whether flood waters rise and fall in phase with the river or whether they become trapped behind flood banks. It is also important to know whether the river is connected to its floodplain along its length or whether there are just a few opportunities for water to discharge from the river onto the floodplain, where it may spread out parallel to the river behind embankments. Detailed information on topography and the locations of drainage channels would be needed for this assessment.

10.1.2 Terrestrial ecosystem impact

The impacts of flooding on terrestrial habitats are affected by a range of factors. The extent and duration of flooding are clearly significant factors which determine the magnitude of impacts of a flood upon a terrestrial ecosystem. In addition, the timing of a flood in relation to the annual vegetation growth cycle will influence whether the flood has a lasting impact on the environment. Floods in winter may have a greater duration without long-term influences on vegetation composition and vigour, whilst even a short duration flood in the middle of the growing season may alter current vegetation communities markedly (Table 2.8). Studies of the eco-hydrological requirements for wetland plant-communities (such as Wheeler *et al*., 2004) characteristically show that whilst many communities tolerate, or indeed benefit from, surface saturation for extended periods in winter, they are very sensitive to even short periods of saturation in spring, summer and early autumn.

These eco-hydrological studies also demonstrate significant differences in the range of hydrological regimes, and hence sensitivity to flooding, between different species and communities within the same broad habitat. For example, Figure 10.1 illustrates water table depth zones for three grassland communities of the national vegetation classification (NVC) which each have very different requirements in terms of the temporal variations in soil moisture through the year. The figure shows, for example, that MG4 is generally intolerant of soil saturation, which would result from flooding, even in the winter. In contrast, soil saturation can be tolerated by MG13 in winter for a number of months. These two communities are probably more sensitive to summer flooding since their persistence requires water tables to fall some distance below the surface at this time. In contrast, the presence of MG8 (on the Somerset Moors) demands relatively high water tables throughout the year, so that very short duration flood events which might temporarily raise water tables may have less impact on this community compared to those associated with larger summer draw-downs.

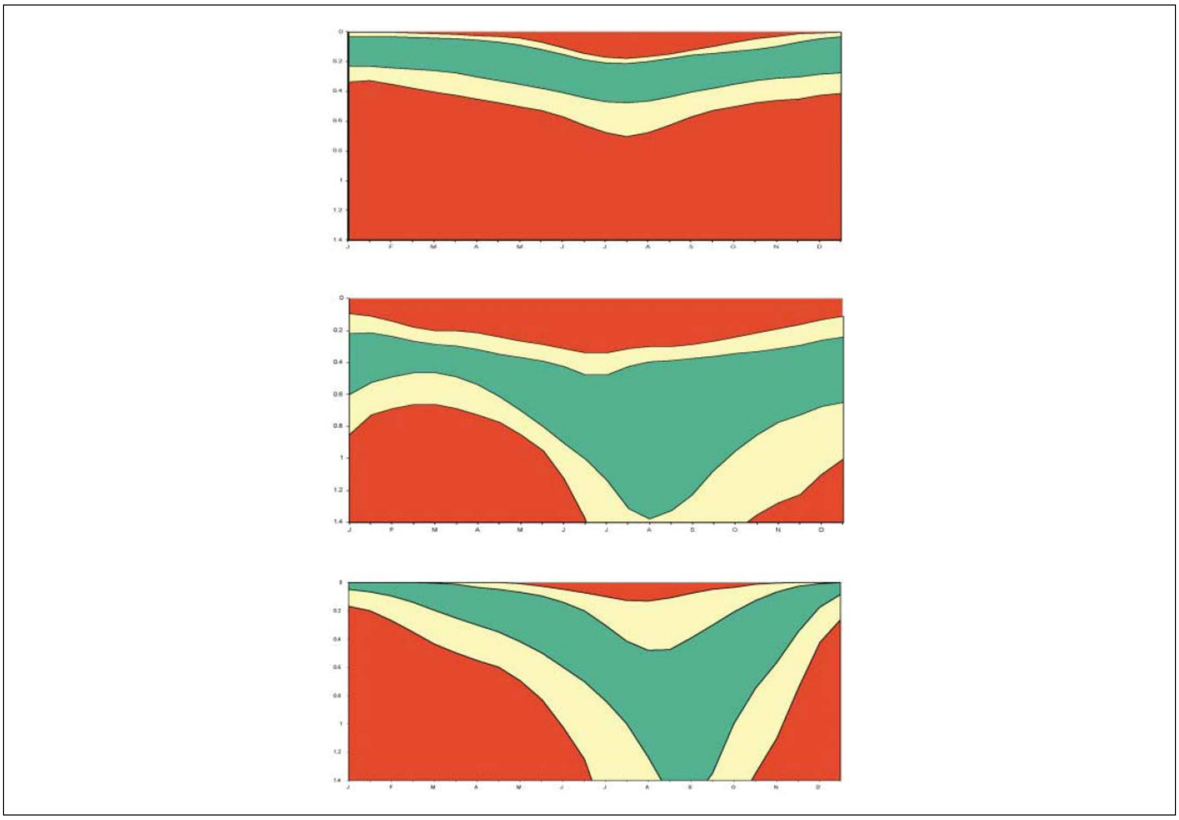

Figure 10.1 Water table depth zones for three grassland communities: top - MG8 on the Somerset Moors, middle – MG4 on fine texture alluvium, bottom – MG13 (source: Wheeler *et al*., 2004)

Such eco-hydrological guidelines are available for wet grassland, fen and mire and swamp/ditch communities and provide potentially valuable tools for assessing the effects of hydrological conditions on specific communities. In areas of particular interest, perhaps due to their designation for nature conservation or where significant changes in flood characteristics are projected, the subdivision of the broad habitat types into more detailed representations of community types (for example, using the national vegetation classification) would be required. The distribution within 10-km grid squares of NVC lowland grassland, woodland, lowland heathland as well as upland communities are available from the JNCC (JNCC, 2010) and could be employed to determine the communities likely to be present. Extant or commissioned sites surveys would be required to assess vegetation community distribution at finer spatial scales.

When assessing the effects of flooding on terrestrial ecosystems (such as wetlands and those on floodplains), another important factor demonstrated by Figure 10.1 is the availability of information on groundwater levels. Thus, it is the water table which exerts a dominant and determining effect on the assembly, composition and persistence of communities within floodplain and wet grasslands by controlling both aeration and drought stress. Floods may temporarily raise water tables and elevated groundwater levels may persist for some time after surface water has drained away and evaporated. The antecedent water table elevation and soil moisture may also exert an influence upon the characteristics of a flood event (such as Baker *et al*., 2009). A flood occurring at a time when groundwater levels are already high or at the surface (more likely in winter) is likely to persist for longer as infiltration of flood water will be impeded (compounded by lower evaporation rates in winter). In contrast, at times of low groundwater level, the same flood may recede more rapidly. Detailed assessments of the impacts of flooding upon terrestrial ecosystems would therefore benefit from routine monitoring of groundwater levels. This can be achieved relatively easily using simple dip wells which are widely used in studies of wetland hydrology (see Gilman, 1994; Gilvear and Bradley, 2000) although decisions are required over whether observations are made manually (resulting in less frequent observations that are less likely to coincide with flood events) or using logging instrumentation (with an initial higher capital outlay but which provide more frequent observations).

Hydraulic models which are used to simulate the extent of flooding tend to be disconnected from the subsurface, perhaps enabling infiltration using a specific rate, but subsequently not simulating the impacts of floods upon subsequent groundwater (and soil moisture) regimes. In cases where detailed assessments of the relationships between flooding, subsurface hydrology and in turn ecosystems are required, suitably calibrated surface-unsaturated-saturated zone (SUZ) models offer a solution (such as Thompson *et al*., 2004). This form of modelling has been employed to assess the impacts not only of floodplain restoration (Hammersmark *et al*., 2008) but also of climate change (Thompson *et al*., 2009) on flood and subsurface hydrology in key floodplain/wetland sites. The resources and time required to set up such models are characteristically large but where available, their results offer the potential for transference to other similar sites.

10.1.3 In-stream impact

Macrophytes

As discussed in Section 2.4 the impacts of floods on macrophytes are often short-term and/or marginal. Thus, it may be decided not to pursue a detailed assessment. Where a detailed assessment is undertaken, knowing which species are present would be important to enable flow tolerance and recovery times to be established from the literature or through experimentation. Evaluating the impact of nutrients and fine sediment would require information on concentrations and their transport through the river channel. Consideration of the hydrological regime to which macrophytes at a site are adapted may be useful in identifying the likely impact of an event.

The data required would include:

- distribution of macrophytes;
- fine sediment and nutrient concentrations of flood water;
- conveyance of sediment in flood water along river channel;
- hydrological regimes of sites.

Invertebrates

A detailed assessment of the impact of flooding on invertebrates would require knowledge of the species present (and thus their flow tolerance) and the available refuge (substrate type and macrophyte coverage). It would also be important to elucidate whether fine sediment would be deposited or eroded by the flood. The data required would include distribution of invertebrates, substrate type and macrophyte coverage.

Fish

To increase the confidence in predictions of the impact of flood events on fish and fisheries, a detailed knowledge of the river's lateral connectivity with its floodplain and how this level of connectivity affects the fish population within the river is required.

Not only is information on the presence/absence of artificial levees needed, but also information on whether these structures inhibit the migration of fish into and back from refuge/feeding areas, and how they may act to constrict the usable habitat within the channel during high flow events. Fish are known to be susceptible to stranding behind artificial floodbanks as floodwaters recede, but the presence of a floodbank can only be used as anecdotal evidence in isolation as stranding is not inevitable; often features such as drainage ditches provide routes for floodplain escapement. Therefore historical records of fish stranding incidents at the surveyed location would help to establish whether the floodbanks actually pose a threat to fish survival during flood events. In this respect, it is also critical to understand the effects season has on stranding, as it is related to the scale of the impact, with late spring/early summer flooding likely to have a great impact as fish actively disperse onto the floodplain to reproduce at this time and are therefore exposed to a greater risk of stranding.

The type of river is also a factor to be considered when weighting the importance of the connectivity available. Artificial levees may not pose a threat to fish where they are in areas that are not exploited by species that use floodplain habitat. In accordance with the serial discontinuity concept (ESDC; Ward and Stanford 1995a), the presence of a flood embankment in an upland catchment, where longitudinal connectivity is more important, would probably not be as big a threat to fish survival (in terms of restricting access to essential habitat elements) than the presence of a floodbank in a lowland reach where lateral connectivity and dispersal onto the floodplain is more prevalent and a critical element in the life history strategy. Thus, **data on the species present or at least the river type** should be considered when assessing the impact of reduced lateral connectivity (by artificial floodbanks) on the resident fish population. These data can also potentially be coupled to River Habitat Survey data that provide a qualitative description of disruption of lateral connectivity.

The effect that a floodbank may have on reducing connectivity with a floodplain will vary with its proximity to the main channel. If the floodbank is located close to the channel, the amount of aquatic terrestrial transition zone (ATTZ; Junk *et al*. 1989) will be limited and the velocities within the main channel may be exacerbated. If, however, the floodbank was set well back onto the floodplain, the ATTZ available to fishes is increased, affording fish access to more refuge/spawning/feeding habitat. Therefore, the **distance of the floodbank from the main channel** should be considered when weighting the effect of such a structure on fish communities.

Land use on the ATTZ should also be a consideration, as this is likely to influence the way fish use the floodplain. Despite a lack of literature in this area (in European systems), it is likely that intensively farmed pasture and arable land produces fewer terrestrial invertebrates for fish to feed on during a flood than natural wetland/meadow habitat.

River modifications such as channelisation and floodbank construction can increase the severity of conditions experienced by fish within the main channel of rivers. The practice of maintaining uniform channels to increase "channel efficiency" to maximise discharge and reduce flood peaks increases the water velocities experienced by fish in the main channel. If velocities are higher than the maximum velocity tolerances or swimming capabilities of resident fish, the amount of suitable “hydraulic habitat” within the channel will decrease, having a negative impact on the fish population. This is another factor to be considered when carrying out this type of detailed assessment. The use of an Acoustic Doppler Current Profiler (ADCP) could be employed to **map channel geomorphology and assess the distribution of suitable flow velocities during high flow events** in constrained rivers. (This kind of assessment has been carried out by Mike Dunbar, CEH).

Detailed hydrological data from flow gauging stations in conjunction with **high resolution fish sampling data** are essential to assess the impact of specific flow events on a fish community. From this hydrological data, several ecologically important components which influence fish need to be extracted, namely: flood amplitude, frequency, seasonal timing, predictability, duration and rate of change of flow conditions (Poff *et al*. 1997; Bunn and Arthington 2002).

When examining the amplitude of floods from hydrographs, the first thing that needs to be established is the **threshold at which the flow becomes an out-of-bank event**. When a flow leaves its channel it provides different ecological services to the biota within the river, such as access to off-channel refuge habitats, therefore the implications of out-of-bank flows are different to in-channel flows and this needs to be recognised. If the amplitude is quantified as a maximum discharge (for example, in m^3s^{-1}), the value gives no indication of the flow’s unique interaction with its channel. **Froude number may be a better measure of flow** as it incorporates velocity and hydraulic depth, which are recognised as components of fish habitat. Froude number can be roughly derived if the wetted area is known using the formula:

$$Fr = \frac{(Q/A)}{\sqrt{gD}}$$

Where Q is discharge (m^3s^{-1}), A is wetted area (m^2), g is acceleration due to gravity ($m\ s^{-2}$) and D is hydraulic depth (cross-sectional area of flow/top width (m)).

During an out-of-bank event, the amplitude of the flood can also be expressed in terms of the **amount of floodplain area covered to a useable depth by fish**. The previous exploratory methodology assumes that the area of inundated floodplain measured around study sites is actually good habitat for fish during a flood. This may not be the case in reality, as an event may only flood an area to a very shallow (for example, less than five cm) depth, therefore restricting its use to fish. Analysis of the topography of the floodplain at the study site and the depth of inundation during an event will give an indication of the suitability of the area to fish. This could be improved if the specific preferences of fish using floodplains are known.

The frequency of floods can be calculated from long-term hydrographs using flood-frequency curves. This parameter is important, as a floodplain that is more frequently inundated has arguably more influence on the biota within the river. An increased frequency may have benefits such as the increased transfer of terrestrial food items into the river, for example, or conversely, it may prove detrimental through increased stranding.

The seasonal timing of flood events can also be observed from hydrographs. The timing of high flows is important to many riverine fish species, as several critical life events (phenology of reproduction, spawning behaviour, larval survival, growth patterns and recruitment) are profoundly linked to increases in flow at certain times of the year (Welcomme, 1985, Junk *et al.* 1989, Copp 1989, 1990, Sparks 1995, Humphries *et al.* 1999). A precise knowledge of the times of year when resident fish species execute different stages of their lifecycle is needed to predict the possible implications of high flows throughout the year.

The duration of floods that provide favourable water depths is important because the longer these flows persist, the greater the amount of time available to biota for optimal feeding, growth and spawning, contributing to an increased chance of survival or recruitment success (Welcomme 1985). Conversely, if flows of too high velocity or too low water volume occur for an extended duration, fish will be exposed to sub-optimal conditions, such as low dissolved oxygen levels in shallow waters, for a longer period, having negative implications for individual and population health.

Examination of the hydrograph will also reveal **the rate of change of a flood pulse**. The rate of change in flood magnitude is often described in terms of its smoothness or flashiness, both terms referring to the steadiness or rapidity with which the river responds to local flood events. Excessively rapid variation in flow can leave the eggs of fish exposed (especially phytophils and lithophils), thus reducing recruitment. Rapid changes in flow can also affect fish more directly, as the rapid currents associated with such transitions in flow rates can sweep away fish before they can reach suitable refuge habitats. This is particularly important immediately after hatching when the fish are at the larval life stage and their swimming capabilities are poor. Furthermore, the overly rapid retreat of flood water increases the risk of stranding fish on floodplains, temporary pools and backwaters inundated by flooding, increasing fish mortality.

One further issue that should be considered is to use quantitative fish data instead of fish types to link flood events with community composition. Where such data exist, it could improve the accuracy of predictions of the impact of flooding on fisheries.

10.1.4 Wetland birds

The broad-scale analysis is based on generalised requirements of wetland birds, primarily waders and homogenous inundation of the floodplain.

A detailed assessment of the impact of flooding on wetland birds would require knowledge of the precise species of birds on the floodplain and their relationship to bird populations and suitable habitat elsewhere in the catchment. The proximity to similar habitats is important as they may act as a refuge when the site is flooded.

A further important issue is micro-topography. Birds prefer the juxtaposition of dry land and wetland, such as raised dry areas (on which they nest) adjacent to ditches, grips, scrapes or other areas of relatively low topography (where they and their chicks feed).

A third issue is the timing of floods. Many wintering birds, particularly water fowl, benefit from floodplain inundation between November and March; reductions in the frequency and duration of winter inundation can be significant for these wetland bird populations. Likewise, wetland birds prefer moist penetrable soils in spring and early summer, together with small areas of open water for feeding. If the wetland dries too quickly (within the breeding season), chick viability can be reduced.

A final issue is the sequence of floods. Some species, such as snipe, may breed several times in the same year, for example after a flood event, and thus are less sensitive to single floods. At a broader timescale, if late/spring summer floods occur in successive years, with large chick mortality, this may have major impacts on bird populations.

The data required includes:

- bird census data from catchment showing populations in different areas;

- topographical data of the floodplain or at least density of ditches, grips and similar microtopographic features;
- frequency and timing of inundation and drying.

10.1.5 Detailed assessment of ecological impacts via sediments

Catchment attributes affecting sediment yield, delivery and sensitivity to disturbance

It is now possible to assess the environmental risks associated with catchment erosion and sediment delivery during floods based on the use of reduced complexity models that simulate slope erosion, surface runoff erosion and sediment delivery to watercourses. With limited further development, these models could be applied to investigate the impacts of climate and land-use changes in order to identify areas that are sensitive and/or vulnerable to sediment-related environmental damage. The sticking points are data availability and the need to convert research models into user-friendly tools.

Inputs required and available catchment sediment models/tools

- rainfall intensity (CEH models);
- non-fluvial sediment sources: e.g. landslides, slope processes (CAESAR model in FRMRC sediment toolbox: Thorne *et al*., 2011);
- surface runoff generation areas: partial source areas (Scimap, FRMRC Polyscape and other less complex hydrological models: see Appendix A);
- soil types and areas of naturally erodible soils (catchment soils maps);
- slope of erodible soil areas (Next map);
- land use as it affects soil erodibility (CEH land use map);
- crop type and position in growing season (CEH land use map);
- connectivity of erodible land to river (Scimap or FRMRC Polyscape: Pagella *et al.* 2009; Jackson *et al.* in review);
- sediment delivery ratio (Psychic, Scimap, FRMRC Polyscapes: see Appendix A);
- floodplain connectivity, type and sediment storage capacity (RHS database, Professor D E Walling's UK-based research).

Factors affecting river sediment dynamics, channel stability and sensitivity to disturbance

Catchment-based approaches cannot be used to predict the sediment-related impacts of floods on rivers because the channels of alluvial streams adjust in response to short-term perturbations (for example, by the flood itself) and longer term changes in the hydrological and sediment regimes. Consequently, when assessing sediment impacts and risks to the environment, the dynamics of sediment within the river channel must be considered and the addition or loss of sediment from the watercourse through degradation or aggradation of the channel bed and erosion or accretion of the channel banks must also be accounted for. Broad-scale sediment dynamics may be modelled based on stream power analyses, with the sensitivity of the river to change being predicted on the basis of its stream type, degree of artificial modification, width of the riparian corridor and density of in-stream vegetation.

Inputs required and available broad-scale models/tools for river sediment dynamics

- specific stream power (FRMRC ST:REAM model: Parker, 2010);
- bed substrate (RHS);
- bed material transport capacity (FRMRC sediment toolbox: Thorne *et al*., 2011);
- heavily modified watercourse (Environment Agency WFD team/database);
- habitat modification score (RHS-Cardiff University);
- stream type (Environment Agency-Defra Sediments and Habitats Project: Modified Montgomery-Buffington typology);
- width of riparian corridor (RHS database, aerial photographs);
- extent and density of in-stream vegetation (RHS database, Environment Agency/local authority/internal drainage board maintenance records).

10.2 Coastal studies

In this section the issues that may need to be considered, the data required and tools available for a detailed level assessment of the impacts of increased tidal inundation of the coastal zone are addressed. In many instances, a detailed analysis is constrained by data availability and our knowledge of environmental tolerances of flooding.

10.2.1 Linking interacting hydrodynamic, geomorphological and ecological processes

Although numerous modelling tools are available, no models can directly link the complex range of interacting hydrodynamic, geomorphological and ecological processes that define the response of the coastline to flooding. Research into morphological responses of coastlines to relative sea level rise by the Engineering and Physical Sciences Research Council (EPSRC) has highlighted their complex and non-linear nature. At best, output from one model, or one set of models, may be used as input to drive another model or set of models. It is axiomatic that the accuracy of the method is dependent on the quality of the input data. As higher resolution tidal levels, more precise habitat mapping information and improved habitat quality indicators become available accuracy will improve.

10.2.2 Defining habitat quality

The requirement to conserve and, where practicable, enhance biodiversity in the course of formulating SMPs brings the need to focus on maintaining, improving and expanding existing habitats. By adopting such an approach, it is assumed that both the habitats and those species associated with them will be conserved and that good ecological status (favourable conservation status) will be achieved. Consequently, the principal indicators currently employed for biodiversity conservation in the coastal zone relate to the areal extent of the different habitats and the quality of the habitat in terms of good ecological status/favourable conservation status.

Because habitats are extremely complex, dynamic features, the number of indicators of structure and function potentially available to define them tends to be large. Moreover, most indicators are resource- and time-intensive (hence expensive) to measure and also difficult to specify with precision as they exhibit substantial levels of inherent variation. As a result they are, at present, not directly useful for management purposes. However, given greater knowledge of the relationships between surface elevation and local tidal frame (frequency and duration of tidal inundation) and the diversity and abundance of the flora and fauna of inter-tidal areas, it might prove possible to construct generalised distribution patterns for the inter-tidal biota in relation to the tidal regime at different shore levels. These could then be employed to more accurately assess the significance of likely changes in the biota as a result of inundation from the sea.

Further assessments could be made as to the condition of vegetated shingle and sand dune habitats using surface elevation. Changes in the cross-sectional profile of a shingle shore or the variability of surface elevation within a sand dune system, for example, might reasonably be expected to correlate with consequent changes in biotic community structure. Any assessment along these lines, however, requires improvements in our understanding of the relationships involved.

10.2.3 Indicators of habitat quality

The strategic goal of the UK BAP is to conserve and enhance biological diversity. The key ecological objective is to maintain and increase priority habitat extent and quality.

The indicator chosen to reflect performance with regard to the extent of priority habitats is that there should be no further net loss. This requires that the annual rate of loss is known and that an equal amount of each habitat is created, annually, to replace the area of habitat lost each year. Thus, the metric is area in hectares; a clearly defined quantitative parameter that can be readily measured and translated onto a map for incorporation into, manipulation within and presentation by a GIS. The information required to ensure that there is no further net loss of any given coastal habitat can, therefore, be easily handled by the approach proposed here.

What is needed in terms of an indicator of coastal habitat quality is a quantitative or semi-quantitative metric, or set of metrics, that is/are readily measurable and able to integrate the principal characteristics of structure and function that define the quality of that habitat. Ideally, the metric(s) should also be generally applicable to all coastal habitat types and suitable for use by a GIS and suitable modelling tools.

Here, the surface elevation of a coastal habitat relative to the local tidal frame has been employed as a general indicator of overall habitat quality. The surface elevation of landforms can be readily determined remotely over wide areas by LiDAR, a remote sensing technology based on data acquisition from an aeroplane. Capable of covering areas of at least 20 km^2 in one day, LiDAR is a cost-effective technique that is particularly well-suited to inter-tidal areas as it can, effectively, ‘see through’ relatively clear, shallow water and maximise coverage of landforms over the limited period of tidal exposure.

10.2.4 Application of remote sensing techniques

Various remote sensing techniques with the potential to provide information on general habitat condition, in terms of the quality of the vegetation community, are available. Typically, they record electromagnetic spectral (EMS) radiation at a range of wavelengths. The reflectance patterns of light from vegetated ground surfaces are known to vary according to the type of vegetation and its condition (such as young - healthy – stressed – senescent - dying). The current condition of vegetation over wide areas can thus be established remotely, from the air, by means of EMS techniques. The most straightforward and well known of these is aerial photography, but the most relevant is, probably, the Compact Airborne Spectrographic Imager (CASI). The CASI system can detect and record twenty-one wavelength bands, enabling a high degree of discrimination between features on the Earth's surface. Aerial photography and CASI recording can be readily undertaken in conjunction with LiDAR measurements. Collectively, they can provide precise mapping of inter-tidal habitat types together with the surface elevation, in relation to the tidal frame, at any given point, thereby providing the basic information required to assess the likely consequences of flooding from the sea for biodiversity in the coastal zone.

11 Concluding remarks

Knowledge from the scientific literature and expert consultations on the sensitivities of coastal and fluvial environmental assets to the impacts of flooding was reviewed. This knowledge was summarised in a series of rules used to produce two spreadsheet-based tools. One coastal tool was produced to assess progressive coastal flooding whereas two fluvial tools were produced, one to assess a new flood regime and the other to assess a specified event. The tools can be used to carry out broad-scale assessments of flooding impacts. Consideration has been given to undertaking a more detailed flood impact assessment.

Pilot testing illustrated the successful application of both tools to assessing the impacts of progressive coastal inundation due to relative sea level change, a future fluvial regime and a specified fluvial event. Verification of the pilot test results provided confidence in the tools. However, the tools developed here should only be used by individuals with a substantial professional knowledge and they are prototypes which need further testing and validation (see Section 12 on future research) before being put into practice. Limitations and uncertainties were discussed and these strongly relate to the resolution and accuracy of available data. It is clear from the discussion of strategy and legislation that both tools have the potential to support the Environment Agency in the entire flood risk management process. As well as assessing gains or losses in habitats, both tools could be used to evaluate the potential of sites for habitat restoration/creation and through studying the results from snapshots in time, they may be used to prioritise flood protection.

12 Future research

12.1 Fluvial Studies

12.1.1 Enhancements to NAFRA

Frequent flooding: environmental conditions reflect more frequent flooding (low return period) than usually considered by NAFRA in assessing economic damage. More information on flood extents is needed at low return periods (up to 10 years). This includes two main aspects: (a) a better assessment of bankfull flow and its variation along river channels – incorporating better information on local channel geometry/configuration, and (b) increasing the number and reducing the width of probability slices used in NAFRA at low return periods.

Drowned channels and surface saturation: many environmental benefits arise prior to true floodplain inundation, with the wetting up of leats and surface depressions. More information on the frequency of sub-bankfull spate flows is needed.

Local flood water: the impact of local runoff and groundwater needs to be defined better.

Flood duration: a significant component of environmental consequences that is not considered in either the peak flow loading or the simplified flood spreading method currently in NAFRA is flood duration. Assessing how quickly flood waters drain away requires channel hydrographs and hydraulic routing calculations.

Catchment flood drivers: NAFRA concentrates on the uncertainty of flood defence failures, but ignores uncertainties in other factors affecting flood response – for example: storm patterns; antecedent conditions, soil and topographical changes; hydrograph shapes, tributary impacts, flood duration and seasonality. Such uncertainties are rolled into the methods that underlie the depth frequency loading curves used by NAFRA. QMED has a factorial standard error of about 1.45, giving about a 67 per cent chance that the true value is between +45 and -31 per cent of the estimate. Factorial error bands associated with rarer floods are not well quantified, but may be expected to be larger. Traditional choices of design return periods reflected such uncertainties, but no account is taken in NAFRA.

Seasonality: although the pilot work on seasonality in this project, using daily mean flow data, has not been included directly in the tool, seasonality remains a significant control on the environmental consequences of flooding. While benefits may arise from frequent winter flooding, growth and breeding season floods could be very damaging. The pilot work aimed to apply seasonality factors to the NAFRA annual flood probabilities, but seasonality would better be applied to the flood loading curves while generating the NAFRA outputs. The strong seasonality found in the pilot study (spring and summer overbank floods were on average only eight and as likely as winter floods) combined with the lack of detail in NAFRA for frequent floods has not allowed realistic assessment of seasonal flood probabilities and their impact on habitats. Further work on seasonality is necessary, considering instantaneous flood peaks and possibly different seasonal periods.

12.1.2 Sediment impacts

The ecological implications of fine sediment are currently an active area of research (see, for example http://www.floodrisk.org.uk). Further research is required to extend the scope of engineering and geomorphic research to account for the environmental consequences of flood-related sediments and morphological changes. This work should be supported, as the results will be critical here.

Recent research on sediment dynamics in fluvial systems has focused on coarse bed material (for recent reviews, see Henshaw, 2009 and Parker, 2010). Understanding impacts of fine sediment on ecology requires a better knowledge of its entrainment, transport and deposition throughout catchments and in river channels, and further fundamental research is essential in this context.

12.1.3 Hydraulics

National mapping of specific stream power may be useful in assessing ecological impacts and environmental consequences of floods (see Parker, 2010 for arguments).

Improved knowledge of floodplain hydraulics and their interaction with flow within, exiting and re-entering the channel is required to better understand the exchange of water, momentum, sediments, seeds and propagules between the channel, its riparian corridor and floodplain during floods.

12.1.4 Ecology

Given that the eco-hydrological requirements of fens, lowland grasslands and swamps are increasingly well known, the priority should be to investigate empirically the tolerances of those habitats where some preliminary studies and reviews have occurred such as for wet woodland and wet heathland, and then expand the coverage to include the full range of broad habitats potentially affected by flood.

12.2 Coastal studies

Further research that would help improve the coastal tool developed here has already been alluded to. It is summarised below:

- Improvement in the quantity (extent of coverage) and quality of base data on habitats, surface elevations and tidal levels used by the coastal tool.
- Incorporation of latest understanding of coastal process information, perhaps via links with modelling techniques.
- Better indicators of habitat quality.
- Improved understanding of relationship between surface elevations and local tidal frame and the distribution and abundance of flora and fauna.
- Improved understanding of the tolerance/sensitivity of biota to frequency and duration of inundation by seawater.
- Assignment of realistic monetary values and social benefit judgements to environmental and ecological assets in the coastal zone.

- Use of suitable remote sensing techniques, such as aerial photography and CASI, to better inform the coastal tool in terms of habitat quality.

12.3 Further validation

Validation of the EIA F and EIA C tools was limited to expert review of pilot test results from two fluvial catchments and two coastal regions. This successfully demonstrated the applicability of the prototype tools. Experts commented on the likely accuracy of the predicted impacts, as validating pilot tests through groundtruthing is extremely difficult.

Ground-truthing the scenario-driven fluvial and coastal pilot tests was problematic as there were no precedents. Ground-truthing the event-driven fluvial pilot test was also problematic. Firstly, the simulated July 2007 flood event was based on a broad estimate of hydrology. The return period of the event was estimated and the closest NAFRA flood probability outline was used. Secondly, assessing the impact of large events is not independent. Expert knowledge used to define many of the rules in the tool originated from the impacts of recent large events. Thus, it is not valid to test impacts of a simulation of one of these events with rules based on observations from the same event. Thirdly, even if it were valid to validate the tool using historic events, the lack of systematic monitoring of impacts means that this is extremely difficult. Most impacts of floods are anecdotal. Fourthly, assessing the impact of a given event in a given season in just two catchments meant that not all potential impacts of flooding could be assessed.

The project team propose that the tools should be validated in two ways, both of which require effort and careful planning. Firstly, through systematic monitoring of the impacts of future flood events the validity of the tool could be assessed. Secondly, the predicted impacts of several scenarios in several catchments could be reviewed in a workshop forum (possibly international). The collective knowledge of many experts on a range of scenarios should reduce the personal bias and subjectivity in the validation.

References

Amoros C. and Bornette G.. 2002. Connectivity and biocomplexity in water bodies of riverine floodplains. *Freshwater Biology,* 47, 761-776.

Armitage, P.D. and Ladle, M. 1991. Habitat preferences of target species for application in PHABSIM testing. In: A. Bullock, A. Gustard and E.S. Granger (editors) *In-stream Flow Requirements of Aquatic Ecology in Two British Rivers*, Institute of Hydrology, Report No. 115, p. 87-122.

Ausden, M., Sutherland, W.J. and James, R. 2001. The effects of flooding lowland wet grassland on soil macroinvertebrate prey of breeding wading birds. *Journal of Applied Ecology*, 38, 320-338.

Ausden, M. and Hirons, G.J.M. 2002. Grassland nature reserves for breeding wading birds and the implications for the ESA agri-environment scheme. *Biological Conservation*, 106, 279-291.

Baker, C., Thompson, J.R. and Simpson, M. 2009. Hydrological dynamics I: Surface waters, flood and sediment dynamics. In: Maltby, E.B., Barker, T. (editors) *The Wetlands Handbook.* Chichester: Wiley-Blackwells, 120-168.

Baras, E. and Lucas, M.C. 2001. Impacts of man's modifications of river hydrology on the migration of freshwater fishes: a mechanistic perspective. *Ecohydrology and Hydrobiology,* 1, 291-304.

Bischoff, A. and Wolter, C. 2001. The flood of the century on the River Oder: Effects on the 0+ fish community and implications for floodplain restoration. *Regulated Rivers: Research and Management*, 17, 171-190.

Bradford, MJ. 1997. An experimental study of stranding of juvenile salmonids on gravel bars and in side channels during rapid flow fluctuations. *Regulated Rivers: Research and Management*, 13, 395-401.

Bradford, M.J., Taylor, J.A., Allan, J.A. and Higgins, P.S.. 1995. An experimental study of stranding of juvenile coho salmon and rainbow trout during rapid flow decreases in winter conditions. North *American Journal of Fisheries Management,* 15, 473-479.

Bunn, S.E., and Arthington, A.H. 2002. Basic principles and ecological consequences of altered flow regimes for aquatic biodiversity. *Environmental Management*, 30, 492-507.

Carline, R.F. and McCullough, B.J.. 2003. Effects of Floods on Brook Trout Populations in the Monongahela National Forest, West Virginia. *Transactions of the American Fisheries Society*, 132, 1014-1020.

Clark, C,F. 1950. Observations on the spawning habits of the northern pike, Esox lucius, in north western Ohio. *Copeia*, 4, 285-288.

Conlan, K., Wade, T., Dangerfield, S., Nottage, A., Dangerfield, H., Ramsbottom, D., Holmes, N., Richards, K. and Allen, J. 2006. Broad-scale ecosystem assessment (BSEA) BSEA Toolbox 1, Environment Agency/Defra R&D Technical Report FD2112/TR, 224pp.

Conlan, K., Nottage, A., Elliott, M., Painter, D., Seynour, R., Richards, K. and Hull, S. 2002. Broad-scale Ecosystem Impact Modelling Tools: Scoping Study. Final Report on FD2108 to Defra and the Environment Agency.

Copp, G.H. 1989. The habitat diversity and fish reproductive function of floodplain ecosystems*. Environmental Biology of Fishes*, 26, 1-27.

Copp, G.H. 1990. Effect of regulation on 0+ fish recruitment in the Great Ouse, a lowland river. *Regulated Rivers: Research and Management,* 5, 251-263.

Cortes, R.M.V., Ferreira, M.T., Oliveira, S.V. and Oliveira, D. 2002. Macroinvertebrate community structure in a regulated river segment with different flow conditions. *River Res. Applic*. 18, 367-382.

Cowx, I.G., Noble, R.A., Nunn, A.D., Harvey, J.P., Welcomme, R.I. and Halls, A.S.. 2004. *Flow and level criteria for coarse fish and conservation species*. Environment Agency publication.

Crisp, D.T. 2000. *Trout and Salmon: Ecology, Conservation and Rehabilitation*. Oxford: Fishing News Books, Blackwell Science.

Defra, 2006. Flood and Coastal Defence Appraisal Guidance FCDPAG3 Economic Appraisal Supplementary Note to Operating Authorities – Climate Change Impacts, Department for Environment, Food and Rural Affairs, October 2006.

Environment Agency, 2002. R&D Technical Report E2A: *Biodiversity Key Resources Inventory*.

Elwood, J.W. and Waters, T.F. 1969. Effects of floods on food consumption and production rates of a stream brook trout population. *Transactions of the American Fisheries Society,* 98, 253-262.

FAME. 2004. Development, Evaluation & Implementation of a Standardised Fish-based Assessment Method for the Ecological Status of European Rivers - A Contribution to the Water Framework Directive (FAME). Final Report to the European Union. FAME EVK1-CT-00094-2001.

Fleituch, T. 2003. Structure and functional organisation of benthic invertebrates in a regulated stream. *Internat. Rev. Hydrobiol*., 88, 332-344.

Garner, P. 1997. Seasonal variation in the habitat available for 0+ *Rutilus rutilus* (L.) in a regulated river. *Aquatic Conservation - Marine and Freshwater Ecosystems,* 7, 199-210.

Gilman, K. 1994. Hydrology and Wetland Conservation, Wiley, London, UK.

Gilvear, D.J. and Bradley, C. 2000. Hydrological monitoring and surveillance for wetland conservation and management; a UK perspective. *Physics and Chemistry of the Earth (B),* 25(7-8), 571-588.

Gowing, D.J.G, Gilbert, J.C., Youngs, E.G. and Spoor, G. 1997. *Water regime requirements of the native flora - with particular reference to ESAs.* Final report to Ministry of Agriculture, Fisheries and Food. Cranfield University.

Gowing, D.J.G., Lawson, C.S., Youngs, E.G., Barber, K.R., Rodwell, J.S., Prosser, M.V., Wallace, H.L. Mountford, J.O. and Spoor, G. 2002. *The water regime requirements and the response to hydrological change of grassland plant communities.* Final report for Defra-commissioned project BD1310. Silsoe: Cranfield University.

Green, R.E. 1986. The management of lowland wet grassland for breeding waders. Royal Society for the Protection of Birds.

Grift, R.E., Buijse, A.D., Van Densen, W.L.T., Machiels, M.A.M, Kranenbarg, J., Breteler, J.P.K. and Backx, J. 2003. Suitable habitats for 0-group fish in rehabilitated floodplains along the lower River Rhine. *River Research and Applications,* 19, 353-374.

Hammersmark, C.T., Rains, M.C. and Mount, J.F. 2008. Quantifying the hydrological effects of stream restoration in a montane meadow, northern California, USA. *River Research and Applications*, 24(6), 735-753.

Harvey, G.L. and Wallerstein, N.P. 2009. Exploring the interactions between flood defence maintenance works and river habitats: the use of River Habitat Survey data. *Aquatic Conservation: Marine and Freshwater Ecosystems*, 19, 689-702.

Hendry, K., Cragg-Hine, D., O'Grady, M., Sambrook, H. and Stephen, A. 2003. Management of habitat for rehabilitation and enhancement of salmonid stocks. *Fisheries Research*, 62, 171-192.

Henshaw, A.J. 2009. Impacts of land use changes and land management practices on upland catchment sediment dynamics: Pontbren, mid-Wales. Unpublished PhD thesis. University of Nottingham.

Hughes, F.M.R. 2003. *The Flooded Forest: Guidance for policy makers and river managers in Europe on the restoration of floodplain forests.* FLOBAR2, Department of Geography, University of Cambridge, UK.

Humphries, P., King, A.J. and Koehn, J.D. 1999. Fish, flows and floodplains: links between freshwater fishes and their environment in the Murray-Darling River system, Australia. *Environmental Biology of Fishes,* 56, 129-151.

Jackson, B.M., Pagella, T.F., Sinclair, F.L., Orellana, B., Henshaw, A.J., Reynolds, B., Mcintyre, N., Wheater, H. and Eycott, A. (In review). POLYSCAPE: a GIS mapping toolbox providing efficient and spatially explicit landscape-scale valuation of multiple ecosystem services. *Environmental Modelling and Software*.

JNCC, 2010. www.jncc.gov.uk/page-4267

Junk, W.J., Bailey, P.B. and Sparks, R.E. 1989. The flood-pulse concept in river-floodplain systems. In> Dodge, D.P. (editor). *Proceedings of the International Large River Symposium*. *Canadian Special Publication of Fisheries and Aquatic Sciences.* Pages 110-127.

Kwak, T.J. 1998. Lateral movement and use of floodplain habitat by fishes of the Kankakee River, Illinois. *American Midland Naturalist,* 120, 241-249.

Lane, S.N. and Thorne, C.R. 2007. River Processes. In: Thorne, C.R., Evans, E.P., Penning-Rowsell, E.C. (editors) *Future Flooding and Coastal Erosion Risks*. London: Thomas Telford, 82-99.

Lane, S.N. and Thorne, C.R. 2008. Fluvial Systems and Processes. In: Evans, E.P., Simm, J.D., Thorne, C.R., Arnell, N.W., Ashley, R.M., Hess, T.M., Lane, S.N., Morris, J.,
Nicholls, R.J., Penning-Rowsell, E.C., Reynard, N.S., Saul, A.J., Tapsell, S.M., Watkinson, A.R., Wheater, H.S. (editors) *An update of the Foresight Future Flooding 2004 qualitative risk analysis.* Cabinet Office, London, pages 83-92.

Lane, S.N., Reaney, S.M. and Heathwaite, A.L. 2009. Representation of landscape hydrological connectivity using a topographically driven surface flow index, *Water Resources Research*, 45, W08423, doi:10.1029/2008WR007336.

Lane, S.N., Brookes, C.J., Reaney, S.M., and Heathwaite, A.L. 2006. Surveillant Science: Challenges for the management of rural environments emerging from the new generation diffuse pollution models. *Journal of Agricultural Economics*, 57 (2), 239-257.

Lane, S.N., Reid, S.C., Tayefi, V., Yu, D. and Hardy, R.J. 2008. Reconceptualising coarse sediment problems in rivers as catchment-scale and diffuse. *Geomorphology*, 98, 227-249.

Lapointe, M., Eaton, B., Driscoll, S. and Latulippe, C. 2000. Modelling the probability of salmonid egg pocket scour due to floods. *Canadian Journal of Fish Aquatic Science,* 57, 1120-1130.

Lucas, M. Baras, E. 2001. *Migration of Freshwater Fishes*. Oxford: Blackwell Science.

Madsen, J.D., Chambers, P.A., James, W.F., Koch, E.W. and Westlake, D.F. 2001. The interaction between water movement, sediment dynamics and submersed macrophytes. *Hydrobiologia*, 444, 71-84.

Masse, G., Dumont, P., Ferrais, J. and Fortin, R. 1991. Influence of the hydrological and thermal regimes of the Aux Pins River (Quebec) on the spawning migrations of northern pike and on the emigration of 0+ juveniles. *Aquatic Living Resources,* 4, 275-285.

Masters, J.E.G., Welton, J.S., Beaumont, W.R.C, Hodder, K.H., Pinder, A.C, Gozlan, R.E. and Ladle, M. 2002. Habitat utilisation by pike *Esox lucius* L. during winter floods in a southern English chalk river. *Hydrobiologia,* 483, 185-191.

Mchugh, M., Wood, G., Walling, D., Morgan, R., Yusheng Zhang, Anthony, S. and Hutchins, M. 2002. *Prediction of Sediment Delivery to Watercourses from Land Phase II.* R & D Technical Report No P2-209, Environment Agency, UK.

Montgomery, D.R. and Buffington, J.M. 1997. Channel-reach morphology in mountain drainage basins. *Geological Society of America Bulletin*, 109, 596-611.

Mountford, J.O. 2008. Vegetation and plant ecology – environmental consequences of flooding. In: G.H. Old (editor), *Methods to assess, model and map the environmental consequences of flooding: Literature review*. Science Report SC060062, Environment Agency, Bristol.

Mountford, J.O., Rose, R.J. and Bromley, J. 2005. *Eco-hydrological Guidelines for Wet Heaths Phase 1.* Final Report to English Nature.

Mountford, J.O. 2003. *Guidelines for the management and restoration of lowland wet grassland*. London: Department for Environment, Food and Rural Affairs.

Noble, R.A.A., Cowx, I.G.. 2007. *Development of a predictive fish community typology and sensitivity to abstraction rating system for England and Wales to fit into the RAM Framework review.* Draft report: Hull International Fisheries Institute, University of Hull.

Nunn, A.D., Cowx, I.G., Frear, P.A. and Harvey, J.P. 2003. Is water temperature an adequate predictor of recruitment success in cyprinid fish populations in lowland rivers? *Freshwater Biology,* 48, 579-588.

Old, G.H., Laize, C., Nottage, A. and Ramsbottom, D., Mountford, O. 2011. *Ecological inundation impact assessment tools: Applications and limitations*. Guidance Report SC060062, Environment Agency, Bristol, pp.53.

Old, G.H. 2008. *Methods to assess, model and map the environmental consequences of flooding: Literature review*. Science Report SC060062, Environment Agency, Bristol.

Old, G.H. and Acreman, M.C. 2006. *Guidance on compensation flows and freshets. Task 3: a review of literature on environmental flow requirements of UK river ecosystems*. Project WFD 82, Scotland and Northern Ireland Forum for Environmental Research.

Old, G.H. and Thompson, J.R. 2008. Introduction. In: G.H. Old (editor), *Methods to assess, model and map the environmental consequences of flooding: Literature review*. Science Report SC060062, Environment Agency, Bristol.

Pagella, T.F., Reynolds, B., Wheater, H.S., Marshall, M., Jackson, B.M., Henshaw, A.J. and Sinclair, F.L. 2009. *Impacts of Land Use Change on Ecosystem Service Provision at Pontbren.* FRMRC Report (on Polyscape), University of North Wales, Bangor.

Parker, C. 2010. *Quantifying Catchment-Scale Coarse Sediment Dynamics In British Rivers (ST:REAM model).* Unpublished PhD thesis. University of Nottingham.

Parker, C., Thorne, C.R. and Clifford, N.J. (In review). Development and assessment of ST:REAM: a research-based, sediment balance approach for representing catchment-scale coarse sediment dynamics. Earth Surface Processes and Landforms.

Phillips, R.W., Lantz, R.I., Claire, E.W. and Moring, J.R.. 1975. Some effects of gravel mixtures on emergence of coho salmon and steelhead trout fry. *Transactions of the American Fisheries Society,* 104, 461-466.

Poff, N.L., Allan, J.D., Bain, M.B., Karr, J.R., Prestegaard, K.L., Richter, B.D., Sparks, R.E., Stromberg, J.C. 1997. The natural flow regime. *Bioscience,* 47, 769-784.

Pont, D., Hugueny, B., Beier, U., Goffaux, D., Melcher, A., Noble, R., Rogers, C., Roset, N. and Schmutz, S. 2006. Assessing river biotic condition at a continental scale: a European approach using functional metrics and fish assemblages. *Journal of Applied Ecology,* 43, 70-80.

Radley, G.P. 1994. *Sand dune survey of Great Britain – a National Inventory. Part 1 England* (Peterborough, UK: JNCC, Coastal Conservation Branch).

Ramsbottom, D., Acreman, M.C., Nottage, A. 2005. *Environmental consequences of flood risk assessment.* Scoping study EX 5126. Environment Agency, Bristol.

Rempel, L.L., Richardson, J.S. and Healey, M.C. 1999. Flow refugia for benthic macroinvertebrates during flooding of a large river. *Journal of the North American Benthological Society,* 18, 34-48.

Reyjol, Y. *et al.* 2007. Patterns in species richness and endemism of European freshwater fish. *Global Ecology and Biogeography,* 16, 65-75.

Riis, T. and Biggs, B.J.F. 2003. Hydrologic and hydraulic control of macrophyte establishment and performance in streams. *Limnology and Oceanography*, 48(4), 1488-1497.

Sambrook, H., Cowx, I.G. 2000. Wimbleball pumped storage scheme: integration of water resource management, engineering design and operational control to compliment the needs of salmonid fisheries of the River Exe. In: Cowx, I.G. (editor) *Management and Ecology of River Fisheries*. Oxford: Fishing News Books, Blackwell Science.

Seegrist, D.W. and Gard, R. 1972. Effects of Floods on Trout in Sagehen Creek, California. *Transactions of the American Fisheries Society,* 101, 478-482.

Smith, B.P. and Laffoley, D. 1992. A directory of saline lagoons and lagoon-like habitats in England. *English Nature*, 1992.

Sneddon, P. and Randall, R.E. 1994. Coastal vegetated shingle structures of Great Britain: Appendix 3. Shingle sites in England (Peterborough, UK: JNCC, Coastal Conservation Branch).

Sparks, R.E. 1995. Need for ecosystem management of large rivers and their floodplains. *BioScience,* 45, 168-182.

Thomas, G.J. 1976. Habitat usage of wintering ducks at the Ouse Washes, England. *Wildfowl*, 27, 148-152.

Thomas, G.J. 1981. Field feeding by dabbling ducks around the Ouse Washes, England. *Waterfowl*, 32, 69-78.

Thomas, G.J. 1982. Autumn and winter feeding ecology of waterfowl at the Ouse Washes, England. *Journal of Zoology*, 197, 131-172.

Thompson, J.R., Gavin, H., Refsgaard, A., Refstrup Sørenson, H. and Gowing, D.J. 2009. Modelling the hydrological impacts of climate change on UK lowland wet grassland. *Wetlands Ecology and Management,* 17, 503-523.

Thompson, J.R., Refstrup Sørenson, H., Gavin, H. and Refsgaard, A. 2004. Application of the coupled MIKE SHE/MIKE 11 modelling system to a lowland wet grassland in Southeast England. *Journal of Hydrology*. 293, 151-179.

Thorne, C.R., Wallerstein, N.P., Soar, P.J., Brookes, A., Wishart, D., Biedenharn, D.S., Gibson, S.A., Little, C.D., Mooney, D.M., Watson, C.C., Green, A.P.E., Coulthard, T.J. and Van De Weil, M.J. 2011. Accounting for sediment in Flood Risk Management. In: Pender, G. and Faulkener, H. (editors) *Flood Risk Science and Management*. Wiley-Blackwell, pp. 87-113.

UKHO. 2009. Admiralty Tide Tables Volume 1 NP 201-09 United Kingdom and Ireland (including European Channel Ports), The United Kingdom Hydrographic Office, 2009.

Vaughan, I.P. 2010. Habitat indices for rivers: derivation and applications. *Aquatic Conservation: Marine and Freshwater Ecosystems*, S4-S12.

Ward J.V. and Stanford J.A. 1995a. The serial discontinuity concept - extending the model to floodplain rivers. *Regulated Rivers - Research & Management,* 10, 159-168.

Ward J.V. and Stanford J.A. 1995b. Ecological connectivity in alluvial river ecosystems and its disruption by flow regulation. *Regulated Rivers - Research & Management,* 11, 105-119.

Welcomme, R. L. 1985. River Fisheries. FAO Fisheries Technical Paper 262, Food and Agriculture Organisation of the United Nations 330 pp.

Welcomme, R.L., Halls, A. 2001. Some considerations of the effects of differences in flood patterns on fish populations. *Ecohydrology and Hydrobiology* 1.

Wheeler, B.D., Gowing, D.J.G., Shaw, S.C., Mountford, J.O. and Money, R.P. 2004. Ecohydrological guidelines for lowland wetland plant communities (editors Brooks, A.W. Jose P.V. and Whiteman, M.I.). Environment Agency (Anglian Region).

Appendices

Appendix A: Flooding indicators for impacts on sediment

Purpose

This appendix considers the impacts of flooding as they relate to sediment dynamics in the fluvial system and how these may be assessed using currently available datasets. The information presented here forms the basis of rules that are implemented in the ECF fluvial tool.

Overview

Sediment is eroded, transported and deposited by all floodwaters, although the concentration and calibre of sediment associated with a given flood is not simply a function of the magnitude or duration of the event. The nature of sediment dynamics during a flood can significantly influence the environmental impact of that, and subsequent, floods. Consequently, when characterising and predicting the environmental consequences of floods, and how these are likely to be affected by changes in climate and land use, it is necessary to consider sediment-related impacts as well as hydrological impacts.

The sediment-related impacts of floods may be associated with fluvial processes and morphological responses operating across the catchment, in the channel and/or on the floodplain. In describing these process-response mechanisms and proposing possible approaches to modelling them predicatively at a national scale, it is convenient to discuss catchment sediment yields, channel adjustments and floodplain sedimentation separately. However, the catchment, channel and floodplain are actually components of a joined-up fluvial system. It follows that broad-scale modelling of the fluvial system is required to explain and understand the local and reach-scale environmental impacts of flood-related sediments, and that modelling of this type is necessary to inform regional sediment management policies and practices that are environmentally-aligned and sustainable.

Catchment erosion and sediment delivery to watercourses

Background

The sediment load carried by a river during a flood can be characterised as consisting of two components: the ‘bed material load’ and the ‘wash load’. As its name suggests, the bed material load comprises sediment in transport that has a size distribution similar to that making up the channel bed. As material of this size is readily available to the flow through scouring of the bed, the transport rate for bed material load is limited by the capacity of the flow to erode and transport it: that is, the quantity of bed material load is transport-limited. Wash load comprises sediment in transport that is finer than the bed material load and which is not found in significant quantities in the bed. Wash load is derived from sources other than the bed, with erosion of the catchment usually being a major, if not the dominant, contributor. The transport capacity for wash load is much larger than that for bed material load and the quantity carried by the flow is limited only by its availability: that is, the quantity of wash load is supply-limited. In almost all cases, the total load is predominately comprised of wash load, which typically makes up more than 80 per cent of the total load.

As the quantity of wash load is limited by its availability rather than the capacity of the flow to transport it, wash load cannot be predicted using conventional sediment transport equations. Instead, the wash load must be predicted by estimating its rate of supply to the fluvial system, based on multiplying the rate of catchment erosion by a 'delivery ratio' defining the proportion of the eroded sediment that is actually delivered to the drainage network.

Prediction of the environmental consequences of flooding related to wash load dynamics therefore depends on successful modelling of catchment erosion and sediment delivery, which in turn are controlled by the erosivity of the rain, erodibility of the soil, vegetation, land use and degree of transport connectivity between the site of erosion and the nearest watercourse.

In this regard, recent and ongoing UK studies have the potential to model and map catchment sediment yields and their responses to climate and land-use changes at a variety of scales. These are the approaches reported by McHugh *et al.* (2002) and Lane *et al*. (2009).

National scale

McHugh *et al.* (2002) report the second phase of a study into soil erodibility and sediment delivery to watercourses in England and Wales. In Phase I of this research, a clear understanding was developed of the processes involved in sediment delivery from arable land to surface waters. The main objectives of Phase II were to identify and map erosion from arable, grassland and upland areas and combine erosion estimates with an index of the connectivity between eroding hillslopes and watercourses to predict sediment delivery. The main outcome was two maps, the first illustrating the risk of annual erosion vulnerability and the second the spatially averaged (one-km^2 cells) sediment yield to watercourses for selected return periods (such as one in 10 years). Resource limitations prevented validation of the methodology and maps, though the results for the one-in-10-year return period are broadly consistent with the findings of other researchers. On this basis, McHugh *et al.* concluded that "*The maps may therefore be used by Environment Agency personnel to identify potentially high risk areas of England and Wales.*" However, the authors went on to qualify this statement, stressing that the map showing sediment delivery relates specifically to the movement of sediment from hillslopes into watercourses. They therefore caution that their yield map "*cannot be used to indicate sediment yield from specific catchments because issues such as the fate of sediment within the river channel and the supply of additional sediment to the watercourse from the channel bed and banks are not considered*."

While McHugh *et al*.'s (2002) report usefully identifies areas at risk of erosion and the spatial distribution of sediment delivery to watercourses in England and Wales, the authors pointed out limitations with the data and techniques used. For example, soils data were not sufficient to quantify the risk of erosion from different soils at a more detailed level using, for example, soil series, and calibration and validation of the 'connectivity ratio' used to represent the sediment delivery ratio is needed, based on field-based and experimental investigations to improve our understanding of sediment delivery and the factors controlling slope-channel connectivity. Finally, extrapolation of the erosion data across land use types nationally was, in 2002, limited by the availability of information on vegetation cover and specific land uses, which was lower than that currently available.

Given these improvements in data availability, it should now be possible to use the McHugh *et al.* (2002) approach to produce maps showing the effects of land use on the probability and severity of erosion in England and Wales. For example, the impact of changes in cropping involving winter cereals or sugar beet (that are frequently associated with serious erosion) could be investigated. Similarly, it should be possible to simulate scenarios with different grazing intensities in upland regions.

With respect to sediment delivery, our understanding of the factors controlling connectivity has improved considerably since 2002 and this provides the basis for adding further controlling factors into the procedure used by McHugh *et al*. to estimate the connectivity index. For example, it might now be possible to account better for hydrological connectivity using, for example, Lane *et al.*'s 'network index' and incorporation of preferred pathways for water and sediment such as those provided by field ditches, gateways farm tracks and roads (muddy floods) could significantly enhance the model.

The advantage of McHugh *et al*.'s (2002) report is that it provides a comprehensive assessment of erosion vulnerability and sediment delivery to watercourses at a national level and is capable of supporting comparative studies of the impacts of land use changes across a wide range of slopes and soils. The maps produced could be used to identify areas at greatest risk from the sediment-related consequences of flooding so that more detailed, local investigations could be targeted on the most vulnerable regions.

Catchment scale

Ongoing research led by the Institute of Hazard and Risk Research at Durham University has resulted in 'Scimap' - a GIS-based method of mapping the spatial distribution of the risks associated with diffuse sources of fine sediment at the catchment scale. Scimap estimates erosion probability using a cellular representation of the catchment (cell size is typically 100 m^2) based on land cover (from the CEH land cover map) together with expert judgement of the probability of erosion occurring. It is assumed that eroded sediment is transported from areas experiencing saturation overland flow (SOF), and these are predicted topographically, with simple assumptions on soil thickness and permeability. The probability that the SOF in the source areas for surface runoff will have the capacity to transport the eroded sediment is represented by an index of stream power (upslope drainage area x local slope). Routing of transported sediment through the catchment and to the watercourses is achieved using a 'network index' that accounts for the degree of connectivity between partial source areas for SOF. In calculating the risk that eroded sediment will be delivered to a watercourse, Scimap sums the risks for all contributing cells draining to a given point in the watercourse before dividing by the number of contributing cells to derive the risk concentration. This is then weighted according to the distribution of rainfall over the catchment.

For the analysis of sediment-related risks within the drainage network, a threshold drainage area for there to be a channel is selected (such as 10,000 m^2) and the relative risk (sum of risks in the upstream cells divided by the number of contributing cells) is mapped on a continuous scale from the highest value in the catchment (red) to the lowest (green).

The network index is a key component of Scimap and Lane *et al.* (2009) report that it can be used to generalize a significant proportion of the time-averaged spatial variability in connectivity, in terms of both the propensity to connect and the duration of connection. They also point out that the extent to which this finding holds true varies with the strength with which topography controls hydrological response. Hence, it should work well in catchments with relatively shallow soils and impervious geologies, where it provides a reasonable basis from which to predict the delivery of sediment to the drainage network and so assist with diffuse pollution and climate change impact studies. The converse is also true, however, and it follows that in its current form Scimap should not be expected to perform well in lowland catchments with thick soils and permeable geologies.

A corollary of the use of Scimap to route fine sediments from eroding sources to watercourses is that in addition to mapping preferred sediment pathways, it also provides a means of identifying intermediate storage sites that protect watercourses from critical source areas in river catchments. Hence, Scimap might be used to investigate options for reducing sediment loads in rivers through managing erosion rates and delivery ratios in vulnerable catchments.

Scimap is not currently suitable for national use, first because its applicability is limited to catchments where surface runoff is predominantly generated by SOF and, second, because it represents risk in relative terms within a catchment. That is to say, it could not be used to compare the risks associated with the sediment-related consequences of flooding in, for example, Cumbria and Kent. A further constraint on its applicability stems from the fact that Scimap cannot currently be applied to catchments larger than the River Eden, although this constraint should disappear as the model is further developed over the next couple of years.

Conclusion

It is possible to assess the risks associated with catchment erosion and sediment delivery during floods at the national and catchment scales using the approaches reported by McHugh *et al.* (2002) and Lane *et al*. (2009). With further limited research and development, these approaches could be applied to investigate the impacts of climate and land-use changes in order to identify areas that are particularly vulnerable to sediment-related damage to the environment.

Adjustments of the fluvial system

Background

Catchment-based approaches cannot be used in isolation to predict the sediment-related impacts of floods in rivers because the channel of an alluvial stream is free to adjust in response to short-term perturbations (by the flood itself) and longer-term changes in the hydrologic and sediment regimes. Consequently, when assessing sediment impacts and risks to the environment, the dynamics of sediment within the river channel must also be considered, with the addition or loss of sediment from the watercourse through degradation or aggradation of the channel bed and erosion or accretion of the channel banks being accounted for.

The movement of sediment through river channels is notoriously difficult to predict. Exhaustive tests of competing sediment transport equations suggest that those based on stream power have the widest applicability and it is, therefore, no surprise that a great deal of research is currently being done on the distribution of stream power in British Rivers. However, the way in which stream power is determined is currently being debated. It is universally agreed that stream power may be characterised by the product of energy slope and discharge, but selection of the appropriate slope and discharge for this purpose remains deeply contested. In fact, this research is not yet sufficiently advanced to produce an accurate and complete national map of stream power which could be interpreted in terms of the sediment-related consequences of floods for in-channel habitats and environments (Parker, 2010; Parker *et al*. in review).

An alternative to assessing sediment-related risks based on stream power analysis might be to use regime analysis. Regime analysis is based on the premise that there exist deterministic relationships between an index of discharge (the channel-forming flow) and the resultant dimensions of the channel (width, depth, slope, velocity). Regime equations sometimes include further variables describing the nature of the bed material and the erosion resistance of the bank materials or bank vegetation.

A great deal of research effort has been expended in trying to establish the magnitude and return period of the channel-forming flow. In natural channels that are fully adjusted to the imposed flow and sediment regimes, this usually corresponds to about the bankfull discharge and has a return period of between one and five years. Hence, it is possible to assess the likely impact of changes in the channel-forming flow (or range of flows) on the stable geometry of the channel using regime analysis. This type of approach to predicting the impacts of climate change on British rivers was adopted in considering the implications of morphological changes for flood risk management as part of the Foresight project on future flood risks (Lane and Thorne, 2007; 2008).

The problem with using regime analysis is that predictions apply only to the future stable form of the channel that is achieved once dynamic adjustments have worked themselves out. During the adjustment phase, unstable channels display complex responses that may involve marked departures from the stable form. This is because rivers behave as dynamical, complex systems so that rates and directions of channel change are non-linear and highly variable. As the environmental consequences of sediment-related adjustments depend heavily on the types and sequences of change, as well as the final stable form of the channel, it is unlikely that regime analysis based on the magnitude and direction of changes to the range of channel-forming flows provides an adequate basis from which to assess the risks to habitats and ecosystems. In practice, these impacts are likely to be specific to the flood, site and catchment contexts.

Given this, an alternative approach might be to assess the risks to the environment associated with flood sediments based on the local sensitivity of the channel to destabilisation by flood events and its capacity to accommodate longer-term changes in the hydrologic and sediment regimes in ways that do not pose hazards to in-channel habitats. In natural channels, resilience to perturbation varies between different channel types. The capability of a channel to respond to longer-term changes in the flow and sediment regimes depends crucially on the degree to which the channel is able to operate naturally, through mutual adjustment of its dimensions, cross-sectional geometry, slope and planform. On this basis, environmental risks will be relatively low in natural channels but relatively high in channels that have been modified or constrained artificially. In this respect, in-channel environments within river reaches defined under Water Framework Directive (WFD) as ‘Heavily Modified Water Bodies’ (HMWB) are likely to be particularly vulnerable to sediment-related perturbation and change.

On this basis, treating HMWBs as a sub-set of rivers in general would appear to be a valid step when assessing the in-channel, environmental risks associated with flood-related sediments and the impacts of future climate and land-use changes.

In dealing with reaches not designated as HMWBs, the next step might be to assess risks based first on the type of channel (defined using the Montgomery-Buffington method) and, second, based on its capacity to accommodate changes naturally using the River Habitat Survey’s ‘Habitat Modification Score’.

HMWBs

There is a major divide in the sediment-related risks of floods between heavily modified water bodies (HMWBs) and natural channels. Most HMWBs feature:

1. disconnection between the channel and floodplain;

2. artificial stabilisation of the banks and/or bed.

In the case of channels that are disconnected from their floodplains, floods and associated sediment erosion, transport and deposition are constrained to the area between the levees or flood walls. Consequently, rates of channel erosion or deposition are amplified and may exceed natural rates by orders of magnitude. In a natural, alluvial stream the channel is free to respond to perturbation or change through mutual adjustments to nine degrees of freedom. Specifically, a single-thread channel may adjust its:

1. width
2. mean depth
3. maximum depth
4. bed grain median size
5. bed grain size distribution
6. bedform wavelength
7. bedfrom amplitude
8. meander wavelength
9. bend arc angle.

However, where the channel boundaries are artificially stabilised, the number of morphological degrees of freedom that the river has available to adjust in response to flood flows is reduced. Sediment-driven, morphological responses to floodings, climate change and land use change will be concentrated in those aspects of the channel that remain unconstrained, leading to exaggerated and unnatural types, rates and patterns of channel change.

In natural channels, sediments are exchanged freely with the floodplain and the morphological impacts of floods are distributed between multiple dimensions of channel adjustment. Consequently, the environmental impacts are often beneficial or at least much less damaging than in HMWBs.

The national distribution of HMWBs (at least for main rivers and critical ordinary watercourses (COWS)) has already been mapped by the Environment Agency-WFD team. The first step in assessing the national distribution of environmental risks associated with flood sediments should be to obtain this map and flag HMWBs as candidate sites for high relative risk. Local studies would then be necessary to flesh out the national picture based on the artificially modified form of the channel, the degree to which it is constrained and disconnected from its floodplain and the frequency and intensity of sediment-related maintenance.

‘Natural’ channels

In England and Wales very few river reaches are in a pristine or natural condition and even rivers that are not considered HMWBs display varying degrees of unnatural modification that affects the impacts of flood sediments on the environment. The degree of artificial modification has for some years been represented in the River Habitat Survey methodology by the Habitat Modification Score (HMS). Modification reduces the capacity of the channel to accommodate perturbation and change naturally – increasing risks to habitats and making it more likely that the sediment-related consequences of floods will be environmentally adverse.

The RHS team has recently made great strides in analysing the RHS database and a national map of channel habitat modification could be produced based on HMS scores for nearly 20,000 sites distributed throughout England and Wales. In this regard, the RHS team should coordinate a research effort linking different levels of HMS and different types of modification to adverse sediment-related impacts and the vulnerability of channels to disturbance by climate and land-use related changes to the flow and sediment regimes. This effort would be particularly valuable if it were matched to national classification of channel types based on the Montgomery and Buffington (1997) scheme.

Local adjustments

Shields numbers have been calculated in hydrological investigations performed in the project to determine the environmental consequences of floods. Shields number is a dimensionless bed shear stress that can be used to assess the mobility of bed sediments during floods. At a reach scale, it should be possible to infer whether sediment responses to changes in the range of channel forming discharges are likely to be led by erosion or deposition, depending on whether changes in the formative discharge cause Shields numbers to increase or decrease. If the changes in Shields number could be combined with knowledge of the Montgomery-Buffington stream type, this might support prediction of indicative patterns of channel adjustment (aggradation, degradation, widening, accelerated lateral shifting or planform metamorphosis).

Floodplain sedimentation

By definition, floods are conventionally viewed as events that exceed the conveyance capacity of the channel to inundate the surrounding floodplain. It follows that consideration of the sediment-related, environmental consequences of floods must extend to the floodplain. Generally, floods deposit sediment on the floodplain, although overbank scour also occurs, particularly where natural flow paths for floodwaters are impeded or blocked artificially.

During the last decade, a concerted research effort in the UK has looked at rates of floodplain sedimentation. Much of this work may be traced back to the fundamental research of Professor D E Walling at Exeter University. Based on this work, floodplain sedimentation rates have been established for selected catchments throughout England and Wales, although investigations performed as part of the work reported herein failed to locate a national map. What are available are regional floodplain sedimentation rates and indicative information on sediment sources (gained from 'sediment fingerprinting') such as catchment erosion and bank retreat. If the available information on past regional floodplain sedimentation rates and sediment sources were to be combined with data on catchment sediment delivery (from, for example, McHugh *et al*., 2002), the propensity for channel adjustment (from application of the Montgomery-Buffington typology) and consideration of the degree of channel modification (from the RHS database and WFD-HMWB maps), it should be possible to estimate the indicative impacts of changes in climate and land use on regional floodplain sedimentation rates, at least as a first approximation.

References

Lane, S.N., Reaney, S.M. and Heathwaite, A.L. 2009. Representation of landscape hydrological connectivity using a topographically driven surface flow index, *Water Resources Research*, 45, W08423, doi:10.1029/2008WR007336.

Montgomery, D.R. and Buffington, J.M. 1997. Channel-reach morphology in mountain drainage basins. *Geological Society of America Bulletin,* 109, 596-611.

McHugh, M., Wood, G., Walling, D., Morgan, R., Yusheng Zhang, Anthony, S. and Hutchins, M. 2002. *Prediction of Sediment Delivery to Watercourses from Land Phase II*. R & D Technical Report No P2-209, Environment Agency, UK, 99p.

Parker, C. 2010. Quantifying Catchment-Scale Coarse Sediment Dynamics In British Rivers (ST:REAM model), Unpublished PhD thesis. University of Nottingham.

Parker, C., Thorne, C.R., and Clifford, N.J. (In review). Development and assessment of ST:REAM: a research-based,sediment balance approach for representing catchment-scale coarse sediment dynamics. *Earth Surface Processes and Landforms*.

Appendix B: Seasonal flood risk and relationship with catchment descriptors

Purpose

This appendix describes the research undertaken to augment NAFRA annual inundation probabilities with seasonal adjustments and to provide estimates of typical flood durations. This work was necessary owing to the major impact that timing and duration of flooding is likely to have on ecology.

Background – the approach, data used and choice of seasons

Conventional flood risk analysis is mainly concerned with protecting and alleviating the damage due to flooding of human settlements – by design a relatively rare occurrence and one in which the time of year is usually of little importance. The *UK Flood Estimation Handbook* (FEH), of which a basic understanding is assumed, and indeed the NaFRA mapping that depended on it, is thus aimed mainly at floods of greater than a 10-year return period. Moreover, information on seasonality is only used to assess similarity between catchments in pooling groups. When considering the wider environmental impacts of flooding, severe (rare) flood events are still likely to cause universal damage, but some environments require frequent flooding, especially in certain seasons. More information was therefore needed on frequent flooding (up to five-year return periods) and on the effect of seasonality, both in flood response and in its likely environmental impact.

Although seasonality derives from a continuous cyclic process, it is usually assessed by separating the year into a number of quasi-stable periods. The number and duration of such periods depends on the processes and phenomena under study, and is discussed later.

Ideally, seasonal flood loadings (river depth-probability relationships) at model nodes should be used to generate separate seasonal NaFRA maps. However, as a first step, the aim has been to relate the existing NaFRA flood depth probabilities to equivalent seasonal probabilities. To this end, for each point on the floodplain (x), the corresponding point (r) on the river network that controls flooding at (x) must be found. A suitable procedure to define these points (r) was specified by CEH, and has been applied by HR to create a national GIS layer. Next, for the NaFRA flood depth probability (p) at (x), an equivalent flow rate (q) is read from the annual river flow-probability relationship at (r). Using this (q) value as a pivot, the corresponding seasonal flow-probability relationship at (r) defines an equivalent seasonal probability (p') that can be applied to the floodplain site (x) as well. This procedure can easily be extended to predict duration of floodplain inundation from duration of river flooding. It assumes the levels at floodplain (x) and river (r) are directly linked, and is not therefore applicable to areas of defended floodplain. However, most areas where environmental assessment of flooding is necessary are unlikely to be defended.

Currently there is no ideal source of data to analyse and predict seasonal flow-probability relationships. Some information on flood seasonality for over 850 catchments is held at CEH in the Peaks over Threshold (POT) database (Bayliss and Jones, 1993), but the threshold approach means that information on dry season peak flows is incomplete. An alternative approach has been adopted using the daily-mean-flow data from the National River Flow Archive (NRFA) held at CEH. The assumption is that any relationship between seasonal and annual values for daily floods can be applied, at least on a pilot basis, to instantaneous floods. The NRFA includes over 2,000 catchments, but many are considered unsuitable for flood analysis (for example, bypassing or gauge drowning may occur at high flows, significant land-use change may have occurred). Consequently only selected catchments and record periods have been used, initially matching the selections of Kjeldsen *et al.* (2008) from the HiFlowsUK database for their work to improve the FEH flood frequency method. However, a further criterion to exclude catchments with less than 10 years of data was introduced, reducing their 602 to a total of 545 rural catchments. These form the basis for developing relationships initially between seasonal flood characteristics and catchment descriptors, and potentially to include environmental indicators.

The daily flow series has been analysed in a number of ways. Firstly, both annually and within user-defined seasons, all isolated peaks were identified using algorithms based on the rules described by Bayliss and Jones (1993). Events were allocated to year/season by the time of peak flow. At the same time, both the maximum flow and the maximum isolated peak in each year/season were extracted (the difference being when the maximum flow occurred on the rising or falling phase of an isolated peak flow in the following or preceding year/season). The annual/seasonal maxima were ranked, and using "quartile analysis" (Flood Studies Report, 1975, vol 2, p 10), estimates at two-, five- and 10-year return periods were derived as the median, and the geometric means of the middle half and upper quartile of the data. Quartile analysis avoids most problems of small sample distribution fitting, and covers the return periods of prime interest to this project without the need to consider pooling groups. Tests found that the Q2, Q5 and Q10 estimates were largely the same as those obtained by the FEH at-site procedure of fitting the generalised logistic distribution to the sample L-moments. It was also found that differences between the maximum flow and the maximum isolated peak data were limited to return periods below two years.

Note that Q2 based on annual maximum *instantaneous* flow (named QMED in the FEH and Kjeldsen *et al.,* 2008) is generally larger than the Q2 found here based on annual maximum *daily-mean-flow*. Yet, with *instantaneous* QMED generally taken as equivalent to bankfull flow capacity, the latter *daily-mean-flow* Q2 value is by analogy assumed to indicate the occurrence of bankfull flow at some time during the day. Thus the daily-mean-flow data were re-scanned to determine for each year/season (a) NF - the total number of isolated events that exceeded bankfull, and (b) DF - the total number of days that bankfull flow was exceeded; the years of record NY could then be used to derive the average number and duration of bankfull floods. It had been intended thus to derive the average duration of a bankfull event in each season, but this was frustrated by seasonal boundary effects - where bankfull flow was exceeded but the event peak occurred in the preceding or following season. While some correction could be applied, it was decided to assess bankfull duration on an annual basis alone.

Although the work described below is based on mean daily flow data, it should still give useful pilot information on seasonal flood patterns. The data processing necessary to extend the analysis to instantaneous peak flows could not be undertaken with the project resources available.

As noted above, the choice of seasons to consider depends on the processes and phenomena involved, with two (summer/winter), four and twelve (monthly) seasons frequently adopted. A smaller number of seasons will reduce the seasonal boundary effects mentioned above and increase the data available for each season. However combining, say, April and July conditions in the same season may conceal significant differences. For our study, three seasons were considered: winter, spring and summer. To develop hydrological indicators of environmental use, the timing of the winter-spring boundary is the most difficult. Lengthening and warming days increase convective rainfall and evaporation and also stimulate growth and breeding cycles. Many species and habitats have emerged from winter by mid-March, yet soil moisture and river flows may reflect winter conditions well into May. Following discussion within the project team, the following season dates were adopted as a best compromise to represent changing flood conditions (frontal/convective rainfall, low/high soil moisture conditions), and critical periods for ecosystem development:

Season 1 (S1)	Spring	March 21- June 20
Season 2 (S2)	Summer	June 21 – Sept 30
Season 3 (S3)	Winter	October 1 – March 20

Note that the start of winter was chosen to align with the conventional hydrometric water year. Note also that the qualifier S1, S2, S3 or AN (annual) has been appended to the notation used for the derived flood statistics (Q2, Q5, Q10, NF, DF)

Results from the analysis of peak daily flow rates from 545 of the rural catchments used in the improved FEH procedure (mentioned above) were used. These and the FEH catchment descriptors AREA, BFIHOST, SAAR, FARL and FPEXT form the basis of the seasonal flood analysis described in the following sections. It was not possible within the scope of this project to assess catchments individually or assess any residual data problems.

Annual maximum floods – comparing instantaneous and daily data

Prior to assessing seasonal floods, the figure below compares the instantaneous QMED values obtained by Kjeldsen *et al.* (2008) with the equivalent daily mean flow Q2AN values obtained in this work.

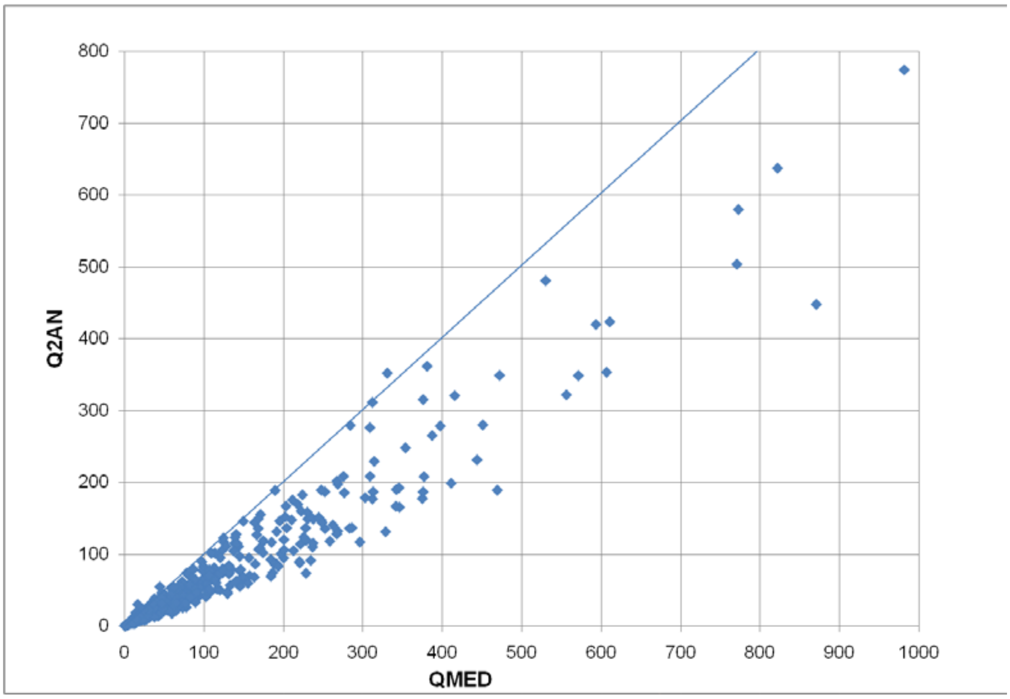

Figure B.1:

Differences between Q2AN and QMED will depend on how quickly floods decay, and thus relate in some way to typical flood durations. The figure shows a scatter rising up to the 1:1 line (the few bad points above the line have not been investigated). The scatter does not show the expected reduction for larger floods (likely from larger catchments and longer flood durations). Overall, the ratio Q2AN/QMED has a geometric mean of 0.624 and a factorial standard error (FSE) of 1.35.

Note that the improved QMED equation given by Kjeldsen *et al.* (2008) for their full 603 catchment data set is:

$$QMED = 8.3062\ AREA^{0.8510}\ 0.1536^{(1000/SAAR)}\ FARL^{3.4451}\ 0.0460^{BFIHsq} \qquad R^2=0.945,\ FSE=1.43$$

where AREA is catchment area (km^2)
SAAR is average annual rainfall (mm)
FARL indexes the extent of lakes and reservoirs (0=many, 1=none), and
BFIHsq stands for $BFIHOST^2$ (BFIHOST=base flow index based on soil type)

An equivalent equation was derived based on the 545 catchment subset considered here. Simple rather than generalised least-squares regression was used, but the same variable transformations were tested (and gave similar improvement), resulting in:

$$QMED = 8.7726\ AREA^{0.8507}\ 0.1572^{(1000/SAAR)}\ FARL^{3.4320}\ 0.0400^{BFIHsq} \qquad R^2=0.945,\ FSE=1.42$$

The similarity in coefficient values, correlation coefficient R^2 and FSE suggests that using the smaller subset of catchments will have limited impact on subsequent conclusions. On this basis, an equation was then derived for the pivotal statistic used in this study, Q2AN, the median annual maximum of mean daily flow.

$$Q2AN = 1.9683\ AREA^{0.9500}\ 0.2136^{(1000/SAAR)}\ FARL^{1.6930}\ 0.0694^{BFIHsq} \qquad R^2=0.967,\ FSE=1.31$$

Note that the same variable transformations were found to improve the fit, and also that the R^2 and FSE values were better than for the instantaneous peak QMED – confirming that Q2AN is inherently more predictable. Comparing the regression coefficients (all significant at well above the 99% level) suggests that daily mean flows depend more on AREA and soil type, but less on SAAR and lake/reservoir attenuation.

Note also that applying the mean ratio of Q2AN/QMED (given above as 0.624) to the QMED equation gave a zero bias estimate of Q2AN but with a higher FSE of 1.41. Including QMED directly in the regression for Q2AN gave the following relationships:

$Q2AN = 0.7073\ QMED^{0.9660}$ R^2=0.979, FSE=1.35

$Q2AN = 0.5207\ QMED^{0.6123} AREA^{0.4291} 0.6634^{(1000/SAAR)} FARL^{-0.4085} 0.4979^{BFIHsq}$
R^2=0.988, FSE=1.18

The large reduction in FSE above confirms the close affinity between Q2AN and QMED and suggests they share the same factors that limit the accuracy of their prediction based on catchment descriptors alone.

For comparison with the seasonal analyses below, geometric mean growth factors based on all 545 catchments were found as follows:

Q5AN/Q2AN = 1.364 FSE=1.11
Q10AN/Q2AN = 1.625 FSE=1.18

Seasonal frequency relationships from daily flood data

The aim of this work was to develop catchment-specific flow-frequency curves for different seasons such that an annual flow rate of any specific frequency could be "read across" to define its frequency in a chosen season. To this end, equations relating seasonal (S1, S2, S3) medians and ratios to Q2AN were derived (see below). Generally, S1, S2 and S3 medians can all be predicted with comparable accuracy to QMED and Q2AN, but of course the regression coefficients change, making general conclusions on which catchments might show greater seasonal differences difficult. Moreover, using separate regressions for each season brings a risk of predicting unrealistic changes between the seasons for particular combinations of catchment descriptors. The alternative approach based on ratios of seasonal to annual median floods was thus assessed, but no strong and concise relationships with catchment descriptors (on which to base simple GIS layers) were obtained. For example, some weak dependence of spring ratios on soil type was found, but the Q2S1/Q2AN regression (Equation 2 below) had an R^2 value of just 0.127, and a standard error no better than the simple geometric mean of 0.410. Consequently, the geometric mean ratios of 0.41, 0,25, 0.95 for spring (S1) summer (S2) and winter (S3) to annual median floods have been recommended as the best interim compromise.

$Q2S1 = 0.6653\ AREA^{0.9768}\ 0.1946^{(1000/SAAR)}\ FARL^{1.9752}\ 0.1252^{BFIHsq}$ R^2=0.958, FSE=1.35
$Q2S1/Q2AN = 0.3562 * 1.6847^{BFIHsq}$ R^2=0.127, FSE=1.29
Q2S1/Q2AN = 0.410 FSE=1.29

$Q2S2 = 1.1032\ AREA^{1.0199}\ 0.0566^{(1000/SAAR)}\ FARL^{2.4050}\ 0.1287^{BFIHsq}$ R^2=0.929, FSE=1.61
Q2S2/Q2AN = 0.247 FSE=1.89

$Q2S3 = 1.9275\ AREA^{0.9554}\ 0.1973^{(1000/SAAR)}\ FARL^{1.6797}\ 0.0734^{BFIHsq}$ R^2=0.968, FSE=1.30
Q2S3/Q2AN = 0.945 FSE=1.07

Beside these Q2 regressions, similar equations were derived for Q5 and Q10, but again no clear reliable relationships were found. Thus, geometric mean ratios were obtained:

Q5S1/Q2AN = 0.658 FSE=1.22
Q10S1/Q2AN = 0.852 FSE=1.23

Q5S2/Q2AN = 0.464 FSE=1.59
Q10S2/Q2AN = 0.660 FSE=1.48

Q5S3/Q2AN = 1.299 FSE=1.10
Q10S3/Q2AN = 1.555 FSE=1.15

With the S1 and S2 ratios less than 1.0, it is clear that for most catchments overbank flooding in spring and summer is rarer than a 10-year event, and thus more likely to be damaging than something on which the ecology would depend.

Note also that, as would be expected, when relating seasonal flood rates to the corresponding seasonal rather than annual medians, the geometric mean growth factors for spring and summer seasons show considerable steeper growth curves than were found previously for overall annual maxima:

Q5S1/Q2S1 = 1.607	FSE=1.19
Q10S1/Q2S1 = 2.078	FSE=1.29
Q5S2/Q2S2 = 1.881	FSE=1.32
Q10S2/Q2S2 = 2.676	FSE=1.54

Number and duration of floods above Q2AN (bankfull estimate)

Taking "bankfull" throughout as the median of the annual maximum series of daily flow (equivalent to a two-year return period, or 1.45-year on the POT series), the average number of independent overbank floods per year and season was derived for each of the 545 catchments. The mean and standard deviation of these catchment average values (variation between years on the same catchment was not assessed) for spring, summer and winter events were found as 0.071 (sd=0.063), 0.054 (sd=0.061), 0.719 (sd=0.196). The risks sum to 0.844 - more than 0.5 because large annual maxima will conceal smaller events in the same year (AM and POT differences). With no clear dependence on catchment descriptors, the simplest statistic to apply to the NAFRA annual risk data would be to rescale these as relative risk factors summing to one (0.084, 0.065, 0.851). Thus, 8.4 per cent of all bankfull events occur in spring, 6.5 per cent in summer, and 85.1 per cent in winter.

There risks do vary between catchments, but good relationships have not yet been found. However, about 23 per cent of the variance in spring risk can be explained by SAAR, and seven per cent of the summer variance by BFIHOST.

It was noted in the previous section that spring and summer floods showed steeper growth rates. However, until further work is done (for example, assessing seasonal differences in the occurrence of five-year annual flows, Q5AN), the relative risk factors given above may be applied to all the annual flood risk values in NAFRA, even though they are derived just for the two-year case.

Flood duration

As discussed above, flood duration (total days of flooding divided by number of independent events) was only assessed on an annual basis. Relationships with catchment descriptors were sought, but with limited success. BFIHsq is very significant, but primarily when greater than about 0.6 (and as shown in the figure below, the scatter is high).

The average and standard deviation of catchment average flood durations (days) for low BFI catchments (BFI<0.75) was 1.46 (sd 0.72), and for high BFI catchments (BFI>=0.75) was 18.90 (sd 18.89), and two preliminary relationships with BFI HOST are given in the figure below

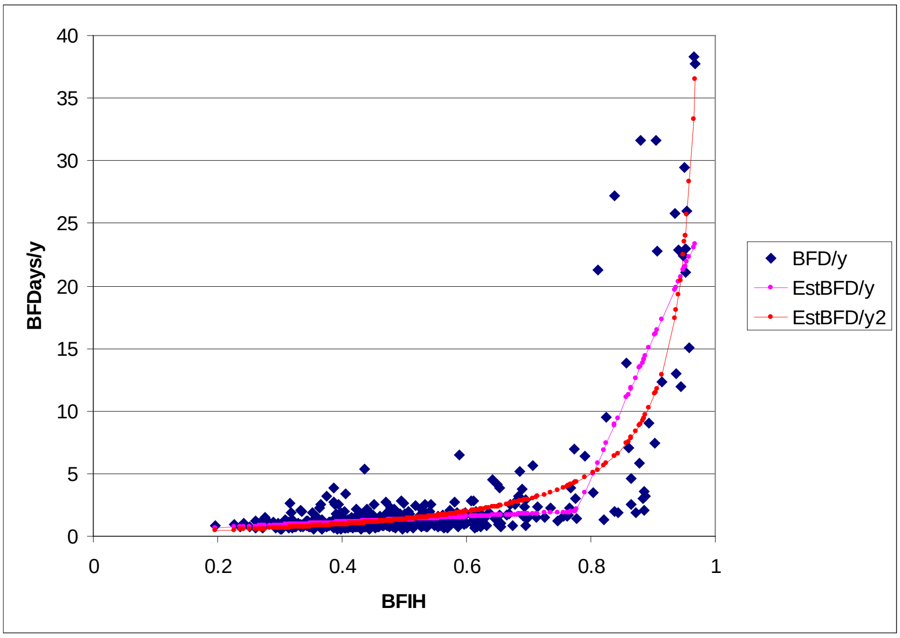

Figure B.2:

Summary

This study has yielded firm evidence of how flood statistics change during a year, and provided provisional factors that can be used to adjust annual to seasonal flood risk. While these factors should depend on local catchment and climate characteristics, no clear and simple procedure to account for these effects has yet been found.

References

Bayliss, A.C. and Jones, R.C. 1993. Peaks-over-Threshold flood database: summary statistics and seasonality. Institute of Hydrology, Report No. 121.

Kjeldsen, T.R., Jones, D.A. and Bayliss, A.C. 2008. *Improving the FEH statistical procedures for flood frequency estimation.* Environment Agency Science Report SC050050.

Appendix C: Flooding indicators for impacts on fish

Purpose

This appendix considers the sensitivities of fish to flooding. The information presented here forms the basis of rules that are implemented in the ECF fluvial tool.

Data requirements for assessment

To "model" the sensitivity of fish species and assemblages to high flow and flooding events, and to generalise season rules for flood risk and pressure (in terms of ecological effects), the following information must be assessed:

- Characterisation of fish assemblages in terms of behavioural response to flooding and high flows (development of new ecological classifications).
- Description of existing fish community structure at a site-specific (or reach-specific) level (this is a modification of existing work but will use new data from the Environment Agency when we receive it).
- Assessment of abiotic and hydrological parameters driving community structure:
    - high flow frequency – frequency of seasonal events (per year, per extended period, for example per 10 years);
    - frequency of flood events (per year, per extended period);
    - channel and floodplain morphology;
    - relationship between high flow, flood and low flow events (relative flows);
    - Richter statistics.
- Assessment of the extent to which changes in assemblage structure can be predicted from altered frequency of seasonal flood events.

Morphology of the channel and the floodplain will be the overarching factor that will determine how high flows and floods will affect fish communities. If we can predict the degree of embankment, type of embankments, and frequency and likelihood of overtopping at different times of the year, we should be able to model the sensitivity of the various communities to flooding events.

However, these data may not be available in most cases (some features may be obtainable from RHS data but not for all fish sampling sites). Morphology characteristics may have to be assumed from surrogate metrics related to known morphology values (gradient, width and so on) and the characteristics of low and flooding flows (Q values) and flood defence information (areas flooded at different levels such as one in five, one in 10, one in 50 and so on) (whether the hydrographs are characteristic of constrained channels and so on).

Essentially, this work would require a hydrology and flooding metric database that matches the fish population database so that multivariate statistics and models can be developed to relate fish assemblage structure to hydrological characteristics.

Rules to deal with the effects of floods on fish should be at least community- or possibly guild-specific. **Time and data constraints prevent these rules being**

applied to individual species. The development of universally applicable rules is impossible without an exact date when fish execute different stages of their lifecycle. For example, a winter flood may be beneficial to population recruitment if it occurs before spawning (gravel cleaning, increasing oxygen permeability) but if it occurs after it could be detrimental (eggs and larvae are susceptible to smothering or displacement). These rules should therefore be treated with caution. Examination of fish abundance data from multiple "reference" sites by cluster analysis revealed eight broad fish assemblage types into which most species can be categorised.

Type 1). *S.salar* zone, *S.trutta fario* may be present.

Type 2). Very high abundance of *S.trutta fario*. high abundance of *S.salar*.

Type 3). High abundance of *S.trutta fario* with rheophilic cyprinids (*L. leucius, L. cephalus, C. gobio*) as next most common guild. Rheophilic minor species (*B. Barbatula, P. Phoxinus*) also present.

Type 4). Trout-dominated community, usually found above the salmon limit in upland streams. Rheophilic minor species are absent.

Type 5). High abundance of *L. cephalus, B. barbus* present and also relatively high in abundance. *E. lucius* and *T. thymallus* also present. Represents upper barbel zone of very large river systems, in particular sampling sites on the main river stem (note that barbel are not present in every river system in the UK, but the zone is nominally designated the barbel zone).

Type 6). Lowland coarse fish type characterised by *L. cephalus, L. leuciscus, G. gobio, R. rutilus, A. brama and E. Lucius*.

Type 7). Generally low overall abundance, *R. rutilus* dominate*, E. lucius* and *A. alburnus*, are relatively abundant. Representative of large lowland rivers, in particular the main river stem, characterised by deeper slow-flowing channels (generally boat-based survey data).

Type 8). Characterised by *S. salar*, *E. lucius* and *T. thymallus* and specifically representative of the chalk rivers of the south coast of England, although this zone will probably also be representative of middle to upper reaches of larger rivers if they were sampled effectively.

These fish community types can be predicted by the abiotic river characteristics they are most commonly associated with. The abiotic characteristic data from the NAFRA data base will need to be matched up to give a fish community for each analysed site.

Type 1

This fish community is typical of upland streams with a flashy permanent hydrological regime. High flows are important in the preparation of substrates for spawning and to facilitate adult salmon migration. Floods (overbank events) are generally not considered important in these reaches because the critical life stages of the resident community are carried out in-stream with no flood plain utilisation.

Spring: floods/high flows for migration.

Summer: no floods – could cause displacement if channelized.

Winter: late summer autumn floods/high flows for migration/gravel cleaning. Peak floods during incubation period could wash out from gravels, but this may be considered a natural event.

Type 2

This fish community is normally found in extreme gradient streams on the salmon limit. Floods/high flows are important to trout for pre-spawning movements and the preparation of substrates for spawning.

Spring: no floods – could cause gravel washout or displacement if channelized.

Summer: no floods – could cause displacement if channelized.

Winter: late summer autumn floods/high flows for migration/gravel cleaning. Peak floods during incubation period could wash out from gravels, but this may be considered a natural event.

Type 3

These habitats are usually in the middle reaches of river systems and can be critical to salmonid migration. Spawning habitat for salmonids is limited in these areas and most will move considerable distances upstream to more suitable areas. Therefore elevated flows are required to allow fish passage over natural/manmade barriers at times of migration.

Spring: floods/high flows for migration.

Summer: no floods – could cause displacement if channelized.

Winter: late summer autumn floods/high flows for migration/gravel cleaning. Peak floods during incubation period could wash out from gravels, but this may be considered a natural event.

Type 4

This community is typical of fast-flowing cold water streams/rivers of high gradients. Usually above the salmon limit where physical barriers prevent occupation by salmon and harsh environmental (high water velocities, low temperatures, low nutrient status) conditions prevent the proliferation of other species. These reaches are more reliant on lateral connectivity, that is, flows through the substrate, rather than lateral connectivity associated with floodplain inundation. Flooding (over bank events) is not common in this river type and is not known to be beneficial or detrimental to this community.

Spring: floods/high flows for migration.

Summer: no floods – could cause displacement if channelized.

Winter: late summer autumn floods/high flows for migration/gravel cleaning. Peak floods during incubation period could wash out from gravels, but this may be considered a natural event.

Type 5

This community is generally rheophilic and depends on relatively high flows in the main channel, the presence of pike indicates that some connectivity with floodplains and backwaters is required to maintain this community.

Spring: Early floods needed for pike to access floodplains. Timing of floods is critical to recruitment success.

Summer: low floods – could cause displacement if channelized or loss over flood banks if topped. Timing of floods is critical to recruitment success.

Winter: need access to overwinter habitat.

Type 6

This community consists of species typically found in the lowland reaches of rivers, where floodplain inundation is common and essential in driving community structure. Both bream and pike are known to make migrations onto floodplains during floods for spawning. Roach as phytophilic habitat generalists will also use floodplain vegetation for spawning.

Spring: floods allow access to floodplain for early spawners. Timing of floods is critical to recruitment success.

Summer: floods needed for bream/roach spawning – flooding is detrimental to other fish through displacement or loss by overtopped embankments. Timing of floods is critical to recruitment success.

Winter: need access to overwinter habitat.

Type 7

This large lowland community is dominated by species such as roach, bleak and pike. All of these require vegetation in lentic habitats for spawning. This is usually associated with floodplain and off-channel habitats so floods are important to provide lateral connectivity to these areas.

Spring: floods allow access to floodplain for early spawners.

Summer: floods might be beneficial to bleak spawning - are detrimental to other fish through displacement. Timing of floods is critical to recruitment success.

Winter: need access to overwinter habitat.

Type 8

The river types in which this community type (chalk streams) is found are generally quite hydrologically stable with only small fluctuations in river level. Fish in these environments are therefore less dependent on floods for population viability.

Spring: floods/high flows for migration.

Summer: no floods – could cause displacement if channelized.

Winter: late summer autumn floods/high flows for migration/gravel cleaning. Peak floods during incubation period could wash out from gravels, but this may be considered a natural event.

Appendix D: Flooding indicators for impacts on birds

Purpose

This appendix considers the sensitivities of birds to flooding. The information presented here was summarised in a series of rules that are implemented in the EIA F Tool.

Wetland birds

Poiani (2006) found that aquatic birds tend to disperse as an immediate response to floods, but they will then gather on flooded areas where food sources are abundant in order to breed. Large concentrations of birds tend to be prominent as floodwaters recede and both adult and young birds concentrate at remaining water bodies.

In winter, many waterfowl species are attracted to standing water and can feed in water depths up to 50 cm (Thomas, 1982). In general, the larger the area flooded the better, especially for roosting waterfowl. However, feeding conditions are usually better for many species at the margins of flooded areas, so several smaller areas of floodwater are usually more beneficial to waterfowl than one large one. Moreover, prolonged deep flooding can make an area as unattractive to waterfowl as areas without any surface water at all (Thomas, 1976).

Many wader species are also attracted to standing water on grasslands in winter. In addition to inundated areas, adjacent saturated soils, such as on wet grasslands, provide important feeding zones for waders, because soil invertebrates are forced closer to the surface as the water table rises. The higher water table levels also increase the penetrability of the soil that aids bird species, such as curlew and snipe, which probe for their prey (Green, 1986). Whilst high water tables are attractive to wading birds, standing water causes the death of many soil-dwelling invertebrates. This can result in short-term benefit to the birds, but prolonged flooding can greatly reduce the food supply available to feeding waders (Ausden *et al*., 2001). Increases in flooding of grassland can be beneficial to species of conservation concern in many floodplain areas (Ausden and Hirons 2002) but the timing of flooding, the underlying soil type and the flooding history are all important in determining the impact on the soil invertebrate community in any given area (Ausden *et al.* 2001). Winter flooding of previously unflooded areas greatly reduces the soil macroinvertebrate prey of many breeding bird species, largely as a consequence of invertebrates vacating flooded areas.

In spring and summer, almost all waterfowl species nest on dry land, preferably along land/water edges (Thomas, 1980). Breeding numbers would therefore tend to be low wherever flooding is widespread and in areas with a low edge/water surface area ratio. Too much open water is not beneficial. Where flooding does extend over large areas in summer, shallow floods are more beneficial than deep floods, particularly for dabbling ducks which require water depths of less than 30 cm to feed (Thomas, 1981). Intermittent out-of-bank flooding is likely to be the most detrimental to breeding waterfowl, resulting in the destruction of nests and lost clutches.

Waders are ground-nesting birds and, in general, the greatest densities of breeding waders will occur in wet grasslands where the water table is high (Beintema, 1987). However, the optimum conditions usually equate to a water table 20-30 cm below the surface in early March (Beintema, 1983) and where wet conditions are restricted to shallow drainage channels, or rills (Milsom *et al*., 2002). Extensive flooding during the breeding season will actually remove breeding habitat for waders and major intermittent floods will destroy nests, clutches and young birds.

In summary, shallow flooding in winter is beneficial to many species of waterfowl and waders and lack of flooding would reduce their presence in any catchment area. Some invertebrates can survive short periods of flooding (Ausden *et al*., 2001) and others can survive shallow floods if there are sufficient variations in local topography to afford nearby refugia of higher ground. However, prolonged and deep flooding is not attractive to either waterfowl or waders and will greatly reduce the density of invertebrates present in any area.

During spring and early summer, raised water tables are of benefit to breeding waterfowl and waders. However, out-of-bank flooding would remove breeding habitat and intermittent flooding will actually destroy nests, clutches and young birds. Some birds such as snipe will re-nest if first nests are destroyed by floods.

In ideal conditions, floods can be very beneficial. On the Ouse Washes, in a typical year, the main winter floods come in late November or early December and leave the washes under a deep bank-to-bank flood along their entire length until March. These floodwaters drain off gradually during early spring to provide ideal conditions for wet grassland breeding species and grazing cattle (an essential management tool). During late spring, summer and autumn, small temporary and permanent pools provide the best areas for birds, but major flooding can have negative consequences. During the June 2008 floods, some 600 pairs of ground-nesting waders (lapwing, snipe and redshank) lost eggs or chicks in the flooding on the Ouse Washes. These floods were also the main cause for the collapse in the Ouse Washes population of black-tailed godwits, one of the UK's rarest breeding waders. Across Cambridgshire, more than 1,600 pairs of wading birds and ducks had their nests destroyed, including more than 1,100 pairs of eight species of duck, including 12 pairs of the rare garganey.

The summer 2007 floods severely affected ground-nesting waders in the Severn and Avon Vales, Gloucestershire and south Worcestershire . Lapwing nesting in wet meadows was severely hit by floods in May and June. Some that tried to produce a second clutch were flooded a second time. Many curlew chicks were drowned in the deep floodwater in late June. Redshank young tend to fledge by mid-June; many moved off the vales before floods rose in late June.

The issues raised here have been recognised worldwide. For example, Knutson and Klass (1997) found that the 1993 Mississippi floods led to declines in many species due to poor reproductive success. However, they felt that in the long term major flooding was important for maintaining suitable floodplain habitat for birds. Tome (2002) studied the density of meadow birds breeding in Slovenia related to three different flooding regimes and found positive effects of floods on many birds including lapwing, sky lark, marsh warbler and corn bunting.

The following are specific examples of bird behaviour related to timing of nesting.

Common snipe (Gallinago gallinago)
These birds breed in marshes and boggy areas and winter on saltmarshes, coastal lagoons and other marshy areas. They feed by probing prey deep in the soil. If the marshes and meadows are well drained — or were not waterlogged at the end of the winter — then the ground may become dry and hard and breeding will cease. The nesting period is late March-July. Snipe build their nests of grass on the ground, often concealing them in clumps of rushes. Late flooding is a hazard, drowning nests. However, snipe are persistent breeders and females may produce three or four clutches in the season before rearing young. In these circumstances the latest nests may be started in July, finishing in August.

Redshank (Tringa totanus)

This bird breeds on wetlands, moorland, water-side meadows, both coastal and inland. Redshanks have highest densities on well-grazed areas of upper saltmarsh dominated by sea-couch grass. They nest from late March to May. The nests are situated on the ground on tussocks or grassy hollows. The young eat mainly midges and flies, with beetles and spiders also being taken. Cattle are put on the marsh towards the end of the nesting season, in late May or early June, to minimise trampling of the eggs.

Lapwing (Vanellus vanellus)
Lapwings are birds of open farmland requiring bare ground or short vegetation. They can also be found on wetlands with short vegetation. They nest between mid-March and June. Birds that nest on arable land often relocate their young to nearby wet ground and appropriately short vegetation (such as grazed pasture) in order to find suitable feeding. A ready abundance of ground and soil invertebrates throughout the year is a requirement of lapwings, their preferences being for earthworms, leatherjackets, insects and their larvae, these are most abundant on wet grassland and grazed pasture.

Curlew (Numenius arquata)
Curlews eat worms, shellfish and shrimps. The largest concentrations are found in major estuaries at Morecambe Bay, the Solway Firth, the Wash, the Dee, Severn, Humber and Thames. In early spring the birds move inland to breed in upland blanket bogs, lowland raised bogs and rough pasture. The breeding season is April to July.

Mallard (Anas platyrhynchos)

Mallards start to nest in March. Eggs are laid between mid-March and the end of July. The normal clutch is about 12 eggs, laid at one- to two-day intervals. After each egg is added, the clutch is covered to protect it from predators. They prefer to nest near water and the nests are generally well covered in vegetation or in a natural hole in a tree. Mallards exploit any open water where food is plentiful, however, and this sometimes results in the choice of less than perfect nest sites, particularly in towns. Nests have been found in boathouses, wood piles, old crows' nests, hay stacks, roof gardens, enclosed courtyards and even in large flowerpots on balconies several floors up.

The risk of flooding for birds depends on the frequency, extent, timing, depth and duration of flooding; timing is particularly crucial. The key seasons for birds are:

Spring = nesting 1 April – 30 June.

Summer = growing before migration 30 June – 30 September.

Winter = over-wintering 30 September – 31 March.

Flooding in the winter is generally good though extended deep flooding can be detrimental. Flooding during the breeding season is generally high risk, but residuals pools of water are good. During the summer, flooding is not so critical as birds can fly to dry sites.

References

Ausden, M., Sutherland, W.J. and James, R. 2001. The effects of flooding lowland wet grassland on soil macroinvertebrate prey of breeding wading birds. *Journal of Applied Ecology*, 38, 320-338.

Ausden, M. and Hirons, G.J.M. 2002. Grassland nature reserves for breeding wading birds and the implications for the ESA agri-environment scheme. *Biological Conservation*, 106, 279-291.

Beintema, A.J. 1983. Meadow birds in the Netherlands. In: *Managing wetlands and their birds*. *A manual of wetland and waterfowl management* (editor D.A. Scott), pp. 83-91. International Waterfowl Research Bureau, Slimbridge.

Beintema, A.J. 1987. Nesting success of birds breeding in Dutch agricultural grasslands. *Journal of Applied Ecology*, 24, 743-758.

Conlan, K., Nottage, A., Elliott, M., Painter, D., Seynour, R., Richards, K. and Hull, S. 2002. *Broad-Scale Ecosystem Impact Modelling Tools: Scoping Study*. Final Report on FD2108 to Defra and the Environment Agency.

Green, R.E. 1986. *The management of lowland wet grassland for breeding waders*. Royal Society for the Protection of Birds.

Knutson, M.G., Klass, E.E. 1997. Declines in abundance and species richness of birds following a major flood on the upper Mississippi river. *The Auk*, 114, 3, 367-380

Milsom, T.P., Hart, J.D., Parkin, W.K. and Peel, S. 2002. Management of coastal grazing marshes for breeding waders: the importance of surface topography and wetness. *Biological Conservation*, 103, 199-207.

Poiani, A. 2006. Effects of floods on distribution and reproduction of aquatic birds. *Advances in Ecological Research*, 39, 63-83.

Thomas, G.J. 1976. Habitat usage of wintering ducks at the Ouse Washes, England. *Wildfowl*, 27, 148-152.

Thomas, G.J. 1980. The ecology of breeding wildfowl at the Ouse Washes, England. *Wildfowl*, 31, 73-38.

Thomas, G.J. 1981. Field feeding by dabbling ducks around the Ouse Washes, England. *Waterfowl*, 32, 69-78.

Thomas, G.J. 1982. Autumn and winter feeding ecology of waterfowl at the Ouse Washes, England. *Journal of Zoology*, 197, 131-172.

Tome, D. 2002. Effect of floods on the distribution of meadow birds on Ljubljansko Barje. *Acrocephalus*, 23, 112, 75-79.

Appendix E: Empirical assessment of BAP priority habitat association with probability of inundation

Purpose

This appendix presents the results of the empirical assessment of the association of BAP priority habitats and the probability of inundation. Areas of flood inundation probability with greater than expected concentrations of specific habitats are taken to be their favoured locations and are used in the ECF fluvial tool. The results of the tendencies for habitats to be associated with specific inundation probability areas are presented in the table below.

Table E.1:

BAP	**RP floodplain (years)**	**Area as a % of the habitat within 100-year floodplain**	**Percentage observed - Percentage Expected**
Blanket bog	100	9.49	-6.36
	50	20.62	-1.57
	20	14.56	-0.97
	10	12.73	-2.89
	5	42.55	16.86
	2	0.06	-5.06
Deciduous woodland	100	8.04	-7.81
	50	15.24	-6.95
	20	17.49	1.96
	10	14.82	-0.80
	5	38.87	13.18
	2	5.54	0.42
Fens & reedbeds	100	7.27	-8.59
	50	15.18	-7.01
	20	13.98	-1.55
	10	20.77	5.16
	5	31.23	5.54
	2	11.57	6.45
Grazing marsh	> 100	0.00	0.00
	100	9.49	-6.36
	50	17.23	-4.96
	20	13.45	-2.08
	10	18.26	2.64
	5	29.90	4.21
	2	11.66	6.54
Lowland acid grassland	100	8.12	-7.74
	50	13.92	-8.26
	20	12.28	-3.25
	10	14.67	-0.95
	5	41.35	15.66
	2	9.66	4.54
Lowland calcareous grassland	100	7.10	-8.76
	50	11.82	-10.36
	20	15.28	-0.25

BAP	RP floodplain (years)	Area as a % of the habitat within 100-year floodplain	Percentage observed - Percentage Expected
	10	13.00	-2.62
	5	36.16	10.47
	2	16.64	11.52
Lowland heathland	100	8.80	-7.05
	50	15.14	-7.05
	20	15.01	-0.52
	10	15.94	0.32
	5	36.52	10.83
	2	8.60	3.48
Lowland meadows	100	16.31	0.46
	50	17.82	-4.37
	20	14.59	-0.94
	10	14.67	-0.95
	5	25.42	-0.27
	2	11.19	6.07
Lowland raised bog	100	15.23	-0.62
	50	17.69	-4.50
	20	10.91	-4.62
	10	16.22	0.60
	5	25.26	-0.43
	2	14.69	9.57
Purple moor grass rush pastures	100	7.65	-8.21
	50	12.19	-10.00
	20	10.60	-4.93
	10	16.48	0.86
	5	42.31	16.62
	2	10.78	5.66
Upland calcareous grassland	100	9.65	-6.20
	50	25.35	3.16
	20	22.98	7.45
	10	10.61	-5.01
	5	31.41	5.72
Upland heath	100	9.27	-6.58
	50	18.21	-3.98
	20	18.05	2.52
	10	13.08	-2.54
	5	41.16	15.47
	2	0.24	-4.88
Upland meadow	100	7.57	-8.28
	50	20.65	-1.54
	20	57.69	42.16
	10	13.76	-1.86
	5	0.32	-25.37
Wet woodland	50	11.70	-4.16
	50	26.16	3.98
	20	25.72	10.19
	10	10.05	-5.57
	5	25.99	0.30
	2	0.38	-4.74

Appendix F: Comments on associations of priority BAP habitats and inundation probabilities

Purpose

The empirical assessment of associations of habitats with areas of specific flood inundation probabilities led to some interesting observations. In particular, the results may reflect major impacts of land management and/or misclassification of habitats.

Blanket bog and lowland raised bog
These habitats are concentrated within areas of frequent inundation 0.5 to 0.2.

However, both bogs rely on rain water inputs rather than inputs from the river. They may have developed in these locations in response to peat accumulation linked to flooding but they do not currently depend on flooding. Both are tolerant of frequent inundation.

Coastal and floodplain grazing marsh
This habitat is concentrated within areas of frequent inundation 0.5 to 0.1. The higher the likelihood of inundation, the greater the concentration of this habitat. It is likely that this habitat actually benefits from frequent inundation.

Lowland calcareous grassland
This habitat is concentrated within areas of frequent inundation 0.5 to 0.2.

This distribution was unexpected. It was expected to occur away from rivers in chalk areas that are rarely flooded. The pattern may reflect the fact that cultivated land has restricted it to this frequently inundated area or that it is being supported by local topographic highs on floodplain areas that receive calcareous floodwater. Alternatively, riparian habitats may have been incorrectly classified as lowland calcareous grassland.

Lowland dry acid grassland
This habitat is concentrated within areas of frequent inundation 0.5 to 0.2. The pattern may reflect the fact that cultivation has restricted it to this frequently inundated area.

Lowland meadows
This habitat is strongly concentrated within the areas most frequently inundated (0.5). The habitat included flood-dependent communities such as MG4.

Purple moorgrass and rush pastures
This habitat is concentrated within areas of frequent inundation 0.5 to 0.2. This suggests that it can tolerate high levels of inundation. The pattern may reflect the fact that cultivated land has restricted it to this frequently inundated area.

Upland calcareous grassland
This habitat has a broad distribution (0.2 to 0.05) which lacks a strong pattern. The habitat was expected to exist in rarely inundated areas. The weak pattern may reflect a lack of data.

Upland hay meadow
This habitat is strongly concentrated in areas that are rarely inundated (0.05). This is what was expected given that it is an upland habitat.

Wet woodland
This habitat was concentrated in areas rarely inundated (0.05 to 0.02). This distribution was not expected. We expected a greater concentration close to the river. It is possible that this pattern reflects the existence of wet woodland at the edges of

floodplains, where wet ground occurs not only due to flooding but runoff and seepage from hillsides. Alternatively, areas of wet woodland have been misclassified as deciduous woodland.

Deciduous Wwodland
This habitat is strongly concentrated in the frequently inundated (0.2) area close to the river. This may reflect the existence of riparian trees that have not been cleared for agriculture.

Fens and reedbeds
These habitats are concentrated in frequently flooded areas (0.5 to 0.1). They are most concentrated in the most frequently inundated area, suggesting they may depend on flooding rather than be tolerant of it.

Lowland heathland
These habitats are concentrated in frequently flooded areas (0.5 to 0.2). The data suggest that they can tolerate a high frequency of inundation.

Upland heathland
This habitat is concentrated in frequently flooded areas (0.2). Such a strong concentration in frequently flooded areas was not expected. It is possible that cultivation has restricted this habitat to this area or that there is an issue with the accurate classification of this habitat.

List of abbreviations

BAP	Biodiversity Action Plan
BSEA	Broad-Scale Ecosystem Assessment
CAMS	Catchment Abstraction Management Strategies
CCW	Countryside Council for Wales
CEH	Centre for Ecology and Hydrology
DEFRA	Department for Environment, Food and Rural Affairs
EA	Environment Agency
ECF	Ecological Consequences of Flooding
EIA C Tool	Ecological Impact Assessment Coastal Tool
EIA F Tool	Ecological Impact Assessment Fluvial Tool
FAME	Fish-based Assessment Method for the Ecological Status of European Rivers
FCRM	Flood and Coastal Risk Management
MDSF	Modelling Decision Support Framework
MHWS	Mean High Water Spring
MHWN	Mean High Water Neap
MLWN	Mean Low Water Neap
MLWS	Mean Low Water Spring
NAFRA	National Flood Risk Assessment
NE	Natural England
RASP	Risk Assessment of Flood and Coastal Defence for Strategic Planning
SAC	Special Area of Conservation
SOF	Saturated Overland Flow
SPA	Special Protection Area
SSSI	Site of Special Scientific Interest
WFD	Water Framework Directive

We are The Environment Agency. It's our job to look after your environment and make it **a better place** – for you, and for future generations.

Your environment is the air you breathe, the water you drink and the ground you walk on. Working with business, Government and society as a whole, we are making your environment cleaner and healthier.

The Environment Agency. Out there, making your environment a better place.

Published by:

Environment Agency
Rio House
Waterside Drive, Aztec West
Almondsbury, Bristol BS32 4UD
Tel: 0870 8506506
Email: enquiries@environment-agency.gov.uk
www.environment-agency.gov.uk