Department for Environment Food & Rural Affairs

Llywodraeth Cymru
Welsh Government

Cyfoeth Naturiol Cymru
Natural Resources Wales

Environment Agency

delivering benefits through evidence


# Blockage management guide

Report – SC110005/R2

Flood and Coastal Erosion Risk Management Research and Development Programme

We are the Environment Agency. We protect and improve the environment.

Acting to reduce the impacts of a changing climate on people and wildlife is at the heart of everything we do.

We reduce the risks to people, properties and businesses from flooding and coastal erosion.

We protect and improve the quality of water, making sure there is enough for people, businesses, agriculture and the environment. Our work helps to ensure people can enjoy the water environment through angling and navigation.

We look after land quality, promote sustainable land management and help protect and enhance wildlife habitats. And we work closely with businesses to help them comply with environmental regulations.

We can’t do this alone. We work with government, local councils, businesses, civil society groups and communities to make our environment a better place for people and wildlife.

**Published by:**
Environment Agency, Horison House, Deanery Road, Bristol, BS1 9AH
www.environment-agency.gov.uk

ISBN: 978-1-84911-439-4



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

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

or our National Customer Contact Centre:
T: 03708 506506

Email: enquiries@environment-agency.gov.uk

**Author(s):**
Jeremy Benn, Barry Hankin, Amanda Kitchen, Rob Lamb, Zora van Leeuwen, Paul Sayers

**Dissemination Status:**
Publicly available

**Keywords:**
Blockage, debris, rivers, flood

**Research Contractor:**
JBA Consulting, 1 Broughton Park, Old Lane, Broughton, Skipton, BD23 3FD, Tel. 01756 799 919

**Environment Agency’s Project Manager:**
Mark Whitling

**Theme Manager:**
Owen Tarrant, Asset Management

**Collaborator(s):**
Sayers and Partners

**Project Number:**
SC110005/R2

# Evidence at the Environment Agency

Scientific research and analysis underpins everything the Environment Agency does. It helps us to understand and manage the environment effectively. Our own experts work with leading scientific organisations, universities and other parts of the Defra group to bring the best knowledge to bear on the environmental problems that we face now and in the future. Our scientific work is published as summaries and reports, freely available to all.

This report is the result of research commissioned and funded by the Joint Flood and Coastal Erosion Risk Management Research and Development Programme. The Joint Programme is jointly overseen by Defra, the Environment Agency, Natural Resources Wales and the Welsh Government on behalf of all Risk Management Authorities in England and Wales:
http://evidence.environment-agency.gov.uk/FCERM/en/Default/FCRM.aspx.

You can find out more about our current science programmes at:
https://www.gov.uk/government/organisations/environment-agency/about/research.

If you have any comments or questions about this report or the Environment Agency's other scientific work, please contact research@environment-agency.gov.uk.

Professor Doug Wilson
**Director, Research, Analysis and Evaluation**

# Executive summary

The blockage of watercourses or structures by debris (that is, any material moved by a flowing stream including vegetation, sediment and man-made materials or refuse) reduces flow capacity and raises water levels, potentially increasing the risk of flooding. High water levels can cause saturation, seepage and percolation leading to failure of earth embankments or other structures. Debris accumulations can change flow patterns, leading to scour, sedimentation or structural failure. Debris can also obstruct navigation and present a hazard to water users.

The management of blockage is essential to avoid increasing these risks. In recent years, environmental legislation has emphasised the need to work with natural processes, promoting a move towards more sustainable practices such as controlling soil erosion. There is also a need for consistent guidance on the economic appraisal of blockage to allow the preparation of a business case for the full range of management measures from maintenance to capital works.

This science report sets out the evidence base to support the Blockage Management Guide on blockage risk assessment, modelling and catchment management. The report presents:

- user requirements for guidance on blockage risk assessment, modelling and catchment management identified during an industry consultation
- an overview of blockage processes including debris sources, debris transport and blockage mechanisms at different asset types
- the findings of a literature review into the source–pathway–receptor approach to debris blockage
- a summary of existing data and methods for predicting debris load and blockage at different structure types
- the findings of a series of evaluation exercises into existing methods of predicting debris load and blockage, which showed that there is still considerable uncertainty
- the background to a new screening method which is intended to identify potential pinch points, screen out low risk assets requiring no further assessment and identify ‘potentially at risk’ assets requiring detailed assessment
- the background to a new detailed assessment method for assets that are considered to be potentially at risk of blockage and guidance on blockage risk management
- suggestions for future work to improve the assessment of the influence of debris and blockage on the probability and extent of flooding (and hence risk)

# Acknowledgements

The support of the Environment Agency throughout this work is gratefully acknowledged.

We are also grateful to the Environment Agency and Leeds City Council for providing blockage data and photographs.

We are grateful to the following organisations for supporting the consultation process: Aberdeen City Council, Edinburgh City Council, Environment Agency, Highland Council, Highways Agency, John Dora Consulting, Leeds City Council, National Roads Authority (Ireland), Natural Resources Wales, Office of Public Works (Ireland), Renfrewshire Council, Shire Group of Internal Drainage Boards, South Wales Trunk Road Agent, Stirling Council and West Dunbartonshire Council.

The contributions of Neil Hunter, John Riddell and Bill Weeks in reviewing the report are also appreciated.

# Contents

# 1 Introduction

## 1.1 Background

This report describes work undertaken during Project EAAA-9BGGER ‘Blockage and Debris Modelling Guidance’, funded by the joint Environment Agency/Defra Flood and Coastal Erosion Risk Management (FCERM) Research and Development Programme and undertaken by JBA Consulting.

There is currently no consistent guidance for estimating the type of debris that can be expected to arrive at a given location, the impact of that debris, or the aggregate susceptibility of a catchment to the impacts of blockage at many locations. This causes problems, for example, when attempting to identify benefits provided by clearance activities for economic appraisal.

The project has developed guidance for use by flood risk management practitioners when managing flood risk from blockages using a risk-based approach.

## 1.2 Project objectives

The project’s purpose was to improve the understanding and management of flood risk from blockages of watercourses and structures by floating debris and sediment.

The project’s objectives were to:

- increase awareness of available research and identify any regional practices for assessing flood risk from catchment-wide scale to single assets
- improve awareness of the catchments and systems where blockages increase flood risk
- develop a risk-based approach for the assessment of blockage risk based on sound evidence
- ensure that future mapping and modelling developments related to debris and blockage are underwritten by a sound evidence base

The outcomes of the project include a blockage management guide and this science report. The primary users of the guidance will be:

- operational asset managers
- flood mapping and modelling staff
- consultants working on the Water and Environmental Management (WEM) framework and its successors

The aim is to empower these groups of people with the information they need to:

- understand the potential for a catchment to supply material
- be able to quantify the scale of the problem
- use the information in the right way

To this end, the guidance covers the 3 areas discussed below:

- source–pathway–receptor analysis
- guidance on different modelling tools
- advice on catchment management

### 1.2.1 Source–pathway–receptor analysis

The source–pathway–receptor model is widely used to help conceptualise flood risk (and some other types of environmental risks). It has been applied in the Environment Agency's analysis of flood risk and is a convenient approach when considering risk associated with blockage.

For a risk to arise there must be a hazard, that is, something that could potentially lead to damage. It can be useful to think of the hazard as having a 'source', which is the physical condition or event that creates the risk, and one or more 'receptors', which suffer the consequences of the risk. The 'pathway' is the link between the source and the receptor. Examples are blockage of a culvert or screen leading to overtopping and flooding. The 'pathway' transfers and modifies the risk between source and receptor.

In this context, source–pathway–receptor analysis allows users to assess:

- **Sources.** The potential type and volume of debris are dependent on physical characteristics and flow conditions in the upstream catchment.
- **Pathways**. These are the circumstances surrounding the blockage itself, potentially expressed in terms of likelihood (probability) or non-probabilistic scenarios of blockage. This will require users to identify:
    - potential blockage locations
    - degree of blockage occurring under a range of loads
    - frequency of debris transport
    - possible or likely blockage rates
- **Impacts**. Determining the impact of blockage and increased flooding on receptors will require users to:
    - assess the impact of blockage using existing data and tools
    - visualise the impact of blockage using mapping
    - quantify the impacts of blockage occurring (and not occurring)
    - measure the benefits of blockage avoidance, that is, the difference in damages (economic or house equivalents per year flooded) between 'blocked' and 'non-blocked' conditions

### 1.2.2 Guidance on different modelling tools

Modelling guidance advises on:

- available methods, from simple to complex, depending on the question being asked and the availability of data – aligned with Flood and Coastal

Erosion Risk Management Appraisal Guidance (FCERM-AG) (Environment Agency 2010b) and the 'Multi-Coloured Manual' (FHRC 2013)

- suitable screening and modelling approaches and tools, including Modelling and Decision Support Framework 2 (MDSF2) but also industry standard tools depending on user needs
- application of MDSF2 to demonstrate the impacts of blockage, including identification of data required, methods of analysis, explanation of data produced, suggested usage scenarios and suitability of results
- choice of data and implications on the final answer (types, quality and volume)
- choice of model parameters and suggested ranges for non-standard situations
- quantifying uncertainty in blockage, hydrology, modelling and mapping
- management and storage of data being produced

The following constraints were applied to the project.

- The development bespoke tools or IT infrastructure was outside the scope.
- The approach must apply current Environment Agency capabilities, systems and data.
- External approaches can be suggested where no other option is suitable but should be activity rather than supplier based.
- The approach must flexible and dynamic since some users will have more data than others.

### 1.2.3 Advice on catchment management

The catchment management guidance is intended to help users to:

- assess the advantages and disadvantages of clearing screens or allowing them to block using information about receptors and benefits
- prepare a business case for clearance activities and/or capital works to reduce risk
- prioritise clearance activities (planned and reactive) using a risk-based and evidence-based approach
- rank high risk flood defence systems and catchments using a rapid, high-level assessment method, looking at likelihood as a minimum, ideally extending to receptor impacts

## 1.3 Project scope

The project was undertaken in 3 stages.

- **Stage 1 Carry out research**. This involved a literature review to identify regional processes, best practice, current Environment Agency capabilities, and existing tools and products

- **Stage 2 Analyse research**. This included mapping the knowledge gained through the research to the list of required topics, identifying gaps in knowledge and validating recent science. The stage concluded with visual mapping between knowledge and requirements, suggestions of additional guidance topics and a summary of the evaluation exercise.
- **Stage 3 Reporting**. This involved developing a blockage management guide to provide the Environment Agency and other flood risk authorities with a consistent baseline for understanding flood risk from blockages based on sound evidence and practical knowledge. This supporting science report was also prepared during Stage 3.

## 1.4 About this report

This science report presents the evidence in support of the blockage management guide.

Chapter 2 summarises user requirements for guidance on blockage risk assessment, modelling and catchment management resulting from industry consultation.

Chapter 3 describes blockage mechanisms at different asset types and provides a summary of existing data and methods for predicting blockage.

Chapter 4 presents the findings of a literature review into the source–pathway–receptor approach to debris blockage, organised according to asset type.

Chapter 5 presents a summary of existing data and methods for predicting aspects of debris load and blockage in various settings. It also identifies knowledge gaps, potential for data transfer between asset types with similar hydraulics or blockage mechanisms, and links to other research.

Chapter 6 discusses a series of evaluation studies. The data and case studies to be used are summarised. The performance of each method is discussed with conclusions and recommendations for application of some of the methods.

Chapter 7 sets out the background to the new screening method. This is intended to identify potential pinch points, identify ‘potentially at risk’ assets requiring detailed assessment and screen out low risk assets requiring no further assessment.

Chapter 8 sets out the background to the new detailed assessment method, which is intended to be used for assets that are considered to be potentially at risk of blockage.

Chapter 9 presents the background to the new management guidance.

Chapter 10 presents a suggested route map for future work to improve guidance, improve modelling capability and extend observational evidence.

It is important to note that some differences may exist between this report and the published guide due to editorial changes and maintaining ease-of-use in the new guide. Changes may include steps (how many or their order), references, logic and wording amongst others.

# 2 User requirements

## 2.1 Introduction

This chapter discusses user requirements for guidance on blockage risk assessment, modelling and catchment management. These have been compiled from the project brief, project steering group, consultation with practitioners throughout the UK and a literature review. Detailed responses to the consultation are given in Appendix A.

## 2.2 Potential users and applications

The potential users and applications of the blockage management guide are listed in Table 2.1. The guide should be suitable for use by both experts and non-experts, who may need to scope, commission and lead modelling studies, or build, run and analyse models.

**Table 2.1 Potential users and applications**

| User | Application |
|---|---|
| Asset owners or managers<br>Risk management authorities | • Assess risk of blockage at assets<br>• Prioritise inspection, monitoring and maintenance<br>• Prioritise incident response<br>• Post-flood investigation<br>• Plan new interventions<br>• Economic appraisal |
| Regulatory or consenting authorities | • Assess impacts of proposals (including environmental enhancement, mitigation and compensation works) |
| Modelling and mapping staff | • As above, plus<br>• Flood risk assessment<br>• Flood risk mapping |
| Consulting engineers | • Flood risk assessment<br>• Flood risk mapping<br>• Planning and design of capital and temporary works<br>• Economic appraisal |

## 2.3 Existing approaches

Three-quarters of the respondents to the questionnaire survey carry out blockage risk assessment. Assessments are most commonly based on prior knowledge, experience and historic practice. The choice of method is influenced by simplicity, cost and availability of data.

Blockage modelling is most frequently conducted using historical practice, rules of thumb or engineering judgement rather than written guidance. It draws on factors such as:

- historical data
- site observations
- structure type (for example, presence of piers)
- local knowledge
- experience
- perception of flood risk

The ‘Culvert Design and Operation Guide’ (Balkham et al. 2010) and the ‘Trash and Security Screen Guide’ (Environment Agency 2009) are used by some practitioners. The Office of Public Works (OPW) in Ireland recently developed an in-house screening and risk assessment process for culverts and screens (OPW 2013).

Few respondents cited guidance for the management of debris, but those who responded use:

- ‘Managing Woody Debris in Rivers, Streams and Floodplains’ (Mott 2005)
- Environment Agency Flood and Coastal Risk Management (FCRM) Maintenance Standards
- Environment Agency Operational Instructions for field teamwork
- case studies

Some respondents were unaware of existing guidance documents and so it is important that the new guidance is well disseminated.

## 2.4 User requirements

### 2.4.1 Blockage risk assessment

Users require guidance on blockage risk assessment to encompass a hierarchy of methods consistent with MDSF2 and FCERM-AG, with at least 2 methods as follows:

- high-level screening for strategic assessment of catchment risk and to help prioritise debris management compared to other interventions
- detailed assessment to help prioritise inspections, incident response, capital works and assessment of proposals

The guidance also needs to advise on how to assess:

- debris load, the probability of debris delivery, probability of blockage and the degree of blockage for different applications
- the impact of debris accumulations on assets (including large woody debris installations) and mapping the impacts
- debris management options and their impact on risk, to support the identification and allocation of funding

- the risk imposed by certain types of debris or large woody debris installations

### 2.4.2 Modelling guidance

Modelling guidance should advise on:

- suitable modelling tools and approaches
- choice of data and the implications for the final answer
- understanding and expressing uncertainty
- the degree of blockage for a range of applications, from strategic to the economic appraisal of capital, operation and maintenance works
- where and how to apply blockage management at a structure

Guidance on the economic appraisal of capital schemes should avoid distorting the choice of preferred option. The ‘do nothing’ option is often assessed using a high degree of blockage that is removed for the ‘do minimum’ option, giving significant benefits to ‘do minimum’. This can mean there is insufficient incremental benefit to justify further improvements or ‘do something’ options.

### 2.4.3 Catchment management

Catchment management guidance should cover:

- responsibilities and methods for handling natural debris and sediment, as well as man-made debris
- successful methods for reducing flooding caused by fly-tipping when enforcement proves unsuccessful
- how to assess the benefits and risks associated with woody debris installations, and particularly balancing infrastructure and biodiversity needs
- rapid, high-level assessment of catchments and systems at higher risk of blockage, resulting in a score that allows systems to be ranked in order of risk or receptor impacts
- how to assess the benefits of debris management and provide a robust business case for maintenance actions (planned and reactive)
- how to improve the justification of capital works to reduce flood risk

### 2.4.4 Data sources

Data used by practitioners to assess blockage risk are summarised in Table 2.2, together with potential sources.

**Table 2.2 Data used for blockage risk assessment**

| Factor | Influences | Data sources |
|---|---|---|
| Source (possible sources, volumes and types of debris) | Depends on catchment type and response time, length of contributing watercourse, adjacent land use | • Flood Estimation Handbook CD-ROM<br>• Ordnance Survey (OS) or online mapping<br>• Inspection and maintenance records<br>• Local knowledge<br>• Rules of thumb |
| Pathway (blockage mechanisms, potentially including likelihood or plausible scenarios) | Depends on flow, water level and velocity, size of debris relative to channel, location and dimensions of pinch points and structures | • Hydraulic model<br>• Asset management system<br>• Site observations<br>• Inspections under the Floods Directive and delegated legislation<br>• Local knowledge<br>• Blockage history<br>• Rules of thumb |
| Receptor (impact of increased flooding caused by the blockage) | Depends on number and type of properties and infrastructure affected by flooding | • Topographic survey<br>• Digital terrain model<br>• Flood outlines<br>• Environment Agency National Receptor Database<br>• Environment Agency National Property Database |

### 2.4.5 Generic requirements

General requirements were that the blockage management guide should provide:

- comprehensive guidance in a single document, but signposting and summarising rather than reproducing guidance readily available elsewhere
- consistent guidance for the flood risk management sector, meeting the needs of multiple organisations
- methods that are compatible with existing tools and approaches such as MDSF2
- guidance that is structured to reflect the asset life cycle
- short, concise, clear, simple and visually appealing guidance
- flow charts for clear, systematic choice of assessment approaches
- tables similar to those in ‘Flood Risk Assessment Guidance for New Development’ (FD2320) (Defra and Environment Agency 2005a) or ‘Flood Risks to People’ (FD2321) (Defra and Environment Agency 2005b)

- case studies and worked examples

### 2.4.6 Other requests

Respondents noted that partnerships with stakeholders are necessary to manage flood risks imposed by debris blockages effectively.

Although beyond the scope of the current work, a policy or strategy document would help to achieve this. There is also a need for a protocol for communication between inspecting organisations so that they can relate the presence of blockages that cause safety hazards effectively.

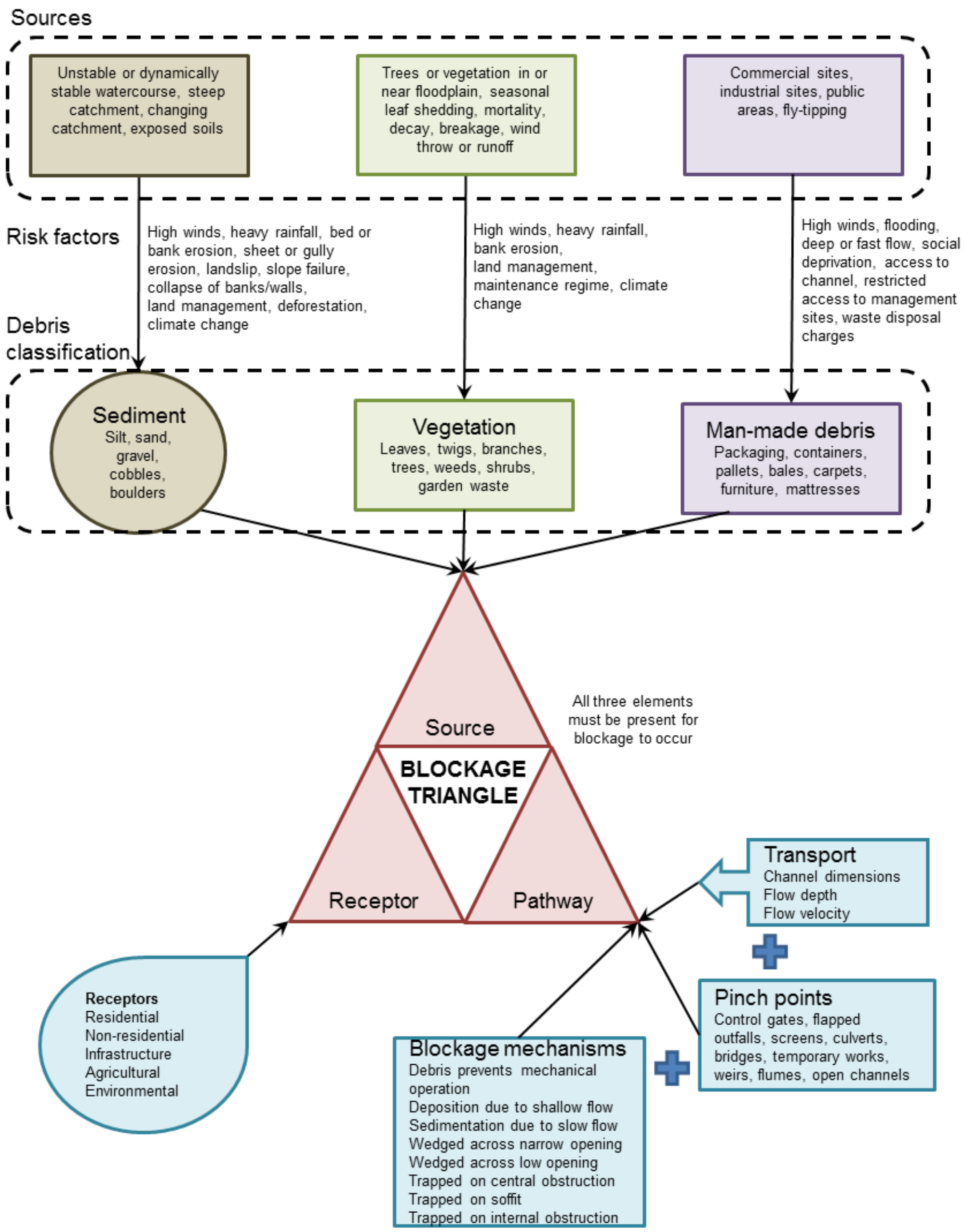
Environment Agency staff requested a single point of contact for modelling advice on debris and blockage.

# 3 Blockage processes

## 3.1 Introduction

The blockage process requires a source of the debris in the channel or on the floodplain, the transport of debris along the watercourse and the accumulation of debris at the structure or pinch point. The impacts of blockage are varied, but are dependent on the presence of a receptor. Figure 3.1 shows the blockage triangle of source, pathway and receptor which can be equated to the fire triangle of fuel, heat and oxygen. If one element is missing, the risk is low – either because blockage will not occur or it will not cause damage.

**Figure 3.1 Visual mapping of the blockage process**



## 3.2 Debris sources

Debris is defined as ‘any material moved by a flowing stream’ (FHWA 2001) and includes floating vegetation and sediment, as well as anthropogenic (man-made) materials.

Debris can be classified according to Table 3.1, which combines the UK classification of floating natural and man-made debris (Environment Agency 2009, Wallerstein and Arthur 2010), the British Soil Classification System and the US classification of sediment (FHWA 2005). Very small floating debris and floating ice are omitted; the former has little potential impact on pinch points while the latter is not often applicable in the UK. Potential sources of debris and risk factors are given in Table 3.2 and discussed overleaf.

**Table 3.1 Debris classification**

| Debris type | Classification | Description |
|---|---|---|
| Man-made | Domestic refuse | Packaging, small containers (cans, bottles, cartons), plastic bags |
| | Large household refuse | Furniture, mattresses, carpets |
| | Large non-domestic refuse | Cars, shopping trolleys, ladders, pallets, straw bales |
| Vegetation | Small vegetation | Leaves, twigs, garden waste, small branches, plants |
| | Large vegetation | Trees, large branches, shrubs, mats of weeds |
| Sediment | Fine sediment | Silts, sand, fine to medium gravel (up to 20mm diameter) |
| | Coarse sediment | Coarse gravel and cobbles (20–200mm diameter) |
| | Very coarse sediment | Boulders (>200mm diameter) |
| Debris | Debris flows | Combinations of vegetation and sediment |

**Table 3.2 Potential sources of debris**

| Debris type | Potential sources | Risk factors |
|---|---|---|
| Man-made | • Commercial sites<br>• Industrial sites<br>• Fly-tipping | • Access to channel<br>• Urbanisation<br>• Social deprivation<br>• Charging regime for disposal of waste<br>• Restricted access to waste disposal or recycling sites<br>• High winds<br>• Deep or fast flow<br>• Flooding<br>• Use of shrink-wrapped round balers |

| Debris type | Potential sources | Risk factors |
|---|---|---|
| Vegetation | • Seasonal leaf shedding<br>• Decay or breakage<br>• Floodplain vegetation<br>• Local run-off<br>• Wind action<br>• Wind throw or collapse<br>• Bank erosion | • Steep catchment<br>• Wooded catchment<br>• High winds<br>• Heavy rainfall<br>• Land management<br>• Maintenance regime<br>• Climate change |
| Sediment | • Bed and bank erosion<br>• Collapse of banks/walls<br>• Sheet erosion<br>• Gully erosion<br>• Slope failure<br>• Landslips<br>• Catchment changes | • Steep catchment<br>• Steep watercourse<br>• Unstable watercourse<br>• Land use<br>• Agricultural practices<br>• Deforestation<br>• Climate change |

### 3.2.1 Man-made materials

Man-made materials with the potential to cause blockage are most likely to arise from refuse, fly-tipping or litter. Refuse is any household or commercial waste or rubbish, including fly-tipped waste, while fly-tipping is the illegal disposal of waste. Litter is materials – often associated with smoking, eating and drinking – that are improperly discarded and left by members of the public, or spilt during business or waste management operations. In this report, the terms 'man-made material' and 'refuse' are used interchangeably, although strictly refuse is a subset of man-made material.

Refuse arises when man-made objects or debris in the floodplain are mobilised and transported to a structure (Haehnel and Daly 2002). This may be caused by the transport of materials from other land by the wind, or the collapse of structures in the floodplain such as river walls. Factors affecting debris load can include whether supermarkets near the river have a deposit scheme for trolleys, restrictions on access to public recycling or waste disposal sites, charging regimes for disposal of waste and the availability of collection centres.

Man-made materials that have not been deliberately dumped such as wheelie bins, pallets and packaging materials can also be washed or blown into a channel during high winds or flood conditions. In rural areas, shrink-wrapped round bales are larger and more buoyant than traditional rectangular bales – and often just the right size to plug a culvert or single arch bridge!

Webb et al. (2006) investigated the causes of fly-tipping (and hence potential sources of refuse) by examining data such as the Flycapture database of fly-tipping incidents in England, police records, a household survey, and interviews with offenders and tradespeople. A survey of waste collection and disposal authorities in England revealed that the most important drivers for fly-tipping were the costs of legitimate disposal and the availability of civic amenity and other waste disposal sites. Some trends were observed:

- Seasonality – less fly-tipping in the winter months
- Locality – higher rates of fly-tipping were found in more densely populated areas, especially where these suffered from multiple deprivation; indicators of this were found to be ‘overcrowding, poverty and unemployment’
- Quantity – typically relatively small (a boot or small van full)
- Type – most common is household waste, hazardous waste is relatively rarely fly-tipped

The Flycapture database recorded 1.1 million incidents of fly-tipping during a 12-month period from July 2004 to June 2005, although the reliability and validity of the data have been questioned as the database was launched just a few months earlier and there was a steep learning curve.

### 3.2.2 Vegetation

Vegetation arises from materials present in the watercourse or floodplain, released by bank erosion or washed or blown into the floodplain.

Modelling approaches to estimate the input of coarse woody debris from trees close to the riverbank exist in the USA (McDade et al. 1990, Robison and Beschta 1990, van Sickle and Gregory 1990; among others cited in Gurnell et al. 1995). The methods are based on different factors such as the tree height, the size and character of the forest, and decay rates in the channel. Care must be taken, however, when applying these methods in the UK as the ‘rafts’ of large woody debris seen in the USA are very uncommon in the UK due to its less densely wooded catchments and different commercial forestry practices.

Regression analysis has been carried out to identify the primary factors that describe the delivery of debris at a site (Piégay and Gurnell 1997, Braudrick and Grant 2000, Rigby et al. 2002, Wallerstein et al. 2010). Factors such as braiding index, presence of wooded islands, seasonality, total annual rainfall and social deprivation were identified as significant factors in various studies (Piégay and Gurnell 1997, Wallerstein and Arthur, 2012d.

Young (1991) used flume experiments to examine the effect of different amounts and orientations of coarse woody debris on flood levels in lowland rivers and found that debris orientation had a more significant effect on water levels than debris volume.

The stream size and channel roughness influence the mobility of different sizes of coarse woody debris and hence the permeability of debris dams which may build up.

Diehl and Bryan (1993) studied 12 sites and 51km of channel reaches in Tennessee, USA, to determine the amount of large woody debris, of at least 1.5m length, that could be transported to bridges. It was found that debris production can be associated with bank instability and that it is possible to identify areas likely to have a high potential for debris production by looking for signs of bank erosion such as lateral channel migration and widening (which can be detected on aerial photographs and maps), high, steep banks and the presence of erodible bank materials.

Gurnell et al (1995) noted that debris delivery is a complex system that may change over time. For example, the presence of a debris dam may cause ponding on the river banks, leading to changes in vegetation growth and changes in the nature of the coarse woody debris input to the river.

FHWA (2001) suggested a field investigation to examine the impact on debris delivery of:

- stream velocity, slope and alignment
- the presence of shrubs and trees on eroding banks
- watershed land uses, particularly logging, cultivation and construction
- stream susceptibility to flash flooding
- storage of debris and materials within the flood plain (logs, lumber, solid waste and so on)

The FHWA report provided equations for head loss through in-line structures such as screens and recommended that debris build-up potential is taken into account. It also recommended that the reduction of blockage risk should also be taken into account in preliminary design decisions.

FHWA (2012b) provided guidelines for identifying stream stability problems at highway crossings and estimating debris production, transport and delivery potential using the three-phase structure devised by Diehl (1997). The report provides a decision process for assigning a high or low classification for the potential for debris production. The maximum size of potential debris delivered to a structure depends on the stream's ability to transport the debris and is mainly influenced by the width of the channel which gives a maximum bound for transportable debris. Alternatively, the length of the longest observed debris in the watercourse can be used as maximum design log length.

### 3.2.3 Sediment

Sediment can be defined as granular and non-cohesive (for example, cobbles, gravel and sand) or cohesive (silt and clay). Granular sediments are mobilised when the lift and drag forces imposed by the flow exceed the resisting force due to weight and friction due to contact with adjacent particles. Cohesive sediments have some cohesion due to clay content (or biological action) and therefore require greater forces to mobilise particles.

Table 3.3 summarises the factors that influence sediment supply.

**Table 3.3 Factors influencing sediment supply**

| Type | Variable | Risk factors |
|---|---|---|
| Weather | Rainfall intensity | Intense rainfall mobilises soil particles |
| | Average monthly rainfall | High rainfall run-off transports particles to river |
| | Average annual rainfall | Saturated antecedent conditions increases run-off |
| Land | Solid geology | Impermeable – more overland flow and soil erosion |
| | Soil type | Light, sandy soils – readily eroded |
| | Catchment altitude | Upland catchment – 70% of area above 300m above Ordnance Datum (AOD) |
| | Slope | Steep slopes (>7º) |
| | Wind erosion | Fine, sandy soils and exposed drained peaty soils particularly at risk |

| Type | Variable | Risk factors |
|---|---|---|
| Channel | Flashiness | Flashy watercourse - higher energy to erode and transport |
| | Channel characteristics | Dense stream network or meandering channel |
| | Natural bank erosion | Active erosion |
| | Dredging | Dredging of material can re-mobilise sediment or remove ‘armour’ layers leading to increased supply of sediment |
| Land use | Agricultural | Bare soil, large fields, grazing, high risk crops, over-wintering stock, land drainage |
| | Industrial | Natural erosion, engineered channels, flood defences, dredging |
| | Urban | Roads, urban drainage |

Note: After Environment Agency (2011a)

For granular sediments, the critical velocity (the flow velocity required to cause movement) is related to the particle size, shape, density, packing and orientation in the bed, as well as the depth and turbulence of the flow. The critical velocity is difficult to define mathematically, so the thresholds of erosion and deposition are typically based on empirical relationships. Two of the most well-known are the Shields diagram, which relates a non-dimensional grain diameter to the non-dimensional critical bed shear stress for motion of the particle, and the Hjülstrom curve, which gives boundaries for erosion, transportation and sedimentation based on mean flow velocity and grain size. Mobilisation of cohesive sediments takes larger mobilising forces to overcome the resistance provided by cohesion.

Several empirical relationships have been developed between critical shear stress and bulk density of cohesive sediments (for example, Hwang and Mehta 1989, van Rijn 1993; quoted in USBR 2006). Tables of erosion rate parameters are provided where the critical shear stress for surface erosion is given for different soil types and bulk densities (quoted in USBR 2006). However, their application should be treated with care as none of the studies are deemed to have successfully linked mechanical properties to the erosion properties (USBR 2006).

## 3.3 Debris transport

### 3.3.1 Man-made materials

This study found little research into the transport of man-made material or refuse, although the accumulation of debris (including refuse) at screens was examined by the Flood Risk Management Research Consortium Phase 2 (FRMRC2) (Wallerstein and Arthur 2012c) and the hazard to people due to floating debris was considered to vary with flow depth (Defra and Environment Agency 2005b).

### 3.3.2 Vegetation

Much of the research concerning the transport and accumulation of debris has been carried out in the USA and therefore concerns the transport of drift (large woody debris) and large rafts of large woody debris that can develop on watercourses in heavily wooded catchments. Rivers in the UK do not tend to develop these large rafts.

The delivery of debris in terms of both frequency and type depends on: the channel's ability to transport debris; the geometry, volume and density of the debris; and the depth and velocity of the flow (Haehnel and Daly, 2002). Critical variables are:

- the relationship between the length of the debris and the channel width
- the ratio between debris diameter and flow depth
- the orientation of the debris within the channel and the channel slope

The main transport mechanism of large woody debris differed depending on the relative size of the debris and channel (Lagasse et al. 2010) or the ratio of channel to boundary particle size (Piégay and Gurnell 1997). The stream size affects the likelihood and frequency of debris transport, and the nature of debris accumulation. In smaller streams, debris tends to be longer than the channel width and is mobilised only during high flow events. In larger streams, debris is shorter than the channel width and mobilised more easily. The regular flushing of small pieces reduces the frequency of accumulations.

Woody debris is mostly transported at the water surface and where flow is deepest and fastest; this typically coincides with the thalweg of the stream (Diehl 1997, Parola et al. 2000). Large woody debris is expected to be transported with the long dimension of its trunk parallel to the flow. Submerged debris, on the other hand, is transported near the bed at a slower velocity and often comes to rest before a structure (Diehl 1997).

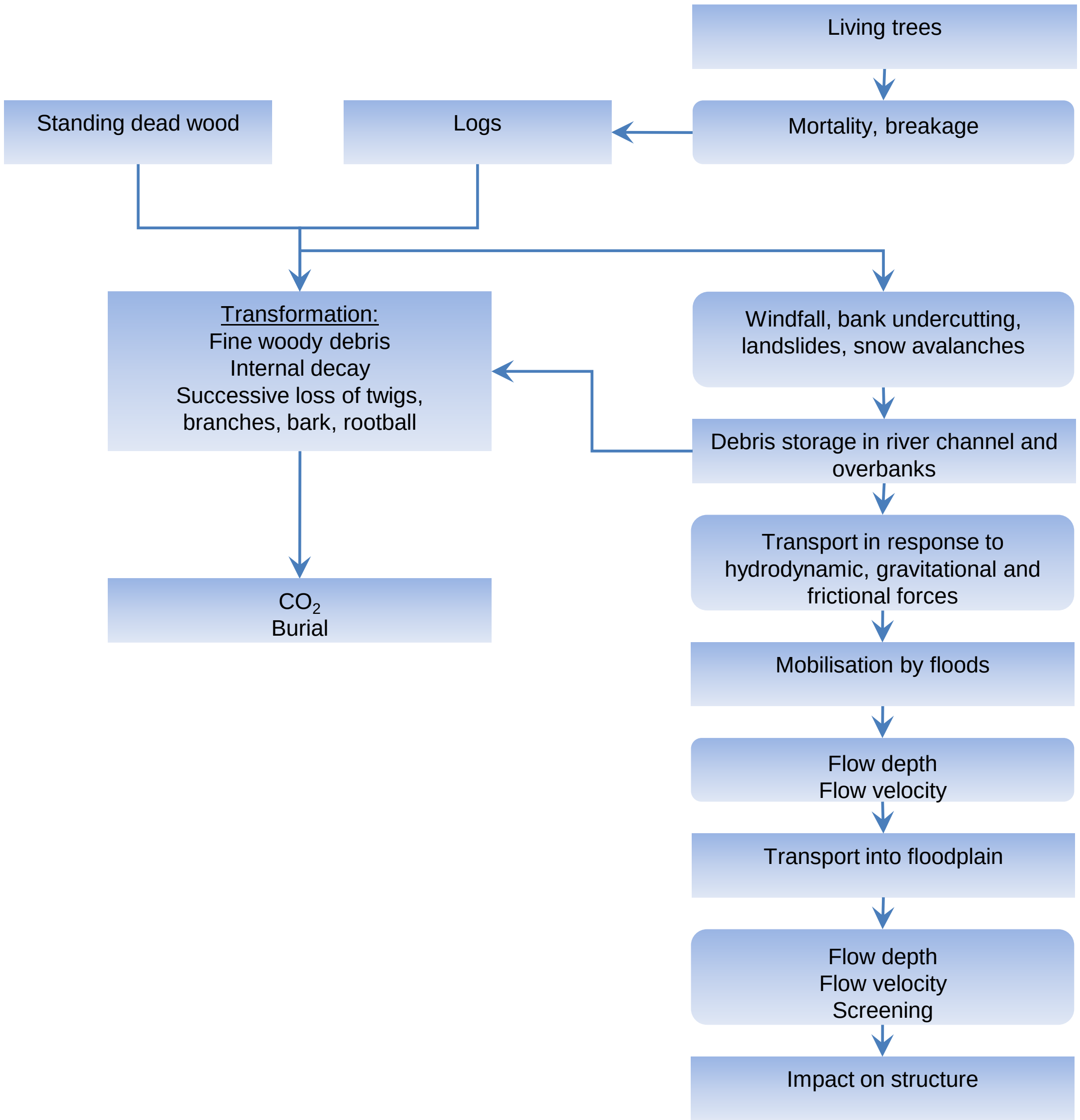
Haehnel and Daly (2002) illustrated the blockage process for natural debris (Figure 3.2) and identified 3 modes of transport for large woody debris, depending on the flow depth:

- Shallow flow – insufficient to float large woody debris
- Intermediate flow – debris floats but portions of the rootball or branches may be in continual contact with the bed (contact will develop friction forces with the bed that will reduce the transport velocity of the debris compared with the flow velocity)
- Full flow – large woody debris not in any substantial contact with the bed and transported at the flow velocity

Braudrick et al (1997) carried out preliminary work to define a flotation threshold for the entrainment of wood, similar to the critical shear stress threshold used in sediment transport. Flume experiments showed that large woody debris can be transported in uncongested, semi-congested or congested flow patterns. In intermediate channels (debris in contact with bed), drift is transported in large logjams which may be deposited and cause blockages throughout the channel (though these are not likely in the UK).

Debris accumulations that rotate off piers may travel as large mats (Parola et al. 2000).

**Figure 3.2 Blockage process for natural debris**




Source: Haehnel and Daly (2002)

### 3.3.3 Sediment

As might be expected, the majority of sediment is transported during high flow events (Ho et al. 2013). Although some authors argue that recruitment, transport and accumulation is a random process, others suggest that there are complex non-linear processes which describe this (Parola et al. 2000, Lyn et al. 2006). Opinions vary as to the drivers and primary factors of the process. According to Lagasse et al. (2010) these include:

- channel meandering
- attendant bank undercutting
- mass failure
- input of trees

- landslides
- debris flows
- reach stability
- channel sinuosity

Sediment transport and deposition can be widespread or local; there are 3 modes of sediment transport (Sear et al. 2003):

- Bedload – coarse sediment (fine sand or larger) transported along the river bed by rolling, sliding and/or saltation (hopping)
- Suspended load – finer material (clay, silt or sand) carried in suspension; sediment load increases with discharge to the point at which supplies become exhausted
- Dissolved (or wash) load – the finest particles carried in near-permanent suspension

Regime flow occurs when erosion and deposition are in equilibrium in a watercourse. Aggradation or degradation are long-term, widespread changes, perhaps over a decade or a century, which affect the longitudinal profile of a watercourse. They normally occur as a series of progressive steps, predominantly during floods, but exclude the more localised effects of scour during a particular flood event. This can be the result of an imbalance between sediment supply and sediment transport capacity, arising from natural and/or man-made changes in the catchment or watercourse such as natural morphological changes such as meander progression, deforestation, urbanisation, land drainage, inter-basin transfers and the removal of an upstream structure (for example, a reservoir, weir or bridge).

The mechanism can be expressed as (Sear et al. 2003):

Sediment supply > sediment transport = sediment storage (or deposition)

Sediment transport > sediment supply = sediment removal (or scour)

## 3.4 Blockage mechanisms

Blockage can occur in channels and at structures such as screens, culverts, bridges, control gates, flap valves, weirs and flumes. Blockage mechanisms for a range of blockage-susceptible asset types are summarised in Table 3.4. It can be seen that screens, flapped outfalls and control gates have unique combinations of blockage mechanisms. However, unscreened culverts, bridges and temporary works are susceptible to similar blockage mechanisms, as are weirs, flumes and open channels.

Haehnel and Daly (2002) noted that blockage risk is influenced by the ratios between the size of the opening in a structure and the effective diameter of the large woody debris. If the spacing between structure supports is less than or equal to either diameter, the structure will be effective in keeping large woody debris from passing through (though this does somewhat state the obvious). Blockage may also occur at structures that produce a bend in the water flow with a radius of curvature that is less than or equal to the length of the large woody debris.

Environment Agency (2004a) identified that blockage risk is influenced by factors such as:

- the width or height of an opening

- opening ratio (the ratio between the cross-sectional area of the structure and the channel upstream)
- angle of flow approach
- shape of structure
- changes in width or height along a structure's length
- obstructions (for example, service crossings, protruding structural elements)
- failure of the structure (for example, partial collapse, gates becoming inoperable)
- maintenance regime

**Table 3.4 Blockage mechanisms by asset type**

| | Blockage mechanism | Control gate | Flap valves | Screen | Culvert | Bridge | Temporary works | Weir | Flume | Open channel |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | Debris prevents mechanical operation | Y | Y | – | – | – | – | – | – | – |
| 2 | Debris trapped on central obstruction | Y | – | Y | Y | Y | Y | – | – | – |
| 3 | Debris trapped on internal obstruction | – | – | – | Y | Y | Y | – | – | – |
| 4 | Debris wedged across narrow opening | Y | Y | Y | Y | Y | Y | Y | Y | Y |
| 5 | Debris wedged across low opening | Y | Y | Y | Y | Y | Y | – | – | – |
| 6 | Debris trapped on soffit | Y | Y | – | Y | Y | Y | – | – | – |
| 7 | Deposition due to shallow flow | – | – | – | Y | Y | Y | Y | Y | Y |
| 8 | Sedimentation due to slow flow | – | Y | – | Y | Y | Y | Y | Y | Y |

### 3.4.1 Control gates

Control gates are used to control flow and water levels for flood risk management, navigation and abstraction. Blockage at control gates is influenced by factors such as gate type and size, operating rules (a single large opening is better than several small openings) and snagging points on the gate or adjacent structures (ASCE 2012).

Deep undershot gates are ineffective at passing floating debris when partly open but effective at sluicing sediment, while overshot gates can be effective at passing debris. Vertical and radial gates may pass floating debris, depending on the vertical clearance between the water surface and gate when fully open.

Blockage can occur at any time due to events such as fly-tipping or bank erosion, although the likelihood is substantially increased during flood events and high winds, which can blow materials such as sand from the river banks into the channel.

Blockage is often initiated by large debris such as trees, which then allow the accumulation of smaller debris such as grasses and weeds. Where there is tidal flow, gates may be subject to siltation.

### 3.4.2 Flap valves

Flap (or non-return) valves are fitted to culverts and pipes to prevent reverse flow at times of high downstream water level – typically during floods or high tide.

Sedimentation (for example, due to an accreting estuary) can accumulate downstream and prevent opening of the valve. Debris arising from the discharging or receiving watercourse can also block top-hinged flap gates in the open or closed position. Side-hinged (mitre) gates are reported to be less susceptible to blockage due to the wide opening. As for control gates, debris accumulations are often initiated by a larger piece of debris, which in turn has the ability to trap smaller debris. Blockage can occur at any time but the likelihood is increased during storm events.

Elastomeric check valves (such as Tideflex or WaStop) are squeezed open under a positive head difference and seal against an adverse head. These valves are reported to convey very small debris only. Periodic removal of larger debris is required and manual removal is reported to be difficult (Juel Tide Gates 2010).

### 3.4.3 Screens

Trash screens are installed at a culvert inlet to trap debris and prevent internal blockage that might be difficult to remove. Security screens may be installed at both the inlet and outlet to prevent access by unauthorised persons. Trash and security screens are similar in design, the main difference being that the bar spacing of trash screens needs only be wide enough to trap debris with the potential to cause blockage whereas security screens must have a clear bar spacing of 140mm or less.

Screens play an important role in protecting assets such as pumping stations, which are costly to replace or repair, from blockage by floating weeds or debris. These cause a drawdown effect when pumping water out of low-lying land which attracts debris to the screen. The weight of the debris can cause significant damage to the screen.

Blockage of screens occurs when debris bridges across 2 or more bars, balances across one bar, or becomes wedged between 2 bars, a bar and sidewall or the headwall (Wallerstein et al. 2013). Floating debris tends to accumulate at the water surface and fill down to the bed, sometimes creating a near-impermeable barrier to flow. If the screen angle is shallow, debris can ride up the screen onto the working platform during flood conditions. Large items of refuse such as mattresses or small sheet materials such as posters can block a screen quickly.

Factors such as debris length, bar spacing, screen position and bar angle (rake) have been identified as significant factors in blockage potential (Wallerstein et al. 2013). Research has shown that the probability of blockage decreases slightly, the closer a screen is to the culvert inlet, as faster flow near the culvert inlet is more likely to carry material past the screen.

### 3.4.4 Culverts, bridges and temporary works

*Culverts*

Culverts are covered channels or pipes that prevent the obstruction of a watercourse or drainage path by an artificial construction (Flood and Water Management Act 2010). A culvert generally has an integral invert (bed), walls and soffit (roof); hydraulically, a conduit is a culvert when the ratio of its length to the height of the opening is >5.

Many culverts in the UK have been built piecemeal over time, leading to multiple ownership and many changes in cross-section. Blockage mechanisms for culverts are many and varied. Debris can become wedged across the inlet or against an internal obstruction such as service crossings, steps, bends or changes in cross-section. Sediment can also accumulate within the barrel or upstream at areas of slow flow or stagnation, although good culvert design would generally aim for a barrel flow velocity sufficient to maintain equilibrium between erosion and deposition in the barrel. Research in Australia into blockage at culverts showed that structures with opening dimensions less than 6m were more prone to blockage during flood conditions than larger openings (Rigby et al. 2002).

The prediction of bed load transport and sediment deposition in culverts is subject to some uncertainty due to the difference between open channel flow and pipe (pressure) flow, as well as the complication of flow conditions at the inlet and outlet (Goodridge 2009). Some design tools based on research into homogenous flows are reported to incorrectly predict deposition in culverts for larger particle sizes.

*Bridges*

Blockage at bridges has been widely studied in the USA, Australia and New Zealand, albeit often with the aim of assessing impact on scour rather than flood risk.

There are 3 main types of debris accumulation:

- single pier accumulations
- blocked bridge spans
- deck accumulation

Pier accumulations are more likely to occur at blunt piers, piers on the outside of bends and piers in the thalweg of the stream, although research findings were not unanimous on the last point (Lyn et al. 2006). As expected, short spans block more frequently than large spans (Lyn et al. 2006).

Debris may become trapped on the bridge deck unless the freeboard between the flood level and the soffit is sufficient to allow debris to pass freely below the structure. In the UK, a freeboard of 600mm is recommended for highway bridges in ‘The Design Manual for Roads and Bridges’ (Highways England 2012).

It is thought that the potential for a bridge to trap debris is affected by ‘tree height, trunk diameter, canopy or root bole diameter (whichever is greater), and pier span distance’ Downs and Simon 2001; quoted in Lagasse et al. 2010) as well as ‘the placement, type and skew of bridge piers’ (Lagasse et al. 2012).

Sedimentation and debris accumulation can occur in areas of slow or stagnant flow - typically outer spans or the inside of bends.

*Temporary works*

Temporary works such as cofferdams or scaffolding may be constructed in or above a watercourse to provide a dry working area or safe working platform for survey, construction or maintenance works to structures or their foundations. These can narrow the watercourse or reduce freeboard, change flow presentation to structures and trap debris. This occurred at the Dodder underbridge near Dublin in 2012.

### 3.4.5 Weirs, flumes and open channels

Weirs are raised structures in an open channel used to control grade and water levels for offtakes, amenity and navigation, and often for flow gauging. Deep, slow flow upstream of a weir can lead to sediment accumulation, while shallow flow over the weir crest and apron can trap debris.

Flumes are open channel structures with a narrow throat, and sometimes a raised bed, typically used for flow measurement or control (for example, to divert flow to flood storage or at abstraction points). The transition to the throat is generally streamlined, with gradual reduction in width and/or depth, and flow through the throat is critical with a known stage–discharge relationship. Debris may accumulate at the throat of flumes due to the reduction in width and flow depth, but the flumes should be capable of passing small debris (Environment Agency 2010a).

Blockage in open channels can occur when the stream velocity drops below the threshold velocity for the deposition of sediment, typically due to a change in the cross-section of the channel. Sedimentation may occur in areas of local stagnation, for example, downstream of bends or at culverts with skew approach flow.

Piégay and Gurnell (1997) found that debris that extends above the water surface is likely to be deposited in shallow water as the hydraulic force of the flow available to overcome the weight of debris is reduced. A study of 76 dams in the USA showed that, in small to medium channels, large woody debris accumulates as transverse dams, spanning the entire channel, or even beyond it on the bank. In smaller streams, large woody debris accumulations are fairly unstructured as medium to large pieces of wood cannot be transported and therefore lie where they fall. However, smaller debris may form fairly compact, small, dams. Larger channels are capable of mobilising large debris and forming large accumulations of large woody debris, which can be classed as active dams, complete dams and partial dams.

Parola et al. (2000) noted that vegetation tends to remain in transport until secondary currents transport it into slack water or floodplain vegetation, or it is caught on an obstacle, lodged against other vegetation along stream banks, or beached as a result of local change in flow depth or recession of floodwaters.

## 3.5 Impacts of blockage

The short-term impacts associated with blockage are summarised below.

- Increased flood risk due to reduced conveyance capacity and increased upstream water levels. This can increase flood depths and flood risk at receptors already within the floodplain, and/or increase flood risk at new receptors due to greater flood extents.
- Increased flood risk due to blockage preventing the operation of control gates or flap valves, leading to unwanted backflow. A gate may become

stuck due to changes in the centre of gravity, additional weight or debris jammed between the gate and its guides, leading to misalignment and differential movement. Debris or sediment blocking the inlet to a float chamber may prevent the operation of a drum gate. Siltation can wedge a gate open or shut.

- Flood risk can arise due to bulking of the flow by air, debris or sediment entrainment.
- Saturation, seepage and percolation can lead to structural failure of earth embankments.
- Structural failure – increased mobilising forces on a structure due to debris impact, hydrostatic pressure and hydrodynamic forces (such as drag and lift) as the water level approaches the soffit level of a structure. This can cause structural failure by uplift, sliding or rotation, or the deformation of structural elements (Kirby et al. 2015).
- Abstraction – sedimentation of pump screens can restrict the volume of water which can be abstracted.
- Scour – reduced flow area can cause backwater upstream of a blockage, acceleration through the opening and erosion of the stream bed and banks. Local increases in velocity and turbulence, possibly with changes in flow patterns can increase local scour and lead to foundation undermining and structural failure. Flow can also be diverted towards other structural elements such as river walls.
- Weir or dam failure – blockage of weir and dam spillways can raise the retained water level, possibly threatening the security of the water-retaining structure. The sudden release of a large debris raft over a spillway may damage infrastructure crossings downstream (Engineers Australia 2013).
- Failure of temporary works – reduced freeboard or flow area due to temporary works such as scaffolding or a cofferdam can trap debris, leading to excessive loading on a temporary structure.
- Obstruction to navigation – blockages can obstruct passage, either by limiting navigable width or reducing the draught available to boats. On informal navigable watercourses, full-width blockages such as strainers convey water but obstruct passage by water users such as kayakers, leading to entrapment, injury or death.
- Loss of public confidence – blockage is usually highly visible and quickly noticed by the general public. If flooding occurs, a link is quickly made between the two. The presence of blockages and apparent failure to remove them in a timely fashion is often taken as an indicator of a ‘failure’ to manage flood risk.

In the long term, the impacts of blockage can include:

- **Infill blockage**. Once a blockage has formed, sediment, small woody debris and man-made materials can fill in the spaces within the initial debris, increasing the degree of blockage (Parola et al. 2000; quoted in Lagasse et al. 2010).
- **Sedimentation**. Blockages that remain in place for long periods of time can induce the formation of bars or islands (Lagasse et al. 2010).

- **Debris management costs**. Inspection and maintenance can impose a cost burden on asset owners. Responses may involve removing or moving debris from a pinch point or the catchment upstream, or the installation of structures such as screens or debris deflectors to reduce the risk of blockage.
- **Habitat**. Blockages create local changes in water velocity, with slower flow and sedimentation upstream and faster flow and scour downstream. Over time, this creates a more diverse habitat for spawning fish and emergent vegetation, such as deep pools, shallow gravel beds and silt banks; still backwaters and fast water; and shady areas with lower water temperatures.
- **Water quality improvements**. Large woody debris tends to accumulate leaf litter and smaller debris which provides habitat and food for invertebrates, improving water quality, ecological potential and invertebrates (Ing 2011, Pinto 2013).
- **Flood attenuation**. Debris dams where appropriately designed and managed may also attenuate flood peaks.

Thus it can be seen that the impacts of blockage can be both negative and positive.

# 4 Literature review

## 4.1 Introduction

This chapter presents the findings of a literature review into the source–pathway–receptor approach to debris blockage. Table 4.1 summarises the sources and their outputs. The findings are discussed in Sections 4.2 to 4.6, with the full methods given in Chapter 5. Tools for modelling blockage are discussed in Section 4.7 and catchment management methods in Section 4.8.

**Table 4.1 Summary of literature review by asset type**

| Asset type | References | Outputs | Data sources (country/region) |
|---|---|---|---|
| **All structures** (Section 4.2) | Magenis and successors<br>Magenis (1988)<br>NRA (1992)<br>Environment Agency (2002, 2009)<br>Balkham et al. (2010) | Method for predicting debris volume arriving at a structure | Thames catchment |
| | Engineers Australia (2009, 2013, 2015) | Methods for estimating degree of blockage at bridges and culverts | Australia |
| | Schmocker and Weitbrecht (2013) | Method for predicting debris volume arriving at a structure | Switzerland, Japan & USA |
| **Screens** (Section 4.3) | FRMRC2<br>Wallerstein et al. (2009, 2010, 2013)<br>Wallerstein and Arthur (2012a, 2012b, 2012c)<br>Streftaris et al. (2013) | Methods for predicting probability and degree of blockage at screens | Belfast |
| **Culverts** (Section 4.4) | Environment Agency (1998, 2004c) | Procedure for assessing probability of blockage at culverts | UK |
| | FHWA (1990) | Guidance on taking debris into account during design | USA |
| | Vassilios and Tsihrintzis (1995) | Study of sedimentation in a long culvert | USA |
| | Molinas and Koester (2001) | Comparison of debris flow modelling methods | USA |
| | Rigby et al. (2002) | Study of cause and effect of culvert blockage during large storms | Australia |

| Asset type | References | Outputs | Data sources (country/region) |
|---|---|---|---|
| | TRTA (2011) | Qualitative risk assessment method | Australia |
| **Bridges**<br>(Section 4.5) | RSSB (2004, 2005) | Method for predicting debris blockage potential (based on Environment Agency 1998) | UK |
| | Melville and Dongol (1992) | Equation for effective width of bridge piers with debris accumulation | USA |
| | Diehl (1997) | Methods for predicting blockage area at bridge piers, bridge decks, and narrow or low openings | USA |
| | SANRAL (2002) | Guidance on blockage at bridge piers | Unknown |
| | New Zealand Transport Agency (2003) | Guidance on blockage at bridge piers | Unknown |
| | Lyn et al. (2006) | Design guidelines for new bridges to reduce debris accumulation at piers | USA |
| | Lagasse et al. (2010) | Guidelines for blockage assessment | USA |
| **Open channel**<br>(Section 4.6) | Piégay and Gurnell (1997) | Impact of channel size and geomorphology on large woody debris build-up | South-east France<br>Southern England |

## 4.2 All structures

### 4.2.1 Magenis (1988)

Magenis devised an empirical method for estimating debris load and sizing screens using 10 years of data on screens in the Thames catchment. The ratio between screen area and culvert area was obtained for 31 screens and the volume of debris for 17 screens. Despite being based on limited data, the method has performed reasonably well and is still in use today (see Section 4.2.4).

### 4.2.2 NRA (1992)

The ‘Design and Operation of Trash Screens’ published by the Environment Agency’s predecessor, the National Rivers Authority (NRA), aimed to communicate best practice design and authority policy, and minimise the NRA’s liability. The lack of literature and research was identified and further work was recommended, including the production of a detailed design manual.

### 4.2.3 Environment Agency (2002)

The 'Trash Screens Design and Operation Manual' replaced the 1992 NRA guide and provided a method for estimating annual debris load arriving at a structure and blockage risk based on Magenis (1988).

### 4.2.4 Environment Agency (2009)

The Trash and Security Screen Guide replaced the 2002 guide and gives a method for estimating annual debris load arriving at a structure and blockage risk. The guide recommends using site-specific data where these are available for a reasonable length of time (say 2 years). An evidence-based method is provided for the design of new screens where little or no site data are available, based on Magenis (1988).

### 4.2.5 Balkham et al. (2010)

CIRIA's Culvert Design and Operation Guide reproduces the method in Environment Agency (2009); the 2 guides were prepared in parallel and intended to be consistent. No new data were gathered for the guide and it incorporates neither the latest research from FRMRC2)nor the specific approaches required to assess risk using MDSF2 or the Risk Assessment Field-based Tool (RAFT). The guide comments on factors that can affect sediment load but no quantitative advice is given.

### 4.2.6 Engineers Australia (2009)

This report was the first of two aimed at improving blockage risk guidance in Australia. The standard approach to modelling flooding assumed a no blockage or 'all clear' scenario, with local knowledge applied inconsistently when designing new structures. One exception was the guidance produced by Wollongong City Council, which utilised data from 2 historic floods to derive blockage factors for structures.

This Stage 1 report described blockage processes, the approaches used to analyse blockage, and the management and maintenance methods employed to mitigate associated flood risk. It outlined the potential locations and types of blockage, and the classification of the types, availability and mobility of debris that could cause blockage.

The impact of site-specific features, such as inlet features and handrails, on blockage likelihood and the subsequent hydraulic, economic, social and environment impacts were discussed and the considerations that local engineers should take into account summarised.

The report also summarised equations for hydraulic analysis of blockage and design considerations for hydraulic structures and noted that conflicting recommendations emphasise the uncertainty in the results from various blockage analyses. The lack of data to support qualitative assertions was highlighted and recommendations for further research were given (see Section 4.2.7).

### 4.2.7 Engineers Australia (2013 and 2015)

The Stage 2 report (2013) and subsequent 'Blockage Guidelines for Culverts and Small Bridges' presented good practice guidance for application across Australia.

The guide takes into account up-to-date research, including additional detail regarding debris dimensions for classification, formulation of blockage mechanisms and the inclusion of the effect of windstorms and event magnitude on debris availability and mobility. The findings of research by Rigby and Barthelmess (2011) on the effects of blockage timing on the release of discharge from hydraulic structures are incorporated into a table relating the debris type with the likely timing of peak debris mobilisation.

The guide recommends hydraulic assessment of 3 blockage conditions – all clear, design blockage and twice the design blockage (up to 100%) – to identify sites where flood risk upstream or downstream of the structure is particularly sensitive to the degree of blockage.

The guide gives a procedure for assessing the degree of blockage at waterway structures. The debris availability, mobility, transportability and debris potential are classed as high, medium or low. This is then adjusted for flood magnitude and translated into a design blockage level (as a percentage of opening area). The guide advocates reflecting observed blockage where data are available.

Although its Australian origin means that not all the quantitative outcomes from this study are likely to be of use in the UK, the philosophy of the 2 blockage assessment schemes could be applied to the blockage management guide.

### 4.2.8 Schmocker and Weitbrecht (2013)

Schmocker and Weitbrecht (2013) of the Swiss Federal Institute of Technology (ETH) devised a method for estimating the volume of debris using a debris balance sheet showing inputs and deposition locations along a 140km length of river. The study examined the available wood stock per hectare along the watercourse and the proportion of that area that with the potential to contribute to debris load, either due to bank erosion, landslides or being in the floodplain.

## 4.3 Blockage at screens

### 4.3.1 FRMRC2

FRMRC2 promoted research into the prediction and management of flood risk associated with trash screens at culverts as part of a multi-disciplinary programme of work. FRMRC2 was funded by the UK Engineering and Physical Sciences Research Council (EPSRC), with co-funders including the Environment Agency, Rivers Agency Northern Ireland and the Office of Public Works, Ireland.

The work aimed to develop a model to estimate:

- the rate at which debris (natural and anthropogenic) reaches blockable structures (that is, culverts and bridges)
- the extent of any blockage
- the probability of a blockage occurring
- the type of material that causes blockage
- the uncertainty associated with the methods

The Rivers Agency Northern Ireland provided data for 140 screens around Belfast Lough. Asset maintenance staff made a total of 25,265 observations between April 2002 and October 2008, inspecting each screen roughly every 7 days throughout this period to remove all material blocking the screen and recording the percentage of the screen area blocked by debris and a breakdown of the composition of that material. These screens were a subset of the 459 maintained by the Rivers Agency and chosen as critical screens with an annual average blocked area of 10%. This was the most comprehensive dataset identified during the course of this literature review. In particular, it includes data for when screens did not have debris – often missing from such datasets.

In the study, debris refers to organic and anthropogenic materials but excludes sediment. Land use in the study area ranged from agricultural and open moorland to more developed suburban, urbanised and industrial areas. The watercourses have been modified to varying degrees. In low-lying and suburban areas, especially, there are many culverts and accompanying trash screens of various sizes and complexity.

Blocked materials were removed at each inspection and hence the probability of blockage at each inspection was assumed to be independent.

The relationships established in this research are summarised in Table 4.2 and discussed in chronological order below. The methods should, strictly speaking, only be used for catchments with similar characteristics to those in Belfast (that is, urban catchments). Reliability will decrease for sites with different geography, land use, climate and screen properties. However, the equations are, in theory, transferable to screens across the UK.

**Table 4.2 Summary of FRMRC2 relationships**

| No. | Output metric | Input variables |
|---|---|---|
| 1 | Blocked area (%) (Wallerstein et al. 2009) (see Section 4.3.2) | • Peak discharge (weak) |
| 2 | Blockage frequency (Wallerstein et al. 2010) (see Section 4.3.3) | • Total annual rainfall |
| 3 | Probability of delivery of debris to screen which cause blockage of some degree (Wallerstein and Arthur 2012a) (see Section 4.3.4) | • Upstream channel network length<br>• Contributing rural land use cover<br>• Contributing agricultural land use cover<br>• Income Domain Score<br>• Seasonality (month or season) |
| 4 | Blocked area ($m^2$) (Wallerstein and Arthur 2012a) (see Section 4.3.4) | • Contributing suburban catchment area<br>• Screen bar spacing<br>• Screen angle from horizontal<br>• Seasonality (month or season) |
| 5 | Probability of blockage (Streftaris et al. 2013) (see Section 4.3.6) | • Upstream channel network length<br>• Channel slope<br>• Urban land use<br>• Mean daily rainfall<br>• Northern Ireland Multiple Deprivation Measure |

### 4.3.2 Wallerstein et al. (2009)

This paper aimed to establish a relationship between river discharge and debris blockage at culvert trash screens to:

- determine whether the relationship varied seasonally
- evaluate the effectiveness of the statistical methods used

Peak discharge and percentage blockage of screens yielded a statistically significant positive relationship when the full dataset was analysed. However, the strength of the relationship varied between screens and a more consistent relationship was found in the winter months than the summer months. This was thought to be due to the larger and flashier discharges of the observed storms in winter. It was suggested that this type of analysis should be performed on a full dataset or a winter subset where enough data are available. This is not believed to be have been done.

### 4.3.3 Wallerstein et al. (2010)

This study on predicting flood risk associated with debris at screens investigated monthly and annual trends in blockage frequency and blockage material type. Debris was classified according to Environment Agency (2009). Temporal as well as spatial variables were investigated.

It was found that a wide range of blockage frequencies occurred, confirming that the catchment characteristics affect blockage potential significantly. Distinct seasonal trends in blockage frequency were found in regression analysis with the winter months showing higher rates. This trend was also observed in a small dataset for Edinburgh and in a survey of practitioners.

Blockage frequency and total annual rainfall were positively correlated. This was thought to be due to a higher potential for debris to be washed from the catchment surface into the channel as well as the higher flows caused by larger rainfall events. The relationship between monthly average blockage frequency and rainfall was stronger than for discharge.

Only small vegetation (leaves and twigs) showed temporal variation and was strongly linked to the natural growth–decay cycle of deciduous trees.

The large presence of urban debris causing blockage suggested that treating problems at the source by improving land management may be an effective strategy in reducing culvert blockage.

### 4.3.4 Wallerstein and Arthur (2012a)

This FRMC2 report examined the potential for predicting and managing flood risk associated with trash screens at culverts.

The probability of delivery and thus blockage of trash screens was found to be subject to distinct seasonal trends. This was attributed to both the mean monthly rainfall washing more, and larger, debris to the screen site in winter and the annual cycle of deciduous plant growth increasing the volume of small vegetation (leaves and twigs) delivered to the blockage site.

Empirical equations for the probability of significant debris delivery (%) and average probable blocked screen area (in $m^2$) were developed, improving on earlier work by Wallerstein et al. 2010 (see Section 4.3.3). The average probability of debris delivery can be used to quantify the temporal risk of blockage and associated flood consequences and hence to prioritise screens that require frequent inspection. The screen area likely to block at any time of year can be used to optimise screen design and evaluate whether the proposed area is able to convey design flows in-bank with acceptable flood consequences for people and property.

The authors reported that the results agreed with Magenis (1988) in highlighting the importance of network length and land use for predicting debris delivery (see Section 4.2.1). However, channel slope and percentage of urban land use did not have a statistically significant effect on either variable, whereas channel slope was a driving variable in Magenis' work. Verification of the predictive capacity of the equations using alternative screens was hampered by incomplete datasets.

The probability and rate of blockage was found to be affected by the order of the delivery of debris as larger items often initiate blockages. Further investigation was recommended in this area to assess the relative impact of various classes of debris.

### 4.3.5 Wallerstein and Arthur (2012b)

This paper reported on the findings of Wallerstein and Arthur (2012a) (see Section 4.3.4) with additional commentary on the probability of significant debris delivery (causing 10% blockage of screen area or more) plotted over the year for each of the 140 screens, with 10% class intervals. This gave a near normal distribution with a modal value of 40–50%, showing that a high proportion of screens had around 50% probability of receiving significant debris loads, but some screens had a much higher or lower probability. A scheme for the analysis of blockage risk was proposed based on the product of probability and consequence scores (high, medium or low). This could be simplified to a 3 × 3 matrix.

### 4.3.6 Wallerstein and Arthur (2012c)

The paper presented a new method for estimating trash screen blockage potential based on the work Wallerstein and Arthur (2012a) work (see Section 4.3.4). Annual and monthly predictive equations were presented along with a blockage management flow chart as a proposed method for practical application.

The paper acknowledged that model verification is an important step in improving confidence in the methods and noted that ongoing research and the use of other datasets from the UK was being investigated.

### 4.3.7 Streftaris et al. (2013)

This study undertook a Bayesian (uncertainty) analysis to develop an equation for the probability of significant (5% or more) debris blockage at screen for each month of the year, depending on characteristics of the contributing catchment area. A threshold of 5% blockage was chosen as the point at which maintenance intervention may be required to prevent further accumulation and potential increased flood risk. Sensitivity analysis using thresholds of up to 20% gave similar results.

The study examined the influence of 4 sets of variables; channel, meteorological, land use and social deprivations. It differed slightly from the FRMRC2 study (Wallerstein and Arthur 2012a) in the variable definitions, with a Multiple Deprivation Measure (MDM) instead of Income Domain Score representing social deprivation, and simple urban and rural classifications for land use adopted over the 5 classes used previously. It was found that 6 of the 7 variables had a statistically significant, positive influence on blockage probability, with average daily rainfall having the strongest effect and percentage land use multiplied by MDM having no statistically significant influence.

Based on these results, a Bayesian stepwise method was used to develop a model which incorporated the 6 significant variables. The model was validated by leaving 250 observations (1% of the dataset), selected at random, out of the model development and using them to test how well the model predicts blockage. The total number of blocked screens was predicted accurately and increased confidence in the predictive capacity of the model.

In addition, the Bayesian approach allowed 5 other verification measures to be deduced, including the proportion of screens correctly classified as blocked.

The advantage of being able to explicitly account for the uncertainty surrounding predictions enables this model to be used effectively as a tool for asset managers to allocate maintenance resources, knowing the likelihood that a site predicted to be blocked may actually be clear.

This method appears to improve on that given by Wallerstein and Arthur (2012a) given the validation techniques employed and the methods by which uncertainty is accounted for.

### 4.3.8 Wallerstein et al. (2013)

This technical note published by CIRIA supplements the guidance in the Trash and Security Screen Guide (Environment Agency 2009) and the Culvert Design and Operation Guide (Balkham et al. 2010). It focuses on the work published in the FRMRC2 report (Wallerstein and Arthur 2012a) and highlights the scientific advances and key guidance that should be incorporated into day-to-day screen management.

The report details the perceptions of asset managers involved in screen maintenance and potential considerations for resource allocation.

Laboratory flume experiments showed that screen angle, bar spacing, discharge and debris length all have a significant influence on the blockage potential of a trash screen.

## 4.4 Blockage at culverts

### 4.4.1 Environment Agency (1998)

This report set out a risk assessment procedure for structure blockage risk and provided guidance on assessing the probability of blockage at culverts and blockage effects. The procedure aimed to identify structures prone to blockage and to develop a consistent set of rules for flood risk mapping studies. However, it was also seen as suitable for the design and checking of new culverts and for establishing maintenance priorities on existing structures. The procedure consisted of:

- a spreadsheet tool to assess the probability of blockage using 28 hydrological, debris and culvert parameters (such as the presence of a trash screen or loose bank material)
- a decision tree to select a course of action depending on the probability and consequences of blockage

The probability of blockage was classed as low, medium or high, while the degree of blockage was typically set at 75%. The procedure did not include detailed consequence models.

The procedure was developed through consultation with practitioners rather than field or laboratory data. Attributes with the potential to affect blockage risk were ranked and weighted to identify the frequency of blockage due to each attribute in isolation. The overall risk was taken as the sum of the individual attribute scores. The attributes can be weighted by the practitioner where they are thought to be less influential.

### 4.4.2 Environment Agency (2004c)

This study evaluated Environment Agency (1998) as part of the Afflux Estimation System review of current practice. Eight consultants with experience in the use of the procedure completed a questionnaire and evaluated its strengths and weaknesses.

It was agreed that the procedure was practical, easy to apply and most useful for comparison purposes, although it had some use as a deterministic approach. It was noted that the attribute scores were based on anecdotal information from a limited number of sources, giving them little statistical reliability, and that the attribute weightings were somewhat arbitrary.

The report recommended that:

- the number of attributes be reduced from 28 to 5–6 (say: ratio between discharge and capacity of structure; type of structure, debris potential from upstream; hydraulic efficiency of approach; and maintenance frequency)
- the method of obtaining an overall risk rating be improved

It was also recommended that more quantitative data on the blockage potential created by each attribute be obtained, either using model-scale simulations of representative box and arch culvert structures at a range of flows and blockage-creating conditions, or using Monte Carlo simulations to produce a probability distribution of the potential amount of debris arriving at a structure.

### 4.4.3 FHWA (1990)

This USA good practice guide, 'Highways in the River Environment (HIRE)', laid the groundwork:

> 'for application of the concepts of open-channel flow, fluvial geomorphology, and river mechanics to the design, maintenance, and related environmental problems associated with highway crossings and encroachments.'

The guide recommended taking debris into account in the design of structures. In particular, culvert design should take into account the transport of sediment so as not to cause large backwater effects or blocking of the culvert. It acknowledged the difficulty of predicting sediment transport in enclosed culverts and recommended a design equation (after Graf and Acaroglu 1968).

The guide noted that serious sediment problems can be attributed to channel degradation as a result of channel straightening or dredging. Lateral erosion and unstable banks were known to increase debris problems and were thought to be a good indicator of the presence of debris.

### 4.4.4 Vassilios and Tsihrintzis (1995)

This study examined sedimentation in a 560m long culvert during construction in order to improve its design. The culvert conveyed an alluvial stream in an arid to semi-arid region of California. A period of drought followed by large rainfall events led to sedimentation and consequently flooding.

The study concluded that it is cost-effective to design culverts to flush sediment through. The study recommended designing new culverts to convey open channel flow and modifying inlet and outlet configurations to improve siltation conditions. It was noted that sediment can have a large impact on head loss through a culvert and that pressure flow is complicated and difficult to model.

### 4.4.5 Molinas and Koester (2001)

This study examined debris flow and the design of highway culverts along a section of highway along the Snowmass Canyon in Colorado, USA. Debris flow was defined as a slurry of sediment and water with a water content of less than about 50% by volume. The study catchment experienced periodic debris flow, sometimes caused by intense summer thunderstorm rainfall and rapid snowmelt transporting deposits of eroded material in valleys and at the base of hill slopes.

Modelling showed that traditional, clear water hydraulic modelling can significantly undersize culverts subject to debris flow. Debris flows are usually accounted for by applying a bulking factor to design discharges which are then modelled using clear water analysis. In this study, alternative debris flow modelling techniques were used and found to be appropriate, robust and reliable for short, steep catchments.

### 4.4.6 Rigby et al. (2002)

This study examined the cause and effect of culvert blockage during large storms, following a severe storm at Wollongong, Australia, in 1998. The storm caused extensive flooding, damage to infrastructure and property, and the loss of one life. Factors contributing to flooding included short duration, intense rainfall, saturated ground, and blockage of culverts and bridges.

The size of the clear opening of culverts was found to be the primary factor in determining potential to block. No culverts above a size of 6m were found to be blocked, whereas culverts below 6m were subject to the full range of blockage from 0% to 100%.

None of the other factors studied – material type, land use, stream slope, contributing catchment area, number of culverts upstream and blockage of upstream culverts – was found to have an effect on blockage. It was noted that blocked culverts can have major impact on the expected flow paths of flood flows.

The findings of this study will have limited application to UK locations due to the distinctive characteristics of the catchment. The city of Wollongong is located on a narrow coastal plain at the base of a steep escarpment, with many short, steep streams running off the escarpment before levelling out. The streams are sensitive to short duration and high intensity rainfall, and the high flow velocities mobilise sediment and vegetation as well as any other loose material. The main cross-drainage structures are located on flat sections of the stream channels at the toe of the slopes – the natural location for debris deposition.

### 4.4.7 TRTA (2011)

This presentation by the Transport Roads and Traffic Authority (TRTA) of the New South Wales Government was given at a culvert risk assessment training workshop in 2011. The presentation detailed a method for systematic risk assessment of culverts to identify the need for maintenance and allocate funds appropriately. It focused on identifying whether a culvert is at risk of failure. It identified 4 failure mechanisms:

- structural collapse of the culvert
- slope instability
- piping
- hydraulic flow

Urgent attention is required if the culvert inlet, outlet or barrel is blocked by 50% or greater, causing an immediate risk to the public. However, the rationale behind a threshold of ‘50% blockage’ is not given.

The presentation did not include detailed information pertaining to the risk associated with culvert blockage, but instead looked at the range of factors that could cause culvert failure.

A matrix-based qualitative risk assessment methodology was presented where the risk level is determined using likelihood and consequence analyses. This is simple and effective in accounting for the variety of risks due to the failure modes to road users, buildings, pedestrians, roads and furnishings, vehicles, infrastructure, structures, services and other property, their likelihood and the consequences of failure.

Where limited data are available for a quantitative analysis, this matrix-based approach was considered appropriate for incorporation into the blockage management guide.

## 4.5 Blockage at bridges

### 4.5.1 RSSB (2004, 2005)

These studies by the UK Rail Safety and Standards Board aimed to improve the assessment of scour at rail bridges through the analysis of a database of 134 bridge failures due to scour in the UK. Debris accumulation was thought to be a contributory factor at 8 sites.

A procedure was devised to identify structures at risk from water pressure and debris impact using simple information on the type of structure and the water level relative to the soffit of the structure. A second procedure was given for assessing debris blockage potential, based on the Environment Agency (1998) method (see Section 4.4.1), but with 3 design flows instead of 6.

### 4.5.2 Melville and Dongol (1992)

This study developed an equation for the effective width of bridge piers with debris accumulation for use in estimating local scour. The equation was based on laboratory experiments and research by the National Cooperative Highway Research Program (NCHRP) in the USA (Lagasse et al. 2010). It suggested that the equation over-estimated effective pier width.

### 4.5.3 Diehl (1997)

In this report for the US Federal Highways Administration, Diehl established guidelines for quantifying drift (floating debris) accumulation potential and size at bridges through a literature review, analysis of 2,557 drift accumulation reports and 144 field investigation sites between 1992 and 1995 from sites across the USA. Some of the field investigation sites were visited repeatedly in the 3-year period of the study to monitor development of the blockage or recurrence of incidents.

The drift accumulation reports provided information on the size of accumulation, pier location, skew and type, span length, channel width and bank height. Other variables including width of drift accumulations, percentage of channel blocked, effective span width and ratio of drift width to span length were derived from the reported data. The field investigations provided information on drift size, drift characteristics related to origin and transport, and the shape and structure of drift accumulations.

Debris load was found to depend on channel instability, which was related to characteristics such as bank height, bank angle, bank materials, erosion rates and drift concentrations. This was found to be very variable along a channel reach and should therefore be inspected along the entire river reach rather than just at the bridge site. It was found that bank erosion, and therefore debris production, was largest at the outside of bends due to higher shear stresses.

Debris delivery was found to depend on discharge, channel characteristics and the size of drift pieces relative to the channel dimensions – the latter being critical in determining the type and amount of drift stored in the channel as well as the velocity and mechanism of transport. Depth and channel slope were found to be secondary factors. No minimum slope or velocity necessary for drift transportation had been established by the time the report was written.

Floating debris was found to float at the deepest, fastest part of the channel and was therefore transported at the average water velocity of the channel. Submerged drift, on the other hand, was transported more slowly by the flow near the river bed and often came to rest away from bridges.

Single pier blockages at bridges were often in the shape of an inverted half cone. Pier trapping was reduced by 'appropriate design features such as adequate freeboard, long spans, solid piers and careful pier placement'.

Diehl found that spans with an effective width greater than the design log length have a low potential for blockage. The design log length was taken as the minimum of upstream channel width, the maximum length of sturdy logs (or in the USA, 9m + channel width/4). The risk of blockage and additional costs due to greater spans should therefore be balanced in the design of bridges. Single pier accumulations can be minimised by not placing piers in the path of drift, placing piers on banks and choosing a suitable pier type.

A 3-stage assessment of potential of drift accumulation at a bridge was developed.

- Phase 1 determined the potential for debris delivery through the use of flow charts, splitting into high and low potential depending on criteria such as whether there is direct or indirect evidence of debris production.
- Phase 2 identified the location and characteristics of the substructure, piers, abutments, span widths, and bridge and pier skew using a flowchart. The potential for debris accumulation was then determined separately for each pier, submerged substructure and horizontal and vertical gaps based on the bridge characteristics, location category and potential for delivery of debris.
- Phase 3 defined the overall potential for debris accumulation of the bridge as the maximum potential found in Phase 2. For relatively long structures, this could result in unnecessary overdesign of the bridge as the overall rating of the bridge could be based on a high rating for only 1 or 2 bridge elements. Therefore it is suggested that the bridge elements be compartmentalised into zones of adjacent bridge elements with similar debris accumulation potential ratings for design and maintenance purposes.

Direct evidence was preferred over indirect evidence for the assessment. The most direct evidence included site observations, other indications such as abundant debris in the channel, and multiple or severe cases of drift accumulations at structures. Indirect evidence requires a larger degree of subjective judgement as it entails information that may or may not indicate the presence of debris, such as widespread erosion of banks upstream and a history of changes to the channel such as lateral migration.

### 4.5.4 SANRAL (2002)

The South African Roads Agency's 'Code of Procedure for the Planning and Design of Highway and Road Structures in South Africa' recommends that, where large debris is likely to be carried in a flood, the clear span should be at least at least 15m on strategic or larger roads and 7.5m on other roads. The guidance recommends adopting rounded or chamfered square end pier shapes and avoiding sharp edges at the leading edge.

### 4.5.5 New Zealand Transport Agency (2003)

The second edition of the New Zealand 'Bridge Manual'[1] recommends designing bridges for water pressure on a driftwood raft lodged against the pier. The size of driftwood should be determined using engineering judgement, but as a rule of thumb, the guide recommend taking height as half the water depth, but no greater than 3m, and the width as half the sum of adjacent span lengths but no more than 15m.

### 4.5.6 Lyn et al. (2006)

This study provided design guidelines for new bridges to reduce debris accumulation at bridge piers in response to significant problems with blockages at bridges in Indiana, USA. The work involved:

- studying underwater bridge inspections at 370 structures over 10 years
- periodic site visits to blockage-prone structures
- video monitoring and analysis of 3 structures

It was found that 20% of the sites suffered from debris accumulation, most often in the form of single pier debris accumulation. It was found that debris accumulation patterns are repeatable, suggesting that the process is not random but more likely to be affected by specific local factors.

It was found that the thalweg was not necessarily related to greatest debris accumulation and point bars were moderately related to debris accumulation. Piers close to the river bank at low stage had little or no debris accumulation. Bridges with long spans (>100 feet (30.5m)) did not suffer repeated, heavy debris accumulation, while shorter spans experienced repeated, heavy debris accumulation.

With regard to the timing of debris delivery, this occurred during the rising limb of the hydrograph and during prolonged events, transport and accumulation occurred well before the flow peak. Bursts of small amounts of debris occurred more frequently than expected; this was thought to be due to the destabilisation of larger accumulations 'shedding' debris.

### 4.5.7 Lagasse et al. (2010)

This NCHRP report into the effects of debris on bridge pier scour aimed to deliver guidelines for the prediction of bridge scour in the USA, taking into account the size and geometry of debris accumulation. This was achieved through a literature review (including collation of a photo archive), a pilot study, physical modelling and a case study.

---

[1] For the latest edition see https://www.nzta.govt.nz/resources/bridge-manual/bridge-manual.html

Physical model tests were carried out with different pier types and widths with different sizes and shapes of debris build-ups. A shape factor and a factor describing the intensity of the plunging flow are used to modify the equivalent width of piers to represent debris for scour estimation.

The report provided guidelines for blockage assessment after Diehl (1997) (see Section 4.5.3).

## 4.6 Blockage of open channels

### 4.6.1 Piégay and Gurnell (1997)

This study investigated the impact of channel size and geomorphology on the build-up of large woody debris for rivers based on semi-natural watercourses in south-east France and southern England. Large woody debris was defined as pieces greater than 0.1m in diameter or 1m in length.

The study defined 3 river channel types based on the ratio between channel size and boundary particle size (after Church 1992). Large rivers are channels in which purely fluvial processes and geological constraints determine the morphology. For medium to small rivers, secondary factors, particularly individual roughness elements such as rocks and pieces of wood become increasingly important.

This classification reflects the River Continuum Concept which defines 12 'orders' along a river from source to sea (Vannote et al. 1980). This 'provides a framework for integrating predictable and observable biological features of flowing water systems with the physical/geomorphic environment' and also 'characterises the occurrence and processing of organic material, of which large woody debris is an important component, according to a longitudinal gradient along a river's course'.

The authors found that the size of the river channel influenced the rate and form of woody debris retention and the speed of migration.

In small rivers, large debris tended to accumulate where it falls because a large proportion exceeds the river width and the flow is not strong enough to transport it. Large woody debris accumulated in transverse dams where one tree spans all or part of the channel width. Smaller debris created compact dams.

In medium rivers, more debris was moved because of the higher stream power and a greater proportion of debris pieces are shorter than the channel width.

In large rivers, debris transport varied spatially and did not always follow a downstream progressive continuum. There was a longitudinal discontinuity in the retention capacity, the speed of debris transfer and the local volumes of debris delivered to the river system according to the geomorphic pattern of the river. In larger streams, debris volumes and accumulations could be quite large, although debris accumulation was less likely as the span of the river was wider than the debris.

The study found that braided and migrating rivers were subject to debris accumulation, and braided channels had a lower retention capacity than wandering channels.

The paper noted that there are 3 types of transverse debris dam (after Gregory et al. 1985):

- active dams which span the entire channel and induce a pronounced step in the water surface profile even at low flows

- complete dams which span the entire channel but do not induce a significant step at low to medium flows
- partial dams which do not completely span the channel

It also gave an equation for number of wood pieces located within 500m lengths of the bed of the Drôme river.

## 4.7 Modelling blockage

### 4.7.1 Deterministic modelling

Deterministic modelling generates outcomes that are uniquely determined by the starting conditions and known relationships between variables, and the results are reproducible. Tools available for the deterministic modelling of water levels and flood outlines with and without blockage are:

- hand calculations or spreadsheets
- one-dimensional (1D) computer models – for in-bank flow, combined with non-modelling evaluation of where excess water would go
- two-dimensional (2D) computer models – suitable for assessing out-of-bank flow and flood extents resulting from blockage
- three-dimensional (3D) numerical models – for complex geometry or to identify locations in the channel where debris transport or sedimentation is likely to be highest
- physical modelling – for complex geometry or to validate other methods. Can be difficult to scale correctly, especially floating debris

Some of these can be linked, for example, a 1D computer model for in-bank flow and a 2D computer model for out-of-bank flow.

The blockage modelling capabilities of some computer models used in the UK are summarised in Table 4.3. This draws on a review of computational models as part of the development of the Conveyance and Afflux Estimation System (CES/AES) (Environment Agency 2004b).

It can be seen from Table 4.3 that, although all models can model structures such as culverts, bridges and weirs, the modelling capability of some of the more blockage-susceptible structures such as screens, control gates and flap valves is limited. However, most models include the capability for the user to define a head loss or a rating at any particular point within the system, allowing theoretical, physical model experiment or field data relationships to be included in the model.

**Table 4.3 Blockage modelling capabilities of software**

| Approach | Blockage modelling capability | | | | | |
|---|---|---|---|---|---|---|
| | CES/AES | ESTRY TUFLOW | HEC-RAS | Info Works | ISIS | Mike11/ Mike-Flood |
| Blockages | Y[1] | Y | Y | Y[1] | Y | N |
| Ineffective flow area | N | Y[1] | Y | N | Y[1] | N |
| User-defined head loss | N | Y[1] | Y | Y | Y | Y |
| Screens | N | N | N | Y | Y | N |
| Control gates | N | N | Y | Y | Y | Y |
| Flap valves | N | N | N | Y | Y | Y |
| Culverts | Y | Y | Y | Y | Y | Y |
| Bridges | Y | Y | Y | Y | Y | Y |
| Weirs | Y[1] | Y | Y | Y | Y | Y |

Notes: [1] Indirect method, for example, adjust structure geometry, sluice gate.

### 4.7.2 Probabilistic modelling

*Overview*

Probabilistic modelling aims to compute risk by approximating the statistical distribution of flood consequences – a function of the distribution of loading conditions and the associated system states (asset failure states). The idea is to combine the damage resulting from the few, very rare, high-damage events with the damage from the many smaller, lower consequence events, and all combinations in between. A source–pathway–receptor method is adopted; where the source is a fluvial hazard, the pathway is the physical flood risk system and the receptor is people and property in the floodplain.

*MDSF2 approach*

In the UK, MDSF2 (Environment Agency 201b, 2013a) uses Risk Assessment for Strategic Planning (RASP) methods to produce national flood risk assessment data (NaFRA) (Hall et al. 2003, Sayers and Meadowcroft 2005, Gouldby et al. 2008).

MDSF2 combines probabilistic analysis and scenario analysis by modelling just 2 culvert states rather than a full distribution of blockages. It estimates flood risk and attributes this risk to specific assets to provide evidence to support multi-objective and multi-criteria risk management and investment decisions (Environment Agency 2013a).

MDSF2 considers the hydraulic loads (in-channel water levels or coastal overtopping rates) at q discrete levels l1, l2, … lq, typically associated with specified (annual) return periods. Defence system states are then sampled using a Monte Carlo simulation for each discrete loading event. The resulting inundation and associated consequences for each system state are determined and summed across all loads. This process of estimating risk (R) (in terms of the Expected Annual Damages (EAD)) can be expressed as:

$$R \approx \sum_{i=2}^{q-1}\left[\left[p\left(L \geq \frac{l_i + l_{i+1}}{2}\right) - p\left(L \geq \frac{l_i + l_{i-1}}{2}\right)\right]\bar{c}_{l\,i}\right]$$

where:

p (L ≥ l) = probability of hydraulic load exceeding a level l

L = hydraulic load, treated as a random variable

$l_i$ = hydraulic load (for example, water level) for the $i^{th}$ of q discrete probability levels

$\bar{c}i_j$ = expected consequences for the $i^{th}$ discrete loading probability level integrating over potential defence failure scenarios

## *Fragility curves*

MDSF2 uses fragility curves to express the likelihood of failure for a given hydraulic loading (that is, the conditional probability of failure given load). Loading refers to flow or water level rather than debris load, which has not been explicitly built into the software.

A set of high-level fragility curves were first developed for 61 RASP types and condition grades 1 to 5 (Environment Agency 2004d). These were subsequently updated (Buijs et al. 2007a, 2007b)[2] and are available to MDSF2. These represent the varying performance of flood defences as they deteriorate over time and are based on failure mode analysis of standardised structures.

Structure-specific fragility curves express the probability of failure of an asset depending upon the loading, with different curves to take account of condition grade. Curves were based on an understanding of defence failure modes, fault trees and limit state equations.

Culverts are treated as an ‘in-line’ point asset (that is, they are in the channel and can be considered to exist at a point). The performance of the culvert has no impact on the in-river flows or water levels elsewhere (and hence the loads experienced by other defences).

A culvert has 2 states:

- failure (complete blockage due to collapse)
- non-failure (surcharged flow)

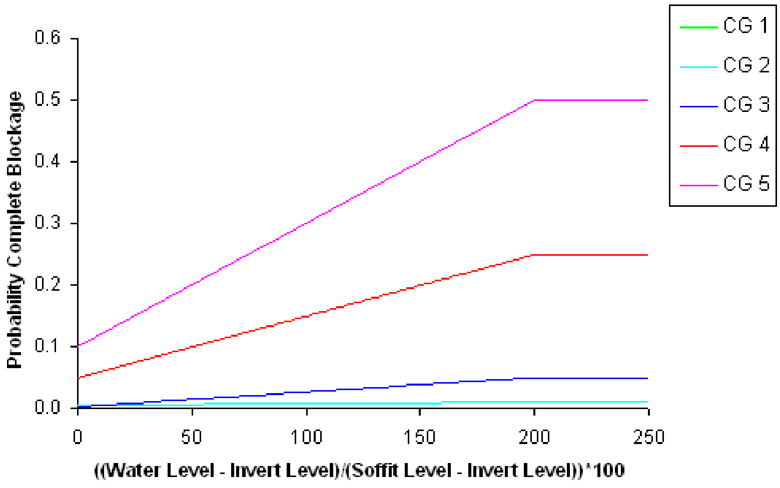
In the non-failed case (that is, no further constriction of the opening or barrel due to debris or collapse), a culvert is are assumed to convey flow up to its design capacity (expressed in years as a return period) and, once this is surcharged, there is overflow onto the floodplain at the upstream end.

In the failed case (that is, the culvert becomes partially or fully blocked), there is a chance of overflow on to the floodplain prior to the in-river flow reaching the culvert design capacity.

[2] The latest update is currently in publication.

Generalised fragility curves for culvert blockage are given in Figure 4.1.

**Figure 4.1 Fragility curves for culvert blockage**




Source: Environment Agency (2011b)

The probability of failure is given for 5 condition grades (CG1 to CG5) and a load (or submergence ratio, the ratio between water depth and barrel height) of zero to 250% (Figure 4.1). The load axis is characterised by:

$$Load = \frac{(SWL - IL)}{(SL - IL)}.100$$

where:

SWL = [sea] water level (m AOD)

IL = invert level inside the lowest portion of the culvert (m AOD)

SL = soffit level the inside upper surface or highest portion of the culvert (m AOD)

Note that the culvert fragility curves are based on limited research and evidence. In particular, they do not take into account of the probability of blockage due to sediment and debris.

### *Estimating inflows onto the floodplain and associated risk*

To estimate risk from point asset failure, MDSF2 requires the user to supply an estimate of the inflow into the floodplain in the case of surcharge or failure (blockage). That volume is then spread across the floodplain using the Rapid Flood Spreading Method (RFSM) (Sayers and Marti-Mulet 2006, Lhomme et al. 2008) and the associated damages estimated.

Unlike for raised river defences, MDSF2 does not include default inflow volume calculations in the case of culvert surcharge (in either the failed or non-failed state). Users must provide these manually based on some form of external modelling.

Inflow volumes must be provided for all discrete load events (that is, for different modelled annual exceedance probabilities) and culvert states, that is,

- non-failed (but surcharged)
- failed (culvert blocked/collapse)
- already failed (do nothing only – if different from the failed case)

Any estimate of the inflow onto the floodplain from the culvert provided by the user is then considered together with inflow estimates from all assets within the system as part of the wider 'volume capping' process within MDSF2.

Although MDSF2 does not provide for an inbuilt calculation, guidance is provided on the appropriateness of different external modelling approaches (Table 4.4). The 'types' refer to the different asset states and are explained below.

**Table 4.4 Summary of optional models and methods for establishing inflow volumes**

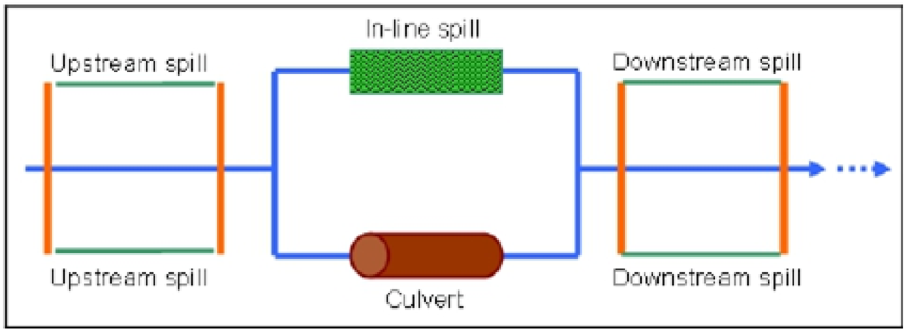
| Asset type | State | Flow | Method/model summary | Reference |
|---|---|---|---|---|
| Culvert (fluvial) | Non-failed | Surcharged flow | Simple hand/spreadsheet calculation based on culvert capacity | Type 5a |
| | | | Simple tools such as the Conveyance and Afflux Estimation System (CES-AES, Knight et al. 2009) | Type 6a |
| | | | Quasi-1D or 1D-2D hydrodynamic model | Type 1c |
| | Failed | Blocked flow | Simple hand/spreadsheet calculation based on culvert capacity | Type 5b |
| | | | Simple tools such as the CES-AES, Knight et al. 2009) | Type 6b |
| | | | Quasi-1D or 1D–2D hydrodynamic model | Type 1d |

Source: HR Wallingford (2012)

### Type 1c: Quasi-1D hydrodynamic model – non-failed culverts

The in-line culvert is represented in the 1D channel element of the model. It typically will have a neighbouring in-line spill to represent flow over the top of the embankment/high ground that it passes through (Figure 4.2). The capacity of the culvert will be reflected in the model and, once exceeded, the upstream water profile will change (the so-called 'backwater effect'). The raised water levels upstream of the culvert will result in more spilling at the culvert entrance and, for channels with small longitudinal gradients, this may result in increased spilling for some distance upstream.

**Figure 4.2 Schematic representation of an in-line culvert in the 1D element of a model**




Source: HR Wallingford (2012)

The MDSF2 guidance suggests that the external model is run for 2 scenarios:

- Scenario 1 – culvert present as usual
- Scenario 2 – culvert removed and replaced by channel sections similar to the upstream and downstream sections

The spill units on the left and right banks upstream of the culvert entrance can be used to evaluate the inflow volume for each scenario. It may be appropriate to also incorporate the flow over the in-line spill where the water is unlikely to re-enter the channel (for example, for a long culvert). The difference between the inflow volumes for the 2 scenarios will be the inflow volume due to culvert surcharge.

**Type 1d: Quasi-1D hydrodynamic model – failed culverts**

The MDSF2 guidance suggests that, as in Type 1c, the in-line culvert is represented in the 1D channel element of the model together with an in-line spill. The culvert capacity and any reduced capacity (that is, blockage) will be reflected in the upstream water profile, altering the amount of spilling to the floodplain.

The guidance suggests it may be appropriate to run the model run for 2 scenarios:

- Scenario 1 – culvert present as usual (same as Scenario 1 in Type 1c)
- Scenario 2 – culvert removed to reflect zero capacity (full blockage); all through flow in the channel will then be over the in-line spill only

Once run, the spill units on the left and right banks upstream of the culvert entrance can be used to evaluate the inflow volume for each scenario. It may be appropriate to also incorporate the flow over the in-line spill where the water is unlikely to re-enter the channel (for example, for a long culvert). The difference between the inflow volumes for the 2 scenarios will be the inflow volume due to culvert surcharge.

The MDSF2 guidance also highlights that in practice, removing the culvert may cause model instability. Depending on what flow modelling package is being used it may be appropriate to introduce a narrow slot into the in-line spill profile to ensure it is never 'dry'.

**Type 5a: Simple methods for culverts – non-failed**

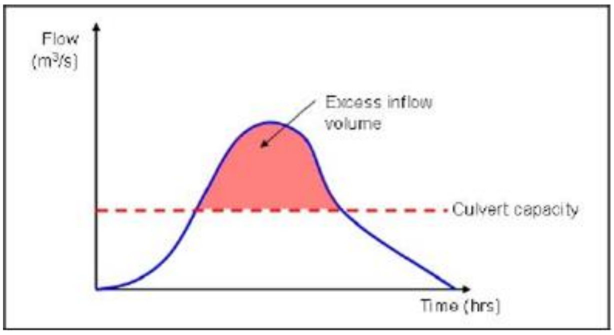
Type 5a focuses on providing a simple approach to estimate culvert surcharge in the absence of detailed models (for example, Type 1c). For example, users may simply:

1. Consider the culvert capacity (for example, using methods described in Balkham et al. 2010).

2. Consider the flow in the channel for the duration of the event.
3. Determine the duration and magnitude of ‘excess’ flow.

Figure 4.3 illustrates this concept. This information can then be used to estimate the potential inflow volume to the floodplain.

**Figure 4.3 Example of a simple culvert inflow volume calculation**




Source: HR Wallingford (2012)

**Type 5: Simple methods for culverts – failed**

Type 5b focuses on providing a simple approach to be used when the culvert is blocked. Assuming blockage represents a complete blockage of the structure, a simple approach is similar to the shown in Figure 4.3 but with the culvert capacity reduced to zero.

The MDSF2 guidance also reminds the user that an important consideration in implementing the Type 5a and 5b approaches is whether the excess water re-enters the channel further downstream (for example, for short culverts). In this instance, the excess inflow volume onto the floodplain may need to be reduced to reflect this re-entry.

**Type 6a: CES-AES – non-failed culverts**

Type 6a refers to a surcharged culvert in a non-failed state. The Environment Agency’s CES-AES software[3] is useful here as it enables users to insert cross-section and culvert information and then carry out a simple backwater calculation for steady flow. The CES-AES may be used to explore 2 scenarios:

- Scenario 1 – culvert present as usual
- Scenario 2 – culvert removed and replaced by channel sections similar to the upstream and downstream sections

**Type 6b: CES-AES – failed culverts**

Type 6b provides support for a failed culvert. The CES-AES can be used to explore 2 scenarios:

- Scenario 1 – culvert present as usual (same as Scenario 1 in Type 6a)
- Scenario 2 – culvert with approximately zero capacity

For both Types 6a and 6b, the MSDF2 guidance notes that the difference between the backwater profiles can be used to inform the change in ‘head of water’ due to culvert surcharge. This can then be used as input to the weir equation.

[3] This can be downloaded from www.river-conveyance.net

*Limitations*

There are some limitations with the MDSF2 approaches. Data uncertainties include:

- boundary conditions (water levels)
- defence crest levels
- inflow volumes
- the use of volume capping to ensure that the floodplain volume does not exceed the volume in the channel

Methods for dynamic feedback (floodplain flow returning to the river channel) are also limited.

The RASP algorithm embedded in MDSF2 uses a Monte Carlo simulation procedure to sample from the joint distribution of loading conditions and flood defence system failure states, which are computed conditional on the load using fragility curves. This is computationally demanding and typically involves hundreds or thousands of simulations. It has therefore been necessary for MDSF2 to make use of a highly simplified flood spreading model, the RFSM so as to achieve run times that are acceptable for practical applications. This may result in inaccurate flood depth and extent predictions in some situations, especially in floodplains with complex topography and steep gradients.

*Research and development*

Lamb et al. 2013 examined opportunities for improving probabilistic flood risk management capabilities with the aim of developing a method to augment RASP. The method involves modelling a small number of carefully selected system states according to their importance and contribution to flood risk, rather than the Monte Carlo simulation of a large number of system states, some of which may be similar. The use of fewer runs and computing power would therefore allow the use of more detailed local models (giving greater accuracy), rather than a large number of runs using coarse models.

The work included a case study where the flood risk pathway was controlled by culvert failure scenarios and would offer an approach suitable for using culvert or bridge blockage fragility functions within an existing river model to generate risk estimates based on more detailed predictions of flow pathways than in MDSF2. This research and development project did not address the question of what the blockage fragility function should be.

## 4.8 Catchment management

### 4.8.1 Introduction

Catchment management involves meeting legal obligations relating to public safety, flood risk management, environmental protection and maintenance or the improvement of the ecological status of watercourses, while balancing the costs and benefits of maintenance with the costs and benefits of flooding, structural repairs or environmental benefits. This can present complex challenges.

### 4.8.2 Legal framework

The general duties of landowners relating to blockage and debris management are broadly similar throughout the UK, although there are some differences in statute law.

In England and Wales, landowners have a responsibility to 'let water flow through their land without obstruction, pollution or diversion affecting the rights of others' (Environment Agency 2014a). This means that they must keep structures (such as culverts and screens) clear of debris and clear blockages on their land or under their property. Similar duties apply in Ireland.[4]

'Living on the Edge' (Environment Agency 2014a) states that landowners are responsible for maintaining the bed and banks of the watercourse and should keep the banks clear of anything that could cause an obstruction and increase flood risk, either on their land or downstream if it is washed away. They should also clear any litter and animal carcasses from the channel and banks, even if they did not come from their land. At first glance, advice on the retention of large woody debris appears to contradict this, although it does recommend that debris should be removed if there is a risk of adverse consequences such as blockage of structures (Mott 2005).

In Scotland, local authorities have a duty under the Flood Risk Management (Scotland) Act 2009 to 'clean, repair and maintain in any watercourse which may pose a risk of flooding of non-agricultural land'.

In Northern Ireland, occupiers of land adjoining undesignated watercourses are required to remedy any drainage problems on their land under the Drainage (Northern Ireland) Order 1973. This may include the removal of obstructions, accretions, silt, deposits or falls to restore the normal depth of the watercourse.

The European Union's Water Framework Directive and delegated legislation imposes a legal requirement to maintain or improve the ecological status of a watercourse (although not at disproportionate cost). Ecological status depends on multiple factors relating to water quality and habitat. Measures to improve this might include:

- retention rather than removal of large woody debris
- controlling soil erosion to prevent silt smothering clean gravels that might provide habitat
- removing litter

The Environmental Protection Act 1990 affects potential sources of man-made materials and requires certain public bodies in Great Britain to ensure that their land (or land for which they are responsible) is, so far as is practicable, kept clear of litter and refuse. Duty holders that allow their land to fall below acceptable standards for longer than the allowed response time may be subject to a litter abatement order. For land with a low intensity of use, including waterside land, the required response time is 14 days. For areas where maintenance work is constrained by health and safety, environmental or practicability such as adverse weather, the response time increases to 28 days (Defra 2006). Waste regulation authorities or waste collection authorities have powers to remove waste in order to remove or prevent pollution of land, water or air or harm to human health, and to recover the costs of removal and disposal.

Littering is an offence in public places but also on any private land (including land covered by water), as long as it is open to the air (ENCAMS 2006), since material may blow from one place to another.

[4] www.flooding.ie/Farming/RightsResponsibilitiesofriparianlandowners/

### 4.8.3 Existing standards

Existing maintenance standards acknowledge the need to balance flood risk and infrastructure needs with those of the environment.

The Environment Agency's Maintenance Standards have a traffic light or red–amber–green (RAG) system for maintenance actions, where red actions have the greatest environmental impact and green have the least impact (Environment Agency 2012b). Priority is given to green actions, unless 2 or more of the risk factors are red. Options for the management of trees and bushes along watercourses and woody debris are summarised in Table 4.5.

The Scottish Environment Protection Agency (SEPA) has a suite of good practice guides covering, among other things, river crossings, sediment management and vegetation management (SEPA 2009, 2010a, 2010b). The river crossings guide (SEPA 2010b) acknowledges that sediment and debris accumulation at culverts and bridges can increase flood risk and the risk of collapse, and notes that this is often removed. It recommends retaining sediment and large woody debris within the channel where possible for ecological reasons.

**Table 4.5 Environment Agency's traffic light system for maintenance**

| | **Green** | **Amber** | **Red** |
|---|---|---|---|
| Flood risk | Low | Medium | High |
| Downstream blockage risk | Low | Medium | High |
| Location | Rural | Parkland | Urban |
| Woody debris height | <0.5 × channel depth | ≈ channel depth | > channel depth |
| Tree and bush management | Cut to bank height, remove cuttings from channel; consider retaining for reuse elsewhere | Cut to bank height; consider retaining for reuse elsewhere | Remove all trees and bushes; consider retaining for reuse elsewhere |
| Woody debris management | Retain all woody debris; peg to bed and banks of channel | Selective removal and re-orientation to enable conveyance | Remove all woody debris |

### 4.8.4 Reduce debris load

*Refuse*

Guidance on measures to reduce debris load due to refuse is given in the Trash and Security Screen Guide (Environment Agency 2009). Larger items of refuse are often only mobilised under high flow conditions and can cause blockage quickly, either by a single large item arriving at a structure or a large volume of debris accumulating.

Domestic refuse such as small containers and food packaging is usually placed in a watercourse by high winds, riparian owners tipping over the garden fence or by casual tippers at known fly-tipping hotspots. Riparian owners are sometimes unaware of the potential risk caused by this type of debris and a public awareness campaign targeted at riparian owners may reduce the debris load.

Large household refuse such as furniture, mattresses and carpets is usually deposited by casual tippers at known fly-tipping hotspots. Options to reduce the volume of this kind of debris include the provision of recycling areas, enforcement action by the local authority and/or waste regulation staff, or a public awareness campaign at the fly-tipping hotspot. Alternatively, routine 'scavenging' of the watercourse can remove debris before it is transported downstream to the screen site, subject to negotiation with riparian owners.

The source of large non-domestic refuse is often commercial or industrial land adjacent to the watercourse. If the debris can be traced to a particular site, options include:

- enforcement action against the site owner or operator
- liaison with the site owner to secure the material and reduce the possibility of it becoming debris load
- installation of a physical barrier to reduce the debris load entering the channel (provided that this does not compromise flow capacity or prevent access for maintenance)

For supermarkets and DIY stores, the use (or not) of deposits for trolleys and the siting of trolley parks can influence the dumping of these items in rivers.

### *Vegetation*

The volume of large vegetation can be reduced by removing material before it becomes debris or routine clearance of material from the watercourse and floodplain upstream. However, this option is environmentally unfavourable and requires negotiation with landowners.

Small vegetation is likely to have a minimal impact on debris load unless the length of contributing channel is significant. The installation of upstream screens could reduce the load at a critical location, although this creates a maintenance burden.

### *Sediment*

'Sediment Matters' (Environment Agency 2011a) provides checklists for identifying impacts and sources of sediment, although the guidance does not extend to responses. Some of the factors contributing to sediment load are uncontrollable, but some, such as land use and land management, can be addressed to reduce sediment load.

The importance of woodlands in improving soil structure and reducing erosion, thereby reducing siltation and increasing bank stability, is highlighted in 'Forests and Water: UK Forestry Standard Guidelines' on Sustainable Forest Management (Forestry Commission 2011). The guidelines note that badly managed forests can cause coarse sediments to enter surface waters in large quantities, destabilising stream beds and channels as well as blocking pipelines and water intakes. The importance of the role of trees in providing the right amount of shade for the river banks is also pointed out; too much shade can cause vegetation loss and erosion of the river banks.

Sediment load due to run-off from agricultural land can be reduced by changes in land management according to the guidance given in 'Controlling Soil Erosion' (Defra 2005). The guidance recommends preparing an erosion risk map showing:

- potential sources of sediment

- pathways for sediment movement
- location of potential mitigation measures

The map should include the factors affecting the quantity of sediment from the catchment:

- catchment size
- catchment response time (flashiness)
- soil type
- slope angle
- slope and nature of watercourse channel
- farming or crop type and farming techniques
- opportunities for flooding and deposition of sediment before a lake is reached

The erosion map can help to identify a suite of measures to prevent sediments from reaching a watercourse.

In some cases, land use changes may be the best way to solve the problem.

On arable land, soil erosion may increase due to changes in arable rotations, autumn cultivation, heavy machinery, irrigation, de-stoning of soils and factors that leave the soil unstable and unstructured. Measures to reduce erosion and stop eroded soil from reaching lakes can include:

- ensuring soil has good organic matter content
- retaining surface roughness in soils
- sowing spring crops and leaving ground fallow in autumn and winter
- reinstating interceptors such as hedges, field ponds, grass waterways

On pastoral land, erosion can be increased by increased grazing intensity, pasture management (re-seeding, use of fertiliser), collapse of old stock watering structures. Mitigation measures can include:

- reducing stocking levels
- careful siting of feeders and gateways
- fencing of river and lake banks
- retention of wetlands and spongy features in landscape
- measures to encourage good infiltration capacity in soils

The delivery of silt can be accelerated by heavily -modified watercourses or artificial drains, roads and tracks, gullies within fields, gateways or compacted access routes. Sediment may be transported along tracks during heavy rainfall. Where problems are identified, mitigation might include:

- restoring natural channels (from straight to meandering)
- restoring historic drainage systems
- diverting connections to watercourses

- installing settling ponds or physical barriers
- keeping track surfaces grassed
- moving gateways

The sediment or debris load arriving at a pinch point can also be reduced by primary screens installed some distance upstream. These consist of vertical or raked bars embedded into the watercourse bed and which are designed to retain a full height of sediment or debris and to overtop safely when completely blocked, without causing scour or flooding. A low boulder screen traps sediment, while a higher roughing screen traps floating debris such as tree branches. However, these can have adverse impacts on ecology and the Water Framework Directive supports a presumption against the management of sediment in watercourses unless the sediment-related problem produces an unacceptable risk to people, property or infrastructure.

A sediment trap installed in the channel allows sediment to settle out by reducing flow velocity over a length of channel. However, these require inspection and maintenance, and finding suitable locations can be difficult on steep watercourses.

In Switzerland, flexible net barriers designed to trap coarse sediment and woody debris have been adopted on steep watercourses (Volkewein et al. 2011) (Figure 4.4). However, these are unsuitable for larger watercourse where sediment continuity is important to prevent erosion downstream.

**Figure 4.4 Flexible net barrier upstream of a culvert**

Source: Volkwein et al. (2011)

For larger watercourses, a 'bypass retention' scheme can direct floating debris towards a bypass channel constructed on the outside of a bend, separated from the main channel by a lateral weir (Schmocker and Weitbrecht 2013). This retains bedload within the main river channel and has the advantage of having little impact on water levels.

### 4.8.5 Reduce blockage probability

*Structure design*

The probability of blockage can be reduced by design for new structures or by retrofitting existing structures.

Screens should be designed to avoid trapping debris that would otherwise pass freely through the culvert. The bar spacing should be no closer than necessary, with the exception of security screens, which must have a bar spacing no greater than 140mm.

Culverts should be designed for free flow rather than full flow conditions, with sufficient freeboard to allow the passage of debris through the culvert. A single barrel is preferable to several multiple openings and the culvert should be well-aligned with the approach flow if possible, with a smooth inlet transition. Skewed approach flow and internal obstructions such as steps, bends and changes in cross-section should be avoided (FHWA 2001). At sites with higher blockage risks, debris could be intercepted upstream of the structure or deflected away from the structure. Consideration should be given to the possibility of using a bridge structure rather than a culvert where this is economically beneficial.

At new bridges, the probability of blockage can be reduced by providing long spans and adequate freeboard (Diehl 1997). Solid, rounded piers shed debris more easily than pile groups, blunt or sharp-nosed piers. Piers should be placed on or near the riverbank rather than in the path of debris or at locations of in-stream sedimentation. At existing bridges, the degree of blockage can be reduced by retrofitting cutwaters.

Floating booms or surface skimmers reduce blockage of control structures such as weirs, flumes and control gates, although they must be inspected and maintained. Safe access should be provided for the removal of debris and sediment accumulations, while discouraging unauthorised access. Options include:

- provision of a footbridge
- retractable booms
- a sufficiently broad crest and harness points on the side walls
- space for lifting equipment adjacent

### *Inspection*

Inspection can reduce the impact of blockage by allowing timely intervention. High risk locations such as screens should be inspected routinely according to the risk, with the frequency of inspection and removal of debris varying according to the likelihood and consequences of blockage (typically weekly, fortnightly, monthly or quarterly). Additional inspections may be carried out after a weather warning, a flood warning or the triggering of a water level alarm.

Taking photographs before and after cleaning can build a record of the rate of debris accumulation.

For lower risk structures such as bridges, a less frequent inspection regime may be appropriate, with inspections before the start of the flood season and before an event, based on forecast or observed rainfall, flows or water levels, or on receipt of a weather or flood warning. Some asset owners inspect culverts annually to biannually, depending on size.

An important aspect of any inspection regime is to have a process of capturing reports from third parties (such as the general public) of blockage and ensuring these are passed on to those in an organisation best placed and competent to respond.

### *Monitoring*

Monitoring is the systematic or regular surveillance of an asset. It can be used to trigger inspection and maintenance, before or during a high flow event.

Differential water level monitoring across a structure can be used to detect blockage, with levels transmitted to a control room or network via telemetry and triggering an alarm if the head difference exceeds a defined threshold. This can be supported by webcam or closed circuit television (CCTV) images transmitted at intervals. An infrared sensor can be used to provide images after dark.

Combined level and velocity monitoring has potential for the future (Whalley 2012). An increase in water level upstream of a structure accompanied by a reduction in velocity indicates blockage, whereas an increase in both water level and velocity indicates no blockage. Real-time blockage estimation has also been attempted by comparing observed stage and discharge with a known rating curve for the 'no blockage' scenario (Whitlow and Morgan 2012).

The viability of monitoring depends on factors such as access, power supply, data logging and transmission of results. Data can be transmitted to a control centre, mobile phones or the 'cloud' (for viewing by authorised users) by telephone landline or wireless technology such as mobile phone (signal required). Alternatively, results can be displayed on-site using light-emitting diode (LED) displays (for example, road closed signs), lights or alarms.

### 4.8.6 Remove debris

During the consultation for this project, the main reasons for the removal of debris were identified as the need to maintain flow capacity and to prevent flow around the blockage from eroding the bed and banks of the watercourse, potentially undermining nearby structures. Debris may also be removed if it could affect gauging equipment. The removal of debris is prioritised with regard to the potential impact on flood risk and available funding.

Consultees stated they either remove debris themselves or advise the asset owner or riparian owner of the problem.

The method of removal depends on size and safety factors associated with the location. Small, manageable blockages are removed using appropriate hand tools and more extensive sediment and debris blockages with specialist contractors and equipment.

Measures commonly used to manage deposition are summarised in Table 4.6.

**Table 4.6 Measure to manage sedimentation**

| Problem | Measure | Description |
|---|---|---|
| Sediment transfer | Re-grading | Large-scale modification of the longitudinal bed profile |
| | Re-sectioning | Large-scale modification of channel cross-section |
| | Gravel trapping | Installation of structures to prevent coarse sediment transport |
| Deposition | Dredging | Underwater excavation, may be spread on land for environmental benefit |
| | De-silting | Removal of accumulated sediment from the bed of a channel |
| | Shoal removal | Selective removal of individual bars and riffles |
| | Groynes/deflectors | Installation of structures to promote change in deposition patterns |

Source: After Environment Agency (2011a)

The SEPA good practice guide on sediment management provides a flow chart to assist decision-making in sediment removal (SEPA 2010a). Sediment removal is only recommended if infrastructure or an activity such as navigation is at risk and there are no sustainable options for addressing the causes or consequences. Advice on the re-introduction of removed sediment to mitigate against the impacts of removal (such as sediment starvation) is also given.

Consultees advised that sediment removal is generally planned work and disposal depends on the nature of the material. Sediment is either returned to the river downstream of the structure or tested for waste acceptance criteria and disposed of at an exempt site or landfill site, depending on the result.

Consultees segregate debris into green waste and general debris, with green waste sent for recycling or shredded on-site and left on the river banks, and general debris returned to depots for disposal to a licensed tip.

### 4.8.7 Retain debris

The retention of woody debris in rivers is promoted by several good practice texts as woody debris plays an important role in ecosystems and can create dams capable of storing flood water, leading to flood peak attenuation (Mott 2005, SEPA 2009, SEPA 2010b, Forestry Commission 2011).

The Forestry Commission guidelines recommend the management of riparian woodland so as to sustain the delivery of large woody debris to small watercourses. Retained woody debris should be pegged to the bed or the banks of the watercourse, although care is required where debris can wash out and cause blockages.

The guidance advises that removal may be justified:

- if there is a risk of debris accumulating at bridges and culverts, leading to flooding
- if debris could act as a barrier to navigation or migratory salmonids
- if debris could accumulate sewage, litter and rubbish in urban areas

# 5 Existing data and methods

## 5.1 Introduction

Existing blockage data and methods for predicting aspects of debris load and blockage in various settings are summarised in 5 groups (A–F) in Tables 5.1 and 5.2 with further detail in Sections 5.2 to 5.7. Methods to visualise the impact of blockage occurring, quantify impact of blockage occurring (or not occurring) or to measure benefits of preventing blockage are not considered here since these are generic rather than blockage specific.

**Group A** consists of largely qualitative screening methods for predicting potential blockage locations. Method A1 was developed for the UK some 17 years' ago using practitioner elicitation rather than evidence. Method A2 was developed for Ireland more recently, again drawing on engineering judgement. Finally, Method A3 was developed for Australia, drawing on limited observed data supplemented by theoretical analysis, published reports and guidelines, and the experience of practitioners. All 3 methods identify similar risk factors and are considered applicable to the UK.

**Group B** contains simple methods for predicting locations of sedimentation. Methods B1, B2 and B4 were developed in the UK, while Method B3 is a generic method applicable to the UK. Numerical models to simulate sediment fluxes and morphological changes could be used to estimate rate of blockage build-up, but these were considered to be over-complicated for the purpose of this study.

**Group C** contains 4 methods for predicting the type and volume of floating debris. Method C1 covers urban debris and was derived using data from the Thames catchment. This method is applicable to the UK but may have limitations when applied to steeper catchments. Methods C2 and C3 used data from mountain torrents in Japan, Switzerland and the USA, and are considered to be of limited applicability to the UK. Method C4 used data from a range of river types in France, but considers only large woody debris and is considered unsuitable for urban or suburban land use watercourses in the UK.

**Group D** gives 2 methods to estimate the probability of blockage, both based on a set of observations from Belfast, but derived using slightly different variables and statistical approaches. Both methods are recent and potentially applicable to mainland Britain.

**Group E** contains 9 methods to predict the degree of blockage at screens and bridges, with methods for bridge piers, bridge decks, narrow gaps, low gaps and drainage structures generally. Method E1 for screens used data from Belfast and as such has greatest potential for application to mainland Britain. Methods E2 to E9 for bridges were all developed for flat bridges rather than masonry arches; they therefore have limitations for application to the UK but are worthy of closer examination. Methods E2, E7 and E8 were based on observed blockage in the USA and may over-estimate due to the prevalence of large debris rafts in that country.

In **Group F**, Method F1 from Australia was the only method to predict the rate of debris blockage build-up. Since the method is based on first principles rather than observed data, the method should be transferable to the UK

The mapping of published methods onto asset types in Table 5.2 highlights the specific nature of most studies and the considerable gaps in knowledge. The table shows that guidance on high risk structures such as screens, culverts and bridges is most readily available, although still limited. There are no data or methods for control gates, flapped outfalls, temporary works, weirs, flumes or open channel.

**Table 5.1 Summary of existing methods identified by the literature review**

| Output | Method | Data sources |
|---|---|---|
| **A Potential blockage locations (debris)** | Method A1: Environment Agency (1998) | Practitioner elicitation |
| | Method A2: OPW (2013) | Engineering judgement |
| | Method A3: Engineers Australia (2015) | Wollongong, Australia |
| **B Potential blockage locations (sediment)** | Method B1: Identify geomorphic watercourse typology (Environment Agency 2014b) | Catchments throughout England and Wales |
| | Method B2: Fluvial audit | |
| | Method B3: Velocities for erosion and deposition | Empirical |
| | Method B4: Stream power and/or shear stress analysis | UK catchments |
| **C Debris load** | Method C1: Magenis (1988) | 31 sites in the Thames catchment, UK |
| | Method C2: Uchiogi et al. (1996) | Flooding in Japan |
| | Method C3: Rickenmann (1997) | Mountain torrents in Japan, Switzerland, USA |
| | Method C4: Piégay and Gurnell (1997) | River Drôme, France |
| **D Probability of blockage** | Method D1: Wallerstein and Arthur (2012a) | Belfast, Northern Ireland: 140 sites, 25,265 readings |
| | Method D2: Streftaris et al. (2013) | |
| **E Degree of blockage** | Method E1: Wallerstein and Arthur (2012a) | Belfast, Northern Ireland: 140 sites, 25,265 readings |
| | Method E2: Bridge piers (Diehl 1997) | 2,557 blockage reports and 144 field investigation sites |
| | Method E3: Bridge piers (Wellwood and Fenwick 1989) | Australia |
| | Method E4: Bridge piers (New Zealand Transport Agency 2003) | Not specified |
| | Method E5: Bridge piers (NAASRA 1976) | Not specified |
| | Method E6: Bridge decks (Diehl 1997) | As Method E2 |
| | Method E7 Narrow gaps (Diehl 1997) | As Method E2 |
| | Method E8 Low gaps (Diehl 1997) | As Method E2 |
| | Method E9: Drainage structures (Engineers Australia 2013) | Single event, Wollongong, Australia |
| **F Rate of blockage** | Method F1: Engineers Australia (2015) | Observations in Australia |

**Table 5.2 Applications of existing methods**

<table>
<tr><th>Group</th><th>Method</th><th>Control gate</th><th>Flapped outfall</th><th>Screen</th><th>Culvert</th><th>Bridge</th><th>Temp works</th><th>Weir</th><th>Flume</th><th>Open channel</th></tr>
<tr><td>A</td><td>Potential blockage locations (debris)</td><td></td><td></td><td colspan="2">A1, A2, A3</td><td>A2, A3</td><td></td><td></td><td></td><td></td></tr>
<tr><td>B</td><td>Potential blockage locations (sediment)</td><td colspan="9">B1 to B4</td></tr>
<tr><td>C</td><td>Type and volume of debris</td><td colspan="9">C1 to C4</td></tr>
<tr><td>D</td><td>Probability of blockage</td><td></td><td></td><td>D1, D2</td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>E</td><td>Degree of blockage</td><td></td><td></td><td>E1</td><td colspan="2">E2 to E9</td><td>E7 to E9</td><td></td><td></td><td></td></tr>
<tr><td>F</td><td>Rate of blockage build-up</td><td></td><td></td><td colspan="3">F1</td><td></td><td></td><td></td><td></td></tr>
</table>

Notes: See Table 5.1 for explanation of the codes A1, A2, A3 and so on used here.

## 5.2 Group A: Potential blockage locations (debris)

### 5.2.1 Method A1: Environment Agency (1998)

The risk assessment procedure for structure blockage is a semi-quantitative method to identify which culverts and screens should be assessed for blockage in flood risk mapping. The procedure is based on experience rather than objective quantitative evidence.

The procedure uses 28 variables to class risk (that is, probability) of blockage as low (<20%), medium (20–40%) or high (>40%) (Table 5.3).

The consequences of blockage are classed as:

- mild – rural areas, areas with isolated properties or urban areas with adjacent ground levels well above river bank levels at the structure
- severe – existing or proposed urban areas, industrial areas, or major transport routes with ground levels close to river bank level

The need for more detailed assessment is determined using a decision tree based on probability and consequences. The next 3 options are:

- no further action
- assess blockage using manual method
- assess blockage using hydraulic model

**Table 5.3 Method A1: Blockage risk factors**

| Group | Factors |
|---|---|
| **Flood growth curve** | |
| Structure details | • Upstream and downstream invert levels<br>• Barrel length<br>• Bed slope<br>• Shape code<br>• Span or diameter<br>• Rise<br>• Number of openings<br>• Manning's roughness for barrel and bed<br>• Trash screen fitted? |
| Structural factors | • Multiple openings in structure<br>• Poor entrance or exit conditions<br>• Poor barrel condition<br>• Poor river approach<br>• Aspect ratio (span < rise) |
| Flood hydrology factors | • Capacity [of structure] relative to target flood<br>• Proximity of design flow to soffit<br>• Frequency of flash flooding<br>• Frequency of long slow rise floods |
| River condition | • Level of urbanisation near structure<br>• Evidence of tipping into river<br>• Density of bankside growth (large or small)<br>• Amount of loose bankside material |
| Maintenance | • Frequency of maintenance visits |

### 5.2.2 Method A2: OPW (2013)

The culvert blockage analysis identifies culverts at low risk and potential risk of blockage. The basis of the method was not given, although it was tested on a pilot study on the Poddle River.

The Stage 1 applicability test screens out low risk culverts and identifies culverts where significant risks might arise due to blockage, which are carried forward to Stage 2. This qualitative test uses a flow chart to consider 7 risk factors (Table 5.4).

The Stage 2 significance test uses hydraulic modelling to assess whether the consequences of blockage are likely to be significant and to identify which culverts to carry forward to the more time-consuming (and expensive) Stage 3 assessment. Stage

2 assumes 60% blockage for the 1% Annual Exceedance Probability (AEP) event (1 in 100 year return period flood). It also assumes that the blockage occurs at the culvert invert (meaning that 40% of the cross-sectional area closest to the culvert soffit remains available for flow conveyance).

Stage 3 is a quantitative assessment of flood outlines and damages. The guidance recommends that pinch points in series along a watercourse should each be assessed in isolation.

Informal feedback suggests that the 3-stage process would benefit from streamlining (personal communication from Jonathan Cooper and Amanda Kitchen).

**Table 5.4 Method A2: Blockage risk factors**

| Method | Risk factors |
|---|---|
| Stage 1: Applicability test | • Predominantly urban or wooded catchment<br>• High priority watercourse<br>• Poorly performing screen that may require improvement<br>• Culvert barrel area <3m2<br>• Full or nearly full flow for 1% AEP flood<br>• Blockage history |
| Stage 2: Significance test | • Flood depth increased by more than 0.5m at any location beyond the river channel<br>• More than one individual risk receptor (property or infrastructure asset) flooded as a result of the blockage<br>• More than 10 additional receptors flooded as a result of the blockage<br>• Any other or combined reasons |

### 5.2.3 Method A3: Engineers Australia (2015)

This method assesses the potential for blockage at drainage structures, drawing on observations and theoretical work by Rigby and Silveri (2001), Rigby and Barthelmess (2011) and others.

First, the debris availability, mobility and transportability are rated as high, medium or low (Table 5.5). These factors are combined to give the 'debris potential' (again high, medium or low), which is adjusted for flood magnitude. The most likely inlet blockage levels (as a percentage) is obtained from a matrix comparing 'at site debris potential' and the control dimension (the ratio between the debris length and structure opening diameter or width). A similar matrix is given for most likely depositional blockage levels (as a percentage) for sediment, based on mean sediment size, peak velocity through the structure and the AEP adjusted debris potential.

The likely blockage timing is obtained from a matrix as a function of:

- dominant source material (floating or submerged)
- delivery (progressive, pulsed, top-down, bottom-up or porous plug)
- likely blockage location

This stage is not evidence-based and further refinement was recommended.

**Table 5.5 Method A3: Blockage risk factors**

| Step | Description | Output |
|---|---|---|
| 1 | Debris availability | H, M or L |
| 2 | Debris mobility | H, M or L |
| 3 | Debris transportability | H, M or L |
| 4 | Debris potential | H, M or L |
| 5 | Debris potential adjusted for flood magnitude | H, M or L |
| 6 | Likely degree of blockage ($B_{des}$) | 0–100% |

Notes: H = high, M = medium, L = low.

The 2013 report (Engineers Australia 2013) rated the consequences of blockage from 1 to 5 based on estimated flood damages and qualitative assessment of health, environment, social, community and legal impacts, although this was omitted from the 2015 guide (Engineers Australia 2015), which gives concise guidance on the management of blockage.

## 5.3 Group B: Potential blockage locations (sediment)

### 5.3.1 Method B1: River typology (Environment Agency 2014b)

This method is described in the 'Aquatic and Riparian Plant Management: Technical Guide' (Environment Agency 2014b). It involves identifying the geomorphic watercourse typology and hence the dominant processes – erosion or deposition. This is a desk study approach using readily available data such as photographs, aerial imagery, historic maps, existing maps or local knowledge of the watercourse.

Blockage risk could be higher for:

- assets in the lower energy reaches of rivers with a high sediment load, where sediment is transported readily and frequently
- assets located on watercourses where upstream incision increases sediment load arriving at the asset
- assets located in low energy zones (for example, upstream of an impounding structure), particularly if the asset has a low conveyance capacity; impoundment zones can be readily identified using aerial imagery

Signs of channel stability and factors indicating risk of deposition are given in Tables 5.6 and 5.7 respectively.

**Table 5.6 Method B1: Signs of channel stability**

| Signs of deposition | Signs of stability | Signs of incision |
|---|---|---|
| • Large, uncompacted bars<br>• Eroding banks at shallows<br>• Contracting bridge openings<br>• Deep, fine sediment over coarse sediment<br>• Buried structures | • No evidence of planform change on old maps<br>• Little bank erosion<br>• Well-established trees on banks<br>• Vegetated banks and bars<br>• Compacted, weed-covered bed<br>• Old structures in position | • Old channels in floodplain<br>• Trees collapsing or leaning towards channel<br>• Bank failures on both banks<br>• Armoured or compacted bed |

Notes: Adapted from Sear et al. (2003)

**Table 5.7 Method B1: Factors indicating risk of deposition**

| Element | Higher risk of deposition | Low risk of deposition |
|---|---|---|
| Catchment | • Climate change (> rainfall)<br>• Upland or agricultural drainage<br>• Afforestation<br>• Urban development | • Climate change (< rainfall)<br>• Dams/river regulation<br>• Reduced cropping/grazing<br>• Vegetation of slopes/scars<br>• Sediment management |
| Watercourse | • Mild slope<br>• Downstream weirs or bed controls<br>• Steep tributaries<br>• Agricultural run-off<br>• Tidal sediment input<br>• Upstream erosion or bank retreat<br>• Upstream embanking<br>• Channel straightening | • Upstream weirs or bed controls<br>• Sediment traps<br>• Upstream deposition<br>• Fast flow, whitewater |
| The structure | • Asset opening larger than upstream watercourse<br>• Bed slope through asset is milder than upstream and downstream watercourse<br>• Skew approach flow | • Asset opening smaller than watercourse |

Notes: Adapted from Sear et al. (2003)

### 5.3.2 Method B2: Fluvial audit

A fluvial audit involves a catchment- and reach-scale assessment of sediment sources, transfer and storage reaches within a river network, with the aim of understanding the factors that influence sediment transport. This allows a catchment-scale approach to be taken to solving specific sediment-related problems.

An audit uses a combination of desk study information (for example, evidence of catchment and channel changes, historic maps and aerial photographs) and field survey data. Outputs include:

- a time chart of the catchment and river channel showing changes that may have affected the geomorphology of the system
- a catchment map showing features that are important to the development of the river channel
- a detailed map of the reach under consideration

Further information about fluvial audits is given in Defra (2009), Environment Agency (2011a) and Sear et al. (2003).

### 5.3.3 Method B3: Hjülstrom curve

This method uses a Hjülstrom curve (Hjülstrom,1935) to determine whether a watercourse is likely to erode or deposit. It has the advantage that it takes sediment type into account, although it does not allow for flow depth. The estimated flow velocity in the stream is compared with the velocity for deposition for the bed material from the Hjülstrom curve. The flow velocity can be readily obtained from existing flood models while sediment size can be obtained during a site visit or fluvial audit.

### 5.3.4 Method B4: Stream power and/or shear stress analysis (various authors)

This method is based on various studies in the UK including Wallerstein (2006) and Sear et al. (2003). The likelihood of sedimentation is estimated by comparing specific stream power with thresholds for stability and instability. Shear stress is sometimes used as an alternative to stream power.

Specific stream power (in $W/m^2$) is given by:

$$\omega = \frac{\rho g Q S}{w}$$

where:

$\rho$ = density of water ($kg/m^3$)

g = acceleration due to gravity ($m/s^2$)

Q = discharge ($m^3/s$)

S = slope (m/m)

w = channel width (m)

Indicative rules are as follows:

- Low energy ($\omega < 10W/m^2$) – sedimentation likely
- High energy streams ($\omega > 35W/m^2$) – erosion likely

This method is best suited to a broad-scale assessment as the relationship between stream power and channel stability is poorly defined. Furthermore, this method does not take bed sediment type into account.

A computerised tool for estimating stream power and predicting stream channel adjustment – Sediment Transport: Reach Equilibrium Assessment Method or ST:REAM – was developed under the FRMRC2 programme (Parker 2010, Parker et al. 2014). The tool uses simple hydrological data and remotely sensed slope and width data, and splits reaches into erosion or deposition dominated. However, the tool has limitations in its applicability.

## 5.4 Group C: Debris load/debris volume

Methods for estimating debris load were in some cases intended for the design of screens. However, but might – with validation – be transferrable to other structure types.

### 5.4.1 Method C1: Magenis (1988)

This method gives annual debris load ($m^3$/year) as a function of upstream catchment type. The method is based on 10 years of data from 17 screens on the Ravensbourne in the Thames catchment. Guidance in the Trash and Security Screen Guide and its predecessors (NRA 1992, Environment Agency 2002, Environment Agency 2009) and the Culvert Design and Operation Guide (Balkham et al. 2010) is based on this method.

The design debris amount, Dda ($m^3$/year) is given by:

$$Dda = Da \times F$$

where:

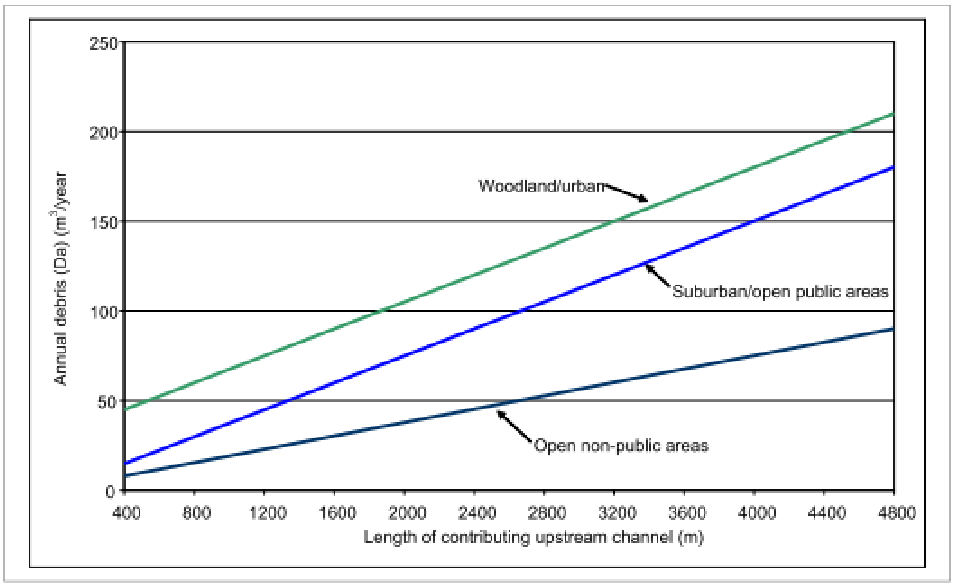
Da = annual debris amount (m3/year) (Figure 5.1)

F = stream slope adjustment factor (based on S1085) (Table 5.8)

The annual debris amount, Da ($m^3$/year) arriving at a structure is based on contributing length of river and land use (Figure 5.1).

The method does not describe how to deal with differing land use on the left and right banks. Possible approaches are to take the predominant land use type, or to determine the land use for each bank and take the average.

**Figure 5.1 Method C1: Annual debris load**




Source: Environment Agency (2009)

**Table 5.8 Method C1: Stream slope adjustment factors**

| Average gradient (S1085) | Slope factor, F |
|---|---|
| Steeper than 1 in 250 | 1.00 |
| One in 250 to 1 in 500 | 0.75 |
| One in 500 to 1 in 1000 | 0.50 |
| Milder than 1 in 1000 | 0.25 |

Notes: 'S1085' refers to the average gradient of a watercourse determined over the contributing upstream length. It is the measurement of the largest stream length in the catchment upstream of the culvert – from the culvert to the furthest point upstream. Points at 10% and 85% along this main length are identified and the elevation noted. The slope between these 2 points is the average gradient (Environment Agency 2009).
Source: Magenis (1988)

### 5.4.2 Method C2: Uchiogi et al. (1996)

This method consists of 3three empirical equations for the volume of driftwood transported during floods and was based on observations during several floods in Japan. The loosely placed driftwood volume ($V_L$) is the volume occupied by the wood and voids, while potential driftwood volume ($V_{LP}$) is presumed to be the volume of solids only, rather than solid plus voids (both in $m^3$).

$$V_L = 0.02F$$

$$V_{LP} = (10 - 1{,}000)A_F \text{ for coniferous forest}$$

$$V_{LP} = (10 - 100)A_F \text{ for deciduous forest}$$

where:

F = volume of sediment transported during the flood event ($m^3$)

$A_F$ = forested area ($km^2$)

### 5.4.3 Method C3: Rickenmann (1997)

This method consists of a suite of empirical equations for the volume of driftwood transported during floods based on observations during floods in Switzerland, the USA and Japan. Again, the loosely placed driftwood volume ($V_L$) is the volume occupied by the wood and voids, while potential driftwood volume ($V_{LP}$) is presumed to be the volume of solids only, rather than solid plus voids (both in $m^3$).

$$V_L = 45A^{2/3}$$

$$V_L = 4V_W^{2/5}$$

$$V_{LP} = 90A_F \text{ for } A_F < 100\text{km}^2$$

$$V_{LP} = 40L_F^2 \text{ for } L_F < 20\text{km}$$

where:

A = catchment area ($km^2$)

$V_W$ = volume of water (that is, hydrograph volume) ($m^3$)

$A_F$ = forested area ($km^2$)

$L_F$ = forested river length (km)

Most of the data originated from mountain torrents with small catchment areas and therefore results in large scatter when applied to larger catchments. The first 3 equations above have been found to underestimate driftwood volume for most rivers, while the fourth one has been found to mostly over-estimate (Schmocker and Weitbrecht 2013).

### 5.4.4 Method C4: Piégay and Gurnell (1997)

This method predicts the number of wood pieces (Y) located in a 500m length of river bed, where woody pieces are defined as those exceeding 0.1m in diameter or 1m in length. The method was based on regression analysis of data from the Drôme river in France.

$$Y = 11.99X_1 + 10.44X_2 + 6.21X_3 - 22.6$$

where:

$X_1$ = braiding index in the 500m length = ratio of total wetted channel length to valley length

$X_2$ = number of wooded islands in the 500m length

$X_3$ = length of eroding wooded banks in the 1km section immediately upstream (m)

## 5.5 Group D: Probability of blockage

### 5.5.1 Method D1: Wallerstein and Arthur (2012a)

This method gives the probability of significant debris delivery at screens (sufficient for some material to be retained as a blockage) based on logistic regression analysis of the Belfast dataset. The probability of blockage is defined through the logistic transform:

$$P_d = \frac{e^{\log it(P_d)}}{\left(1 + e^{\log it(P_d)}\right)}$$

where:

$$\log it\left(P_{d(a,m,s)}\right) = \alpha + \beta_1 NL_{\log} + \beta_2 SL + \beta_3 Q_{n\log} + \beta_4 R_{\log} + \beta_5 A_{\log} + \beta_6 S_{\log} + \beta_7 SO_{\log} + \beta_8 U_{\log} + \beta_9 ID$$

and

NL = upstream network length (m)

SL = upstream channel slope (m/m)

$Q_n$ = n-return period flow (2, 10, 50 and 100 years) ($m^3/s$)

R = contributing rural land use cover (%)

A = contributing agricultural land use cover (%)

S = contributing suburban land use cover (%)

SO = contributing suburban open land use cover (%)

U = contributing urban land use cover (%)

ID = Income Domain Score

$\alpha$, $\beta_1$ to $\beta_9$ = coefficients

Summary statistics for the source dataset are given in Table 5.9 and the equations for each month, season and annual average are given in Table 5.10.

**Table 5.9 Method D1: Summary statistics for the independent variables and how typical they are of those found elsewhere in the UK**

| | *NL* (m) | *SL* (m/m) | $Q_2$ ($m^3/s$) | $Q_{10}$ ($m^3/s$) | $Q_{50}$ ($m^3/s$) | $Q_{100}$ ($m^3/s$) | *ID* (%) | $SA_t$[1] ($m^2$) | *S* (m) | *A* (deg.) |
|---|---|---|---|---|---|---|---|---|---|---|
| **min.** | 19 | 0.001 | 0.1 | 0.1 | 0.1 | 0.1 | 0.04 | 0.4 | 0.07 | 40 |
| **max.** | 8538 | 0.505 | 8.3 | 13.0 | 19.4 | 22.2 | 0.68 | 16.4 | 0.50 | 90 |
| **mean** | 1044 | 0.047 | 1.4 | 2.2 | 3.4 | 3.9 | 0.16 | 4.0 | 0.16 | 55 |
| **std. dev.** | 1170 | 0.062 | 1.4 | 2.2 | 3.3 | 3.9 | 0.13 | 3.4 | 0.08 | 16 |
| **typical for UK?** | typ. range | steep | - | - | - | - | sig. disparity[2] | typ. range | typ. design[3] | typ. design[3] |

Notes: [1] Denotes total screen area.
[2] ONS (2010)
[3] Environment Agency (2009)
Source: Wallerstein and Arthur (2012a, Table 3)

**Table 5.10 Method D1: Equations for probability of blockage**

| | $P_d$ | logit $P_d$ | F | $F_{crit}$ | $R^2$ |
|---|---|---|---|---|---|
| **Av.** | $P_d = e^{\text{logit } P_d} / (1 + e^{\text{logit } P_d})$ | -1.14 + (logNL × 0.28) + (logR × -0.19) + (logAG × -0.24) + (ID × 1.12) | 13.0 | 2.4 | 0.26 |
| **Jan.** | | -0.06 + (logSU × 0.31) | 8.4 | 3.9 | 0.06 |
| **Feb.** | | -0.71 + (logAG × -0.18) | 5.2 | 3.9 | 0.03 |
| **Mar.** | | -1.03 + (logNL × 0.33) + (logAG × -0.32) | 10.4 | 3.0 | 0.12 |
| **Apr.** | | -0.49 + (logR × -0.35) + (logAG × -0.29) | 10.6 | 3.0 | 0.12 |
| **May** | | -1.56 + (logSU × 0.24) + (ID × 2.68) | 13.9 | 2.6 | 0.16 |
| **Jun.** | | -2.30 + (logNL × 0.32) + (logAG × -0.22) + (logSU × 0.31) + (ID × 1.92) | 21.9 | 2.4 | 0.38 |
| **Jul.** | | -1.54 + (logAG × -0.28) + (logSU × 0.31) + (ID × 3.00) | 25.9 | 2.6 | 0.35 |
| **Aug.** | | -1.90 + (logNL × 0.25) + (logAG × -0.22) + (logSU × 0.25) + (ID × 2.30) | 17.2 | 2.4 | 0.32 |
| **Sep.** | | -1.62 + (logNL × 0.28) + (logR × -0.28) + (logAG × -0.33) + (ID × 1.62) | 12.6 | 2.4 | 0.25 |
| **Oct.** | | -0.44 + (logSU × 0.30) | 12.6 | 3.9 | 0.08 |
| **Nov.** | | -0.62 + (logNL × 0.44) + (logAG × -0.48) | 19.9 | 3.0 | 0.21 |
| **Dec.** | | -0.81 + (logNL × 0.28) + (logAG × -0.20) + (ID × 1.57) | 9.1 | 2.6 | 0.15 |
| **Spr.** | | -1.10 + (logNL × 0.23) + (logSU × 0.17) | 6.7 | 3.0 | 0.08 |
| **Sum.** | | -1.45 + (logNL × 0.26) + (logR × -0.24) + (logAG × -0.25) + (ID × 1.12) | 12.4 | 2.4 | 0.25 |
| **Aut.** | | -1.60 + (logR × -0.19) + (logAG × -0.24) + (logSU × 0.22) + (ID × 2.12) | 21.5 | 2.4 | 0.37 |
| **Win.** | | -0.51 + (logNL × 0.30) + (logAG × -0.31) | 12.4 | 3.0 | 0.14 |

Source: Wallerstein and Arthur (2012a, Table 4)

### 5.5.2 Method D2: Streftaris et al. (2013)

This method gives the probability of significant blockage (5% or more) at screens based on Bayesian analysis of the Belfast dataset. The probability of significant blockage of screen i at time j (0/1 or not blocked/blocked) is given by:

$$Y_{ij} \sim \text{Bernouilli}(p_{ij})$$

$$\log it\left(p_{ij}\right) = \beta_0 + \beta_1 L_i + \beta_2 S_i + \beta_3 U_i + \beta_4 MDM_i + \beta_5 R_{ij} + \beta_6 L_i \times S_i + m_{Month(ij)}$$

where:

$L_i$ = network length (m)

$S_i$ = channel slope (m/m)

$U_i$ = urban land use (%)

$R_{ij}$ = mean daily rainfall between inspections (mm/day)

$MDM_i$ = Multiple Deprivation Measure (index)

$\beta_0$ to $\beta_6$ = coefficients

$m_{Month(ij)}$ = month factor

Summary statistics for the source dataset are given in Table 5.11. Model coefficients are given in Table 5.12.

**Table 5.11 Method D2: Summary statistics for the channel, meteorological, land use and social deprivation variables**

| Statistics | *L* (m) | *S* (m/m) | *R* (mm/day) | *U* (%) | MDM (index) |
|---|---|---|---|---|---|
| Minimum | 19 | 0.001 | 0.0 | 0.0 | 2.2 |
| Maximum | 8,538 | 0.505 | 57.4 | 100.0 | 80.3 |
| Mean | 1,044 | 0.047 | 3.0 | 64.3 | 16.5 |
| Standard deviation | 1,170 | 0.062 | 3.1 | 43.6 | 15.6 |

Note: *L* = network length; *S* = channel slope; *R* = mean daily rainfall between inspections; *U* = percentage urban land use; and MDM = multiple deprivation measure.

Source: Streftaris et al. (2013, Table 2)

**Table 5.12 Method D2: Posterior estimates of model coefficients (full model)**

| Coefficient | Variable | Mean | Standard deviation | 2.50% | 97.50% |
|---|---|---|---|---|---|
| $\beta_0$ | | −0.434 | 0.017 | −0.467 | −0.401 |
| $\beta_1$ | *L* | 0.115 | 0.017 | 0.082 | 0.147 |
| $\beta_2$ | *S* | 0.073 | 0.019 | 0.034 | 0.111 |
| $\beta_3$ | *U* | 0.325 | 0.018 | 0.290 | 0.359 |
| $\beta_4$ | MDM | 0.182 | 0.022 | 0.138 | 0.226 |
| $\beta_5$ | *R* | 0.558 | 0.016 | 0.526 | 0.589 |
| $\beta_6$ | $L \times S$ | 0.067 | 0.023 | 0.022 | 0.113 |
| $\beta_7$ | $U \times MDM$ | −0.002 | 0.026 | −0.052 | 0.047 |
| $m_1$ | January | 0.596 | 0.052 | 0.493 | 0.699 |
| $m_2$ | February | −0.242 | 0.054 | −0.349 | −0.138 |
| $m_3$ | March | 0.171 | 0.047 | 0.080 | 0.263 |
| $m_4$ | April | −0.259 | 0.047 | −0.351 | −0.168 |
| $m_5$ | May | −0.302 | 0.044 | −0.389 | −0.217 |
| $m_6$ | June | −0.352 | 0.045 | −0.442 | −0.265 |
| $m_7$ | July | −0.432 | 0.044 | −0.517 | −0.348 |
| $m_8$ | August | −0.328 | 0.043 | −0.412 | −0.245 |
| $m_9$ | September | −0.262 | 0.044 | −0.348 | −0.175 |
| $m_{10}$ | October | 0.312 | 0.042 | 0.230 | 0.394 |
| $m_{11}$ | November | 0.757 | 0.046 | 0.667 | 0.845 |
| $m_{12}$ | December | 0.342 | 0.048 | 0.246 | 0.435 |

Source: Streftaris et al. (2013, Table 3)

# 5.6 Group E: Degree of blockage

## 5.6.1 Overview

The consultation for this project revealed that industry practitioners commonly estimate the degree of blockage using engineering judgement or as a fixed proportion of structure opening area. A minority of the respondents take blockage as a fixed height or width. The degree of blockage used by practitioners varies between structure types and is inconsistent, even within the same organisation. Methods for predicting the degree of blockage are summarised in Table 5.13.

**Table 5.13 Methods for predicting degree of blockage**

| Asset type | Description | Source |
|---|---|---|
| All types | Low–medium–high (30%, 67%, 95%) | Industry practice |
| | 20 (100% if local knowledge or inspection indicates high risk) | |
| | 100% blockage to mirror NaFRA and System Asset Management Plans (SAMPs) benefits assumptions | |
| | Site-specific blockage, based on nature of the catchment and opening area of structure | |
| | Design: 10–50% | Engineers Australia (2013) |
| | Extreme: 25–100% | |
| | Depending on opening dimensions | |
| Screen | Empirical equation | Wallerstein and Arthur (2012a) |
| | 33%, 67%, 100% | Environment Agency (2009) |
| Screen or culvert | 75% | Environment Agency (1998) |
| Culvert | 60% | OPW (2013) |
| | 0% or 100% (blocked or unblocked) | MDSF2 (Environment Agency 2013a) |
| | Blockage or blinding: 33%, 67%, 100% | Balkham et al. (2010) |
| | Sedimentation: 5%, 15–25%, 80–100% | |
| Bridge (generally) | 5%, 25%, 80% | Industry practice |
| | Design: 0% to judgement | Engineers Australia (2013) |
| | Extreme: up to 100% | |
| Bridge (deck) | Span × (height of deck + 1.2m) | Diehl (1997), Wellwood and Fenwick (1989) |
| | Handrails: 100% | Engineers Australia (2013) |
| Bridge (low opening) | Width of gap × height of gap | Diehl (1997) |
| Bridge (narrow opening) | Width of gap × smaller of height of gap or flow depth | Diehl (1997) |
| Bridge (pier) | Design log length × flow depth, up to 3m unless site evidence warrants a greater height | Diehl (1997) |
| | Depends on size of pier | Engineers Australia (2013) |

### 5.6.2 Method E1: Wallerstein and Arthur (2012a)

This method gives the degree of blockage (that is, the screen area blocked by debris) and was developed by regression analysis of the Belfast dataset. The blocked area (in $m^2$) is estimated from:

$$\ln(SA_b) = \alpha + \beta_1 \log NL + \beta_2 SL + \beta_3 \log Qn + \beta_4 \log R + \beta_5 \log AG + \beta_6 \log SU + \beta_7 \log SU + \beta_8 \log U + \beta_9 .ID + \beta_{10} \log S + \beta_{11} \log A$$

where:

$Q_n$ = n-year return period flow ($m^3$/s)

R = contributing rural land use cover (0–100%)

S = contributing suburban land use cover (0–100%)

SO = contributing suburban open land use cover (0–100%)

ID = Income Domain Score (%)

S = screen bar spacing (m)

A = screen angle from horizontal (degrees)

$\alpha$, $\beta_1$ to $\beta_{11}$ = coefficients

Summary statistics are in Table 5.9 and Table 5.14 gives the equations for blocked area for each month and the annual average.

**Table 5.14 Method E1: Equations for degree of blockage**

| Area blocked | $A_{b(a,m)} = e^{\ln A_{b(a,m)}}$ |
|---|---|
| ln Area blocked | |
| annual | $lnA_{b(a)}$ = 7.41 + ($log$SO × -0.21) + ($log$BS × 2.69) + ($log$SA × -3.27) |
| january | $lnA_{b(j)}$ = 6.68 + ($log$SO × -0.27) + (ID × 2.33) + ($log$BS × 2.99) + ($log$SA × -3.16) |
| february | $lnA_{b(f)}$ = 4.51 + ($log$BS × 2.55) + ($log$SA × -2.60) |
| march | $lnA_{b(mr)}$ = 6.35 + ($log$BS × 2.93) + ($log$SA × -3.16) |
| april | $lnA_{b(ap)}$ = 6.00 + ($log$R × -0.44) + ($log$BS × 2.93) + ($log$SA × -3.30) |
| may | $lnA_{b(ma)}$ = 5.65 + ($Q_2$ × 0.19) + ($log$S × 0.37) + ($log$BS × 2.22) + ($log$SA × -3.85) |
| june | $lnA_{b(ja)}$ = 5.71 + ($log$S × 0.41) + ($log$BS × 3.00) + ($log$SA × -3.27) |
| july | $lnA_{b(jl)}$ = 5.22 + ($log$S × 0.29) + (ID × 2.60) + ($log$BS × 2.60) + ($log$SA × -3.30) |
| august | $lnA_{b(au)}$ = 6.50 + ($log$S × 0.32) + (ID × 1.68) + ($log$BS × 3.35) + ($log$SA × -3.50) |
| september | $lnA_{b(se)}$ = 4.63 + ($log$S × 0.24) + (ID × 1.91) + ($log$BS × 2.60) + ($log$SA × -2.79) |
| october | $lnA_{b(o)}$ = 5.70 + ($log$S × 0.27) + ($log$BS × 3.10) + ($log$SA × -2.79) |
| november | $lnA_{b(n)}$ = 4.65 + ($log S$ × 0.30) + (ID × 1.44) + ($log$BS × 2.94) + ($log$SA × -2.36) |
| december | $lnA_{b(d)}$ = 8.25 + ($log$BS × 2.79) + ($log$SA × -4.06) |

Source: Wallerstein and Arthur (2012a, Table 5)

### 5.6.3 Methods E2 to E5: Blockage at bridge piers

Four methods are available for estimating blockage dimensions for debris accumulation at bridge piers (Table 5.15).

Method E4 is aimed at the assessment of water pressure during design and recommends applying a triangular debris raft to bridge piers (Figure 5.2). The basis of the guidance is not given.

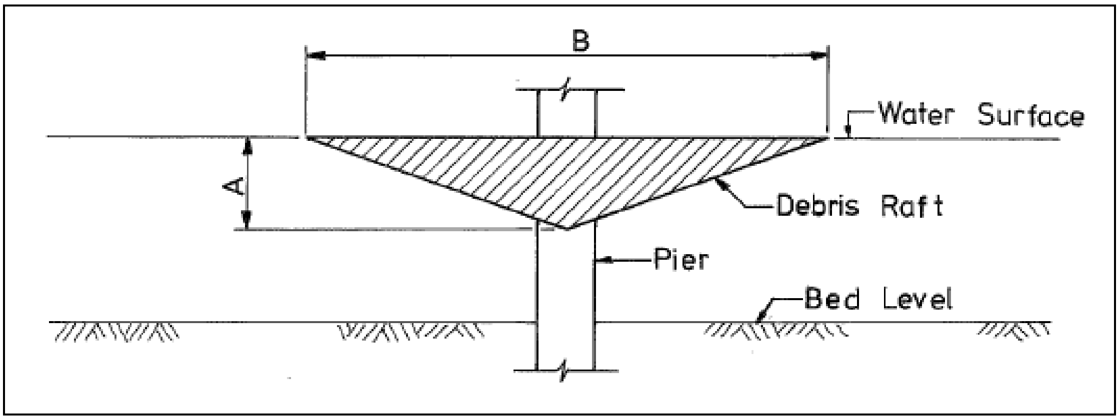
The remaining methods recommend applying rectangular rafts of debris to bridge piers.

**Table 5.2 Methods E2 to E5: Recommended blockage at bridge piers**

| Method | Blockage dimensions |
|---|---|
| Method E2 (Diehl 1997) | Rectangular raft, design log length × flow depth (up to 3m) |
| Method E3 (Wellwood and Fenwick 1989) | Average of adjacent spans (up to 20m) × 1.2m minimum |
| Method E4: (New Zealand Transport Agency 2003) | Inverted triangular raft (see Figure 5.3), where A = half the water depth, but no greater than 3m, and B = half the sum of adjacent span lengths, but no greater than 15m |
| Method E5 (NAASRA 1976) | 20m wide × 1.2m deep rectangular raft |

Notes: The design log length is taken as the minimum of upstream channel width, the maximum length of sturdy logs (or in the USA, 9m + channel width/4).

**Figure 5.2 Method E4: Recommended blockage at bridge piers**




Source: New Zealand Transport Agency (2003)

### 5.6.4 Method E6: Debris on bridge decks

This method recommends blockage dimensions for debris on bridge decks (Diehl 1997, Wellwood and Fenwick 1989) (Table 5.16). The evidence base is unknown but is presumed to be observations in Australia.

**Table 5.16 Method E7: Recommended blockage for bridge decks**

| Method | Blockage dimensions |
|---|---|
| Method E6 | Length of deck × height of deck + 1.2m below deck (up to 3m) |

### 5.6.5 Method E7 and E8 Debris across gaps

These methods give blockage dimensions for narrow and low gaps (Diehl 1997) (Table 5.17).

**Table 5.3 Methods E7 and E8L Debris across gaps**

| Method | Blockage dimensions | |
|---|---|---|
| Method E7 Narrow gaps | If design log length > width or height of gap | Width of gap × smaller of flow depth and height of gap |
| Method E8 Low gaps | | Width of gap × height of gap |

Notes: The design log length is taken as the minimum of upstream channel width, the maximum length of sturdy logs (or in the USA, 9m + channel width/4).

### 5.6.6 Method E9: Engineers Australia (2013)

This method estimates the degree of blockage at bridges and culverts (Engineers Australia 2013). The work is based on observations of blockage at 18 bridges and 63 culverts after a single storm in Wollongong, Australia (Rigby and Silveri 2001, Rigby and Barthelmess 2011).

Table 5.18 gives the most likely blockage level, $B_{DES}$ (%), based on the ratio of between the width of the controlling openings of structures (for example, bridge pier spacing or diameter or width of a culvert), W, to the length of the longest 10% of debris that could arrive at the site (termed here as $L_{10}$).

**Table 5.4 Method E6: Recommended degree of blockage**

| Control Dimension | At-Site Debris Potential | | |
|---|---|---|---|
| | High | Medium | Low |
| $W < L_{10}$ | 100% | 50% | 25% |
| $W \geq L_{10} \leq 3{*}L_{10}$ | 20% | 10% | 0% |
| $W > 3{*}L_{10}$ | 10% | 0% | 0% |

Source: Engineers Australia (2013, Table 3.6)

## 5.7 Group F: Rate of debris blockage

### 5.7.1 Method F1: Engineers Australia (2015)

This method gives the likely mobilisation time and timing of blockages at bridges and culverts (Engineers Australia 2015). The work is based on first principles rather than evidence. The rate of blockage is thought to be governed by the mobilisation mechanisms of different types of debris and affected by many factors such as the time of transport from mobilisation to the structure and the blockage type or location on the structure. Thus blockage at bridge piers may build up progressively, top-down blockage of an opening is initiated when water level approaches soffit level and blockage of railings occurs when the structure has been overtopped.

Table 5.19 gives the likely debris mobilisation times while Table 5.20 gives likely blockage timing. Key variables are:

- $B_{DES}$ = likely degree of blockage, based on size of available debris relative to structure opening width
- $T_P$ = likely time to peak
- $T_{O/T}$ = likely time of over topping

**Table 5.5 Method F1: Likely timing of peak mobilisation of debris**

| Debris type | Likely timing of peak mobilisation |
|---|---|
| Reeds and aquatic vegetation | Progressively during rising limb of a hydrograph with most mobilisation coinciding with peak in-bank flow. |
| Sediment<br>Rocks and boulders | Typically on the rising limb of flood hydrograph, around bankfull discharge. Peak deposition normally occurs on the falling limb as velocities reduce. |
| Grass and garden mulch | Commencement of overland flow, especially in rural areas. |
| Litter | Progressively during rising limb of a flood hydrograph once overland flows develop. |
| Urban debris | Likely to coincide with period of significant overbank flow (when depth × velocity ≥ 0.3 along overland flow paths). |
| Building debris | Often pulse-like delivery once significant overbank or overland flow develops. |

Source: Engineers Australia (2015)

**Table 5.6 Method F1: Likely blockage timing**

| DOMINANT SOURCE MATERIAL | SUPPLY RATE | BLOCKAGE LOCATIONS | | | |
|---|---|---|---|---|---|
| | | **Inlet** | **Barrel** | **Outlet** | **Handrails** |
| **FLOATING** | **Progressive** | $1.5T_P$ to $B_{DES}$ at $2.0T_P$ | Unlikely | Unlikely[2] | $T_{O/T}$ to $B_{DES}$ at $T_P$ |
| | **Pulse[1]** | $B_{DES}$ @ $0.5T_P$ | Unlikely | Unlikely | $T_{O/T}$ to $B_{DES}$ at $T_P$ |
| **NON FLOATING** | **Progressive** | $0.5T_P$ to $B_{DES}$ at $T_P$ | $0.5T_P$ to $B_{DES}$ at $T_P$ | $0.5T_P$ to $B_{DES}$ at $T_P$ | Unlikely |
| | **Pulse[1]** | Unlikely[3] | Unlikely | Unlikely | Unlikely |

*1. Pulse blockages are more likely in systems subject to infrequent flooding*

*2. Unlikely - but could become likely if inlet is open and outlet grated.*

*3. Unlikely – but could become likely if upstream bed/banks unstable and/or prone to scour*

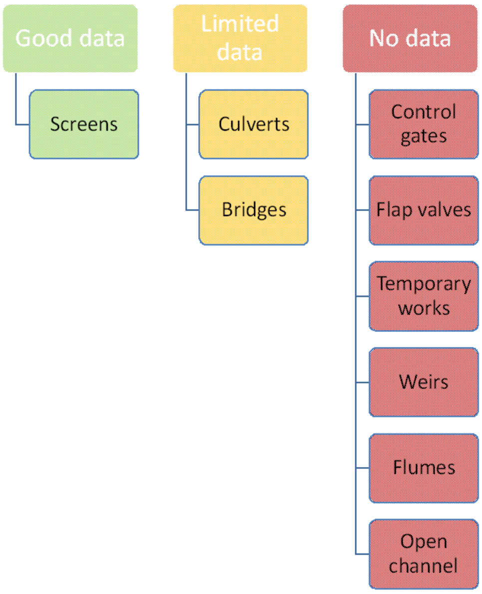
Source: Engineers Australia (2013, Table 3.7)

## 5.8 Knowledge gaps

Figure 5.3 summarises the quality of blockage data and knowledge gaps by asset type. Good data are defined as systematic monitoring of the degree of blockage with dates, while limited data are defined as snapshots of information on the frequency of blockage, degree of blockage or rate of blockage.

The best data are available for screens, with some data for bridges and culverts. Knowledge gaps exist for a wide range of assets: control gates, flap valves, temporary works, as well as all 3 open channel types (weirs, flumes and open channels).

**Figure 5.3 Summary of data and knowledge gaps by asset type**




There is potential to transfer data from one asset type to another and to simplify modelling approaches by defining groups of assets which behave in similar ways, either hydraulically, by blockage mechanism or the scale of impacts on water level and receptors. This would maximise the use of limited data and streamline the number of modelling methods required. Potential data transfers are identified in Figure 5.4 and Table 5.21. No potential data transfers were identified for weirs, flumes or open channels.

**Figure 5.4 Potential for data transfer**

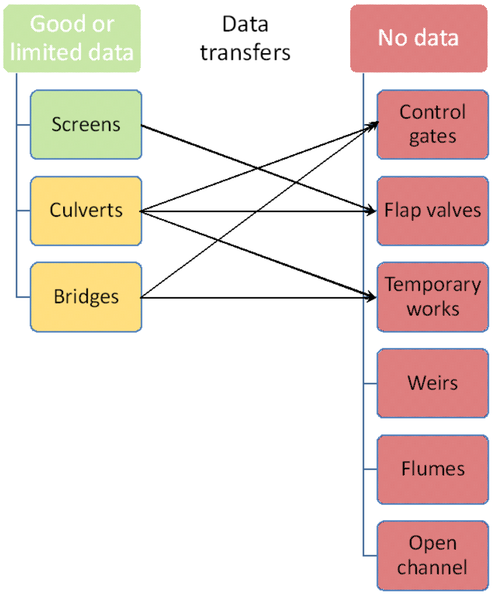



**Table 5.7 Potential for data transfer**

| No. | Recipient | Potential donor | Notes |
|---|---|---|---|
| 1 | Control gates | Culverts | Similar hydraulics: act as orifices |
| 2 | | Bridges | Similar scale of effects: widespread effects on water levels and significant effects on downstream flows |
| 3 | Flapped outfalls | Screens | Similar scale of effects: local effects on water levels and limited effect on downstream flows |
| 4 | | Culverts | Similar hydraulics: act as orifices |
| | | | Similar scale of effects: typically local effects on water levels and limited effect on downstream flows |
| 5 | Temporary works | Culverts | Similar blockage mechanisms |
| 6 | | Bridges | Similar blockage mechanisms |

## 5.9 Links to other research

Herriot-Watt University has funding to look at the performance of 2 automated trash screens. Work started in June 2014 with installation of the screens and may generate new data. The university is also developing a user-focused spreadsheet tool based on the FRMRC2 work, although this work is not expected to introduce new datasets.

An Exeter University project, ‘Risk Assessment of Masonry Bridges under Flood Conditions: Hydrodynamic effects of debris blockage and scour’, also began in 2014. This research will develop methods to evaluate the hydrodynamic effects of debris accumulation underneath or upstream of masonry bridges and typical bridge piers under flooding scenarios. The findings will be integrated into a risk-based strategy for assessment of bridges under hydraulic action. The project is mainly concerned with the assessment of scour at piers and abutments, and of lateral and uplift forces on the bridge due to floating debris blockage.

The Consortium on Risk in the Environment: Diagnostics, Integration, Benchmarking, Learning and Elicitation (CREDIBLE), with the JBA Trust and Bristol University, is conducting a project on the quantification of risks to bridges from erosion and blockage. The work will derive a synthesis of scientific and engineering knowledge, generate quantitative fragility curves and estimates of uncertainty, and demonstrate how the outputs can be applied. This work is receiving funding from the Natural Environment Research Council (NERC).

# 6 Performance of existing methods

## 6.1 Introduction

This chapter describes the evaluation of recent science on blockage. Selected methods were applied to realistic case studies with the aim of promoting confidence before taking these forward to the new guidance on blockage management.

## 6.2 Scope of evaluation

The methods chosen for evaluation are summarised in Table 6.1. The evaluation of all available blockage prediction methods was beyond the scope of this study and hence only 4 methods were assessed to inform the quantitative assessment of blockage.

Methods C and F have the potential to inform operation, maintenance and investment decisions. Method C estimates the volume of debris arriving at a pinch point; This is useful to estimate storage and disposal requirements and costs. Method F predicts the rate of blockage build-up and is useful to assess the required frequency of intervention and operational response time, and hence the need to undertake improvement works.

Methods D and E have the potential to inform modelling and mapping studies, and project appraisal for operational or capital works. Group D examines methods for predicting the probability of blockage at screens. Group E examines methods for predicting the area of blockage at screens and bridges.

**Table 6.1 Methods chosen for evaluation**

| No. | Variable | Method |
|---|---|---|
| C | Volume of debris | Method C1: Magenis (1988) |
| D | Probability of blockage at screens (monthly or annual) | Method D1: Wallerstein and Arthur (2012a) |
| | | Method D2: Streftaris et al. (2013) |
| E | Area of blockage at screens | Method E1: Wallerstein and Arthur (2012a) |
| | Area of blockage at bridge piers | Method E2: Diehl (1997) |
| | | Method E3: Wellwood and Fenwick (1989) |
| | | Method E4: New Zealand Transport Agency (2003) |
| | | Method E5: NAASRA (1976) |
| | Area of blockage on bridge decks | Method E6: Diehl (1997) |
| | Area of blockage across gaps | Method E7: Narrow gaps (Diehl 1997) |
| | | Method E8: Low gaps (Diehl 1997) |
| F | Rate of blockage build-up | Method F1: Engineers Australia (2015) |

## 6.3 Observed data

Observations for evaluation were gathered from consultees, post-flood photographs and forensic engineering reports, among other sources (Table 6.2). Systematic observations of debris volume and area of blockage at 2 screens were kindly provided by Leeds City Council (Sites 1 and 2, Figure 6.1) and used to evaluate methods for predicting the volume of debris, and the probability and degree of blockage at screens. Sites 3 and 8 were used to evaluate the rate of blockage. Sites 4 to 8 were used to evaluate methods for predicting the area of blockage at bridges.

**Table 6.2 Summary of observations for evaluation**

| Site | Location | Description |
|---|---|---|
| **Blockage at screens** | | |
| 1 | Halton Moor grid, Wyke Beck, Leeds (Leeds City Council) | Systematic fortnightly record of area of blockage, volume and type of debris (October 2012 to July 2013; 22 months, 49 readings) |
| 2 | Stanks grid, Cock Beck, Leeds (Leeds City Council) | Systematic fortnightly record of area of blockage, volume and type of debris (October 2012 to July 2013; 22 months, 55 readings); also recorded water levels. |
| 3 | Broadway Underpass, Westlink, Belfast (Amey 2008) | Rate of blockage at a culvert screen, 16 August 2008 |
| **Blockage at bridges** | | |
| 4 | Dodder underbridge, Ireland (Fluvio R&D Limited 2012) | Area of blockage at a flat bridge with temporary scaffolding, 24 October 2011 |
| 5 | Lower Ashenbottom viaduct, Lancashire (Benn 2013) | Area of blockage at a bridge pier, 14 June 2002 |
| 6 | River Crane, Feltham, Greater London (RAIB 2010) | Area of blockage across a span, 14 November 2009 |
| 7 | Worcester Bridge (New Civil Engineer, 2014) | Volume of debris and area of blockage at masonry arch bridge, February 2014 |
| 8 | Boscastle, Cornwall (HR Wallingford 2005, Roca and Davison 2010) | Rate and area of blockage at masonry arch bridge, 16 August 2004 |

**Figure 6.1 Screens at Halton Moor and Stanks (Sites 1 and 2)**


Photographs: Leeds City Council

Only one site in Northern Ireland was used as the FRMRC2 methods were derived using data from Belfast.

Summary statistics for the data are given in Table 6.3 for screens in the context of the Belfast dataset. The contributing land use cover was taken as a percentage of the contributing catchment area and determined using aerial photography and geographical information system (GIS) tools. The contributing catchment area was taken as the network length multiplied by an arbitrary offset of 100m on each side of the watercourse (after Wallerstein and Arthur 2012a).

**Table 6.3 Summary statistics for observations for screens**

| | Variable | Belfast dataset | | | Observed data | | Position of observed data in range* |
|---|---|---|---|---|---|---|---|
| | | Min | Mean | Max | Min | Max | |
| **Watercourse** | Upstream network length (m) | 19 | 1,044 | 8,538 | 250 | 749 | low |
| | Upstream channel slope (m/m) | 0.001 | 0.047 | 0.505 | 0.007 | 0.012 | low |
| **Contributing land use cover** | Rural (%) | | 12 | | 39 | 68 | mid |
| | Agricultural (%) | | 24 | | 21 | 32 | mid |
| | Suburban (%) | | 38 | | 0 | 40 | mid |
| | Suburban open (%) | | 17 | | 0 | 0 | low |
| | Urban (%) | | 10 | | 0 | 0 | low |
| **Screen geometry** | Bar spacing (m) | 0.07 | 0.16 | 0.5 | 0.12 | 0.13 | mid |
| | Angle from horizontal (degrees) | 40 | 55 | 90 | 45 | 45 | low |
| **Social deprivation measure** | Income Domain Sscore | 0.04 | 0.16 | 0.68 | 0.04 | 0.42 | mid |
| | MDM (index) | 2.2 | 16.5 | 80.3 | 14.5 | 67.3 | mid |
| **Return period flow** | 2-year ($m^3/s$) | 0.1 | 1.4 | 8.3 | 2.0 | 6.6 | high |
| | 10-year ($m^3/s$) | 0.1 | 2.2 | 13.0 | 3.4 | 10.9 | high |
| | 50-year ($m^3/s$) | 0.1 | 3.4 | 19.4 | 5.2 | 16.2 | high |
| | 100-year ($m^3/s$) | 0.1 | 3.9 | 22.2 | 6.2 | 19.2 | high |
| **Rainfall** | Mean daily rainfall between inspections (mm/day) | 0 | 3 | 57 | 1.7 | 1.7 | low |

Notes: * 'high' = where both the minimum and maximum are above the average; 'mid' = where the minimum is below average and the maximum is above average; 'low' = where both the minimum and maximum are below average.

For bridges, the summary statistics are given in Table 6.4 in the context of the structures investigated in the development of Diehl's 1997 method (see Section 5.6.3).

**Table 6.4 Summary statistics for observed data for bridges**

| | Variable | Study data (Diehl) | | Observed data | | | Position |
|---|---|---|---|---|---|---|---|
| | | Min | Max | Min | Mean | Max | |
| **Bridge geometry** | Length of deck (m) | – | – | 10.4 | 12.3 | 17.7 | n/a |
| | Height of deck (m) | – | – | 5.0 | 5.3 | 6.0 | n/a |
| | Width of gap (m) | 2 | 37 | 6.1 | 10.9 | 17.7 | in range |
| | Height of gap (m) | – | – | 2.5 | 4.7 | 9.6 | n/a |
| | Average of adjacent spans (m) | – | – | 6.0 | 8.6 | 10.0 | n/a |
| **Watercourse and debris** | Upstream channel width (m) | 3 | 300 | 6.0 | 29.8 | 74.0 | in range |
| | Flow depth (m) | – | – | 0.5 | 2.1 | 3.8 | n/a |
| | Design log length (m) | 12 | 45 | 6 | 15.3 | 27.5 | in range |

Notes: n/a = not applicable

## 6.4 Approach

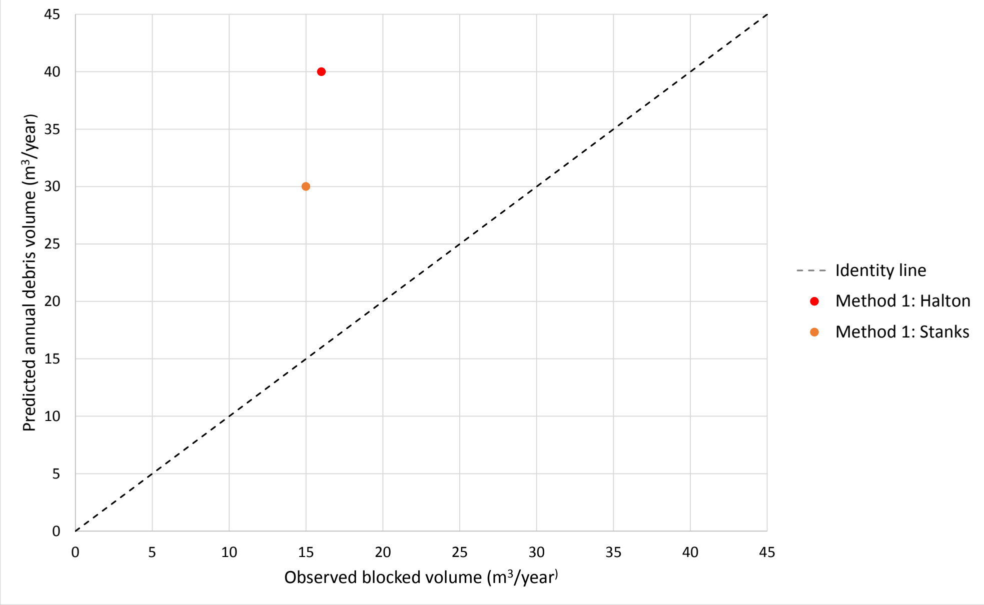
The method adopted for each evaluation exercise was as follows:

- **Step 1 Assess observations.** Determine the observed probability, area, dimensions or volume of blockage for a given event or observation period.
- **Step 2 Predict blockage**. Predict the probability, area, dimensions or volume of blockage using variables determined from site-specific data, such as maps, aerial photographs, site photographs and reports.
- **Step 3 Compare predicted and observed values**. Quantify the difference between predicted and observed values.
- **Step 4: Sensitivity testing**. Conduct sensitivity testing for a range of values beyond the applicable range for the source dataset using a spreadsheet tool for the method. Determine whether the output values are still realistic and whether the method is overly sensitive to some variables.
- **Step 5 Define limitations of methods**.

## 6.5 Group C: Debris volume

The observed annual debris volume arriving at the Halton Moor and Stanks screens over 21 months was found to be 16 and 15m$^3$/year respectively. This was compared with the volume predicted by Method C1 (Magenis 1988) (Figure 6.2).

**Figure 6.2 Scatter plot of predicted against observed volume of debris**




It can be seen from Figure 6.2 that the method over-predicts in both cases by a factor of 2.0–2.7.

Possible reasons for this difference are lower than average rainfall during the study period (1164mm at Knostrop rain gauge from 1 October 2012 to 1 August 2014) or restricted vehicular access to the watercourse which would limit fly-tipping. Catchment management to reduce debris load in the channel and floodplain seems an unlikely cause as the owner of the screen does not undertake proactive clearance work upstream of the screen.

## 6.6 Group D: Probability of blockage

The probability of blockage during any 2-week period within a given month or year was estimated from almost 2 years of fortnightly observations at the two Leeds screens.

Figure 6.3 compares the predicted and observed annual probability of blockage at Halton Moor and Stanks. The observed annual probability of blockage at Stanks was 69%, considerably higher than at Halton Moor (20%), possibly due to a greater suburban land use or higher Income Domain Score.

It can be seen from Figure 6.3 that Methods D1 and D2 consistently over-predict at Halton Moor and under-predict at Stanks.

**Figure 6.3 Predicted against observed probability of blockage (annual)**

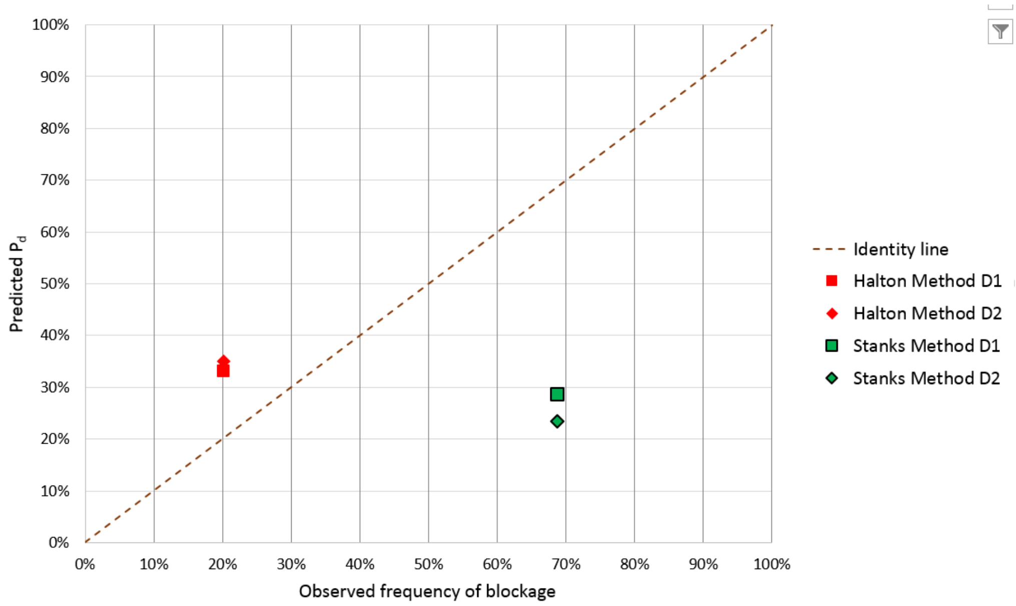



Figure 6.4 and 6.5 give the predicted and observed monthly probability of blockage at Halton Moor and Stanks respectively. At Halton Moor (less susceptible to blockage), observed probability varied from 0% to 50%, while predicted probability of blockage varied from 17% to 55%. At Stanks (relatively frequent blockage), observed probability varied from 0% to 100%, and predicted probability from 16% to 61%.

As with the annual methods, the monthly methods tended to over-predict at Halton Moor and under-predict at Stanks. Both methods predicted higher probability of blockage from October to January, as would be expected during wet and windy conditions.

Note that in some months, blockage was observed none of the time or all the time giving a blockage frequency of 0 or 1; this is unlikely over the long-term and was rightly not predicted by either method.

**Figure 6.4 Predicted and observed probability of blockage at Halton Moor (monthly)**

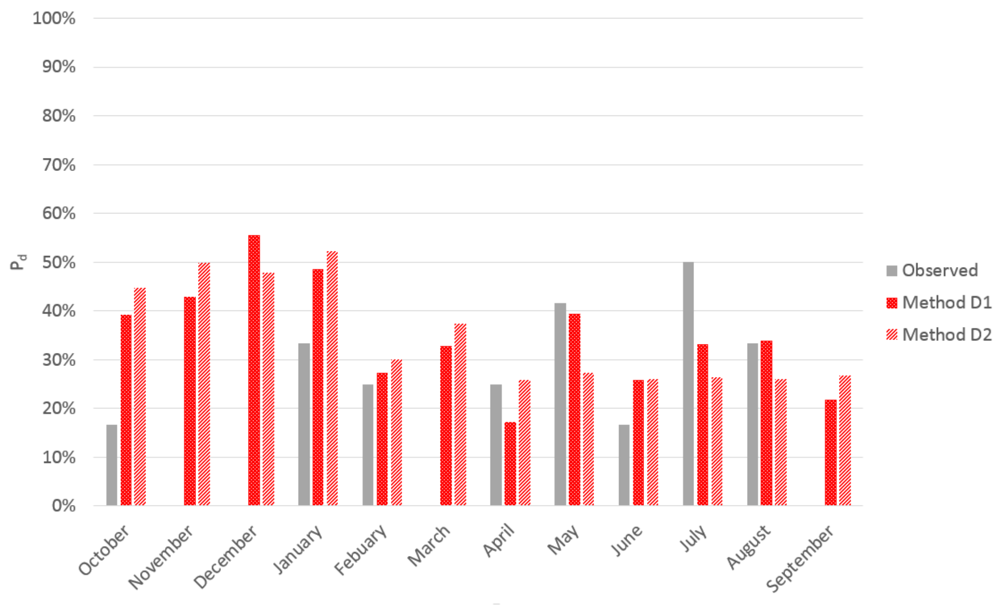
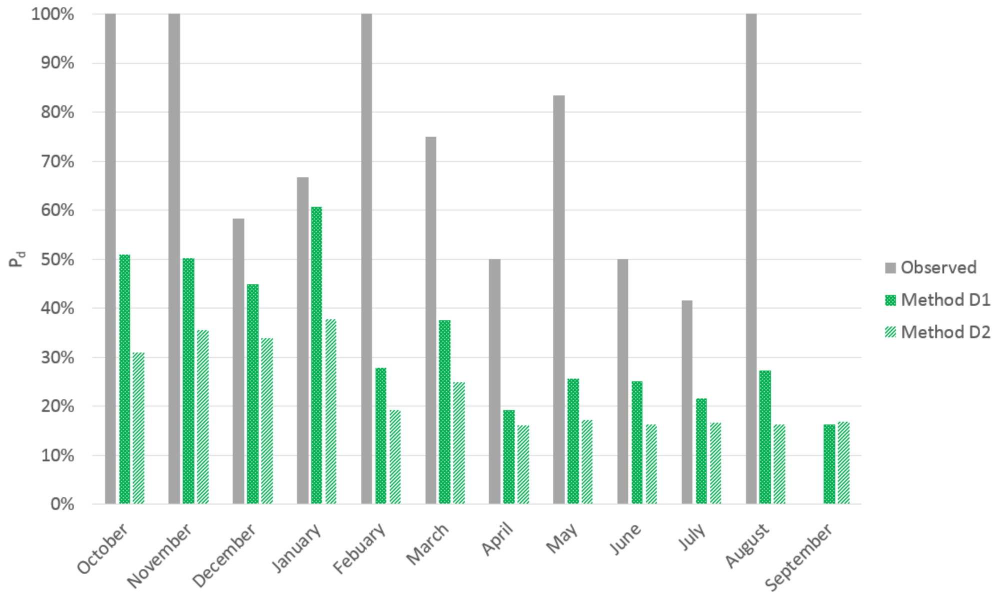


**Figure 6.5 Predicted and observed probability of blockage at Stanks (monthly)**




The root mean square error (RMSE) (in base unit of %) for the annual methods is slightly lower than that for the monthly methods (Table 6.5). The dimensionless $r^2$ value (square of correlation coefficient) indicates how close the method predictions are to the observed data. An $r^2$ value of 1 indicates that the observed data are completely replicated by the method. An $r^2$ value of 0 indicates that there is no relationship between the method predictions and the observed data. The $r^2$ values for methods D1 and D2 are low, indicating that there is a weak relationship between the predictions made by the methods and the observed data.

Since the methods both under- and over-predict, it is not possible to attribute the error due to, say, drier than average conditions during the study period. Analysis of a larger number of sites would help to draw meaningful conclusions.

**Table 6.5 Summary statistics for predicted probability of blockage**

| Method | Absolute error for annual methods (%) | | RMSE for monthly methods (%) | | $r^2$ for monthly methods | |
|---|---|---|---|---|---|---|
| | Halton | Stanks | Halton | Stanks | Halton | Stanks |
| Method D1 | 13 | 40 | 25 | 43 | 0.01 | 0.23 |
| Method D2 | 15 | 45 | 27 | 53 | 0.16 | 0.11 |

Sensitivity testing was carried out to investigate the influence of each variable on the predicted probability of blockage (Figures 6.6 to 6.9). Methods D1 and D2 use network length, land use and Income Domain Score or MDM as predictors of annual probability of blockage. Method D2 also uses channel slope and mean daily rainfall.

Figure 6.6 shows that the annual probability of blockage increases with network length as expected. However, Method D1 shows a noticeable reduction in probability for very short network lengths (less than 900m), which is unlikely to be the case in practice.

**Figure 6.6 Variation in predicted annual probability with network length**

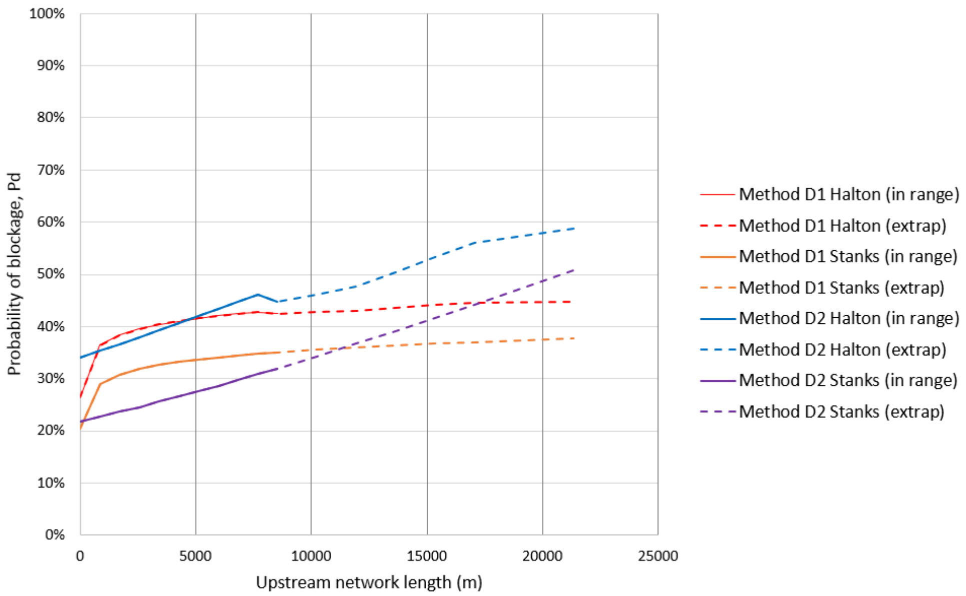



Figure 6.7 shows a slight increase in blockage probability with slope, reflecting the increase in flow velocity and hence debris mobilising capacity (slope is used in Method D2 only).

**Figure 6.7 Variation in predicted annual probability with channel slope**

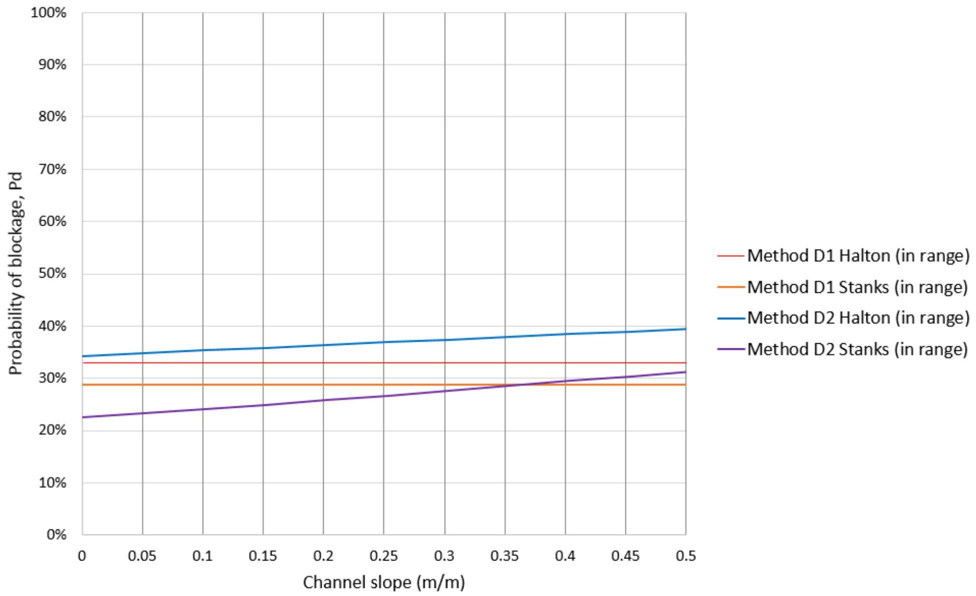



Figure 6.8 shows that the probability of blockage increases dramatically with rainfall, tending to unity at a mean daily rainfall of around 30mm (Method D2 only). This implies that blockage is almost certain during heavy rainfall, which is not unreasonable. Conversely, under conditions of low rainfall, the probability of blockage remains resolutely greater than 0.18, reflecting perhaps the urban nature of the study area used to derive the equations.

Given the sensitivity of Method D2 to rainfall, it is somewhat surprising that Method D1 does not use rainfall. However, this may have been omitted for pragmatic reasons – asset management activities such as screen clearance are more commonly triggered indirectly by weather warnings or flood warnings (as a result of recorded rainfall) rather than directly by recorded rainfall.

**Figure 6.8 Variation in predicted annual probability with mean daily rainfall**

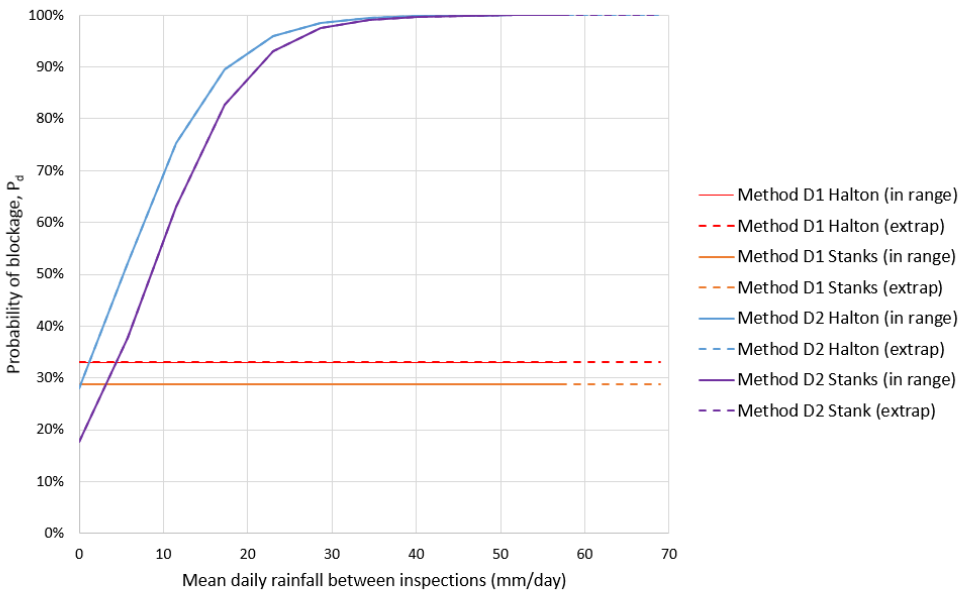



Figure 6.9 shows an inverse relationship between blockage probability and contributing rural land use cover for Method D1, which breaks down for rural land use cover of less than 3%. Method D2 does not use rural land use cover.

**Figure 6.9 Variation in predicted annual probability with rural land use**

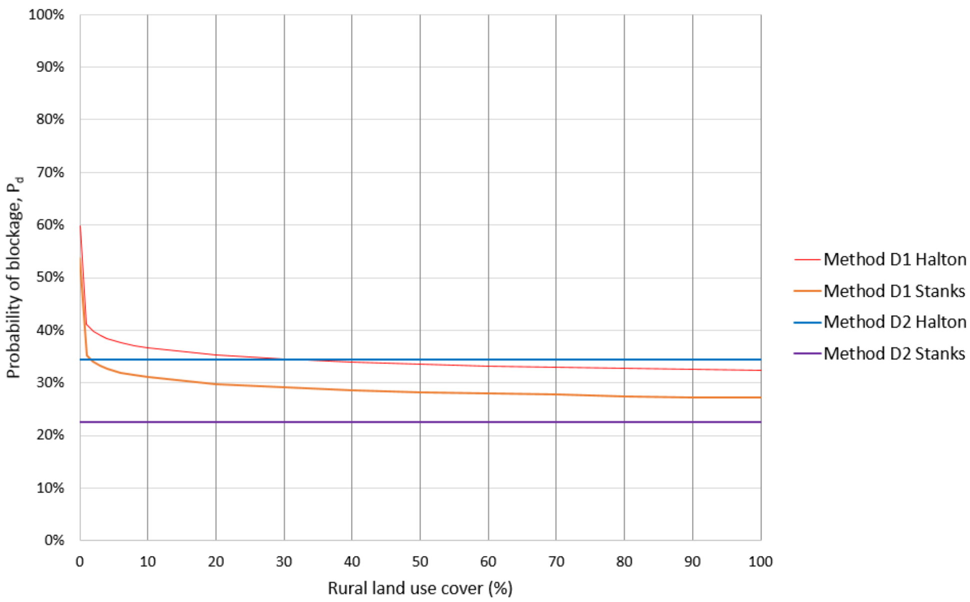



Figure 6.10 shows that the probability of blockage decreases as contributing agricultural land use cover (as a percentage of contributing catchment area) increases, perhaps because other land uses decrease as a result. Method D1 breaks down for agricultural land use cover of less than 3%.

**Figure 6.10 Variation in predicted annual probability with agricultural land use**

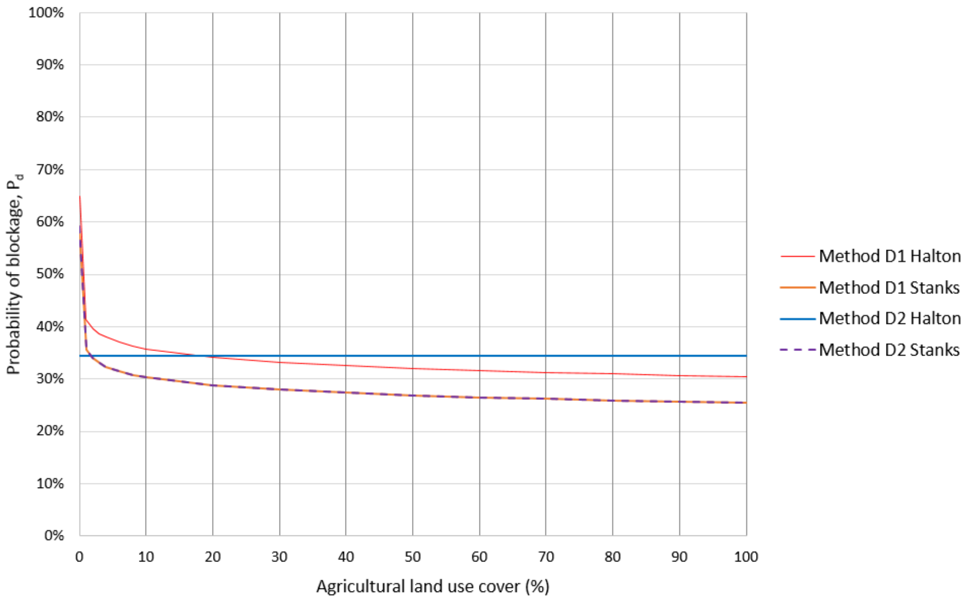
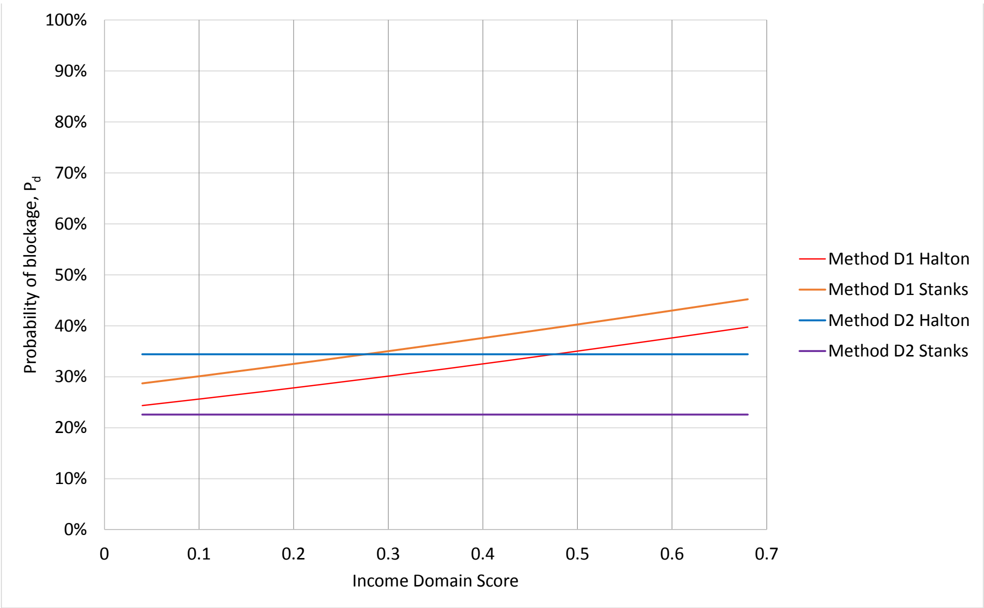



Figure 6.11 shows that the probability of blockage increases with Income Domain Score, indicating that the probability of blockage is higher in areas with higher deprivation (Method D1 only). Income Domain Score represents the number of households in each ward that receive financial support from the government and thus a high score indicates high deprivation.

**Figure 6.11 Variation in predicted annual probability with Income Domain Score**



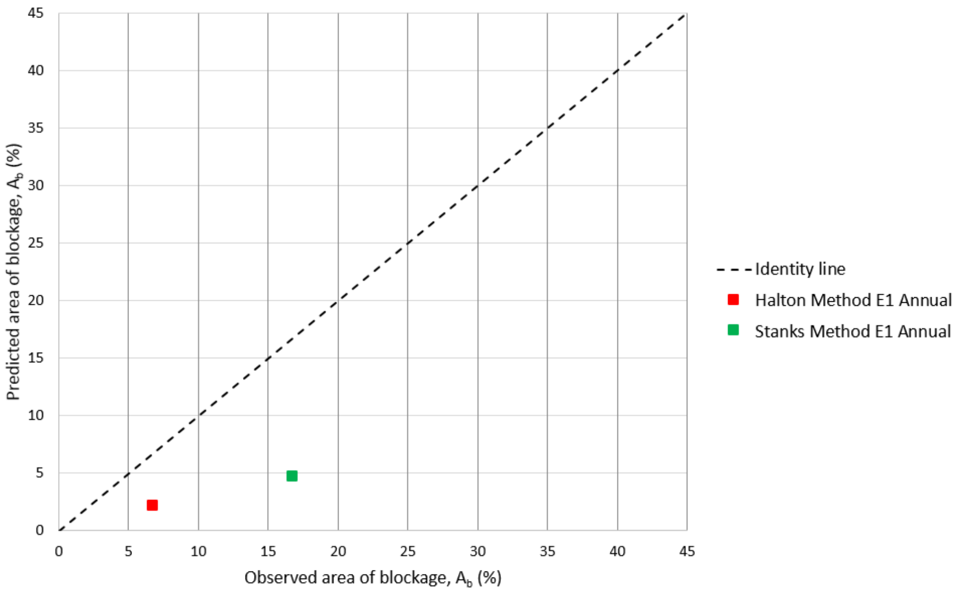
## 6.7 Group E: Degree of blockage

### 6.7.1 Method E1: Screens

The degree of blockage (as a percentage of screen area) during any 2-week period within a given month or year was estimated from almost 2 years of fortnightly observations at Halton Moor and Stanks screens respectively. These values were compared with predicted degree of blockage for any given month or year, determined using Method E1, using both annual and monthly equations.

Observed mean annual degree of blockage was 7% at Halton Moor and 17% at Stanks. It can be seen that Method E1 under-predicts at both screens, with predicted blockage being about one-third of observed (Figure 6.12).

**Figure 6.12 Scatter plot of predicted against observed area of blockage (annual)**




The observed mean monthly degree of blockage varied from 0% to 30% at Halton Moor and 0% to 42% at Stanks. The predicted values are considerably lower than the observed (Figures 6.13 and 6.14).

Table 6.6 shows that the RMSE in degree of blockage is large. The absolute error for annual predictions is lower than the RMSE for monthly predictions, suggesting that the annual predictions are a better match. The $r^2$ value for the monthly methods is low, indicating that there is a weak relationship between the predictions made by the method and the observed data.

The calculation is somewhat limited by the number of sites and assessment of a larger number of sites would be helpful.

**Figure 6.13 Predicted against observed area of blockage at Halton Moor (monthly)**

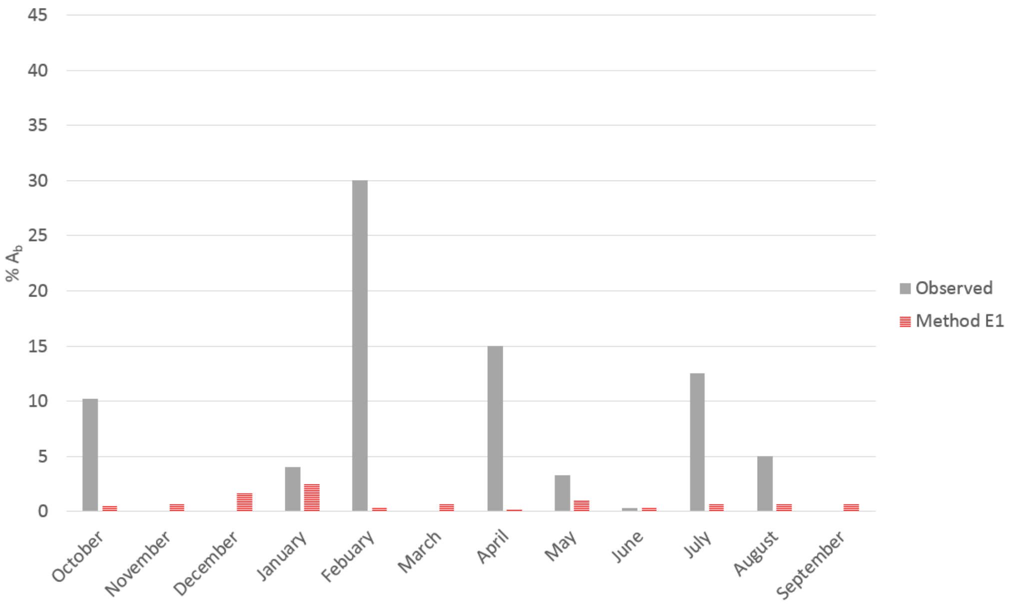



**Figure 6.14 Predicted against observed area of blockage at Stanks (monthly)**

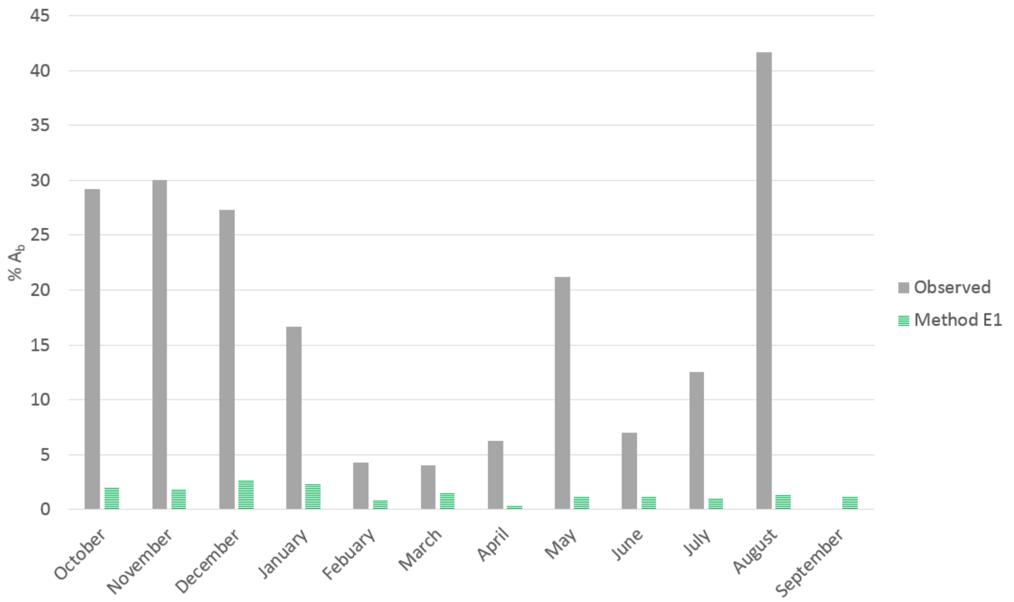



**Table 6.6 Summary statistics for predicted area of blockage**

| Method | Absolute error for annual methods (%) | | RMSE for monthly methods (%) | | $r^2$ for monthly methods | |
|---|---|---|---|---|---|---|
| | Halton | Stanks | Halton | Stanks | Halton | Stanks |
| Method E1 | 4.5 | 12.0 | 10.6 | 19.6 | 0.12 | 0.25 |

Figures 6.15 to 6.17 illustrate sensitivity testing showing the variation in predicted annual degree of blockage with bar spacing, screen angle and suburban land use.

Figure 6.15 shows that the degree of blockage is directly proportional to bar spacing. This is counter-intuitive: one would expect the blockage to decrease as bar spacing increases. As noted in the FRMRC2 work that developed the method, this is thought to be due to the use of larger bar spacings with larger culverts, which are in turn situated on larger watercourses with higher debris-carrying capacities. Hence it is the increase in watercourse size, rather than the increase in bar spacing that accounts for the increase in blockage potential.

In Figure 6.16, the degree of blockage decreases as the screen angle from the horizontal increases, that is, the screen becomes flatter. The recommended screen angle is 45° to 60° to the horizontal, although horizontal screens can be installed on compound screens. The degree of blockage becomes very large for angles less than 20°, exceeding 100% for angles less than 10°, and hence the relationship is unsuitable for use on mild to horizontal screens.

Finally, Figure 6.17 shows that degree of blockage is mildly sensitive to suburban land cover and again breaks down for suburban land cover less than 3%.

**Figure 6.15 Variation in predicted degree of blockage with bar spacing**

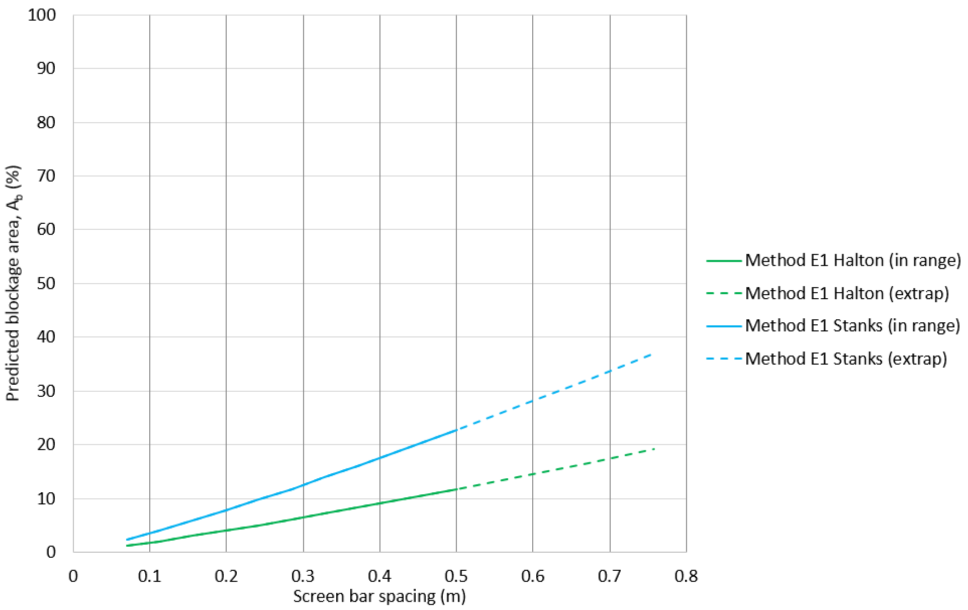



**Figure 6.16 Variation in predicted degree of blockage with screen angle**

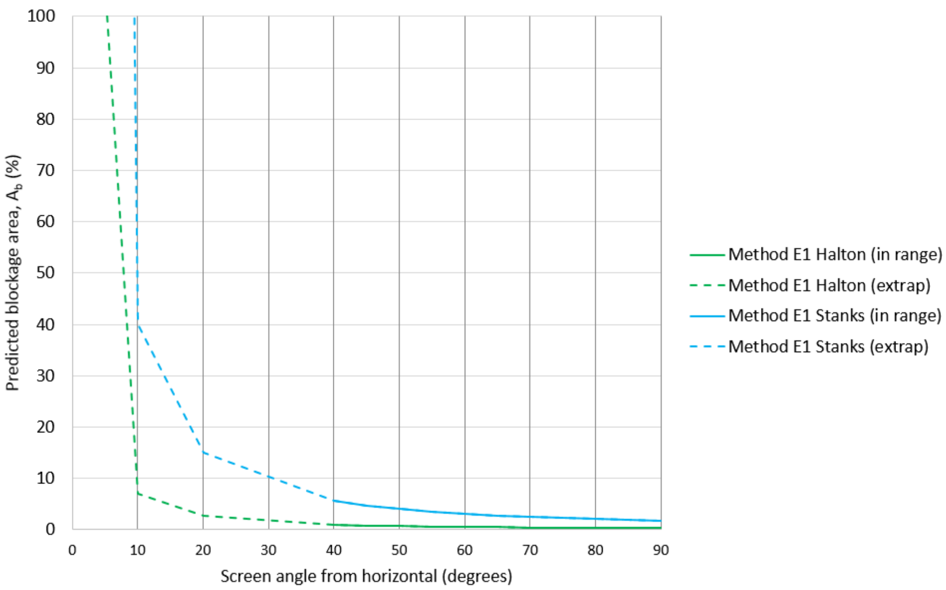
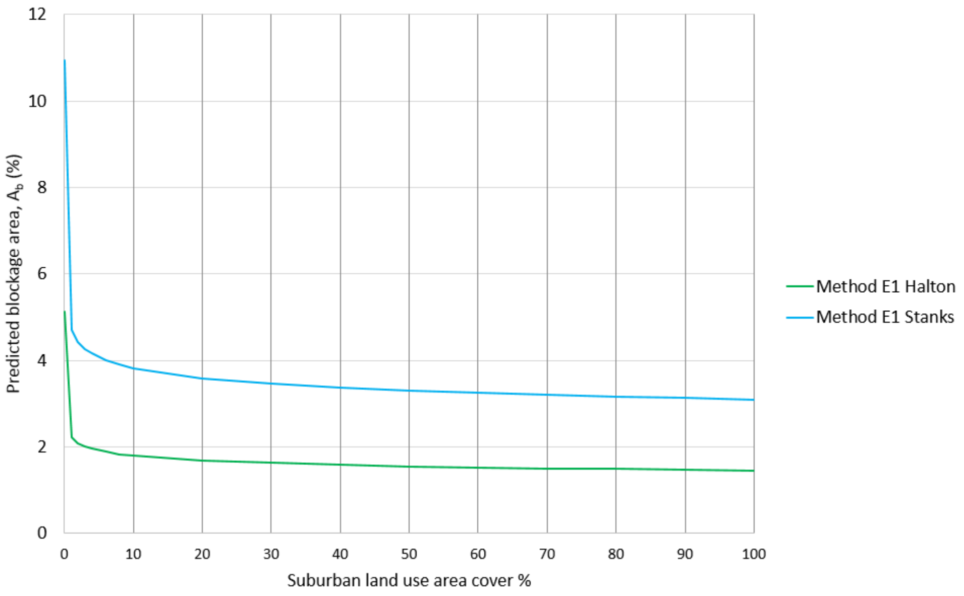


**Figure 6.17 Variation in predicted area of blockage with suburban land use**




### 6.7.2 Method E2 to E6: Bridges

The area of blockage observed for single events was estimated at 4 bridges, with a range of blockage mechanisms and areas of blockage:

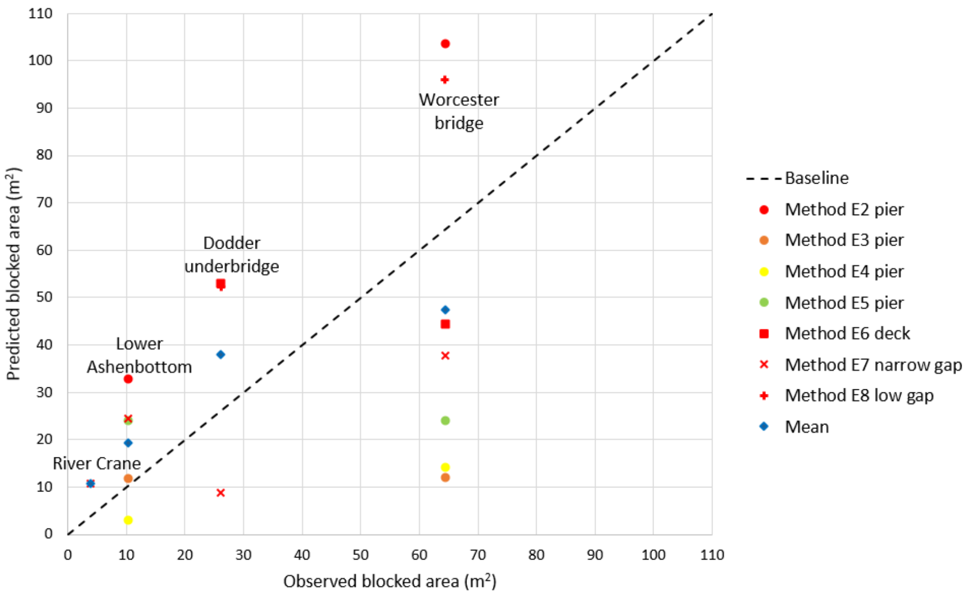
- River Crane: blockage across bridge span, area of blockage $4m^2$
- Lower Ashenbottom viaduct: blockage at a pier and across the bridge span, area of blockage $10m^2$
- Dodder underbridge: blockage on partially submerged temporary scaffolding (equivalent to a bridge deck), area of blockage $26m^2$
- Worcester bridge: blockage of surcharged masonry arch bridge, equivalent to a pier, deck, low and narrow gap, area of blockage $64m^2$

The degree of blockage was predicted using 7 methods – 4 for bridge piers and one each for bridge decks, narrow and low gaps.

Figure 6.18 compares the predicted and observed degree of blockage. As can be seen, there is considerable scatter and poor agreement for the majority of estimates.

The mean estimate obtained from all methods was also calculated and found to give poor agreement. For example, Method E4 for piers consistently under-predicts.

**Figure 6.18 Scatter plot of predicted against observed area of blockage**




## 6.8 Group F: Rate of debris blockage

Method F1 was used to predict the rate of blockage for 2 structures:

- Westlink: blockage of screen with time to blockage of 1 hour
- Boscastle: blockage of bridge with time to blockage of 3 hours

For both events, the blockage was reported to involve floating debris, with pulsed (or intermittent), rather than progressive, build-up.

The observed blockage rates were compared with predicted blockage rates for varying blockage types (Figure 6.19):

- progressive and pulse build-up of floating debris
- progressive build-up of non-floating debris

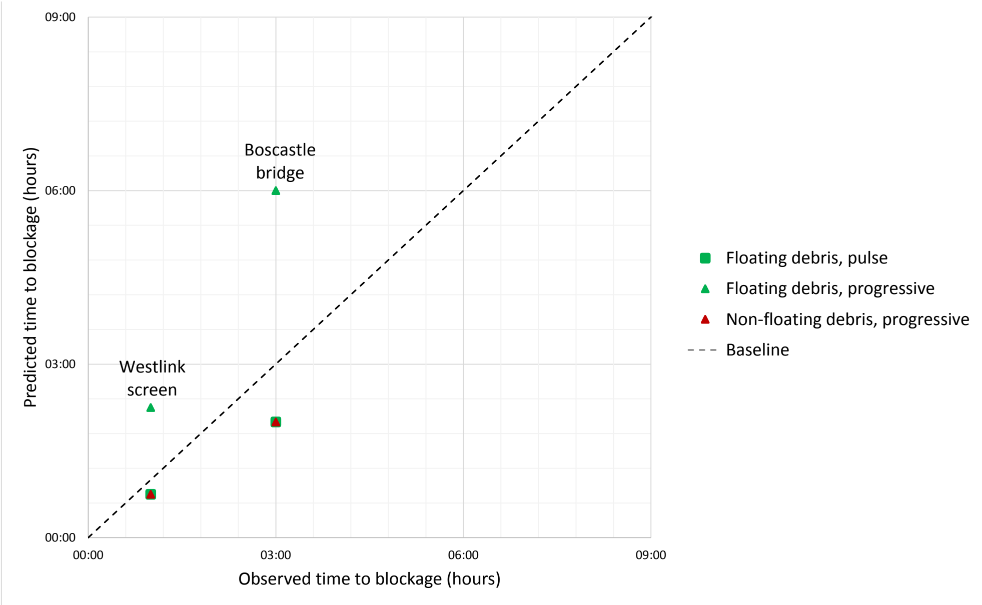
For floating debris, the method for pulsed delivery (the most appropriate method for these cases) predicted a shorter time to blockage (that is, a faster blockage rate). This is desirable to ensure one of the following.

- The response time for operatives is sufficient.
- The screen is sized to accommodate sufficient blockage without the need for a rapid response for clearance.

However, the method for progressive build-up predicts a slower blockage rate than observed. This is undesirable and could lead to a tardy operational response.

For non-floating debris, the method for progressive build-up predicts more rapid blockage than observed and is therefore conservative.

**Figure 6.19 Scatter plot of predicted against observed rate of blockage**




## 6.9 Conclusions

A range of blockage prediction methods were evaluated to give confidence before taking methods forward to the blockage management guidance. Although observed data were obtained for 3 screens and 5 bridges, all the conclusions here would benefit from evaluation against more case studies.

Case study C for debris volume showed that the Magenis (1988) method tends to over-predict debris volume by a factor of at least 2. There may be scope to apply a reduction factor, though assessment of further sites would be advisable.

Case study D for probability of blockage at screens showed that Methods D1 (Wallerstein and Arthur 2012a) and D2 (Streftaris et al. 2013) give a great deal of scatter. The annual methods give a smaller error than the monthly methods, though with only 2 test sites available and 2 years of observations, these results may not provide conclusive evidence for generalised application of the methods. Method D1 became unreliable for short networks (less than 900m) and areas with rural land use and agricultural land use of less than around 3%. Method D2 was highly sensitive to rainfall, tending to 100% probability of blockage for a mean daily rainfall of 30mm.

Case study E1 for degree of blockage at screens again gave some scatter and the annual method gave a lower error than the monthly method. Method E1 broke down for screens with a slope of less than 20° to the horizontal.

Case studies E2 to E8 for degree of blockage at bridges gave considerable scatter. The following methods for predicting blockage are tentatively suggested:

- Blockage at bridge piers: Method E3 or E5 tend to over-predict blockage and would therefore be conservative when estimating flood risk.
- Blockage at bridge decks or temporary works: The average of Methods E7 and E8 for narrow and low gaps would over-predict blockage area slightly, giving slightly conservative results when predicting flood risk.

- Blockage at masonry arch bridges, avoid methods for piers. Instead, the bridge should be treated as a low gap. The height of the opening taken requires further analysis but may be around the mean arch height.

Finally, Case study F for rate of blockage shows that the method for predicting pulsed blockage by floating debris estimated time to blockage to be about half that which was observed. There is scope to apply an adjustment factor to improve prediction, though more data would be helpful.

In general, the tests have identified some sensitivities within the methods and begun to make comparisons with independent observations. The wide scatter in the results demonstrates that the currently available methods cannot be 'validated' in absolute terms. However, it is not known whether this is a reflection of the limited pool of test data or of the limitations of the estimation methods.

It is clear, however, that the results indicate quantitative blockage predictions need to be made with caution and should not be relied as a sole source of evidence in a blockage risk assessment. Qualitative assessment should remain as important, and arguably more important, in the development of blockage management guidance.

# 7 New screening method

## 7.1 Introduction

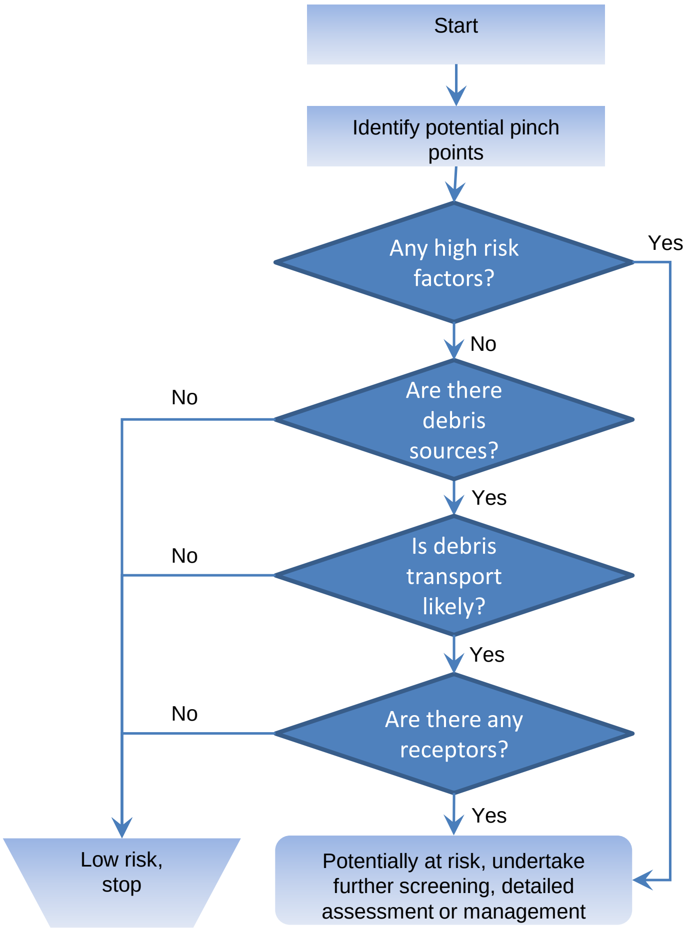
This chapter sets out the background to a new screening method (see Figure 7.1) designed to:

- identify potential pinch points
- identify 'potentially at risk' assets requiring detailed assessment
- screen out low risk assets requiring no further assessment

Screening is a quick and simple desk study approach using readily available data. It is suitable for the assessment of catchment-wide risk, the initial assessment of individual assets or the quick selection of management techniques.

It is important to note that some differences may exist between this report and the published guide due to editorial changes and maintaining ease-of-use in the new guide. Changes may include steps (how many or their order), references, logic and wording amongst others.

**Figure 7.1 Screening method**




As shown in the flow chart in Figure 7.1, the method has 7 steps:

- Step 1: Identify potential pinch points
- Step 2: Are there any high risk factors?
- Step 3: Are there any debris sources?
- Step 4: Is debris transport possible?
- Step 5: Are there any receptors?
- Step 6: Risk score and blockage risk
- Step 7: Uncertainty

These steps are described in the following sections.

The assessment of high risk factors, debris sources, debris transport and receptors draws on existing screening methods (Table 7.1). All factors are quick and easy to estimate. Factors that require local knowledge, a site walkover or detailed assessment were avoided as were factors specific to individual weather or flow events. Factors used in other methods that were rejected or used indirectly are listed in Table 7.2.

### Table 7.1 Summary of factors used in screening

| No. | Factor | Reasons for inclusion |
|---|---|---|
| **Step 2: Are there any high risk factors?** | | |
| 1 | History of blockage [4] | Good indicator of future blockage |
| 2 | If blockage occurred, would properties or infrastructure be at risk upstream? | Most common and highest impact consequences of blockage |
| 3 | If blockage led to overflowing, would properties or infrastructure at risk downstream? | |
| 4 | If blockage occurred, is there a risk of embankment breach due to seepage or external erosion? | |
| 5 | Is the structure a screen with an area <3 times culvert area? | Likely to trap high proportion of debris |
| 6 | Is the structure a culvert with barrel area less than 3m$^2$? [2] | |
| 7 | For structures other than screens, is the opening width ≤6m? [1] | |
| 8 | Could the structure be blocked by small debris? | |
| 9 | Is the structure located on a rapid response catchment? | Tends to generate high debris load and leads to rapid blockage |
| 10 | Is there debris accumulation within the channel or floodplain upstream?[1] | Influences debris load mobilised in a single event |
| **Step 3: Are there debris sources?** | | |
| 11 | Length of contributing watercourse | Influences quantity of debris |
| 12 | Land use | Influences quantity and type of debris |
| 13 | Riverside vegetation[2] | Contributes large woody debris |
| 14 | Fly-tipping, vehicular access or private gardens adjacent to watercourse | Sources of man-made refuse |
| 15 | Storage of materials near watercourse | |
| 16 | Watercourse instability | Influences quantity of debris |
| 17 | Debris accumulation in channel or floodplain | |
| **Step 4: Is debris transport likely?** | | |
| 18 | Watercourse slope [1] | Influences transport of all debris |
| 19 | Channel width relative to debris length | Influence transport of floating debris |
| 20 | Flow depth relative to debris draught | |
| 21 | Opening dimensions relative to debris length or height [2,4] | Influences trapping of debris |
| 22 | Flow velocity | Influences transport of all debris types |
| 23 | Areas of slow flow | Influences sedimentation |

| No. | Factor | Reasons for inclusion |
|---|---|---|
| 24 | Stream power [1] | Influences deposition of debris |
| **Step 5: Are there any receptors?** | | |
| 25 | Flooding | Common impact of blockage |
| 26 | Structure failure | High consequence impacts |
| 27 | Embankment breach | |
| 28 | Contraction or local scour | Due to flow acceleration or turbulence |
| 29 | Environmental effects | |
| 30 | Injury or loss of life | Potential impact of flooding, breach and so on |
| 31 | Direct damages | Catch-all |

Sources: [1] Engineers Australia (2013)
[2] Environment Agency (1998)
[3] Environment Agency (2012a)
[4] OPW (2013)

**Table 7.2 Factors rejected or used indirectly**

| No. | Factor | Reason for exclusion |
|---|---|---|
| **Source** | | |
| 1 | Catchment type [4] | Covered by 'land use' |
| 2 | Channel use [2] | |
| 3 | Tree density, location and tree cover [1] | |
| 4 | Level of urbanisations near structure [2] | |
| 5 | Density of buildings in floodplain | |
| 6 | Geology of watercourse [1] | Data time-consuming to obtain |
| 7 | Landslips/slides [1] | Covered by 'watercourse instability' |
| 8 | Amount of loose bankside material [3] | |
| 9 | Degree of sediment control measures [1] | Unsuitable for high-level method |
| 10 | Clearance activities (for example, street sweeping) [1] | Data difficult to obtain, may vary over time |
| 11 | Growth opportunities of aquatic vegetation (for example, annual rainfall) [1] | Difficult to measure |
| 12 | Seasonal factors – leaf fall from deciduous trees [1] | Screening does not take seasonality into account. Tree cover already scored. |
| 13 | Degree of building activities [1] | Covered by 'storage of materials' |
| **Pathway** | | |

| No. | Factor | Reason for exclusion |
|---|---|---|
| 14 | Shear stress of in-bank or overland flows[1] | Covered by 'flow velocity' |
| 15 | Bed and bank irregularity (for transport of non-floating debris) [1] | Requires local knowledge or site walkover |
| 16 | Critical storm duration at structure [1] | Covered by 'rapid response catchment' |
| 17 | Severity of winds and rainfall [1] | Study of individual events unsuited to high-level screening |
| 18 | Average recurrence interval of flood [1] | |
| 19 | Average recurrence interval of storm [1] | |
| **Receptor** | | |
| 20 | Frequency of maintenance visits (as measure of blockage frequency) [2] | Covered by 'history of blockage' |
| 21 | Number of openings [2] | Could include as 'obstructions in channel' |
| 22 | Aspect ratio (span < rise) [2] | Unsuited to high-level method |
| 23 | Structure shape [2] | |
| 24 | Approach flow conditions [2] | Data not readily available at screening stage |
| 25 | Condition of entrance, exit and barrel [2] | |
| 26 | Barrel and bed Manning's n [2] | |
| 27 | Culvert capacity relative to target flood [2,4] | Unsuited to high-level method, requires hydraulic assessment |
| 28 | Proximity of design flow to soffit [2] | |
| 29 | Frequency of bank full flows [1] | Covered by 'debris accumulation' |
| 30 | Receptors local to culvert entrance [4] | Covered by 'flooding' |

Sources: [1] Engineers Australia (2013)
[2] Environment Agency (1998)
[3] Environment Agency (2012a)
[4] OPW (2013)

## 7.2 Step 1: Identify potential pinch points

The first step is to identify potential pinch points such as screens, culverts, bridges, control gates, flap valves, weirs and flumes, or sections of channel that are narrower or shallower than the watercourse upstream. This is typical practice when screening for large groups of assets, such as the assessment of scour at bridges.

## 7.3 Step 2: Are there any high risk factors?

### 7.3.1 Overview

High risk factors can be identified using a checklist such as the one shown in Table 7.3.

If the answer to any of the questions is ‘yes’, then the asset is ‘potentially at risk’. Depending on the scale of the problem, the reader is advised to select management techniques (Chapter 3 of the guide) or perform a detailed assessment (Chapter 5 of the guide).

If the answer to all of the questions is ‘no’, the asset could still be at risk of blockage – and the reader is directed to Step 3 for further screening (see Section 3.4 of this report).

**Table 7.3 Checklist for high risk factors**

| No. | Question | Yes | No |
|---|---|---|---|
| 1 | Is there a history of blockage? | | |
| 2 | If blockage occurred, would properties or infrastructure be at risk upstream? | | |
| 3 | If blockage led to overflowing, would properties or infrastructure at risk downstream? | | |
| 4 | If blockage occurred, is there a risk of embankment breach due to seepage or external erosion? | | |
| 5 | Is the structure a screen with an area <3 times culvert area? | | |
| 6 | Is the structure a culvert with barrel area less than $3m^2$? | | |
| 7 | For structures other than screens, is the opening width $\leq$6m? | | |
| 8 | Could the structure be blocked by small debris? | | |
| 9 | Is the structure located on a rapid response catchment? | | |
| 10 | Is there debris accumulation within the channel or floodplain upstream? | | |

### 7.3.2 History of blockage

It is recommended that a history of blockage is taken as high risk, implying a regular source of debris and regular mobilisation (say, due to annual decay cycles or fly-tipping). This follows guidance in Engineers Australia (2015), which recommends categorising the likelihood of blockage according to blockage frequency if sufficient long-term records exist (for example, memory of locals, maintenance personnel or other records).

### 7.3.3 Receptors

Receptors (or consequences) should be considered at an early stage to ensure the effort spent on assessment is proportionate to the risk. There is little merit in assessing risk of blockage if the only consequence is that the water flows over a minor road at a shallow depth and low velocity to re-enter the watercourse downstream of the road.

The overflow or relief level should also be considered. This usually, but not always, found close to the structure. It is frequently the level of the road or railway crossing the watercourse, although more complicated situations can exist where a watercourse passes below larger areas of land, particularly in urban areas. This can indicate the potential consequences of blockage.

- **Flooding upstream of the asset**. This is indicated by projecting the overflow or relief level upstream. What is inundated before relief to rising water level occurs?
- **Flooding along the relief flow path downstream of the asset**. This is determined by identifying the downhill flow route. This may include temporary storage areas that would fill before water continues downstream. The best way of determining the relief level, relief flow path and consequences of blockage is a walkover site inspection by a person with the knowledge and experience to answer the 'what if' question in a qualitative (if not a quantitative) way.
- **Embankment breach leading to catastrophic failure of infrastructure and/or flood damages downstream**. If there is a risk of surcharging, the asset will be impossible to clear, and for an embankment that has not been designed as water-retaining, there is a risk of seepage and internal erosion. Overtopping of an embankment without scour protection can also lead to external erosion of the downstream face, particularly if there are trees or other local structures in the flow path. The blockage management guide signposts the 'International Levee Handbook' (CIRIA et al. 2013) for guidance on predicting and modelling embankment breach, which can be freely downloaded.

### 7.3.4 Structure type and dimensions

As recommended in the blockage management guide, the following structure types should be taken as high risk:

- **Screens with area of less than 3 times the culvert opening area**. Trash and security screens are known to increase blockage risk and have been the focus of several studies (Magenis 1988, Wallerstein and Arthur 2012a, OPW 2013, Streftaris et al. 2013). Work by Magenis suggested that the screen area should be 3–30 times the culvert opening area, based on a study of a number of screens that perform well or badly. This rule of thumb gives a wide range and there is a risk of perpetuating a past mistake if a culvert has been undersized. Nevertheless, it provides a useful quick check on the adequacy of a screen.
- **Culvert with a barrel area <3m$^2$.** A screening method developed by OPW (2013) assumes a low risk of blockage for culverts with an opening area <3m$^2$, although no evidence for this is given.
- **Structures other than screens with an opening dimension of <6m**. Structure dimensions are influential in blockage risk and a range of

thresholds has been used by different studies. Research into a flash flood at Wollongong, Australia, showed that blockage was unlikely at culvert or bridge openings greater than about 6m and that, if blockage does occur, it is likely to be only a partial blockage (Rigby et al. 2002).

- **Structures capable of being blocked by small material**. Experience indicates that these are vulnerable to blockage.

### 7.3.5 Rapid response catchment

A rapid response catchment area is an area known to be at risk of flash flooding. Flash floods are characterised by:

- a short lead time (<6 hours)
- a short duration of flooding
- a link to heavy rainfall
- a high volume and velocity of water
- a danger presented by debris
- potential to cause material damage and an urgent threat to life

Flash flooding can increase blockage risk by destroying buildings, roads and bridges, uprooting trees, and mobilising debris, boulders and vehicles. Furthermore, the flood mobilises debris quickly, leading to rapid blockage at structures.

A rapid response catchment with a lead time to the pinch point of interest of less than 6 hours should be considered to be high risk.

The Boscastle 2004 flash flood led to rapid blockage of structures, with heavy debris loads arise from a rapid increase in water level, and high sediment loads due to erosion and downcutting (HR Wallingford 2005; Roca and Davison, 2010). Environment Agency (1998) included a high frequency of flash flooding as an indicator of blockage risk.

### 7.3.6 Debris accumulation

Debris accumulation within the channel or floodplain should be classed as high risk. The amount of debris available for mobilisation within a catchment or arriving at a structure during a given flow event is influenced by:

- debris-creating events such as wind storms or fly-tipping
- catchment management to remove debris
- the frequency of debris mobilisation in the channel or floodplain

Wind storms tend to increase the quantity of debris by breaking branches or blowing man-made debris towards the watercourse or floodplain, whereas frequent flood events typically reduce the debris available by transporting it downstream. The degree of blockage experienced following a given flood event will be lower if the flood had been preceded by a smaller flood event than if there had been no recent significant flow events. This is because the previous flood would likely clear the catchment of some available debris.

The frequency of significant wind or rain events is used in several screening methods. Engineers Australia (2015) correlates event magnitude and debris potential at a site, but only considers relatively high flood flows (5% AEP or 20-year return period) (Table 7.4). The Trash and Security Screen Guide (Environment Agency 2009) recommends taking the number of significant events as 3 per year unless there evidence to suggest otherwise, implying that a flow smaller than the median annual flow is capable of mobilising debris. The blockage management guide does not give quantitative guidance as the science behind existing guidance is unclear.

**Table 7.4 Relationship between event magnitude and debris potential**

| AEP (%) | 1% AEP debris potential at structure | | |
|---|---|---|---|
| | **High** | **Medium** | **Low** |
| >5% (frequent) | Medium | Low | Low |
| 0.5% to 5% | High | Medium | Low |
| <0.5% (rare) | High | High | Medium |

Source: Engineers Australia (2015)

# 7.4 Step 3: Are there any debris sources?

## 7.4.1 Overview

A checklist for potential debris sources, such as the one in Table 7.5, is helpful to:

- classify debris potential as high, medium or low
- determine a source score as the sum of each factor (maximum of 14 from Table 7.5)
- to determine the likely debris type for use in Step 4

**Table 7.5 Checklist for potential debris sources**

| Low<br>(score 1 for each) | Medium<br>(score 2 for each) | High<br>(score 3 for each) |
|---|---|---|
| • Short length of contributing watercourse | • Intermediate length of contributing watercourse | • Long length of contributing watercourse |
| • Pastoral or rural land use | • Suburban open land use (for example, parks, golf courses) | • Woodland, suburban (with dwellings) or urban land use<br>• Arable land producing straw or hay (baled or unbaled)<br>• Timber operations or felled timber awaiting collection |
| • Small riverside vegetation | • Small trees or bushes along riverbank | • Large mature trees along riverside |
| • No vehicular access points or private gardens adjacent to watercourse | • Vehicular access points or private gardens | • History of fly-tipping |
| • No storage of materials in floodplain or within 100m of watercourse | • Storage of materials in floodplain or within 100m of watercourse | • Storage of materials adjacent to watercourse with no barrier |
| • Stable watercourse or mild bed slope<br>• Cohesive sediment to bed and banks of watercourse | • Dynamically stable watercourse | • Steep or unstable watercourse<br>• Light sandy soils to bed and banks of watercourse<br>• Extensive soil erosion in catchment |
| • Little debris accumulation in channel or floodplain | • Some debris accumulation in channel or floodplain | • Extensive debris accumulation in channel or floodplain |

### 7.4.2 Length of contributing watercourse

The length of contributing watercourse influences debris volume, although the definitions of short, intermediate and long are left to the asset owner as these will vary between different geographical areas. Asset owners may wish to define their own boundaries to suit their group of assets.

### 7.4.3 Land use

Research has shown a strong link between land use and the availability of debris. Land use classification is taken into account in many blockage risk analysis methods and studies (Environment Agency 1998, 2009, 2012a, Magenis 1988, Wallerstein and Arthur 2012a, Engineers Australia 2013, OPW, 2013). Land use classes used in the past include woodland, urban, suburban, open public areas, open non-public areas, land with road access and farmland/agricultural (Table 7.6).

The land uses classed as high risk in Table 7.6 have evolved over time and there are some conflicts.

- Woodland is classed as high risk in 3 out of 4 methods, but low risk by FRMRC2. Practitioners report that timber operations, particularly felled timber awaiting collection, increase the potential for large debris, trash and sediment to enter a watercourse.
- Suburban land use (with dwellings) is classed as high risk due to garden waste and fly-tipping (Wallerstein and Arthur 2012a).
- Urban land use is generally seen as high risk, although this was classed as medium by FRMRC2.
- Farmland/agricultural land is reported to be low risk by many methods, possibly influenced by the study areas. Practitioners report an increased blockage risk in late summer due to straw or hay, whether baled or unbaled. Large, round bales weighing in at over 300kg can cause sudden blockage and are difficult to remove.

**Table 7.6 Land use class and risk of debris**

| Source | Low risk | Medium risk | High risk |
|---|---|---|---|
| Magenis (1988) | • Farmland, non-wooded golf courses, parkland | • Suburban gardens | • Adjacent to road, council estate, woodland |
| Environment Agency (2009) | • Open non-public areas | • Suburban, open public areas | • Woodland, urban |
| Wallerstein and Arthur (2012a) | • Rural (non-agricultural grassland, woodland and moors)<br>• Agricultural (arable and pastoral) | • Suburban open (public access land, parks and golf courses)<br>• Urban (industrial land, urban wasteland, city centres and shopping precincts) | • Suburban (cover with dwellings) |
| OPW (2013) | • Not specified | • Not specified | • Predominantly urban or woodland |
| Blockage management guide | • Rural<br>• Agricultural<br>• Open non-public | • Suburban open | • Woodland<br>• Urban<br>• Suburban |

The blockage management guide recommends taking woodland, urban and suburban land use as high risk, taking the most conservative classification from existing methods. Arable land producing straw/hay and timber operations are also classed as high risk, drawing on practitioner experience.

Land use can be determined using online mapping, aerial photographs or site walkover. The Government's Generalised Land Use Database (GLUD) and National Land Use Database (NLUD) were rejected as being too detailed for a simple screening method.

### 7.4.4 Riverside vegetation

In addition to woodland, large riparian vegetation has been identified as an important factor affecting debris load. Diehl and Bryan (1993) found that mature trees along the riverbank that had been undermined by erosion – as illustrated in Figure 7.2 – were a major source of debris in one study catchment. An inspection of aerial photographs of the UK indicates that large riparian vegetation can be present in every land use type, not just woodland.

Riparian vegetation is taken into account in several methods (Environment Agency 1998, Engineers Australia 2013, OPW 2013).

**Figure 7.2 Riverside trees affect debris load**

Notes: Photograph courtesy of A.H. Kitchen

### 7.4.5 Fly-tipping, vehicular access or private gardens

Fly-tipping is a source of man-made debris within a watercourse and strongly linked to the likelihood of blockage. Wallerstein and Arthur (2012a) used Income Domain Score as an indicator of social deprivation and hence the likelihood of fly-tipping, while Environment Agency (1998) related blockage risk to knowledge of tipping into the river.

These factors can be determined using anecdotal evidence, a site walkover or the Environment Agency's Flycapture database (used to record fly-tipping activities in England).

### 7.4.6 Storage of materials

The storage of materials adjacent to the watercourse or in the floodplain can contribute to debris load. This can be either directly when mobilised by overland flow or out-of-bank flow, or indirectly when the materials are blown into the watercourse or floodplain. Blockage can occur rapidly with large sheet materials.

Construction sites, warehouses, distribution centres and supermarkets can contribute man-made debris such as pallets, packaging and sheet materials, or sediment due to erosion or silty run-off (Murnane et al. 2006).

The risk should be lower for well-managed construction sites, for example, those operated by members of the considerate constructors scheme, the Civil Engineering Environmental Quality Assessment and Award Scheme (CEEQUAL) or similar (Murnane et al. 2006). Construction activity is included as a risk factor in some studies (Environment Agency 2012a, Engineers Australia 2013).

Risk sites can be identified using aerial photographs, street view images or a site walkover.

### 7.4.7 Watercourse instability

Watercourse instability contributes to both woody debris and sediment load, as bank erosion releases sediment and causes vegetation to fall into the watercourse. Indeed, Diehl (1997) stated that bank instability seemed to be the channel characteristic most useful in identifying channel reaches with high potential for the production of large woody debris.

Watercourse stability is used as an indicator of high debris load in several methods (Piégay and Gurnell 1997, Environment Agency 1998, 2012a, Engineers Australia 2013). Watercourse instability can be assessed using historic maps, aerial photography or site walkover. Table 7.7 provides a list of indicators of watercourse stability.

**Table 7.7 Checklist for watercourse stability**

| Stable | Dynamically stable | Unstable |
|---|---|---|
| • Little or no erosion<br>• Slow changes in plan form and cross-section<br>• Mature bankside trees or stable bank vegetation | • Some erosion during moderate to high flows<br>• Gradual changes in plan form and cross-section | • High rate of erosion<br>• Rapid changes in plan form and cross-section<br>• Bank erosion (especially on straight reaches)<br>• Structure undermining or outflanking<br>• Exposed bank material or tree roots, tilted vegetation<br>• Slip scars or tension cracks, slumping<br>• Disturbed fences or footpaths<br>• Bank protection works |

Source: after Diehl and Bryan (1993) and HR Wallingford (1993)

### 7.4.8 Debris accumulation

The degree of debris accumulation within the channel or floodplain is a measure of the potential debris load (as in Step 2; see Section 7.3.6). This is left to judgement rather than specified in the method as the boundaries between small, intermediate and large will depend on the area in question.

## 7.5 Step 4: Is debris transport possible?

### 7.5.1 Overview

The checklist for debris transport in Table 7.8 can be used to classify debris transport potential as high, medium or low, or to determine a source score as the sum of each factor (maximum 14). Some judgement is required to determine the debris transport potential.

**Table 7.8 Checklist for debris transportation**

| **Low (score 1 for each)** | **Medium (score 2 for each)** | **High (score 3 for each)** |
|---|---|---|
| • Mild watercourse (0.1% or milder) | • Moderate slope (0.1–1.0%) | • Steep watercourse (steeper than 1%) |
| • Narrow watercourse: upstream channel width < debris length | • Upstream channel width ≈ debris length | • Wide watercourse: upstream channel width > debris length |
| • Shallow flow: flow depth < debris draught | • Flow depth ≈ debris draught | • Deep flow: flow depth > debris draught |
| • Opening dimensions < debris length or height | • Opening dimensions ≈ debris length or height | • Opening dimensions < debris length or height |
| • Flow velocity/threshold velocity < 0.375 (no scour) | • Flow velocity/threshold velocity = 0.375–1.0 (clear water scour) | • Flow velocity/threshold velocity >1.0 (live bed scour) |
| • Few areas of slow flow | | • Areas of slow flow |
| • High energy flow (stream power >35W/m$^2$) | • Intermediate energy (stream power 10–35W/m$^2$) | • Low energy flow (stream power <10W/m$^2$) |

### 7.5.2 Watercourse slope

Watercourse slope influences flow velocity and therefore the mobilising capacity of the flow, particularly for sediment, which may be transported as suspended load or bed load (rolling, sliding or saltation along the bed of the watercourse).

Watercourse slope is taken into account in several studies and good practice guides (Environment Agency 2009, SEPA 2010b, Wallerstein and Arthur 2012a, Engineers Australia 2013) (Table 7.9). Engineers Australia (2013) provides a relationship between bed slope and the transportability of debris. Of these sets of guidance, the SEPA approach is recommended, with amendment to the range giving medium risk to avoid overlapping.

For larger watercourses, watercourse slope can be estimated using online maps. Alternatively, local knowledge of the river bed can be used to assess the likelihood of sediment mobilisation. If the river bed consists of unconsolidated gravel or cobbles, these are likely to move in flood.

**Table 7.9 Influence of watercourse slope on debris transport**

| Bed slope | Low risk | Medium risk | High risk |
|---|---|---|---|
| Engineers Australia (2013) | <1% | 1-3% | >3% |
| Sear et al. (2003) | | <2% | 4–35% |
| SEPA (2010b) | <0.1% | 0.1–3% | >1% |
| Blockage management guide | <0.1% | 0.1–1% | >1% |

### 7.5.3 Channel width relative to debris length

Research has shown that the length of debris relative to the stream width affects the likelihood and frequency of debris transport and the nature of debris accumulation (Piégay and Gurnell 1997). Where debris size exceeds channel width, debris will tend to lie where it falls rather than be transported downstream to a structure, although it may be mobilised during high flow events. This debris can trap smaller debris and create a debris dam in the open channel that is not detrimental to flood risk. In larger streams, debris is shorter than the channel width and is mobilised more easily. The regular flushing of small pieces reduces the frequency of accumulations.

### 7.5.4 Flow depth relative to debris draught

Flow depth is also influential in the transport of floating debris. Haehnel and Daly (2002) noted that debris will not be transported in shallow flow that is insufficient to float the debris. For intermediate flow, debris floats but portions of the root ball or branches may be in continual contact with the bed. This contact will develop friction forces with the bed that will reduce the transport velocity of the debris compared with the flow velocity. For deep flow, large woody debris that is not in any substantial contact with the bed will be transported at the flow velocity.

### 7.5.5 Opening dimensions relative to debris size

The risk of blockage can be classed as:

- low – if debris length is less than the opening dimension
- medium – if debris length is about the same as opening dimension
- high – if debris length is greater than structure opening

The debris dimension relative to channel width and structure opening dimension is taken into account in several reports (FHWA 2005, Lagasse et al. 2010, Engineers Australia 2013). Research has shown that most blockages across narrow openings are initiated by some sort of bridging material (Engineers Australia 2013) or 'key log' which spans the structure opening (Diehl 1997). The size of the bridging material required depends on the size of the opening and can range from a tree trunk to span a culvert inlet, to small vegetation such as leaf litter to block a screen (Wallerstein et al. 2013). Although the majority of relevant research refers to large woody debris (Diehl and Bryan 1993, Diehl 1997, Piégay and Gurnell 1997), similar logic will apply to other floating debris.

Diehl (1997) found that structures with an opening width greater than the 'design log length' were found to block very rarely, and defined the 'design log length' as:

> 'a length above which logs are insufficiently abundant or insufficiently strong throughout their full length to produce drift accumulations equal to their length'.

The design log length is taken as the smallest of the minimum upstream channel width, the available sturdy logs based on mature tree height, or 9m (for the USA) plus a quarter of the upstream channel width.

### 7.5.6 Flow velocity relative to threshold velocity

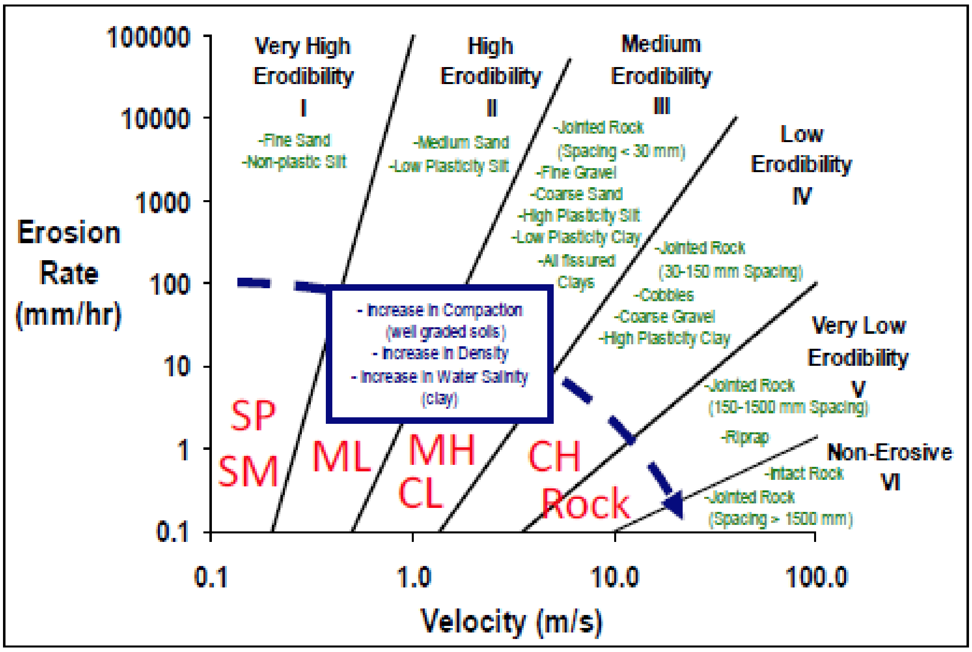
The ratio between flow velocity during flood conditions, U, and the velocity for sediment motion, $U_c$, is an indicator of the likelihood of sediment transport (or deposition). Three risk classes are specified (Kirby et al. 2015):

- High risk: $U/U_c > 1.0$ live bed scour, considerable sediment transport both at structures and upstream
- Medium risk: $U/U_c = 0.375$ to 1.0, clear water scour at structures, some sediment transport
- Low risk: $U/U_c < 0.375$ = no scour

The onset of sediment motion or deposition can also be predicted using graphical methods. A Shields diagram gives an empirical relationship between dimensionless critical stress and dimensionless viscosity. The Hjülstrom curve shows the critical velocities for erosion and deposition against particle size, and is quick and simple to use, but is less rigorous than a Shields diagram as flow depth is not taken into account. Figure 7.3 shows a graph showing erosion rates against velocity for a range of soils.

In practice, the prediction of sediment transport is difficult due to variations in flow depth, velocity and turbulence, non-uniform particle sizes within a watercourse, and armouring (a selective erosion of finer particles leading to an armour layer of coarser particles).

**Figure 7.3 Erosion rate versus velocity for a range of soils**




Notes: Based on the Unified Soil Classification and other factors.
SP = poorly graded soil; SM = silty sand; ML = silt; MH = elastic silt; CL = lean clay; CH = fat clay.
Source: FHWA (2012a, Figure 4.7), after Briaud et al. (2011)

### 7.5.7 Areas of slow flow

Areas of slow flow can increase the likelihood of debris deposition. Local sedimentation occurs when the stream velocity drops below the threshold velocity for the deposition of the sediment, typically due to a change in cross-section of the channel. Sedimentation may occur in areas of local stagnation, for example, downstream of bends or at culverts with skew approach flow.

### 7.5.8 Stream power

Stream power has been identified as an indicator of debris transportability for all types of debris (Engineers Australia 2013). The likelihood of scour or sedimentation can be estimated by comparing specific stream power with thresholds for stability and instability, although the relationship between stream power and channel stability is poorly defined and the method does not take bed sediment type into account (Sear et al. 2003, Wallerstein 2006).

Stream power can be estimated using a look-up table or the stream power equation. Low energy flow ($\omega < 10 W/m^2$) indicates sedimentation is likely, while high energy ($\omega > 35 W/m^2$) indicates erosion. Specific stream power (in $W/m^2$) is given by:

$$\omega = \rho g q S$$

where:

$\rho$ = density of water ($kg/m^3$)

g = acceleration due to gravity ($m/s^2$)

q = discharge per unit width of channel ($m^3/s/m$)

S = watercourse slope (m/m)

## 7.6 Step 5: Are there any receptors?

Potential impacts of blockage include flooding, embankment breach or structural failure, scour, environmental damage and economic damages (as a catch-all for unspecified impacts). The blockage management guide gives a checklist drawing on guidance by the Canal and River Trust, Engineers Australia, the Environment Agency, OPW and Highways England (Table 7.10). Social, community and legal impacts are omitted as these are not generally assessed as part of FCERM project appraisals in the UK.

The Canal and River Trust (2014) defines 5 consequences of failure (CoF) grades for canals (Table 7.11). Qualitative descriptions are also provided for failure of culverts and embankments.

Engineers Australia (2013) provides a comprehensive consequence of flooding scale that examines economic damages and health, environmental, social, community and legal impacts (Table 7.12).

Environment Agency (1998) uses 2 categories of impact, but these are somewhat dated in omitting critical infrastructure (although transport routes are included). 'Mild' consequences are classed as flood damages affecting rural areas, areas with isolated properties, urban areas where adjacent ground levels are well above river bank levels at the structure. 'Severe' consequences are classed as flooding affecting any existing or proposed urban areas (>25% density), industrial areas or major transport routes with ground levels close to river bank level.

OPW (2013) considers the impacts of blockage to be significant if blockage leads to:

- flooding of more than 10 additional receptors are as a result of blockage
- flooding of more than one individual risk receptor (essential infrastructure assets or environmental sites with significant pollution potential at significant risk of flooding)
- an increase in flood depth by more than 0.5m at any location beyond the river channel; or combinations of the above or any other impacts

BD97/12 of the 'Design Manual for Roads and Bridges' (Highways England 2012) provides a method for prioritising highway bridges according to the impacts of scour. The 'importance factor' varies according to the road classification, traffic flow, or other impacts such as community severance (Table 7.13).

**Table 7.10 Checklist for potential impacts**

| Risk | Description |
|---|---|
| H<br><br>(score 3) | • Widespread flooding (>0.5 km$^2$), affecting large urban area or commercial operations<br>• Failure or breach affecting road or rail with very long diversion route; no suitable diversion route, serving port link to island communities with no diversion route; causing unacceptable community severance<br>• Very serious, long-term environmental effects<br>• Multiple deaths<br>• Damages in excess of £5 million |
| M$^+$ | • Flooding of small community affecting groups of >4 houses or >1 commercial operation |

| Risk | Description |
|---|---|
| (score 2.5) | • Failure or breach affecting a motorway or an A road (> 30,000 vehicles per hour)<br>• Very serious, long-term environmental effects<br>• Multiple serious injuries or single death<br>• Damages £2 million to £5 million |
| M<br>(score 2.0) | • Widespread flooding of agricultural land (>0.5$km^2$)<br>• Significant crop loss or inability to plant<br>• Failure or breach affecting motorway or an A road (9,999 to 29,999 vehicles per hour)<br>• Serious medium-term environmental effects<br>• Serious injury (<3 in number)<br>• Damages £250,000 to £2 million |
| M$^-$<br>(score 1.5) | • Limited flooding of gardens or agricultural land (<0.5$km^2$)<br>• Failure or breach affecting an A or B road (1,000 to 9,999 vehicles per hour)<br>• Moderate, short-term environmental effects<br>• Minor injuries<br>• Damages £25,000 to £250,000 |
| L<br>(score 1.0) | • Localised wet areas affecting gardens or agricultural land<br>• Failure or breach affecting a B or unclassified road (<1,000 vehicles per hour).<br>• Minor environmental effects<br>• Single minor injury<br>• Damages £1,000 to £25,000 |

## Table 7.11 Consequence of failure

| CoF grade | (Primary) Life | (Secondary) Flooding | (Tertiary) Claims or prosecution |
|---|---|---|---|
| 5 | Multiple deaths | Widespread flooding (>0.5km$^2$), large urban area or commercial operations affected | In excess of £5 million |
| 4 | Multiple serious injuries or single death | Flooding of small community. Groups of >4 houses or >1 commercial operation affected. Flow across A class roads | £2 million to £5 million |
| 3 | Serious injury ( less 3 in number) | Disruption of a major transport link. Widespread flooding of agricultural land (>0.5 km$^2$). Significant crop loss or inability to plant. Flow across B class roads | £250,000 to £2 million |
| 2 | Minor injuries | Limited flooding to gardens or agricultural land (<0.5km$^2$). Minor transport link disrupted. Minor roads may become icy. | £25,000 to £250,000 |
| 1 | Single minor injury | Seepage to gardens/agricultural land. Flows <0.5l/s causing localised wet areas. | £1,000 to £25,000 |

Source: Canal and River Trust (2014)

## Table 7.12 Consequences of flooding

| Level [2] | Consequence type | | | | | |
|---|---|---|---|---|---|---|
| | Damage | Health | Environment | Social | Community | Legal |
| V | > $10M | Multiple fatalities | Very serious, long-term environmental impairment of ecosystem functions | Significant irreversible damage to cultural values | Serious public or media outcry with international coverage | Significant prosecution and fines including class action |
| IV | $1M to $10M | Single fatality and/or severe irreversible injuries to one or more persons | | On-going serious social issues, or significant, but mostly reversible damage to cultural values | Serious public or media outcry | Major breach of regulations or risk of litigation |
| III | $100K to $1M | Moderate irreversible injuries to one or more persons | Serious medium-term environmental effects | On-going moderate social issues, or moderate, but reversible damage to cultural values | Significant adverse national media or public attention | Serious breach of regulations with moderate fines possible and compensation |
| II | $10K to $100K | Objective but reversible disability requiring hospitalisation | Moderate, short-term effects by not affecting ecosystem functions | On-going social issues, or minor, reversible interference to cultural values | Significant adverse local media or public attention | Minor legal issue with low risk of fines |
| I | < $10K | No medical treatment required | Minor effects on biological or physical environment | Short-term social issues, or reversible interference to cultural values | Minor adverse local media or public attention | Minor legal issue |

Notes: [1] The consequences of an under-estimation of the design discharge may be significantly different from the consequences of debris blockage. The consequence scale should be determined from an assessment of the consequences of: an under-estimation of the design discharge when assessing hydrologic conditions; or the consequences of debris blockage in excess of that assumed within the design when assessing design flood levels adjacent an individual hydraulic structure.
[2] Adopt the highest value achieved for any of the consequence types.
Source: Engineers Australia (2013, Table 3.11)

## Table 7.13 Consequence of failure

| Importance factor | Description |
|---|---|
| 1.3 | No suitable diversion route or the diversion route is very long. Crossing on rural roads to ports serving island communities where there is no diversion route. Crossing provides link within a community where loss of the bridge would result in unacceptable community severance. |
| 1.0 | Motorway or A road, traffic flow >30,000 vehicles per hour |
| 0.9 | Motorway or A road, traffic flow 9,999–10,000 vehicles per hour |
| 0.8 | A or B road, traffic flow 1000 to 9,999 vehicles per hour |
| 0.7 | B or unclassified road, traffic flow <1,000 vehicles per hour |

Source: Highways England (2012)

The presence of an emergency bypass, overflow or flood relief channel can reduce the impacts of blockage by providing an alternative route for exceedance flow. It is recommended that design for exceedance should form part of the consequence assessment. This factor has not been used in blockage assessment methods to date, but is included based on practitioner experience.

## 7.7 Step 6: Risk score and blockage risk

The initial blockage risk should be estimated using the risk scores from Steps 3 to 5 (in any order). This approach recognises that 3 ingredients are essential for blockage risk:

- a source
- transport to a pinch point
- receptors that are susceptible to scour or flood damage such as properties or infrastructure

All 3 factors must be present; if one is missing, the risk is low, either because blockage will not occur or will not cause damage.

The initial blockage risk can be presented as high, medium or low to suit asset owners who simply need to select a management approach (Table 7.14).

**Table 7.14 Initial blockage risk**

| **Factors** | **HHH** | **HHM** | **HMM** | **MMM** | **HML** | **MML** | **HLL** | **MLL** | **LLL** |
|---|---|---|---|---|---|---|---|---|---|
| Initial risk | High | | Medium | | | | Low | | |

Alternatively, for asset owners who need to rank and prioritise multiple sites, a risk score can be taken as the product of the 3 numerical scores (each 7 to 21), divided by 549 to give a range of approximately 0 to 5.

The blockage management guide presents both qualitative and quantitative scoring systems.

## 7.8 Step 7: Uncertainty

Screening for blockage risk is uncertain due to:

- the random nature of blockage
- the numerous influential variables
- lack of systematic data gathering on the nature and impacts of blockage

Where data are available, predicted and observed blockage risk should be compared to confirm that:

- the predicted and observed blockage risk are comparable
- the ranking list of multiple structures (from high to low risk) reflects expectations

In addition, sensitivity testing should be carried out to assess the impact of variables on the final result. Tests should focus on the variables that are both influential and uncertain. The data quality score indicates the level of uncertainty associated with different types of data. It can be used to prioritise areas for sensitivity testing or to identify where more data should be collected.

# 8 New detailed assessment method

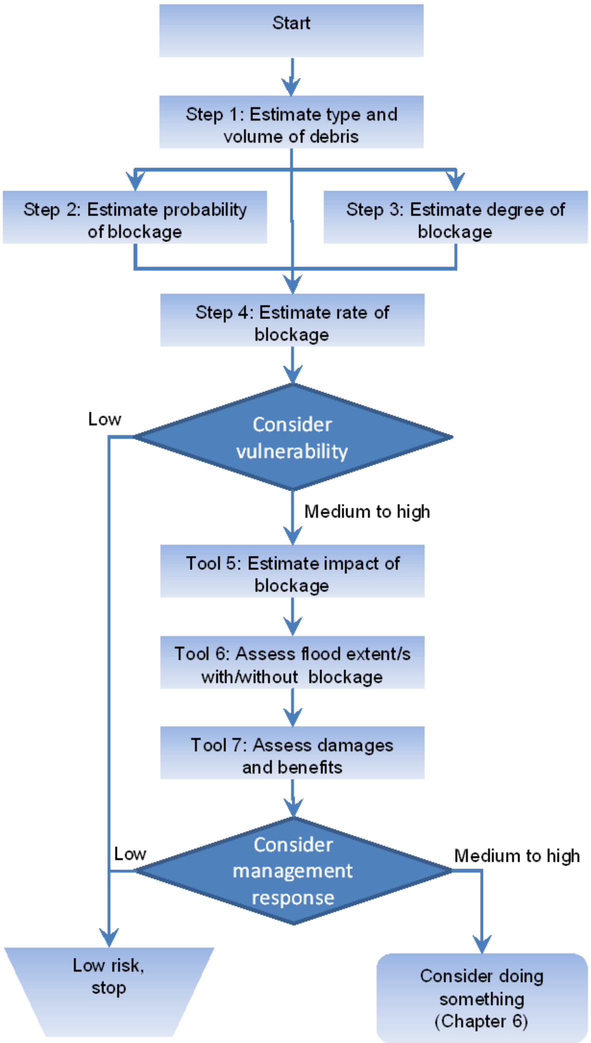
## 8.1 Overview

This chapter sets out the background to the new detailed assessment method proposed for assets that are potentially at risk of blockage. This is a quantitative approach using more detailed information than screening. The methods here are deterministic; recommendations for a probabilistic approach are given in Chapter 10.

The detailed assessment process includes 8 steps to quantify debris volume, probability and degree of blockage, rate of blockage, impacts on water levels and/or flood extents (with and without blockage), flood damages (with and without blockage) and overall risk (Figure 8.1 and Table 8.1).

It is important to note that some differences may exist between this report and the published guide due to editorial changes and maintaining ease-of-use in the new guide. Changes may include steps (how many or their order), references, logic and wording amongst others.

**Figure 8.1 Detailed assessment process**




At the halfway stage, the reader is advised to consider vulnerability to blockage before proceeding to the potentially time-consuming (and expensive) impact assessment. Care is needed to avoid spending more on analysis than it would cost to address the problem.

The method is suitable for:

- flood risk mapping and assessment
- design
- economic appraisal
- prioritisation of inspections and incident response

The method draws on existing, yet disparate, guidance from the UK, USA and Australia. In some places, new guidance has been developed based on the findings of the evaluation exercises or first principles. Where existing guidance exists and is readily accessible, or where an assessment is particularly complex, the guide does not reproduce the method, but signposts other documents.

**Table 8.1 Summary of detailed assessment factors**

| Step | Activity | Role |
|---|---|---|
| Step 1 | Debris type and volume | Informs Steps 3, 4, 6 and 7. |
| Step 2 | Rate of blockage | Informs decision to proceed to Steps 5 and 8. |
| Step 3 | Probability of blockage | Informs decision to proceed to Steps 5 and 8.<br>Informs inspection frequency. |
| Step 4 | Degree of blockage | Informs decision to proceed to Step 5.<br>Informs Step 5. |
| Step 5 | Model blockage | Informs Step 6 impacts. |
| Step 6 | Extent of impacts | Informs Step 7. |
| Step 7 | Economic appraisal | Informs Step 8. |
| Step 8 | Assess risk | Informs ranking of several sites, decision-making between do something and do nothing, inspection frequency and choice of management technique. |

## 8.2 Step 1: Debris type and volume

### 8.2.1 Overview

The type and volume of debris arriving at a structure can inform inspection and maintenance regimes, or help to size a new or replacement screen.

### 8.2.2 Type of debris

The type of debris arriving at a pinch point informs the choice of approach to probability and degree of blockage. The blockage management guide recommends determining debris type from the land use along the contributing length of watercourse upstream, plus risk factors such as social deprivation or access to waste facilities, using a table of debris types, potential sources and risk factors (Table 8.2).

**Table 8.2 Types of debris, potential sources and risk factors**

| Type | Sub-type | Description | Potential sources | Risk factors |
|---|---|---|---|---|
| Man-made | Small domestic refuse | Plastic bags, packaging<br>Small containers (cans, bottles, cartons)<br>Newspapers, magazines | Fly-tipping, commercial and industrial sites | Vehicular access to channel, urban land use, social deprivation, charging regime for disposal of waste, restricted access to waste disposal or recycling sites, high winds, deep or fast flow, flooding |
| | Large domestic refuse | Furniture, mattresses, carpets | | |
| | Large non-domestic refuse | Shopping trolleys, ladders, pallets, straw bales, cars | | |
| Vegetation | Small vegetation | Leaves, twigs, small branches<br>Garden waste, plants | Seasonal leaf shedding, decay or breakage, floodplain vegetation, local run-off, wind action, wind throw or collapse, bank erosion | Steep or wooded catchment, high winds, heavy rainfall, land management, maintenance regime, climate change |
| | Large vegetation | Large branches or trees<br>Shrubs, mats of weeds | | |
| Sediment | Fine sediment | Silt (diameter 0.006–0.06mm)<br>Sand (0.06–2mm)<br>Fine gravel (2–6mm) | Bed and bank erosion, collapse of banks or walls, sheet or gully erosion, slope failure, landslips, catchment changes | Steep catchment or watercourse, unstable watercourse, land use, agricultural practices, deforestation, climate change |
| | Coarse sediment | Coarse gravel (6–60mm)<br>Cobbles (60–200mm) | | |
| | Boulders | Boulders (>200mm) | | |

## 8.2.3 Volume of debris

The debris volume is used in estimating the cost of debris management and helps to choose between management techniques. One option is to take site observations either at the site or on a similar watercourse. An alternative is to use the method given in the Trash and Security Screen Guide (Environment Agency 2009), which applies to floating debris (refuse and vegetation) and is derived from fieldwork by Magenis (1988).

The evaluation exercise showed that this method over-estimated by a factor of around 2, although testing at further sites would be helpful (see Chapter 6). Sensitivity testing is therefore recommended to examine the impact of halving the debris load, after the findings of the evaluation exercise.

Other methods are aimed at woody debris and are unsuited to sites with man-made refuse as part of the debris load.

### 8.2.4 Sediment

Sedimentation is a complex process and a less common problem than blockage by man-made refuse or woody debris. Furthermore, methods for estimating sediment load, such as fluvial audit, sediment budget analysis and geomorphic dynamics assessment, are complex and require expertise (Defra 2009). The blockage management guide signposts Sear et al. (2003) for further information and recommends seeking expert advice for the estimation of sediment load.

## 8.3 Step 2: Probability of blockage

Step 2 predicts the probability of blockage which in turn informs the overall risk of blockage. This can be used in hydraulic modelling or MDSF2 for flood risk mapping, flood risk assessment or economic appraisal.

For screens, the blockage management guide recommends estimating the annual probability of blockage by vegetation and man-made debris (but not sediment) using 2 empirical equations from FRMRC2 (Wallerstein and Arthur 2012a) and Streftaris et al. (2013), both based on the Belfast dataset (see Chapter 6). The FRMRC2 equation is unsuitable for upstream network lengths below 900m or catchments with less than 3% agricultural or rural land use cover. Neither equation considers the impacts of debris management on the probability of blockage risk.

The guide also gives a method based on experimental work by Wallerstein et al. (2013), which developed a logarithmic relationship between the probability of blockage at screens and the ratio between debris length (L) and opening size (S), where L:S varied from about 0.5 to 12. For values of L:S up to 2.0, the relationship between probability and ratio is approximately linear, with probability of blockage varying from 35% to 45% for L:S = 2, with an average of 40%. Thus the probability of blockage can be taken as 17.5–20 times (L:S). Note that the probability of blockage depends on a range of factors not examined as part of the experimental work, including debris length and buoyancy, location and alignment of the debris in the channel, flow depth and velocity, and flow patterns both upstream and at the structure.

The guide suggests that, with care, the method developed by Wallerstein et al. (2013) may be applied to narrow gaps at larger structures in the absence of other methods (since the mechanisms of blockage would be similar), although this approach has not been validated.

For low gaps and other structure types, there are no methods available to predict the probability of blockage. No guidance was found during this project on the probability of blockage due to sediment.

## 8.4 Step 3: Degree of blockage

The blockage management guide provides a suite of methods for estimating the degree of blockage at different structure types. These methods draw on industry practice, existing guidance and research, and transferring methods from one structure type to another where the mechanisms of blockage are similar (Table 8.3).

The methods apply to floating debris (vegetation and some man-made refuse), but not sediment, and are not linked to a particular flood event. All methods should be used with caution and sensitivity tests should be carried out (see Section 8.10).

The modelling of blockage (that is, where to apply the blockage) is covered in Section 8.6.

**Table 8.3 Methods for estimating degree of blockage**

| Asset type | Description | Limitations |
|---|---|---|
| Screen | Blocked area from FRMRC2 method | Unsuitable for horizontal or mild sloping screens (<20° from horizontal) or suburban land use <3% |
| Bridge (low opening) | If design log length [1] > width of gap, width of gap × height of gap | Blockage potential depends on upstream channel curvature, pier location, pier shape. See Diehl (1997) for more. |
| Bridge (narrow opening) | If design log length [1] > width of gap, width of gap × smaller of flow depth and height of gap | |
| Bridge (pier) | Rectangular raft, 1.2m deep, width = average of adjacent spans (up to 20m) | |
| Bridge (masonry arch) | Treat as low gap where height of gap is mean arch opening height | Not validated |
| Culvert | Blockage/blinding: 33%, 67%, 100% | Not validated |
| Control gate | Sedimentation 5%, 15–25%, 80–100% | |
| Flap valve | | |
| Flume | If debris draught > flow depth, design log length × estimated log diameter | Not validated |
| Open channel | | |
| Weir | | |
| Multiple openings (any structure type) | Spans within debris transport zone: as single opening | Not validated |
| | Spans outside debris transport zone: half the blockage | |

Notes: [1] Design log length is the lesser of upstream channel width, or the maximum length of sturdy log that can bridge the gap without breaking, or 9m plus a quarter of the upstream channel width (USA only).

For screens, the findings of the evaluation exercise led to the recommendation in the guide of adopting the FRMRC2 equation, with sensitivity testing to assess the impact of halving and doubling the degree of blockage (Wallerstein and Arthur 2012a).

For flat bridges with narrow openings, low openings and piers, the guide recommends 3 approaches by Diehl which are based on empirical research in the USA. Narrow openings are defined as those where the distance between 2 piers is less than the design log length, while low openings are those where the height between the bridge soffit and bed or floodplain is less than the design log length. The design log length is the lowest of the upstream channel width, the maximum length of sturdy logs (log length that can withstand the hydrodynamic forces on the debris accumulation), or 9m plus a quarter of the upstream channel width (USA only). The evaluation exercise showed that none of these methods hit the mark, either under- or over-estimating the degree of blockage; the guide recommends sensitivity testing to examine the impact of halving and doubling the degree of blockage. For debris on piers, the width should be varied. For other blockage types, the height should be varied.

For masonry arch bridges, the guide recommends treating a masonry arch bridge as a low gap, with the height equal to the mean arch opening height. This is a new approach combining the work of Diehl with the findings of the evaluation exercise, as no existing methods are directly applicable to masonry arch bridges (which are common in the UK).

For culverts, control gates and flap valves, in the absence of other methods the guide recommends adopting the approaches in the Culvert Design and Operation Guide (Balkham et al. 2010), since the mechanisms of blockage are similar. A 5% sedimentation depth examines the effect of sedimentation on flow capacity due to increased bed roughness and nominal loss of section, while a 15–25% sediment depth examines the partly blocked condition that may occur before maintenance if a culvert is not self-cleansing.

For weirs, flumes and open channels, the guide recommends assuming a blockage with the dimensions of the design log length and estimated log diameter, provided that the debris draught is greater than the flow depth. This is a pragmatic approach based on engineering judgement as no existing methods were found during this project.

The guide recommends varying the degree of blockage for structures with multiple openings, where not all openings may block to the same degree. This is based on the approach in Engineers Australia (2015) but has not been validated.

## 8.5 Step 4: Rate of blockage

The rate of debris delivery and timing of blockage can be used to:

- assess overall blockage risk
- choose between proactive or reactive management measures
- determine the required operational response time for existing screens
- inform the design of new or replacement screens, such that complete blockage does not occur before operatives can mobilise to clear debris

Research and guidance into the rate of blockage are limited. The blockage management guide presents a method from Engineers Australia (2015) based on first principles which applies to all types of debris, including sediment, and all structure types, including open channels and overland flow paths. The method involves determining whether debris delivery is likely to be pulsed (intermittent) or progressive using the likely debris type from Step 1 and Table 8.4, then determining the likely blockage timing using Table 8.5.

Sensitivity testing is recommended to examine the impact of halving and doubling the time to blockage, based on the evaluation exercise which showed a wide variation between observed and predicted rate of blockage (see Chapter 6).

**Table 8.4 Rate of debris delivery**

| Debris type | Likely timing of peak mobilisation |
|---|---|
| Reeds and aquatic vegetation | Progressively during rising limb of a hydrograph with peak mobilisation coinciding with peak in-bank flow |
| Grass and garden mulch | Commencement of overland flow, especially in rural areas |
| Refuse | Progressively during rising limb of a flood hydrograph, once overland flows develop |
| Refuse: urban | Periods of significant overbank flow, when depth × velocity ≥0.3 along overland flow paths |
| Refuse: building | Often pulse-like delivery once significant overbank or overland flow develops |
| Sediment | Rising limb of flood hydrograph, around bankfull discharge<br>Peak deposition normally on falling limb as velocity drops |

**Table 8.5 Blockage timing**

| Dominant debris type | Supply rate | Blockage locations | | | |
|---|---|---|---|---|---|
| | | Inlet | Barrel | Outlet | Handrails |
| Floating | Progressive | $1.5T_P$ to $A_b$ at $2.0_{TP}$ | Unlikely | Unlikely[1] | $T_{O/T}$ to $A_b$ at $T_P$ |
| | Pulse | $A_b$ at $0.5_{TP}$ | Unlikely | Unlikely | |
| Non-floating | Progressive | $0.5T_P$ to $A_b$ at $T_P$ | | | Unlikely |
| | Pulse | Unlikely[2] | Unlikely | Unlikely | Unlikely |

Notes: [1] Unlikely, but could occur if inlet is open and outlet grated.
[2] Unlikely, but could occur if upstream bed/banks are unstable and/or prone to scour.

## 8.6 Step 5: Model blockage

The blockage management guide gives some general principles and recommends methods of blockage modelling suitable for hand calculation or computer modelling (both are used by practitioners) (Table 8.6). These are based on modelling guidance, industry practice and engineering judgement.

For clean and partially blocked screens (screens with permeable debris), the recommendation is to reduce the effective width of the screen opening, equivalent to applying a full height impermeable barrier over part of the screen width. For blinded screens with an impermeable barrier across the lower part of the screen, similar to a weir, the guide recommends adding an in-line weir upstream of the screening (Balkham et al. 2010).

The guide also gives recommended values for hydraulic parameters:

- hydraulic roughness coefficient and guidance on estimating compound roughness (Balkham et al. 2010)
- contraction and expansion coefficients for bridges (USACE 2010)

- contraction and expansion coefficients for screens (Clark et al. 2010)
- orifice coefficient for control gates and flap valves based on recommended drag coefficients for debris on bridges (in the absence of specific guidance on orifice coefficients) (Parola et al. 2000)
- weir discharge coefficient extrapolated after Wallingford Procedure User Group (WaPUG) User Note No. 2 (Balmforth 2009), which recommends increasing weir coefficient by 20% for the addition of a scum board, more for ragging, based on engineering judgement

**Table 8.6 Detailed blockage modelling approaches**

| Blockage type | Debris type | Description |
|---|---|---|
| Top-down | Floating | Reduce bridge soffit level, model bridge opening as an orifice, and increase expansion and contraction coefficients (for example, bridge superstructure). |
| Water surface to bed | Impermeable | Add in-line weir upstream of structure (for example, screen, bridge). |
| Bottom-up (at inlet or in barrel) | Non-floating | Add obstruction at inlet and change inlet efficiency (for example, culvert, bridge, flume). |
| Bottom-up (long structure) | Sedimentation | Reduce cross-sectional area and increase hydraulic roughness (for example, culvert, bridge, flume). |
| Bottom-up (weir crest) | Any type | Raise part of weir crest and increase weir discharge coefficient (Balmforth 2009). |
| Porous plug | Permeable debris | Reduce effective opening width, increase contraction and expansion loss coefficients. |
| Control gate or flap valve blocked open or closed | Any type | Amend opening dimensions, invert level or gate level, and amend orifice or head loss coefficient. |
| Mid-stream obstruction (for example, bridge pier/s) | Debris on single pier | Increase pier width from water surface to bed, increase expansion and contraction coefficients (1:1 contraction rate upstream, 1:4 expansion rate downstream) and designate ineffective flow areas (Parola et al. 2000). |
| | Debris on 2 adjacent piers | Increase pier widths from water surface to bed such that the piers touch, increase expansion and contraction coefficients, and designate ineffective flow areas (as above). |

Existing approaches to modelling blockage at each type of asset are summarised in Table 8.7. These are drawn from the Culvert Design and Operation Guide (Balkham et al. 2010), the HEC-RAS Hydraulic Reference Manual (USACE 2010), research in the USA for the NCHRP (Parola et al. 2000) and industry practice in the UK (see Appendix A). There is little conflict between the various sources.

Note that blockage cannot be modelled by increasing hydraulic roughness in isolation; a proof of this is given in Box 8.1.

**Table 8.7 Existing blockage modelling approaches**

| Asset type | Description | Source |
|---|---|---|
| Screen (blockage) | Amend opening width.<br>Amend loss coefficients. | Balkham et al. (2010) |
| Screen (blinding) | Add weir upstream of screen. | Balkham et al. (2010) |
| Culvert blockage at inlet or within barrel | Add obstruction at inlet, change inlet efficiency or reduce the barrel area. | FHWA (2005) |
| Culvert sedimentation | Add blocked obstruction, or amend culvert cross-sectional area and roughness coefficient.<br>Unsuitable for partial blockage of long culverts (>50m long) as could over-estimate friction loss. | Industry practice |
| Bridge | Alter bridge geometry to simulate presence of debris, modify contraction and expansion losses where this would be caused by the debris, and add ineffective flow areas upstream and downstream of the bridge to simulate the debris accumulation and wake created by the debris. | FHWA (2005) |
| Bridge (deck) | Lower bridge soffit to represent debris, model the bridge opening as an orifice, and increase expansion and contraction loss coefficients to 0.3 and 0.5 respectively. | Parola et al. (2000) |
| Bridge (narrow gap) | Increase pier widths from water surface to bed such that the piers touch, increase expansion and contraction coefficients to 0.6 and 0.8 respectively for severe blockage (blockage ratio of 0.3 or higher), and designate ineffective flow areas with 1:1 contraction rate upstream and 1:4 expansion rate downstream. | Parola et al. (2000) |
| Bridge (pier) | Increase pier width from water surface to bed, increase expansion and contraction loss coefficients to 0.3 and 0.5, and designate ineffective flow areas as above. | Parola et al. (2000) |
| Weir | Reduce weir coefficient (by 10–20% to allow for addition of scumboard, more for ragging) (aimed at sewers). | Balmforth (2009) |
| Flumes, open channel | Amend channel cross-sectional area and hydraulic roughness. | Engineering judgement |

**Box 8.1: Proof that blockage cannot be modelled by roughness alone**

Head loss across a structure is the sum of expansion and contraction losses, and friction loss:

$$h_T \approx 1.5\frac{V^2}{2g} + h_f$$

where:

V = flow velocity through structure (m/s)

$h_f$ = head loss due to friction (m)

From Manning's equation (assuming normal flow through the structure):

$$Q \approx \frac{1}{n} A R^{2/3} S_f^{1/2}$$

where:

n = roughness coefficient

A = flow area ($m^2$)

R = hydraulic radius (m)

$S_f$ = friction slope (m/m)

This can be re-arranged to give:

$$S_f \approx \left(\frac{nQ}{AR^{2/3}}\right)^2$$

It is known that friction slope is:

$$S_f \approx \frac{h_f}{L}$$

And that flow velocity is:

$$V \approx \frac{Q}{A}$$

Thus:

$$h_f \approx L\left(\frac{nV}{R^{2/3}}\right)^2$$

Hence the head loss due to blockage at a structure is:

$$h_T \approx 1.5\frac{V^2}{2g} + L\left(\frac{nV}{R^{2/3}}\right)^2$$

Thus, ignoring the expansion and contraction losses would lead to an under-estimation of the head loss.

## 8.7 Step 6: Extent of impacts

Step 6 involves estimating the extent of the blockage impacts so as to quantify impacts and determine the benefits of intervention. The blockage management guide recommends 3 broad approaches to modelling the extent of impacts (Table 8.8). The choice of method depends on the question being asked and the scale of the problem; the method should be proportionate to the scale of the problem.

**Table 8.8 Methods for assessing impacts of blockage**

| Type | Method | Description |
|---|---|---|
| Change in water level due to blockage | Historic water levels or flood outlines | Estimate change in water level due to blockage (see Box 8.2) and likely change in flood extent from ground slope. Consider change in receptors. |
| | Flood Zones | Estimate change in water level due to blockage (see Box 8.2) and likely change in flood extent from ground slope. If flood zones are close together, benefit area is insensitive to blockage. |
| Water level | Relief level | Identify overflow or relief level by inspection. |
| | Structure model | Estimate water level with and without blockage using structure model (for example, CulvertMaster, HY-8). Need estimate of tailwater level. |
| Flood extent | Projected relief level | Project relief level or modelled water level upstream using engineering judgement. |
| | Relief flow path | Estimate extent of flooding downstream of asset by visual inspection of flow path. |
| | Large-scale model | Estimate water level and flood outlines with and without blockage, using coarse model such as MDSF2 or other off-the-shelf tools. |
| | Reach-scale model | Estimate water level and flood outlines with and without blockage, using 1D or 2D hydraulic model and a digital terrain model. |
| Embankment breach due to external erosion | Resistance to external erosion | Estimate overflow velocity and compare with limiting design values for erosion resistance of different erosion countermeasures – see Chapter 8 of the International Levee Handbook (CIRIA 2013). |
| Embankment breach due to internal erosion | Simple | Assume at risk unless designed as water-retaining structure. |
| | Detailed | See the International Levee Handbook (CIRIA 2013) or consult a geotechnical engineer. |
| Contraction scour | Competent mean velocity | Estimate additional flow area required to reduce flow velocity to that which would not cause further scour (see Highways England 2012). |
| Local scour | Rule of thumb | Estimate maximum local scour depth ≈ 2 × width of obstruction. |
| | Equation | Estimate local scour depth at structure using appropriate equation (see Kirby et al. 2015). The extent of scour can be estimated from the angle of repose of the bed or bank material. |

Methods to determine the change in water level due to blockage are suitable for hand calculations, users without access to computer software, quick checks of the outputs of computer modelling, or in combination with modelling where the model lacks the capability to model blockage directly. These methods are concerned with the change in impacts rather than the absolute magnitude of impacts, similar to the ecosystems approach of project appraisal (see Section 8.8). The impact on flood extents can be estimated from known flood maps and the ground slope.

The proof of a quick method of estimating the increase in water level due to blockage is given in Box 8.2; it is based on head losses due to expansion and contraction around the structure and debris. It is suitable for subcritical flow conditions and initial assessment of point assets or short assets, but unsuitable for supercritical flow conditions (such as sluices or culverts operating under inlet control) or long, linear assets (as it ignores friction).

**Box 8.3: Proof of quick method for estimating increase in water level**

Water level increase due to blockage is

$$\Delta WL = Afflux(with\_blockage) - Afflux(without\_blockage)$$

The afflux across a structure (with blockage) can be estimated from the losses due to expansion and contraction through the structure:

$$\Delta WL \approx 1.5 \frac{U^2}{2g}$$

where: U = flow velocity through structure without blockage (m/s)

The afflux across a structure (without blockage) can be estimated similarly:

$$\Delta WL' \approx 1.5 \frac{U'^2}{2g}$$

where: U' = flow velocity through structure with blockage (m/s)

We know that:

$$U = \frac{Q}{A} \text{ and } U' = \frac{Q}{A - A_b}$$

where:

A = area of unobstructed flow ($m^2$)

$A_b$ = area of debris blockage ($m^2$)

Thus:

$$U' = U.\left(\frac{A}{A - A_b}\right)$$

Hence:

$$\Delta WL \approx 1.5 \frac{U^2}{2g}.\left(\frac{A}{A - A_b}\right)^2 - 1.5 \frac{U^2}{2g}$$

The water levels and flood extents (with and without blockage) can be estimated by identifying the relief level and projecting this upstream, or by inspection of the flow path downstream. A structure model, typically available for culverts, allows the modeller to determine the water level upstream of a structure, provided that an estimate of tailwater level is available. This method is only suitable for simple structures:

- uniform culverts
- single barrels
- identical multiple barrels
- barrels with simple cross-sections

For assets where the probability or consequences of blockage are high, a 1D or 2D hydraulic model, digital terrain model data and property data are recommended. A coarse model such as MDSF2 allows a quick assessment, while a reach-scale model provides the most detailed answer.

The prediction of embankment breach due to internal or external erosion is a complex matter and the reader is referred to the International Levee Handbook (CIRIA 2013), although a conservative approach is to assume that the asset is at risk unless it has been designed as a water-retaining structure. The failure of structures due to additional hydrodynamic forces on both the structure and debris is similarly complex, and the reader should refer to CIRIA's 'Manual on Scour at Bridges and Other Hydraulic Structures' (Kirby et al. 2015).

A further impact of blockage is scour, that is:

- contraction scour due to flow acceleration through a restricted opening
- local scour due to flow acceleration and turbulence at a structure such as a pier

The CIRIA manual gives a rule of thumb, based on industry practice for scour at piers, and signposts good practice guidance (Kirby et al. 2015).

## 8.8 Step 7: Economic appraisal

Economic appraisal of the impacts of blockage is essential to:

- help choose between management options
- prepare a business case for capital or maintenance works

Five alternative methods of economic appraisal suitable for debris management activities are summarised in Table 8.9. The methods range from qualitative to monetised to enable a proportionate approach to be taken – particularly as blockage management tends to be low cost compared with capital works.

An appraisal should consider:

- short-, medium- and long-term impacts
- whole-life costs and benefits
- the risks associated with an option

**Table 8.9 Methods of quantifying impacts**

| Method | Applications | Description |
|---|---|---|
| Appraisal summary table | Screening or initial assessment | Describe, quantify and value impacts (if possible) and who may be affected. |
| Scoring and weighting | Screening or to supplement other methods, or if intangible impacts are significant | Score and weight options against a list of objectives to generate implied values. |
| Cost-effectiveness analysis (CEA) | Mandatory works to achieve regulatory compliance at least cost | Monetised method to determine least cost option that will achieve the objective(s) |
| Cost–benefit analysis (CBA) | Detailed assessment, to compare options when there is no legal obligation to do the work | Monetised method using benefit–cost ratio, net present value or internal rate of return |
| Ecosystem approach (ESS) | Policies or projects that are expected to have impacts on the environment | Scoring and weighting, or quantitative assessment of changes to ecosystem services |

The ecosystems approach is as an emerging method which is likely to gain importance due to increasing emphasis on sustainable development. This approach is suited to blockage management as it focuses on environmental impacts (important when considering whether to retain or remove debris) and the change in an impact, rather than the absolute value (which lends itself to quick, simple assessments).

The blockage management guide provides brief guidance on cost estimating for the monetised approaches, based on industry practice. It also signposts sources of damage data, such as the Multi-Coloured Manual (FHRC 2016) and the Multi-coloured Handbook (FHRC 2014). It does not provide advice on how to calculate event damages as that falls out of the scope of this guide.

For high-level assessments, the guide recommends estimating impacts using existing flood outlines and property counts, rather than bespoke flood outlines, property thresholds and depth-damage data. A project appraisal for Defra flood risk management funding must also consider outcome measures. For a high-level assessment, a property count is sufficient with the weighted annual average damage method.

## 8.9 Step 8: Assess risk

Assessment of the overall blockage risk is essential to decide which sites to prioritise, whether to do something or do nothing at a given site, and if do something, what management technique to adopt.

Blockage risk is a function of the quantitative outputs of detailed assessment, plus qualitative factors. Qualitative factors include:

- the ease of intervening to remove a blockage during a flood event – which in turn depends on the likely location of the blockage and access to remove it

- the proximity to disposal sites – which in turn depends on the debris type, debris volume and contamination of the debris

Not all these factors can be quantified – some engineering judgement will be required.

Considering a wide range of options is recommended, screening out those that are technically unviable or environmentally adverse, and comparing do something options with a baseline option (typically do nothing or do minimum). An exception is mandatory work where all options must achieve regulatory compliance. Working with natural processes and addressing the cause of the problem rather than managing the symptom over the long term is also recommended.

- For **strategic assessment**, several sites can be ranked using the risk score (from screening), the benefit–cost ratio (from monetised assessment) or the impacts score (for example, from the appraisal summary table or ecosystems approach). The approach to ranking will depend on the asset owner's priorities and performance measures.
- For **single-site assessments**, the decision to do something or do nothing can be based on the risk score (from screening), the benefit–cost ratio (from monetised assessment) or an impacts score (for example, from the appraisal summary table or ecosystems approach). The threshold for action will depend on the asset owner’s budget and approach to risk.
- For **option appraisals**, the choice of management technique will depend on the quantitative and qualitative risk factors. The decision process involves identifying suitable methods for the site, then considering their environmental and economic viability.

## 8.10 Step 9: Uncertainty

Due to the lack of systematic data gathering on the nature and impacts of blockage, the detailed assessment methods are highly uncertain. Sensitivity testing is recommended to assess the impact of variables on the results and the verification of the results against observations.

Suggested ranges for sensitivity testing are given in Table 8.10; these ranges should be tested one at a time. The data quality score should be used to prioritise areas for sensitivity testing or identify where more data should be collected. The sensitivity tests should focus on those variables that are both influential and uncertain, and the impacts which contribute a significant proportion of the costs or benefits.

It is important to verify the findings of the detailed assessment against blockage history (where available). In particular, the verification should check for consistency of:

- blockage mechanism (location, type and timing)
- probability or degree of blockage
- frequency of overflow or flooding
- head loss across the structure
- impacts of blockage

The observed blockage should take precedence over predicted blockage for post-event analysis, particularly where good quality data are available.

**Table 8.10 Suggested ranges for sensitivity testing**

| Variable | Recommendation |
|---|---|
| Impact of blockage | Degree of blockage (from Step 3) |
| | Hydraulic roughness, expansion and contraction coefficients and/or discharge coefficients: viable ranges (see Section 4.6) |
| Degree of blockage | Screen: area × 2 |
| | Bridge (low opening, masonry arch): |
| | blockage height ±20% (from the top) |
| | Bridge (narrow opening, pier): |
| | blockage width ±20% |
| Probability of blockage | Probability × 2, Probability/2 |
| Debris load | Volume/2 |
| Rate of blockage | Duration × 2, Duration/2 |

# 9 New management guidance

## 9.1 Overview

This chapter gives the background to the new guidance on management techniques, including choice of approach and regulatory compliance.

Blockage management involves meeting legal obligations relating to public safety, environmental and flood risk management, while balancing the costs and benefits of maintenance with the costs and benefits of flooding, structural repairs or environmental benefits. This can present complex challenges. The asset manager faces a number of decisions, including:

- whether or not to intervene
- whether to be proactive or reactive
- the choice of technique

It is important to note that some differences may exist between this report and the published guide due to editorial changes and maintaining ease-of-use in the new guide. Changes may include steps (how many or their order), references, logic and wording amongst others.

## 9.2 Choosing an approach

This section sets out a 3-step process for choosing an approach.

- Step 1: Identify techniques which are suitable for the site.
- Step 2: Consider the environmental impact of those techniques.
- Step 3: Consider the economic viability of the shortlisted options.

For **Step 1**, there are a suite of management techniques, ranging from proactive to reactive measures (Table 9.1). Measures are classed according to whether they reduce debris load, reduce the probability of blockage, or reduce the consequences of blockage, based on engineering judgement. The influential factors and philosophy are as follows:

- **Risk**: while any measure is suitable for low risk sites where the probability or consequences of blockage are low. For high risk sites, proactive measures are preferred.
- **Type of debris**: refuse is potentially harmful to the environment and should be removed rather than retained. For vegetation, any measure is suitable. The removal of sediment can cause loss of habitat or species, and hence other measures are preferable.
- **Volume of debris**: where the volume of debris is low, any measure can be applied. For high debris volumes, measures that reduce probability (either by design or retrofitting) impose a lower maintenance burden on the asset owner than those measures that involve removing debris.

- **Rate of blockage**: proactive measures are recommended for locations that are susceptible to rapid blockage and which may block before operations teams are able to mobilise to remove the blockage. Where blockage occurs slowly, the full range of measures may be used.

- **Ease of intervention**: any measure may be adopted for a location where it is easy to intervene to remove a blockage, but sites that are difficult to access should adopt proactive measures.

- **Proximity to disposal sites**: the distance to a disposal site influences whether it is cost-effective to remove debris. Where disposal is remote from the site, measures which avoid transporting debris are preferred. If disposal is local, a wider range of measures can be adopted although the removal of debris, either through source control or at the structure, is less desirable due to transport and disposal costs.

**Table 9.1 Suitability of management techniques**

| | Proactive → | → | → | Reactive | |
|---|---|---|---|---|---|
| Blockage type | Load | Probability | | Consequences | |
| | Source control | Design or retrofit | Inspect or monitor | Remove debris | Retain debris |
| High risk | Y | Y | Y | N | N |
| Low risk | Y | Y | Y | Y | Y |
| Refuse | Y | Y | Y | Y | N |
| Vegetation | Y | Y | Y | Y | Y |
| Sediment | Y | Y | Y | Y | Y |
| High volume | Y | Y | N | N | N |
| Low volume | Y | Y | Y | Y | Y |
| Rapid blockage | Y | Y | N | N | N |
| Slow blockage | Y | Y | Y | Y | Y |
| Difficult to intervene | Y | Y | N | N | N |
| Easy to intervene | Y | Y | Y | Y | Y |
| Remote disposal | N | Y | N | N | Y |
| Local disposal | Y | Y | Y | Y | Y |

Key: Y = suitable; Y = may be suitable, N = unsuitable.

For **Step 2**, the environmental impact of management techniques is presented in a red–amber–green table (Table 9.2). This adapts the approach taken by the Environment Agency's Maintenance Standards (Environment Agency 2012b). Ideally, the option with least impact should be chosen.

- **Reduce debris load**. The control of debris at source is classed as green, removal of selective debris as amber, and removal of all debris as red, based on the hierarchy of measures for sediment management (SEPA 2010a) and large woody debris (Mott 2005).

- **Reduce blockage probability**. The removal of a man-made structure to restore the natural channel is classed as least impact, in accordance with the Water Framework Directive. Modification or replacement of a structure that cannot be decommissioned is classed as amber, since construction would have some environmental impact but may reduce the need for long-term debris management. Finally, inspection and monitoring is classed as red, since this necessitates reactive intervention to remove debris. These measures have been classed using engineering judgement.
- **Remove or retain**. The retention of refuse (man-made) is potentially harmful to the environment and is therefore classed as red, while removal is favourable and classed as green (after the Water Framework Directive). The retention of woody debris is taken as green, selective removal as amber and full removal as red (after Environment Agency 2012b). Finally, the retention and removal of sediment is classed according to SEPA's sediment management guidance (SEPA 2010a). Retention is preferable to removal, and returning to the river downstream is preferable to off-site use or disposal to landfill.

**Table 9.2 Environmental impact of management techniques**

| Impact | Reduce debris load | Reduce blockage probability | Remove or retain |
|---|---|---|---|
| Red (greatest impact) | • Remove all debris from channel and floodplain upstream | • Inspect or monitor to allow timely intervention | • Retain refuse<br>• Remove debris or sediment and use off-site or dispose to landfill |
| Amber | • Remove selective debris and re-align remainder to improve flow | • Modify or replace structure | • Remove debris or sediment and return to river downstream |
| Green (least impact) | • Identify debris sources and control at source | • Remove structure and restore natural channel | • Remove refuse<br>• Retain woody debris or sediment |

Notes: Options are classed as red (greatest environmental impact), amber (intermediate impact) and green (least impact).

Finally, for **Step 3**, the preferred option for mandatory work will be the least cost option with an acceptable environmental impact. If the work is not mandatory, the preferred option will be that with highest benefit–cost ratio and positive incremental benefit–cost ratio, or highest net present value.

## 9.3 Regulatory compliance

Appendix A of the blockage management guide presents a summary of general duties relating to debris management and regulatory compliance requirements. These are broadly similar throughout the UK, although there are some differences in statute law. The summary does not attempt to be comprehensive and notes that the law is changing all the time, so readers are advised to seek independent advice.

## 9.4 Management techniques

The blockage management guide presents the full range of techniques identified during the literature review and industry consultation. Rather than reproducing detailed guidance, it provides an overview of each method and signposts other reference documents. It endeavours to be impartial and provides information on all methods, rather than steering the reader towards a particular method.

# 10 Suggestions for future work

## 10.1 Introduction

This chapter presents suggestions for future research and development to:

- improve the ability to assess the influence of debris and blockage on the probability and extent of flooding (and hence risk)
- respond to a recommendation in the NaFRA method improvements study (Environment Agency 2013b)

It builds on the work for this project and various previous studies including the original MDSF2 development (Environment Agency 2011b, 2011c), FRMRC1 and FRMRC 2 (particularly SWP4 as summarised by Wallerstein and Arthur 2012a) and the recent guidance on estimating inflow volumes for MDSF2 (HR Wallingford 2012).

Debris and associated blockage present a number of analysis and modelling challenges.

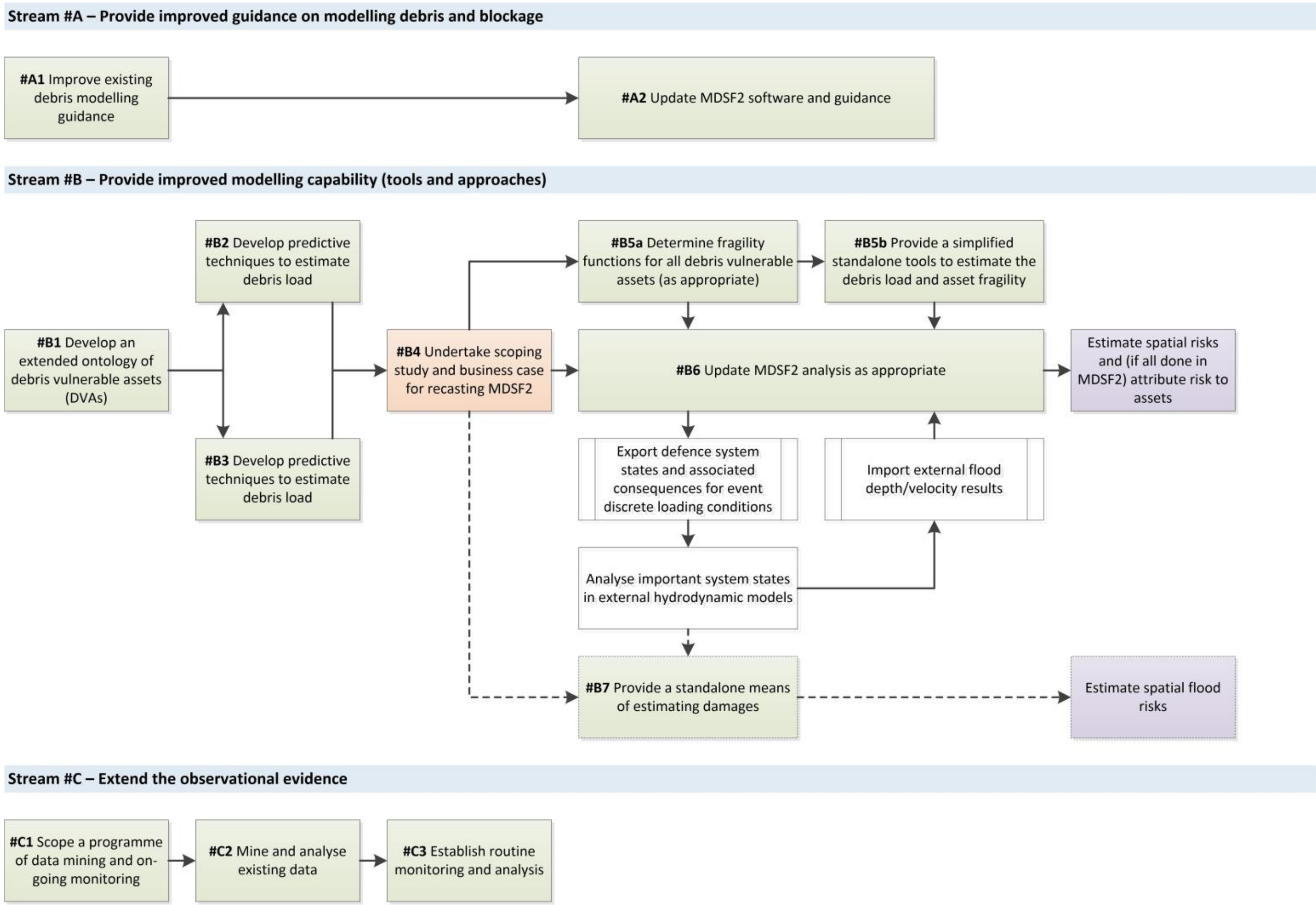
The route map shown in Figure 10.1 identifies a series of research tasks that progress towards a more credible and comprehensive understanding of debris-related flood risk issues. The route map is divided into 3 streams:

- Stream #A covers the development of guidance (see Section 10.2)
- Stream #B focuses on tools and approaches (see Section 10.3)
- Stream #C covers data and observations (see Section 10.4)

It seeks to support decisions about how approaches to assessing debris-related risks should be improved and is aimed at those with a good understanding of MDSF2 and debris-related issues. It focuses on the analysis of debris-related flood risk and associated guidance; it does not cover the development of additional guidance on best practice in the management of debris or the design of structures that will no doubt also be required.

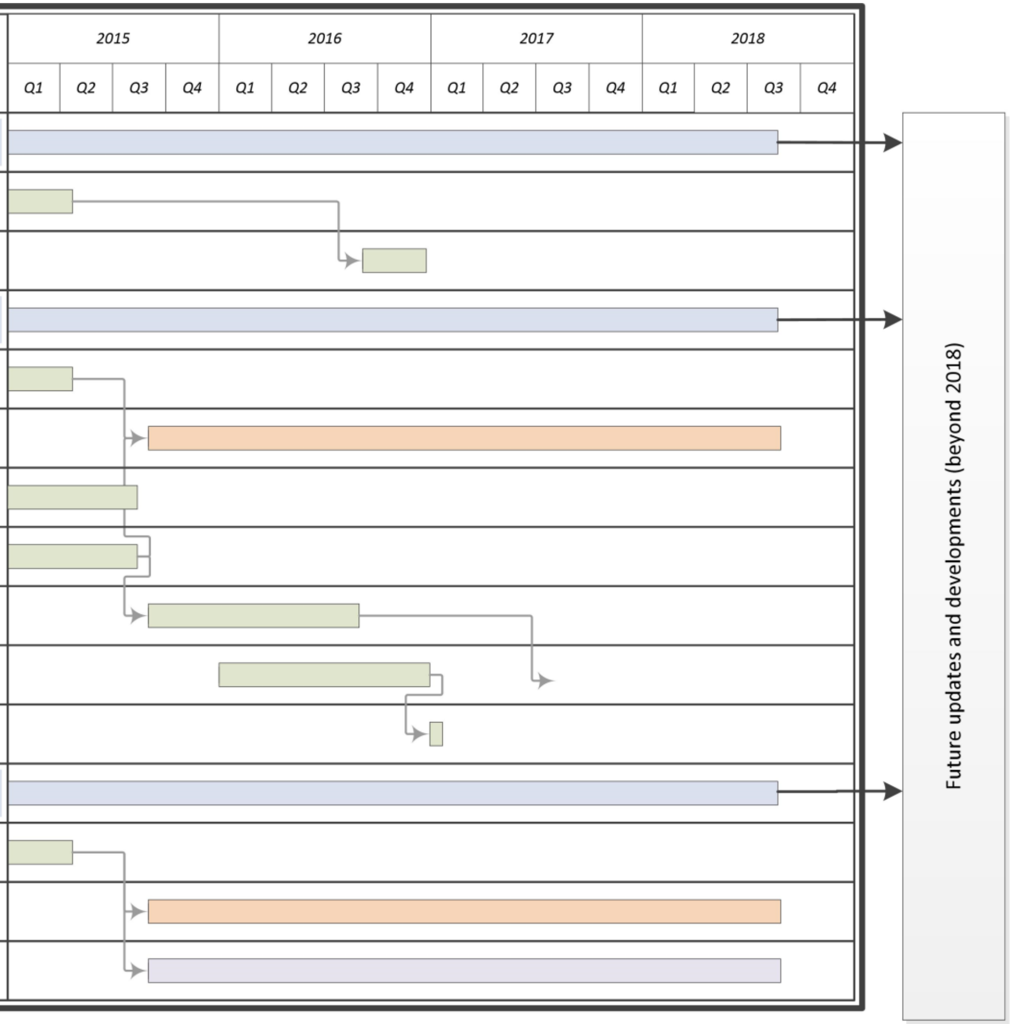
A programme of activities and indicative funding levels is presented in Figure 10.2. An indication is also given as to whether the activity is likely to be best taken forward through the joint Environment Agency and Defra programme, research council or operational funding routes. Short-term quick wins are included as well as longer term developments. The programme extends to 2018; though the scoping studies proposed in #B3 (methods and tools) and #C1 (data and observations) should look beyond this date.

## Figure 10.1 Suggested route map



## Figure 10.2 Programme and indicative funding

| ID | Task Name | Likely costs (£) | Lead funder |
|---|---|---|---|
| 1 | **Stream #A – Guidance** | | |
| 2 | #A1 Improve existing debris modelling guidance | <£25k | Joint Programme |
| 3 | #A2 Update MDSF2 software and guidance | See B5 below | Joint Programme |
| 4 | **Stream #B – Improved tools** | | |
| 5 | #B1 Develop an extended ontology of debris vulnerable assets (DVAs) | £25-35k | Joint Programme |
| 6 | #B2 Develop predictive techniques to estimate debris load (with C2) | £200k (incl. C2) | RCUK |
| 7 | #B3 Develop an approach to better utilize local modelling results to support MDSF2 | £30-40k | Joint programme |
| 8 | #B4 Undertake scoping study and business case for recasting MDSF2 | £40-50k | Joint Programme |
| 9 | #B5a&b Determine fragility curves and simplified support tools for DVAs | £30-50k | Joint Programme |
| 10 | #B6 Update MDSF2 analysis as appropriate | £50-150k (incl. A2) | Joint Programme |
| 11 | #B7 Provide a standalone means of estimating damages | £20-30k | Joint Programme |
| 12 | **Stream #C – Observational evidence** | | |
| 13 | #C1 Scope a programme of data mining and on-going monitoring | £25-30k | Joint Programme |
| 14 | #C2 Mine and analyse existing data (with B2) | See B2 | RCUK |
| 15 | #C3 Establish routine monitoring and analysis | Operational costs | Operations |



## 10.2 Stream #A: Improve debris modelling guidance

### 10.2.1 #A1: Improve existing debris modelling guidance

**The research challenge and why it is needed**: Existing guidance on representing debris blockage within MDSF2 is rather ad hoc. This task will bring together the information available through Wallerstein and Arthur (2012a) on assessing the chance of blockage, recent HR Wallingford guidance on using external models to estimate inflows and the findings within this ongoing study into a concise guidance note on modelling debris-related issues within MDSF2. In particular this will provide guidance on the following.

- **Improving the fragility representation (adopting user-defined curves).** Within MDSF2, an option is available to incorporate an asset specific fragility curve (without modification of the software). This allows users to update the default curves. This is rarely done for a number of reasons – not least because few users would feel confident to revise the default values. In the case of culverts (where a myriad of types exist), however, expert-based improvement of the fragility curves could be a useful way forward. As a quick win, this would not involve more complex reliability analysis and would require the revised curves to be provided in the same format as the existing curves, that is, X values [that is, (SWL – IL) / (SL – IL)] and corresponding probability values (see Section 4.7).
- **Improving the use of external models to provide inflow volumes in the non-failed and failed case.** External modelling should be used to estimate the inflow volume that enters the floodplain in the non-failed and failed states for each discrete load condition. Some guidance has been put together already (HR Wallingford 2012), but this needs reviewing and making more widely known (see Box 10.1).
- **Describing 'work arounds' for major point assets.** It is necessary to explain how to account for major point structures (such as barriers) that may control the flow in the watercourse (such as the Thames Barrier). Within the Thames Estuary 2100 project, for example, a method based on the 'zone of influence' was used which enables the performance of major point structures to be accounted for probabilistically. In essence, this approach requires 2 MDSF2 runs to be completed – one assuming the major point structure (for example, barrier) to operate as required and the second assuming a failure scenario. The results are then combined through a simple post processing probability weighting within the 'zone of influence' identified. Note that, although possible, this approach is likely to become too complex if more than one major structure exists within a study area.

**Recommendation**: Provide supplementary guidance that:

- supports users in modifying the default culvert fragility curves and recording their evidence and reasoning
- provides clear guidance on approaches to estimating inflow volumes into the floodplain for culverts using external models (support if appropriate by a simplified standalone tool)
- provides supplementary guidance or improve existing guidance to provide a clear example of the 'zone of influence' approach

**Interdependencies with other research**: None – can move ahead without other tasks.

**Cost**: Low <£25,000 – funded through the joint programme (Asset Management)

**Box 10.1: Improving deterministic modelling**

There is scope to improve deterministic modelling capabilities, as highlighted in Environment Agency (2004a). These include the ability to:

- model screens
- block part of a structure without altering its unblocked geometry
- apply blockage at the inlet/outlet of a structure only, or throughout its length
- model transient rather than permanent blockage
- choose a fixed or moving debris level
- integrate blockage into the methods for the estimation of afflux
- automate the representation of blockage of structures by debris

### 10.2.2 #A2: Update MDSF2 software and guidance

**The research challenge and why it is needed**: To make the new research proposed through Stream #B (Section 10.3) accessible to users, the MDSF2 software and guidance will need to be updated. This activity links closely with #B6 below and is not discussed further here.

**Recommendation**: See #B6 below.

**Interdependencies with other research**: Linked closely with #B6.

**Cost**: Included in #B6 below.

## 10.3 Stream #B: Improve modelling capability (tools and approaches)

### 10.3.1 #B1: Develop an extended ontology of debris vulnerable assets

**The research challenge and why it is needed**: Within MDSF2, RASP type 21 refers to a culvert. This is currently a very basic definition with no subtypes. The classification of in-line assets should be expanded to capture a more complete range of debris vulnerable assets (DVAs) where performance is influenced by blockage/debris, while maintaining a hierarchical classification system that uses data (and asset features) held within the Environment Agency's Asset Information Management System (AIMS) (where possible). It may be appropriate to incorporate screen types and the bar spacing as subclassifications (as an analogy to the wide, narrow and other subclasses used for linear defences). The definition of failure is also limited; referring only to complete blockage or surcharge. This restricts the ability to represent the complexity of the real systems and the influence of debris on those systems.

This task should develop a more comprehensive ontology of asset types (including a full range of both active and passive point assets) and their critical debris-related failure modes (partial or full blockage, failure to open or close). In developing the ontology, careful consideration will need to be given to the way individual asset types are differentiated and how subclasses of assets are defined. For example, the DVA classifications will need to distinguish features that make an individual asset more or less susceptible to failure for a given debris load – for example, shape, screen design and channel approach.

**Recommendation**: A report should be prepared setting out a comprehensive ontology of DVAs to supplement the existing RASP defence types. Achieving this is a prerequisite to advancing the ability to assess debris-related flood risks.

**Independencies with other research**: None – can move ahead without other tasks.

**Cost**: £25,000–£30,000

### 10.3.2 #B2: Develop better predictive techniques to estimate debris load (with #C2)

**The research challenge and why it is needed**: Despite good progress being made within FRMRC, limited capability exists to predict either the rate or nature of the debris that arrives at any given DVA. Further science is needed to develop the underlying relationships. In particular this activity will need to develop credible predictive techniques (validated against observational data – see #C2 and #C3) that consider the recruitment phase; transport phase and accumulation phase.

The predictive techniques should consider a full range of debris type including anthropogenic and natural debris, floating and non-floating debris, sediment and vegetation. Consideration should also be given to the performance of sediment traps and other interventions in managing debris flows.

**Recommendation**: Significant supporting science is needed to advance existing predictive capabilities. This is likely to be best taken forward through the joint Environment Agency and Defra programme in partnership with an academic institution to provide a short-term measured step forward and a long-term, more in-depth, science output.

**Independencies with other research**: To follow on after the completion of #B3 (scoping of MDSF2 developments) to ensure there is a clear line of sight between this research and how it will be used in MDSF2. To be undertaken in parallel with #C2 and #C3 on the mining of existing data and the development of operational monitoring systems.

**Cost**: £50,000 joint programme and £150,000 for a fully funded 3-year PhD

### 10.3.3 #B3: Develop an approach to better utilise local modelling results to support MDSF2

**The research challenge and why it is needed**: Significant resources have frequently been invested in the development of local hydraulic models. Such models are often well calibrated and represent the hydraulic response of the system accurately. Detailed local models are also likely to offer velocity data and other outputs. However, they are typically more expensive in terms of run time than the rapid flood spreading of MDSF2. This would be prohibitive for large Monte Carlo ensembles, although for small models, runtimes are fast and it would be practical to run thousands of simulations.

However, there is a clear opportunity to better link the RASP approaches (embedded in MDSF2) within local models to maximise the benefit each provides. Such an approach would potentially enable the technical advantages offered by MDSF2 (that is, the probabilistic representation of the system states) and those offered by the local modelling (the accuracy of the hydraulic simulation) to be retained. To achieve this linkage in practice would be relatively straightforward and would require the following developments:

- **Export of important defence system states conditional on load**: One option is to use MDSF2 in effect as a screening tool to select a subset of important 'scenarios' that could then be run in the detailed local model. First, the conditional probability of alternative system states given a particular storm load, together with an initial estimate of the associated consequences, would need to be determined. With some limited development, this could be done directly within MDSF2 and the listing exported. This information could be used to identify a limited number of the most important system states (based on a consideration of the associated consequences and their contribution to the probability density for a given discrete loading condition, that is, a 1:10, 1:50 year storm event and so on). This limited set of system states, each with a probability of occurrence conditional on the storm event, could then be used to drive local deterministic models.
- **Improved ability to import external results**: The local flood depth/velocity results could then be either re-imported into MDSF2 (for integration with receptor terms and interpolation) or potentially into a standalone consequence model (such as FDEM or an equivalent). In theory, MDSF2 already possesses this ability but it has never worked well. The supporting tools and associated guidance on how to do this will both need improving; the improved ability to import the output from external flood models would also pave the way for users to bypass the MDSF2 Monte Carlo engine if they had access to suitable higher resolution alternative system models.

The primary disadvantage of this approach is that the ability to attribute risk to individual assets is likely to be lost. However, this disadvantage is outweighed in more complex settings where the benefits of using local hydrodynamic models are significant. This approach is also likely to be a useful approach beyond simply the consideration of debris and blockage issues.

**Recommendation**: Develop the automated scenario generation method in MDSF2, fix the 'import depth grids' and provide associated guidance.

**Interdependencies with other research**: None

**Cost**: £30,000–£40,000

### 10.3.4 #B4: Undertake scoping study and business case for improving MDSF2

**The research challenge and why it is needed**: There is a need to consider the options for modifying MDSF2 in a way that best addresses current shortcomings in the analysis of debris-related risks. In particular the scoping study should consider:

1. How to incorporate a wider range of DVAs and, if necessary, recast the analysis framework. This should include the following.

- Consider how best to incorporate additional RASP types based on the extended ontology (from #B1).
- Explore the benefits and feasibility of recasting the analysis away from annual extremes in seasonal extremes. this may have additional benefits the assessment of deterioration, agricultural damages and other aspects that depend upon seasonal loading.
- Consider how to represent the fragility of the DVAs, in particular the most appropriate loading variable. For example, a discharge or a proxy for debris load may be more appropriate than a simple water level characterisation. Simple approaches to help reflect upstream land use and demographics, antecedent conditions (temporal sequencing of events) and season (that is, the availability of debris in the upstream catchment) within the fragility function should be considered. The approach will require careful consideration to ensure compatibility with any proposed modification of the analysis framework.
- Consider how to represent large point assets (in-line barriers and gates) that are vulnerable to debris to be assessed more readily (including failed and non-failed states).

2. How to update the confidence scoring systems

   NaFRA and MDSF2 have a well-structured data quality and model performance confidence scoring approach (Environment Agency 2013c). Incorporating debris and blockage will be important uncertainties in some systems. As a minimum, both Flood Area typologies and the Confidence Index Scores should be reviewed and updated to incorporate the uncertainties associated with DVAs.

3. Consider the feasibility and benefits of adopting a continuous simulation risk analysis

   Continuous simulation methods (CSM) (that is, continuous in time) have been explored for use in flood risk modelling (for example, the NERC FRACAS – a next generation national Flood Risk Assessment under climate ChAnge Scenarios Project – lead by CEH Wallingford). These types of approach have, in principle, at least, a natural capability to incorporate factors such as antecedent conditions, seasonality and progressive accumulation of debris without modification. However, there are 2 reasons why it is unlikely such approaches will be adopted into mainstream practice. The first is because such approaches rely on process-based relationships and, as yet, credible models of recruitment, transport and accumulation do not exist. The second reflects the capacity for uptake. The move towards a fully probabilistic continuous simulation model, although very possible in some contexts, is unlikely to be widely taken up and its application is likely to require a disproportionate level of effort in most situations. But in some instances, for example, when embedding debris and blockage issues into real-time forecasting (that is, operational continuous models) or in appraisal of complex interacting systems, CSM could provide a powerful approach. While it is likely to be sometime before such approaches are used routinely in practice (and will require science advances to support the necessary practical developments), it is nonetheless important that this scoping study provides some commentary on the potential of such approaches.

**Recommendation**: A scoping study will be needed to determine the future development of MDSF2 as whole prior to developing the fragility curves for DVAs and related advances. In particular it will need to determine the wider business case and the practicality of constructing a blockage-related fragility response that appropriately links various failure modes (failure to open, close or partial blockage) to a related loading condition (for example, a flow or debris load). The outcome of this scoping should be used to inform how best to take forward the issues above in association with considerations around recasting the basis of MDSF2 on seasonal extremes.

The scoping study should also explore and set out the business case to carry out the following.

- Extend the Confidence Index methods to include debris-related issues. This will include, as a minimum, updating the Flood Area typologies, the data quality flags and scoring system.
- Review the potential for promoting the necessary science advances in the academic institutions that will be required to take forward probabilistic CSM in practice. In the case of planning tools, the benefits and disadvantages of moving towards a CSM approach to replace MDSF2 would need to be carefully scoped. More immediate opportunities may exist by incorporating debris issues into real-time forecast models – though this too would rely on significant advances in the underlying science.
- Develop and test approaches based on 'offline' batch simulation to establish the precision and feasibility of achieving adequate convergence of probabilistic calculations. This would lead to a specification of a bespoke tool to enable third parties to implement a risk calculated using local hydrodynamic tools if/where appropriate to do so (outside of MDSF2).

**Interdependencies with other research**: The approval of the business case should act as the gateway to the follow on activities within the route map.

**Cost**. £40,000–£50,000

### 10.3.5 #B5a and #B5b: Determine fragility curves and simplified support tools for DVAs

**The research challenge and why it is needed**: Work within FRMRC2 (summarised in Wallerstein and Arthur 2012a) suggests there is a weak relationship between 'storm load' and the potential for blockage. This means fragility curves conditional on load would be a horizontal line (with an equal probability of blockage regardless of the storm load). However, the work in FRMRC does suggest a stronger relationship with the following.

- **Upstream land use and demographics**: The Belfast studies in particular highlighted the importance of land use/demographics in terms of determining the nature of the debris that enters the channel. It may be possible, for example, to reflect the nature of the upstream catchment through an 'adjustment' factor applied to the default curves to reflect this. The scale of the adjustment could be pre-processed using standard land use information.
- **Antecedent conditions (temporal sequencing of events):** The sequence of storm events has some impact on the volume of debris that is recruited and transported. Further research would be required to understand this relationship and how best to modify MDSF2 to reflect this. This may be possible through additional pre-processing, but is likely to require the way the loading condition is assessed within MDSF2 (that is, as an annual load event) to be recast or adjusted.

- **Season (that is, the availability of debris in the upstream catchment)**: MDSF2 is currently based on annual extremes, but Wallerstein and Arthur (2010) found the strongest relationship between blockage and storm load when seasonality was taken into account. Rather than recasting the analysis presented by Wallerstein into annual terms (which may provide a credible approach at a broad scale but is unlikely to be credible more locally), the MDSF2 analysis framework could be recast to use seasonal extremes of loading conditions. Technically, the change would be relatively straightforward to implement but it would have a knock-on impacts in terms of load estimation and add complexity to the MDSF2 analysis. However, it may have wider benefits for the users and credibility of MDSF2 including, for example, the assessment of agricultural damages and seasonal differences in storm persistence.

It is recommended that this task addresses 2 issues:

1. The development of a credible set of fragility responses for each asset type within the extended ontology (see #B1). In doing so, 2 fundamental questions will need to be answered.

    - **What are the failure states for each DVA to be assessed?** Debris-related failure is more than simply a complete blockage. Debris can cause problems such as a partial or full blockage, or preventing a barrier or gate closing or opening. In determining the mode of failure, the design of the asset (the shape of the openings, trash screen design and so on) and its operational performance will both need to be considered.

    - **How best to define the conditional chance of 'failure'?** New fragility functions will be needed to explain the relationship between an appropriate conditional 'load' and each failure state. It is unlikely that a single hydraulic load (for example, water level) will be appropriate. It may be that a 'debris load' may need to be defined (see #B2). As currently, multiple fragility responses will be needed to reflect the 'condition' of the asset, that is, issues that influence the chance that, a given asset type, when faced with a given 'debris load' will block (for example, condition of the automated screen clearance).

2. Explore the feasibility of a simplified tool to explore the risk attributed to a DVA. Over the past 10-–15 years, various simplified tools have been developed to help estimate the chance of debris blockage and the associated consequences such as the risk assessment procedure for structure blockage (Environment Agency 1998) that enables the user to enter a small number of variables and the tool returns probability of blockage (see Section 5.2.1). More recently RAFT has proved to be a useful approach for exploring the risk associated with individual linear assets. Attempts to extend RAFT to include 'in-channel' related issues (blockage, vegetation and so on) have been less successful. This may be due to the difficulty in reflecting the complex in-channel processes within simplified tools in a way that is credible. Within this task the feasibility of developing a standalone tool to enable users to explore the performance of DVAs and their propensity to fail (in an open, closed or partially blocked state) based on the characteristics of the catchment and structure should be explored. The outputs will enable a better understanding of the chance of blockage and an initial view on the criticality of a structure. The outputs should also help provide informed user modifications to the default fragility curves (developed in (1) above). The simplified tool should not attempt to create a full risk analysis tool as it is unlikely to provide sufficient credibility without repeating either the use of a local dynamic tool (above) or an MDSF2 analysis.

**Recommendation**: Develop a set of fragility curves to support the extended ontology of DVA types and associated modification to characterisation of the loading space (reflecting any modification to the fragility response and the loading space as set out in the scoping recommended under #B4). Scope and develop a simplified tool for attributing a risk (or risk category) to a given DVA.

**Interdependencies with other research**: This activity cannot go ahead until completion of #B1 to #B4. In particular the scoping study will confirm the nature of the constraints within the loading characterisation that will shape the development of the new fragility functions.

The development of the high-level fragility curves for DVAs is a prerequisite to the further developments proposed in #B5.

**Cost**: £30,000–£50,000

### 10.3.6 #B6: Update MDSF2 analysis as appropriate and trial

**The research challenge and why it is needed**: To implement the developments in the preceding activities into MDSF2 analysis methods, it will be necessary to trial and confirm them. This will act as a precursor to the update of the software and guidance proposed in #A2 and will include interaction with Environment Agency Area teams and other stakeholders in confirming the overall approach to implementation.

**Recommendation**: This is a 'must have activity' if full implementation is to go ahead.

**Interdependencies with other research**: This activity cannot go ahead until completion of #B1 to #B4. It should go ahead in association with #A2.

**Cost**: £50,000–£150,000 (including #A2 costs). Cost will depend on the ambition set out in earlier tasks.

### 10.3.7 #B7: Provide a standalone means of estimating damages

**The research challenge and why it is needed**: Consultants often find it easier and quicker to import 'flood grids' into a standalone 'damage estimator'. In part this is because of the complexity and, to date, non-functional 'import' capability within MDSF2. This activity would seek to develop a simplified damage estimator.

**Recommendation**: This is a 'could have' activity – if there is demand and a robust business case is made for it in #B3 (taking account of the broader benefits and dis-benefits associated with a standalone damage estimator).

**Interdependencies with other research**: To be completed alongside the completion of #B5.

**Cost**: £20,000–£30,000

## 10.4 Stream #C: Extend observational evidence

### 10.4.1 #C1: Scope a programme of data mining and ongoing monitoring

**The research challenge and why it is needed**: The ability to assess debris and blockage is fundamentally constrained by the lack of observational data. Wallerstein and Arthur (2012a) collated some very useful data from Belfast, Northern Ireland, and this is the most comprehensive dataset available: 25,265 observations at 140 sites over 6 years, taken roughly every 7 days. Magenis (1988) used the observed volume of debris from routine observations at 17 screens over 10 years. Despite multiple CCTV monitoring sites, data provided by Environment Agency have been sparse and reflects the limited systematic gathering. There are also opportunities to gather additional data from local authorities; for example, Leeds City Council has data from regular inspections at 120 screens over 3 years. However, it would require significant effort to extract meaningful data from this information.

This activity will therefore scope a sustainable programme of data collation, collection and analysis to support the development of better debris management practice and provide the underlying evidence to form the basis of improved analysis methods. In particular the scoping study should set out how best to:

- mine and analyse existing data (see Section 10.4.2)
- establish routine monitoring and analysis (see Section 10.4.3)

Close liaison with stakeholders is advisable to develop a strong business case for embedding operational long-term collection of data and the systematic recording of debris issues in standard procedures. Ways of encouraging local authority and Environment Agency staff to contribute to the process of collating observations should be explored and recommendations made (for example, online collection of the data from automated devices and CCTV could be used to facilitate this).

**Recommendation**: A 'must have' recommendation – the lack of observational data continues to severely restrict the ability to provide credible and well-validated analysis approaches across a range of different settings.

**Interdependencies with other research**: Ideally to be started as soon as possible as the findings of the scoping study should be used to inform #B2. Is a precursor to #C2 and #C3.

**Cost**: £25,000–£30,000

### 10.4.2 #C2: Mine and analyse existing data (with B2)

**The research challenge and why it is needed**: It will important to focus on identifying and analysing the significant data that already exists in various forms but which is often difficult to access or is in an unprocessed state, for example, data on the removal of sediment from sediment traps, routine maintenance records and CCTV.

**Recommendation**: A 'must have'

**Interdependencies with other research**: The specification for this task will need to be scoped in #C1. The data that are mined should be used to support the development of new predictive techniques (#B2).

**Cost**: Included in #B2.

### 10.4.3 #C3: Establish routine monitoring and analysis

**The research challenge and why it is needed**: Many debris observations are made by Environment Agency staff as part of normal debris management activities. This task will seek to work with these activities (and supplement them if necessary) to establish a sustainable programme of data collection that can be used to unpin more fundamental science developments and practical guidance in the medium to longer term (see Box 10.2).

**Recommendation**: A 'must have' if it is going to prove possible to predict and manage debris-related flood risks better in the longer term.

**Interdependencies with other research**: The specification for this task will need to be scoped in #C1. Any data gathered will support #B2 and, in the longer term, future updates to methods, tools and guidance.

**Cost**: Included in operational costs (a modification of business as usual with limited additional costs if done smartly).

**Box 10.2: Extending observational evidence**

Priorities for monitoring and analysis are influenced by existing data and knowledge gaps, the number of each asset type, the potential scale of impacts arising from blockage at different asset types and the type of questions to be addressed.

The questions to be addressed are:

- What is the mechanism of blockage at different asset types?
- What is the probability of blockage at a range of asset types?
- How quickly does blockage occur?
- Can existing predictive relationships for probability and degree of blockage at screens be applied to other catchments and watercourse types? If so, what are the limitations of applicability?
- Can predictive relationships be developed for blockage at other asset types?

Data gathering should focus on assets that are present in large numbers, assets with the potential widespread impacts (on larger watercourses), permanent assets (rather than temporary works) and assets with no blockage data. These are in order of decreasing priority:

- **Screens and culverts –** present in large numbers, although on smaller watercourses
- **Control gates** – typically present on large, mature watercourses, with limited freeboard and broad floodplains (for example, River Thames) and may be blocked open or closed, leading to flooding upstream or downstream
- **Flapped outfalls –** typically present on small, culverted watercourses at tidal outfalls, or at the outlet of pumped catchments, and may be blocked open or closed, leading to upstream flooding
- **Masonry arch bridges** common throughout the UK (US research focuses

on relatively modern bridges with flat decks and piers)

- **Weirs, flumes and open channels –** present on any size of watercourse (except flumes which are typically on smaller watercourses)
- **Temporary works –** limited in number, duration and diverse, although daily site presence by construction workers would facilitate regular observations

For structures that already have some record of observations, it is worth continuing to record data because statistical analysis will generally benefit from longer records. This boosts the value of the observations.

A monitoring strategy, such as the one outlined below, would help to further increase the benefits, applicability and evaluation of methods should current science found to be unfit for purpose.

Phase 1: Consultation and development (Year 1)

- Step 1: Consult asset owners to identify asset monitoring regimes where data can be readily extracted. This may involve Environment Agency staff visiting the offices of Lead Local Flood Authorities or infrastructure owners to extract data.
- Step 2: Consult asset owners to identify blockage-susceptible assets on a range of catchment and watercourse types, which are either inspected systematically (for example, weekly or fortnightly) or monitored via CCTV (continuously or intermittently).
- Step 3: Develop an online tool to allow asset owners to upload blockage data, tailored to suit the working methods of asset owners.

Phase 2: Data gathering (Year 1 to 4 or beyond)

- Step 4: Undertake short-term CCTV monitoring or fixed point photography of debris accumulation at a range of asset types during a single event to provide information on blockage mechanisms and the rate of blockage build-up. Monitor for at least 2 years to ensure a range of floods are captured.
- Step 5: Conduct long-term systematic monitoring of debris types and quantities arriving at screens on different types of catchment and river.

Phase 3: Collation and analysis (Year 1 to 4 or beyond)

- Step 6: Collate and analyse data on debris accumulation to develop an understanding of blockage mechanisms and rate of blockage build-up. Develop predictive relationships to assist operational staff. This would require academic or consultant input.
- Step 7: Collate and analyse data on debris load, probability and degree of blockage. Test existing predictive relationships for blockage at screens by comparing observed and predicted blockage (probability, area and so on) for a range of catchments and watercourse types. Develop new predictive relationships for other asset types.

A longer monitoring period of 6 years would provide data to match the Belfast dataset.

# References

AMEY, 2008. *Broadway Underpass – Westlink, Belfast. Independent report into the flooding incident on 16 August 2008*. Amey Consulting.

ASCE, 2012. *Water control gates. Guidelines for inspection and evaluation.* Reston, VA: American Society of Civil Engineers.

BALKHAM, M., FOSBEARY, C., KITCHEN, A. AND RICKARD, C., 2010. *Culvert design and operation guide*. C689. London: CIRIA.

BALMFORTH, D., 2009. *Modelling ancillaries, orifice coefficients*. WaPUG User Note No. 2, Wallingford Procedure User Group (WaPUG). Available from: http://www.ciwem.org/groups/udg/user-notes/ [Accessed 29 July 2016].

BENN, J., 2013. Railway bridge failure during flood in the UK and Ireland: Learning from the past. *Proceedings of the ICE – Forensic Engineering*, 166 (4), 163-170.

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

BRAUDRICK, C. A., GRANT, G. E., ISHIKAWA, Y. AND IKEDA, H., 1997. Dynamics of wood transport in streams: A flume experiment. *Earth Surface Processes and Landforms*, 22 (7), 669-683.

BUIJS, F., SIMM, J., WALLIS, M. and SAYERS, P., 2007a. *Performance and reliability of flood and coastal defences.* R&D Technical Report FD2318/TR1. London: Department for Environment, Food and Rural Affairs.

BUIJS, F., SIMM, J., WALLIS, M. and SAYERS, P., 2007b. *Performance and reliability of flood and coastal defences*. R&D Technical Report FD2318/TR2. London: Department for Environment, Food and Rural Affairs.

CANAL AND RIVER TRUST, 2014. *CRT Mandatory Standard: Asset inspection procedures (AIP2014).* Milton Keynes: Canal and River Trust.

CHURCH, M., 1992. Channel morphology and hydrology. In *The Rivers Handbook: Hydrological and Ecological Principles*, Vol. 1 (ed. P. Calow and G.E. Petts), pp. 126-143. London: Blackwell Science [Cited in Piégay and Gurnell 1997].

CIRIA, US ARMY CORPS OF ENGINEERS AND FRENCH MINISTRY OF ECOOGY, 2013. *The International Levee Handbook.* C731. London: CIRIA.

CLARK, P., TSIKATA, J.M. AND HARESIGN, M., 2010. Experimental study of energy loss through submerged trashracks. *Journal of Hydraulic Research*, 48 (1), 113-118.

DEFRA, 2005. *Controlling Soil Erosion: A manual for the assessment and management of agricultural land at risk of water erosion in lowland England*. London: Department for Environment, Food and Rural Affairs.

DEFRA, 2006. *Code of practice on litter and refuse*, 3rd edition. London: Department for Environment, Food and Rural Affairs.

DEFRA, 2009. *WFD expert assessment of flood management impacts.* R&D Technical Report FD2609/TR. London: Department for Environment, Food and Rural Affairs.

DEFRA and ENVIRONMENT AGENCY, 2005a. *Flood Risk Assessment Guidance for New Development, Phase 2. Framework and guidance for assessing and managing flood risk for new development – full documentation and tools.* R&D Technical Report FD2320/TR2. London: Department for Environment, Food and Rural Affairs.

DEFRA and ENVIRONMENT AGENCY, 2005b. *Flood Risks to People, Phase 2. The Flood Risks to People Methodology.* R&D Technical Report FD2321/TR1, Flood and Coastal R&D Programme. London: Department for Environment, Food and Rural Affairs.

DIEHL, T.H., 1997. *Potential drift accumulation at bridges*. Publication no. FHWA-RD-97-28. Washington DC: Federal Highways Administration, US Department of Transportation.

DIEHL, T.H. AND BRYAN, B.A., 1993. Supply of large woody debris in a stream channel. In *Proceedings of Hydraulic Engineering Conference* (San Francisco, 1993), edited by H.W. Shen, S.T. Su and F. Weng, Vol. 1, pp. 1055-1060. Reston, VA: American Society of Civil Engineers.

DOWNS, P.W. AND SIMON, A., 2001. Fluvial geomorphological analysis of the recruitment of large woody debris in the Yalobusha River network, Central Mississippi, USA. *Geomorphology*, 37 (1-2), 65-91.

ENCAMS, 2006. *Your rubbish and the law: A guide for business*. ENC/04/06. Wigan: Environmental Campaigns.

ENGINEERS AUSTRALIA, 2009. *Australia Rainfall & Run-off Manual*. *Revision Project 11. Blockage of hydraulic structures. Stage 1 report.* Barton, Australian Capital Territory: Engineers Australia.

ENGINEERS AUSTRALIA, 2013. *Australia Rainfall & Run-off Manual*. *Revision Project 11. Blockage of hydraulic structures. Stage 2 report*. Barton, Australian Capital Territory: Engineers Australia.

ENGINEERS AUSTRALIA, 2015. Australian Rainfall and Runoff: A Guide to Flood Estimation; Book 6 - Flood Hydraulics; Chapter 6 - Blockage of Hydraulic Structures. Barton, Australian Capital Territory: Engineers. [Accessed 11/10/2016]

ENVIRONMENT AGENCY, 1998. *A risk assessment procedure for structure blockage.* Bristol: Environment Agency.

ENVIRONMENT AGENCY, 2002. *Trash screens – design and operations manual.* R&D Manual W5A-001/M-1. Bristol: Environment Agency.

ENVIRONMENT AGENCY, 2004a. *Afflux at bridges and culverts: Review of current knowledge and practice*. R&D Technical Report W5A-061/TR1. Bristol: Environment Agency.

ENVIRONMENT AGENCY, 2004b. *Afflux at bridges and culverts: Review of current knowledge and practice. Annex 2: Hydraulic model implementation of bridge and culvert afflux and blockage*. R&D Technical Report W5A-061/PR1. Bristol: Environment Agency.

ENVIRONMENT AGENCY, 2004c. *Afflux at bridges and culverts: Review of current knowledge and practice. Annex 5: Review of the Environment Agency South West Region study 'Risk assessment of structure blockage during flood flows'*. R&D Project Record W5A-061/PR5. Bristol: Environment Agency.

ENVIRONMENT AGENCY, 2004d. *Risk assessment for flood and coastal defence for strategic planning*. 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, 2009. *Trash and security screen guide.* 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. *Sediment matters: A practical guide to sediment and its impacts in UK rivers*. Bristol: Environment Agency.

ENVIRONMENT AGENCY 2011b. *Modelling and Decision Support Framework 2 final technical report.* Bristol: Environment Agency.

ENVIRONMENT AGENCY, 2011c. *Modelling and Decision Support Framework 2 – software user manual, Version 1.7*. Bristol: Environment Agency.

ENVIRONMENT AGENCY, 2012a. *Improving probabilistic flood risk management capabilities. Work Package 2 Phase 2a – Task 2 report*. Science Project SC090008. Bristol: Environment Agency.

ENVIRONMENT AGENCY, 2012b. *FCRM Asset Management. Maintenance Standards, Version 3*. Environment Agency internal guidance. Bristol: Environment Agency.

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

ENVIRONMENT AGENCY, 2013b. *NaFRA method improvements (WP2) Work Stream 4: future needs.* Bristol: Environment Agency.

ENVIRONMENT AGENCY, 2013c. *Measuring confidence in NaFRA outputs.* FCPIF00151B00/R2. Bristol: Environment Agency.

ENVIRONMENT AGENCY, 2014a. *Living on the Edge: A guide to your rights and responsibilities of riverside ownership*, 5th edition. Bristol: Environment Agency. Available from: https://www.gov.uk/government/publications/riverside-ownership-rights-and-responsibilities [Accessed 3 August 2016].

ENVIRONMENT AGENCY, 2014b. *Aquatic and riparian plant management: Controls for vegetation in watercourses*. *Field guide*. Project SC120008/R1. Bristol: Environment Agency.

FHRC, 2014. *Flood and Coastal Erosion Risk Management: Handbook and Data for Economic Appraisal* (Multi-Coloured Handbook and Data 2014). London: Flood Hazard Research Centre. Available from: http://www.mcm-online.co.uk [Accessed 3 August 2016].

FHRC, 2016. *Flood and Coastal Erosion Risk Management: A Manual for Economic Appraisal*. Multi-Coloured Manual. London: Flood Hazard Research Centre. Available from: http://www.mcm-online.co.uk [Accessed 3 August 2016].

FHWA, 1990. *Highways in the river environment (HIRE).* Report No. FHWA-HI-(0-016). Washington DC: Federal Highways Administration, US Department of Transportation.

FHWA, 2001. *Hydraulic Design Series No. 5. Hydraulic design of highway culverts*. Report No. FHWA-IP-85-15. Washington DC: Federal Highways Administration, US Department of Transportation.

FHWA, 2005. *Hydraulic Engineering Circular No. 9. Debris control structures: Evaluation and countermeasures*, 3rd edition. Publication No. FHWA-IF-04-016, Washington DC: Federal Highways Administration, US Department of Transportation.

FHWA, 2012a. *Hydraulic Engineering Circular No. 18. Evaluating scour at bridges*, 5th edition. Publication no. FHWA-HIF-12-003. Washington DC: Federal Highways Administration, US Department of Transportation.

FHWA, 2012b. *Hydraulic Engineering Circular No. 20. Stream stability at highway structures*, 4th edition. Publication no. FHWA-HIF-12-004. Washington DC: Federal Highways Administration, US Department of Transportation.

FLUVIO R&D LIMITED, 2012. *UB63 Dublin–Wexford Line, River Dodder flood study. Summary report.* Dublin: Iarnród Éireann (Irish Rail).

FORESTRY COMMISSION, 2011. *Forests and Water: UK Forestry Standard Guidelines*. Edinburgh: Forestry Commission Scotland.

GOODRIDGE, W.H., 2009. *Sediment transport impacts upon culvert hydraulics*. PhD thesis, Utah State University. Available from: http://digitalcommons.usu.edu/etd/416 [Accessed 3 August 2016].

GOULDBY, B.P., SAYERS, P.B., MULET-MARTI, J., HASSAN, M. AND BENWELL, D., 2008. A methodology for regional-scale flood risk assessment. *Proceedings of the Institution of Civil Engineers – Water Management*, 161 (3), 169-182.

GRAF, W.H. AND ACAROGLU, E.R., 1968. Sediment transport in conveyance systems (Part I) / A physical model for sediment transport in conveyance systems. *International Association of Scientific Hydrology. Bulletin*, 13 (2), 20-39.

GREGORY, K.J., GURNELLL, A.M. AND HILL, C.T., 1985. The permanence of debris dams related to river channel processes. *Hydrological Sciences Journal*, 30 (3), 371-381.

GURNELL, A.M., GREGORY, K.J. AND PETTS, G.E., 1995. The role of coarse woody debris in forest aquatic habitats: implications for management. *Aquatic Conservation: Marine and Freshwater Ecosystems*, 5 (2), 143-166.

HAEHNEL, R.B. AND DALY, S.F., 2002. *Maximum impact force of woody debris on floodplain structures.* Technical Report ERDC/CRRELL TR-02-2. Vicksburg, MI: US Army Corps of Engineers, Engineering and Research Development Center.

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 & Maritime Engineering*, 156 (3), 235-247.

HIGHWAYS AGENCY, 2012. *Design Manual for Roads and Bridges. Volume 3, Section 4, Part 21. The assessment of scour and other hydraulic actions at highway structures, BD 97/12*. London: The Stationery Office. Available from: http://www.standardsforhighways.co.uk/dmrb/ [Accessed 3 August 2016].

HJÜLSTROM, F., 1935: *Studies of the morphological activity of rivers as illustrated by the River Fyris*. Bulletin of the Geological Institute University of Uppsala, 25, 221-527.

HO, H.-C., MUSTE, M. and ETTEMA, R, 2013. Sediment self-cleaning multi-box culverts. *Journal of Hydraulic Research*, 51 (1), 92-101.

HR WALLINGFORD, 1993. *Hydraulic aspects of bridges: Assessment of the risk of scour*. Report EX 2502. Wallingford: HR Wallingford.

HR WALLINGFORD, 2005. *Flooding in Boscastle and North Cornwall, August 2004: Phase 2 studies report*. Report EX 5160. Wallingford: HR Wallingford.

HR WALLINGFORD, 2012. *MDSF2: Volume and volume capping using detailed hydraulic models.* Technical Note MCR4886-04. Wallingford: HR Wallingford.

HWANG, K.N. AND NEHTA, A.J., 1989. *Fine sediment erodibility in Lake Okeechobee.* Report UFL/COEL-89/019. Gainesville, FL: Coastal Engineering Department, University of Florida.

ING, R., 2011. *Assessing the hydrogeomorphological effects of large woody debris in rivers: A study of both natural and restored wood in the River Blackwater, UK.* Unpublished MSc thesis, Queen Mary University of London.

JUEL TIDE GATES, 2010. *Flap gate / tide gate alternatives* [online]. Seattle, WA: Juel Tide Gates. Available from: www.jueltide.com [Accessed 11 February 2014].

KIRBY, A., ROCA, M., KITCHEN, A., CHESTERTON, J. and ESCARAMEIA, M., 2015. *Manual on scour at bridges and other hydraulic structures*, 2nd edition. C742. London: CIRIA.

KNIGHT, D.W., MCGAHEY, C., LAMB, R. and SAMUELS, P., 2009. *Practical Channel Hydraulics*. Boca Raton, FL: CRC Press.

LAGASSE, P.F., CLOPPER, P.E., ZEVENBERGEN, L.W., SPITZ, W.J. AND GIRARD, L.G., 2010. *Effects of debris on bridge pier scour.* NCHRP Report 653, Washington DC: Transportation Research Board.

LAMB, R., KEEF, C., WICKS, J., MCGAHEY, C. and LAEGER, S., 2013. A 'blue print' for local system-based probabilistic flood modelling. In Comprehensive Flood Risk Management: Research for Policy and Practice, Proceedings of FLOODrisk 2012 (Rotterdam, 2012), edited by F. Klijn and T. Schweckendiek, Chapter 30. Boca Raton, FL: CRC Press.

LHOMME, J., SAYERS, P.B., GOULDBY, B., SAMUELS, P., WILLS, M. AND MULET-MARTI, J., 2008. Recent development and application of a rapid flood spreading method. In *Flood Risk Management: Research and Practice*, Proceedings of FLOODrisk 2008, (Oxford, 2008), edited by P. Samuels, S. Huntingdon, W. Allsop and J. Harrop, p. 15. London: Taylor & Francis Group.

LYN, D.A., COOPER, T.J., CONDON, C.A. and GAN, L., 2006. *Factors in debris accumulation at bridge piers*. Publication no. FHWA/IN/JTRP-2006/36. West Lafayette, IN: Joint Transportation Research Program, Department of Transportation and Purdue University.

MAGENIS, S.E., 1988. Trash screens on culverts in urban areas. *Water and Environment Journal*, 2 (5), 476-484.

MCDADE, M.H., SWANSON, F.J., MCKEE, W.A., FRANKLIN, J.F. AND VAN SICKLE, J., 1990. Source distances for coarse woody debris entering small streams in western Oregon and Washington. *Canadian Journal of Forest Research*, 20 (3), 326-330.

MELVILLE, B.W. and DONGOL, D.M., 1992. Bridge pier scour with debris accumulation. *Journal of Hydraulic Engineering*, 118 (9), 1306-1310.

MOLINAS, A., WU, B. and KOESTER, R.D., 2001. Debris flow simulation for highway cross culverts. *Transportation Research Board: Journal of the Transportation Research Board*, 1770, 220-226.

MOTT, N., 2005*. Managing woody debris in rivers, streams and floodplains*. Stafford: Staffordshire Wildlife Trust.

MURNANE, E., HEAP, A. and SWAIN, A., 2006. *Control of water pollution from linear construction projects: Technical guidance*. Report C648. London: CIRIA.

NAASRA, 1976. *NAASRA bridge design specification.* Sydney: National Association of Australian State Road Authorities [cited in Diehl 1997].

NEW CIVIL ENGINEER, 2014. *Flood debris cleared from Worcester Bridge*, 19 February 2014.

NEW ZEALAND TRANSPORT AGENCY, 2003. *Bridge manual*, 2nd edition. Section 3, Design loading. Wellington: New Zealand Transport Agency.

NRA, 1992. *Design and operation of trash screens*. R&D Project Record 300/2/T, Bristol: National Rivers Authority.

ONS, 2010. *Comparing across country's indices of deprivation: Guidance paper.* Newport: Office for National Statistics.

OPW, 2013. *Eastern CFRAM (Catchment Flood Risk Assessment and Management) Study. Culvert blockage analysis – Poddle pilot.* Belfast: RPS Consulting Engineers.

PARKER, C., 2010. *Quantifying catchment-scale coarse sediment dynamics in British rivers.* PhD thesis, University of Nottingham.

PARKER, C., THORNE, C.R. AND CLIFFORD, N.J., 2014. 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.

PAROLA, A.C., APELT, C.J, AND JEMPSON, M.A., 2000. *Debris forces on highway bridges*. NCHRP Report 445. Washington DC: National Academy Press.

PIÉGAY, H. and GURNELL, A.M., 1997. Large woody debris and river geomorphological patterns: Examples from SE France and S England. *Geomorphology*, 19 (1-2), 99-116.

PINTO, C.O., 2013. *River Blackwater Project: Effectiveness of wood in river restoration* [online]. Available from: http://woodinrivers.blogspot.co.uk/2013_07_01_archive.html [Accessed 3 August 2016].

RAIB, 2010. *Failure of Bridge RDG1 48 (River Crane) between Whitton and Feltham 14 November 2009*. Report 17/2010. Derby: Rail Accident Investigation Branch.

RICKENMANN, D., 1997. Schwemmholz und Hochwasser [Driftwood and flood]. *Wasser, energie, luft*, 89, 5/6, 115-119 [in German].

RIGBY, E.H. and BARTHELMESS, A.J., 2011, Culvert blockage mechanisms and their impact on flood behaviour. In *Balance and Uncertainty – Water in a Changing World*, Proceedings of the 34th World Congress of the International Association for Hydro-Environment Engineering and Research (Brisbane, 2011), edited by E.M. Valentine, C.J. Apelt, J. Ball, H. Chanson, R. Cox, R. Ettema, G. Kuczera, M. Lambert, B.W. Melville and J.E. Sargison, pp. 380-387. Barton, Australian Capital Territory: Institution of Engineers Australia.

RIGBY, E.H. and SILVERI, P., 2001. The impact of blockages on flood behaviour in the Wollongong Storm of August 1998. In *The State of Hydraulics*, Proceedings of 6th Conference on Hydraulics in Civil Engineering (Hobart, 2001), pp. 523-532. Barton, Australian Capital Territory: Engineers Australia [cited in Engineers Australia 2013].

RIGBY, E.H., BOYD, M.J., ROSO, S., SILVERI, P. and DAVIS, A., 2002. Causes and effects of culvert blockage during large storms. In *Global Solutions for Urban Drainage*, Proceedings of the 9th International Conference in Urban Drainage (9ICUD 2002) (Portland, OR, 2002), edited by E.W. Strecker and W.C. Huber, doi: 10.1061/40644(2002)298. Reston, VA: American Society of Civil Engineers.

ROBISON, E.G. AND BESCHTA, R.L., 1990. Characteristics of coarse woody debris for several coastal streams of southeast Alaska, USA. *Canadian Journal of Fisheries and Aquatic Sciences*, 15 (2), 149-156.

ROCA, M. and DAVISON, M., 2010. Two-dimensional model analysis of flash-flood processes: application to the Boscastle event. *Journal of Flood Risk Management*, 3 (1), 63-71.

RSSB, 2004. *Impact of scour and flood risk on railway structures.* London: Rail Safety and Standards Board.

RSSB, 2005. *Safe management of railway structures. Phase 1: Flooding and scour risk.* London: Rail Safety and Standards Board.

SAYERS, P. and MARTI-MULET, J., 2006. *Thames Estuary 2100: Rapid flood spreading methodology (RSFM) – technical report.* Bristol: Environment Agency.

SAYERS, P.B. and MEADOWCROFT, I.C., 2005. RASP – a hierarchy of risk-based methods and their application. In Proceedings of the 40th Defra Conference on River and Coastal Management (York, 2005).

SCHMOCKER, L. and WEITBRECHT, V., 2013. Driftwood: risk analysis and engineering measures. *Journal of Hydraulic Engineering*, 139, 7, 683-695.

SEAR, D.A, NEWSON, M.D. AND THORNE, C.R., 2003. *Guidebook of applied fluvial geomorphology.* R&D Technical Report FD1914. London: Department for Environment, Food and Rural Affairs.

SEPA, 2009. *Engineering in the Water Environment: Good practice guide. Riparian vegetation management,* 2nd edition. WAT-SG-44. Stirling: Scottish Environment Protection Agency.

SEPA, 2010a. *Engineering in the Water Environment: Good practice guide. Sediment management.* WAT-SG-26. Stirling: Scottish Environment Protection Agency.

SEPA, 2010b. *Engineering in the Water Environment: Good practice guide. River crossings*, 2nd edition. WAT-SG-25. Stirling: Scottish Environment Protection Agency.

SIMM, J., 2010. *Fragility curves and their use in UK flood risk management.* Practitioner workshop on asset management, HR Wallingford.

STREFTARIS, G., WALLERSTEIN, N.P., GIBSON, G.J. AND ARTHUR, S., 2013. Modeling probability of blockage at culvert trash screens using Bayesian approach. *Journal of Hydraulic Engineering*, 139 (7), 716-726.

SANRAL, 2002. *Code of procedure for the planning and design of highway and road structures in South Africa*. Pretoria: South African Roads Agency.

TRANSPORT ROADS AND TRAFFIC AUTHORITY, 2011. *Culvert risk assessment training workshop*. Sydney: Transport Roads and Traffic Authority, New South Wales Government. Available from: http://www.rms.nsw.gov.au/documents/business-industry/partners-and-suppliers/lgr/downloads/information/culvert-risk-assessment-guideline-training-notes.pdf [Accessed 3 August 2016].

UCHIOGI, T., SHIMA, J., TAJIMA, H., AND ISHIKAWA, Y., 1996. Design methods for wood-debris entrapment. In Proceedings of the international symposium, Interpraevent (Garmisch-Partenkirchen, 1996), Volume 5, pp. 279-288 [cited in Schmocker and Weitbrecht 2013].

USACE, 2010. *HEC-RAS River Analysis System. Hydraulic reference manual, Version 4.1*. Davis, CA: Hydrologic Engineering Center, US Army Corps of Engineers.

USBR, 2006. *Erosion and sedimentation manual.* Denver, CO: US Department of the Interior, Bureau of Reclamation.

VANNOTE, R.L., MINSHALL, G.W., CUMMINS, K.W., SEDELL, J.R. AND CUSHING, C.E., 1980. The river continuum concept. *Canadian Journal of Fisheries and Aquatic Sciences*, 37, 130-137.

VAN RIJN, L.C., 1993. *Principles of sediment transport in rivers, estuaries and coastal seas*. Amsterdam: Aqua Publications.

VAN SICKLE, J. AND GREGORY, S.V., 1990. Modeling inputs of large woody debris to streams from falling trees. *Canadian Journal of Forest Research*, 20 (10), 1593-1601.

VASSILIOS, A. AND TSIHRINTZIS, A., 1995. Effects of sediment on drainage culvert serviceability. *Journal of Performance of Constructed Facilities*, 9 (3), 172-183.

VOLKWEIN, A., WENDELER, C. AND GUASTI, G., 2011. Design of flexible flow barriers. In *Mitigation, Mechanics, Prediction and Assessment,* Proceedings of the 5th International Conference on Debris Flow Hazards (Padua, 2011), Paper 2011-03-B-118, pp. 1093-1100. Available from: http://www.wsl.ch/wsl/info/mitarbeitende/volkwein/pdf/11204.pdf [Accessed 3 August 2016].

WALLERSTEIN, N., 2006. *Accounting for sediment in rivers*. FRMRC Research Report UR9. Manchester: Flood Risk Management Research Consortium.

WALLERSTEIN, N. AND ARTHUR, S., 2010. Development of equations for prediction of blockage at trash screens. First European Congress of the International Association of Hydraulics Research, Edinburgh, 4-6 May 2010.

WALLERSTEIN, N. AND ARTHUR, S., 2012a. *Predicting and managing flood risk associated with trash screens at culverts*. FRMRC SWP4.1 Final Science Report. Manchester: Flood Risk Management Research Consortium.

WALLERSTEIN, N.P. AND ARTHUR, A., 2012b. Trash screens at culverts. In *Flood Risk: Planning, Design and Management of Flood Defence Infrastructure* (ed. P. Sayers), Chapter 9. London: Thomas Telford.

WALLERSTEIN, N.P. and ARTHUR, S., 2012c. A new method for estimating trash screen blockage extent. *Proceedings of the Institution of Civil Engineers – Water Management*, 166 (3), 132-143.

WALLERSTEIN, N.P. AND ARTHUR, S., 2012d. Improved methods for predicting trash loading at culverts and trash screens. *Journal of Flood Risk Management*, 5 (1), 23-36.

WALLERSTEIN, N. P., ARTHUR, S. and SISINNGGIH, D., 2009. Relationships between river discharge and debris blockage at culverts with trash grilles. In *Road Map Towards a Flood Resilient Environment*, Proceedings of Final Conference of COST Action C22 Urban Flood Management in cooperation with UNESCO IHP/PARIS (Paris, 2009), edited by E. Pasche, N. Evelpidou, C. Zevenbergen, R. Ashley and S. Garvin. Hamburg: Technical University Hamburg-Harburg.

WALLERSTEIN, H., ARTHUR, S. AND SISNNGGIH, D., 2010. *Towards predicting flood risk associated with debris at structures*. In Proceedings of 17th Congress of the Asia and Pacific Division of the International Association for Hydro-Environment Engineering and Research (IAHR-APD), Auckland, 2010. Available from: https://web.sbe.hw.ac.uk/staffprofiles/bdgsa/Scott%20Arthur%20Papers/TOWARDS%20PREDICTING%20FLOOD%20RISK%20ASSOCIATED%20WITH%20DEBRIS%20AT%20STRUCTURES.pdf [Accessed 15 August 2016].

WALLERSTEIN, N.P., ARTHUR, S. AND BLANC, J., 2013. *Culvert design and operation guide. Supplementary technical note on understanding blockage risks*. C720. London: CIRIA.

WEBB, B., MARSHALL, B., CZARNOMSKI, S. AND TILLEY, N., 2006. *Fly-tipping: causes, incentives and solutions.* London: Jill Dando Institute of Crime Science, University College London.

WELLWOOD, N. and FENWICK, J., 1989. A flood loading methodology for bridges. In *Proceedings of 15th ARRB Conference*, Part 3, pp. 315-341 [cited in Parola et al. 2000].

WHALLEY, N., 2012. *Culvert blockage monitoring*. Presentation to a meeting of the British Hydrological Society South West Section (Bristol, 2012). Available from: http://www.hydrology.org.uk/assets/bhssw_files/n.whalley_20120731.pdf [Accessed 3 August 2016].

WHITLOW, C. AND MORGAN, G., 2012. Real-time blockage estimation: Case study from Ashton Vale. Presentation to a meeting of the British Hydrological Society South West Section (Bristol, 2012). Available from: http://www.hydrology.org.uk/assets/bhssw_files/c.whitlow_20120731.pdf [Accessed 3 August 2016].

YOUNG, W.J., 1991. Flume study of the hydraulic effects of large woody debris in lowland rivers. *Regulated Rivers: Research and Management*, 6 (3), 203-211.

# Bibliography


ENVIRONMENT AGENCY, 2015. *Channel management handbook*. Science Report SC110002. Bristol: Environment Agency.

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

GOULDBY, B. AND WALLERSTEIN, N., 2011. *Incorporating culvert blockage research within flood risk analysis models*. FRMRC Research Technical Note SWP4.1. Manchester: Flood Risk Management Research Consortium. Available from: http://www.fcerm.net/resource/incorporating-culvert-blockage-research-within-flood-risk-analysis-models [Accessed 3 August 2016].

FRMRC2, 2011. *FRMRC2: WP4.1 Comments on Work Content 9V1469/R0002//Pbor*. Peterborough: Royal Haskoning.

HOOPER, R., ARMITAGE, R., GALLAGHER, A. AND OSORIO, T., 2009. *Whole-life infrastructure asset management: Good practice guide for civil infrastructure*. Report C677. London: CIRIA.

JBA TRUST, 2013. *Flood and scour failure incident database for railway assets 2002-2013*. Skipton: JBA Trust

KOSICKI, A. AND DAVIS, S., 2000. Consideration of stream morphology in culvert and bridge design. *Transportation Research Record: Journal of the Transportation Research Board*, 1743, 57-59.

MCINTYRE, N. AND THORNE, C., 2013. *Land use management effects on flood flows and sediments: Guidance on prediction*. Report C719. London: CIRIA.

ROBINWOOD AND FORESTRY COMMISSION WALES, 2008. *Evaluation of large woody debris in watercourses*. Robinwood Robinflood report for the Interreg IIIC project, Robinwood. Available from: http://www.robin-wood.eu/uploads/robinwood_flood.pdf [Accessed 3 August 2016].

ROCA, M. AND GLASGOW, G., 2010. *Flood risk attribution to river defences*. Presentation at River Flow 2010 (Germany, 2010). Available from: http://eprints.hrwallingford.co.uk/412/ [Accessed 3 August 2016].

SEPA, 2006. *Conceptual design guidelines: Application of engineered logjams.* WAT-SG-37. Stirling: Scottish Environment Protection Agency.

# List of abbreviations

| | |
|---|---|
| AEP | Annual Exceedance Probability |
| AIMS | Asset Information Management System |
| AOD | above Ordnance Datum |
| CCTV | closed circuit television |
| CES/AES | Conveyance and Afflux Estimation System |
| CSM | continuous simulation methods |
| Defra | Department for Environment, Food and Rural Affairs |
| DVA | debris vulnerable asset |
| FCERM | Flood and Coastal Erosion Risk Management |
| FCERM-AG | Flood and Coastal Erosion Risk Management Appraisal Guidance |
| FHWA | Federal Highway Administration |
| FRMRC2 | Flood Risk Management Research Consortium Phase 2 |
| GIS | geographical information system |
| IL | invert level |
| MDM | Multiple Deprivation Measure |
| MDSF2 | Modelling and Decision Support Framework 2 |
| NaFRA | National Flood Risk Assessment |
| NCHRP | National Cooperative Highway Research Program [USA] |
| NIRS | National Incident Reporting System |
| NRA | National Rivers Authority |
| OPW | Office of Public Works [Ireland] |
| OS | Ordnance Survey |
| RAFT | Risk Assessment Field-based Tool |
| RASP | Risk Assessment for Strategic Planning |
| RFSM | Rapid Flood Spreading Model |
| RMSE | root mean square error |
| RSSB | Rail Safety and Standards Board [UK] |
| SEPA | Scottish Environment Protection Agency |
| SL | soffit level |
| SWL | sea water level |
| TRTA | Transport Roads and Traffic Authority [Australia] |

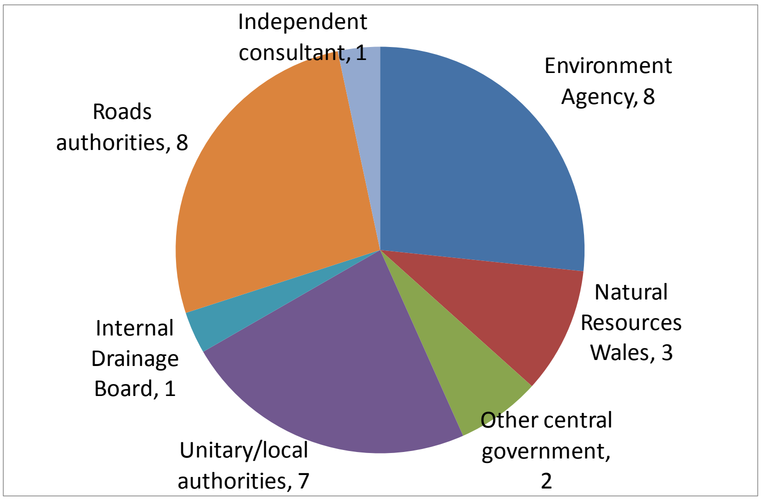
# Glossary

| | |
|---|---|
| **AEP neutral** | The concept of ensuring that the annual exceedance probability of the design blockage and design flood discharge (and design rainfall input) are the same. |
| **Bar** | An elevated feature in a watercourse caused by sediment deposition. |
| **Blockage** | An accumulation of debris in a watercourse, potentially leading to flooding, scour or other impact. |
| **Coarse woody debris** | Accumulations of branches, twigs and leaf litter (smaller than large woody debris). |
| **Control gate** | Gate installed on a watercourse to control flow and water levels. |
| **Culvert** | Covered channels or pipes that prevent the obstruction of a watercourse or drainage path by an artificial construction. |
| **Debris** | Any material moved by a flowing stream. |
| **Flap valve** | Non-return valves fitted to culverts to prevent reverse flow at times of high downstream water level. |
| **Flume** | Open channel structures with a narrow throat, and sometimes a raised bed, typically used for flow measurement or control. |
| **Fly-tipping** | The illegal disposal of controlled waste. |
| **Large woody debris** | Trees, roots, trunks, logs, branches and other large pieces of wood that are no longer attached to the ground, typically defined as exceeding 0.1m in diameter and 1.0m in length. |
| **Open channel** | A natural or artificial conduit capable of conveying water with a free surface. |
| **Refuse** | Waste or rubbish, including household and commercial waste, and can include fly-tipped waste. |
| **Security screen** | A structure installed at the inlet (and possibly the outlet) of a culvert or abstraction point to prevent access by unauthorised persons. |
| **Sediment** | Natural granular or cohesive material from clay to boulders that is transported by flowing water. |
| **Trash screen** | A structure installed at a culvert inlet to trap debris and to prevent internal blockage that might be difficult to remove. |
| **Vegetation** | Natural material such as leaves, twigs, branches, trees, garden waste, small, plants or shrubs. |

# Appendix A: Consultation results

## A1 Consultees

**Figure A.1 Breakdown of consultees' affiliations**




## A2 Blockage risk assessment

**Figure A.2 Do you assess the risk of blockage occurring?**

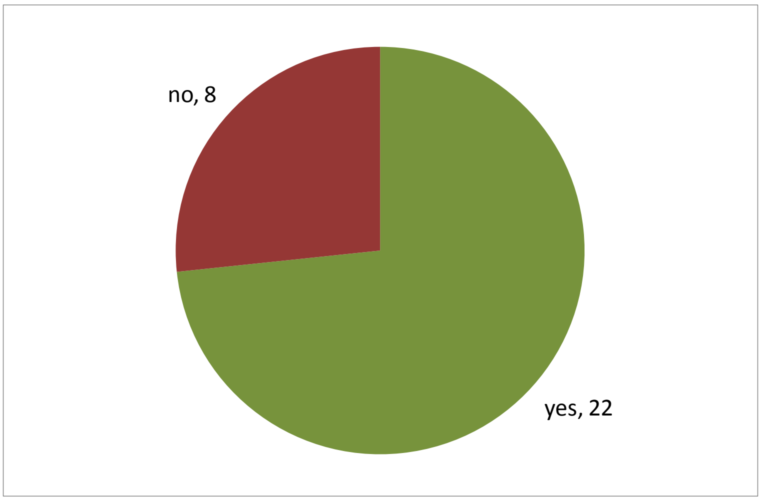


**Figure A.3 Why do you assess blockage risk?**

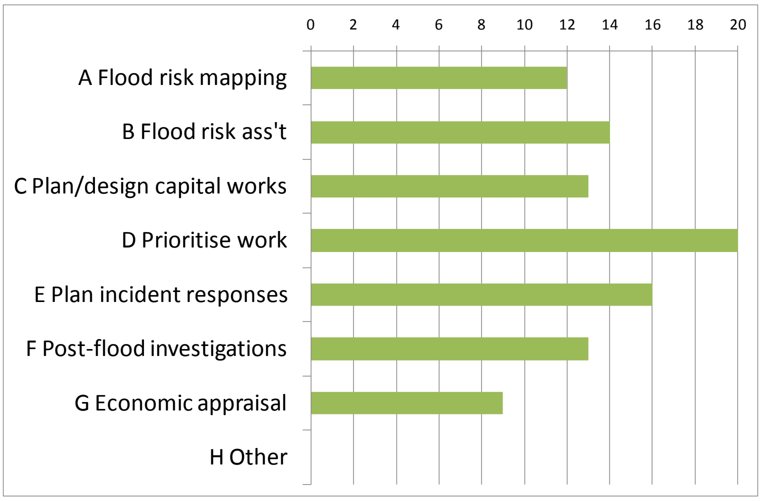
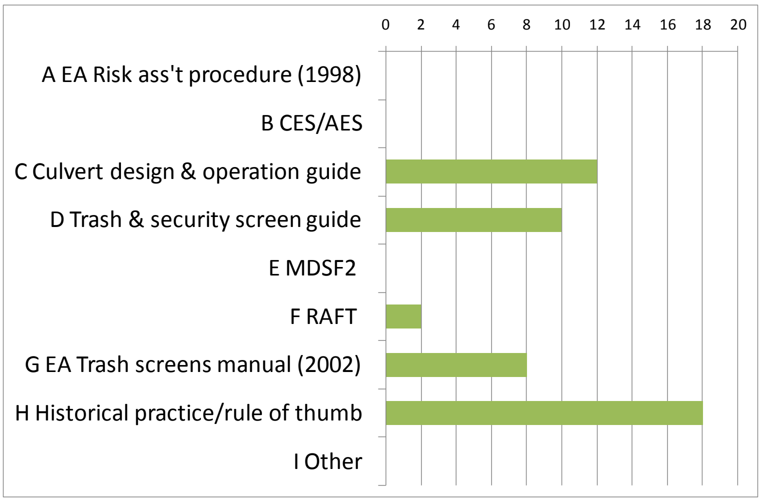



**Figure A.4 Which approaches or tools do you use for blockage risk assessment (if any)?**




## A2.1 Which factors influence your choice of method?

Guidance documents

- 'If designing a new screen then will try and follow guidance a far as possible within confines of site.'
- 'As I don't actually do the modelling, I usually request that blockage analysis is completed by the consultant and leave the method choice to them. To be honest I do not refer the clients to the above guidance, other than trash screen manual when discussing an Environment Agency project to install a trash screen.'
- 'Construction of new screens, we use the Trash and Security Screen Guide.'

- ‘We have to date used guidance docs we knew were available which are readily available and understandable.’

Ease of use

- ‘Cost, ease of use with Environment Agency data’
- ‘Simplicity for screening purposes at strategic level’
- ‘The tools must be straightforward and quick to apply.’

Experience or historic practice

- ‘The approach that has been used historically (convention).’
- ‘Historical incident data along with inspection and maintenance records.’
- ‘Knowledge and availability of documentation’
- ‘Historic practice/knowledge of the river system’

Specifics

- ‘Statutory requirements’
- ‘Financial and non-financial resources and on-site constraints’
- ‘What the Highways Agency wish to see on their database and require for evidence when bidding for monies.’
- ‘Design requirements’
- ‘Information available’
- ‘Type of structure’
- ‘Type of culvert: size, area, gradient and location’
- ‘I think urgency will define method, if blockage has led to a NIRS [National Incident Reporting System] we’d get blockage out faster. If blockage is more of a long-running issue where we need a long-term solution then any of the above depending on site specifics.’
- ‘Whether we intend to replace the screen or culvert. Preference is always to make a culvert big enough not to need a screen.’
- ‘Becks inspection reports’
- ‘Reports from members of the public’

## A2.2 What data do you use for blockage risk assessment?

Experience

- Experience
- Rules of thumb
- Historical records
- Local knowledge
- Engineering judgement

- Inspection and maintenance records
- Visual assessment
- ‘We have been clearing the grids for many years. Impacts of blockage assessed using engineering judgement. Telemetry installed at one of our grids.’
- ‘Very much reactive process to date’

Catchment and channel

- Catchment type and land use, for example, woodland, urban
- Catchment response time (flashy or not)
- Watercourse type
- Flood or river levels
- Channel data and dimensions
- Topographic survey data or LiDAR
- Map outlines
- ‘Flood events, flood hotspot, rainfall, topography, priority assets such as culverts, soakaways and outlets’

Assets

- Property data to see how many affected by blockage
- [Asset Information Management System] AIMS for asset information
- National Receptor Dataset (NRD)
- Digital River Network (DRN)
- Local receptors
- NIRS incidents, number of properties at risk of flooding (flood zones/NaFRA)

Structure

- Presence of trash screen, screen design
- Structure data
- Culvert cross-sectional area, or best available dimensions, discharge capacity
- Development and flood risk information – which structures are critical to assess

Debris

- Historic volumes and types of debris

## A2.3 What additional blockage risk assessment guidance is needed?

Management

- ‘A policy/strategy document’
- ‘We need to be able to calculate the economic benefits of undertaking regular maintenance and incident response (that is, clearing blockages) to improve conveyance.’
- ‘The issue on the ground is who is going to manage the blockage risk upstream of a potential blockage area within a flood defence scheme. The Environment Agency is increasingly unable to fund maintenance works to reduce the blockage risk. Some form of communication/partnership with stakeholders is required.’

Impacts

- ‘How likely the blockage is in terms of probability so that any calculations are compatible with MDSF2 / NaFRA.’
- ‘Percentage of channel/culvert to be blocked’
- ‘Guidance on risks affecting the structure’
- ‘None, but guidance on avoiding screens would help (size and length of culvert/hazard).’

Woody debris

- ‘Guidance on potential blockage from woody debris would be most welcome. As a consenting officer, I fairly often am subjected to vastly differing opinions from the ‘biodiversity’ and the ‘operational’ side of our business.’
- ‘Whether to leave woody debris in’
- ‘Whether it’s OK to install new woody debris to create new habitat’
- ‘... to assess the effects of woody debris on channel capacity/blockage risk to decided’

Clarity/simplicity

- ‘A flow chart to help identify what assessments are required systematically.’
- ‘Clarity on the approach to use’
- ‘Simple guidance on how to assess the risk of blockage’
- ‘One to bring all guidance together as a single reference’
- ‘High level and simple screening methodology for strategic-scale blockage risk assessment’
- ‘Guidance, clearly linked to existing CIRIA trash screen design and maintenance guidance’‘
- ‘One comprehensive all-encompassing document would be very helpful which takes you from assessment to modelling to design’

# A3 Modelling blockages

**Figure A.5 Do you assess the potential impact of blockages by modelling or other processes?**

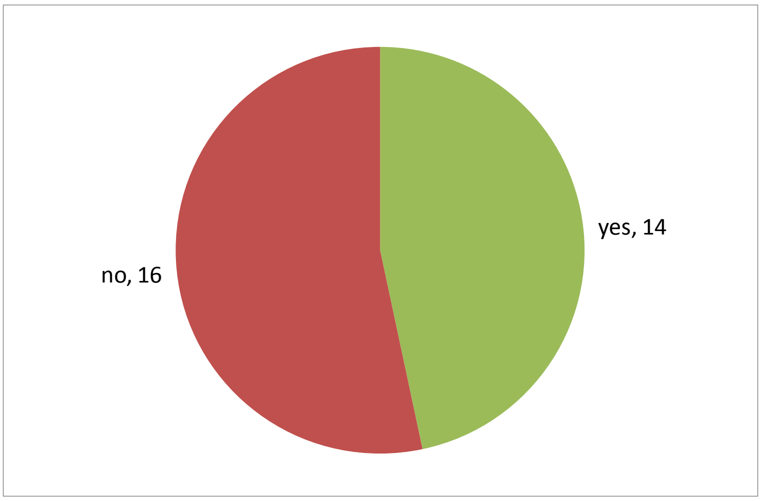



**Figure A.6 How do you assess the potential impact of blockages?**

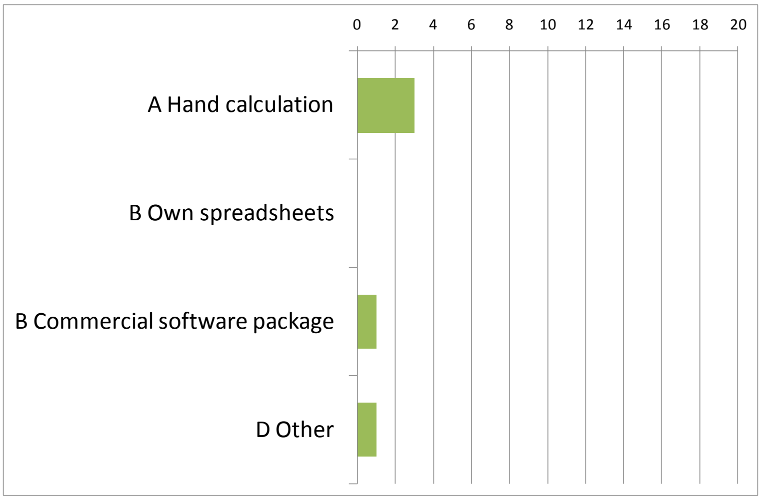


**Figure A.7 How do you estimate the amount of blockage?**

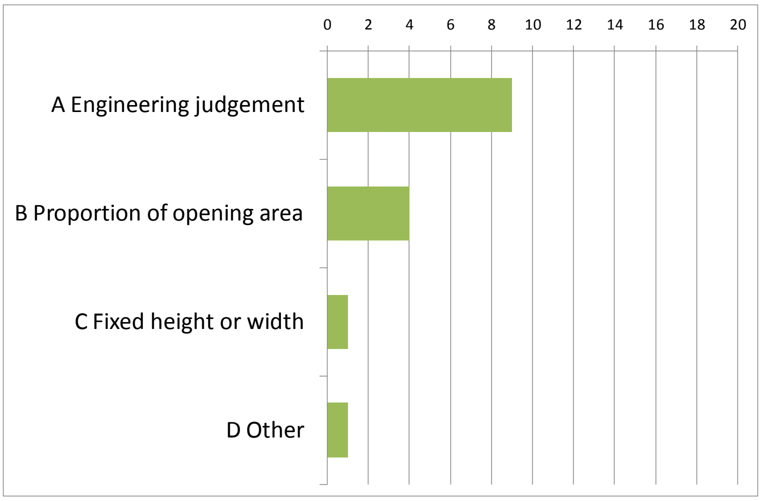



**Figure A.8 How do you represent blockage?**

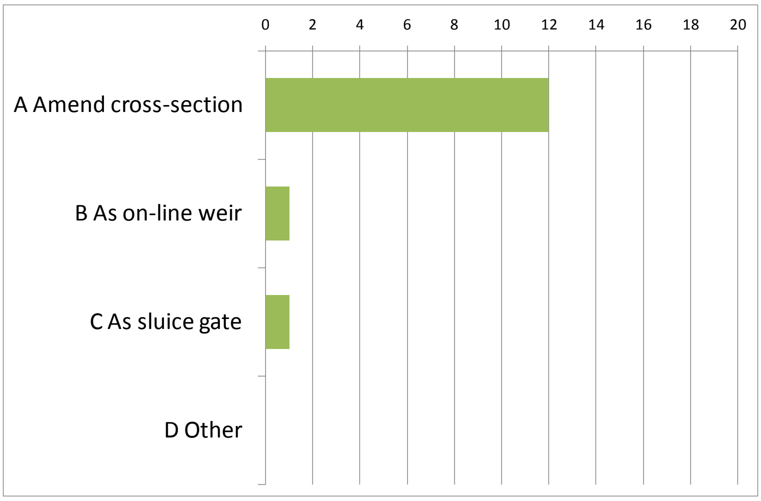
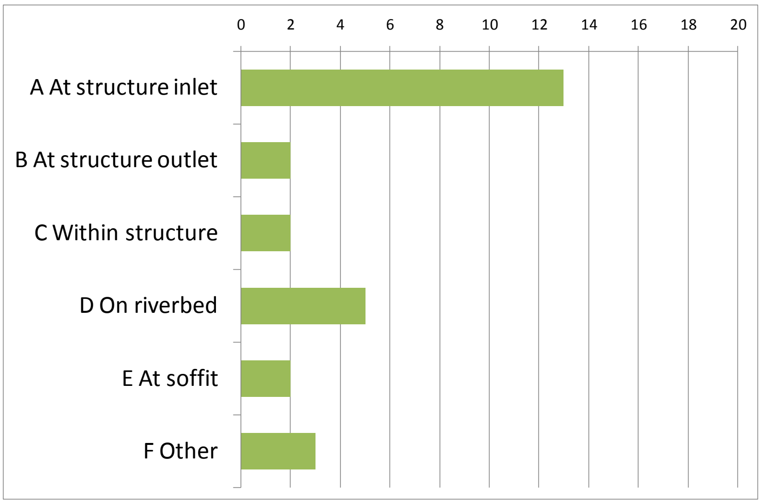



**Figure A.9 Where do you place the blockage?**



## A3.1 Which guidance or methods do you use for modelling blockages?

- CIRIA's Culvert Design and Operation Guide (Balkham et al. 2010)
- Trash and Security Screen Guidance (Environment Agency 2009)
- Highway Agency procedure
- Risk Assessment Field-based Tool (RAFT)
- 'HEC-RAS or ISIS for bridges, where there is a screen, don't bother modelling it.'
- 'Engineering judgement taking into consideration historic information, type of structure (for example, does it have any piers), local knowledge, site observations and our perception of flood risk.'
- 'Experience'
- 'Do not use any formal guidelines. Decision is made based on historic data, type of structure (for example, does it have any piers), local knowledge, site observations and our perception of flood risk.'
- 'None'

## A3.2 What additional blockage modelling guidance is needed?

Consistency

- 'A consistent approach across the business would be encouraged.'
- 'A fixed method […] so that we can be consistent. This could include a range of scenarios (25, 50, 75% and on on) and guidance of what to use each percentage for, that is, for capturing benefits to fund operational work through SAMPs, please use 50%.'
- 'Guidance, clearly linked to existing [Trash and Security Screen Guide] and maintenance guidance'

Guidelines

- 'A tool that allows us to calculate the economic benefits of blockage removal at trash screen/bridges/weirs and in culverts would be very useful. Currently we struggle to justify the blockage removal from the channel in financial terms, so we would welcome a tool that would allow us to estimate the benefits of our incident response work.'
- 'Clear guidance is required to identify how blockage should be applied at structures. For example, for capital scheme assessment, a high level of blockage is often applied in the do nothing option. This means that there is significant benefit gained under the do minimum option where this debris is removed. This can distort the selection process as there is insufficient incremental benefit to justify further scheme improvements (for example, do something).'
- 'Simple and straightforward guidance that I can pass onto clients would be welcome.'
- 'What level of blockage should be modelled'

- ‘Clearer guidance on how to assess and quantify the impact of a blockage would be useful.’
- ‘Something more formal than ‘experience’’

Woody debris

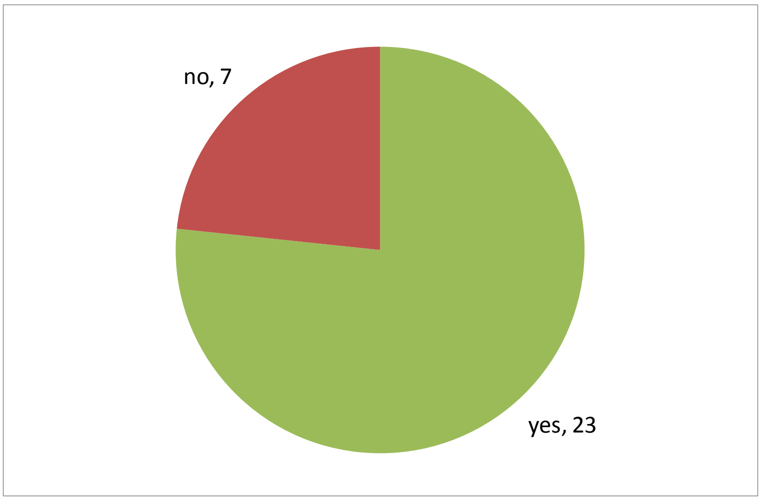
- ‘… staff need to be able to assess the effects of woody debris on channel capacity/blockage risk to decided’
- ‘Whether to leave woody debris in’
- ‘Whether it’s OK to install new woody debris to create new habitat.’

Support

- ‘A single point of contact where Asset Performance teams could access a modelling service would be good (this probably exists already!).’

# A4 Debris management

**Figure A.10 Do you remove and dispose of debris and sediment blockages?**




## A4.1 How do you remove and dispose of debris and sediment blockages?

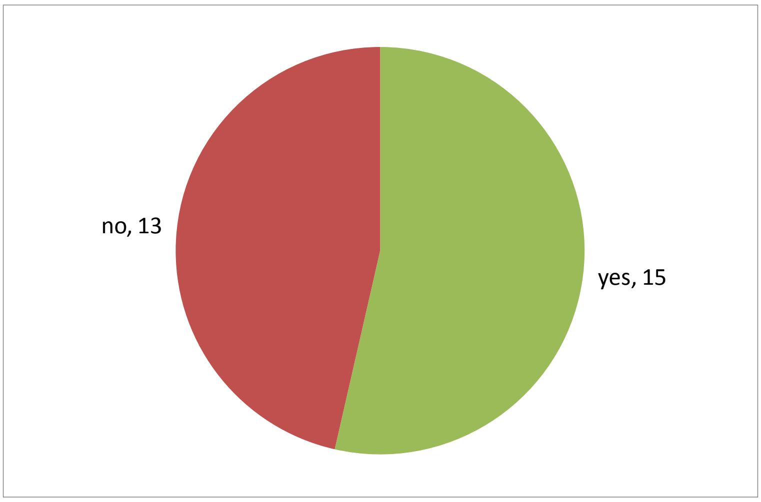
- ‘Removed debris is segregated into green waste and general debris. Green is sent for recycling or shredded on-site and left on banks. Other debris is either general waste. Sediment is tested for waste acceptance criteria and depending on result will either go to an exempt site or a landfill site. An interesting point is that in many cases the reason for removing sediment blockages is twofold. Firstly, channel capacity and secondly what effect the shoal [shallow place in a body of water] is having on flow; we have several instances where shoals are removed to prevent flow from eroding revetments and flood banks/berms, in a way to stop the river meandering!’
- ‘Remove trees if they cause a risk to dwellings or the drainage of tributaries.’
- ‘Remove sediments/trees if they cause an issue to gauging equipment; gravels placed back into the river downstream.’

- ‘Screens are raked by field teams and debris brought back to depots. Sediment blockages are generally non-reactive works and disposal depends on the nature of the sediment/silt.’
- ‘As necessary – either as routine maintenance or schemes in accordance with our contract.’
- ‘Debris and sediment blockages are removed using appropriate hand tools or small plant, dependent on size and safety factors associated with the location.’
- ‘Debris is generally removed as necessary with sediment removed further to detailed consultation and planning. Hand methods are used for small manageable blockages, and specialist contractors and equipment used for more extensive sediment and debris blockages.’
- ‘Debris and blockages are subjectively assessed on-site by staff with a view to their impact on flood risk. If the blockage is considered to be causing an unacceptable impact on flood risk and it is safe to do so, we remove it otherwise we will advise the asset owner or riparian owner.’
- ‘We assess the potential safety implications of each blockage against available funding allocations to determine the priority. Should works progress, the method of removal is determined by our supply chain.’
- ‘Yes, or deposit on banks on occasion for later pick up.’
- ‘We have a contract for watercourse maintenance. The contractor uses various plant as well as human resources to clear the grids.’
- ‘Debris is removed to a licensed tip.’
- ‘Usually by hand. Machines used where practical.’
- ‘Different depending on whether the location is a stretch of watercourse or at an inlet with or without a hake.’
- ‘Sediment is usually removed from a sump by hand digging or an excavator depending on location.’
- ‘Material is removed from site whether it’s fly-tipping, sediment or woody debris – all to landfill which costs us a lot to dispose of.’
- ‘Yes, contractor is required to dispose of all material in accordance with all waste legislation.’
- ‘In most cases the debris is left on-site but sometimes we need to dispose of it (for example, invasive species, large items of rubbish, construction waste, white goods, cars(!) and so on).’
- ‘Biodegradable matter or silt and sediments may be left in situ wherever possible. Trees will be removed and left on bank tops or may be cut up and disposed of. Some landowners request trees are left so they can use them for fuel.’
- ‘With regards to animal carcasses, the Lead Local Flood Authority is contacted so they can dispose of the remains.’
- ‘Depending on the area, it is always the preferred option to remove all items apart from animal carcasses off-site immediately, otherwise they are inevitably returned to the watercourse.’

- '"Light" debris and blockages are removed by hand using hand tools at the time of inspection. Other 'heavier' blockages are recorded and a works instruction raised for removal of blockages by the council's labour team.'
- 'Debris is removed and taken to landfill.'
- 'If flooding is being caused to the highway or third party land, then the blockage is removed. This is done by subcontractors and any debris/sediment disposed of in the correct manner.'
- 'Blockages in drain lines are removed by jetting. The downstream gullies are then cleaned and the water/sediment mix is treated and recycled. Blockages in ditch lines are removed by hand unless size dictates otherwise. Generally, natural material is disposed of on-site, for example, branches will be chipped on-site and arisings disposed of under existing vegetation. Man-made material is removed from site and disposed of appropriately, for example, car tyres are removed and recycled.'

## A4.2 Environmentally focused options

**Figure A.11 Do you used environmentally focused options (for example, leaving woody debris on-site)?**




If yes

- 'Low risk areas, the trees are left in the watercourse to slow flows to the next urban area. Any woody debris removed will be stacked on the riverbank as virgin timber for habitat (hibernacula). Timber rarely if ever goes to landfill/waste management. Timber is reused wherever possible.'
- 'Where possible'
- 'Arisings are generally left on-site if a suitable place is available.'
- 'When schemes have been undertaken to resolve drainage concerns, environmentally focused options such as leaving woody debris on-site have been taken.'
- 'Aware of Environment Agency guidance for management of woody debris, which we aim to follow.'

- ‘Not at screens. Our parks department do, elsewhere, with a code of practice agreed with us.’
- ‘Where the debris is big enough we may ask for it to be left in channel, but where we have hakes [trash screens], all debris is removed.’
- ‘Educating the squads doing the work on the ground about good and bad debris is an ongoing process.’
- ‘Only by default’

If no

- ‘On sections of main river that we maintain for flood risk, we generally don’t leave woody debris in place – often the cost of removal is far cheaper than trying to tie it into the bank or moving it. We have previously used woody debris to create revetments and reduce erosion. Fallen trees tend to be removed and the wood left on-site for the landowner to deal with.’
- ‘Typically we would seek to clear the site to prevent recurrence.’

Other responses

- ‘Advise FCRM function, along with Biodiversity, on value of woody habitat, and bed substrate, retained within the river corridor where flood risk permits.’
- ‘This would be a decision taken by the supply chain.’
- ‘[…] County Council ecologist consulted if necessary.’

## A4.3 If yes, has this had any adverse impacts?

Yes

- ‘Often leaving woody debris in will create shoaling and erosion of the river banks, in some cases the actual blockage risk is small but the erosion risk from the debris to say a flood bank is the reason why the blockage may be removed.’
- ‘Screens became blocked with cut timber over the Christmas period.’
- ‘Sometimes the arisings in periods of high water flow can make it back into the area from which they were removed.’
- ‘During “high” levels of rainfall, we have found that the debris can be washed into ditches and lead to blockages being formed.’
- ‘Wood debris is set aside either at a higher level than the flooded location, as long as there is no further risk, or downstream of the culvert, and this is generally effective. On occasion, due to further debris or additional flooding this set aside debris then contributes further to the blockage.’
- ‘Sometimes the people who own the properties push it [debris] into the river, channel or stream again.’
- ‘Results in complaints from the public who believe that we have not carried out maintenance.’

- ‘As previously mentioned, leaving items on bank tops will mean they will be returned to the watercourse.’

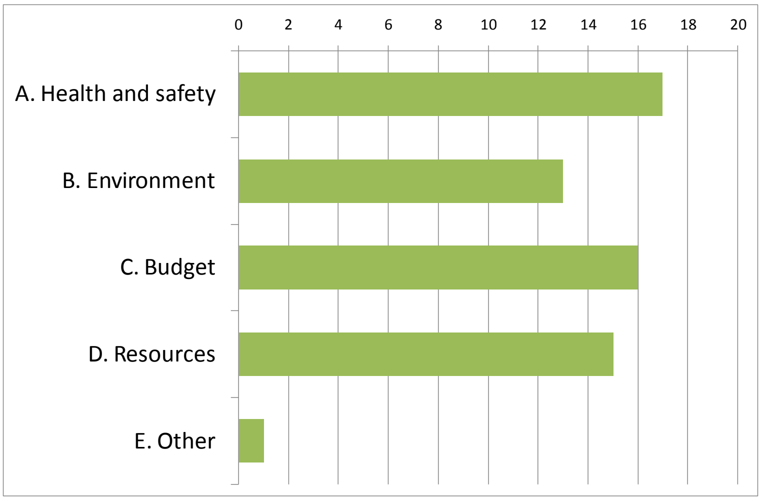
No

- ‘In my experience no, but FCRM will inspect regularly and have records that may be more thorough.’
- ‘Not to date.’
- ‘... logs were taken away by the local residents (to use as fuel).’

Don't know

- ‘Not known as yet, though some members of the public perceive this as lack of maintenance and consider that all woody debris/sediment ought to be removed.’

**Figure A.12 What constraints affect your approach to debris management?**




## A4.4 Have you changed your approach to debris management in recent years? If so, please explain how and why

- ‘In the last 8 years since I have been working in the Environment Agency the active removal of fallen trees from watercourses has massively reduced and we now only concentrate on urban flood defence systems. Riparian landowners are being pushed to carry out their responsibilities for the more urban catchments. Generally there is no one policing those sections of main river where the Environment Agency don’t carry out flood risk works, so there are many fallen trees littered along these sections of river, which one day will probably cause a problem!’
- ‘We have looked at the grids we visit and handed some of the lower risk ones back to local authorities and other agencies. We have implemented the woody debris guidance but actually didn’t actively clear much rural debris anyway. Our works were already focused on urban flood risk works.’
- ‘The fundamental approach of using known historical data to react to severe weather events has not changed, however the management systems to manage and record have been developed and improved.’

- ‘Reduction in sediment management as evidence now shows limited reduction in flood risk from the work. Debris management is prioritised through urban areas.’
- ‘This was changed because of the River Crane incident [bridge scour failure due to debris accumulation].’
- ‘Increasing pressure on budgets is resulting in more critical assessment of the necessity for removing debris and blockages.’
- ‘In process of formally scheduling activities to comply with FRMSA 2009 [Flood Risk Management (Scotland) Act].’
- ‘Increasing emphasis on health and safety.’
- ‘Woody debris and fallen trees are left in watercourses in rural locations. We have approached the local landowners and asked them to undertake the blockage removal in rural areas, where land ownership is more straightforward and farmers have the necessary tools to do the job.’
- ‘Because of the costs involved there has been a drive to ensure that this work can be justified, is focused and is necessary.’
- ‘Yes. More frequent and consistent approach to inspections as a result of FRMA duties. Flood incidents which have resulted from blockage of poorly designed screens.’
- ‘Yes – required to comply with SEPA regulations.’
- ‘Prior to the flood team formation, debris management was purely reactive only occurring during/after a flood event so it could be argued there was none. We now have a maintenance schedule in place which adheres to CARs [Controlled Activities Regulations].’
- ‘Only by consulting SEPA before removal of any silt or earth (if you consider that debris).’
- ‘We follow the inspection regime laid down by the Highways Agency, but debris management is still mostly reactive when there is inclement weather and where flooding is occurring.’
- ‘More focus on keeping drains, gullies and ditches clear given higher instances of heavy rain.’

## A4.5 Which guidance do you use for debris management (if any)?

- Wildlife Trusts ‘Managing Woody Debris in Rivers, Streams and Floodplains’ [Mott 2005]
- CIRIA’s Culvert Design and Operation Guide [Balkham et al. 2010]
- [Environment Agency] FCRM Maintenance Standards
- [Environment Agency] Operational Instructions for field team work
- Environment Agency Pollution Prevention Guidelines, for example, PPG5 ‘Works and Maintenance In or Near Water’
- EU Waste Framework Directive

- Environmental permitting for waste
- Flood Risk Management (Scotland) Act 2009
- Hazardous waste regulations
- EU Landfill Directive
- SEPA guidance
- 'Case studies on the [intranet]'
- '… specification for waste disposal within our watercourse maintenance contract'
- 'Work within the CARs [Controlled Activities Regulations]. Our team is different than your average flooding team in that we have less engineers and more environmental managers so try to be sympathetic to the environment where possible.'
- None

## A4.6 What additional debris management guidance is needed?

Responsibilities and management

- 'The Environment Agency needs to educate riparian landowners about their responsibilities and make it easier for these landowners to carry out these works. A good example is highway bridges. Highway authorities will complain to the Environment Agency about debris caught on their bridges. In my area we expect the highways authorities to keep their bridges clear. At the moment there is no one talking to landowners upstream about riparian responsibilities to try and reduce the debris being washed down onto the bridge. Who should do this, the Environment Agency as its main river, if so who in the Environment Agency? There is no flood risk to property from the bridge blocking, just the road flooding occasionally so no flood risk incentive to carry out work!'
- '[Organisation name] guidance and policy – then clear pathway for identifying/allocating available funds.'
- 'Better clarity on responsibility for dealing with river debris that has been generated by local landowners. Better understanding of responsibility for removing sediment and debris build up due to normal river deposition.'
- 'There needs to be good communication protocols between inspecting organisations so they can relate the presence of blockages that cause safety hazards quickly and to the right department.'

Source control

- 'Specifically in our area it would be good to know if there is a successful method for reducing flooding caused by fly-tipping as our efforts to date haven't proven the most successful. Enforcement action seems almost impossible so other methods of dealing with it would be very helpful.'

Woody debris

- ‘While not a lead in this area […] have a strong desire to see woody habitat retained in low risk scenarios, and removed sediment returned to the system at an appropriate lower risk location.’
- ‘More case studies of successful techniques of tying/clamping woody debris to the banks in/above high risk areas. A way to match technique to flow levels and help […] be confident that the debris will not cause an issue.’

Other

- ‘Guidance clearly linked to existing CIRIA trash screen design and maintenance guidance.’

# A5 Other comments

## A5.1 Would you like to add any other comments?

General

- ‘Many [...] teams are stretched for resources and need simple and quick to use solutions that will help them to deliver the actual work on the ground.’
- ‘I do not consider computer modelling suitable for this purpose. Local knowledge and experience is all that is needed.’
- ‘A table like in FD2321 [Defra and Environment Agency 2005a] or FD2320 [ Defra and Environment Agency 2005b] would be useful.’
- ‘Some more information on Environment Agency’s blockage modelling would be useful as it may assist in the development of the Highways Agency’s Drainage Data Management System (HADDMS) with a view to using it more proactively.’

Source

- ‘Type of upstream catchment will affect the blockage risk. Wooded or urban areas (or those where fly-tipping is common) will have a higher risk of blockage.’

Screens

- ‘Clear guidance on security versus debris screens would be useful, with guidance on how security screen sizes should be amended to account for smaller bar spacings.’
- ‘... guidance on the horizontal loading imposed on debris screens. One of our debris screens failed a few years ago because it was not strong enough to withstand the horizontal thrust imposed on it by the debris. When we rebuilt the screen, we went for massive overdesign and that seems to have done the trick.’
- ‘Clearing screens and debris from high risk areas needs to understood alongside the construction of defences. If capital budgets are to increase, the capacity to reduce risk through blockage clearance must be protected in the revenue funding stream.’

Techniques

- ‘A lot of river sections are left to nature to manage. In these cases I think it is difficult for the Environment Agency to say it is doing any form of blockage or debris management, it may be monitoring. We have been trialling the use of herbicides to keep vegetation from growing on shoals at critical locations, as well as hand digging small trenches across shoals to help get the river to keep shoals mobile. This has worked quite well in several locations and saves the cost of wholescale removal of a shoal.’
- ‘[Department names] have used a range of techniques to protect banks through reuse of woody debris and material from bankside tree works to provide more natural bank and toe protection. Case studies, such as the trial bank protection at Purslow, show these to be effective techniques using material that would have had to be disposed of as valuable bank protection and habitat. Additionally, a strategic approach needs to be adopted whereby we detain and delay flows in low risk systems through floodplain connectivity and in-channel features to reduce peaks in high risk systems. In-channel features and woody habitat, either natural or planned, have a role to play here. Where the securing of woody habitat is required for habitat/Water Framework Directive purposes, there are emerging techniques such as ground anchors and pletching that can achieve this. Wider use and knowledge of these would be of benefit to all involved in managing river systems, especially if formal approval/sign-off of these techniques can be agreed by [the Environment Agency].’

## 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.