Department for Environment Food & Rural Affairs

Llywodraeth Cymru Welsh Government

Cyfoeth Naturiol Cymru Natural Resources Wales

Environment Agency

delivering benefits through evidence

How to model and map catchment processes when flood risk management planning

Project SC120015/R1

Flood and Coastal Erosion Risk Management Research and Development Programme

We are the Environment Agency. We protect and improve the environment and make it a better place for people and wildlife.

We operate at the place where environmental change has its greatest impact on people's lives. We reduce the risks to people and properties from flooding; make sure there is enough water for people and wildlife; protect and improve air, land and water quality and apply the environmental standards within which industry can operate.

Acting to reduce climate change and helping people and wildlife adapt to its consequences are at the heart of all that we do.

We cannot do this alone. We work closely with a wide range of partners including government, business, local authorities, other agencies, civil society groups and the communities we serve.

This report is the result of research commissioned by the Environment Agency's Evidence Directorate and funded by the joint Flood and Coastal Erosion Risk Management Research and Development Programme.

Published by:
Environment Agency, Horizon House, Deanery Road, Bristol, BS1 9AH
www.gov.uk/government/organisations/environment-agency

ISBN: 978-1-84911-377-9

Email: fcerm.evidence@environment-agency.gov.uk.

Further copies of this report are available from our publications catalogue:
www.gov.uk/government/publications

or our National Customer Contact Centre:
T: 03708 506506

Email: enquiries@environment-agency.gov.uk

Author(s):
Barry Hankin, Lydia Burgess-Gamble, Seb Bentley, Steve Rose

Dissemination Status:
Publicly available

Keywords:
Working With Natural Processes, Flood Risk Management, Catchment Processes, Modelling

Research Contractor:
JBA Consulting
Bank Quay House
WARRINGTON
WA1 1NN
Tel 01925 570876

Environment Agency's Project Manager:
Lydia Burgess-Gamble, Evidence Directorate

Theme Manager:
Dan Hine, Incident Management and Modelling

Collaborator(s):
Keith Beven, Trevor Page, Mark Wilkinson, Paul Quinn and Greg O'Donnell

Project Number:
SC120015

Evidence at the Environment Agency

Evidence underpins the work of the Environment Agency. It provides an up-to-date understanding of the world about us, helps us to develop tools and techniques to monitor and manage our environment as efficiently and effectively as possible. It also helps us to understand how the environment is changing and to identify what the future pressures may be.

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

This report was produced by the Scientific and Evidence Services team within Evidence. The team focuses on four main areas of activity:

- **Setting the agenda**, by providing the evidence for decisions;
- **Maintaining scientific credibility**, by ensuring that our programmes and projects are fit for purpose and executed according to international standards;
- **Carrying out 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.

Miranda Kavanagh

Director of Evidence

Acknowledgments

Thank you very much to all those who have contributed to the development of this report, decision support tools and case studies including:

- our academic partners:
    - Keith Beven and Trevor Page (Lancaster Environment Centre, Lancaster University), Mark Wilkinson and Leah Jackson-Blake (James Hutton Institute), Paul Quinn and Greg O'Donnell (Newcastle University).
- the project's steering group members and workshop attendees:
    - Nick Steele, Rachel Sion and Jenny Dickinson (Natural Resources Wales); Danni Murren (SEPA); Robert Grabowski (Cranfield University); and from the Environment Agency Lydia Burgess Gamble (Project Manager), Sue Reed (Project Executive), Greg Whitfield, Chris Burgess, Duncan Wishart, John Lymer, Rachael Dils, Kirsten Foot and Rhys Hobbs
- all those who provided and reviewed case studies:
    - Hannah Clilverd and Julian Thompson (University College London); Tom Nisbet (Forest Research); Jacques Sisson (Natural Resources Wales); Michael Hollaway (Lancaster Environment Centre); Peter Metcalfe (Lancaster Environment Centre); Chris Uttley (Stroud Council): Robert Grabowski's MSc students (Cranfield University); Pippa Lewis (Environment Agency); Tom Ormesher (National Farmers' Union); Samantha Boyes (Environment Agency); Ted Thomas (Environment Agency); Phil Welton (Environment Agency); Alex Nicholson (Arup); Peter Kerr (Environment Agency); John Douglass (Environment Agency) and Oliver Southgate (Environment Agency)

And a big thank you to our 2 peer reviewers: Colin Thorne (Nottingham University) and Tom Coulthard (Hull University).

Executive summary

The Pitt Review after the flooding in summer 2007 concluded that flooding from a range of sources can no longer be managed by building ever higher, lengthier and heavier defences in urban and rural areas. The review emphasised the need to ‘work with natural processes’ (WwNP) as part of integrated portfolios of responses to flooding and coastal erosion. WwNP means:

> ‘taking action to manage fluvial and coastal flood and coastal erosion risk by protecting, restoring and emulating the natural regulating function of catchments, rivers, floodplains and coasts’.

While there are many different tools and levels of approximation that can be used to model a catchment’s hydrology, the models, data and tools available for this alternative form of flood and coastal erosion risk management have not been benchmarked. This means it can be hard to select tools that help you understand the potential benefits of adopting WwNP measures in your catchment.

The purpose of this project was to review existing modelling software, mapping techniques and data to establish how they could be used to assess a wide range of catchment processes to help develop flood and coastal erosion risk management projects involving WwNP to reduce flood risk. The review focused on models that have been used to assess:

- run-off generation
- sediment processes
- in-channel barriers
- river floodplain barriers
- diffuse pollution

The project involved the development of:

- a **catchment process flow chart** to help you understand how your catchment works and to identify potential data, tools and models you could use to undertake a detailed assessment and then to design, construct and monitor a WwNP scheme in your catchment
- an **electronic library of tools** which provides a detailed summary of a range of tools, data and models to help you select suitable tools for your catchment; its purpose is to provide practitioners with as much information as possible about different approaches, since the availability of existing models and data and user-experience often dictates the software that can be used.
- a **detailed summary of models, tools and data** to help understand how different tools can be used to assist planning from flood source to flood scheme
- a series of **20 case studies** which provide examples of how different models have been used to model a range of catchment processes across the UK

Selecting suitable tools for the job

A 3-step process is presented to help you select the most suitable models, data and tools to use in a catchment study:

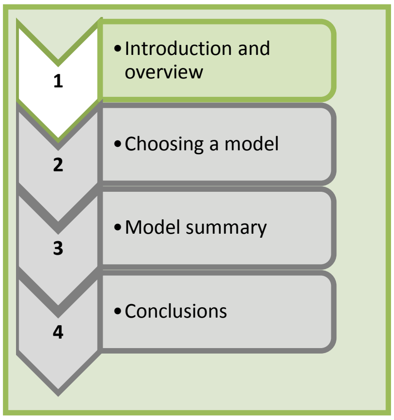
Step 1 involves using the Microsoft® Excel based model library to help select suitable models, data and tools which are the most relevant to your study. This library was compiled through a literature review, an expert workshop and the experience of the project team.

Step 2 allows you to find out more about the models, data and tools selected from the model library. The detailed review of these provided in the report introduces a range of data, data analysis tools and models which can be used to assess a range of catchment processes. For each process, details are given of the key functionality of a range of tools.

Step 3 involves using the 20 detailed case study examples to explore whether the models, data and tools you have selected are appropriate for use in your catchment.

Contents

1 Introduction



This project aims to improve understanding of how existing modelling software, mapping techniques and data can be used to assess a wide range of catchment processes to help develop flood and coastal erosion risk management (FCERM) projects which involve working with natural processes (WwNP) to reduce flood risk.

This chapter outlines the project's scientific, policy and catchment context. It explains what is meant by WwNP and the scientific background behind catchment modelling. It also stresses the importance, when developing a WwNP scheme, of understanding the catchment and the FCERM problems it faces so as to select the tools, models and data. A catchment process flow chart is presented to help you identify potential data, tools and models you could use to carry out a detailed assessment and then to design, construct and monitor a WwNP scheme in your catchment.

Chapter 2 explains how to use an electronic library of tools, a Microsoft® Excel spreadsheet developed as part of this project, which can be interrogated to help select suitable modelling, data and mapping tools.

Chapter 3 begins by describing the datasets that can help you understand a catchment's characteristics. It then gives details of some of the data, tools and models included in the model library which will help you model:

- run-off generation
- sediment processes
- in-channel barriers
- river floodplain barriers
- diffuse pollution

The model library and the descriptions of model in this chapter are supported by 20 case studies. These provide examples of how different models have been used to model a range of catchment processes across the UK.

Chapter 4 presents the study's conclusions and recommendations for future work.

The report is fully referenced and also includes a bibliography which lists reference was used when undertaking the literature review used to develop this report.

1.1 Policy context

1.1.1 What is WwNP?

WwNP means:

> 'taking action to manage fluvial and coastal flood and coastal erosion risk by protecting, restoring and emulating the natural regulating function of catchments, rivers, floodplains and coasts' (Environment Agency 2012a, p. 10)

It takes many different forms and can be applied in urban and rural areas, and on rivers, estuaries and coasts. Figure 1.1 demonstrates the variety of different measures it encompasses.

1.1.2 Where did WwNP come from?

The Pitt Review following the flooding in summer 2007 concluded that flooding from a range of sources can no longer be managed by building ever higher, lengthier and heavier defences in urban and rural areas (Pitt 2008). The review emphasised the need to 'work with natural processes' as part of integrated portfolios of responses to flooding and coastal erosion. Recommendation number 27 states that:

> 'Defra, the Environment Agency and Natural England should work with partners to establish a programme through Catchment Flood Management Plans and Shoreline Management Plans to achieve greater working with natural processes'.

In response to this recommendation, Defra set up 3 catchment pilots to demonstrate a series of multi-objective flood management schemes, each of which included WwNP measures particularly focused on catchment land use management. The pilots were:

- Pickering, North Yorkshire (Slowing the Flow) – led by Forest Research
- Holnicote, Somerset (Source to Sea) – led by the National Trust
- Upper Derwent, Derbyshire (Making Space for Water) – led by Moors for the Future

These projects aimed to demonstrate how land management, working with natural processes and partnership working, could contribute to reducing flood risk locally while providing wider benefits to the environment and communities. Although these pilots provided an excellent basis for testing some WwNP approaches, they were limited in scale and scope. They leave a number of questions to be answered about the benefits of natural flood management and WwNP at larger scales and with more combinations of measures.

WwNP involves enhancing the capacities of catchments to store, convey and attenuate floods in ways that reduce the negative impacts of flooding in flood vulnerable areas while enhancing its positive impacts in flood suitable areas (Sniffer 2011). WwNP often uses measures and techniques that slow, store and filter water to reduce the rate it enters watercourses. WwNP can complement traditional flood and coastal defences as part of the range of measures that risk management authorities can use to reduce the risk of flooding and coastal erosion to people, property, businesses and infrastructure. WwNP will help ensure that FCERM is carried out sustainably and as cost-effectively as possible by reducing future maintenance costs and maximising the wider benefits to society and the economy. It may do this, for example, by improving water quality, enhancing human well-being and providing opportunities for relaxation and recreation.

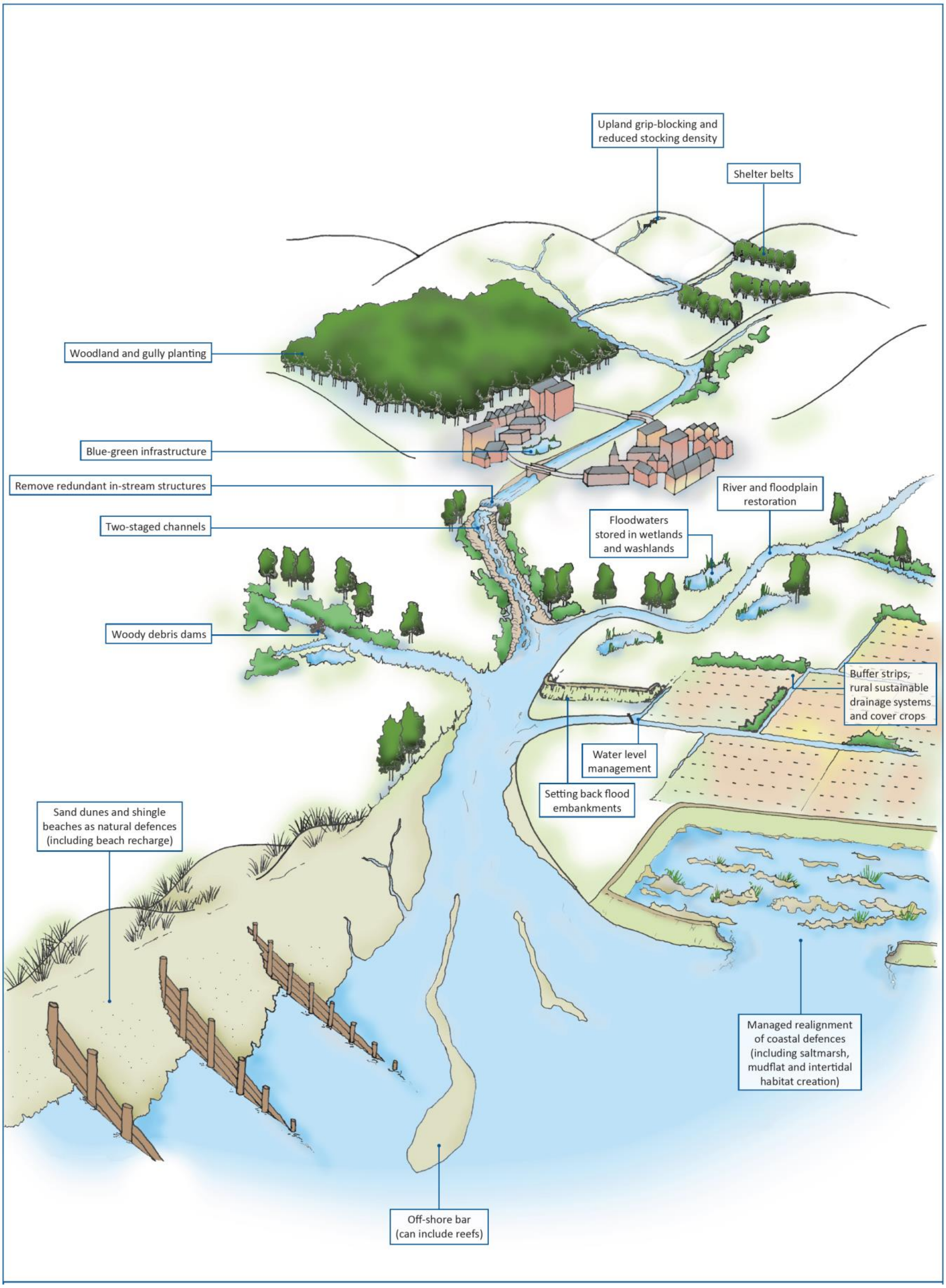


Figure 1.1 Examples of WwNP to reduce flood and coastal erosion risks in a conceptual catchment–estuary–coastal system

Source: Environment Agency (2014a)

WwNP can help improve the environmental condition of rivers, wetlands and coastal areas in urban and rural areas, and provide economical local solutions to smaller scale flood problems. WwNP can also improve water quality and help to mitigate and adapt to the impacts of climate change such as sea level rise and more extreme weather events (Nicholson et al. 2012, Wilkinson et al. 2013).

WwNP can help meet the requirements of environmental legislation and achieve broader environmental benefits (referred to as 'ecosystem services') by:

- reducing flood risk sustainably (that is, in terms of cost efficiency, social equity and environmental quality)
- providing opportunities for local stakeholder engagement and community participation
- conserving, creating and restoring habitats
- enhancing biodiversity
- capturing carbon
- reducing excessive sediment inputs or managing sediment more sustainably
- improving water quality

Since these 3 pilot projects, the number of WwNP projects being developed has increased as the FCERM community has started to gain greater understanding of the impacts of land use management on downstream flood risk (Hardiman et al. 2009, Hess et al. 2010, Wilkinson et al. 2010b, Geris 2012, Salazar et al. 2012 and Marshall et al. 2014).

1.1.3 Legislation and policy background

The main policies and legislation that currently encourage the use of WwNP in FCERM are summarised in Figure 1.2.

WwNP contributes to the Environment Agency's ambition to develop an integrated programme to achieve more environmental benefits with its FCERM activities (Environment Agency 2013). This includes:

- joining up river basin management plans, flood risk management plans, shoreline management plans and catchment flood management plans
- achieving a catchment-based approach
- providing a unified planning approach to meet the requirements of the Water Framework Directive (WFD), Habitats Directive, Floods Directive and Eel Regulations

1.1.4 Is WwNP being readily adopted?

While past flood events and their review have contributed to the development of WwNP as a concept for flood risk management, recent flooding has increased its profile further.

Significant river, coastal and surface water flooding occurred in England and Wales between December 2013 and February 2014. WwNP as a way of reducing flood risk featured highly in the media.

The need to consider alternative forms of flood management, including natural flood management and WwNP, was discussed in Parliament (Hartwell-Naguib and Roberts 2014).

A position statement from the Chartered Institute of Water and Environmental Management (CIWEM) on FCERM in light of the winter 2013 t0 2014 floods stated that:

> FCERM should look to work with natural processes to reduce flood and erosion risk, benefit the natural environment and reduce costs of schemes (adapted from CIWEM 2014).

There is now a wide range of WwNP schemes globally, with over 300 in the UK. Details of some of these UK projects are captured in an online map-based catalogue (http://naturalprocesses.jbahosting.com) developed by the JBA Trust and Lancaster Environment Centre. Its primary aim is to identify how the long-term performance of the measures is being assessed.

There is considerable momentum for WwNP to be used more widely, become more integrated into flood risk management practice and the development of better understanding of when its use would be most effective.

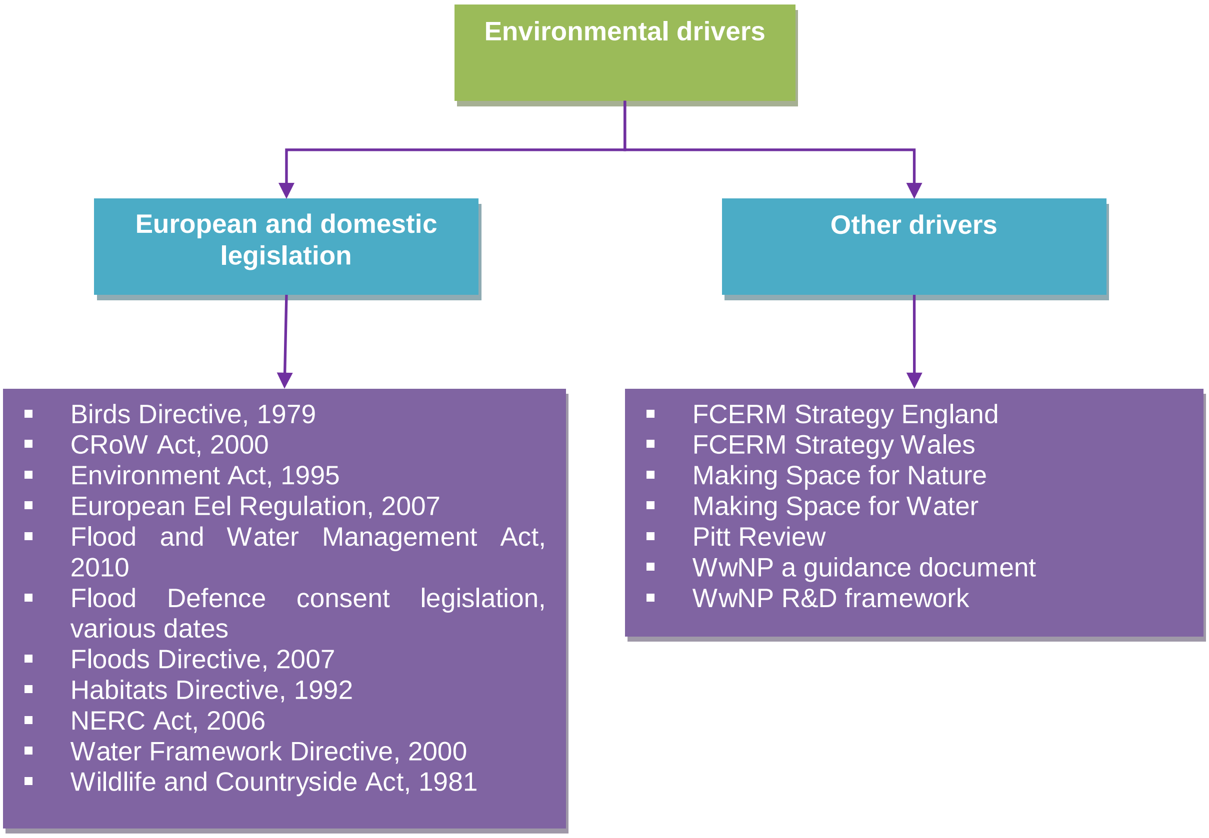


Figure 1.2 Main legislative and policy drivers of WwNP in FCERM

Source: Environment Agency (2014a)

1.1.5 What are the barriers to WwNP?

There are a number of barriers to WwNP (Environment Agency 2014a). A significant one is that, although a catchment's hydrology can be approximated at many different levels from use of the Flood Estimation Handbook to detailed physically based approaches, the models, data and tools available for modelling this alternative form of FCERM have not been benchmarked. This means it can be hard to select tools that help you understand the potential benefits of WwNP measures within your catchment.

Sections 2 and 3 consider the catchment processes which the FCERM community needs to understand if it is to develop strong schemes involving WwNP which reduce flood risk. These processes are:

- run-off generation
- sediment processes
- in-channel barriers
- river floodplain barriers
- diffuse pollution

The science behind WwNP is discussed in the next section.

1.2 Scientific context

This section sets the scientific context for catchment modelling and provides a useful background to help understand how to select suitable model(s) for your study.

1.2.1 Introduction

The UK approach to flood risk management was influenced by the government's Future Flooding Project (Evans et al. 2004a, 2004b). One of its main findings was that, to manage flood risk effectively, it is necessary to evaluate and manage the range of probabilities and consequences of flooding from different sources. This resulted in a change in focus from flood defence and coast protection to the management of risk (Environment Agency 2011). Combined with the requirements of the EC Floods Directive, this led to a shift in focus to risk management and to the development of tools to better understand the spatial distribution of probability and consequences (Equation 1.1), known as the source–pathway–receptor framework.

$$\text{Risk} = \text{Probability} \times \text{Consequence} \qquad (1)$$

Based on Equation 1.1, a generalised framework called 'Risk Assessment for Strategic Planning (RASP) was developed for quantifying flood and coastal erosion risks nationally (Hall et al. 2003, Environment Agency 2005). RASP considers fluvial and coastal sources of flooding and predicts the probability of inundation due to either defence overtopping or defence failure. The Environment Agency developed a software package to implement RASP called the Modelling and Decision Support Framework (MDSF), now available as version 2 (Environment Agency 2013). In parallel, the Flood Hazard Research Centre at Middlesex University produced the 'Multi-Coloured Manual' which estimates flood damage as a function of inundation depth, land use and building type (Penning-Rowsell et al. 2005 and more recent updates in 2013).

The RASP and Multi-Coloured Manual approaches help FCERM practitioners to manage whole catchment flood risk by considering the distributions of potential flood inundation and the severity of impacts. What is important here is that risk depends not only on probability of an area being inundated, but also on the numbers of people, properties and vital pieces of infrastructure in that area. In managing flood risk (rather than the probability or extent of inundation) it is therefore essential to consider how flood risk is distributed across the catchment.

This study draws together a wide range of tools, data and models which can help you assess WwNP measures for a wide spectrum of flood events. It focuses on the tools needed to assess whole catchment measures that promote WwNP taking a source–pathway–receptor approach. Being able to visualise the potential benefits of these WwNP measures is important because it can help practitioners select the right measure(s) to reduce flood risk at the catchment scale (Wilkinson and Quinn 2010, Environment Agency 2012a).

An integrated portfolio of approaches made up of a variety of FCERM measures is usually the most effective way of managing risk within a catchment. This might include the use of WwNP measures, conventional engineering infrastructure (for example, flood walls) and non-structural measures (for example, better flood warnings, improved preparedness and flood proofing buildings). A mix of measures, designed to work together synergistically can produce a cumulative reduction in flood risk much greater than that that could be achieved by the measures acting individually. However, designing integrated systems of measures requires the use of a suite of complementary tools to model and optimise their performance.

1.2.2 Probabilistic risk assessment

MDSF2 was used to produce the National Flood Risk Assessment (Environment Agency 2008), which is used strategically for long-term investment planning. In MDSF2, the 'source' is the fluvial and coastal flood hazard, the 'pathway' is the route by which floodwaters move across the landscape (or breaches through a defence asset) and the 'receptors' are the people and property located in the area at risk of inundation. MDSF2 produces an estimate of the resulting damage to flood receptors and is also used to develop a hazard map. The damages predicted on the basis of the hazard maps for each simulation are weighted according to the probability of that flood hazard actually occurring and the overall risk is estimated in terms of Annual Expected Damages for a given future climate/land use scenario.

MDSF2 also allows the economic and social impacts of flooding and coastal erosion to be quantified for different scenarios, including present day and future conditions, as well as different flood risk management options. Flood damages are derived using the depth damage curves in the Multi-Coloured-Manual. MDSF2 helps to identify low and high risk areas and apportions risk to assets, allowing vital components in the flood defence system to be assessed.

Appraisal of alternative FCERM options is often based on the analysis of scenarios with and without flood defences, combined with modelling the principal modes of asset failure under different defence options. This provides a clear understanding of flood risks in defended and undefended areas of the floodplain, and permits the use of much more accurate hydrodynamic modelling. It also enables model uncertainties to be assessed (Leedal et al. 2010, Neal et al. 2013, Beven et al. 2014a).

MDSF2 is a powerful tool and can be used to quantify the flood risks associated with probabilistic failures in a system of flood defence assets. However, it does not include all the factors known to affect asset performance and fragility. For instance, natural processes such as sediment transport are not simulated and the probability of asset failure during multiple peaked flood events cannot be modelled. The importance of this omission is illustrated in the Brompton case study, where WwNP measures can be adversely affected by double-peaked flood hydrographs. Removing these limitations would require development of new approaches to simulating spatially and temporally realistic flood 'event sets' rather than individual flood peaks (Lamb et al. 2010).

1.2.3 Probability of asset failure

MDSF2 uses fragility curves (Figure 1.3) to describe the probability of failure or breaching of a flood defence asset depending on the flood levels it experiences (Simm, 2011). Generalised fragility curves were developed for a range of asset types and conditions to represent the varying performance of defences as they deteriorate. These curves show the probability of an asset failing depending on the asset's condition and flood levels. These curves are based on failure mode analyses of standardised structures.

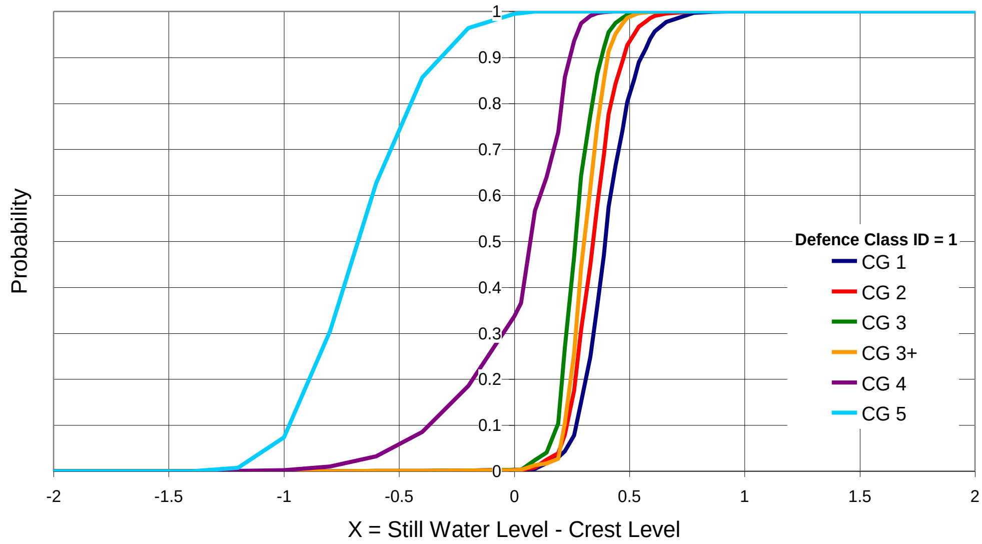


Figure 1.3 Flood defence performance as represented by fragility curves

Notes: CG = Condition Grade, with 1 indicating best condition

It is difficult to define fragility curves for WwNP measures compared with conventional engineered defences because the same level of detail on their expected engineering performance is not available. In addition, WwNP to reduce flood risk can involve installing many small measures in a catchment; it is therefore necessary to understand how they all perform together to understand their flood risk management benefit and their risk of failure.

Nonetheless it is still essential to assess the potential for failure of WwNP measures. As with conventional engineered defences, WwNP measures reduce flood risk for events less than or equal to that which they were designed to attenuate. In addition, WwNP measure might fail to work if the measures implemented were damaged by a previous flood and not repaired or maintained. Practitioners have already started developing rules of thumb to assess the potential for increases in downstream flood hazard due to failure of WwNP measures, but there is an urgent need for research to develop methods for quantifying this potential risk.

1.2.4 Understanding model uncertainty

When modelling catchment processes it is important to be fully aware of the associated risks and uncertainties. Beven et al. (2007) developed a catalogue of approaches to uncertainty analysis of complex catchment processes. The subject of different uncertainty estimation and classes of approaches in environmental modelling is well documented (Beven 2009).

A useful technique to help understand model uncertainties is the Generalised Likelihood Uncertainty Estimation (GLUE) framework (Beven and Binley 1992,, Beven and Binley 2014), which has been applied to a wide variety of environmental modelling applications (for examples see Aronica et al. 1998, Beven and Freer 2001a, Hankin et al. 2001, Leedal et al. 2010, Neal et al. 2013). The Flood Risk Management Research Consortium (FRMRC) developed a generic decision tree for use when modelling environmental processes (Beven et al. 2007), together with a condition tree approach to the recording and communicating the assumptions required to support uncertainty analysis (Beven et al. 2014b). There are now a number of tools and software which can apply the GLUE framework to explore how sensitive catchment process and flood risk models are to uncertainty in the input data.

Beven (2009) classified uncertainty estimation techniques in the following categories:

- **Forward uncertainty estimation.** This ensures known and/or estimated uncertainties in model inputs are represented in model outputs. These uncertainties can be associated with the model inputs and/or parameters and are most often represented by statistical distributions.
- **Likelihood conditioning.** Here model parameters and/or inputs are conditioned based on comparison with data. Likelihoods (weightings) can then be assigned to different combinations of parameters and inputs. There is a significant distinction in methodologies that provide formal likelihoods (Bayesian statistical methods) and informal likelihood weightings (for example, the GLUE framework).
- **Data assimilation**. This is used for real-time forecasting and is a process where a model is run continuously in time to provide forecasts (for example, a 12-hour ahead river level) and the model states (internal model variables) and/or parameters are updated at each time step depending on the deviation between the simulated and observed river levels.

When selecting model(s) for your study, it is essential to understand any uncertainties and risk associated with its use.

1.2.5 The role of scale in catchment modelling

Understanding the hydrology of a catchment is complicated, because measurement techniques mean it is generally only possible to study detailed catchment processes at point or plot scales, while monitoring and management normally take place at the catchment scale. When attempting to understand the hydrology of a catchment, approximations about the average run-off responses over a catchment are used based on point source measurement and this can lead to errors (Beven 1995, Addiscott and Mirza 1998). To counter this, models must be calibrated against as long a period of data as possible.

It is currently possible to show the flood risk benefits of WwNP measures locally (Wilkinson et al. 2010b), but it is much more difficult to demonstrate their effectiveness at the large catchment scale (Blanc et al. 2012). The FRMRC work at Pontbren (see case study) aimed to collect data and develop models to better understand how water moves through the catchment and to upscale these models to predict catchment scale effects of land use change. The study showed that strategic tree planting could be modelled to show a 30% reduction in flood peaks for short duration events and up to 5% for a long duration extreme event.

McIntyre and Thorne (2013) modelled a realistic suite of land use management change in a larger catchment and saw only a 2% reduction in the median flood peak during an extreme event. This is supported by the research of Archer (2003) and Geris (2012) which showed there is still little science that demonstrates that these sorts of measures reduce flood risk in catchments greater than 10km^2 in size. To make it even more complicated, it is hard to transfer model results from one catchment to another because catchments are so different in terms of their geology, topography, land use and response to flood conditions. These factors also make it hard to upscale a model's response across a larger catchment.

Notwithstanding the difficulties of modelling the effects of WwNP at the large catchment scale, scenario modelling using the CAESAR model suggests that implementing WwNP measures could counter the adverse effects of climate change. Furthermore, research on the River Swale has shown that WwNP is a powerful method for reducing sediment-related flood risks downstream in a catchment (Lane, S. and Raven, E., personal communication).

The scaling of models is necessary to fully understand the wider catchment impacts of WwNP measures on flood risk and water quality (Addiscott 1998). For example, not all of the diffuse pollutants mobilised in subcatchments will be distributed across the larger catchment during heavy rainfall as re-deposition and re-adsorption may take place during transport (de Vente et al. 2007).

When selecting modelling tools for your catchment it is important to understand the issue of scale so as to be able to express fully the likely benefits of WwNP measures and any uncertainties associated with the modelling approach used.

1.2.6 Visualising model outputs

It is also important to develop tools and models that can be used to visually represent the risk of flooding and any potential solutions. Model visualisations can be used to engage stakeholders and to check the validity of model outputs and scheme options (Maslen and Rose 2012, Ghimire et al. 2014Metcla, Metcalfe et al. in press). Figures 1.4 and 1.5 show the outputs of a model developed by Newcastle University to visualise the downstream impacts of WwNP measures.

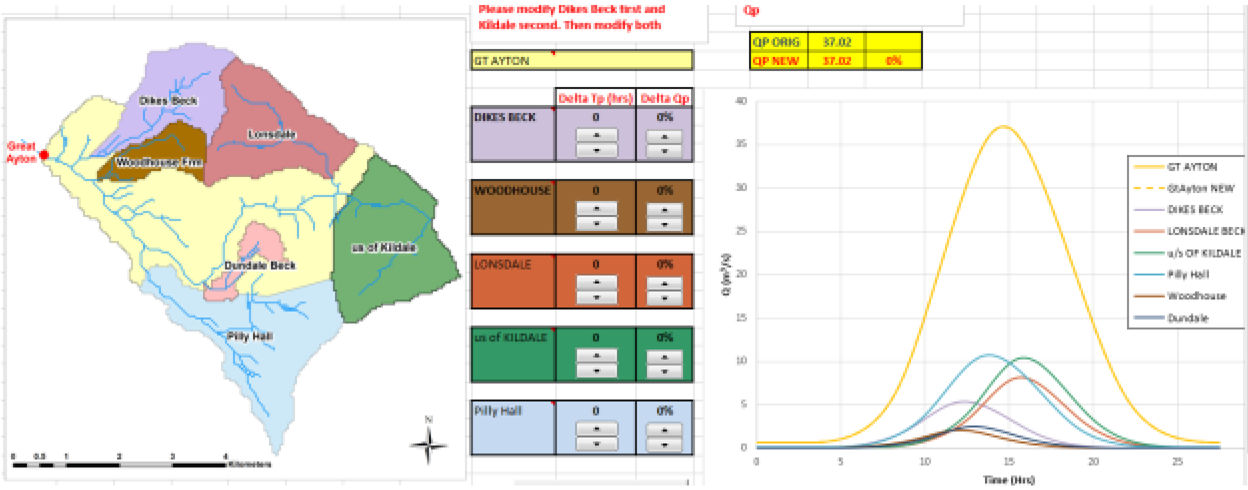


Figure 1.4 Relative impact of subcatchments on the flood impacted zone – extract from the Flood Impact Model

Source: Environment Agency Great Ayton flood study project

Visualisation can help engage with a range of stakeholders in a catchment. For example, in Ryedale (Lane et al. 2011), knowledge about flooding was co-produced by scientists and local people. Co-production of knowledge is important because it can help counter the uncertainties (see above) in catchment process modelling (Beven and Alcock 2012). Because model results alone will seldom provide a sufficient base on which to understand and make future investment decisions (Landström et al. 2011, Lane et al. 2011), it makes sense to develop models in partnership with your main stakeholders. Posthumus et al. (2008) and Wilkinson et al. (2013) also used visualisation tools such as FARM tool (see Figure 1.6) as an engagement tool to help discuss with land managers the effects of farming practices on runoff rates and potential measures to reduce runoff rates at the farm scale.

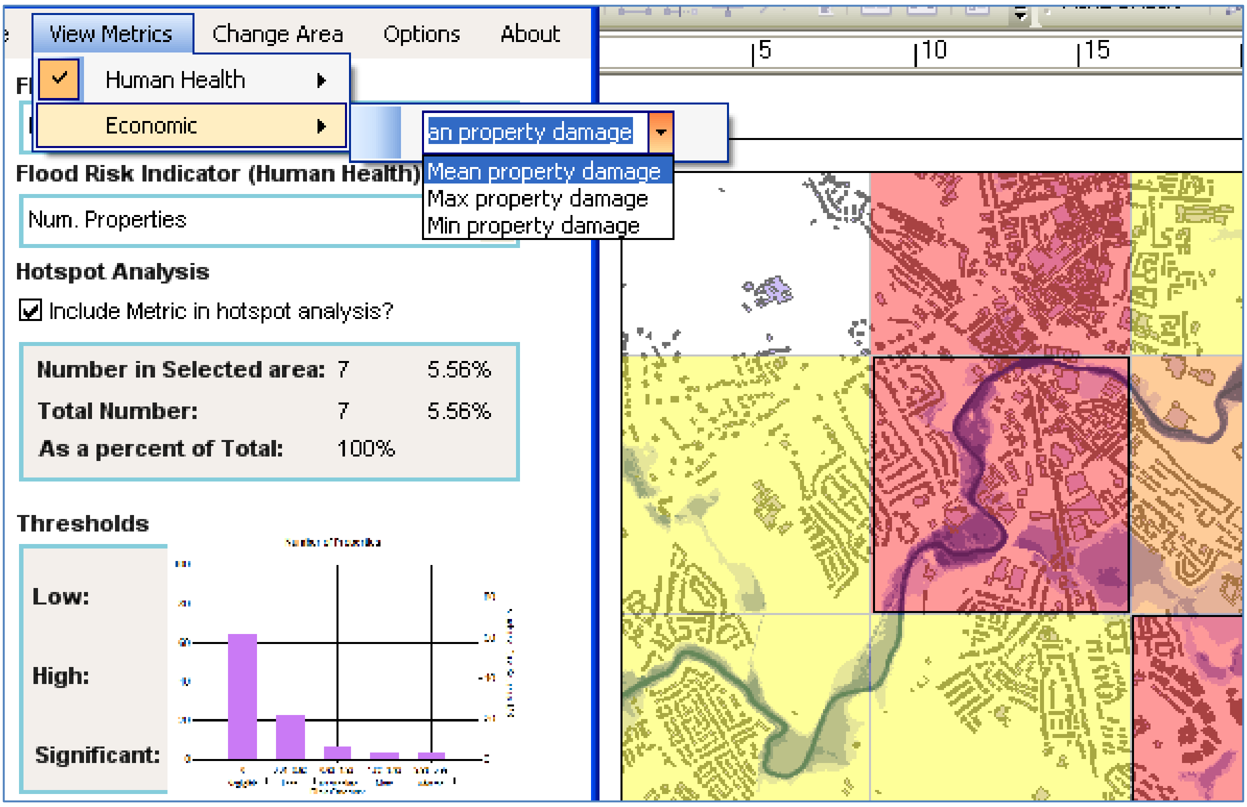
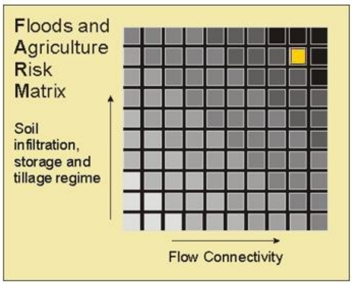
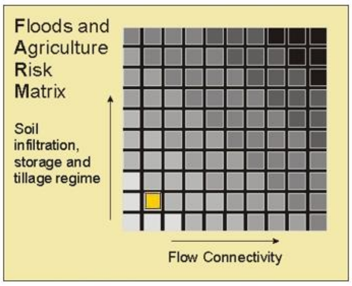


Figure 1.5 Visualising multiple flood risk metrics at different scales using ArcGIS



Farmer consensus – this is bad

Farmer consensus this is good



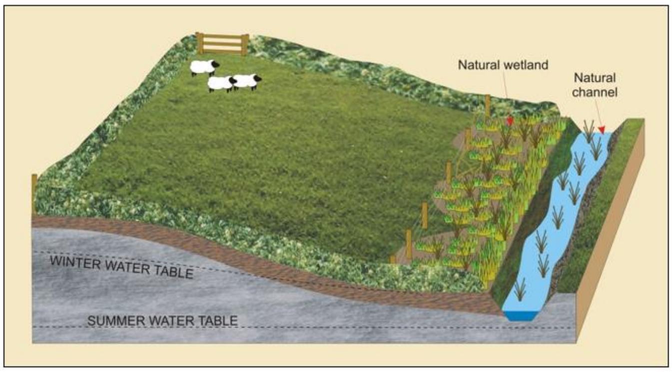


Figure 1.6 FARM tool on the Ripon project showing land-use impact on runoff rates

Source: Wilkinson et al. 2013

1.3 Catchment context

1.3.1 Introduction

To develop a WwNP scheme requires a good understanding of the catchment within which you are working. To do this you need to understand some important factors such as its typology (Figure 1.7).

River types vary across the country and are often a product of geology, slope and human intervention. Understanding river typology can help you understand how your catchment functions hydrologically and geomorphologically. This is useful in helping you decide where best to locate WwNP measures and also to choose the right model to assess their potential flood risk benefits.

1.3.2 Catchment process flow chart

Understanding watercourse typology can help you assess the sources, pathways and receptors of flooding.

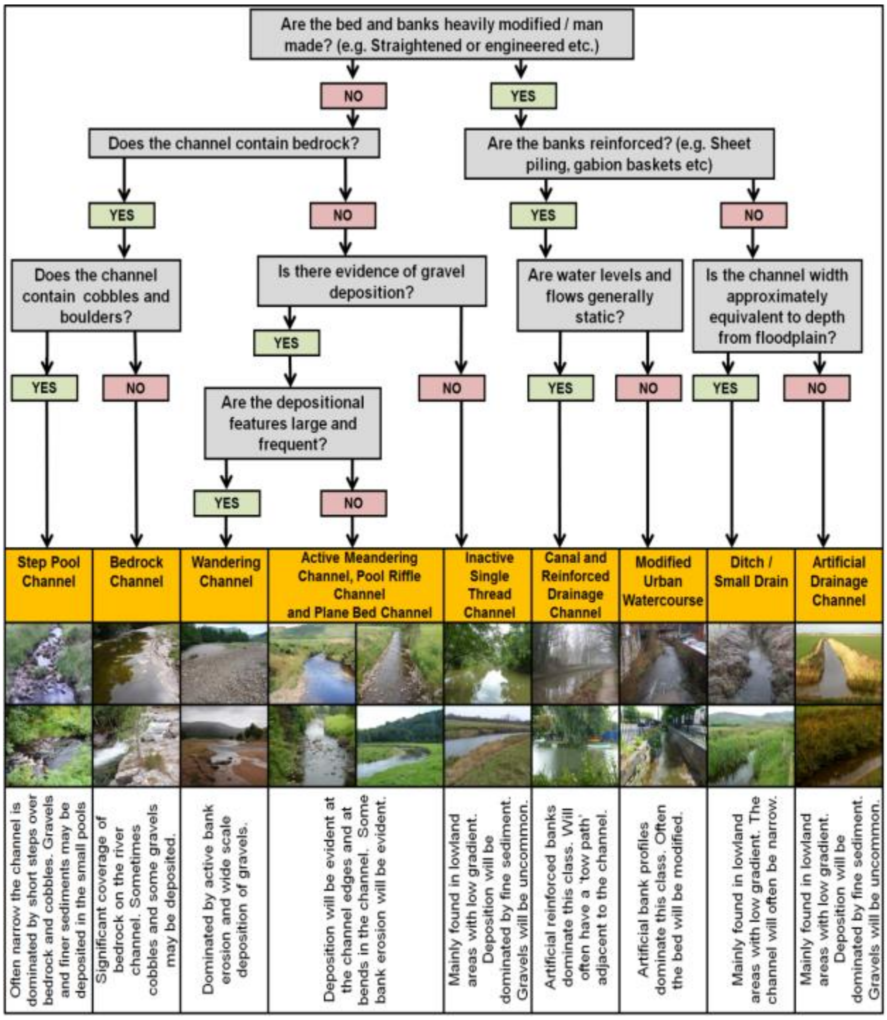


Figure 1.7 Flowchart for identifying geomorphic watercourse types

Source: Environment Agency (2014b)

The catchment process flow chart in Figure 1.8 sets out a series of steps which could be used to help understand how your catchment works and which tools to use to assess, design and implement WwNP options.

Whilst this report is focussed on how to model catchment processes, modelling and data are just one step used in developing a plan for a catchment. Figure 1.8 sets out five steps to help develop a catchment based plan to reduce flood risk this involves:

- **Talk to people –** Undertake a full and inclusive engagement process that facilitates knowledge gathering. A wide range of local partners could meet at the location where there is problem and commit to solving the flooding issue. Good engagement and a simple message that forges a common understanding of the problem and the way forward is needed.
- **Understand the problem(s) –** Use local knowledge and data help to visualise the flood flow pathways and understand their impacts. Any local issues such flood damaged properties, culverts, farming and local priorities can quickly be integrated into a plan. Simple visual tools and case studies can explore the appetite for where flood attenuation features could take place. An estimate of the flood reduction strategies and at what likely cost can be discussed.
- **Develop solutions -** Depending on the nature of the problem and the types of catchment, a mixture of different interventions might be possible to reduce flood risk. The team can then simulate different options using models to stimulate debate and agree possible solutions.
- **Articulate the benefits -** Catchment models or flood impact modelling tools can be used to explore a range of options for the catchment. These tools can be used to understand the flood risk benefits of a proposal and can help give confidence that the plan will achieve good outcomes at reasonable cost.
- **Build, monitor and adapt it –** Once the scheme is constructed develop a plan to monitor its effectiveness, this will help guide the need for any future maintenance or adaptive management which might be needed to ensure the WwNP features perform in the long-term.

The Belford case study followed this approach, highlighting the important role that models and data play in developing a catchment plan.

Belford case study

The Belford example followed the approach used in Figure 1.8. Local engagement champions from a range of organisations used the FARM visualisation tool and google earth to talk to the local community and understand the flood problem. A range of datasets and tools were used to simulate flood events and develop a suite of options to help reduce flood risk. 2 dimensional hydraulic models were used alongside site visits to find suitable locations for WwNP measures, and to help design them. A flood impact model was developed to understand the impacts of preferred design options, to estimate the cost per feature and to set out long-term maintenance requirements.

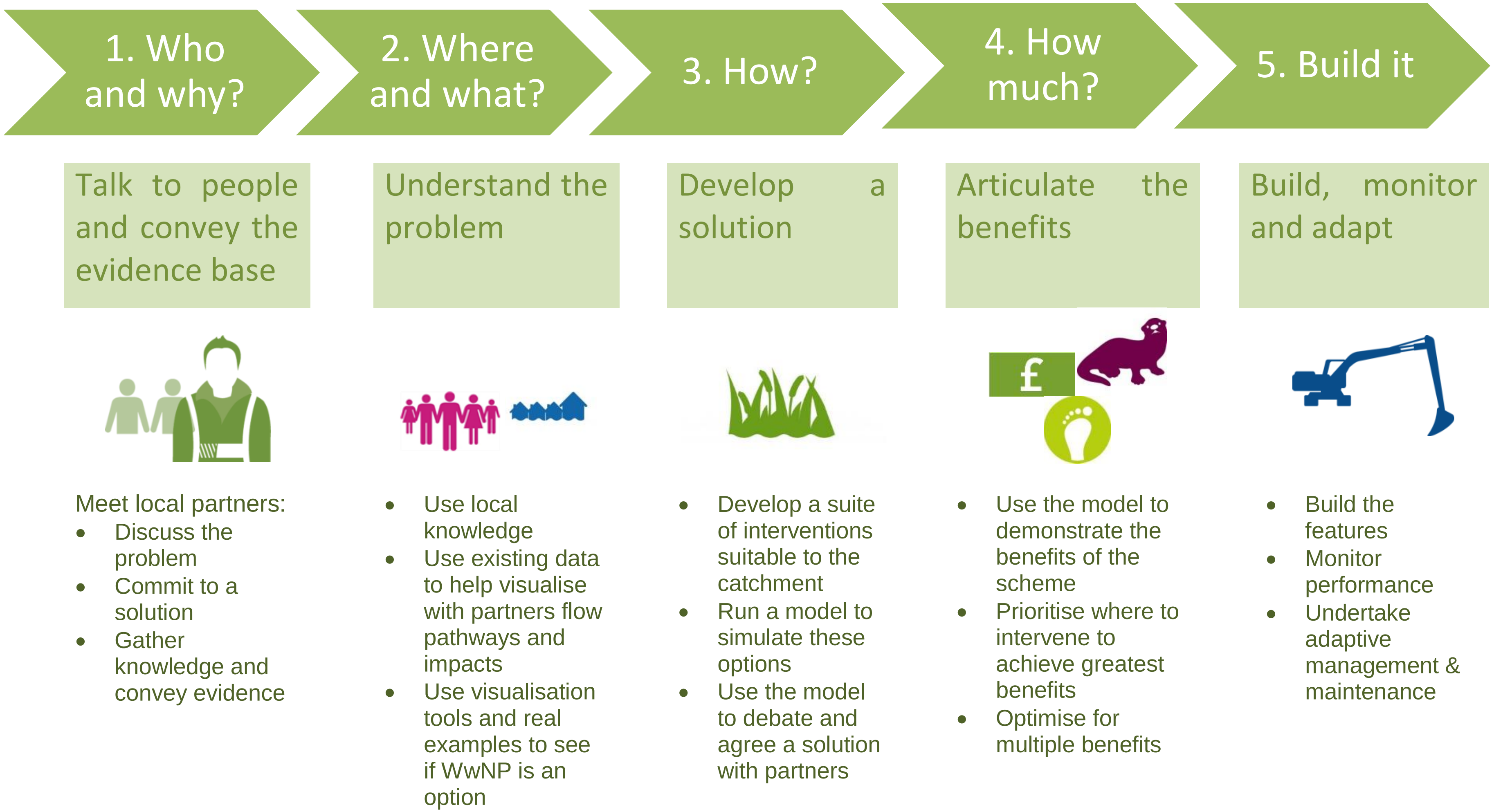


Figure 1.8 Five steps to develop a catchment-based plan

Source: Paul Quinn, Newcastle University

1.4 Conclusions and recommendations

Much of the expense of modelling stems from the need to collect detailed topographic, hydrological and hydrometric data with which to calibrate the model. The Environment Agency has access to a very large library of detailed one-dimensional (1D) and linked one-dimensional to 2-dimensional (1D–2D) models for flood risk mapping and forecasting.

Although many models have been built and calibrated to provide inundation outlines for particular extreme events, most models have also been adapted to enable continuous simulation which can be more appropriate for assessment of whole catchment processes. An important starting point for any modelling study is to assess what models already exist and which tools are readily available, and assess how these might be adapted for use in the new study. The main river modelling packages – Flood Modeller, HEC-RAS (US Army Corp of Engineers Hydrologic Engineering Center's River Analysis System) and MIKE 11 – all have sediment and water quality modules, so the first consideration when starting to model wider catchment processes should be to obtain an understanding of what additional data are required to drive these extra modules. When starting to develop a catchment wide plan it is important to be mindful that data and models are only one tool to help develop a solution and that they need to form part of a wider approach to developing a catchment plan (see Figure 1.8).

This chapter has provided the scientific context behind catchment modelling. Chapter 2 describes Step 1 of the model selection process (Figure 1.8). It will introduce you to the model library, so that once you understand your catchment's context, you can move on to select suitable tools and models to assess the benefits of your planned interventions.

Step 1	Step 2	Step 3
Use the model library to choose model(s)	Read Chapter 3 to understand the model(s)	Read case studies

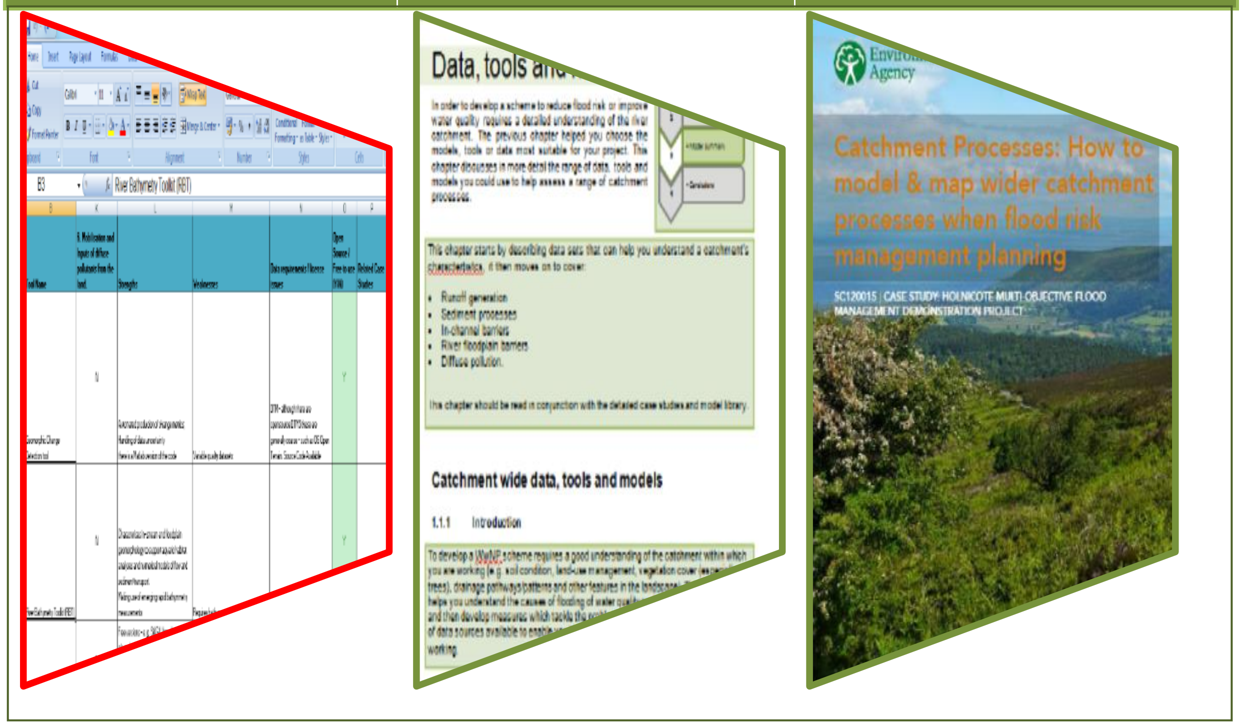
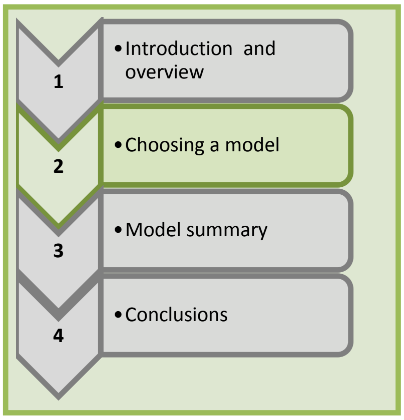


Figure 1.8 Moving on to Step 1 in the model selection process

2 Choosing suitable models



A large number of data, tools and models are available to help you understand the processes operating in your catchment. These can be used to help you plan and develop a WwNP scheme.

This chapter explains how to use the model library to help select the right model for the job in hand. The model library was compiled through a literature review, an expert workshop and the experience of the project team.

The model library should be used in conjunction with Chapter 3, which gives the details behind some of the models. The 20 case studies provide real examples where some of these models have been used.

Figure 2.1 presents a 3-step process for choosing suitable models, data and tools.

Step 1	Step 2	Step 3
Use the model library to choose model(s)	**Read Chapter 3 to understand the model(s)**	**Read case studies**

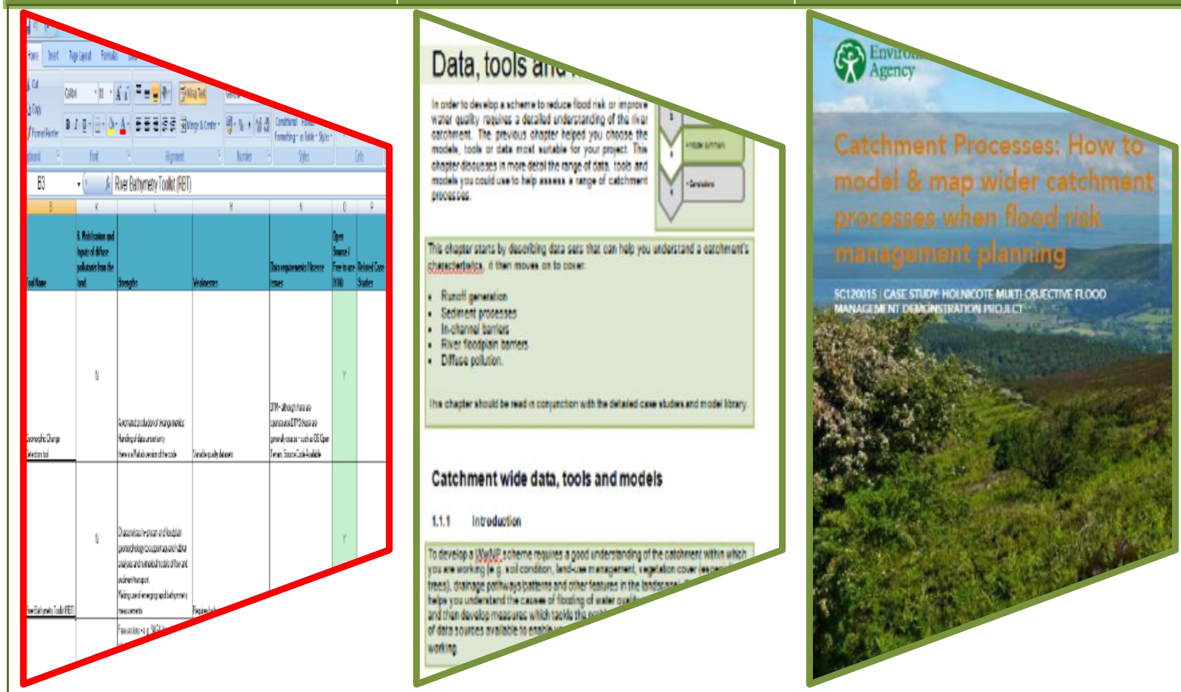


Figure 2.1 Three steps to help choose a suitable model

2.1 Choosing model(s) from the model library

2.1.1 Introduction

To develop a successful WwNP scheme requires a good understanding of the catchment within which you are working. The model library can help you define the sorts of data, tools and model you could use to understand how your catchment works.

2.1.2 Using the model library

The model library is an Excel spreadsheet tool. When using it, make sure macros are enabled to ensure its full functionality is available.

When you open the spreadsheet you will be taken to a tool selector (Figure 2.2) which allows you to access and search the model library. Based on your chosen filters the tool will retrieve for you the models, data and tools most relevant to your study. For example, you can select:

- the level of sophistication you want
- catchment processes you are interested in
- whether you need open source data

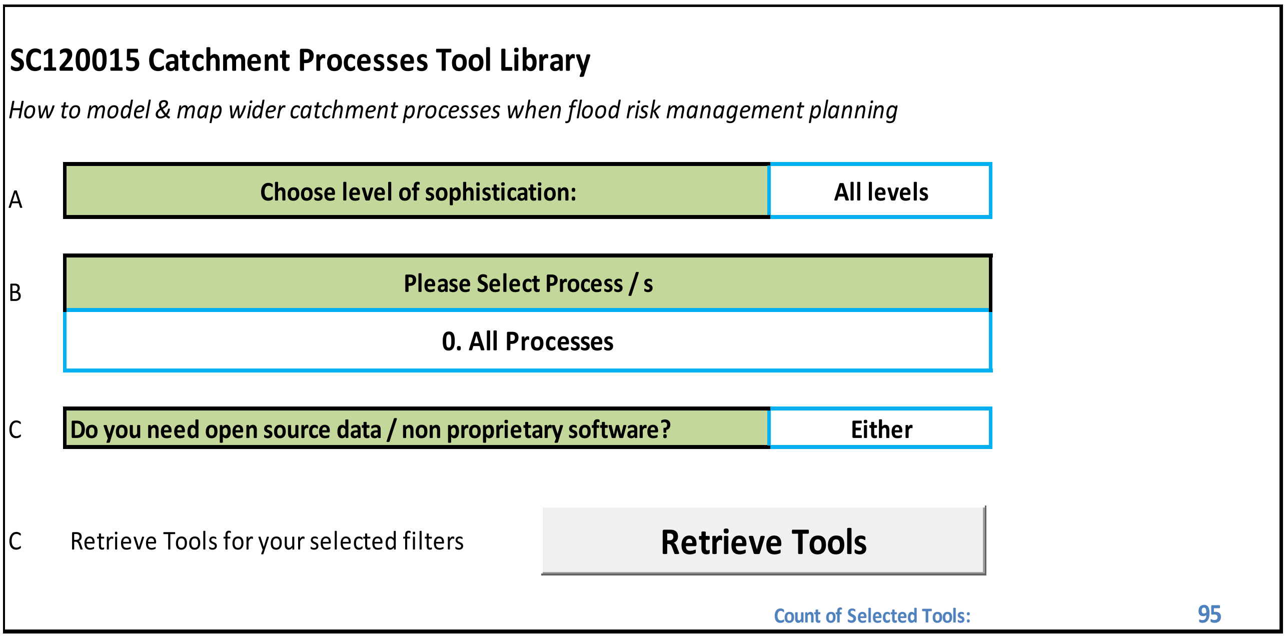


Figure 2.2 Screenshot of tool selector entry page

Clicking the ‘Retrieve Tools’ button (Figure 2.2) will take you to the tool library where all the models, data and tools relevant to your study, as selected by your chosen filters, will be displayed. You can also view all the models, data and tools using the Master Table (Tab 2).

The entry for each tool defines:

- main catchment processes the tool models
- scale of application

- level of complexity
- strengths and weaknesses of the approach
- data limitations
- usability
- accuracy
- costs
- availability
- references to further information
- links to case studies illustrating its use in practice.

Figure 2.3 shows the entry for the tool called ‘Fluvial Audit’.

The Excel format makes it easy for users to search for and identify tools of different types. The user can then refine the set of tools by changing the filters and re-running the search.

Tool	**Fluvial Audit**			**ID**	**8**
Processes	Understanding wider catchment processes			Process IDs	23456
Description	Fluvial audit is a very powerful tool in understanding catchment wide processes (as it considers both the channel and floodplain) and can be used to infer other mapping and modelling information. It is a method to capture and identify river and floodplain processes and forms at all temporal scales and involves a site/catchment walkover as well as a desktop assessment (utilising some of the data listed above). Included within this would be able to identify dominant sediment sources, sinks and transport pathways at the catchment and local scale. It allows a qualitative model of system functioning to be produced that can be used to describe system response over time and to imposed changes (such as flood mitigation measures).				
Strengths	Considers channel and floodplain	**Weaknesses**	Qualitative		
Data requirements/issues	Cost of fieldwork	**Key case studies**	River Irwell and Roch Ribble		
Typology dependencies	Y	**Ecosystem services/goods**	Y		
Web address		**Open source?**	Y	**Citations**	McIntyre and Thorne, 2012

Figure 2.3 Example entry from the model library

2.2 Conclusions and recommendations

This chapter presents a 3-step process to help you select appropriate models tools and data (Figure 2.1). The chapter explains Step 1 and how you can use the model library to help narrow the range of appropriate tools.

Depending on the budget and scale of the scheme, different levels of modelling can be performed. It is recognised that model choice may be influenced by:

- what existing models are available
- the resources available to modify the model such that it can be used to model the desired catchment process

Chapter 3 describes Step 2 of the model selection process (Figure 2.4). It provides details of important data, tools and models and is a useful resource which should be used in conjunction with the model library and the case study examples (Step 3).

Step 1	Step 2	Step 3
Use the model library to choose model(s)	Read Chapter 3 to understand the model(s)	Read case studies

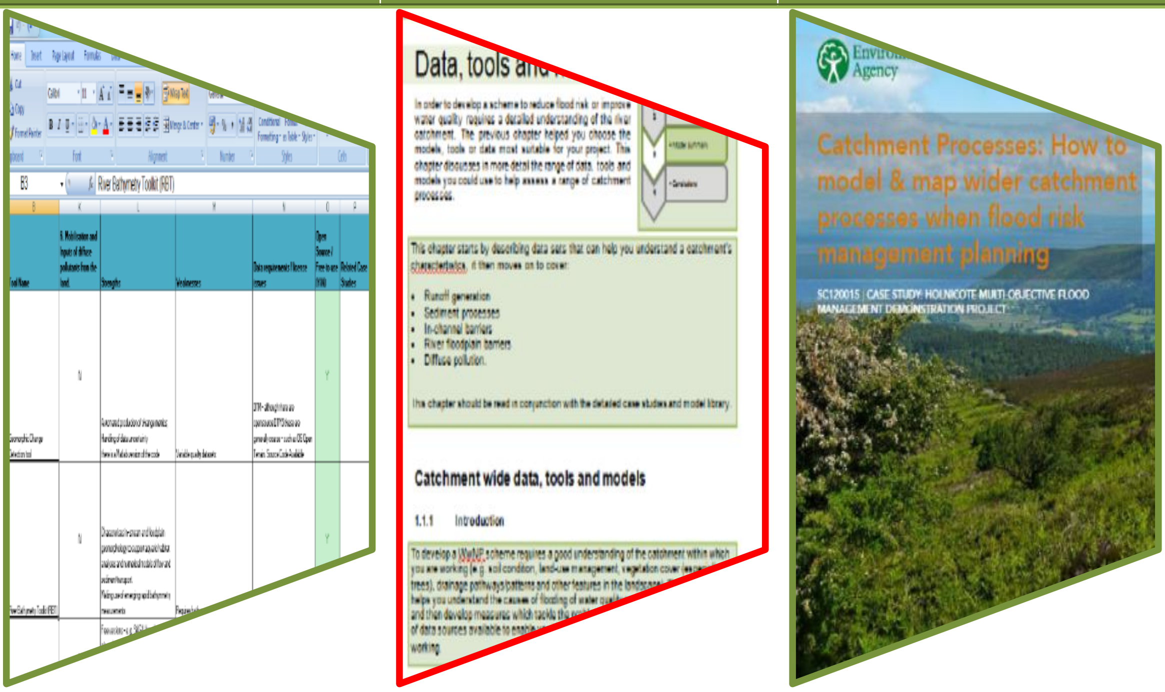
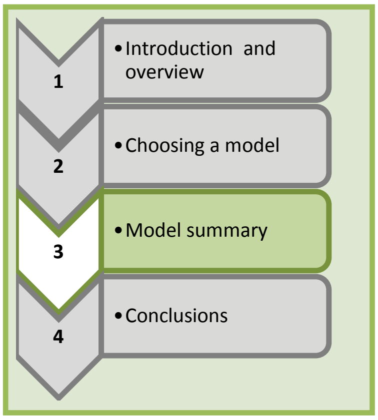


Figure 2.4 Moving on to Step 2 in the model selection process

3 Data, tools and models



Developing a scheme to reduce flood risk or improve water quality requires a detailed understanding of the river catchment. Step 1 (set out in Chapter 2) is designed to help you choose from the model library the models, tools or data most suitable for your project. This chapter sets out Step 2 of the 3-step process for choosing suitable models, data and tools (Figure 3.1). It discusses in more detail the range of data, tools and models you could use to help assess a range of catchment processes.

This chapter begins by describing datasets that can help you understand a catchment's characteristics. It then considers:

- run-off generation
- sediment processes
- in-channel barriers
- river floodplain barriers
- diffuse pollution

This chapter should be used in conjunction with the case studies and model library.

Step 1	Step 2	Step 3
Use the model library to choose model(s)	Read Chapter 3 to understand the model(s)	Read case studies

Figure 3.1 Three steps to help choose a suitable model

3.1 Catchment wide data, tools and models

3.1.1 Introduction

To develop a successful WwNP scheme requires a good understanding of the catchment within which you are working (for example, soil condition, land use management, vegetation cover (especially trees), drainage pathways/patterns and other features in the landscape). A wide range of data sources are available to enable you to do this. The information obtained will help you understand the causes of flooding and water quality problems in the catchment and then develop measures which tackle the issues at source.

3.1.2 Datasets

A catchment's characteristics control the hydrologic response of the landscape to rainfall and influence the nature of the drainage network and downstream flood risks. Table 3.1 gives details of existing datasets that can be analysed to determine a catchment's characteristics.

Table 3.1 Datasets for use in catchment-wide assessment models

Dataset type	Dataset description
FEH catchment descriptors	These are a range of descriptors on a 50m grid of the UK that reflect physical characteristics and catchment typology such as: • average flow path length • average slope • annual average rainfall • percentage run-off • Base Flow Index (BFI) • urban extent Data from the Flood Estimation Handbook (FEH) (Institute of Hydrology 1999) can be queried for these descriptors averaged over catchments with drainage areas down to a minimum of approximately 0.5km^2. The FEH also links hydrological catchment characteristics, such as time-to-peak (Tp) run-off, to these descriptors using empirical equations.
Catchment baseline surveys and fluvial audits	These enable hydrological and geomorphic processes and problems in the project reach to be understood within a wider, catchment context. These datasets will define the river type and explain the basis for the typology used including parameters such as channel gradient, stream power, and energy and general system dynamics/stability (for example, mapping of reaches as sediment sources, transfers, exchanges and sinks). The main outputs of a fluvial audit are: • historical events and changes that produced significant hydrologic or geomorphic responses • potentially destabilising phenomena capable of triggering

Dataset type	Dataset description
	changes in future
River Habitat Survey (RHS)	An RHS is conducted for a 500m stretch of watercourse and provides detailed written and photographic records of: • channel form • natural morphological features • anthropomorphic modifications to channel form and features • in-channel plus riparian habitats RHS records are analysed to produce: • a Habitat Quality Assessment that indicates the range and quality of habitats the reach provides • a Habitat Modification Score which defines the extent to which habitat in the reach has been degraded by channel engineering and/or maintenance RHS records and other available desktop information (for example, historical aerial imagery or maps) can be used to infer catchment characteristics and river type.
Historical maps, photographs, accounts and pictures	These form a useful resource that can be used to identify how a system has changed over time.
Flow records	The Environment Agency holds an extensive network of gauged data for many main rivers in England and Wales that provide records of daily flow data often stretching back many years. These data have been compiled into the National River Flows Archive which collates, quality controls and archives hydrometric data from gauging station networks across the UK. Analysis of these data can identify system flashiness and potential flow energy/dynamics.

3.1.3 Data analysis tools

Table 3.2 provides details of tools that can be used to analyse existing datasets to build a picture of catchment and drainage system characteristics and their susceptibility to change.

Table 3.2 Data analysis tools for catchment-wide assessment

Type of data analysis tool	Data analysis tool description
River typologies	UK rivers have been assessed using several river typologies which can help understand hydrology and geomorphological forms and processes. The insights gained can be applied to existing catchment knowledge and data to help define river and/or catchment characteristics and sensitivities to change (see, for example, the Tarland Burn case study).
Analysis of a Digital	A wide range of geographical information system (GIS)

Type of data analysis tool	Data analysis tool description
Elevation Model (DEM) or Digital Terrain Model (DTM)	spatial analysis toolsets are available for characterising hydrologic sinks, slope, connectivity, flow paths and hydrological watersheds.
Light detection and ranging (LiDAR) based analysis tools	LiDAR-based tools can be used to characterise hydromorphological conditions and processes at a catchment scale. This includes planform change, bed slope calculation, degree of bank erosion/deposition, floodplain type and extent.
Historical maps, aerial and ground-based imagery and flow records	These can be used to carry out a historic trend analysis to build a timeline of system change. This yields insights into system dynamics, energy levels and the potential for change over time or in response to disturbance/intervention.
Stream power	This is a measure of the time rate at which a river can do geomorphological work in forming and altering its channel. Reach-specific levels of stream power, and the way they change with distance downstream in the drainage network, can be interpreted and compared with published thresholds to determine the potential for erosion, deposition and resultant channel instability (Brookes and Wishart 2006).

3.1.4 Key findings from the case studies

The Brompton, Clwyd, Eden, Elwy, Pontbren, Tarland Burn, Thames Headwaters and Wyre case studies all used detailed catchment system information. A summary of the Brompton case study is given below.

Brompton case study

Dynamic TOPMODEL (Metcalfe et al. 2015) was used to investigate the impact on catchment characteristics of WwNP by installing 3 sets of 20 online 'leaky dams'. With 60 permeable structures, the maximum flood storage was around 65,000m^3; for a single peaked, 'design flood' of moderate magnitude, run-off was reduced by up to 0.38mm per hour and the time-to-peak discharge was increased by up to 45 minutes. It was concluded that this might be sufficient to reduce flooding during moderate events. However, when the model was used to simulate a real event from 2012, it was found that the leaky dams would have been inadequate to prevent flooding. This was because, although similar in magnitude to the 'design event', the real event had a double peaked hydrograph.

Modelling the real, double peak event highlighted that storage provided by the leaky dams was not always able to recover from the first flood peak before the second flood peak arrived, so careful design is required. This case study demonstrates that just that modelling an idealised design event may miss an important run-off feature resulting from characteristics specific to the catchment. This highlights the significance of accurately representing catchment characteristics, and changes therein.

3.2 Run-off assessment data, tools and models

3.2.1 Introduction

Hydrologists need to understand the movement and distribution of water within a catchment. This helps them to understand the sources, pathways and receptors of flooding.

Water enters rivers by flowing over land, through groundwater pathways and by draining through soils. This flow is measured in watercourses using a gauge.

Where, when and how run-off is generated depends on a range of factors such as the physical landscape, the river network, land use, underlying soil types, geology and previous rainfall. Run-off can be difficult to predict because it is generated by many surface and subsurface flow pathways that cannot be seen or measured (Figure 3.1).

This section describes a range of tools and models, providing an overview of flow estimation techniques.

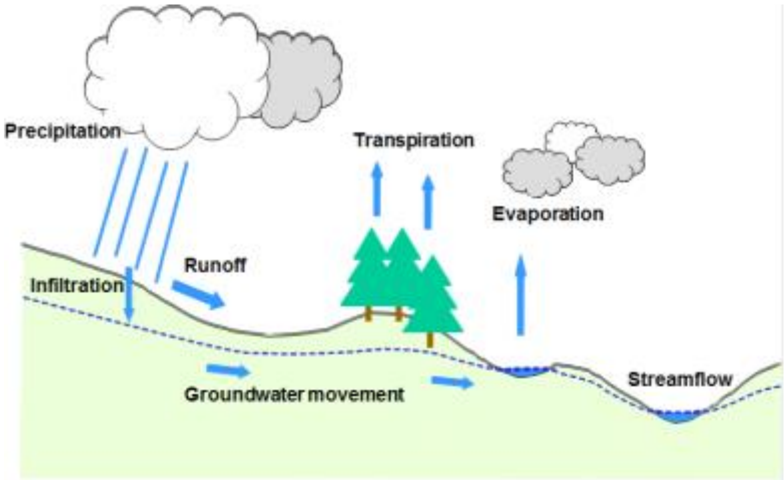


Figure 3.1 Run-off generation process

Modelling at the catchment scale involves a combination of:

- **Run-off-generation modelling** to predict the response to rainfall
- **Hydraulic or routing models** to predict how the run-off is conveyed downstream and combined when, for example, tributaries come together

How the land is used and managed influences run-off generation. A large number of tools (described below) are available to model both these aspects of catchment hydrology. Note that when using hydrological and catchment models, previous detailed investigations by Defra and the Environment Agency into the impacts of climate change on flood flows at a regional scale should also be considered (Crooks et al. 2010).

Run-off and water movement around the catchment is significantly influenced by pathways such as subsurface drainage and macropores which can transport water and contaminants at orders of magnitude faster than if the subsurface is a homogeneous porous medium (Beven 2006a, Beven 2012, Beven and Germann 2013). Flood hydrographs are also controlled by flood wave speed which, in both surface and subsurface flow pathways, can be significantly faster than water velocities. Flood hydrographs may comprise water stored in the catchment prior to an event and water displaced from storage by rainfall during that event (McDonnell and Beven 2014).

To calculate the downstream impacts of a land use management change, scenario modelling of current and future scenarios is required using a calibrated model. If measures such as soil de-compaction are proposed then the run-off modelling must be able to simulate the change to the system in terms of the physical process (for example, increased infiltration) and spatially so the distributed impacts can be assessed.

It is useful to differentiate the patterns of surface and subsurface run-off generation in a catchment from the routing of that run-off to the point of interest such as a gauging station or area at risk of flooding. Both aspects are subject to a significant lack of knowledge and uncertainties, so that the application of models of the processes is often associated with the local calibration of parameters where calibration data are available.

Calibration is used to compensate for lack of knowledge and the lack of a theory for scale-dependent run-off process representations (Beven 2006a). This has led to a variety of hydrological techniques such as:

- stormflow–baseflow separation
- the use of hydrological response units to combine similar run-off responses for parts of the catchment, typically using similar soil, land use and slope characteristics (see, for example, the use of the Soil and Water Assessment Tool reported in the Eden case study)

For a full description of the range of hydrological models and calibration techniques see Beven (2012) and Shaw et al. (2010).

Although rainfall monitoring and records are widely available in the UK, flow monitoring records to calibrate models and test assumptions are less so (Shaw et al. 2010). The majority of UK rainfall records are in daily time steps whereas flood run-off models require hourly resolution or better. Despite advances in ultrasonic low intrusiveness flow gauging, this can still be difficult, especially in gauging low flow headwater streams. Rainfall measurement and interpolation errors, and rating curve uncertainties, mean that datasets used for modelling will contain inherent uncertainties (Beven 2006b, McMillan et al. 2010, McMillan et al. 2012, Beven and Smith 2015).

3.2.2 Datasets

The Environment Agency holds an extensive network of gauged flow data for many rivers in England and Wales that provide records of daily flow data. These data now form the National River Flows Archive. Table 3.3 lists other datasets that can be of use when developing a run-off model.

The majority of point rainfall measurements are gathered at either daily or monthly time steps. The daily data are collected by a network of volunteers and some rain gauges have records that extend as far back as the 1800s. There are an increasing number of 15 minute time step rain gauges, which are managed by the Environment Agency and Natural Resources Wales. These are vital for flood forecasting models and provide high resolution data.

Rainfall radar, managed by the Met Office, provides a UK-wide spatial rainfall dataset, allowing users to spatially understand rainfall dynamics. When used with point measurements, these datasets can be usefully included in catchment models. The Natural Environment Research Council (NERC) also holds data which can be downloaded via the British Atmospheric Data Centre.

Table 3.3 Datasets needed for run-off generation models

Dataset type	Dataset description
Evapotranspiration data	For example, the Met Office Rainfall and Evapotranspiration Calculation System (MORECS) and the Met Office Surfaces Exchange Scheme (MOSES) Needed in continuous simulation run-off models.
Soil moisture data	See the new Centre for Ecology and Hydrology (CEH) COSMOS-UK network (http://cosmos.ceh.ac.uk).
Flow data	For model calibration and validation, or for monitoring change
FEH descriptors	See FEH methods for estimating floods in ungauged basins, including: • SPRHOST (Standard Percentage Run-off – Hydrology of Soil Types) • BFIHOST (Base Flow Index – Hydrology of Soil Types)
DEM	Based on: • synthetic aperture radar (SAR) data such as NEXTmap® Britain • LiDAR data • photogrammetry from unmanned aerial vehicles (UAVs)
DEM or bare-earth models	Where trees and other vegetation have been digitally removed
Edited DTMs	Where gaps have been edited through bridges to ensure hydrological connectivity
Soil datasets	• National Soils Resources Institute (NSRI)/National Soil Map of England and Wales (NATMAP) • Hydrology of Soil Types (HOST) • Grid-2-Grid database of parameters
Land cover	• European Union's CORINE (CoORdination of INformation on the Environment) land cover database • CEH's Land Cover Map 2007 (LCM2007)

3.2.3 Data analysis tools

Table 3.4 lists some of the wide range of tools is available to help analyse run-off data.

Table 3.4 Tools for analysing run-off generation data

Type of data analysis tool	Data analysis tool description
Rainfall spatial interpolation	Such as Thiessen polygons, kriging, inverse distance

Type of data analysis tool	Data analysis tool description
methods	weights, double mass plots to check for quality and consistency
Discharges	Rating curve uncertainties, standard interpolation and infilling methods (see National River Flows Archive)
Mass balance checks	
GIS tools for a variety of analyses (for example, ArcGIS, MapInfo, SAGA-GIS, R)	• Computation of sinks (depressions) in a DTM • Computation of DTM slope • flow direction grid for a sink-filled DTM • Watershed definition • Path distance length tools • Topographic index • Stream network identification • Editing tools for burning in stream definition

3.2.4 National tools

Table 3.5 gives details of the range of tools that can be used at a national level to help understand run-off production and areas more susceptible to surface water flooding.

Techniques for estimating run-off production based on catchment descriptors have been widely used for flood risk assessments at different levels. The FEH (Institute of Hydrology 1999) provides a method of generating the catchment descriptors and rainfall parameters necessary for estimating run-off based on a 50m resolution grid of data that includes important parameters from percentage run-off to the BFI and average channel length and slope. These are used with standard methods to compute estimates of, for instance, Tp (that is, the average lag between centre of mass of rainfall and river flow, or the average time between event rain falling and flows reaching the pour-point of a catchment).

Table 3.5 National tools for use in modelling run-off generation

National tool name	National tool description
Flood Impact Model Tool	This tool allows multiple sub-catchments to be simulated together and to test the impact of the local flow arising from a sub-catchment on the larger downstream catchment outfall. This allows the issue of flood synchronisation to be studied and allows a range of sub-catchment flood management impacts to be propagated downstream.
Continuous Estimation of River Flows (CERF) model **National Grid-2-Grid model**	Series of linear stores representing aggregated stores of soil moisture, groundwater and run-off are calibrated against flow data. In the Clwyd case study, components of the model were switched off to emulate ditch blocking.
Updated Flood Map for	Incorporates the ReFH run-off model to reflect local and antecedent conditions. The map was generated using the

National tool name	National tool description
Surface Water	blanket rainfall approach such that the effective run-off produced for a suite of summer rainfall events (with different return periods and durations) was then routed in 2D over a 2m DTM (made up of LiDAR and NEXTmap Britain). 2D routing was achieved using the graphics processing unit enhanced 2D shallow water equation solver, JFLOW (Lamb et al. 2009); peak flow depths, velocities and hazard ratings were stored throughout each event. The end product, is a merged depth grid across 3 durations (1, 3 and 6 hours), representing the worst flooding for any of these durations.
Revitalised Flood Hydrograph (ReFH) rainfall run-off model	Calculates the soil moisture capacity throughout an event which affects the percentage run-off. Maximum soil moisture capacity is computed based on the catchment descriptors, PROPWET and BFIHOST, which can be modified to simulate the effect of different WwNP measures.
PROPWET (proportion of time when the soil moisture deficit was <6mm, that is, the catchment is saturated)	PROPWET can be used to look at the effects of changes in land use in a catchment. These changes can be represented in ReFH and the impacts on run-off response modelled. If this is combined with a 2D overland routing model (for example, LISFLOOD, MIKE 21, Flood Modeller, JFLOW or TUFLOW) the changes in storage volume can be explored.

3.2.5 Local tools

Table 3.6 gives details of the variety of tools which can be used at a local level (catchment or subcatchment) to model run-off.

Table 3.6 Local tools for use in modelling run-off generation

Local tool name	Local tool description
Probability Distributed Soil Moisture (PDM), North American Mesoscale (NAM), Catchmod	Used as flood forecasting models, but also to model WwNP measures. In the Holnicote case study, maximum soil moisture storage was increased to better reflect land management and the impact of changes in land management on run-off generation.
Dynamic TOPMODEL **Soil and Water Assessment Tool (SWAT) model**	Models such as Dynamic TOPMODEL (used in the Brompton case study) and semi-distributed models such as SWAT require delineation of hydrological response units. The user combines different datasets and overlays classes of variables such as example, soil type, land cover, upslope contributing area, aspect and slope angle. There are processing tools to undertake this classification, such as ArcSWAT, which sequentially classifies subcatchments using soils, land cover and slope for the SWAT model.

Local tool name	Local tool description
	Dynamic TOPMODEL is flexible in how it defines its calculation units. It also allows for surface and subsurface flows to be routed downslope to account for topographic convergence and divergence on run-off contributing areas (Beven and Freer 2001b, Beven 2012).
MIKE SHE	A detailed physical process based model with integrated surface/subsurface modelling In the Glaven case study, a detailed model incorporating integrated groundwater/river interactions was developed (Clilverd et al. 2015). The model could be used to look at potential improvements in habitat dues to changes to the water table.
HYPE (HYdrological Predictions for the Environment) and Integrated Catchment Model (INCA) suite, INCA-P and INCA-N	HYPE software (see the Eden case study), uses a combination of soils and land classes without slope (although this could be used), whereas INCA-P and INCA-N use land cover data only on the assumption that this reflects the soil types (Flynn et al. 2002, Whitehead et al. 2007).
Grid-2-Grid	This raster grid conceptual modelling framework uses a version of the probability distributed model in each grid square (Bell and Moore 1998a, Bell and Moore 1998b, Bell et al. 2009). It is used operationally to make national predictions of flood run-off at 5km and 1km resolutions.
SHETRAN	Fully distributed models such as SHETRAN (Ewen et al. 2000, Birkenshaw et al. 2010) allow detailed catchment processes to be defined in a model. These models have a large number of parameters which allow the models to fit under test situations, but can lead to significant uncertainties when used for model predictions (see, for example, Vázquez et al. 2009).

3.2.6 Key findings from the case studies

Several of the case studies modelled run-off generation including Belford, Brompton, Clwyd, Eden, Elwy, Glaven, Holnicote, Pontbren and Thames Headwaters. Summaries of the key findings from the Pontbren example are given below.

Pontbren case study

The original Pontbren project was set up when farmers noticed that tree planting seemed to reduce run-off during storm events. The FRMRC project aimed to improve the modelling and understanding of how land use changes affect run-off processes.

The study showed that strategic tree and hedgerow planting has the potential to reduce peak flows in upper catchments and thus reduce the need for downstream flood defences.

3.3 Sediment assessment data, tools and models

3.3.1 Introduction

Sediments can originate from surface and subsurface erosion of hillslopes and valley floors from processes such as overland flow, gullying and erosion of channel banks. The processes responsible for the transport of sediment through a river system out to sea are complex (see Figure 3.2) and depend on the intrinsic characteristics of the catchment and river in question.

The Pontbren case study provided evidence that the sediment transfer system can affect flood risk more significantly than the run-off system (McIntyre and Thorne 2013) and hence the importance of sediment models.

It is estimated that three-quarters of sediment in rivers comes from agricultural activity. High quantities of sediment deposition can alter river channels by raising bed elevation and reducing width and flood conveyance. It can take many years for sediment in the upper reaches of a river to be transported out to sea, or stored long term in the floodplain, as a result of the infrequency of geomorphologically effective flows in many of the UK's river systems. However, datasets, publications, tools and science are available to assist in predicting and quantifying sediment sources, pathways and receptors for the different fractions that include bedload and suspended loads.

Soil erosion, considered the most important source of fine sediment production, has intensified as a result of changes to agricultural practices and land cover (for example, deforestation). Compaction of soil, downhill tillage and the clearance of vegetated areas, such as wetlands and woodlands, are examples of factors that can contribute to the increased generation of surface run-off (Beven et al. 2008a). WwNP measures have been developed on the premise that these trends need to be reversed.

An important compilation of methods for accounting for sediments in relation to flood risk in the UK was developed into an FRMRC toolbox (Wallerstein 2006, Thorne et al. 2010). There were 2 arguments for this work. The first was that there were insufficient UK datasets on sediments to use a detailed US–UK model – the HEC-RAS/Sediment Impact Analysis Methods (SIAM) model – throughout. The second was that there were a wide range of community requirements. Hence there was a need to develop simple sediment assessment tools while improving existing tools and models that quantify sediment continuity in the river system to identify which reaches act as:

- sources (degradational reaches)
- pathways (transportation reaches)
- exchanges (inputs and outputs are balanced, but sediment is exchanged between transport and storage)
- sinks (aggradational reaches plus floodplains that are connected to river channels) in the sediment transfer system

A fluvial audit is an important tool that is often used in river restoration. This detailed geomorphological assessment of a river/watercourse and its associated catchment records both qualitative and some quantitative information about the river form and processes. It also identifies pressures on the river system that are causing geomorphological issues. This leads to the identification of measures to improve the conditions of the river/waterbody.

The Scottish Environment Protection Agency (SEPA) uses the reduced complexity, sediment transfer model ST:REAM (Parker et al. 2015) to produce catchment-scale sediment risk maps. These are based on division of the fluvial system into reaches that are classified (using NEXTmap, LiDAR and synthetic hydrology) as being dominated by erosion, deposition or in 'dynamic equilibrium' based on application of the Bagnold (stream power) bedload equation and an assessment of the balance between local transport capacity and sediment supply from upstream.

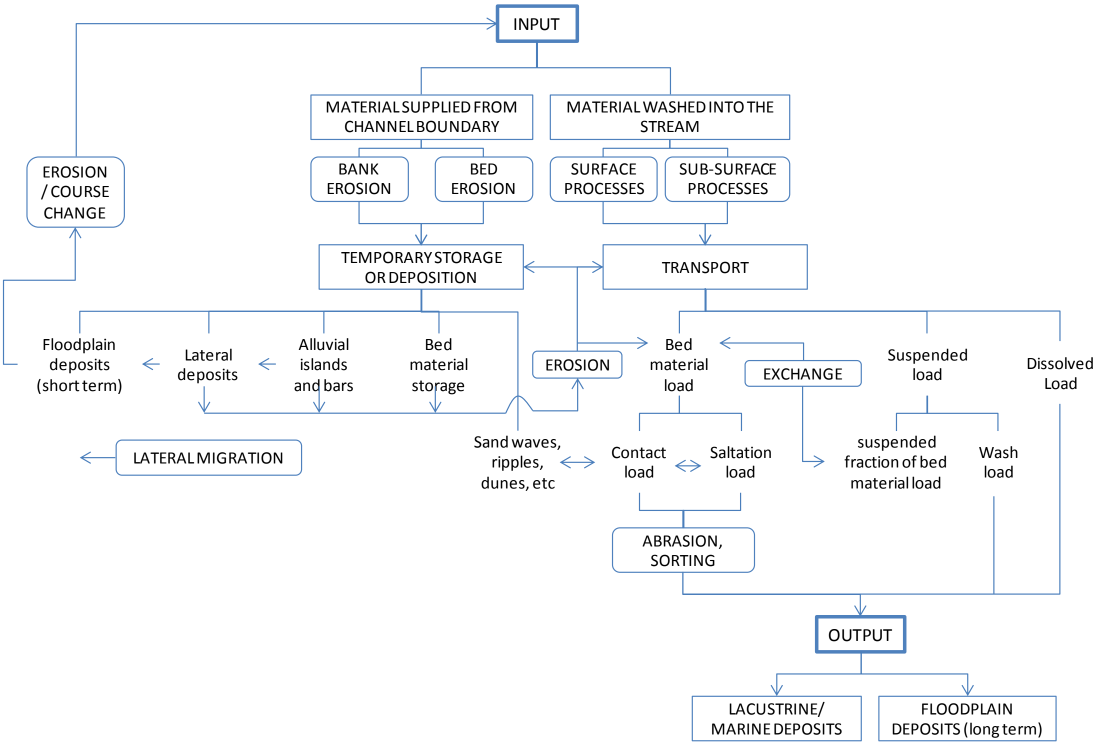


Figure 3.2 Sediment movement in and through the fluvial system

Source: Knighton (1998)

3.3.2 Datasets

Catchment sediment yield and sediment inputs into rivers come from surface and subsurface erosion of hillslopes and valley floors by processes such as overland flow, gullying and erosion of channel banks (Knighton 1998). In general, upper catchment areas will be erosion-dominated due to the steep gradients and strong connectivity of the river with surrounding hill slopes. This supplies the sediment that is transported to middle reaches dominated by the exchange of sediment supplied from upstream sources with that stored in bars, islands, floodplains and alluvial fans. In the lower course of the river, sediment storage increases due to the generally lower bed slopes, but the supply of sediment from bank erosion remains important for the overall sediment load due to lateral shifting of the channel across the flood or coastal plain.

The dominant sediment sources include those identified in Figure 3.3 to Figure 3.6. Field photographs and remotely sensed images are a valuable tool when considering erosion risk, in that they help to identify sediment sources and explain the processes responsible.

The transport and movement of sediment through a fluvial system can be measured, monitored or modelled. Sinks, such as lakes, floodplains, fans, and estuaries can also be analysed to generate long-term sedimentation rate, which can also demonstrate how sensitive UK river systems are to land use and climate changes.

There are few national datasets available that provide information relating to the movement and storage of sediment in fluvial systems. Table 3.7 provides details of datasets available to assess sediment sources, pathways and sinks.

Figure 3.3 Hillslopes and valleys (Google Earth)

Figure 3.4 Stored sediment in the floodplain (Google Earth)

Figure 3.5 River sources: hillslopes, channel bars and stream banks

Figure 3.6 Fine sediment inputs from agricultural and urban run-off

Table 3.7 Datasets used in modelling sediment processes

Type of dataset	Dataset description
Aerial imagery	Aerial images can often help to identify hillslope slumping/failure and sinks such as sediment stored on bars or in the floodplain.
British Geological Survey (BGS) solid and superficial geology maps	Useful for finding out the distribution of glacial, meltwater and alluvial sediment deposits. Rock type is a crucial control on the erodibility of a catchment and the grain size of material.
DEMs	• Channel and floodplain change over time mapped • Channel and floodplain long-stream and lateral connectivity • Obstructions to sediment transport • Floodplain depression storage • Riparian zone condition and extent
Fluvial audits	Detailed source of information on a catchment's dominant sediment processes.
Fluvial audits and photos	Information on sediment processes, transport and rates.
Land use and coverage datasets	Provide indications of likely type of sediment delivered to a river (for example, LCM2007 and CORINE)
LiDAR	Provides information on the frequency and size of sediment features within river systems .
ST:REAM (Sediment Transport: Reach Equilibrium Assessment Method)	Catchment maps to derive reach-based classification for reaches that are dominated by erosion or deposition or in 'dynamic equilibrium' based on a stream power
Stream power tool	Assess stream power in catchment.
UAVs	Improved resolution aerial imagery to identify sediment sources at a range of scales.

3.3.3 Data analysis tools

Table 3.8 gives details of the tools available to help analyse sediment data.

Table 3.8 Tools for analysis of sediment processes

Type of data analysis tool	Data analysis tool description
DTM	Bed slope can be estimated from the slope of a DTM.
Hjulström curve	Much can be interpreted from data analysis using the classic Hjulström curve (**Error! Reference source not found.**3.7), though it has been shown to be inaccurate in assessing sediment grain size and velocity.
LiDAR	Can be used to determine the hydromorphological condition and processes operating within a catchment:

Type of data analysis tool	Data analysis tool description
	• Segmenting the watercourse and floodplain • Channel-floodplain connectivity – height difference between average channel elevation and local floodplain segment • In-channel obstructions – detection of vertical drop in the long profile • Embankment delineation – moving window local elevation difference algorithm • Floodplain extent – algorithm to determine extent from topographic flatness index • Planform change – difference between old and new LiDAR datasets • Riparian margin – categorisation of LiDAR Digital Surface Model within the riparian zone
River typology	Slope can be linked to sediment load to determine river typology (Figure 3.8). Scale-independent diagrams have been derived linking planform pattern to channel type.
Stream power	Can be interpreted and compared with published thresholds to determine the potential for erosion and transport of various classes of sediment given in Table 3.9. Variances published across a range of studies have highlighted the importance of local controls when defining the potential for erosion and transport of sediment.

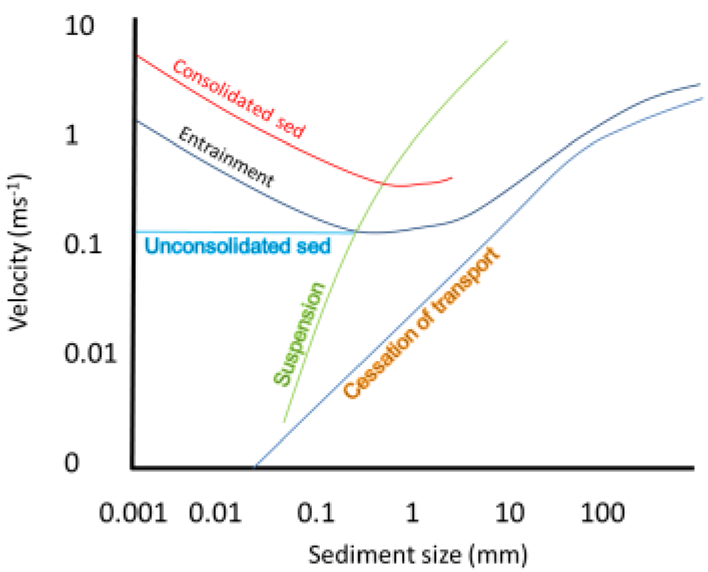


Figure 3.7 Hjulström curve

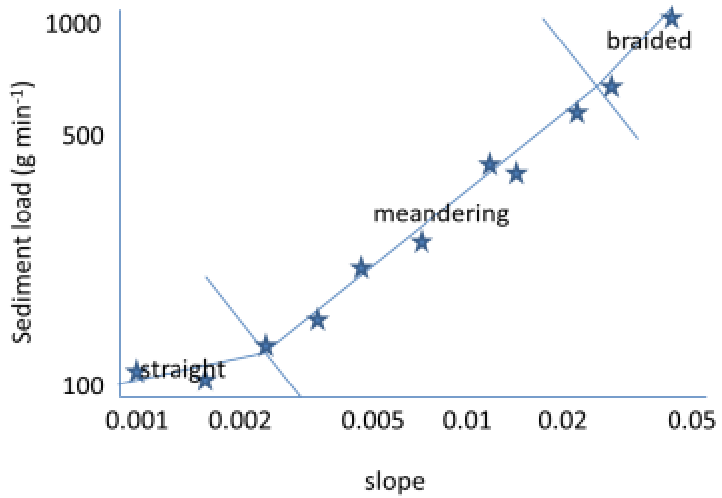


Figure 3.8 Example of slope and sediment load to determine basic river typology

Source: Schumm and Khan (1972)

Table 3.9 Stream power thresholds for movement of sediment

Size group	Bed stable		Bed unstable	
	Median stream power (Wm^{-2})	Range of stream power (Wm^{-2})	Median stream power (Wm^{-2})	Range of stream power (Wm^{-2})
Silt	47.5	13.8–81.1	37.8	8–105
Gravel	107	12–1766	73.3	4–489.6
Gravel/cobble	135.6	58.8–269.1	78.8	57.7–482
Cobble	No data	No data	142	7.2–427

Source: Environment Agency (1999)

3.3.4 National tools

Table 3.10 describes national tools available for assessing sediment.

Table 3.10 National tools for assessing sediment processes

National tool name	National tool description
Aerial imagery (for example, Google Earth, Ordnance Survey (OS), Bing Mapping, Environment Agency's detailed aerial imagery database, RHS and UAV technology)	Can be used to identify numerous processes: • Significant areas of erosion and deposition within the river channel and floodplain • Broad sediment types – it is sometimes possible, dependent on quality, to determine whether a reach is general bedrock, cobble, gravel or fine sediment dominated • Catchment-wide sediment sources such as valley sides, scree slopes and hill slopes • Hydraulic habitat (biotopes) within the channel, though

National tool name	National tool description
	this is heavily dependent on image resolution and scale • Structure and condition of the riparian zone • Channel change over time where historic datasets exist and can be compared with current land use changes over time
Combining high resolution outputs for velocities from 2D inundation models (for example, CAESAR-Lisflood, JFLOW, TUFLOW and HEC-RAS-2D)	JFLOW, a 2D hydrodynamic model (Lamb et al. 2009), has been adapted to allow representation of detailed bathymetry data within the river in combination with floodplain data to delineate downstream and cross-stream shear stress variability. This allows estimates of current erosion, transport and deposition trends as well as responses to various WwNP or restoration measures. The approach requires detailed topographic data, is depth-averaged and ignores turbulence (should be considered when interpreting outputs).

3.3.5 Local tools

Table 3.11 describes local tools for assessing sediment.

Table 3.11 Local tools for assessing sediment processes

Local tool name	Local tool description
CAESAR-Lisflood	This 2D–2D hill slope, flow and sediment transport model can simulate morphological changes in river catchments and reaches, with potential to simulate thousands of years of data (McIntyre and Thorne 2013). It was used in the Pontbren case study to predict how sediment yields change under a variety of future land use and climate change scenarios. The modelling process highlighted the unpredictability of geomorphologically effective events and hence the associated sediment yield.
HEC-RAS/SIAM	Quantifies local sediment imbalances and downstream sediment yields under different catchment and river management scenarios. SIAM allows a rapid assessment of catchment-wide scenarios, but requires transfer of channel change information to quantify impacts on flood risk to another model. The model, requires significant sediment load and size information to reduce uncertainty and improve the accuracy of sediment and process change predictions.
Flood Modeller sediment transport modelling	Flood Modeller has a 1D dynamic bed module that allows for simulation of bed change over time by specifying various sediment information and applicable transport equations suitable for the identified reach. It can be used to simulate a series of flood events over time. However, as a 1D model it does not simulate lateral movement of the channel plan position and this will limit its applicability where such processes are significant

Local tool name	Local tool description
	There is a free version of Flood Modeller (Flood Modeller Free) it provides full hydrodynamic 1D / 2D capabilities and 1D sediment transport and 1D water quality solvers (limited to 250 1D nodes and 100,000 2D cells – which may be sufficient for many studies). For more information, see: www.floodmodeller.com
MIKE 21C	Simulates changes to river bed and planform using a rectilinear grid. It is able to provide detail at the reach level but it is not yet known whether it can be applied at a catchment scale.
Non modelling-based tools	• Sediment monitoring – tracking of particles (coarse) through a river system, local accretion/erosion monitoring or floodplain sediment coring and dating • Repeated topographical cross sections of riverbeds, possibly using bedload traps • Visual field based mapping (Hooke 2003) to understand a sediment system
Sediment transport equations	Where data on sediment types and budgets are available, sediment transport equations can be used to determine the rate of sediment transport within a fluvial system (see, for example, Bagnold 1966). The performance of bedload equations can be variable and often inaccurate (Gomez and Church 1989), mainly due to local controlling factors such as gravel armouring and vegetation colonisation.
SHETRAN	Physically based, distributed model that can simulate the entire land phase of the hydrological cycle including surface water flow and groundwater flow. Includes a fully 3-dimensional (3D) subsurface or variably saturated subsurface component.

3.3.6 Key findings from the case studies

Sediment processes were modelled in the Calder and Brun, Elwy, Glaven, Medlock, Pontbren, Wensum and Wyre case studies. Below is a summary of the most important findings from one of these examples.

Medlock case study

The fluvial audit and geomorphological modelling for this study demonstrated that removing the brick lining for part of the River Medlock, alongside morphological restoration of the channel, will improve the hydromorphology and fish passage through the study reach.

3.4 In-channel barrier assessment data, tools and models

3.4.1 Introduction

In-channel barriers within river systems include weirs, barriers and barrages (with or without locks), bridges, culverts, sluices/tide gates and other structural blockages. These can increase water levels upstream, or afflux (Figure 3.9), but can also affect geomorphological river processes in various ways. The severity of the impact depends on factors including:

- the type and size of the structure
- the location and orientation of the structure
- the age of the structure
- the type of river within which the structure is located

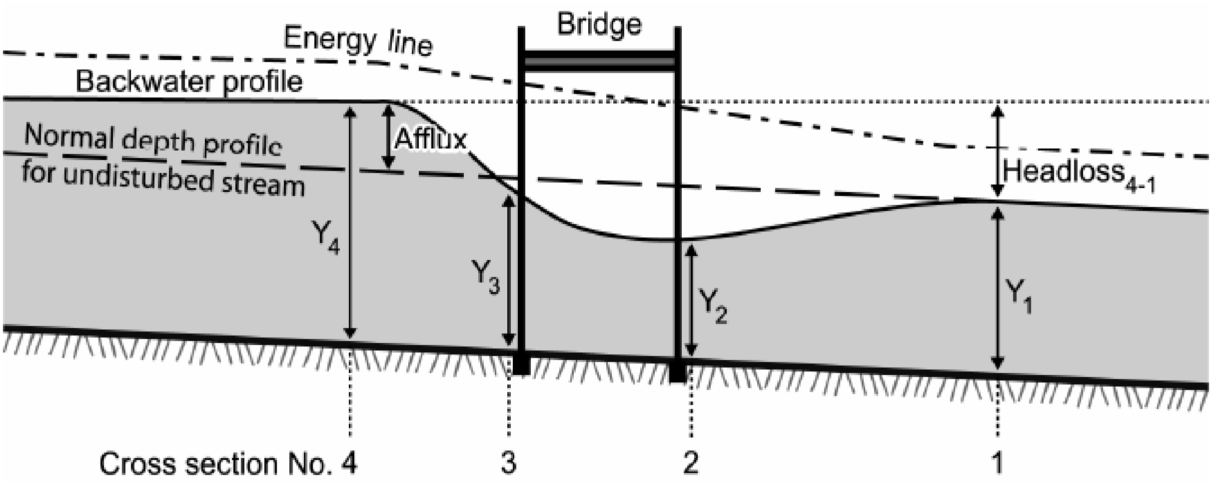


Figure 3.9 Effect of in-river structures

Source: Mantz (2007)

In-channel structures serve a variety of purposes and weirs and culverts and barriers/barrages can provide local flood defence benefits for events up to their design capacities. However, in-channel structures also introduce their own flood risks and their potential impacts can also include:

- creating an impoundment zone upstream of a weir providing low energy flow conditions that impede flood debris passing downstream, substantially increasing flood risk immediately upstream of the structure (exacerbated for structures that constrict the flow or are undersized relative to the lengths of wood pieces typically transported by the stream or which feature inappropriately designed or maintained trash screens)
- interrupting the sediment transfer system by inducing deposition of sediment within the impoundment zone, raising bed levels, clogging the bed with fines and reducing local channel capacity and conveyance – trapping sediment can also potentially starve downstream reaches of sediment, destabilising the sediment supply/transport balance to generate bed scour and bank erosion that increases the fragility of flood defence assets

- increased water levels, depths and flow widths upstream of the structure – especially high flow events
- reduced flow velocities upstream – allowing seeds and plant propagules to deposit, colonise the channel and reduce its capacity to convey floods
- increased velocities and scour in vicinity of the structure leading to local and constriction scour that damage flood defence assets
- unnatural changes to the flow regime to downstream reaches with risks to the river environment and ecosystem
- modification to floodplain wetting frequency, with consequential environmental and ecological impacts
- blocking passage of migratory and anadromous fish – especially eels
- potential for sudden collapse during flood events with extreme risks to life as well as property and transport infrastructure – illustrated by the tragic death of PC Bill Barker when a bridge collapsed due to channel scour during the Cumbria floods of 2009

3.4.2 Datasets

Table 3.12 lists various datasets that can be used to assess in-channel barriers.

Table 3.12 Datasets needed to identify in-channel barriers

Type of dataset	Dataset description
Aerial imagery **Catchment walkovers, rapid geomorphic risk surveys and WFD assessments**	Can be used to locate channel barriers. They do not provide information about the size of the barrier but can provide an indication of the impoundment length.
Existing survey and hydraulic models	Many river systems in England and Wales have frequently been modelled using 1D or 1D–2D software packages to assess flood risk to people and property. These models are mostly owned by the Environment Agency and are likely to include surveyed information on in-channel barriers and structures such as weirs, bridges, culverts, barrier/barrages and sluices.
River obstructions	Environment Agency dataset containing information on the location and height of weirs, dams and locks.
Fluvial audits	Existing fluvial audits should provide a commentary on the geomorphological impacts of any in-channel structures on channel forms and processes.
River Habitat Survey	Conducted at 500m stretches of watercourse – should provide detail on the nature of any in-channel obstructions. Also includes detailed photographic record accompanying each surveyed reach.
Environment Agency's Asset Information Management	Information on in-stream assets such as culverts and their associated maintenance regime

Type of dataset	Dataset description
System (AIMS) database	
Eel and fish barriers	Environment Agency database which identifies structures that are a barrier to fish and eels

3.4.3 National tools

Table 3.13 lists various national tools that can used to assess in-channel barriers.

Table 3.13 National tools for assessing in-channel barriers

National tool name	National tool description
Low flow restoration measures	A matrix to help assess the sensitivity of various river types across the UK to channel impoundments and structures such as weirs, dams, sluices and culverts has been developed (Environment Agency 2016). This will help determine the sensitivity of a river to an impoundment/barrier and the likely impacts on the river system.
Aerial imagery	Aerial imagery is a useful in helping to determine the presence of in-channel barriers within a river or catchment. High level geomorphological impacts can be detected depending on the scale and accuracy of the imagery.

3.4.4 Local tools

Table 3.14 gives details of the various local tools that can be used to assess in-channel barriers.

Table 3.14 Local tools assessing in-channel barriers

Local tool name	Local tool description
1D, 2D and 3D tools	There are a range of hydraulic 1D, 2D and 3D tools that can be used to assess the impacts of in-channel structures on water levels upstream and downstream. Fully hydrodynamic solutions of the 1D St Venant equations (for example, HEC-RAS, Flood Modeller, MIKE 11) and 2D shallow water equations (for example, TUFLOW, JFLOW, Flood Modeller, MIKE 21) are widely available. Simplified solutions such as the backwater model (for example, HEC-RAS) can often provide insight and model afflux accurately as long as there are no attenuation effects.
Afflux Estimation System (AES)	Designed to improve the understanding of the effects of in-channel structures such as bridges and culverts on water levels at high flows. This relates particularly to the representation of afflux (the increase in upstream water levels caused by the structure).
Conveyance Estimation System (CES)	Developed to integrate years of research into the different energy losses associated with bedforms, channel constrictions, bend curvature and seasonal roughness.

Local tool name	Local tool description
Dynamic TOPMODEL	Modified with enhanced flood routing and the ability to incorporate channel blockage effects using sluices that pass flow underneath and over them during high flows.
1D models	Water levels and flow depths can be interpreted to determine the influence of an in-channel barrier. For instance, flow velocity (depth averaged) can be interpreted and cross-referenced with the Hjulström curve (Figure 3.7) to determine the approximate impacts on the sediment regime. Hydraulic parameters can also be used to calculate indicative bed shear stress. These are useful tools, particularly when appraising the benefits and risks of a restoration measure.
2D models	Provide hydraulic variance across the channel width and often output bed shear stress and stream power automatically with no post-processing of hydraulic data. This is particularly important where channel sinuosity is affecting flow dynamics. A fluvial audit can be conducted by an experienced geomorphologist to determine the impacts of in-channel barriers on river forms and processes.

3.4.5 Key findings from the case studies

The Brompton and Burnley case study are examples where in-channel barriers were fully considered. A summary of the Burnley case study is given below.

Burnley case study

This case study demonstrated how an existing 1D flood model (Flood Modeller) could be used to assess changes to in-channel features proposed as part of a river restoration scheme. 2D modelling was also used to understand the cross-stream distribution of velocities, while velocity and shear stress data from the 1D and 2D models were useful for estimating sediment mobility and habitat quality (aquatic, bankside and floodplain).

The modelled afflux for a range of flood flows was only marginal greater following implementation of the restoration scheme than under current conditions.

3.5 River floodplain barrier assessment data, tools and models

3.5.1 Introduction

Floodplain restoration through embankment removal and the reconfiguration of river channels helps to re-establish river–floodplain connectivity though modelling the hydrodynamics can be complex. There can, of course, be significant connectivity between the channel and the floodplain via subsurface pathways even in the presence of raised defences (Figure 3.10), although often this connection is also blocked by sheet piles driven below the embankments.

Channelisation (involving dredging, widening and/or straightening, plus incision of the channel bed) and embanking rivers have been demonstrated to have significantly degraded aquatic, riparian and floodplain habitats worldwide (Pilcher et al. 2004, Clilverd et al. 2013, Clilverd et al. 2015) resulting in the loss of natural resources and ecosystem services of enormous economic value (Costanza et al. 1997).

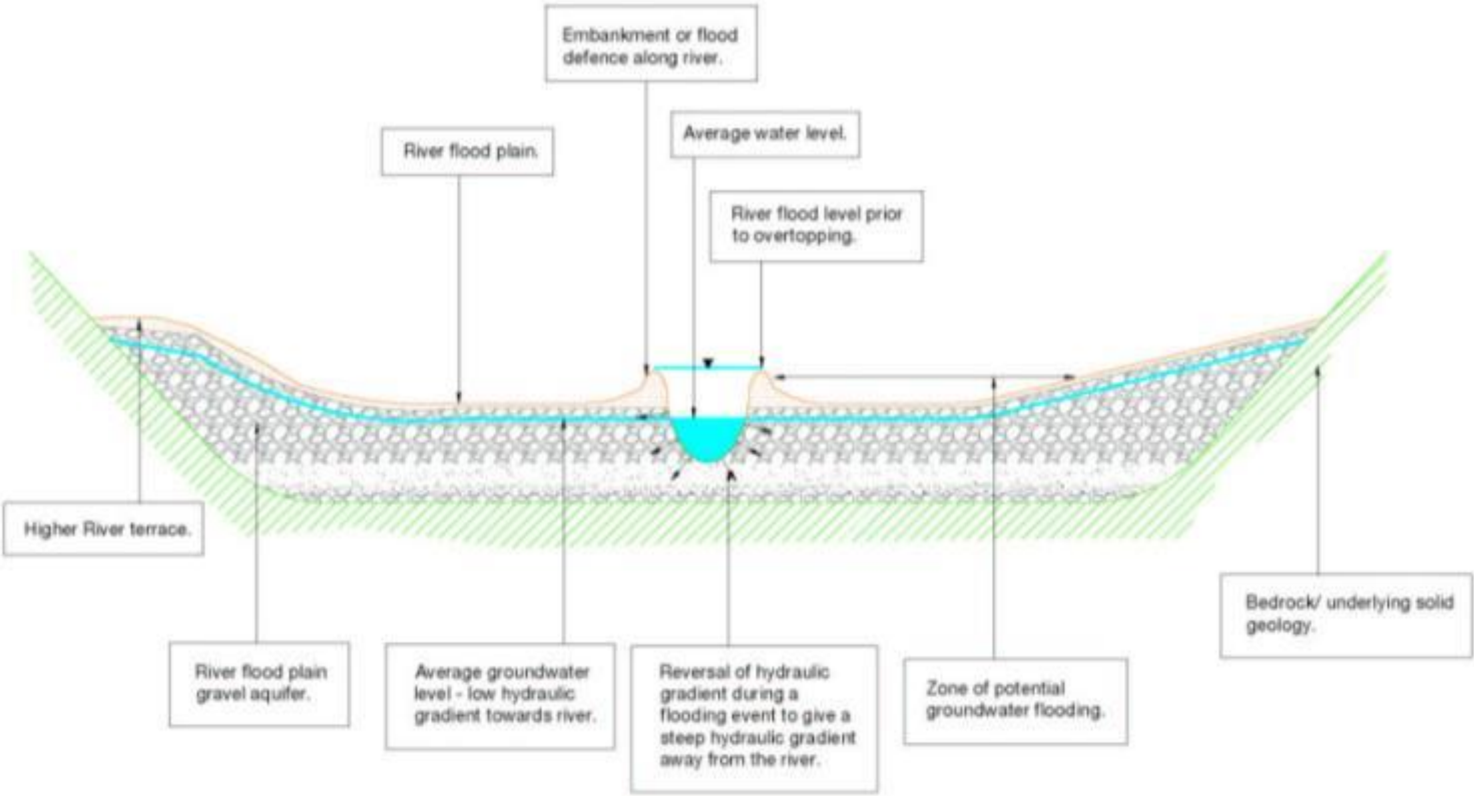


Figure 3.10 Longitudinal barriers and potential flood pathways

Source: Defra (2004)

Improved connectivity between the river and its floodplain can be restored through local bank and floodplain works, including flood bank removal or in-channel morphological works to raise incised river beds. This is beneficial because lack of connectivity means that high flows are prevented from spreading across the floodplain, instead being passed downstream without the flood peak being attenuated. As high flow events are generally the most geomorphologically effective, concentrating them within the channel focuses erosion, transport and deposition in a smaller area, altering local morphology and disrupting the sediment transport regime up and downstream, with knock-on effects throughout the drainage system. Under these conditions, the morphology for lower flows is also altered (Clilverd et al. 2015) and low flow habitats in the channel are degraded due to drying of the floodplain aquifer and loss of supported vegetation.

Where floodplain connectivity is poor, aquatic species are denied access to the floodplain during floods, which may prevent spawning or result in loss of vital rearing habitats and high flow refugia. It follows that re-connecting the floodplain can generate multiple benefits by, for example, encouraging deposition of fine sediment load on the floodplain, attenuating downstream flood peaks, storing flood water and recharging floodplain aquifers, improving water quality and enhancing habitats to increase the economic, social and environmental values of ecosystem services.

3.5.2 Datasets

There are numerous existing national datasets including OS maps that can be interpreted to provide varying degrees of information about longitudinal barriers that disconnect rivers from their floodplains. Details of some of these datasets are given in Table 3.15.

Table 3.15 Datasets needed to identify river floodplain barriers

Type of dataset	Dataset description
Aerial imagery	Aerial imagery can be used as a data source to determine the presence and location of longitudinal barriers in the floodplain, such as flood embankments, although the scale and resolution may preclude identification of small barriers or those that blend into the surrounding landscape.
Existing survey and hydraulic models	Existing hydraulic model information, particularly where these are flood models, are likely to contain surveyed information on local flood defences. These could be represented as part of cross-section geometry within the 1D model component, or as 2Delements in the floodplain, depending on their location (for example, bank top or set back defences).
LiDAR	Can provide a dataset that can identify the spatial location, height, width and length of longitudinal barriers in the floodplain or on bank tops.
Existing fluvial audits and RHS records	Should provide details of any longitudinal barriers or floodplain areas that are poorly connected to the channel, including interpretation of how this is influencing river forms, processes and habitats both locally and up and downstream.

3.5.3 Data analysis tools

Table 3.16 describes useful data analysis tools for assessing river floodplain barriers.

Table 3.16 Tools for analysing data on river floodplain barriers

Data analysis tool name	Data analysis tool description
DTM analysis packages	Used to analyse the cross-sectional profiles of watercourses and their floodplains, and to provide a basic understanding of fluvial geomorphology so as to help understand artificial disconnection between channel and floodplain that will reduce storage at high flows.
LiDAR	LiDAR can be analysed to determine hydromorphological condition for the WFD. A study by JBA Consulting for the Environment Agency used LiDAR and an elevation algorithm

Data analysis tool name	Data analysis tool description
	across the floodplain to determine embankment profile patterns (Environment Agency 2012b). A protocol was developed to measure the height difference between the average channel elevation and local floodplain height to provide a metric for channel–floodplain connectivity.

3.5.4 National tools

Table 3.17 describes useful national tools for assessing river floodplain barriers.

Table 3.17 National tools for assessing river floodplain barriers

National tool name	National tool description
Aerial imagery	Can be used as a tool in itself to initially identify the length, type and extent of a longitudinal barrier at either the reach or catchment scale. It may also be possible to infer the influence on local geomorphological forms and processes depending on the resolution of the data. For example, habitat features may be identified using high resolution data.

3.5.5 Local tools

Table 3.18 describes useful local tools for assessing river floodplain barriers.

Table 3.18 Local tools for assessing river floodplain barriers

Local tool name	Local tool description
Hydrological models (MIKE SHE/MIKE 11)	These have been used to assess the impacts of removing longitudinal barriers as part of river restoration at Hunworth Meadows on the River Glaven, a small lowland, calcareous river in north Norfolk (Clilverd et al. 2015) (see Glaven case study). A fully coupled MIKE SHE/MIKE 11 model was applied to understand the effects of embankment removal on river–floodplain hydrology including water table elevation, the frequency and extent of floodplain inundation, and flood peak attenuation under a range of expected river flow conditions. Although modelling floodplain re-connection demonstrated an increase in the water table elevation and the frequency of flooding, only a small increase in flood attenuation was predicted. Re-connection did create conditions important for the recovery and maintenance of river health and ecosystem services.
JFLOW	Impacts of flood embankment removal were modelled in 2D using JFLOW on the River Wharfe in Yorkshire (Environment Agency 2016). This included analysis of floodplain inundation frequency and interpretation of hydraulic impacts to identify any changes to the sediment regime locally, and up and downstream. The modelling showed an increased potential for deposition of gravel, which is characteristic of the River Wharfe.
Geomorphic dynamics	Builds on a catchment baseline survey and fluvial audit to predict the impacts of longitudinal barriers (and their removal) on river

Local tool name	Local tool description
assessment	forms and processes, based on expert knowledge of fluvial system behaviour. This may be done in conjunction with, or as a qualitative alternative to, using the quantitative modelling tools described above (Sear et al. 2010, Thorne et al. 2010).

3.5.6 Key findings from the case studies

The Ribble and Glaven case studies are examples of where river floodplain barriers were considered. A summary of the findings from the Glaven study is given below.

Glaven case study

The River Glaven is a dynamic, calcareous hydrological system characterised by strong interaction between surface and subsurface flows. A coupled MIKE SHE/MIKE 11 model was used to simulate the site's hydrological complexity.

The investigation was able to assess the improvements to river–floodplain functioning associated with enhanced hydrological connectivity, groundwater retention and flood peak attenuation. The findings suggest the potential use of longitudinal embankment removal as a tool for buffering the hydrological regime of wetlands and other aquatic ecosystems against some of the extreme climate variability predicted in the UK over the next century.

3.6 Diffuse pollution data, tools and models

3.6.1 Introduction

Inputs of fine sediments and pollutants to the drainage system are an important consideration when managing a catchment. Fine sediments deposited on floodplains across the UK can be heavily contaminated with pollutants from past mining activities, including lead and other heavy metals (Coulthard and Macklin 2003). Although fine sediments and diffuse pollutants may not be the primary concern when using WwNP to manage flood risk, it makes sense to design WwNP measures to manage both water quantity and quality.

When designing WwNP measures it is important to consider if specific features should be included to trap contaminated sediments and reducing pollution downstream. Whole catchment models are needed consider the sources, pathways and receptors of pollutants, along with the mapping of point and diffuse sources (Figure 3.11).

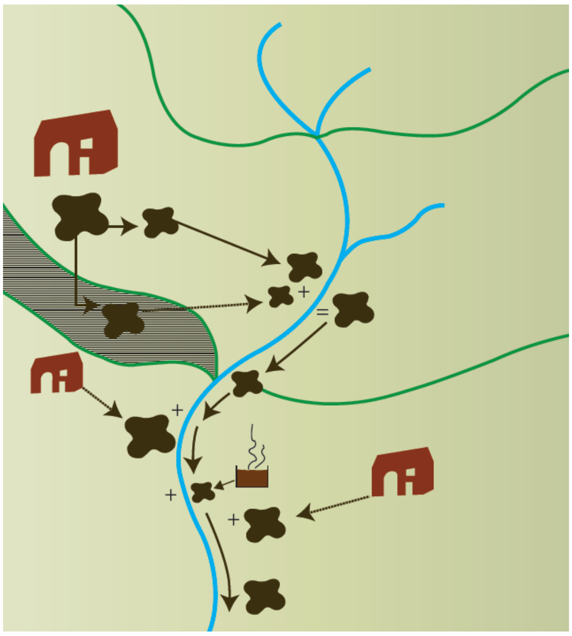


Figure 3.11 Schematic of the diffuse pollution transport model Fieldmouse

The Wyre case study develops a simple GIS transport model that possesses these important features, while the Eden case study investigates the same processes using more complex models including SWAT, HYPE and INCA.

A wide range of diffuse pollution models and maps are available for the UK (Newell-Price et al. 2011), most of which are included in the model library and covering a range of diffuse pollutants. Pollutants of major concern are:

- suspended sediments
- faecal indicator organisms (FIO)
- pesticides
- nutrients

Phosphorus is of particular concern since human effluent and farming practices have increased the amount of phosphorous in watercourses above what is considered to be consistent with good ecological status under the Water Framework Directive. Phosphorous has been modelled at the national scale using PSYCHIC-P (Phosphorus and Sediment Yield Characterisation In Catchments for Phosphorus) (Davison et al. 2008) and nitrate using NEAP-N (Anthony et al. 1996) to inform WFD risk assessment.

Measures aimed at slowing the flow of flood waters often result in extended retention times (Heal et al. 2006), which can in turn lead to a long period of, for instance, die-off for FIOs (Kay et al. 2007). Modelling and understanding this catchment process is therefore helpful for achieving multiple benefits alongside reducing flooding.

While significant point sources of phosphorus have been tackled through end-of-pipe phosphate stripping at larger sewage treatment works, significant distributed interventions are still needed on the application of fertilisers and manures to minimise the impact of agricultural activities on the water environment (Haygarth et al. 2012). There have been several national initiatives aimed at managing these risks such as environmental stewardship schemes, which include the Catchment Sensitive Farming (CSF) initiative.

Diffuse fluxes are dependent on run-off generation, but pollutants behave very differently in the way in which they are mobilised, bound to fine sediments and transported through catchments. For example, phosphorus can be adsorbed and tightly bound to soils and fine sediments from which it can subsequently be released depending on a range of physical and chemical processes. In contrast, nitrate is more soluble and more readily mobile, passing through soils with less interaction. The transport characteristics of pesticides, herbicides and degradation products can also be quite different.

The most complex models are process-based simulations of the relevant hydrological, geochemical and biochemical processes, notably SWAT which has been developed over 30 years and has numerous peer-reviewed applications (Gassman et al. 2007). SWAT uses hydrological techniques (curve numbers) which are more widely applicable in the USA and which means that many of SWAT's parameters need to be converted from British customary to SI units. Use of SWAT requires a good knowledge of hydrological modelling, as illustrated in the Wyre case study (alongside Fieldmouse). Application of SWAT and other integrated catchment models such as MIKE SHE is illustrated in the Glaven case study.

WwNP measures are more likely to interact directly with some aspects of diffuse pollution risk than others. For example, WwNP measures are most likely to mitigate surface-derived transfers of diffuse pollutants by increasing within-catchment deposition and retention of fine sediment and attached pollutants. The type of pollutant (especially how mobile/soluble it is and whether it does or does not decay over time) is significant. For example, FIO populations tend to decrease exponentially with time so that even a relatively short period of retention may provide significant benefits, whereas attenuation of other pollutants may be short-lived or just may just promote transfer via different pathways. Consequently, the need to predict the effects of WwNP measures on diffuse pollution may concentrate attention on tools and models capable of simulating specific processes (that is, they have the required functionality) at the scale relevant for a given application.

In selecting models to predict the effectiveness of WwNP measures in managing pollutants, one of the most important steps is to build a conceptual model of how the catchment functions with respect to the pollutant(s) of interest.

3.6.2 Datasets

Table 3.19 gives details of datasets used in diffuse pollution models.

Table 3.19 Datasets needed for in diffuse pollution models

Data name	Data description
Environment Agency monitoring programme data	Includes relevant WFD datasets, including the reasons for WFD failure dataset.
Environment Agency's Water Management Information System (WIMS) database	Wide coverage of sampling for phosphorus, nitrogen and suspended solids
UKWFD Technical Advisory Group (TAG) data	Includes datasets to understand the latest recommended standards for phosphorus.
Water company data	Such as flow monitoring data and quality for returns to OFWAT needed to ensure compliance with the Drinking Water Directive
Demonstration Test Catchment data	Data collected in several demonstration catchments such as Wensum, Eden and Hampshire Avon.
CSF enhanced water quality monitoring programme	Recent evaluation of CSF measures shows very high uptake (62%) of one-to-one advice on diffuse pollution mitigation measures by thousands of farmers. This

Data name	Data description
	programme monitors and models change in 8 of the 40 CSF catchments. Based on monitoring, mean suspended solids concentrations are approximately 0.7% lower than they would have been without CSF for every 1% reduction in predicted load (Environment Agency 2014c).

3.6.3 Data analysis tools

Table 3.20 describes data analysis tools for diffuse pollution.

Table 3.20 Tools for analysing data on diffuse pollution

Data analysis tool name	Data analysis tool description
Water quality statistical analysis packages	Statistical analyses of water quality can be conducted in a range of statistical packages and then visualised spatially using GIS. The open source R package has an exceptional range of highly tested statistical tests and different ways to visualise the data. There are some software packages used by the Environment Agency (for example, AARDVARK from WRc which analyses WIMS data).

3.6.4 National tools

Table 3.21 describes useful national models for modelling diffuse pollution.

Table 3.21 National tools for modelling diffuse pollution

National tool name	National tool description
Catchment Change Matrix (CCM)	Analyses effectiveness of CSF measures. It is a data-driven model of farm-scale emissions data with scaling for different CSF interventions (see Environment Agency 2014c). It links agricultural mitigation measures to individual model farms that represent each of the 100,000 commercial farms in England. It combines measures to create a total farm-scale pollutant reduction and then aggregates these results to a variety of spatial scales. Such modelling has shown that CSF is effective in terms of achieving sediment reductions and that predicted reductions vary greatly across catchments.
PSYCHIC-P and National Environment and Agricultural Pollution – Nitrate (NEAP-N)	Diffuse pollution tools that take into account land use management and stocking. They are used to generate 1km gridded outputs for estimated nutrients reaching a watercourse in modes such as SIMCAT and SAGIS. SAGIS is a GIS implementation of SIMCAT which combines a large number of diffuse pollutants and incorporate loads from discharges.
Fieldmouse	The Environment Agency has developed Fieldmouse (see Wyre case study), an ArcGIS based diffuse pollution

National tool name	National tool description
	transport model that takes farm emissions data from the CCM database and models losses in the land phase. This is then linked to the Detailed River Network using GIS hydrology and pathway tools. The model transports flows and loads through the network, allowing the introduction of point inputs and in-stream losses.
SCIMAP	A range of models have been used to estimate relative erosion risk, notably for sediments. SCIMAP has a risk mapping package that can be used in combination with a DTM and land cover data to understand relative risks of erosion and deposition.

3.6.5 Local tools

Detailed diffuse pollution models typically simulate a larger number of physical processes than run-off models which, in turn, results in an increased number of parameters. This can introduce more flexibility, but also more uncertainty.

These models typically include an integrated hydrological model. This is used to generate run-off which is then used to drive the fluxes of pollutants that undergo transformations and reactions as they interact with each other as well as with sediments. Table 3.22 gives details of useful local tools for modelling diffuse pollution.

Table 3.22 Local tools for modelling diffuse pollution

Local tool name	Local tool description
SWAT	SWAT (see the Wyre and Eden case studies) is an open source, semi-distributed hydrology and water quality model, capable of modelling nutrient and suspended sediment transport. It requires detailed datasets, and builds hydrological response units from unique combinations of land cover (LCM2007, CORINE), soils (NSRI/NATMAP) and slopes (derived from a DTM). The hydrology is based on the US SCS run-off curve approach and the model includes representations of nutrient cycles.
HYPE	HYPE is an open source hydrological and water quality nutrient package. It uses a combination of land cover (for example, CORINE, LCM2007) and soils (for example, NSRI/NATMAP) to derive hydrological response units, and incorporates phosphorus and nitrate nutrient cycles.
INCA	These nutrient cycle models with land and in-stream phases encompass a wide range of physicochemical and biological parameters, INCA-P and INCA-N for phosphorus and nitrogen, respectively (Flynn et al. 2002, Whitehead et al. 2007). INCA requires a separate hydrological model to drive the flow balance, which can be based on rainfall and evaporation data from MORECS or it can be generated using the HYPE model.

3.6.6 Key findings from the case studies

The Eden, Glaven, Wensum and Wyre case studies are examples where diffuse pollution was modelled. A summary of the main findings from the Wyre case study is given below.

Wyre case study

This case study included use of the GLUE framework to assess uncertainties in the Fieldmouse diffuse pollution model. Application of GLUE requires a high level of skill and experience, although there are now various tools both online (www.uncertain-future.org.uk/RSoftware.htm) and offline that can be used to apply the framework. Use of GLUE illustrated how uncertain the model results were compared with uncertainties in the observed data used to apply the model.

The investigation also tried to overcome scaling issues through calibration of the SWAT model to produce a detailed, process-based model of the Wyre. While this helped with calibration in the Fieldmouse model of parameters for losses at the sub-basin scale, it was difficult to transfer the analysis, despite allowing for typological differences in different catchments such as the Eden. This reinforces the fact that the detailed character of every catchment is unique. While the catchment characteristics can be represented by typology, drainage pattern and topography, it remains risky to transfer findings from one catchment to another.

3.7 Conclusions and recommendations

This chapter provides an introduction to a range of data, data analysis tools and models covering a range of catchment processes that are important when considering measures to work with natural processes. The key functionality of a range of tools for each process is presented.

This chapter does not prescriptively recommend specific software. Instead you are encouraged to:

- learn more about your catchment
- chose a level of complexity of modelling
- use this chapter to learn about available tools and the limitations of particular packages

Table 3.23 gives details of the websites for some useful datasets and models.

Table 3.23 Summary of useful datasets and models

Data	Models

Data	Models
BGS solid and superficial geology maps www.bgs.ac.uk/data/services/digmap50wms.html	**Afflux Estimation System** www.river-conveyance.net/aes/
Demonstration Test Catchment data www.demonstratingcatchmentmanagement.net/	**Conveyance Estimation System** www.river-conveyance.net/ces/
Environment Agency monitoring programme data www.geostore.com/environment-agency	**COSMOS network** http://cosmos.ceh.ac.uk
FEH Web Service www.hydrosolutions.co.uk/products.asp?categoryID=4670	**HYPE model** www.smhi.net/hype/wiki/doku.php
National River Flows Archive http://nrfa.ceh.ac.uk	**SEPA ST:REAM model** http://map.sepa.org.uk/floodmap/map.htm
UKWFD TAG data www.wfduk.org	**SCIMAP model** www.scimap.org.uk

The information provided in this chapter is the second step in the 3-step process for selecting models, tools and data (Figure 3.12). The detailed model library (Step 1) should also be used to make more informed decisions about the most suitable tools to use.

Step 3 involves using the case study examples to explore in more detail whether the models, data and tools you have selected are appropriate for use in your catchment. Table 3.24 lists all the case studies and their key purpose.

Step 1	Step 2	Step 3
Use the model library to choose model(s)	**Read Chapter 3 to understand the model(s)**	**Read case studies**

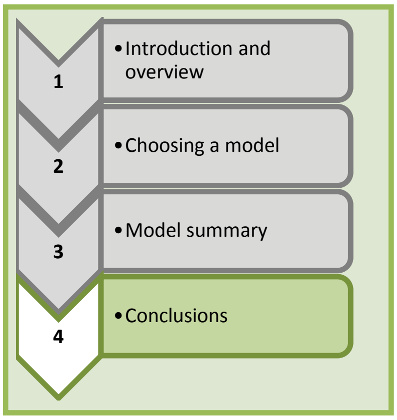
Figure 3.12 Moving on to Step 3 in the model selection process

Table 3.24 List of case studies and their main focus

	Case study	Main focus
1	Tarland Burn – Aberdeenshire	WwNP scheme
2	Brompton – North Yorkshire	WwNP scheme
3	Holnicote – Somerset	WwNP scheme
4	Wensum – Norwich	Sediment management
5	River Frome – Stroud	WwNP scheme
6	Medmerry – West Sussex	Managed realignment on the coast
7	River Glaven – North Norfolk	River floodplain restoration
8	Woodlands for Water - National	National mapping to identify locations where trees can be planted to reduce flood risk and improve water quality
9	River Elwy - Denbyshire	WwNP
10	Clwyd - Denbyshire	WwNP
11	Thames Headwater – Oxfordshire	WwNP

	Case study	Main focus
12	River Eden – Cumbria	Water quality
13	Lustrum Beck – Stockton on Tees	WwNP
14	Belford Burn – Northumberland	WwNP
15	Hodder Catchment – Lancashire	Changes in land management
16	Pontbren Catchment – Powys	Changes in land management
17	River Wyre – Lancashire	Water quality
18	River Calder and Brun – Burnley	River restoration
19	River Medlock – Manchester	River restoration
20	River Ribble - Yorkshire	River floodplain restoration

4 Conclusions and recommendations



This report gives details of a wide range of model, tools and data that can be used to consider a range of catchment processes when developing an FCERM scheme. It is accompanied by a spreadsheet-based model, data and tool library which can help you select suitable tools for the job. This library is supported by a summary of these tools in Chapter 3 and 20 case study examples of how catchment processes have been modelled previously across the UK.

The project has involved the development of:

- a **catchment process flow chart** (see Figure 1.8) to help you understand how your catchment works and to identify potential data, tools and models you could use to carry out a detailed assessment and then to design, construct and monitor a WwNP scheme
- an **electronic library of tools** (see Chapter 2) which provides a detailed summary of a range of tools, data and models to help you select the right tools for your catchment; its purpose is to provide practitioners with as much information as possible about different approaches, since the availability of existing models and data and user-experience often dictates the software used
- a **detailed summary of models, tools and data** (see Chapter 3) to help you understand how different tools can be used to assist in planning a flood scheme
- a series of **20 case studies** (available separately) which provide examples of how to model a range of catchment processes across the UK

4.1 Recommendations

The report identified a number of research gaps. There is no systematic approach for assessing the performance of WwNP measures. Although there are some ‘rules of thumb’ used by experienced practitioners, it is recommended that data are collated on likely system performance for case studies. A geodatabase of WwNP measures and interventions is recommended that is similar to AIMS but for natural measures. The project team has developed a prototype of such a resource which is available online (http://naturalprocesses.jbahosting.com). Such a resource could be used to understand performance across different types of catchment..

Some of the modelling of real events has demonstrated that a system-based approach such as RASP would not capture the spatiotemporal complexity of catchment response in its current format. The use of realistic spatially correlated ‘event sets’ (Lamb et al. 2012) of rainfall or flows with which to test the performance of WwNP would potentially overcome this.

There is a lack of evidence of whether field-scale land management changes can reduce flood risk at large catchment scales. There is a lack of comprehensive sediment and detailed geomorphology typology datasets that could be used to inform modelling of WwNP schemes in England and Wales.

Abbreviations

AIMS	Asset Information Management System [Environment Agency]
BeST	Benefits of SUDS Tool
BFI	Base Flow Index
BFIHOST	Base Flow Index – Hydrology Of Soil Types
BGS	British Geological Survey
CCM	Catchment Change Matrix
CEH	Centre for Ecology and Hydrology
CES	Conveyance Estimation System
CES/AES	Conveyance and Afflux Estimation System
CORINE	CoORdination of INformation on the Environment
CSF	Catchment Sensitive Farming
DEM	Digital Elevation Model [typically unfiltered terrain data]
Defra	Department of Environment, Food and Rural Affairs
DRN	Digital River Network
DTM	Digital Terrain Model
FCERM	Flood and Coastal Erosion Risk Management
FEH	Flood Estimation Handbook
FFC	Flood Frequency Curves
FIO	faecal indicator organism
FRMRC	Flood Risk Management Research Consortium
GIS	geographical information system
GLUE	Generalised Likelihood Uncertainty Estimation [framework]
HEC	Hydrologic Engineering Centre
HEC-RAS	Hydrologic Engineering Center's River Analysis System [US Army Corp of Engineers]
HOST	Hydrology of Soil Types
HRU	Hydrological Response Unit
JRAFF	JBA Run-off Attenuation Feature Finder
LiDAR	light detection and ranging
LCM2007	Land Cover Map 2007 [CEH]
MDSF	Modelling and Decision Support Framework

MORECS	Met Office Rainfall and Evapotranspiration Calculation System
MOSES	Met Office Surfaces Exchange Scheme
NATMAP	National Soil Map of England and Wales
NEAP	National Environment and Agricultural Pollution
NSRI	National Soils Resources Institute
OS	Ordnance Survey
PDM	Probability Distributed Moisture
PROPWET	proportion of time when soil moisture deficit was below 6mm
PSYCHIC-P	Phosphorus and Sediment Yield Characterisation In Catchments for Phosphorus
RASP	Risk Assessment for Strategic Planning
RAF	run-off attenuation feature
RBMP	River Basin Management Plan
ReFH	Revitalised Flood Hydrograph
RHS	River Habitat Survey
SAR	Synthetic Aperture RADAR
SEPA	Scottish Environment Protection Agency
SIAM	Sediment Impact Analysis Methods
SPR	standard percentage run-off
SPRHOST	Standard Percentage Runoff – Hydrology of Soil Types
SUDS	sustainable urban drainage system
SWAT	Soil and Water Assessment Tool
TAG	Technical Advisory Group
Tp	time-to-peak
UAV	unmanned aerial vehicle
WFD	Water Framework Directive
WIMS	Water Management Information System [Environment Agency]
WwNP	Working with Natural Processes

References

ADDISCOTT, T.M., 1998. Modelling concepts and their relation to the scale of the problem. *Nutrient Cycling in Agroecosystems*, 50 (1-3), 239-245.

ADDISCOTT, T.M. AND MIRZA, N.A., 1998. Modelling contaminant transport at catchment or regional scale. *Agriculture Ecosystems and Environment*, 67 (2-3), 211-221.

ANTHONY, S., QUINN, P. AND LORD, E., 1996. Catchment scale modelling of nitrate leaching. *Aspects of Applied Biology*, 46, 23-32.

ARCHER, D., 2003. Scale effects on the hydrological impact of upland afforestation and drainage using indices of low variability: the River Irthing, England. *Hydrology and Earth System Sciences*, 7 (3), 325-338.

ARONICA, G, HANKIN, B.G. AND BEVEN, K.J, 1998. Uncertainty and equifinality in calibrating distributed roughness coefficients in a flood propagation model with limited data. *Advances in Water Resources*, 22, 4, 349-365.

BAGNOLD, R.A., 1966. *An approach to the sediment transport problem from general physics.* US Geology Survey, Professional Paper 442.1. Washington DC: US Government Print Office.

BELL, V.A. AND MOORE, R.J., 1998a. A grid-based distributed flood forecasting model for use with weather radar data: Part 1. Formulation. *Hydrology and Earth System Sciences Discussions*, 2 (2/3), 265-281.

BELL, V.A. AND MOORE, R.J., 1998b. A grid-based distributed flood forecasting model for use with weather radar data: Part 2. Case studies. *Hydrology and Earth System Sciences Discussions,* 2 (2/3), 283-298.

BELL, V.A., KAY, A.L., JONES, R.G., MOORE, R.J., AND REYNARD, N.S., 2009. Use of soil data in a grid-based hydrological model to estimate spatial variation in changing flood risk across the UK. *Journal of Hydrology*, 377 (3), 335-350.

BEVEN, K.J., 1995. Linking parameters across scales: subgrid parameterizations and scale dependent hydrological models. *Hydrological Processes*, 9 (5-6), 507-525.

BEVEN, K.J., 2006a. *Streamflow Generation Processes*. IAHS Benchmark Papers in Hydrology Series. Wallingford: IAHS Press.

BEVEN, K.J., 2006b. A manifesto for the equifinality thesis. *Journal of Hydrology*, 320 (1-2), 18-36.

BEVEN, K.J., 2008. *Environmental Modelling: an Uncertain Future?* London: Routledge.

BEVEN, K.J, 2012. *Rainfall–Run-off Modelling – The Primer*, 2nd edition. Chichester: Wiley-Blackwell, Chichester.

BEVEN, K. AND BINLEY, A., 1992. The future of distributed models: model calibration and uncertainty prediction. *Hydrological Processes*, 6 (3), 279-298.

BEVEN K.J. AND FREER J., 2001a. Equifinality, data assimilation, and uncertainty estimation in mechanistic modelling of complex environmental systems. *Journal of Hydrology*, 249, 11-29.

BEVEN, K.J. AND FREER, J., 2001b. A dynamic TOPMODEL. *Hydrological Processes*, 15 (10), 1993-2011.

BEVEN, K.J. AND ALCOCK, R.E., 2012. Modelling everything everywhere: a new approach to decision-making for water management under uncertainty. *Freshwater Biology*, 57 (Suppl. 1), 124-132.

BEVEN, K.J. AND GERMANN, P.F., 2013. Macropores and water flow in soils revisited, *Water Resources Research*, 49 (6), 3071-3092.

BEVEN, K. AND BINLEY, A., 2014. GLUE: 20 years on. *Hydrological Processes,* 28 (24), 5897-5918.

BEVEN, K.J. AND SMITH, P.J., 2015. Concepts of information content and likelihood in parameter calibration for hydrological simulation models. *Journal of Hydrologic Engineering,* 20 (1), CID: A4014010.

BEVEN, K., HARVEY, H., PAPPENBERGER, F., LEEDAL, D. AND HALL, J., 2007. *A user guide to the risk and uncertainty decision tree Wiki site*. FRMRC Research Report UR13. Flood Risk Management Research Consortium.

BEVEN, K., YOUNG, P., ROMANOWICZ, R., O'CONNELL, E., EWEN, J., O'DONNELL. G., HOMAN, I., POSTHUMUS, H., MORRIS, J., HOLLIS, J., ROSE, S., LAMB, R. AND ARCHER, D., 2008a. *FD2120: Analysis of historical datasets to look for impacts of land use management change on flood generation.* R&D Technical Report FD2120/TR. London: Department for Environment, Food and Rural Affairs.

BEVEN, K.J., ROMANOWICZ, R., YOUNG, P., HOLMAN, I., POSTHUMUS, H., MORRIS, J., ROSE, S., O'CONNELL, P.E. AND EWEN, J., 2008b. *An event classification approach to the identification of hydrological change*. Presentation to 43rd Defra Flood and Coastal Management Conference 2008, Manchester University.

BEVEN, K.J., LAMB, R., LEEDAL, D.T. AND HUNTER, N., 2014a. Communicating uncertainty in flood risk mapping: a case study. *International Journal of River Basin Management*, 13 (3), 285-295.

BEVEN, B.J., LEEDAL, D.T. AND MCCARTHY, S., 2014b. *Framework for assessing uncertainly in fluvial flood risk mapping*. Report C721. London: CIRIA.

BIRKINSHAW, S.J., JAMES, P. AND EWEN, J., 2010. Graphical user interface for rapid set-up of SHETRAN physically-based river catchment model. *Environmental Modelling & Software*, 25 (4), 609-610.

BLANC, J., WRIGHT. G. AND ARTHUR, S., 2012. *Natural flood management (NFM) knowledge system: Part 2 – The effect of NFM features on the desynchronising of flood peaks at a catchment scale.* Edinburgh: Centre of Expertise for Waters (CREW).

BROOKES, A. AND WISHART, D., 2006. Application of a stream power screening tool. In *Accounting for sediment in rivers: a tool box of sediment transport and transfer analysis methods and models to support hydromorphologically-sustainable flood risk management in the UK* (ed. N. Wallerstein). FRMRC Research Report UR9, Chapter 2, 13-24. Flood Risk Management Research Consortium.

CIWEM, 2014. *Policy Position Statement – Flood and Coastal Erosion Risk Management.* London: Chartered Institute of Water and Environmental Management.

CLILVERD, H.M., THOMPSON, J.R., HEPPELL, C.M., SAYER, C.D. AND AXMACHER, J.C., 2013. River-floodplain hydrology of an embanked lowland Chalk river and initial response to embankment removal. *Hydrological Sciences Journal*, 58 (3), 1-24.

CLILVERD, H.M., THOMPSON, J.R., HEPPELL, C.M., SAYER, C.D. AND AXMACHER, J.C., 2015. *Removal of river embankments and the modelled effects on river–floodplain* *hydrodynamics*. Poster at European Geophysical Union General Assembly 2015 (Vienna, 12–17 April 2015). Available from: http://presentations.copernicus.org/EGU2015-12974_presentation.pdf [Accessed 12 January 2016].

COSTANZA, R., D'ARGE, R., DE GROOT, R., FARBERK, S., GRASSO, M., HANNON, B., LIMBURG, K., NAEEM, S., O'NEILL, R.V., PARUELO, J., PASKIN, R.G., SUTTON, P. AND VAN DEN BELT, M., 1997. The value of the world's ecosystem services and natural capital. *Nature*, 387, 253-260.

COULTHARD, T.J. AND MACKLIN, M.G., 2003. Modelling long-term contamination in river systems from historical metal mining. *Geology*, 31 (5), 451-454.

CROOKS, S.M., KAY, A.L. AND REYANRD, N.S., 2010. *Regionalised impacts of climate change on flood flows: hydrological models, catchments and calibration.* R&D Milestone Report FD2020/MR1. London: Department for Environment, Food and Rural Affairs.

DAVISON, P., WITHERS, P.J.A., LORD, E., BETSON, MJ. AND STROMQVIST, J., 2008. PSYCHIC – a process-based model of phosphorus and sediment mobilisation and delivery within agricultural catchments. Part 1: Model description and parameterisation. *Journal of Hydrology*, 350 (3-4), 290-302.

DE VENTE, J., POESEN, J., ARABKHEDRI, M. AND VERSTRAETEN, G., 2007. The sediment delivery problem revisited. *Progress in Physical Geography*, 31 (2), 155-178.

DEFRA, 2004. *Making Space for Water: the cross government strategic approach to flooding and coastal erosion management co-ordinated as a programme of work within the Department of Environment, Food and Rural Affairs.* London: Department for Environment, Food and Rural Affairs.

ENVIRONMENT AGENCY, 1999. *River channel typology: feasibility for use in river management.* Research and development. Technical Report W87. Bristol: Environment Agency.

ENVIRONMENT AGENCY, 2005. *Risk assessment of flood and coastal defence systems for strategic planning (RASP).* R&D Technical Report W5B-030/TR. Bristol: Environment Agency.

ENVIRONMENT AGENCY, 2008. *National Assessment of Flood Risk (NaFRA): RASP methodology*. Bristol: Environment Agency.

ENVIRONMENT AGENCY, 2011. *The National Flood and Coastal Erosion Risk Management Strategy for England.* Bristol: Environment Agency.

ENVIRONMENT AGENCY, 2012a. *Greater working with natural processes in flood and coastal erosion risk management. A response to Pitt Review Recommendation 27.* Bristol: Environment Agency.

ENVIRONMENT AGENCY, 2012b. *Remote sensing and RHS.* Bristol: Environment Agency. Unpublished.

ENVIRONMENT AGENCY, 2013. Increasing England's resilience to flood and coastal erosion risk – a 2020 Vision for Flood and Coastal Erosion Risk management. In *The FCRM Environment Programme: Environmental Outcomes Briefing Note – unclassified*. Unpublished FCERM briefing note.

ENVIRONMENT AGENCY, 2014a. *Working with natural processes to reduce flood risk. R&D framework.* Report SC130004/R2. Bristol: Environment Agency.

ENVIRONMENT AGENCY, 2014b. *Aquatic and riparian plant management: controls for vegetation in watercourses.* Technical guide. SC120008/R2. Bristol: Environment Agency.

ENVIRONMENT AGENCY, 2014c. *Catchment Sensitive Farming. Evaluation report – phases 1 to 3 (2006–2014).* CSF156. Peterborough: Natural England.

ENVIRONMENT AGENCY, 2016. *Restoration measures to improve river habitats during low flows.* Report SC120050/R. Bristol: Environment Agency.

EVANS, E.P., ASHLEY, R., HALL, J., PENNING-ROWSELL, E., SAUL, A., SAYERS, P., THORNE, C. AND WATKINSON, A., 2004a. *Foresight. Future Flooding. Scientific summary: Volume I – Future risks and their drivers.* URN 04/939. London: Office of Science and Technology. Available from: https://www.gov.uk/government/publications/future-flooding [Accessed 17 December 2015].

EVANS, E.P., ASHLEY, R., HALL, J., PENNING-ROWSELL, E., SAUL, A., SAYERS, P., THORNE, C. AND WATKINSON, A., 2004b. *Foresight. Future Flooding. Scientific summary: Volume II – Managing future risks.* URN 04/946. London: Office of Science and Technology. Available from: https://www.gov.uk/government/publications/future-flooding [Accessed 17 December 2015].

EWEN, J., PARKIN, G. AND O'CONNELL, P.E., 2000. SHETRAN: distributed river basin flow and transport modelling system. *Journal of Hydrologic Engineering*, 5 (3), 250-258.

FLYNN, N.J., PADDISON, T. AND WHITEHEAD, P.G., 2002. INCA Modelling of the Lee System: strategies for the reduction of nitrogen loads. *Hydrology and Earth System Sciences*, 6 (3), 467-483.

GASSMAN, P.W., REYES, M.R., GREEN, C.H. AND ARNOLD, J.G., 2007. The Soil And Water Assessment Tool: historical development, applications, and future research directions. *Transactions of the ASABE*, 50 (4), 1211-1250.

GERIS, J.R.M.C., 2012. *Multiscale impacts of land use/management changes on flood response in the River Hodder catchment, north-west England.* Newcastle-upon-Tyne: School of Civil Engineering and Geosciences, Newcastle University.

GHIMIRE, S., WILKINSON, M. AND DONALDSON-SELBY, G., 2014. Application of 1D and 2D numerical models for assessing and visualizing effectiveness of natural flood management (NFM) measures. In *Proceedings of the 11th International Conference on Hydroinformatics* (New York, 17–21 August 2014), edited by M. Piasecki, Paper 189, pp. 482-489. New York: International Conference on Hydroinformatics 2014.

GOMEZ, B. AND CHURCH, M., 1989. An assessment of bed load sediment transport formulae for gravel bed rivers. *Water Resources Research*, 25 (6), 1161-1186.

HALL, J.W., DAWSON, R.J., SAYERS, P., ROSU, C., CHATTERTON, J. AND DEAKIN, R., 2003. A methodology for national-scale flood risk assessment. *Proceedings of the Institution of Civil Engineers - Water and Maritime Engineering,* 156 (3), 235-247.

HANKIN, B.G., HARDY, R., KETTLE, H. AND BEVEN, K.J., 2001. Using CFD in a GLUE framework to model the flow and dispersion characteristics of a natural fluvial dead zone. *Earth Surface Processes and Landforms*, 26 (6), 667-687.

HARDIMAN, N., CUNNINGHAM, R. AND JOHNSTONOVA, A., 2009. *Technical review of NFRM techniques: their effectiveness and wider benefits.* Sandy, Bedfordshire: RSPB.

HARTWELL-NAGUIB, S. AND ROBERTS, N., 2014. *Winter Floods 2013/14*. Standard Note SC/06809. London: House of Commons Library.

HAYGARTH, P.M., H. APSIMON, H., BETSON, M., HARRIS, D., HODGKINSON, R. AND WITHERS, P.J.A., 2012. Mitigating diffuse phosphorus transfer from agriculture according to cost and efficiency. *Journal of Environmental Quality*, 38 (5), 2012-2022.

HEAL, K.V., VINTEN, A.J.A., GOURIVEAU, F., ZHANG, J., WINDSOR, M., D'ARCY, B., FROST, A., GAIRNS, L. AND LANGAN, S.J., 2006. The use of ponds to reduce pollution from potentially contaminated steading run-off. In *Agriculture and the Environment VI. Managing Diffuse Agricultural Pollution,* Proceedings of the SAC and SEPA Biennial Conference (Edinburgh, 5–6 April 2006), edited by L. Gairns, K. Crighton and B. Jeffrey, 62-70.

HESS, T.M., HOLMAN, I.P., ROSE, S.C, ROSOLOVA, Z. AND PARROTT, A., 2010. Estimating the impact of rural land management changes on catchment run-off generation in England and Wales. *Hydrological Processes*, 24 (10), 1357-1368.

HOOKE, J., 2003. Coarse sediment connectivity in river channel systems: a conceptual framework and methodology. *Geomorphology*, 56 (1-2), 79-94.

INSTITUTE OF HYDROLOGY, 1999. *Flood Estimation Handbook*, Volumes 1–5, Wallingford: Institute of Hydrology.

KAY, D., EDWARDS, A.C., FERRIER, R.C., FRANCIS, C., KAY, C., RUSHBY, L., WATKINS, J., MCDONALD, A.T., WYER, M., CROWTHER, J. AND WILKINSON, J., 2007. Catchment microbial dynamics: the emergence of a research agenda. *Progress in Physical Geography* 31 (1), 59-76.

KNIGHTON, D.,1998. *Fluvial Forms and Processes*. London: Hodder Headline.

LAMB, R., CROSSLEY, A. AND WALLER, S., 2009. A fast 2D floodplain inundation model. *Proceedings of the Institution of Civil Engineers - Water Management,* 162 (6), 363-370.

LAMB, R., KEEF, C., TAWN, J., LAEGER, S., MEDOWCROFT, I., SURENDRAN, S., DUNNING, P. AND BATSTONE, C., 2010. A new method to assess the risk of local and widespread flooding on rivers and coasts. *Journal of Flood Risk Management*, 3 (4), 323-336.

LAMB, R., KEEF, C., WICKS, J., MCGAHEY, C. AND LAEGER, S., 2012. A 'blue print' for local, system-based probabilistic flood modelling. In *Comprehensive Flood Risk Management: Research for Policy and Practice*, Proceedings of FLOODrisk2012 (Rotterdam, 19–23 November 2012), edited by F. Klijn and T. Schweckendiek, Chapter 30. London: CRC Press.

LANDSTRÖM, C., WHATMORE, S.J. AND LANE, S.N., 2011, Virtual engineering: computer simulation modelling for flood risk management in England. *Science Studies*, 24 (2), 3-22.

LANE, S.N., ODONI, N., LANDSTROM, C., WHATMORE, S.J., WARD, N. AND BRADLEY, S., 2011. Doing flood risk science differently: an experiment in radical scientific method. *Transactions of the Institute of British Geographers*, 36 (1), 15-36.

LEEDAL, D.T., NEAL, J., BEVEN, K., YOUNG, P. AND BATES, P., 2010. Visualization approaches for communicating real-time flood forecasting level and inundation information. *Journal of Flood Risk Management,* 3 (2), 140-150.

MANTZ, P., 2007. *Afflux estimation system user guide*. SC030218/PR. Prepared for the Environment Agency. Skipton: JBA Consulting.

MARSHALL, M.R., BALLARD, C.E., FROGBROOK, Z.L., SOLLOWAY, I., MCINTYRE, N., REYNOLDS, B. AND WHEATER, H., 2014. The impact of rural land management changes on soil hydraulic properties and run-off processes: results from experimental plots in upland UK. *Hydrological Processes*, 28 (4), 2617-2629.

MASLEN, S. and ROSE, S., 2012. *The Somerset WAVE project.* Presented at Environment Agency/Defra FCERM conference.

MCDONNELL, J.J. AND BEVEN, K.J., 2014. Debates – The future of hydrological sciences: A (common) path forward? A call to action aimed at understanding velocities, celerities, and residence time distributions of the headwater hydrograph. *Water Resources Research*, 50 (6), 5342-5350.

MCINTYRE, N. and THORNE, C. (eds), 2013. *Land use management effects on flood flows and sediments: guidance on prediction*. Report C719. London: CIRIA.

MCMILLAN, H., FREER, J., PAPPENBERGER, F., KRUEGER, T. AND CLARK, M., 2010. Impacts of uncertain river flow data on rainfall-run-off model calibration and discharge predictions. *Hydrological Processes*, 24, 10, 1270-1284.

MCMILLAN, H., KRUEGER, T. AND FREER, J., 2012. Benchmarking observational uncertainties for hydrology: rainfall, river discharge and water quality. *Hydrological Processes*, 26 (26), 4078-4111.

METCALFE, P., BEVEN, K., FREER, J., 2015. Dynamic TOPMODEL: a new implementation in R and its sensitivity to time and space intervals. *Environmental Modelling and Software*, 72 (C), 155-172.

METCALFE, P., BEVEN, K., HANKIN, B. AND LAMB, R., in press. Evaluation of run-off attenuation features in natural flood management schemes and their effect on the hydrological response of small catchments.

NEAL, J., KEEF, C., BATES, P., BEVEN, K.J. AND LEEDAL, D.T., 2013. Probabilistic flood risk mapping including spatial dependence. *Hydrological Processes,* 27 (9), 1349-1363.

NEWELL-PRICE, J.P., HARRIS, D., TAYLOR, M., WILLIAMS, J.R., ANTHONY, S.G., DUETHMANN, D., GOODAY, R.D., LORD, E.I., CHAMBERS, B.J., CHADWICK, D.R. AND MISSELBROOK, T.H., 2011. *An inventory of mitigation methods and guide to their effects on diffuse water pollution, greenhouse gas emissions and ammonia emissions from agriculture: user guide.* Report for Defra project WQ0106 prepared by North Wyke Research and ADAS. Available from: http://sciencesearch.defra.gov.uk/Document.aspx?Document=MitigationMethods-UserGuideDecember2011FINAL.pdf [Accessed 17 December 2015].

NICHOLSON, A.R., WILKINSON, M.E., O'DONNELL, G.M., AND QUINN, P.F., 2012. Run-off attenuation features: a sustainable flood mitigation strategy in the Belford catchment, UK. *Area*, 44 (4), 463-469.

PARKER, C., THORNE, C.R. AND CLIFFORD, N.J., 2015. Development of ST:REAM: a reach-based stream power balance approach for predicting alluvial river channel adjustment. *Earth Surface Processes and Landforms*, 40 (3), 403-413.

PENNING-ROWSELL, E., JOHNSON, C., TUNSTALL, S., TAPSELL, S., MORRIS, J., CHATTERTON, J. AND GREEN, C., 2005. *The Benefits of Flood and Coastal Risk Management: A Handbook of Assessment Techniques.* London: Middlesex University Press.

PILCHER, M.W., COPP, G.H. AND SZOMOLAI, V., 2004. A comparison of adjacent natural and channelised stretches of a lowland river. *Biologia*, 59 (5), 669-673.

PITT, M., 2008. *The Pitt Review. Learning lessons from the 2007 floods.* London: Cabinet Office. Available from:

http://webarchive.nationalarchives.gov.uk/20100807034701/http://archive.cabinetoffice.gov.uk/pittreview/thepittreview.html [Accessed 17 December 2015].

POSTHUMUS, H., HEWETT, C.J.M., MORRIS, J. and QUINN, P.F., 2008. Agricultural land use and flood risk management: Engaging with stakeholders in North Yorkshire Agricultural Water Management Volume 95, Issue 7, 787–798.

SALAZAR, S., FRANCES, F., KOMMA, J., BLUME, T., FRANCKE, T., BRONSTERT, A. AND BLOSCHL, G., 2012. A comparative analysis of the effectiveness of flood management measures based on the concept of 'retaining water in the landscape' in different European hydro-climatic regions. *Natural Hazards and Earth System Sciences*, 12 (11), 3287-3306.

SCHUMM, S.A. AND KHAN, H.R., 1972. Experimental study of channel patterns. *Bulletin of the Geological Society of America*, 83 (6), 1755–1770.

SEAR, D.A., NEWSON, M.D. and THORNE, C.R., 2010. *Guidebook of Applied Fluvial Geomorphology*. London: Thomas Telford.

SHAW, E.M., BEVEN, K.J., CHAPPELL, N.A. AND LAMB, R., 2010. *Hydrology in Practice*, 4th edition. Abingdon: CRC Press.

SIMM, J., 2011. *The use of fragility curves for UK flood defences and their implications for flood risk management*. In FRMRC Practitioner Workshop on Asset Management (4 October 2011, London). Available from: http://eprints.hrwallingford.co.uk/523/ [Accessed 17 December 2015].

SNIFFER, 2011. *Natural flood management implementation – Learning from Practice Workshop Report*. Edinburgh: SNIFFER.

THORNE C.R., SOAR, P.J., SKINNER, K.S., SEAR, D.A. AND NEWSON, M.G., 2010. Driving processes II. Investigating, characterising and managing river sediment dynamics. In *Guidebook of Applied Fluvial Geomorphology* (edited by D.A. Sear, M.G. Newson and C.R. Thorne), pp. 120-195. London: Thomas Telford.

VÁZQUEZ, R., BEVEN, K.J. AND FEYEN, J., 2009. GLUE based assessment on the overall predictions of a MIKE SHE application. *Water Resources Management*, 23 (7), 1325-1349.

WALLERSTEIN, N. (ed.) 2006. *Accounting for sediment in rivers: a tool box of sediment transport and transfer analysis methods and models to support hydromorphologically-sustainable flood risk management in the UK.* FRMRC Research Report UR9. Flood Risk Management Research Consortium. Available from: http://web.sbe.hw.ac.uk/frmrc/downloads/UR9%20signed%20off.pdf [Accessed 17 December 2015].

WHITEHEAD, P.G., HEATHWAITE, A.L., FLYNN, N.J., WADE, A.J. AND QUINN, P.F., 2007. Evaluating the risk of non-point source pollution from biosolids: integrated modelling of nutrient losses at field and catchment scales. *Hydrology and Earth System Sciences,* 11 (1), 601-613.

WILKINSON, M., QUINN, P. AND WELTON, P., 2010. Run-off management during the September 2008 floods in the Belford catchment, Northumberland. *Journal of Flood Risk Management*, 3 (2010), 285-295.

WILKINSON, M.E., QUINN, P.F. AND HEWETT, C.J.M., 2013. The Floods and Agriculture Risk Matrix: a decision support tool for effectively communicating flood risk from farmed landscapes. *International Journal of River Basin Management*, 11 (3), 237-252.

Bibliography

ADDISCOTT, T.M. AND MIRZA, N.A., 1998. New paradigms for modelling mass transfers in soils. *Soil and Tillage Research*, 47 (1-2), 105-109.

BAILEY, A., DEASY, C., QUINTON, J., SILGRAM, M., JACKSON, B. AND STEVENS, C., 2013. Determining the cost of in-field mitigation options to reduce sediment and phosphorus loss. *Land Use Policy*, 30 (1), 234-242.

BARBER, N.J., AND QUINN, P.F., 2012. Mitigating diffuse water pollution from agriculture using soft-engineered run-off attenuation features. *Area*, 44 (4), 454-462.

BEVEN, K.J., 2007. Working towards integrated environmental models of everywhere: uncertainty, data, and modelling as a learning process. *Hydrology and Earth System Sciences*, 11 (1), 460-467.

BIGGS, J., 2007. *Small-scale solutions for big water problems*. Report for Defra. Oxford: Pond Conservation: The Water Habitats Trust. Available from: http://freshwaterhabitats.org.uk/wp-content/uploads/2013/09/Defra-small-scale-solutions090108.pdf [Accessed 16 December 2015].

BLÖSCHL, G., SIVAPALAN, M., WAGENER, T., VIGLIONE, A. AND SAVENIJE, H., (eds), 2013. *Run-off Prediction in Ungauged Basins: Synthesis across Processes, Places and Scales*. Cambridge: Cambridge University Press.

BOAVIDA, I., SANTOS, J.M., CORTES, R., PINHEIRO, A. AND FERREIRA, M.T., 2012. Benchmarking River Habitat Improvement. *River Research and Applications*, 28, 10, 1768-1779.

BRAUDRICK, C.A. AND GRANT, G.E., 2000. When do logs move in rivers? *Water Resources Research,* 36 (2), 571-583.

BRIERLEY, G., FRYIRS, K., OUTHET, D. AND MASSEY, C., 2002. Application of the River Styles framework as a basis for river management in New South Wales, Australia. *Applied Geography*, 22 (1), 91-122.

BROADMEADOW, S., THOMS, H. AND NISBWET, T., 2014. *Opportunity mapping for woodland creation to reduce diffuse water pollution and flood risk in England and Wales.* Farnham, Surrey: Forest Research. Available from: http://www.forestry.gov.uk/fr/opportunitymapping [Accessed 17 December 2015].

CIRIA, 2013. *Demonstrating the multiple benefits of SuDS – a business case. Stage 2 scoping report* [prepared by MWH]. CIRIA Research Project RP993. October 2013.

COULTHARD, T.J., KIRKBY, M.J. AND MACKLIN, M.G., 1996. A cellular automaton landscape evolution model. In *Proceedings of 1st International Conference on GeoComputation* (Leeds, 17–19 September 1996), edited by R.J. Abrahart, Volume 1, pp. 248-281.

COULTHARD, T.J., NEAL, J.C., BATES, P.D., RAMIREZ, J., DE ALMEIDA, G.A.M. AND HANCOCK, G.R., 2013. Integrating the LISFLOOD-FP 2d hydrodynamic model with the CAESAR model: implications for modelling landscape evolution. *Earth Surface Processes and Landforms*, 38 (15), 1897-1906.

CUTTLE, S.P., MACLEOD, C.J.A., CHADWICK, D.R., SCHOLEFIELD, D., HAYGARTH, P.M., NEWELL-PRICE, P., HARRIS, D., SHEPHERD, M.A., CHAMBERS. B.J. AND HUMPHREY, R., 2006. *An inventory of methods to control diffuse water pollution from* *agriculture (DWPA). User Manual*. Defra Project ES0203. Available from: http://randd.defra.gov.uk/Document.aspx?Document=es0203_4145_FRA.pdf [Accessed 17 December 2015].

DEFRA, 2006. *Flood Risks to People: Phase 2. The Flood Risks to People methodology.* Flood and Coastal R&D Programme FD2321/TR1. London: Department for Environment, Food and Rural Affairs. Available from: http://randd.defra.gov.uk/Document.aspx?Document=FD2321_3436_TRP.pdf [Accessed 17 December 2015].

ENVIRONMENT AGENCY, 1999. *River channel typology: feasibility for use in river management.* R&D Technical Report W87. Bristol: Environment Agency.

ENVIRONMENT AGENCY, 2007a. *Conveyance and afflux estimation system (CES/AES)* [online]. Available from: http://www.river-conveyance.net [Accessed 17 December 2015].

ENVIRONMENT AGENCY, 2007b. *MDSF2 system design*. Science Report SC050051/SR4. Bristol: Environment Agency.

ENVIRONMENT AGENCY, 2008a. *The Land Use Jigsaw: Prioritising scientific research on land use management and FCRM.* Bristol: Environment Agency.

ENVIRONMENT AGENCY, 2008b. *Continuous Estimation of River Flows (CERF).* Science Report SC030240. Bristol: Environment Agency.

ENVIRONMENT AGENCY, 2008c. *Making information available for integrated catchment management.* Science Report SC060035/SR. Bristol: Environment Agency.

ENVIRONMENT AGENCY, 2009. *Improving probabilistic flood risk management capabilities. Work Package 2 – Technical report.* Project SC090008/SR, Bristol: Environment Agency.

ENVIRONMENT AGENCY, 2010a. *Fluvial design guide.* Bristol: Environment Agency.

ENVIRONMENT AGENCY, 2010b. *Flood and coastal erosion risk management appraisal guidance (FCERM-AG)*. Bristol: Environment Agency.

ENVIRONMENT AGENCY, 2011a. *MDSF final technical report.* Science Report SC050051/SR4. Bristol: Environment Agency.

ENVIRONMENT AGENCY, 2011b. *River sediments and habitats, review of maintenance and capital works*. Project: SC040015/SR1. Bristol: Environment Agency.

ENVIRONMENT AGENCY, 2011c. Key *Recommendations for sediment management – a synthesis of river sediments and habitats (Phase 2).* Project: SC040015/SR2. Bristol: Environment Agency.

ENVIRONMENT AGENCY, 2011d. Sedim*ent matters handbook.* Bristol: Environment Agency.

ENVIRONMENT AGENCY, 2012a. *Maintenance standards, Version 3*. Bristol: Environment Agency.

ENVIRONMENT AGENCY, 2012b. *Waterbody risk assessment for failing to achieve WFD status objectives due to physical modification pressures*. Bristol: Environment Agency.

ENVIRONMENT AGENCY, 2013a. *MDSF2 software user manual,* V 1.11. Science Report SC050051/SR5. Bristol: Environment Agency.

ENVIRONMENT AGENCY, 2013b. *AIMS asset classification*. Bristol: Environment Agency.

ENVIRONMENT AGENCY, 2013d. W*hat is the updated Flood Map for surface water*?, Report version 1.0. Bristol: Environment Agency.

ENVIRONMENT AGENCY, 2014a. *Living on the edge. A guide to the rights and responsibilities of riverside occupation*, 5th edition, Bristol: Environment Agency.

ENVIRONMENT AGENCY, 2014b. *Framework and tools for local flood risk assessment:*

ENVIRONMENT AGENCY, 2015. *Cumulative effects of hydropower schemes on fish migration and populations*. Report SC120078. Bristol: Environment Agency.

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. AND WHEATER, H.S., 2008. *An update of the Foresight Future Flooding 2004 qualitative risk analysis.* London: Cabinet Office.

FORESTRY COMMISSION, 2011. *Forests and water: UK forestry standard guidelines,* 5th edition. Edinburgh: Forestry Commission.

GARNETT, T. and GODFRAY, H.C.J., 2012. *Sustainable intensification in agriculture. Navigating a course through competing food system priorities. A report on a workshop.* Oxford: Food Climate Research Network and the Oxford Martin Programme on the Future of Food, University of Oxford.

GIPPEL, C., 1995. Environmental hydraulics of large woody debris in streams and rivers. *Journal of Environmental Engineering,* 121 (5), 388-395.

GOODAY, R. AND ANTHONY, S., 2010. *Mitigation method-centric framework for evaluating cost-effectiveness (FARMSCOPER).* Defra Project WQ0106, Module 3. Available from: http://randd.defra.gov.uk/Document.aspx?Document=WQ0106_10105_FRP.pdf [Accessed 17 December 2015].

HALCROW, 2008. *Delivery of Making Space for Water: The role of land use and land management in delivering flood risk management.* Final report. Projects HA6 and HA7. Bristol: Environment Agency. Available from: http://webarchive.nationalarchives.gov.uk/20130123162956/http:/www.defra.gov.uk/environment/flooding/documents/manage/deliverymech.pdf [Accessed 17 December 2015].

HANKIN, B. AND DOUGLASS, J.M., 2013. Catchment-scale characterisation using Fieldmouse. In *Spatial targeting of agri-environment measures for mitigating diffuse water pollution*, report of a Defra workshop on 16 July 2013, pp. 28-29. Available from: http://www.demonstratingcatchmentmanagement.net/wp-content/uploads/2013/11/DTC_workshop_on_spatial_targeting_report.pdf [Accessed 17 December 2015].

HANKIN, B., WALLER, S., ASTLE, G., KELLAGHER, R., 2008. Mapping space for water: screening for urban flash flooding. *Journal of Flood Risk Management*, 1 (1), 13-22.

HUNTER, N.M., BATES, P.D., NÉELZ, S., PENDER, G., VILLANUEVA, I., WRIGHT, N.G., LIANG, D., FALCONER, R.A., LIN, B., WALLER, S., CROSSLEY, A.J. AND MASON, D.C., 2008. Benchmarking 2D hydraulic models for urban flood simulations. *Proceedings of the Institution of Civil Engineers: Water Management*, 161 (1), 13-30.

IACOB, O., ROWAN, J., BROWN, I. AND ELLIS, C., 2012. Natural flood management as a climate change adaptation option assessed using an ecosystem services approach. In *Hydrology for a Changing World, Proceedings of 11th BHS National Symposium* (Dundee, 6–8 September 2012). British Hydrological Society.

JACKSON, B., PAGELLA, T., SINCLAIR, F., ORELLANA, B., HENSHAW, A., REYNOLDS, B., MCINTYRE, N., WHEATER, H. AND EYCOTT, A., 2013. Polyscape: a GIS mapping framework providing efficient and spatially explicit landscape-scale valuation of multiple ecosystem services. *Landscape and Urban Planning*, 112, 74-88.

KEMP, P.S. AND O'HANLEY, J.R., 2010. Procedures for evaluating and prioritising the removal of fish passage barriers: a synthesis. *Fisheries Management and Ecology*, 17 (4), 297-322.

KEMP, P.S., RUSSON, I.J., WATERSON, B., O'HANLEY, J. AND PESS, G.R., 2008. *Recommendations for a 'coarse-resolution rapid-assessment' methodology to assess obstacles to fish migration, and associated prioritization tool.* Technical report to Sniffer, Project WFD111. Edinburgh: Sniffer.

KJELDSON, T., 2007. *The revitalised FSR/FEH rainfall-run-off method.* Flood Estimation Handbook Supplementary Report No. 1. Wallingford: Centre for Ecology and Hydrology.

KNIGHT, D.W., MCGAHEY, LAMB, R. AND SAMUELS, P.G., 2010. *Practical Channel Hydraulics: Roughness, Conveyance and Afflux*. Boca Raton, FL: CRC Press.

LAMB, R. AND KAY, A.L., 2004. Confidence intervals for a spatially generalised continuous simulation flood frequency model for Great Britain. *Water Resources Research*, 40 (7),

MCLEAN, L., BEEVERS, L., PENDER, G., HAYNES, H. AND WILKINSON, M., 2013. Natural flood management in the UK: developing a conceptual management tool. In *Proceedings of the 35th IAHR World Congress* (Chengdu, China, 8–13 September 2013). International Association for Hydro-Environment Engineering and Research.

MONTGOMERY, D.R. AND BUFFINGTON, J.M., 1997. Channel-reach morphology in mountain drainage basins. *Bulletin of the Geological Society of America*, 109 (5), 596-611.

MOORE, R.J. AND CLARKE R.T., 1981. A distribution function approach to rainfall–run-off modelling. *Water Resources Research*, 17 (5),1367-1382.

NEAL, C., 1996. Towards lumped integrated models of complex heterogeneous environmental systems. *Science of the Total Environment,* 183 (1-2), 115-124.

NEWSON, M.D., CLARK, M.J., SEAR, D.A. AND BROOKES, A., 1998. The geomorphological basis for classifying rivers. *Aquatic Conservation-Marine and Freshwater Ecosystems*, 8 (4), 415-430.

NISBET, T., SILGRAM, M., SHAH, N., MORROW, K. AND BROADMEADOW, S., 2011. *Woodlands for Water: woodland measures for meeting Water Framework Directive objectives.* Forest Research Monograph: 4. Farnham, Surrey: Forest Research. Available from: http://www.forestry.gov.uk/fr/woodlandforwater [Accessed 17 December 2015].

NUNN, A.D., HARVEY, J.P., NOBLE, R.A.A. AND COWX, I.G., 2010. Prioritising eel-migration barriers for passage improvements. In *Eel Management: The State of the Art* (ed. D. Bunt and A. Don), 145-154. Exeter: Institute of Fisheries Management.

NUTT, N., 2012. *Methods to screen and quantify natural flood management effects.* Report by Halcrow for the Scottish Environment Protection Agency and Forestry Commission Scotland. Edinburgh: Halcrow.

O'CONNELL, P.E., BEVEN, K.J., CARNEY, J.N., CLEMENTS, R.O., EWEN, J., FOWLER, H., HARRIS, G.L., HOLLIS, J., MORRIS J., O'DONNELL, G.M., PACKMAN, J.C., PARKIN, A., QUINN, P.F., ROSE S.C., SHEPHERD, M. AND TELLIER, S., 2004. *Review of impacts of rural land use and management on flood generation: impact study report.* Defra R&D Technical Report FD2114/TR. London: Department for Environment, Food and Rural Affairs.

Available from: http://randd.defra.gov.uk/Document.aspx?Document=FD2114_2197_TRP.pdf [Accessed 17 December 2015].

O'CONNELL, E, EWEN, J., O'DONNELL, G. AND QUINN, P., 2007. Is there a link between agricultural land-use management and flooding? *Hydrology and Earth System Sciences*, 11 (1), 96-107.

O'HANLEY, J.R., 2011. Open rivers: barrier removal planning and the restoration of free-flowing rivers. *Journal of Environmental Management*, 92 (12), 3112-3120.

ORR, H.G., LARGE, A.R.G., NEWSON, M.D. AND WALSH, C.L., 2008. A predictive typology for characterising hydromorphology. *Geomorphology*, 100 (1-2), 32-40.

PACKMAN, J.C., QUINN, P.F., HOLLIS, J. AND O'CONNELL, P.E., 2013. *Review of impacts of rural land use and management on flood generation. Short-term improvement to the FEH rainfall-run-off model: technical background.* R&D Project Record FD2114/PR3. London: Department for Environment, Food and Rural Affairs. Available from: http://randd.defra.gov.uk/Document.aspx?Document=FD2114_2206_OTH.pdf [Accessed 17 December 2015].

PENNING-ROWSELL, E., PRIEST, S., PARKER, D., MORRIS, TUNSTALL, S., VIAVATTENE, C., CHATTERTON, J. AND OWEN, D., 2013. *Handbook for Economic Appraisal (Multi-Coloured-Handbook).* London: Routledge.

PRAIRIE, Y.T. AND KALFF, J., 1986. Effect of catchment size on phosphorus export. *Water Resources Bulletin*, 22 (3), 465-470.

PRICE, D.J., CLOWES, J., SOKMENER, B. AND DONAGHEY, M. 2011. *Development of methodology for assessment required under Section 20.* Report by Jacobs Engineering UK Ltd for SEPA.

RAVEN, E.K., LANE, S.N., FERGUSON, R.I. AND BRACKEN, L.J., 2009. The spatial and temporal patterns of aggradation in a temperate, upland, gravel-bed river. *Earth Surface Processes and Landforms*, 34 (9), 1181-1197.

RAVEN, E.K., LANE, S.N. AND BRACKEN, L.J., 2010. Understanding sediment transfer and morphological change for managing upland gravel-bed rivers. *Progress in Physical Geography*, 34 (1), 23-45.

RSPB, 2014. *Flooding in focus: Recommendations for more effective flood management in England.* Sandy, Bedfordshire: RSPB.

SALAZAR, S., FRANCES, F., KOMMA, J., BLUME, T., FRANCKE, T., BRONSTERT, A. AND BLOSCHL, G., 2012. A comparative analysis of the effectiveness of flood management measures based on the concept of 'retaining water in the landscape' in different European hydro-climatic regions. *Natural Hazards and Earth System Sciences*, 12 (11), 3287-3306.

SEAR, D.A, NEWSON, M.D. and THORNE, C.R., 2008. Guidebook of applied fluvial geomorphology. R&D Technical Report FD1914. London: Department for Environment, Food and Rural Affairs. Available from: http://randd.defra.gov.uk/Document.aspx?Document=FD1914_1147_TRP.pdf [Accessed 17 December 2015].

SEPA, 2006. *Conceptual design guidelines: application of engineered logjams.* Prepared for SEPA by Herrera Environmental Consultants, Inc. Galashiels: Scottish Environment Protection Agency

SEPA, 2009. *Engineering in the Water Environment Good Practice Guide: Riparian Vegetation Management*, 2nd edition. WAT-SG-44. Stirling: Scottish Environment Protection Agency.

SEPA, 2010. *Engineering in the Water Environment: Good Practice Guide: River Crossings,* 2nd edition. WAT-SG-25. Stirling: Scottish Environment Protection Agency.

SENDZIMIR, J., DUBEL, A., LINNEROOTH-BAYER, J., DAMURSKI, J. AND SCHROETER, D., 2013. Assessment of the costs, risks and benefits of selected integrated policy options to adapt to flood and drought in the water and agricultural sectors of the Warta River Basin. RESPONSES project: WP4 Deliverable 4.5. European Responses to Climate Change. Available from: http://www.responsesproject.eu/output2.html [Accessed 17 December 2015].

THORNE, C.R., CASTRO, J.M., CLUER, B., SKIDMORE, P. and SHEA, C., 2014. Project risk screening matrix for stream management and restoration. *River Research and Applications*, 31 (5), 611-616.

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 *Flood Risk Science and Management* (ed. G. Pender and H. Faulkner), pp. 87-113. Chichester: Wiley-Blackwell.

UKNEA, 2011. *UK National Ecosystem Assessment* [online]. Available from: http://uknea.unep-wcmc.org/ [Accessed 17 December 2015].

US BUREAU OF RECLAMATION and US ARMY CORPS OF ENGINEERS, in press. *Large Wood National Manual. Guidelines for planning, design, placement, and maintenance of large wood in fluvial ecosystems: restoring process, function, and structure*.

WALLERSTEIN, N. AND ARTHUR, S., 2012. Performance of flood defence assets: trash screens and culverts. In *Flood Risk: Planning, Design and Management of Flood Defence Infrastructure* (ed. P. Sayers), Chapter 9. London: Thomas Telford.

WHITEHEAD, P.G., HEATHWAITE, A.L., FLYNN, N.J., WADE, A.J. AND QUINN, P.F., 2007. Evaluating the risk of non-point source pollution from biosolids: integrated modelling of nutrient losses at field and catchment scales. *Hydrology and Earth System Sciences*, 11 (1), 601-613.

WILKINSON, M.E., 2009. *A multiscale nested experiment for understanding and prediction of high rainfall and flood response spatial behaviour in the Eden Catchment, Cumbria, UK.* PhD thesis, Newcastle University, UK.

WILKINSON, M., QUINN, P., BENSON, I. AND WELTON, P., 2010. Run-off management: mitigation measures for disconnecting flow pathways in the Belford Burn catchment to reduce flood risk. In *Managing Consequences of a Changing Global Environment,* Proceedings of 3rd BHS International Conference (Newcastle, 19–23 July 2010). British Hydrological Society.

WILKINSON, M.E., QUINN, P.F., BARBER, N.J. AND JONCZYK, J., 2014. A framework for managing run-off and pollution in the rural landscape using a catchment systems engineering approach. *Science of the Total Environment*, 468-469, 1245-1254.

ZHANG, Y., COLLINS A. AND GOODAY, R.D., 2012. Application of the FARMSCOPER tool for assessing agricultural diffuse pollution mitigation methods across the Hampshire Avon Demonstration Test Catchment, UK. *Environmental Science and Policy*, 24, 120-131.

Would you like to find out more about us or about your environment?

Then call us on

03708 506 506 (Monday to Friday, 8am to 6pm)

email

enquiries@environment-agency.gov.uk

or visit our website

www.gov.uk/environment-agency

incident hotline 0800 807060 (24 hours)
floodline 0345 988 1188 / 0845 988 1188 (24 hours)

Find out about call charges (www.gov.uk/call-charges)

Environment first: Are you viewing this on screen? Please consider the environment and only print if absolutely recessary. If you are reading a paper copy, please don't forget to reuse and recycle if possible.