Working with Natural Processes – Using the evidence base to make the case for Natural Flood Management

SC150005

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Professor Doug Wilson
Director, Research, Analysis and Evaluation

Executive summary

This document explains how you can use the flood risk evidence presented in the Evidence Directory to make the case for implementing Working With Natural Processes (WWNP) measures.

The extent of flood risk evidence needed to make the case to fund WWNP in a catchment is varied, but heavily dependent on the magnitude of risk. The spectrum of evidence ranges from local knowledge combined with expert judgement and/or a desk-based study to that obtained from analysing existing models or data, or further detailed modelling.

As part of this project, a two-part approach has been developed to help practitioners to decide what level of flood risk assessment is needed to provide a robust appraisal of the benefits of their proposed WWNP/Natural Flood Management (NFM) project.

Part 1 presents a four-step decision tree and guidance on how to determine whether sufficient evidence is available to make a confident case for NFM, or whether a more detailed assessment of the extent of flood risk is needed.

Part 2 describes potential approaches to undertaking this more detailed assessment of the flood risk impacts and benefits of NFM. The suggested approach is based on a modelling matrix (see Appendix 1) designed to help practitioners select the best approach for them to improve understanding of the flood risk associated with the NFM proposal. Links from the modelling matrix provide case study examples demonstrating differing modelling approaches.

The final section looks in detail at groundwater flood risk and ways to assess the potential impacts (positive and negative) of an NFM proposal on groundwater flood risk.

The terms WWNP and NFM are used interchangeably throughout this report.

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We are also very grateful to our Project Board and Project Steering Group – from Defra, English Severn and Wye RFCC, Forest Research, HR Wallingford, Natural England, Natural Resources Wales, the Rivers Restoration Centre, SEPA and the Woodland Trust – who have reviewed and commented on drafts of this Evidence Directory.

A big thank you to internal colleagues from the Environment Agency's Modelling and Forecasting Service, Partnership and Strategic Overview teams and Groundwater and Contaminated Land teams - who have all provided invaluable comments and suggested improvements to this document.

This evidence base is dedicated to the memory of our friend and colleague Duncan Huggett, whose pioneering work and dedication to the field of Natural Flood Management has had a significant impact on the development of the policy, science and practice which underpins this report.

Duncan Huggett addressing the Flood and Coast Conference 2017 (Source: Flood and Coast Conference 2017)

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1 Introduction

Although the extent of flood risk evidence needed to make the case to fund WWNP measures in a catchment is varied, it depends heavily on the magnitude of risk (Figure 1.1).

At one end of the evidence spectrum, local knowledge combined with expert judgement and/or a desk-based study may be all that is needed to make a robust decision on where/how to implement WWNP and with what impact.

Moving along the evidence spectrum, it can be seen that the level of detail needed in the assessment of flood risk tends to increase as overall project cost and flood risk increases. This increased level of detail can be required to make the case for Flood Defence Grant in Aid (FDGiA) funding, where quantitative evidence may be needed to demonstrate that the risk of flooding to people and property could be reduced via the proposed interventions.

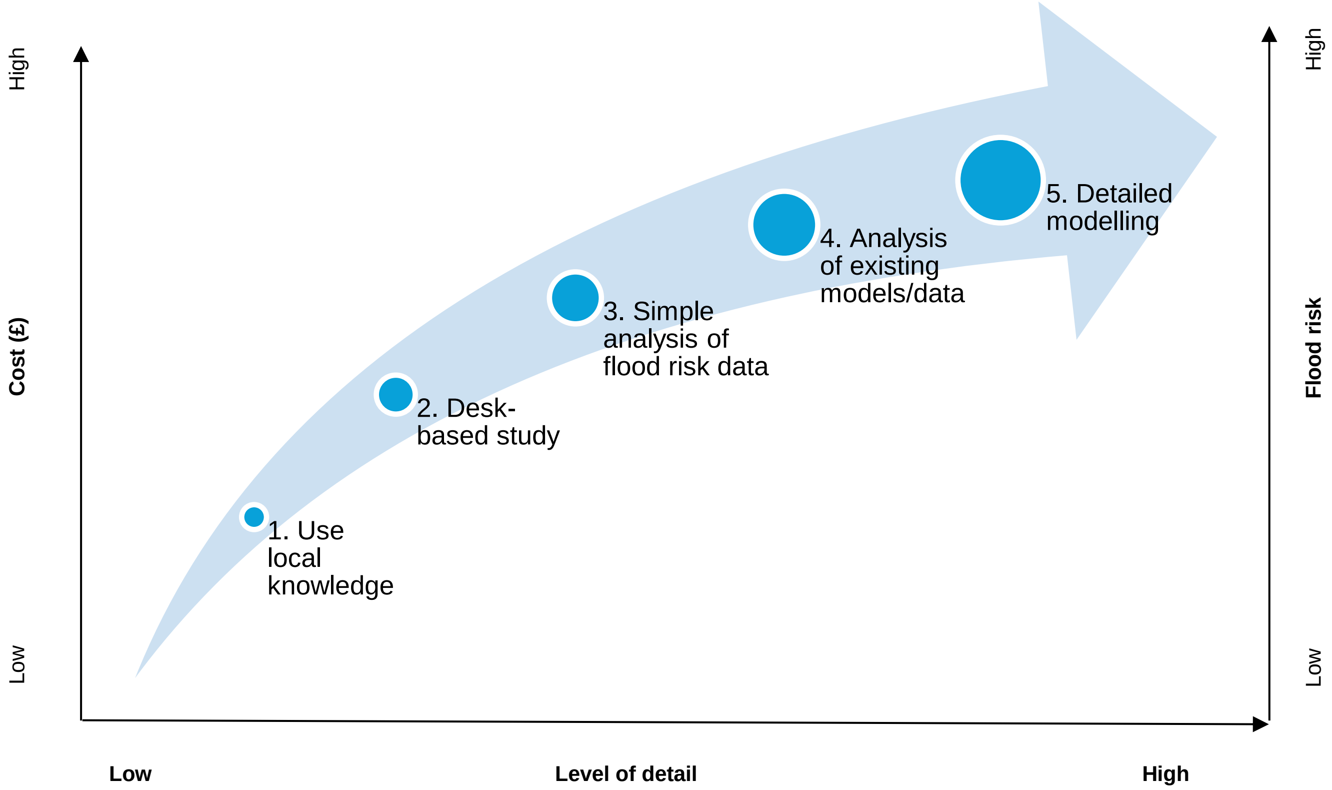


Figure 1.1 Schematic showing how the level of flood risk information needed to make the case for WWNP is proportionate to overall project cost and the level of flood risk

Section 2 of this report provides guidance on:

- the extent of evidence you might need to make the case for NFM
- how you might go about undertaking a more detailed assessment of flood risk

Section 3 looks in detail at groundwater flood risk to help you consider how you might assess the potential impacts (positive and negative) of your proposal on groundwater flooding.

2 Flood risk evidence

A two-part approach described below is designed to help you decide what level of flood risk assessment you might need to determine the benefits of your proposed project.

2.1 Part 1 – Do you have enough evidence?

Figure 2.1 is a decision tree to help decide whether the evidence you already have is enough to make the case for a NFM project or whether you need more information.

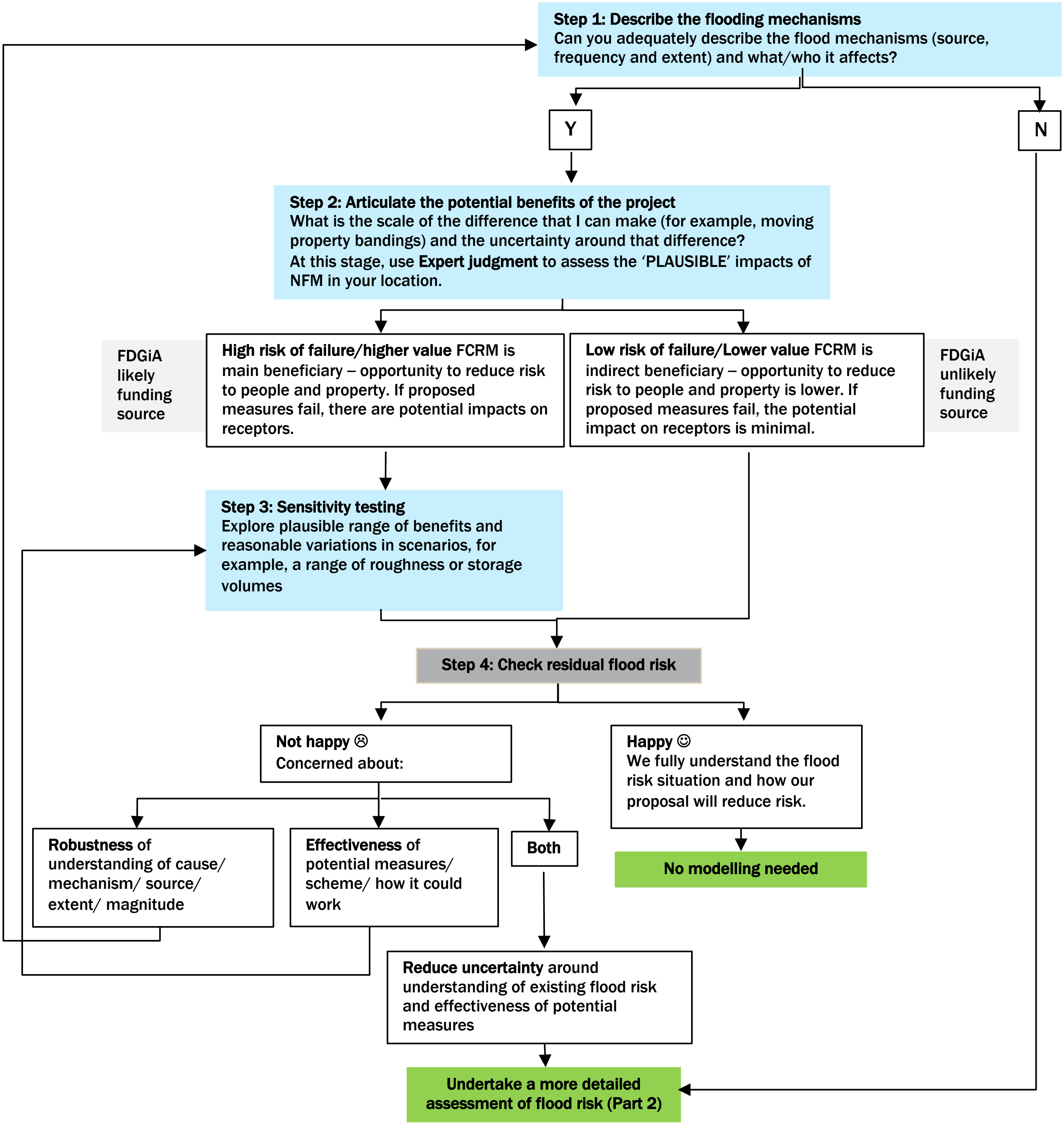


Figure 2.1 Decision tree to help you decide how much evidence is needed to confidently make the case for NFM

2.1.1 Step 1: Describe the flooding mechanisms

At the outset, the first step is to establish if you can we adequately describe the flood mechanisms for the catchment within which you are working using the source–pathway–receptor model (Figure 2.2). To do this you need to be able to explain:

- **Source(s) of the flooding** – fluvial, surface water, pluvial, groundwater, tidal/coastal
- **Pathway** – flow pathways, where it overtops, where gets inundated
- **Receptors** – who and what are affected by the flooding (people, property and environment)
- **Frequency** – how often has the catchment flooded and how long does flooding last
- **Extent of hazard** – depth of flood waters, speed, and speed of onset
- **Consequence of flooding** – for example, property and infrastructure damage

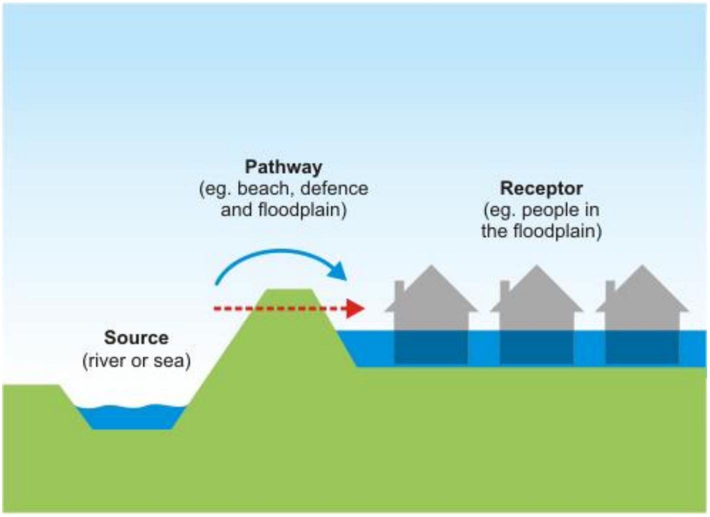


Figure 2.2 Source–pathway–receptor model

Source: Inside out Design

To do this, you need to assess existing available evidence, its limitations and accuracy, including:

- flood maps – Risk of Flooding from Rivers and Sea (RoFRS) map, Risk of Flooding from Surface Water (RoFSW) map and historic flood maps
- existing plans, strategies and assessments
- outputs from existing models (for example, detailed local models may have greater detail on a greater range of flood events including frequent flooding)
- hydrometry data – level, flow and rain gauge data for key events if available
- other data sources – catchment walkover surveys, topographic information
- local knowledge of flood pathways and flood history

If you feel able to describe the flooding mechanism with confidence, move on to Step 2, if not, proceed to Part 2 (Section 2.2).

2.1.2 Step 2: Articulate the potential benefits of the project

Once you have described the flooding mechanisms, use your **expert judgement** to describe the possible flood risk benefits of WWNP in your catchment. This might involve:

- a count of the number of properties that have recently flooded in the vicinity of the proposed project drawing on:
  - communities at risk data (if available)
  - count of properties in the flood zones
  - historical flood outlines
- an understanding of the NFM potential shown on the potential for WWNP maps produced as part of this project, which include:
  - tree planting or 'roughening up' the landscape using (1) floodplain and riparian planting to reduce conveyance and (2) wider landscape scale planting to increase hydrological losses and reduce run-off
  - run-off attenuation features
  - opportunities for soil structure improvements
  - floodplain reconnection opportunities
- a count of properties in the different probability bands in RoFRS maps to get an understanding of the frequency of flooding, which can help understand residual risk, or the risk to properties having taken into account existing defences
- an understanding of which properties are in or close to flow pathways in the 2m resolution RoFSW maps
- assessing any historical flooding data to estimate the volume of water that could be stored to reduce flood risk, for example, using a hydrograph for a flood event to establish:
  - at what point on the hydrograph properties flood
  - how much water you would need to store upstream to reduce the likelihood of property flooding in this event
  - if NFM could potentially be used to store some or all of this water (see Figure 2.3) (in reality, water will be going into storage as the hydrograph rises and so the required storage will be greater than that shown in Figure 2.3)
- looking in the Evidence Directory to help you better understand and articulate the potential flood risk management benefits of the measures you are interested in, and the scientific confidence in their ability to reduce flood risk
- If there are no gauged data, look at flood estimation approaches starting with the Flood Estimation Handbook (FEH)/ Revitalised Flood Hydrograph (ReFH) Model

Describe the potential scale of difference that your project could make (for example, moving properties from the high to the moderate risk banding). Articulate any uncertainties around potential reductions in flood risk that you could achieve.

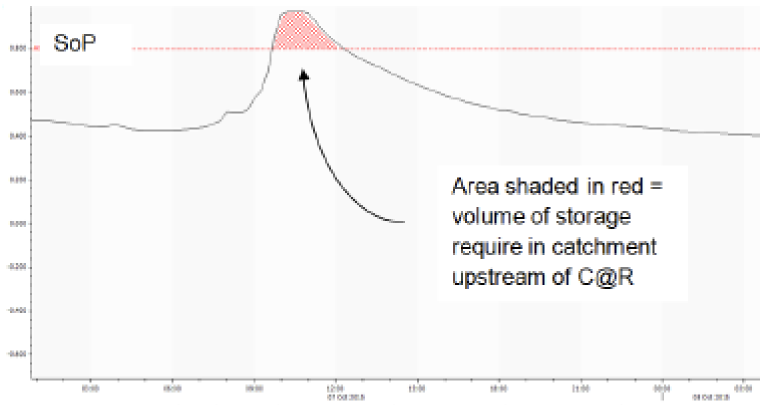


Figure 2.3 Reverse engineering approach used on St Helens woody dam project

Notes: 1 in 75 year event hydrography – the volume of hydrograph above current standard of protection (SoP) gives the minimum volume of additional attenuation needed, helping set the scale of NFM requirement. C@R = Communities at risk
Source: Dave Brown, Environment Agency

If your project does not have flood and coastal risk management (FCRM) as its main driver and non-FCRM funding sources are being sought, go to Step 4. In these sorts of cases when FCRM is not the main beneficiary of the project, it is likely that the project has a different driver such as improving water quality or restoring degraded habitats. This means that:

- there is less opportunity to reduce flood risk through this project
- if the measures implemented failed, there is likely to be less impact on receptors

If your project has FCRM as its main driver and FDGiA is being sought as the main funding source, then you need to go to Step 3 to carry out a sensitivity test. This is because there is an opportunity to reduce flood risk to people and property, and therefore if the measures fail there could be a potentially negatively impact on receptors.

2.1.3 Step 3: Undertake a sensitivity test

Sensitivity testing of the proposed project enables you to explore the plausible range of benefits and reasonable variations in scenarios. It allows you to look at the potential flood risk benefits and dis-benefits that could be achieved through altering your proposal (for example, changing storage volumes, altering measure types and the numbers of measures).

Detailed flood models usually include a sensitivity analysis (that is, the sensitivity to changes in inflow boundary conditions and the roughness – typically by varying the Manning's n roughness by 20%). If the measures you are considering involve broad-scale changes to roughness – or potentially inflow – by a known amount, it may be possible to reuse this information.

It is also possible to look at sensitivity by comparing flood maps for different probabilities. For example, RoFSW maps have 3 bands. If the maps change considerably in extent between 3.3 % annual exceedance probability (AEP) and 1% AEP events, then an area could be said to be sensitive to change (also reflecting flat topography).

In some cases, the now discontinued Catchment Flood Management Plans included some basic information on a catchment's sensitivity to climate change. Different risk analyses such as Strategic Flood Risk Assessments and Surface Water Management Plans also considered sensitivity.

Once your sensitivity testing is complete, move to Step 4.

2.1.4 Step 4: Check the residual flood risk

For your proposal you need to consider the residual flood risk. Residual flood risk is the risk that remains after actions have been taken to reduce flood risk such as:

- the failure of flood management infrastructure (for example a breach of a raised flood defence)
- blockage of a surface water drain
- overtopping of an upstream storage area
- failure of a pumped drainage system or a reservoir
- severe flood events that exceed a flood management design standard (for example, overtopping of a raised flood defence)

The RoFRS dataset is quite coarse (50m grid), but shows the probability of flooding having considered breach and overtopping mechanisms for fluvial and coastal flooding (but not the other mechanisms in the national map). RoFSW maps do not take into account failure mechanisms.

Following your assessment of residual flood risk, if you are happy that you understand the flood risk situation and how your proposal will contribute to a reduction in flood risk then no further flood risk evidence is needed. Having gone through Steps 1 to 4 this is sufficient evidence to be confident that NFM could make a valid contribution to reducing flood risk.

If on the contrary, you are concerned about the **robustness** of your understanding of the cause, mechanism, source, extent and frequency and magnitude of flooding, then return to Step 1.

If you are concerned about the **effectiveness** of potential measures and how they could work, you need to revisit your sensitivity test and return to Step 3.

If you are concerned about **BOTH** the **robustness** and **effectiveness**, then you need to reduce these uncertainties. To do this, go to Part 2 (Section 2.2) to consider what approaches you might need to take to undertake a more detailed assessment of flood risk.

2.2 Part 2 – Undertaking a more detailed assessment of flood risk

Part 2 helps you establish how best to make a more detailed assessment of flood risk, looking at potential approaches you could take to assess flood risk impacts/benefits of your proposal in more detail.

Before reading this section, open the modelling matrix in Appendix 1 (referred to here as 'the matrix'). The matrix includes hyperlinks in cells B2 to F2 that link you to case study examples which you can read for more specific detail on different modelling approaches used. These case studies are some of the examples referred to in the

Evidence Directory and also a further 20 case studies developed in the SC120015 How to model catchment processes project.

Figure 2.4 provides a summary view of this modelling matrix which captures:

- the wide range of flood risk assessment tools available
- how they might be used to represent different WWNP measures
- how they might be used to better understand flood risk and reduce uncertainties

The matrix does not try to include every kind of model. The model library developed as part of Project SC120015 covers a larger range at the time of writing.

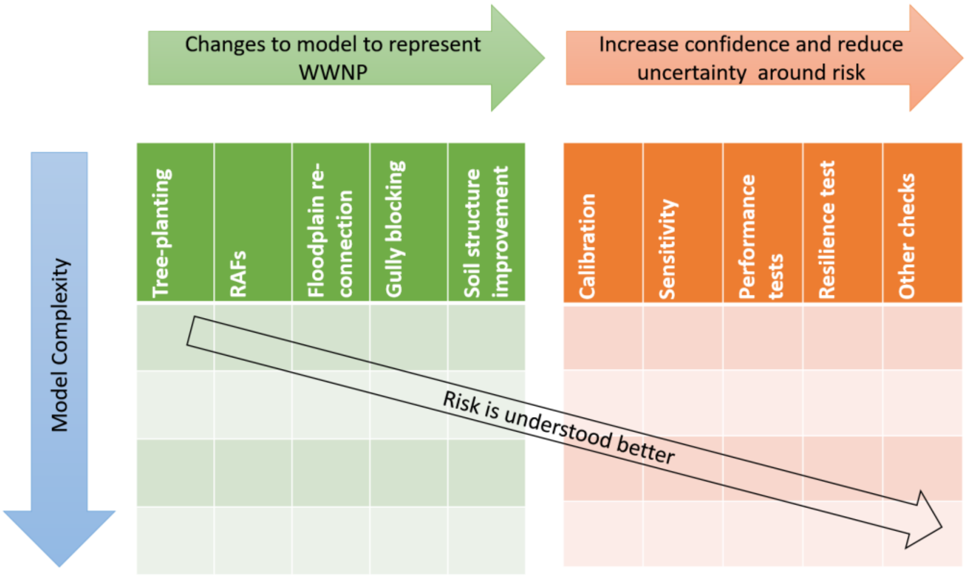


Figure 2.4 Schematic of how to improve knowledge of the effectiveness of WWNP

Notes: RAF = run-off attention feature

2.2.1 Selecting the right approach

Selecting the right approach depends on a range of factors – you may well have already considered in Part 1. They may include:

- scale of funding
- catchment size
- flood history
- local knowledge
- extent of potential downstream risk
- land ownership
- confidence in the effectiveness of proposed measures
- local appetite for NFM

- quality of local model(s) and are there people with skills to use
- whether WWNP can be represented in an available model (see Figure 2.4)
- quality of local hydrometry data (for example, baseline assessment, calibration, sensitivity testing)

There are a wide range of data analysis, tools and models that can be used to help evaluate flood risk. The level of detail needs to be commensurate with the risk and budget of each individual project (Figure 2.1). Many of these flood risk modelling approaches are covered in detail in SC120015 How to model catchment processes.

2.2.2 Changing model parameters and boundary conditions

The vertical axis of the modelling matrix lists different types of model, and shows how model complexity can increase from simple rules of thumb to fully integrated catchment models. For each of these modelling approaches, the green columns look at some different types of measures (see Figure 2.4) and suggests how these could be represented in models by making changes to their parameters or boundary conditions. The matrix summarises how WWNP can be used and how our knowledge of flood risk can be improved through calibration, assessment of sensitivity, performance and resilience. The modelling matrix also links you directly to the relevant chapters and case studies included in the Evidence Directory and other useful modelling case studies.

If you need to make a more detailed assessment of flood risk, you can use the green cells in the matrix to see how you could alter existing models to represent the types of measure you are interested in. Or you could use the matrix to steer you towards selecting a suitable model type.

Changes to existing models

WWNP measures can be represented through changes to model parameters or boundary conditions. These measures fall into 3 broad categories depending on how they:

- influence catchment processes
- increase storage and attenuate
- enhance hydrological losses (for example, infiltration, evaporation and capturing overland flow)

Changes in storage within a catchment can be represented by modifying storage areas within the flood model or Digital Terrain Model. Changes to land cover such as tree planting can be modelled through changes to the effective roughness parameters in a model (e.g. Manning's n). Changes to hydrological losses (for example, due to soil de-compaction or tree planting) can often be more subtle, but might amount to a reduction in the effective rainfall being used to drive the model of overland flow.

Considering peak synchronisation and backwater effects

WWNP measures can potentially increase flood risk by synchronising flood peaks or by causing backwater effects. When assessing the effects of your proposal, you need to consider these potential unintended negative effects; the matrix provides some examples of how to check for upstream or downstream changes in risk as a result of

WWNP. The Roughness Advisor can also be checked to gain a rapid understanding of potential backwater effects.

If there are existing models for your catchment that you could use, it is possible that they are accompanied by a calibration report and a sensitivity analysis.

It is important to establish how well the model represents the system with and without the WWNP measures included, so you can compare the existing situation against your proposed scheme.

Comparative studies enable sensible changes to physically based parameters to be made to provide greater confidence even where there is little or no calibration data. If there is a sensitivity analysis, this can help you understand the influence of increased roughness or inflows, this in turn can help you establish how to alter your model to assess the impact of proposed interventions.

2.2.3 Increasing model confidence and reducing uncertainty

The more complex your model, the more skills, data and time will be needed. However, you are likely to gain more confidence that you have understood the potential role that NFM interventions can play in reducing flood risk if you undertake work to reduce areas of uncertainty.

As we have seen from the Evidence Directory the potential benefits of WWNP can be uncertain. Models too are uncertain because they are simplified version of reality. Due to both these facts, it is important to increase our confidence in models to reduce/minimise areas of uncertainty (see orange part of the modelling matrix, Figure 2.4). This can be achieved by:

- increasing the level of calibration by, for example:
  - comparing model outputs with estimates from the FEH[1]
  - updating a model with new data and checking that it still performs well
- scenario or sensitivity testing (modifying model parameters and gaining a better understanding of sensitivities), for example:
  - changing different physically based factors such as vegetation coverage or channel sinuosity to understand how this influence the hydrograph
- performance and failure testing, for example:
  - **Synchronisation** – Are there adjacent catchments with similar response times, where it might be more effective to slow the flow in just one of them?
  - **Backwater effects** – Are you increasing upstream risk?
  - **Sedimentation** – Are you increasing sedimentation and creating a long-term need to dredge/de-silt a channel? It is possible to model sediment using some of the river modelling standard packages?
  - **Culvert/bridge blocking** – Have you considered downstream risk of blockage?
- uncertainty analysis and other checks

[1] https://www.ceh.ac.uk/services/flood-estimation-handbook

There are a range of different uncertainty analysis tools that can be used to assess model prediction uncertainty, giving estimates of parameter uncertainties and multiple model runs. An important approach is the Generalised Likelihood Uncertainty Estimation (GLUE) framework (Beven and Bingley, 2014), which is a generic approach to formalising uncertainty analysis.

2.2.4 Worked examples of how to use the matrix

Example 1

Figure 2.5 is a worked example of how to use the matrix. In this case a relatively detailed one-dimensional (1D) model is available. The user has identified possible benefits from woodland creation based on a review of the national potential for WWNP maps.

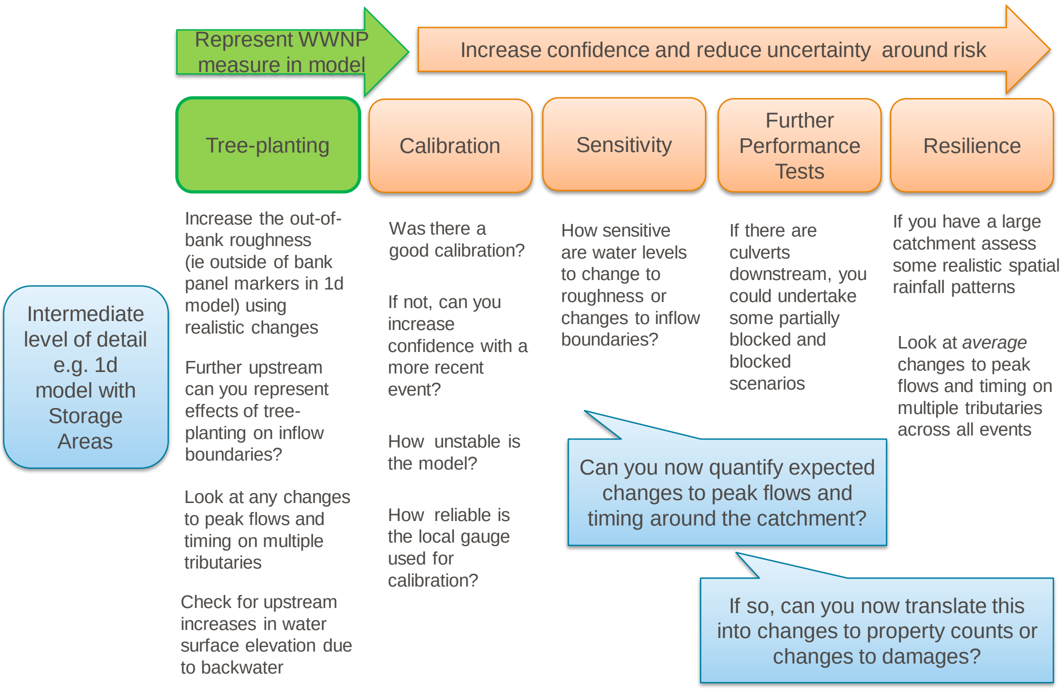


Figure 2.5 Example of using the matrix where there is a 1D model available and the user is focusing on tree planting

In this example, the project needs to understand the flood risk effects of tree planting in the floodplain across a number of tributaries upstream of a settlement with 10 properties in Flood Zone 3.

The first step when using the matrix is to represent the effect of the proposed intervention. In this case, floodplain roughness is increased to represent the effect of trees (roughness will vary depending on the density of planting).

As more of the tests in orange in Figure 2.5 are examined, there will be greater confidence in the assessment. However, budget restrictions may mean it is not possible or realistic to start testing resilience in detail. Even so, it may now be possible to quantify the changes to the model outputs in terms of peak flows, changes to the timings and changes to depth grids.

It is also possible to start quantifying risk in terms of damages avoided as per scheme appraisal if this is needed to show, for instance, there is a reasonable benefit–cost ratio. This can be undertaken using depth–damage tables from the Multi-Coloured-

Manual (Penning-Rowsell et al., 2013). Alternatively, you can look at the changes to the number of properties in different risk bands. Clicking on Cell B2 will take you to links to tree planting case studies.

Example 2

In a low risk catchment, where there are only a few properties at risk and no previous modelling, Figure 2.6 shows some approaches that could be taken using the matrix.

Here the user is exploring the use of a mixture of offline run-off attenuation features and in stream leaky barriers, and has access to some gauged data. It is unlikely that the user will be able to quantify change other than the storage volume needed to prevent the last flood. If the user still has low confidence in their solution, then it would be worth considering building a simple model. Clicking on Cell C2 takes you to links to run-off management case studies.

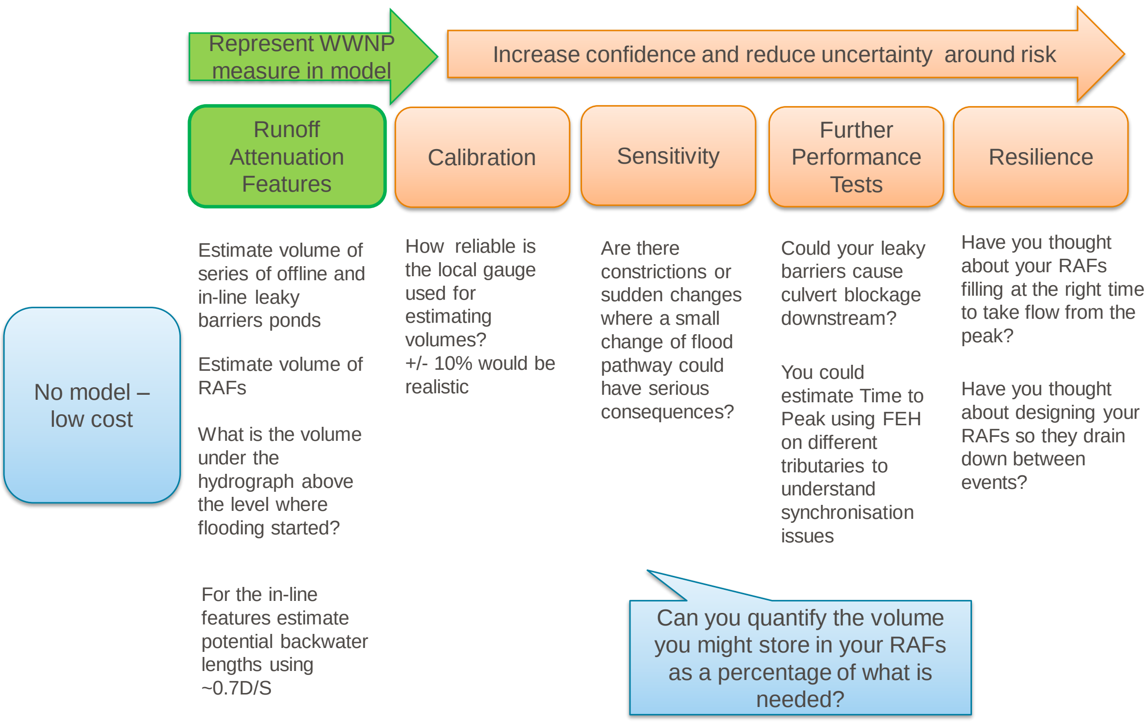


Figure 2.6 Example of using the matrix where there is no model available and the user is focusing on run-off attenuation storage

3 Hydrogeological and geological guidance for NFM

This section provides some generic background information on groundwater and NFM processes. The main points covered in this guidance are:

- importance of geology and soils during NFM mapping and the site selection process to ensure certain NFM measures are as effective as possible for flood mitigation
- different types of groundwater flooding mechanisms, the hydrogeological settings within which they occur, and which NFM measures may be most effective in these settings
- potential benefits that NFM to groundwater and to statutory groundwater drivers
- potential impacts of NFM on some of the groundwater statutory obligations and other geohazards

An important caveat is that information presented in this section cannot account for the complex and localised site-specific factors that will control groundwater flooding, surface water flooding and/or the effectiveness of NFM measures to mitigate flooding events.

Before beginning your NFM project, it is essential to have an understanding of:

- local geology
- groundwater processes
- permeability of soils and geology
- soil types
- flooding mechanisms
- pathways of surface water run-off
- many other processes

It is vital to engage with local groundwater experts who can provide flood risk managers with local advice to create and develop the essential localised conceptual understanding that is required to ensure that your NFM project is effective.

3.1.1 Importance of permeability of underlying geology and soils for NFM storage features

The range of effectiveness of some NFM measures to store and slow water and to mitigate downstream flood events will be influenced by the soils and geology upon which they are placed.

Although this section focuses mainly on the influences of geology, soils are also an important factor for NFM projects as the type and condition of soils will dictate the origin and volume of surface water run-off and infiltration rates across many catchments.

The first factor when considering the permeability of the underlying soils and geology is the influence on the length and the height of the surface water hydrograph and the amount of storage required to reduce the flood peak. For example, small impermeable catchments are likely to produce short peaky hydrographs and a relatively small amount of storage should be able to reduce the flood peak. A Chalk catchment will produce a much longer surface water hydrograph and a substantial amount of storage. For NFM to be effective at reducing flood risk it needs to be located in the right topographical setting and with the right type(s) measure.

Secondly, NFM storage features not only hold surface water run-off, they also provide the opportunity for infiltration and recharge to reduce the volume of water held within the NFM storage feature over time. This time period is significantly influenced by the permeability of the underlying soils and geology.

Figure 3.1 shows the influence of impermeable and permeable soils, and geology, in relation to flood water storage capacity for 2 intensive rainfall events. It shows a scenario where the underlying impermeable soils and geology are restricting the rate of infiltration and recharge from the NFM storage feature into the underlying soils and groundwater. As a result, water is stored within the NFM feature for an extended period of time. When the second intensive rainfall event occurs, the NFM feature is still at maximum storage capacity and any additional floodwater overtops the NFM feature. It then converts readily into surface water run-off, which proceeds to flood downslope properties and contributes to downstream flood events. NFM storage features located on impermeable soils and geology may still be effective for single storm events, but will result in less water being captured than those located on permeable soils and geology for multiple rainfall events.

Figure 3.1 also shows how locating NFM storage areas above more permeable soils and geology (for example, Chalk, Upper Greensand, sandstone) allows greater rates of infiltration and recharge into the bedrock and the groundwater system. The NFM storage feature will drain more quickly in between rainfall events. When the second intensive rainfall event occurs, the NFM storage feature is likely to have more storage capacity and will be able to store more water to effectively mitigate the flooding of downslope properties and downstream flooding.

Furthermore, the water that permeates into the aquifer will be transported over many months or years via groundwater flow paths, where it will be discharged into the river network to support ‘baseflow’ during low flow periods, which is an additional benefit of NFM. Figure 3.1 shows that groundwater flow paths under normal conditions are generally transported beneath properties.

Some NFM storage areas are designed to empty over a set period of time such as 3–12 hours via a discharge pipe. If this water is discharged into the ground, care is needed to ensure the water will not become surface water run-off, which could exacerbate downstream flooding problems. This could occur if the water is discharged directly onto impermeable soils and geology.

Figure 3.1 is a simplification of reality. Because geology typically comprises interbedded units of superficial and bedrock deposits that have contrasting permeabilities, recharge and groundwater flow paths can be complex in some UK catchments. Once flood risk managers have selected appropriate priority NFM catchments and are starting to think about selecting suitable locations for NFM storage features, it is advisable to engage with local groundwater experts. They should be able to offer support in the development of a conceptual model that will assist with the positioning of NFM features over permeable soils and geology to provide maximum storage capacity as shown in Figure 3.1.

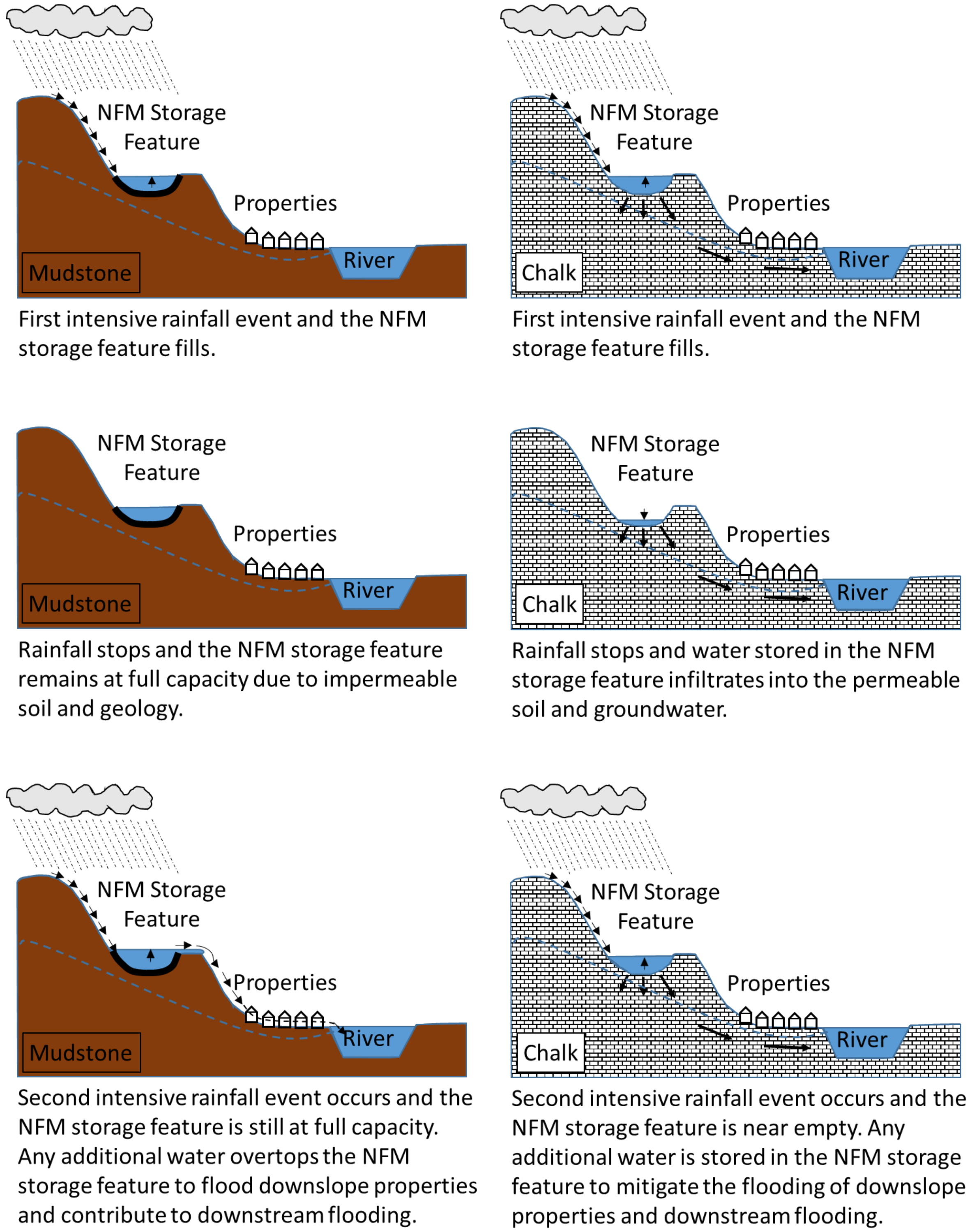


Figure 3.1 Influence of impermeable and permeable soils and geology in relation to storage capacity and efficiency of NFM storage feature to mitigate downstream flooding for 2 intensive rainfall events

Source: Environment Agency

3.1.2 Development of an NFM conceptual model

Many catchment-specific factors need to be taken into account when developing a conceptual model to support NFM such as:

- permeability of underlying soils and geology
- depth of underlying groundwater during peak flooding events across the catchment
- groundwater and surface water flooding processes, including how they interact
- recharge processes
- surface water run-off processes, including pathways and sources
- spring and seepage points
- extent of surface water and groundwater catchment areas

NFM project managers should contact their local groundwater experts to establish a sound conceptual model. The groundwater expert could use published data sources and may also want to consult the British Geological Survey (BGS) Infiltration SuDS Map Viewer for additional information to support the development of an NFM conceptual model.[2] The following data are licensed by the Environment Agency from the BGS as part of the Infiltration SuDS Map Extranet viewer and can be viewed online:

- **Infiltration constraints summary** – this layer highlights all areas where there is potential for a significant constraint
- **Shallow groundwater constraints** – in areas where the water table is shallow either persistently or seasonally
- **Drainage summary** – this layer provides an overview of the extent to which the ground will drain
- **Depth to water table –** this data layer provides an estimate of the depth to groundwater
- **Superficial deposit thickness** -– in some areas, the superficial deposits are thin or absent and hence the permeability of the near-surface may be controlled either by the superficial deposits and bedrock in combination, or by the bedrock alone
- **Superficial deposit permeability** – this data layer states the likely range in permeability for the superficial deposits, thereby indicating the drainage potential of the ground
- **Bedrock permeability** – this data layer states the likely range in permeability for the bedrock, thereby indicating the drainage potential of the ground
- **Geological indicators of flooding** – this data layer will help to identify where floodplains are present and where the water table may respond rapidly to changes in river level

These layers are also available as standalone geographical information system (GIS) layers from BGS under licence conditions at a cost per km^2.

An Infiltration SuDS Map Viewer User Manual is also available to download from the BGS website. Its contents include technical background information, a quick start

[2] The viewer is available from https://extranet.bgs.ac.uk/dana-na/auth/url_14/welcome.cgi (for one concurrent user).

guide, how to use the data, details of data limitations, licensing information and details of intellectual property rights.

Figure 3.2 is a screenshot of the Infiltration SuDS Map Viewer showing the spatial distribution of infiltration constraints across central London. Infiltration constraints are important for deciding the placement of NFM storage because they highlight areas where infiltration may result in the potential for ground dissolution, landslides, shallow mine collapse, groundwater flooding and contamination from artificial ground.

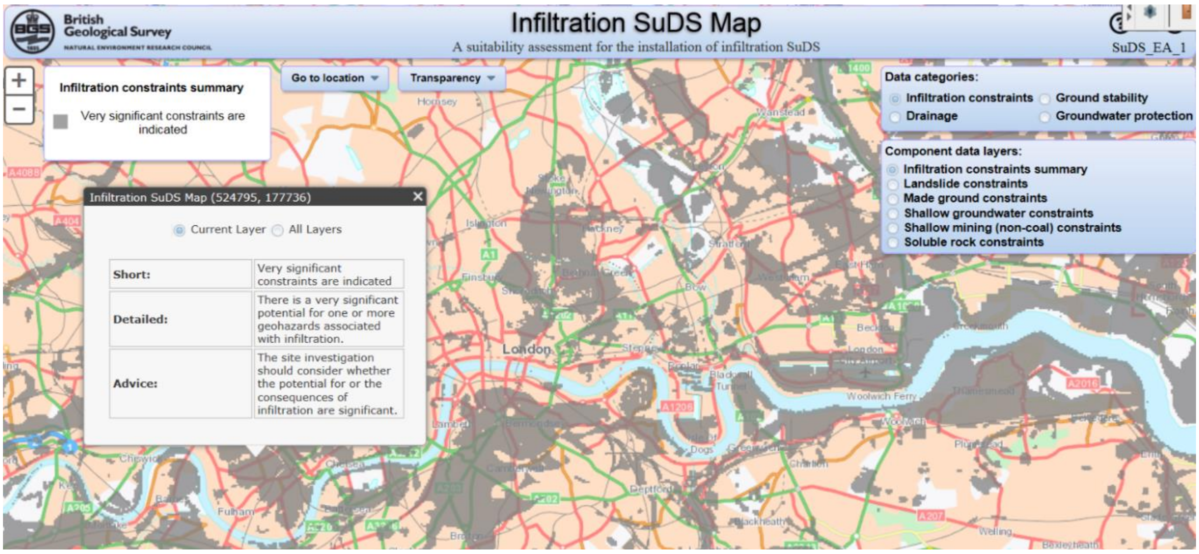


Figure 3.2 Screenshot of central London showing that infiltration constraints are present in the vicinity of Hammersmith

Source: BGS website

3.1.3 Groundwater flooding and NFM measures

There are many reasons why water may appear at the ground surface, ranging from broken drains, sewers and water mains, and rising water levels in abandoned mines or in urban areas where historically high water supply abstraction has fallen significantly.

This section provides background information on the primary mechanisms for groundwater flooding to occur, depending on the geology and flow characteristics of the catchment (ESI, 2016):

- clearwater groundwater flooding
- permeable superficial deposit groundwater flooding
- groundwater driven flooding

Clearwater groundwater flooding

Clearwater groundwater flooding can be associated with all the principal aquifers (Figure 3.3). However, the majority of serious flooding events occur on the outcrop of the Chalk (Figure 3.3A) and to a lesser extent limestone. Sandstones have much higher effective porosity than Chalk, and so more rain recharge is required to saturate the aquifer and therefore the response is slower (Figure 3.3B). Groundwater flooding does not generally occur in sandstone catchments due to this slow response. Groundwater flooding on superficial deposits can occur where the sandstone bedrock is already saturated.

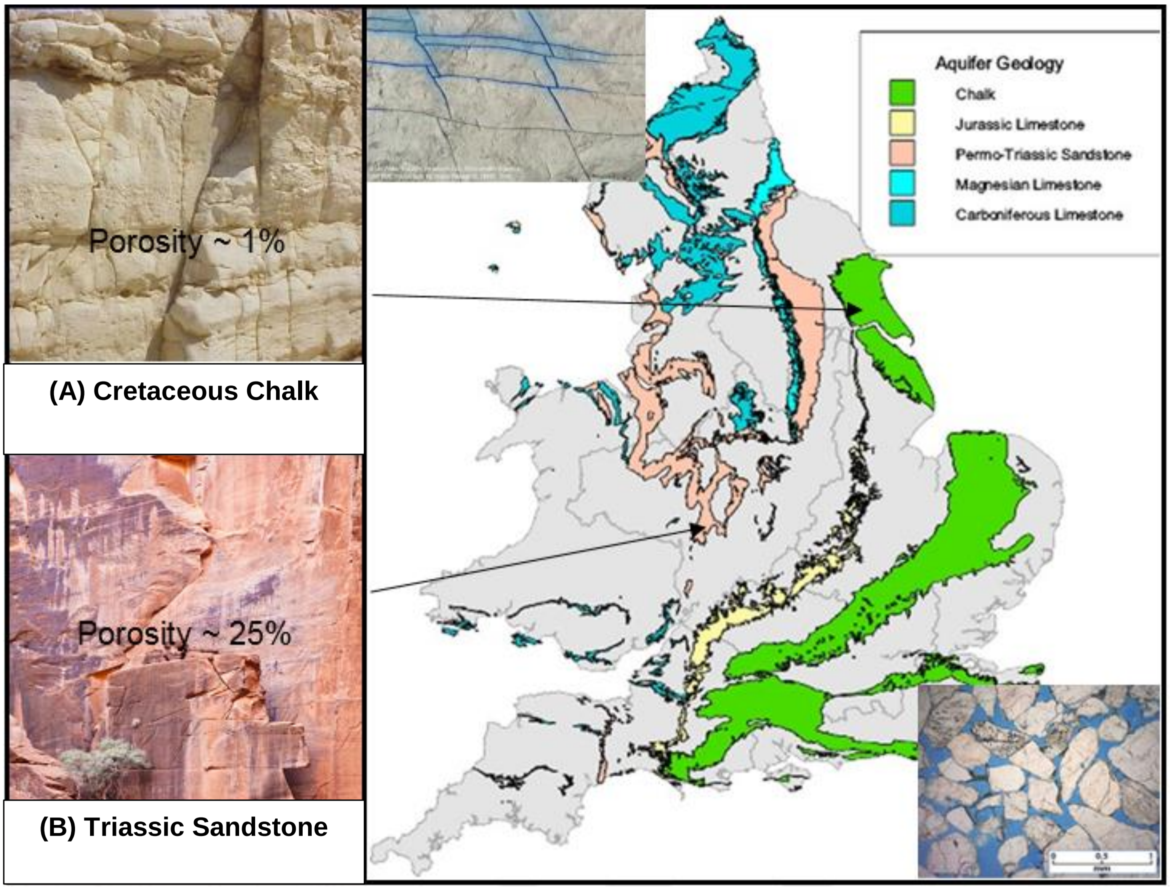


Figure 3.3 Surface distribution of the principal aquifers of Chalk, Limestone and Sandstone across England and Wales

Source: BGS website

Porosity is relevant to groundwater flooding, and is defined as the ratio of the volume of the voids in the rock to the total volume of the rock. It is usually expressed as a percentage.

Water is stored in the pores of Chalk as well as fractures; groundwater movement happens mostly through the fractures (Figure 3.3a). The distribution of these fractures is highly variable. Chalk has a low ‘effective porosity’ (storage capacity within the fractures), but water flows rapidly through them. Hence the fractures fill up quickly, giving a rapid rise to the water table. Due to the permeable nature of Chalk soils, a high proportion of rainfall will infiltrate to the ground. Although Chalk can be highly permeable in zones of enhanced fracturing, a combination of poor bulk permeability and a low density of rivers and streams on the outcrop mean that the time for the Chalk to return to normal levels after a major recharge event can be long. When increased groundwater levels are great enough to cause properties to flood and to have an adverse effect on infrastructure (closure of roads, footpaths, railways, airports and so on), the slow recession can lead to long duration flooding events.

This is called clearwater flooding. It can occur across areas of a catchment where a topographic depression exists, and does not depend on the location of surface water systems. During intense rainfall periods, water table levels rise and they can intercept topographically low depressions as shown in Figures 3.4 and 3.5. Once clearwater groundwater flooding has commenced, very little can be done to mitigate the impacts across the submerged topographically low areas, with the exception of the pre-installation of individual property protection measures and pumping (LGA and Environment Agency, 2011).

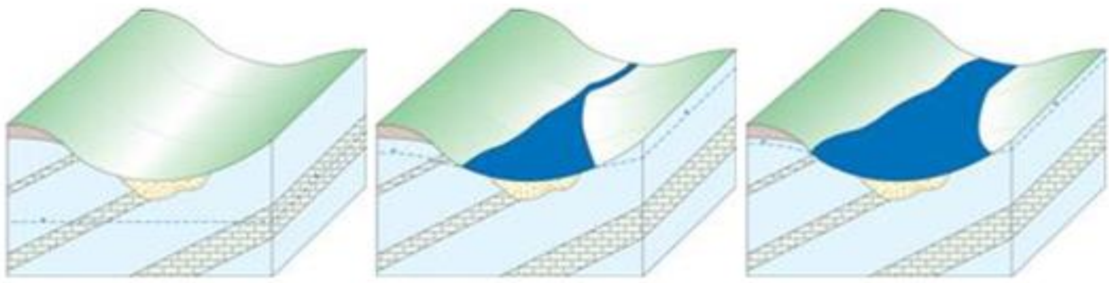


Figure 3.4 Groundwater flooding due to rising groundwater levels in an unconfined principal aquifer (also commonly referred to as clearwater flooding)

Source: BGS website

Figure 3.5 Example of clearwater flooding

Source: Environment Agency, Thames Groundwater Team, 2014

The outputs from your conceptual model should be used to identify feasible NFM measures for your catchment. Upper and middle catchment NFM measures might include:

- increasing evapotranspiration and infiltration rates by encouraging the development of natural grassland communities and woodland
- increasing soil infiltration rates by improving soil management techniques (where applicable)
- removing water from roads and tracks, and temporarily storing this water in deepened cattle grid storage bays that are allowed to drain once the main flood has subsided
- slowing the flow in tributaries and out of bank events by constructing leaky woody dams and encouraging the growth of vegetation on riverbanks and across the floodplain
- managing flows in artificial drainage ditches by blocking ditches where appropriate across the upper and middle catchment – this could decrease flow rates and increase the holding capacity of the ditch

- temporarily storing surface water run-off in run-off attenuation features

When using run-off attenuation features for temporary storage of surface water run-off, consideration should be given to the soils and geology as the following will apply.

- The permeability of the catchment will influence the size and number of NFM storage features required to reduce downstream peak flows.
- The base of the NFM storage feature will influence the volume of water that will drain into the underlying groundwater system. This might continue to support downstream flooding if it continues over a significant period of time.
- The bed of the NFM storage feature, the topographical setting and the depth of the underlying groundwater should be assessed to ensure it does not become a source of flooding. NFM storage features with permeable bases that are located lower than the water table during flood events could act as a seepage point.
- The discharge area of the NFM storage feature should also be considered. Water that is discharged onto impermeable soils and geology could readily convert into surface water run-off, which could continue to exacerbate downstream flooding problems.

Groundwater flooding on permeable superficial deposits

Groundwater flooding in shallow permeable deposits associated with river floodplains is a very complex process and is closely associated with fluvial flooding (Figure 3.6).

Figure 3.6A shows the water table sitting beneath the floodplain and at a similar level to the stage height in the river during normal rainfall levels.

Figure 3.6B shows how a period of sustained rainfall that creates surface water run-off has increased the water table above the ground surface, and water is able to flow freely between the river, the groundwater and the floodplain. This type of flooding can occur over both permeable and impermeable solid geologies.

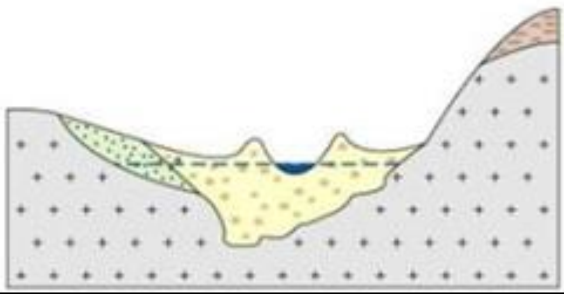
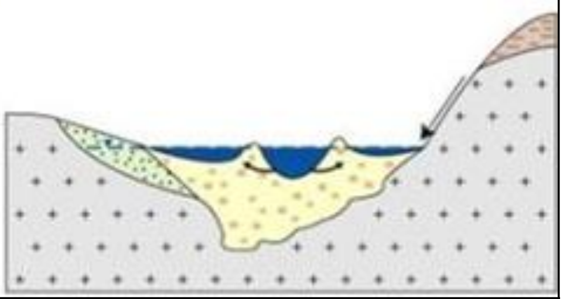
Normal conditions	Flood conditions
	
(A) Groundwater levels in shallow permeable deposits (sands/gravels) in a river floodplain during normal rainfall conditions	**(B) Groundwater levels in shallow permeable deposits (sands/gravels) in a river floodplain during excessive and prolonged rainfall conditions and raised river levels**

Figure 3.6 Groundwater flooding processes across permeable superficial deposits

Source: BGS website

Permeable superficial deposit groundwater flooding will often precede fluvial flooding where river banks are built up to contain rivers. Water that flows through the river bed will raise the adjacent groundwater levels, which can have an impact on below-ground property and infrastructure, and potentially rise above ground level. In reality, flooding in this setting is complex as it can be the result of a series of mechanisms (surface water run-off, direct rainfall, surface water flows, uprising groundwater and so on) and it is best to contact your local Environment Agency groundwater team for more detailed information.

When groundwater flooding does occur along river corridors, it can last substantially longer than surface water flooding events. This is due to the long time it takes for the groundwater to drain into the adjacent surface water system once the stage height in the river has receded. This type of flooding can last from weeks through to months depending on:

- the amount of rainfall
- the volume of surface water run-off (which is also dependent on the surrounding land use and catchment management)
- the extent and permeability of the river floodplain deposits It is essential to gain a good understanding of the likely causes and the source of this type of flooding through the development of a sound conceptual model.

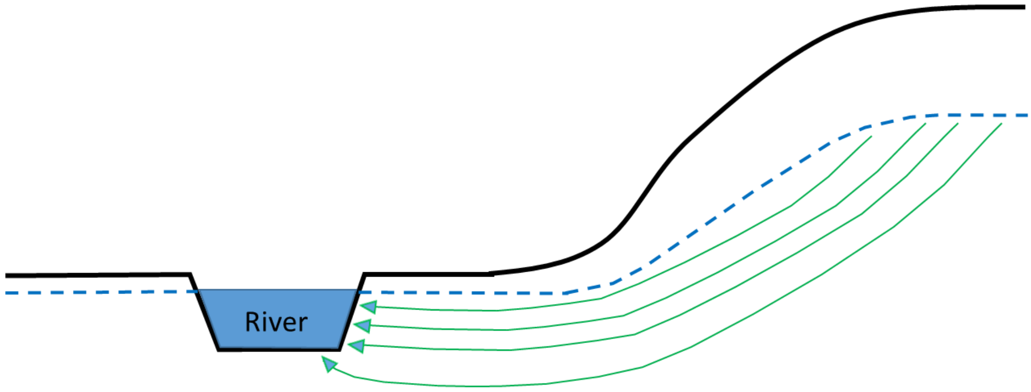
The following upper and middle catchment NFM methods that could be used to mitigate this type of flooding might include:

- increasing evapotranspiration and infiltration rates by encouraging the development of natural grassland communities and woodland
- increasing soil infiltration rates by improving soil management techniques (where applicable)
- removing water from roads and tracks, and temporarily storing this water in deepened cattle grid storage bays that are allowed to drain once the main flood has subsided
- temporarily storing surface water run-off in run-off attenuation features with consideration being given to the permeability of soils and geology (see above for further considerations)
- increasing the roughness of the land surface to slow down surface water run-off by allowing set-aside land to develop, improving soil management and developing woodland buffer strips along field boundaries
- slowing the flow in tributaries and out of bank events by constructing leaky woody dams and encouraging the growth of vegetation on riverbanks
- managing flows in artificial drainage ditches by blocking ditches where appropriate across the upper and middle catchment – this could reduce flow rates and increase the holding capacity of the ditch

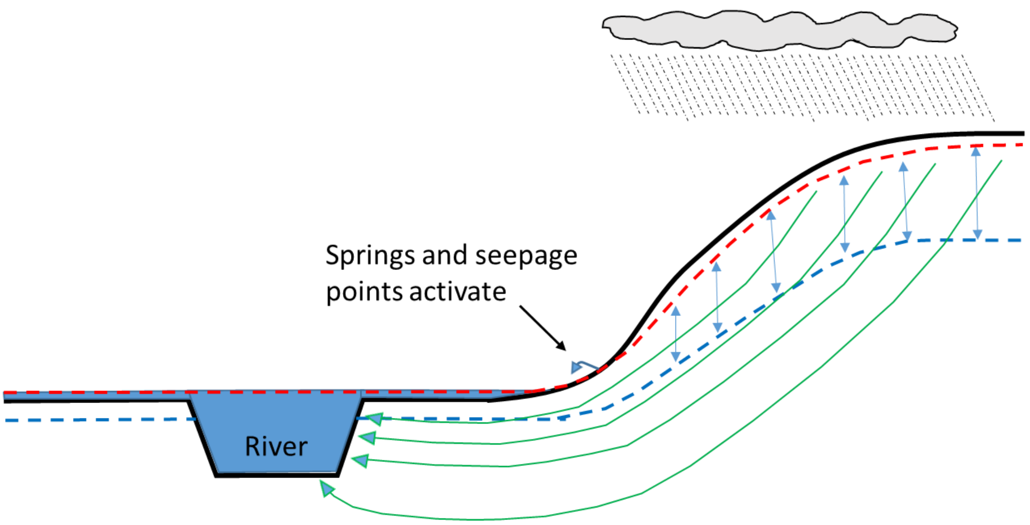
The floodplain is commonly inundated (Figure 3.6B) during permeable superficial deposit groundwater flooding. Slowing out of bank flooding events by encouraging the growth of vegetation on the riverbanks and across the floodplain, along with other floodplain NFM measures, could also be effective.

Groundwater driven flooding

This type of flooding is quite rare compared with fluvial flooding, but is prolonged and damaging to the economic activity of the businesses and infrastructure it affects. It is caused by excessive and sustained rainfall which increases water table levels across the Chalk outcrop (Figure 3.7). Figure 3.7A shows groundwater flow paths, river levels and water table levels under normal rainfall conditions. Figure 3.7B.displays what happens during and after an excessive period of rainfall.



(A) Normal water table heights (blue hashed line) during normal rainfall conditions



(B) Very high water table heights (red hashed line) during excessive and prolonged rainfall conditions

Figure 3.7 Cross-section of groundwater flow paths (green arrows)

Source: Environment Agency

The water table rises throughout the topographically high areas and breaks through the land surface in the base of the river valleys (Figure 3.7B, red hashed line) and activates springs and seepage points on the valley sides (Figure 3.8). The water flowing through the subsurface from the topographically high areas maintains the high water table in the river valley, resulting in continued groundwater flooding. The groundwater flooding in the base of the valley ends only once the river level has receded and groundwater is able to discharge to it at a sufficient rate to drain the aquifer. This process can take weeks through to months depending on the interim rainfall conditions and the time is takes for the river to return to normal levels (Figure 3.9). The Thames catchment is prone to this type of groundwater driven flooding event due to the proportion of the catchment that is underlain by Chalk outcrop but this type of flooding mechanism is also important in other areas of the country with Chalk bedrock (see Figure 3.3).

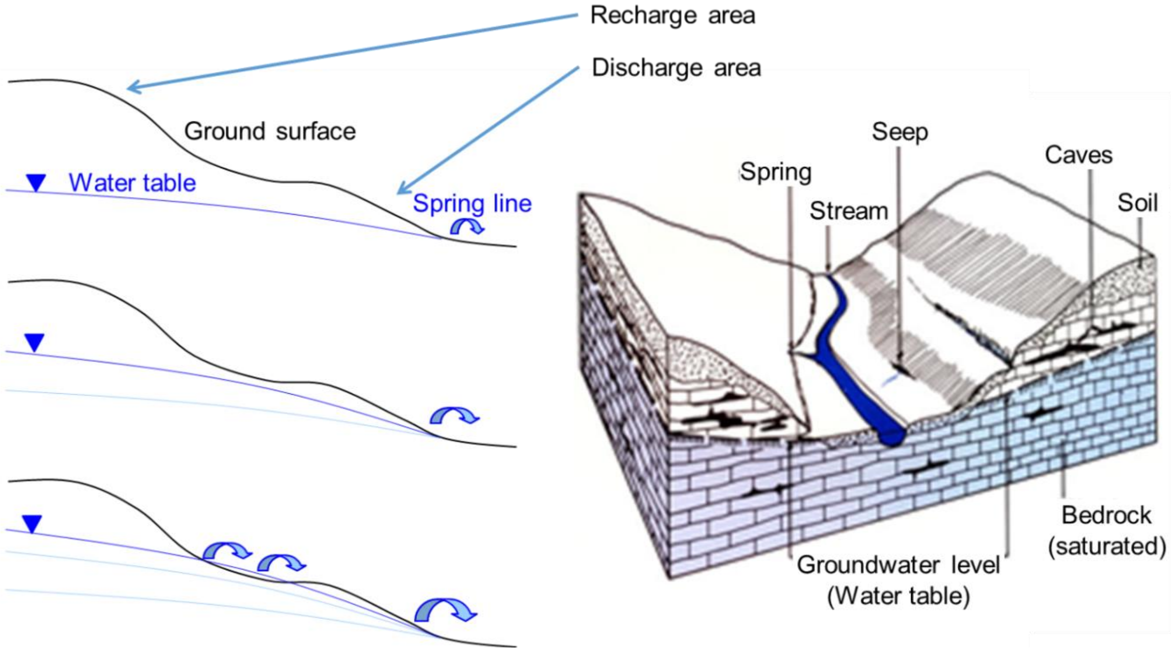


Figure 3.8 Groundwater flooding in a Chalk catchment

Source: BGS website

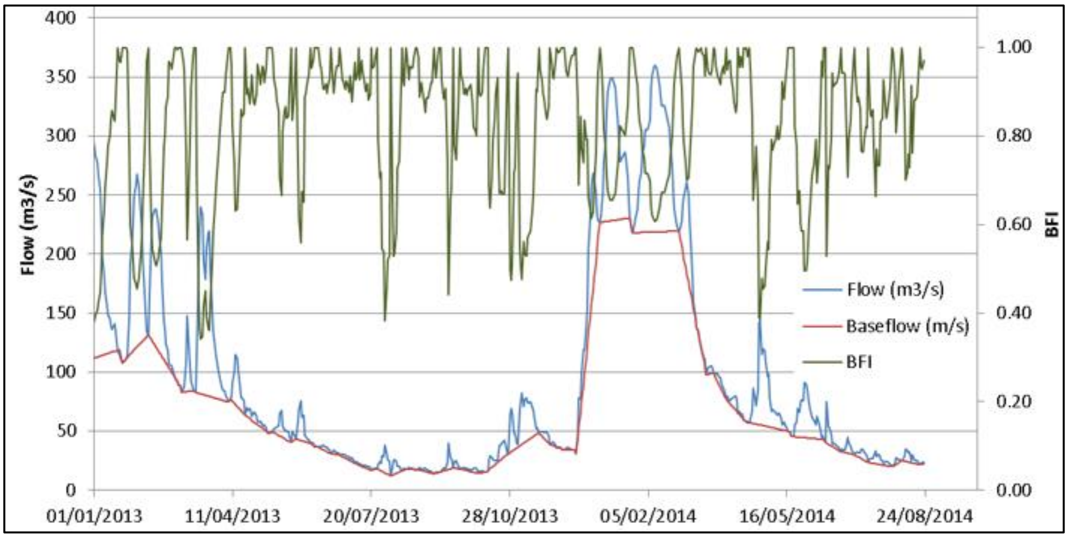


Figure 3.9 Naturalised river flows at Kingston on the River Thames and the impact of groundwater flooding on baseflow inputs into the Thames for many months

Source: ESI (2016)

In reality, this type of groundwater driven flooding and the subsequent impact on surface water flooding is very complicated. Water will be emerging from various springs and seepage points across the outcrop. These will be influenced by the composition of sands and gravels, and the presence of old abandoned Palaeogene river channels. During intense and prolonged rainfall events, the water table will rise and groundwater will flow along preferential flow paths and emerge at seepage points and springs. The higher the water table rise and the more places it intersects the land surface, the greater number of seepage points and springs that will be activated, which will cause flooding and potential property damage further up the valley (Figure 3.8). The springs and seepages will remain active until the water table recedes below them as the source of the groundwater is disconnected.

The upper and middle catchment NFM measures that might be effective in mitigating the flooding impacts of groundwater driven flooding will be the same as those listed for clearwater groundwater flooding.

NFM measures installed downhill of springs and seepage points (Figure 3.8) could also be effective in holding back water and might include:

- increasing evapotranspiration rates by developing natural grassland communities both downhill and across recharge zones
- installing surface water run-off attenuation features downhill of springs and seepage points, with consideration being given to the permeability of soils and geology (see above for further considerations)

Although this section has presented a range of different flooding mechanisms, in reality they are likely to combine during a major flooding event. The development of a sound conceptual model by a local groundwater expert will be able to support flood risk managers in identifying which type of flooding process is likely to be most dominant.

3.1.4 Low permeability catchments

Catchments with low permeability soils and rock (such as Cumbria and Somerset) permit only a very limited amount of infiltration and recharge (ESI 2016). Intense rainfall events often lead to rapid surface water run-off and flash flooding, which quickly recedes once the rainfall event has passed. Antecedent rainfall conditions and saturated ground will also influence the ‘flashiness’ of the flooding event.

River flooding from water that drains the surrounding land is likely to be influenced by:

- the size of the upslope contributing area
- topography
- soil type
- land use
- catchment management (that is, extent of soil compaction)
- infrastructure (that is, roads and tracks that transport water to the river)

These factors will affect the origin, rate and volume of surface water run-off above low permeability soils and geology.

NFM measures installed across the upper and middle topographical reaches of these types of catchments might include:

- increasing evapotranspiration and infiltration rates by encouraging the development of natural grassland communities and woodland
- removing water from roads and tracks, and temporarily storing this water in deepened cattle grid storage bays that are allowed to drain into once the main flood has subsided
- temporarily storing surface water run-off in run-off attenuation features with consideration being given to the permeability of soils and geology (see above for further considerations)

- planting deep-rooted trees within run-off attenuation features could also break up the underlying soil structure and encourage further infiltration and storage within the soil structure
- increasing the roughness of the land surface to slow down and store surface water run-off by allowing set-aside land to develop, and planting woodland buffer strips along field boundaries
- increasing soil infiltration rates by improving soil management techniques (where applicable)
- slowing the flow in tributaries and out of bank events by constructing leaky woody dams and encouraging the growth of vegetation on riverbanks and across the floodplain
- managing flows in artificial drainage ditches by blocking ditches where appropriate across the upper and middle catchment – this could decrease flow rates and increase the holding capacity of the ditch

3.1.5 Multiple benefits of NFM work

Provided appropriate consultation is undertaken, NFM projects could deliver many non-flooding related benefits for example:

- **Reduced sediment deposition** – will help meet the requirements of Water Framework Directive
- **Reduced diffuse pollution –** will support the achievement of Water Framework Directive objectives, contribute to protecting Drinking Water Protected Areas and Groundwater Source Protection Zones, and could contribute towards catchment measures as part of the Water Industry National Environment Programme
- **Increased groundwater recharge** – will support the achievement of Water Framework Directive objectives, provide resilience against the impacts of climate change and help mitigate the impacts of groundwater abstraction
- **Increased baseflow** – will support the achievement of Water Framework Directive objectives and help mitigate the impacts of groundwater abstraction
- **Improved habitats and biodiversity** –will support the achievement of Water Framework Directive and Habitats Directive objectives and the achievement of multiple benefits including carbon retention in soils and contributing to biodiversity targets
- **Wetland creation** – for flood risk management, water quality benefits and as part of a programme of measures to deal with diffuse pollution in the catchment

3.1.6 Statutory obligations

When proposing an NFM scheme, you need to be aware of the potential water quantity and quality impacts that can result from changing water flows and storage, and increasing groundwater recharge, as this could affect certain statutory obligations. There are a number of statutory obligations in relation to groundwater that could be affected by NFM work they include:

- Water Resources Act 1991
- Environment Act 1995
- Groundwater (England and Wales) Regulations 1998, 2009
- Water Environment (Water Framework Directive) (England and Wales) Regulations 2003
- Infrastructure Act 2015

Relevant statutory obligations are summarised below.

- **Source Protection Zones and Safeguard Zones**. These zones contribute to the protection of drinking water supplies. NFM work cannot derogate water quality, including the quality of groundwater or surface water for Public Water Supply abstractions. Please seek advice from your local Environment Agency Groundwater Team and Hydrology Team.
- **Diffuse pollution**. High nitrate levels are a problem for many groundwater and surface water systems, as levels are required to remain below a drinking water threshold. It is important that NFM work does not increase nitrate concentrations in groundwater and surface water above this level. Work needs to be carried out with other Environment Agency Area teams to actively reduce nitrate values – one of the potential benefits of NFM work. Please seek advice from your local Groundwater Team and Hydrology Team.
- **Hazardous substances, historic contamination and closed landfill sites**. NFM projects need to take care to avoid remobilising hazardous substances that may be present in groundwater or leachate from historic (closed) landfill sites. Please seek advice from your local Environment Agency Groundwater and Contaminated Land Team.
- **Water Framework Directive**. This assesses the health of surface water and groundwater systems via numerous tests. NFM work could have an impact on Water Framework Directive assessments and working with other Environment Agency Area teams could be beneficial for meeting Water Framework Directive objectives. Please seek advice from your local Environment Agency Fishery, Biodiversity and Geomorphology Team, Hydrology Team and Groundwater Team.

Those implementing an NFM project are strongly encouraged to conduct a catchment-scale risk assessment to ensure that the project does not have a negative impact on these statutory obligations.

3.1.7 Geohazards

NFM schemes are likely to introduce more water via infiltration into the ground. NFM project managers need to be aware of the geohazard dangers of increased infiltration rates and actively work to avoid siting measures that could induce landslips, slope failures or ground collapses. Your local groundwater expert and the BGS Infiltration SuDS Map Viewer (see Section 3.1.2) should be used to support this task. The following layers and others are licensed by the Environment Agency from the BGS and can be viewed online.

- **Ground stability summary** – this layer provides an overview of the likely extent of ground stability issues that should be considered during the planning and design of infiltration SuDS (or any scheme aiming to infiltrate water to a groundwater system), utilising data from national mapping of the following 7 geohazard phenomena:

- **Compressible ground –** this data layer identifies the potential for subsidence as a result of compressible ground (water infiltrated to compressible ground can reduce the bearing capacity of geological materials, inducing settlement of structures)
- **Landslides –** this data layer indicates the potential for landslide/slope failure if water is infiltrated to the ground (slope stability is a function of pore water pressure and cohesion, especially within the shallow subsurface of slopes)
- **Shallow mining (non-coal) –** this data layer identifies the potential for shallow mining (non-coal) to be present (eater infiltrated to underground workings may pose further hazards of flooding and contamination, or inducing the connection of voids to the surface)
- **Soluble rocks –** this data layer identifies the potential for ground collapse (sinkholes) as a result of the dissolution of rock (water infiltrated to soluble rocks can alter dissolution rates for naturally occurring beds of soluble materials, leading to voids and sinkhole development)
- **Swelling clays –** this data layer identifies the potential for ground movement (heave) as a result of swelling clay (eater infiltrated to some clay-rich soil and geological materials can cause swelling of the clay lattices – volume changes can be small, but can cause damage to fixed structures)
- **Collapsible ground –** this data layer identifies the potential for subsidence as a result of collapsible ground (though a rare phenomenon, water infiltrated to collapsible deposits – typically loessic silts – can induce slope failure as the materials are metastable and sensitive to saturation or shock loading)
- **Running sands –** this data layer identifies the potential for subsidence as a result of running sand (running sand is normally an issue for excavations, or failed pipe/sewerage, where unconfined water flows cause localised slope failure or exfiltration failures)

- **Groundwater protection summary** – this layer provides an overview of the extent to which subsurface factors might also affect the planning and design of infiltration SuDS in respect of protecting groundwater quality. It utilises data from national mapping of:
- **Source Protection Zones (Environment Agency)** – these are long established regions where groundwater recharge to potable supplies is subject to constraints in order to protect supply and quality
- **Made ground constraints** – these are areas where significant quantities of artificially deposited materials may be present (‘made ground’). They may consist of known brownfield sites or other areas of extensive surficial modification/landscaping/mining or redevelopment. Infiltrating groundwater into these materials needs careful consideration of likely pathways, induced settlement and the potential for contamination.

These layers are also available as standalone GIS layers from BGS under licence conditions at a cost per km^2. Those responsible for NFM projects are strongly encouraged to conduct a catchment-scale risk assessment to ensure that the geohazards outlined above are not encountered or triggered as a result of the project.

4 Conclusions

There are a wide range of resources available to help you identify data, tools and models that can help refine the influence of WWNP on the risk for your scheme. These include existing studies and mapping products.

If there is no local detailed model, the matrix shown in Figure 2.4 provides guidance on representing the effects of WWNP measures and how you can assess changes to risk.

There are a range of metrics for evaluating changes to risk that can be estimated from different levels of modelling the system with and without WWNP measures, including:

- peak flow or peak river level reduction
- increases to the timing of the peak flow or level time series (hydrographs)
- counts of properties between modelled outlines with and without WWNP
- flood extent (for different probabilities or events)
- depths at properties
- damages to properties using depth–damage curves using the Multi-Coloured Manual

These metrics provide strong evidence, especially as you use more realistic models further down the vertical axis of the matrix, or as you incorporate more calibration and scenario testing along its horizontal axis for the different types of WWNP. Clearly this needs to be informed by how much confidence there is in the evidence for change (see Evidence Directory) and the modelling uncertainties. Even with a well-calibrated hydraulic model, there can be uncertainties stemming from hydrometry data and processes that are not represented in standard models such as bed–sediment movement.

Whichever approach you use, you will need to be able to describe it and your assessment of the range of measures assessed to a wide range of stakeholders. This should ideally be an iterative process, whereby stakeholders work together to identify and test a range of potential options that could reduce flood risk across a catchment.

A range of case study examples, which can be accessed from Appendix 1, offer ideas on different approaches that you could use in your catchment. Other examples of using model outputs to help visualise proposed NFM schemes include:

- Brompton case study (Metcalfe 2016))
- A whole catchment approach to improve flood resilience in the Eden (Hankin et al. 2017)

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List of abbreviations

AEP	annual exceedance probability
BGS	British Geological Survey
C@R	Communities at Risk
FCRM	flood and coastal risk management
FDGiA	Flood Defence Grant in Aid
NFM	natural flood management
RoFRS	Risk of Flooding from Rivers and Sea [map]
RoFSW	Risk of Flooding from Surface Water [map]
SoP	standard of protection
SuDS	sustainable urban drainage
WWNP	Working With Natural Processes

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