



Programme Area: Nuclear

Project: Natural Hazards Phase 3

Title: Volume 5: River Flooding

Abstract:

This technical volume addresses:

- Introduction
- Description of the main phenomena; causes and types of flooding, some examples of river flooding, flood risk and vulnerability classification, definition of flood zones, Government's strategy and policy, organisations responsible for flood risk management
- Observations, measurements techniques and modelling tools
- Methodologies
- Related phenomena
- Regulation
- Emerging trends

Context:

The Natural Hazards Review project will develop a framework and best practice approach to characterise natural hazards and seek to improve methodologies where current approaches are inefficient. This is to improve energy system infrastructure design and the project is intended to share knowledge of natural hazards across sectors. The project will be completed in three stages. Phase one will focus on a gap analysis. Phase two will look at developing a series of improved methodologies from the gaps identified in phase one, and phase three will demonstrate how to apply these methodologies. Finally, phase 3 will develop a "how to" guide for use by project engineers.

Enabling Resilient UK Energy Infrastructure:
Natural Hazard Characterisation Technical Volumes
and Case Studies

Volume 5:
River Flooding



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This document forms part of the Energy Technologies Institute (ETI) project 'Low Carbon Electricity Generation Technologies: Review of Natural Hazards', funded by the ETI and led in delivery by the EDF Energy R&D UK Centre. The aim of the project has been to develop a consistent methodology for the characterisation of natural hazards, and to produce a high-quality peer-reviewed set of documents suitable for use across the energy industry to better understand the impact that natural hazards may have on new and existing infrastructure. This work is seen as vital given the drive to build new energy infrastructure and extend the life of current assets against the backdrop of increased exposure to a variety of natural hazards and the potential impact that climate change may have on the magnitude and frequency of these hazards.

The first edition of *Enabling Resilient UK Energy Infrastructure: Natural Hazard Characterisation Technical Volumes and Case Studies* has been funded by the ETI and authored by EDF Energy R&D UK Centre, with the Met Office and Mott MacDonald Limited. The ETI was active from 2007 to 2019, but to make the project outputs available to industry, organisations and individuals, the ETI has provided a licence to the Institution of Mechanical Engineers and Institution of Chemical Engineers to exploit the intellectual property. This enables these organisations to make these documents available and also update them as deemed appropriate.

The technical volumes outline the latest science in the field of natural hazard characterisation and are supported by case studies that illustrate how these approaches can be used to better understand the risks posed to UK infrastructure projects. The documents presented are split into a set of eleven technical volumes and five case studies.

Each technical volume aims to provide an overview of the latest science available to characterise the natural hazard under consideration within the specific volume. This includes a description of the phenomena related to a natural hazard, the data and methodologies that can be used to characterise the hazard, the regulatory context and emerging trends. These documents are aimed at the technical end-user with some prior knowledge of natural hazards and their potential impacts on infrastructure, who wishes to know more about the natural hazards and the methods that lie behind the values that are often quoted in guideline and standards documents. The volumes are not intended to be exhaustive and it is acknowledged that other approaches may be available to characterise a hazard. It has also not been the intention of the project to produce a set of standard engineering 'guidelines' (i.e. a step-by-step 'how to' guide for each hazard) since the specific hazards and levels of interest will vary widely depending on the infrastructure being built and where it is being built. For any energy-related projects affected by natural hazards, it is recommended that additional site- and infrastructure-specific analyses be undertaken by professionals. However, the approaches outlined

aim to provide a summary of methods available for each hazard across the energy industry. General advice on regulation and emerging trends are provided for each hazard as context, but again it is advised that end-users investigate in further detail for the latest developments relating to the hazard, technology, project and site of interest.

The case studies aim to illustrate how the approaches outlined in the technical volumes could be applied at a site to characterise a specific set of natural hazards. These documents are aimed at the less technical end-user who wants an illustration of the factors that need to be accounted for when characterising natural hazards at a site where there is new or existing infrastructure. The case studies have been chosen to illustrate several different locations around the UK with different types of site (e.g. offshore, onshore coastal site, onshore river site, etc.). Each of the natural hazards developed in the volumes has been illustrated for at least one of the case study locations. For the sake of expediency, only a small subset of all hazards has been illustrated at each site. However, it is noted that each case study site would require additional analysis for other natural hazards. Each case study should be seen as illustrative of the methods outlined in the technical volumes and the values derived at any site should not be directly used to provide site-specific values for any type of safety analysis. It is a project recommendation that detailed site-specific analysis should be undertaken by professionals when analysing the safety and operational performance of new or existing infrastructure. The case studies seek only to provide engineers and end-users with a better understanding of this type of analysis.

Whilst the requirements of specific legislation for a sub-sector of energy industry (e.g. nuclear, offshore) will take precedence, as outlined above, a more rounded understanding of hazard characterisation can be achieved by looking at the information provided in the technical volumes and case studies together. For the less technical end-user this may involve starting with a case study and then moving to the technical volume for additional detail, whereas the more technical end-user may jump straight to the volume and then cross-reference with the case study for an illustration of how to apply these methodologies at a specific site. The documents have been designed to fit together in either way and the choice is up to the end-user.

The documents should be referenced in the following way (examples given for a technical volume and case study):

ETI. 2018. *Enabling Resilient UK Energy Infrastructure: Natural Hazard Characterisation Technical Volumes and Case Studies*, Volume 1 — Introduction to the Technical Volumes and Case Studies. IMechE, IChemE.

ETI. 2018. *Enabling Resilient UK Energy Infrastructure: Natural Hazard Characterisation Technical Volumes and Case Studies*, Case Study 1 — Trawsfynydd. IMechE, IChemE.

1. Introduction	7
2. Description of main phenomena	9
2.1 Causes and types of flooding	9
2.2 Some examples of river flooding	10
2.3 Flood risk vulnerability classification	15
2.4 Definition of flood zones	16
2.5 Government’s strategy and policy	17
2.6 Organisations responsible for flood risk management	18
3. Observations, measurement techniques and modelling tools	19
3.1 Hydrometric data observation	19
3.1.1 Water level observation	19
3.1.2 Flow measurement	20
3.2 Hydrometric gauge network	21
3.3 National river flow archive	22
3.4 Met Office data	23
4. Methodologies	24
4.1 Introduction	24
4.2 Online flood risk maps	24
4.3 Flood risk modelling tools and technologies	25
4.4 Hydrological modelling	27
4.5 Hydraulic modelling.....	28
4.6 Flood forecasting and warning	30
4.7 Climate change allowance	33
4.8 Joint probability.....	35
5. Related phenomena	37
6. Regulation	38
7. Emerging trends	43

References	45
Glossary	51
Abbreviations	54

Flooding is the second most serious natural hazard risk for the UK (following the potential for a flu epidemic, see *HM Government (2017)*) with over 5 million (M) properties — equivalent to one in every six — being at risk in England alone (*EA, 2009a*). More than 2.4 M properties are at risk of flooding from rivers or the sea, of which nearly 0.5 M properties are at significant risk, and 1 M of these are also vulnerable to surface water flooding primarily due to insufficient drainage capacities in urban areas. A further 2.8 M properties are susceptible to surface water flooding alone. Annual damages associated with flooding are estimated at between £500 M and £1 billion (B) (*Penning-Rowsell, 2014*).

It is estimated that probabilities of river flooding could double or quadruple by 2080 relative to 2000 depending on future emissions of greenhouse gases, if relative sea-level rise due to global warming and land subsidence are factored in. The probability of coastal flooding may increase by about a factor of between 4 and 10 (*Bell et al., 2012; Feyen et al., 2012*). This could lead to more river flooding where the river system is tidally influenced.

In 2014 the UK experienced the wettest January since records began in 1766. Between 29th January and 12th February 2014, 1135 homes were flooded, more than 181,000 homes were protected by flood defences and more than 200,000 were sent a flood warning. January 2014 was the wettest month since records began. In the UK there was 183.8 mm of rain recorded in January 2014, which is 151% higher than average recorded in that month. In the south-east and central southern England during December 2013 and January 2014, there was 372.2 mm of rain recorded, the wettest two-month period since 1910. Heavy rainfall is a clear precursor to river flooding as the riverine network is potentially unable to cope with the increased flow.

The majority of the UK population lives in urban areas, and therefore flood damage in urban areas is relatively high compared to that in rural areas. Local authorities and water companies are required to respond to incidents of heavy rainfall, to provide adequate maintenance for storm water drainage and assets, and to improve system resilience.

The floods of December 2013 and January 2014 reinforced the urgent need for more sustainable urban drainage systems (SUDS) and green infrastructure, and reignited widespread public concern over new housing and industrial development, and existing roads, railway lines, treatment plants, and electricity substations in floodplains that are subject to flooding. The fact is, however, that people still want, and often specifically choose, to

1. Introduction

live on floodplains. This is understandable and inevitable, but the probability of flooding cannot be avoided, must be recognised, and is likely to increase due to climate change.

The cost of the 2013/2014 floods was £1.3 B ([EA, 2016a](#)): households and transport (road, rail, airports) were the most affected (£320 M and £295 M); businesses were also badly affected (£270 M); the cost for utilities (energy and water) was relatively low (£30 M).

The effects of flooding, and the costs of managing flood risk in the UK total around £2.2 B each year ([Bennett and Hartwell-Naguib, 2014](#)). This money has been mainly spent on flood defences and on rehabilitation or rebuilding work required to rectify the damage caused to properties and infrastructure by flooding events. It is predicted that annual spending on flood defences would have to increase by £10 M to £30 M in 2035, plus inflation, to maintain existing levels of flood protection against river and coastal flooding. Additional funding, in the order of £150 M a year, will also be needed for dealing with surface and groundwater flooding. The total costs could rise to as much as £27 B a year by 2080 ([Bennett and Hartwell-Naguib, 2014](#)). The Association of British Insurers has estimated the cost of the July 2007 floods, in insurance claims alone, at more than £3 B. See [Section 2.2](#) for more detailed information on specific flood events.

Failure of national critical infrastructure, such as electricity power supply, during flood events could lead to a cascade failure in other sectors which could significantly impact society, the UK economy, the natural environment, and the properties and communities that people live in. Therefore, understanding the flood risk now and in the future, and building infrastructure with resilience to flooding, is critical to the sustainability of the UK and for society's ability to continue going about daily life without disruption, economic damage or environmental cost.

2. Description of main phenomena

2.1 Causes and types of flooding

There is a variety of potential causes of flooding — e.g. high intensity and long duration rainfall, run-off volume in excess of river channel capacity, hydraulic structure and river system capacity, pluvial flooding due to insufficient drainage capacity, blockage of drainage, ageing assets, inadequate maintenance, growing population, urbanisation, pipe burst, overflow from ditches and drainage, groundwater flooding, and water rising out of the ground. As a significant cause of river flooding is heavy rainfall, the reader is encouraged to seek further information from Volume 4 — Extreme Precipitation.

Flooding is a complicated phenomenon and most major floods in the UK have been the result of a combination of causes. There are four natural sources of flooding:

Fluvial flooding/river flooding

Generally occurs when a river flow exceeds the channel capacity, and overtops river banks. This is mainly caused by heavy rains of high intensity and duration in the catchment; the problem is compounded when rain falls in a saturated waterlogged catchment.

Coastal flooding

Generally results from a combination of high tides, storm surge, strong winds and large waves. Where low atmospheric pressure generates a storm surge and this coincides with a period of high tides, there is a risk of serious flooding.

Pluvial flooding

Also called surface water flooding and generally results from intense rainfall, becoming particularly severe when it overwhelms the drainage capacity. It occurs mainly in urban areas when sewers are overwhelmed by heavy rainfall and/or when they become blocked.

Groundwater flooding

Occurs when water levels in the ground rise above surface levels. It is most likely in areas underlain by permeable rocks called aquifers. These can be extensive, regional aquifers, such as chalk or sandstone, or may be more local sand or river gravels in valley bottoms underlain by less permeable rocks.

2. Description of main phenomena

Other types of flooding are:

- reservoir flooding (occurs due to overtopping, breaching of the dam of the reservoir or failure of the control structure associated with the reservoir);
- failure or breaches of flood defences;
- flooding from a combination of sources.

2.2 Some examples of river flooding

Flooding from rivers can be a recurring natural disaster; as the main cause is heavy rainfall, the same catchment could be affected more than once in quick succession. Selected major river floods that occurred in the UK in recent years are discussed below.

1928: London floods

On 7th January 1928, the Thames flooded much of central London. The Houses of Parliament, the Tate Gallery and the Tower of London were all inundated. Fourteen people drowned and thousands were left homeless. The river poured over embankments at Southwark, Lambeth, Temple Pier and the Houses of Parliament, where Old Palace Yard and Westminster Hall were quickly flooded. Flooding occurred as far west as Putney and Richmond. The high waters were caused by a depression in the North Sea which sent a storm surge up the tidal river, producing the highest levels witnessed on the Thames for 50 years. The river's flood defences were designed to cope with a tide of 18 ft above *ordnance datum**. This height had been chosen to exceed the previous record of 17 ft 6 in, which was reached in 1881. The 1928 surge saw this exceeded by 11 inches.

In the wake of the flood, the embankments were raised. The 1953 North Sea flood led to the construction of the Thames Barrier.

1998: Easter floods

Rivers' conveyance capacity was exceeded by torrential rain to a level not experienced in living memory in many places, which overwhelmed arrangements designed for less extreme conditions. On 9th April, a heavy band of rain over the Midlands led to the loss of five lives and many thousands were forced to leave their homes. The whole central area of England, from Worcestershire to the Wash, was affected and many major towns suffered flooding. An independent review of the Easter floods (*Bye and Horner, 1998*) identified a number of shortfalls such as instances of unsatisfactory planning, inadequate warnings for the public, incomplete

*All technical terms marked in blue can be found in the Glossary section.

2. Description of main phenomena

defences, and poor co-ordination with emergency services. Since then a significant effort has been made by the Environment Agency (EA), lead flood authorities, and other emergency responders to improve the situation or overcome those shortfalls.

2000: Millennium floods

Autumn 2000 was the wettest on record across England and Wales for over 250 years. Heavy rainfall in October and November 2000 caused prolonged, extensive and in places repeated, flooding. The flood levels in many places were the highest on record. In many locations there had been no previous record of flooding. 10,000 properties were flooded at over 700 locations, but particularly hard hit were York, Shrewsbury, Lewes and Maidstone. Additionally, there was widespread disruption to road and rail services. The total costs were of the order of £1 B (2000 prices).

2004: The Boscastle flood

On 16th August 2004, exceptional rainfall over an eight-hour period caused the worst flooding in local memory at Boscastle in Cornwall. A 3 m wave was triggered by water pooling behind debris caught under a bridge; when the bridge collapsed, the wave surged down the main road. The flooding caused an estimated £15 M in damages, with 75 cars, 5 caravans, 6 buildings and several boats washed into the sea; around 100 homes and businesses were destroyed.

2007: Summer floods

Over 55,000 homes and businesses were flooded in summer 2007 (EA, 2007). The human impact was significant and the insurance losses alone were nearly £3 B (2007 prices).

May to July 2007 were the wettest for this three-month period since rainfall records began in 1776. Many locations were deluged with a month's rainfall in a few hours. The ground was saturated from heavy rain throughout May and in early parts of June. Extreme rainfall in late June and late July caused widespread flooding. These floods were different in scale and type compared to the 1998 and 2000 floods. A much higher portion of the flooding than normal came from surface water (due to ground saturation) rather than from river flooding. Surface water flooding was at its worst in cities such as Hull.

The ground became saturated by mid-June; many reservoirs that normally have some capacity to absorb run-off were also filled by the May and early June rain, which ultimately resulted in widespread river flooding. The floods of March 1947 resulting from heavy rain and melting snow are often referred to as benchmark events due to their severity. In the River Thames in the

2. Description of main phenomena

upper reaches, the River Avon in Warwickshire and the River Severn between Tewkesbury and upstream of Gloucester, flood levels in summer 2007 were higher than in 1947. At Gloucester, the river level was 0.01 m below the 1947 flood. At Tenbury Wells on the River Teme, a record level was reached in June, only to be topped in July by a further 0.22 m.

More than 9000 homes and businesses were severely affected after the city of Hull received a sixth of its annual rainfall in just 12 hours. The disaster affected an estimated 35,000 people and caused damage estimated at £41 M. More than 6000 people in Hull were forced into temporary accommodation while some 1400 people had to live in caravans until their homes were repaired. The flooding resulted in the loss of one life. Throughout the UK, two-thirds of the properties flooded in summer 2007 were affected because drains and sewers were overwhelmed.

The county of Gloucestershire endured the worst of the 2007 flooding, with 13 people killed. Almost half a million residents were left without drinking water. The army was called in to distribute emergency supplies.

2013/14: The Somerset Levels

Over Christmas 2013 and New Year 2014, storms battered South West England, with heavy rains and high winds resulting in widespread disruption including major road closures, power outages, and the submersion of thousands of acres of the Somerset Levels (*Figure 1*). January's rainfall total in Southern England was 185 mm making this the wettest January since records began in 1766, just ahead of January 1948 (177 mm). *Figure 2* gives percentage rainfall relative to the January average for the period 1981 to 2010 across the UK, and shows that the rainfall in the Somerset area was more than twice the January average (*Thorne, 2014; Met Office, 2014*). The persistent bad weather led to rising flood waters that eventually triggered a large-scale response from local and national government, EA, fire and police services, and the Royal Society for the Prevention of Cruelty to Animals (RSPCA), with the military being called on to provide support. EA carried out the 'biggest pumping operation ever' on the Somerset Levels, in an attempt to remove 1.5 M tonnes of water each day (*EA, 2014; Muchan et al., 2015*).

2. Description of main phenomena



Figure 1. Somerset Levels flooding in December and January 2013/14.
(Source: Shutterstock)

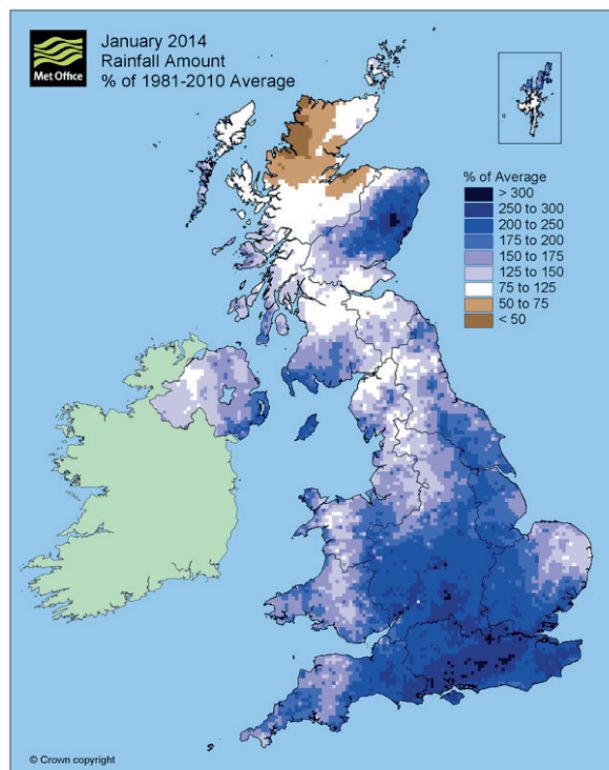


Figure 2. January 2014 rainfall during the 2013/14 Somerset winter floods.
(Source: Met Office (2014) and contains Ordnance Survey data Crown copyright database right © 2018)

2. Description of main phenomena

2015: Cumbria flooding

Heavy rainfall from Friday 4th December to Sunday 6th December 2015 led to widespread flooding in Cumbria and across other parts of northern Britain. Exceptionally high rainfall fell across Cumbria, exceeding 300 mm and breaking existing UK rainfall records. These floods followed severe flooding affecting Cumbria in November 2009 and major floods in Carlisle in January 2005. A total of 341.4 mm of rain fell at Honister Pass, Cumbria, in 24 hours to 18:00 Greenwich Mean Time (GMT) on 5th December, a new UK rainfall record, while at Thirlmere 405 mm also set a new record for two consecutive rain-days (09:00 to 09:00 GMT).

Several thousand homes and businesses were inundated with floodwater across Cumbria, with parts of Lancashire, Northumberland and southern Scotland also affected. Carlisle was worst hit by severe flooding from the River Eden, but many other towns and villages in the area were also affected by flooding. Tens of thousands of homes across Cumbria and Lancashire were without power for several days. A number of bridges were swept away by flood water, including Pooley Bridge, Ullswater, built in 1764. There were two fatalities and many road and rail links were cut for a considerable amount of time, including the West Coast Main Line. Schools and hospitals were closed in the flood affected areas.

2.3 Flood risk vulnerability classification

Table 1 provides the flood risk vulnerability classifications defined by Department for Environment, Food and Rural Affairs (Defra) and EA research on *Flood Risks to People (DCLG, 2012)*. In this table, the requirement for infrastructure assets to remain operational during flooding events is clearly stated.

Building and developments that combine a mixture of uses (among the classes in *Table 1*) should be placed into the higher of the relevant classes of flood risk sensitivity. Developments may cover a large area. The area could fall within several classes of flood risk sensitivity.

The impact of a flood on the uses identified within this flood risk vulnerability classification will vary within each vulnerability class. Therefore, the flood risk management infrastructure, and other risk mitigation measures needed to ensure the development is safe may differ between uses within a vulnerability classification.

2. Description of main phenomena

Table 1: Flood risk vulnerability classification based partly on Department for Environment, Food and Rural Affairs and EA research on Flood Risks to People (FD2321/TR2) and also on the need for some uses to remain operational during flooding. (Source: MHCLG (2014))

Essential infrastructure

- Essential transport infrastructure (including mass evacuation routes) which has to cross the area at risk
- Essential utility infrastructure which has to be located in a flood risk area for operational reasons, including electricity generating power stations and grid and primary substations; and water treatment works that need to remain operational in times of flood
- Wind turbines

Highly vulnerable

- Police stations, ambulance stations, fire stations, command centres and telecommunications installations required to be operational during flooding
- Emergency dispersal points
- Basement dwellings
- Caravans, mobile homes and park homes intended for permanent residential use
- Installations requiring hazardous substances consent. (Where there is a demonstrable need to locate such installations for bulk storage of materials with port or other similar facilities, or such installations with energy infrastructure or carbon capture and storage installations, that require coastal or waterside locations, or need to be located in other high flood risk areas, the facilities should be classified as 'essential infrastructure'.)

More vulnerable

- Hospitals
- Residential institutions such as residential care homes, children's homes, social services homes, prisons and hostels
- Buildings used for dwelling houses, student halls of residence, drinking establishments, nightclubs and hotels
- Non-residential uses for health services, nurseries and educational establishments
- Landfill and sites used for waste management facilities for hazardous waste
- Sites used for holiday or short-let caravans and camping, subject to a specific warning and evacuation plan

Less vulnerable

- Police, ambulance and fire stations which are not required to be operational during flooding
- Buildings used for shops, financial, professional and other services, restaurants and cafes, hot food takeaways, offices, general industry storage and distribution, non-residential institutions not included in 'more vulnerable', and assembly and leisure
- Land and buildings used for agriculture and forestry
- Waste treatment (except landfill and hazardous waste facilities)
- Minerals working and processing (except for sand and gravel working)
- Water treatment works which do not need to remain operational during times of flood
- Sewage treatment works (if adequate measures to control pollution and manage sewage during flooding events are in place)

Water-compatible development

- Flood control infrastructure
- Water transmission infrastructure and pumping stations
- Sewage transmission infrastructure and pumping stations
- Sand and gravel working
- Docks, marinas and wharves
- Navigation facilities
- Ministry of Defence installations
- Ship building, repairing and dismantling, dockside fish processing and refrigeration and compatible activities requiring a waterside location
- Water-based recreation (excluding sleeping accommodation)
- Lifeguard and coastguard stations
- Amenity open space, nature conservation and biodiversity, outdoor sports and recreation and essential facilities such as changing rooms
- Essential ancillary sleeping or residential accommodation for staff required by users in this category, subject to a specific warning and evacuation plan

Notes:

- This classification is based partly on Department for Environment, Food and Rural Affairs and EA research on Flood Risks to People and also on the need for some uses to remain operational during flooding.*
- Buildings that combine a mixture of uses should be placed into the higher of the relevant classes of flood risk sensitivity. Developments that allow uses to be distributed over the site may fall within several classes of flood risk sensitivity.*
- The impact of a flood on the particular uses identified within this flood risk vulnerability classification will vary within each vulnerability class. Therefore, the flood risk management infrastructure and other risk mitigation measures needed to ensure the development is safe may differ between uses within a particular vulnerability classification.*

2. Description of main phenomena

2.4 Definition of flood zones

Flood zones are geographic areas that have been defined according to varying levels of flood risk. These zones are depicted on a flood risk map published by EA. Each zone reflects the severity or type of flooding in the area. The definitions of the flood zones used by the Government are provided in [Table 2](#).

Table 2. Definition of flood zones by EA (Source: MHCLG (2014))

Flood zone	Definition
Zone 1 Low Probability	Land having a less than 1 in 1000 annual probability of river or sea flooding. (Shown as 'clear' on the flood map – all land outside zones 2 and 3)
Zone 2 Medium Probability	Land having between a 1 in 100 and 1 in 1000 annual probability of river flooding; or land having between a 1 in 200 and 1 in 1000 annual probability of sea flooding. (Land shown in light blue on the flood map)
Zone 3a High Probability	Land having a 1 in 100 or greater annual probability of river flooding; or Land having a 1 in 200 or greater annual probability of sea flooding. (Land shown in dark blue on the flood map)
Zone 3b The Functional Floodplain	This zone comprises land where water has to flow or be stored in times of flood. Local planning authorities should identify in their Strategic Flood Risk Assessments areas of functional floodplain and its boundaries accordingly, in agreement with EA. (Not separately distinguished from zone 3a on the flood map)

Note: these flood zones refer to the probability of rivers and sea flooding, ignoring the presence of defences.

[Table 3](#) shows the types of developments that are permitted or not permitted in each flood zone. For example, highly essential infrastructure is permitted in flood zones 1 and 2; if essential infrastructure needs to be developed in flood zone 3, an **exception test** must be carried out. Highly vulnerable development is only permitted in flood zone 1.

2. Description of main phenomena

Table 3. Flood risk vulnerability and flood zone 'compatibility' (Source: MHCLG (2014))

	Essential infrastructure	Highly vulnerable	More vulnerable	Less vulnerable	Water compatible
Zone 1	✓	✓	✓	✓	✓
Zone 2	✓	Exception test required	✓	✓	✓
Zone 3a	Exception test required	✗	Exception test required	✓	✓
Zone 3b	Exception test required *	✗	✗	✗	✓*

Key:

✓ Development is appropriate.

✗ Development should not be permitted.

2.5 Government's strategy and policy

Defra (2005) sets out the cross-government, overarching strategy for flood and coastal erosion risk management in England. The Government's strategy has continued to evolve and broaden:

- The Climate Change Act 2008 (*HM Government, 2008*) requires a UK-wide climate change risk assessment every five years, accompanied by a national adaptation programme that is also reviewed every five years. The Act has given the Government new powers to require public bodies and statutory organisations, such as water companies, to report on how they are adapting to climate change.
- *Future Water (Defra, 2008)* is the Government's overall strategy for water and looks mainly at water supply and provision. It reaffirms *Defra (2005)* as the basis for managing river and coastal flooding. However, it also sets out a vision for better management of surface water to address the dual pressures of climate change and housing development.
- The Pitt Review (*Pitt, 2008*), following the 2007 floods, made 92 recommendations. The Government supports changes that will help achieve all of them. The Government's response to the Pitt Review led to development of the Flood and Water Management Act 2010 (see *Section 6*)

2. Description of main phenomena

2.6 Organisations responsible for flood risk management

The Department for Environment, Food and Rural Affairs (Defra) has national policy responsibility for flood and coastal erosion risk management and provides funding through grants to EA.

The principal flood risk management authorities are: the EA in England; Natural Resources Wales in Wales; the Scottish Environment Protection Agency in Scotland; the Northern Ireland Executive (which currently has no formal definition in legislation) and the Department for Infrastructure (DfI) in Northern Ireland. They are responsible for forecasting and mapping of flood risk, providing warnings, advising on development in the floodplain, building and keeping defences in good order and taking part in emergency planning and response.

Other organisations also play a fundamental role in flood risk management:

- Local authorities take a lead role in reducing risks from development in the floodplain and management of drainage and small watercourses. In December 2008, following the recommendations of the Pitt Review, the Government in England gave new roles to county councils and unitary authorities that allow them to lead on managing local flood risk, surface water, groundwater and ordinary watercourses ([EA, 2010](#)). Local authorities can apply to Defra for funding for all major flood and coastal risk management capital projects.
- Internal Drainage Boards (IDBs) are independent bodies involved in land drainage in areas of special drainage need. These are mostly low-lying areas that need active management of water levels.
- The insurance industry, such as The Association of British Insurers (ABI) and its members, provides cover and handles claims for damages caused by a flood. Under an agreement with the Government, it has committed to continuing insurance coverage.

Additionally, there are other bodies and committees, which also help with flood risk management, including Regional Flood and Coastal Committees (RFCCs), Local Resilience Forums (LRFs), the National Flood Forum (NFF), actioners and researchers.

3. Observations, measurement techniques and modelling tools

3.1 Hydrometric data observation

Flood risk assessment relies heavily on hydrometric data. Hydrometric data include rainfall, river and sea levels, river flow and groundwater level. The following principal measuring authorities collect the data:

- Environment Agency (EA), England;
- Natural Resources Wales (Cyfoeth Naturiol Cymru) (NRW), Wales;
- Scottish Environment Protection Agency (SEPA), Scotland;
- Department for Infrastructure — Rivers (RA), Northern Ireland;
- The Met Office.

There are other public and private measuring authorities such as the Canal & River Trust, Centre for Ecology & Hydrology Wallingford, Essex & Suffolk Water plc, the Geological Survey of Northern Ireland, Northern Ireland Environment Agency, Northumbrian Water Limited, Scottish Water Dunfermline, Southern Water plc, United Utilities plc, and Yorkshire Water.

The data station network (national) can be viewed online ([RiverLevels, 2018](#)); this is an independent website, and is not related to EA, NRW, SEPA, RA or others.

3.1.1 Water level observation

At primary gauging stations, water level (also called stage) is generally measured and recorded against time by instruments activated by a float in a *stilling well*. Solid state loggers are normally deployed to record water level, having gradually replaced the punched tape and analogue chart recorders that were used as standard 30 years ago. At present, for the great majority of the gauging stations in the UK, measurements are taken by electronic sensors in the rivers and automatically transferred to central locations for analysis and storage.

Typically, the primary agencies record hydrometric data every 15 minutes and collect the data from the monitoring site once or twice a day using a telemetry system. Data may be collected more frequently to meet operational needs (e.g. during flood events).

River and sea levels are measured in metres as the depth of water above a known point, which can be the river/sea bed or the crest of a weir. River levels are either measured against a local datum or ordnance datum, usually in metres above ordnance datum (mAOD).

Anyone may use the data for flood risk assessment, subject to the terms and conditions set by the respective primary data collection authorities. Whilst every effort is made to ensure the accuracy,

quality and availability of the information provided, EA, SEPA, NRW, RA and others cannot guarantee it for the near real time hydrometric data; data might contain errors or erroneous readings (e.g. spikes, shifts in the time of recordings) due to instrument faults, environmental conditions or other reasons. Therefore, users should check the data quality prior to use.

3.1.2 Flow measurement

Indirect flow measurement

Most of the flow gauging stations are capable of measuring low to moderate flows while the water remains in the channel, but are not capable of measuring the flow beyond certain thresholds, especially when the water level is very high, exceeding the river banks and water flows on the floodplain. In situations like this, the river flows are normally derived from the relationship of stage (level) with discharge, called a *stage-discharge relationship* or rating curve. For a substantial proportion of UK gauging stations, a stable relationship between river level and river flow is achieved by installing a gauging structure, usually a weir or flume with known hydraulic characteristics. In the absence of such structures, the development of the stage-discharge relationship is a two-stage process. Firstly, stream velocity is measured using propeller-type current meters or other methods — increasingly, *Acoustic Doppler Current Profilers* (ADCPs) are being used which offer significant advantages (e.g. speed of flow assessment and greater safety for the operators) over traditional current meters. In a few cases, where field conditions permit, ADCPs may be used to provide a continuous flow record. Thence, the mean velocity is combined with the cross-sectional area of the river to provide a measurement of flow. This procedure is repeated throughout the flow range allowing *rating equations* to be developed which facilitate the conversion of water levels into river flows. Gauging stations are normally sited in river sections characterised by their ability to maintain a reasonably stable relationship between river level and flow. However, this relationship may be disturbed by changes to the hydraulic characteristics of the *gauging reach* (e.g. due to changes in the bed profile following a flood or the seasonal impact of aquatic plant growth). Such circumstances are relatively common and necessitate an ongoing review, and updating, of the stage-discharge relationship. Sometimes modelling techniques are employed to extend the rating curve to cover the flow range. Having a good understanding of how the flows are measured and/or estimated using a stage-discharge relationship is very important to giving an appreciation of the accuracy and uncertainties in the flow data used for flood risk assessment.

Ultrasonic flow measurement

For ultrasonic gauging stations, which have found wide application since the late-1970s, a stable relationship between river level and flow is not a necessary requirement. Flows are

computed on-site where the times are measured for acoustic pulses to traverse a river section along an oblique path in both directions. The mean river velocity is related to the difference in the two timings and the flow is then assessed using the river's cross-sectional area. Accurate computed flows can be expected for stable river sections and within a range in stage that permits good estimates of mean channel velocity to be derived from a *velocity traverse* set at a series of fixed depths. Accuracy can be compromised by high suspended sediment concentrations or heavy weed growth which can impede the acoustic signal, or by thermal stratification in the water column — serving to deflect the acoustic beams.

Electromagnetic flow measurement

Flow data from electromagnetic gauging stations may also be computed on-site. The technique requires the measurement of the electromotive force (emf) induced in flowing water as it cuts a vertical magnetic field generated by means of a large coil buried beneath the river bed or constructed above it. This emf is sensed by electrodes at each side of the river and is directly proportional to the average velocity in the cross-section. Because of technical, maintenance and health and safety issues there remain only a very modest number of electromagnetic stations operational in the UK.

3.2 Hydrometric gauge network

The hydrometric station network can be viewed on the website of the respective primary data collection authorities; see [EA \(2018a\)](#), [NRW \(2018a\)](#), [SEPA \(2018a\)](#) and [RA \(2018\)](#).

Water level and discharge

In England and Wales, river levels are measured at approximately 2000 sites. Data for about 1750 sites will be available under licence. River flows are derived at about 1250 of the river level sites. At a majority of the sites, EA converts river levels to flows using a defined mathematical algorithm for that site. This is often in the form of a stage-discharge power law equation. At other sites, EA samples the river velocity and produces river flows using a *velocity-discharge equation*.

In Scotland, SEPA has records for river levels at around 563 sites; all stations may not be operational. Data from approximately 330 stations are displayed on the website.

In Northern Ireland, DfI Rivers has a network of 130 active hydrometric stations that measure water level in rivers, sea and loughs. Some 80 gauging stations are situated in rivers.

3. Observations, measurement techniques and modelling tools

Rainfall

The UK has over 3000 rain gauges maintained by different partners, e.g. EA, Met Office, SEPA, NRW, etc. Most rain gauges are of the automated tipping bucket intensity variety. They work by funnelling rainfall into two collection buckets that tip back and forth on a pivot once they collect 0.2 mm of rainfall. The frequency of the tipping movement is directly related to the rainfall intensity.

Across England, EA has approximately 1000 real time rain gauges which are connected by telemetry. Measurements of the amount of precipitation (mm) are captured in tipping bucket rain gauges (TBR). Data recorded give accumulated rainfall total for each 15-minute period. These data are typically transferred once or twice per day to a central location for analysis and storage.

In Scotland, there are over 600 rain gauges; SEPA manages a network of 267 of these. The time of each tip is recorded by a data logger that transmits the information instantly to SEPA offices. SEPA also receives data from public rainfall observers who read storage gauges. Across Wales, there are over 270 rain gauges and across Northern Ireland, there are over 140.

Groundwater

Groundwater data are collected manually at several thousand groundwater sites. These data are not available as near real time data (see below for real time monitoring). Groundwater is reported as a depth to the water from the top of a borehole. They are sampled at a frequency that may be specific to meet the operational needs of each site. They are typically collected once or twice per day.

For real time monitoring, the groundwater observation borehole network comprises 181 sites: 166 in England, three in Northern Ireland and one in Scotland. Water levels are monitored regularly at these sites, providing time-series data that can help us understand the aquifers being monitored and how they are affected by changes in factors such as climate or land use.

Other data

Other hydrometric data are also collected at some selected sites, e.g. climate data such as temperature, wind direction and wind speed.

3.3 National river flow archive

The National River Flow Archive (NRFA) is the main focal point for hydrometric data in the UK,

3. Observations, measurement techniques and modelling tools

providing access to daily, monthly and flood peak river flow data from over 1500 gauging stations. The NRFA (NRFA, 2018) collates, quality controls, and archives hydrometric data from gauging station networks across the UK including the extensive networks operated by EA (England), NRW (Wales), SEPA (Scotland) and DfI (Northern Ireland). The NRFA is a major component of the Centre for Ecology & Hydrology (CEH) Environmental Information Data Centre.

The annual maximum (AMAX) series available from the NRFA contains the largest observed flow in each water year. Users can obtain the AMAX and peak over threshold (POT) from the NRFA. Since April 2014, national peak flow data has formed part of the NRFA data holdings. The national peak flow dataset forms the basis of flood risk estimation in the UK. Prior to April 2014, the data and information outlined here were provided by the HiFlows-UK initiative.

3.4 Met Office data

The Met Office has a weather station network across the entire UK, with more than 200 automatic stations (Met Office, 2016). Rainfall data can be downloaded from the Met Office Integrated Data Archive System (MIDAS) (CEDA, 2018). Annual, monthly and seasonal rainfall maps may be viewed online; data may also be obtained in tabular form. An example rainfall distribution map, for the winter season for the period between 1981 and 2010, is shown in Figure 3.

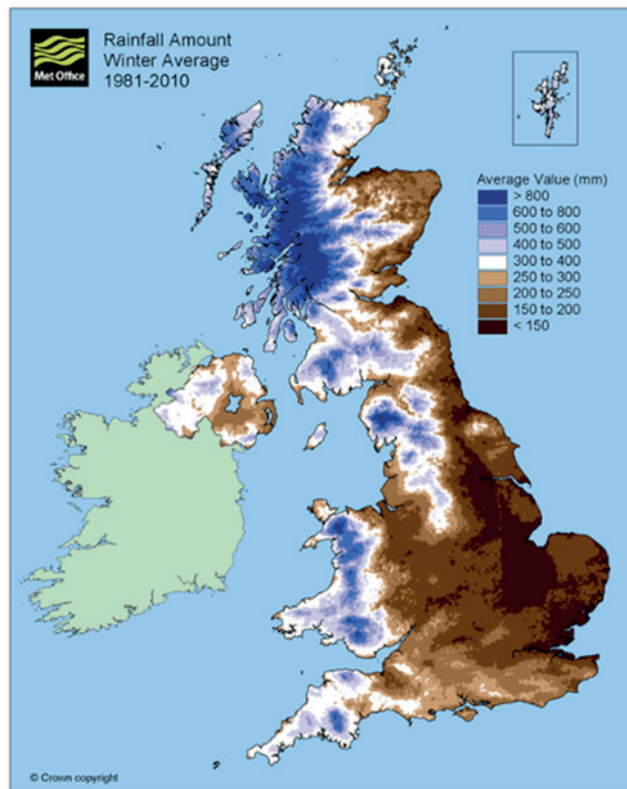


Figure 3. UK winter average rainfall for the period 1981 to 2010. (Source: Met Office (2018) and contains Ordnance Survey data Crown copyright database right © 2018)

4.1 Introduction

Flood risk assessments are needed to understand the magnitude and extent of flooding as well as the source of flooding. To support flood risk assessment (FRA) and strategic flood risk assessment (SFRA), innovative modelling tools and technologies are used in the UK for hydrological and hydraulic modelling and for flood risk mapping.

Hydrological models provide estimates of design flows, which are applied as inflows to the hydraulic models. In turn, the hydraulic models are applied for *hindcast modelling* and prediction of flood risk for flood events of different probabilities of occurring. Hydraulic models are also applied for flood forecasting and warning. Forecasting models are an important and integral part of a flood warning service. Although flood risks cannot be eliminated, real time flood forecasting models can be used to help to provide timely flood warnings with an adequate lead time to allow the public to minimise flood damages, and potentially lead to a reduction in the loss of lives.

The sections below describe methodologies for assessing flood risk.

4.2 Online flood risk maps

Hydraulic models have been developed across numerous catchments in the UK, and flood maps have been produced by EA, SEPA and DfI for the public. Flood risk maps from all sources of flooding (river, surface water, groundwater and coastal) are available online for flood zones 1, 2 and 3:

- EA online flood maps for England at [EA \(2018b\)](#) and [EA \(2018c\)](#);
- NRW online flood maps for Wales at [NRW \(2018b\)](#);
- SEPA online flood maps for Scotland at [SEPA \(2018b\)](#);
- DfI online flood maps for Northern Ireland at [DfI \(2018\)](#).

For any development it is important to understand the present and future flood risk to the site, and the potential impact of the proposals on all parties, to help with the identification of sustainable solutions. The existing flood maps on the websites listed above provide a good indication of the development site's flood zone and enable a quick assessment of flood risk vulnerability against development compatibility, i.e.:

- highly vulnerable;
- more vulnerable, e.g. landfill, waste facility or caravan site;
- less vulnerable, e.g. land or building used for agriculture or forestry; a waste treatment site; a mineral processing site, a water treatment plant; or a sewage treatment plant.

These maps should be used for strategic planning for any development work. They are very useful for initial flood risk screening. However, for design purposes of a proposed development, detailed flood risk assessments need to be carried out as per the requirement of local planning authorities (*Defra/EA, 2017*). The methodologies to be used for such flood risk assessments are described in the next sections.

4.3 Flood risk modelling tools and technologies

Fluvial flood risk maps from river flooding are produced in the UK by using hydrodynamic modelling techniques; either a new model is developed or an existing model is updated (if an older version of the model exists) by following the best practice methodology and using the most recent data, such as topography from Light Detection and Ranging (LIDAR), as well as any updates in hydrological estimation methods.

As a common practice, hydrodynamic models are often developed and used to simulate the flood water in the river system as well as on the floodplain. They are used to predict the flood depth, water level, velocity, flood extent and even flood hazard level. Generally speaking, the river system is represented using one-dimensional (1D) models as the flow travels in the same direction when it remains in the river channel, whilst the floodplain is represented using two-dimensional (2D) models as the flood water spreads in different directions when the water exceeds the river banks. The 1D river channel and the 2D floodplain models are linked to represent the real connection between the river and the floodplain.

In terms of what types of modelling techniques should be used, the following key factors should be considered:

- purpose of the study;
- level of complexity for both in-bank flows and out-of-bank flow paths;
- flow controls and structures in the river system;
- flood storages and their representation in the model;
- requirements on the level of model accuracy;
- data availability and accuracy;
- availability of time and budget.

It is important to use the most appropriate modelling tool for the project rather than merely the tool that is available. Inappropriate tool selection (e.g. using a 1D unsteady model in a dense urban area, when a 1D and 2D linked model would be more appropriate) can have significant technical and cost implications for both current and future needs. In the UK, several modelling

4. Methodologies

software tools which have been tested through benchmarking studies (EA/Defra, 2004; EA, 2013) are employed for flood risk mapping studies (Table 5). In general, software that has not been subject to benchmarking is not recommended for developing models.

Table 4. Hydraulic model types and modelling software in use in the UK for flood risk assessment. (Source: Mott MacDonald)

Model type	Software	Geometry and topographic data requirement
1D unsteady hydrological routing model	Flood Modeller (previously ISIS), MIKE11 and HEC-RAS	Channel cross-sections
1D unsteady hydrodynamics	Flood Modeller Pro, MIKE11, InfoWorks RS and HEC-RAS	Channel cross-sections and structure details and drawings
Quasi-2D floodplain model (also called 2D hydrological routing)	JFLOW, LISFLOOD	DEM/LIDAR
1D hydrodynamic linked to quasi-2D floodplain	Flood Modeller Pro, Hec-RAS, InfoWorks RS, MIKE 11 MIKE FLOOD, JFLOW, LISFLOOD	Channel cross-sections and DEM/LIDAR
1D hydrodynamic linked to fully 2D floodplain	Flood Modeller Pro -TUFLOW, ESTRY-TUFLOW, ISIS1D2D, MIKE Flood, MIKE URBAN, Infoworks ICM	Channel cross-sections, structure details and DEM/LIDAR

Note: ESTRY, Infoworks ICM and MIKE URBAN also model urban storm water pipe flows.

Table 5. List of modelling software and websites for the respective developers. (Source: Mott MacDonald)

Software	1D	2D	1D-2D	Source
HEC-RAS	✓			http://www.hec.usace.army.mil/software
Flood Modeller (previously ISIS)	✓	✓	✓ ¹	https://www.floodmodeller.com/about/
InfoWorks RS/2D	✓	✓	✓	http://www.innovyze.com/products/infoworks_rs/
MIKE11/21	✓		✓	https://www.mikepoweredbydhi.com/products/mike-11
JFLOW		✓ ²		http://www.jbaconsulting.co.uk
TUFLOW	✓ ³	✓	✓ ^{1,4}	http://www.tuflow.com

¹Available through ISIS-TUFLOW link; ²Not fully hydrodynamic (does not solve momentum); ³Available as ESTRY (provided with TUFLOW); ⁴Links to ESTR

4.4 Hydrological modelling

To run the hydraulic models, flow hydrographs are needed to feed into the hydraulic models at key locations to represent how the water from the catchment contributes to a river system. To derive the flow hydrographs, the standard and recommended methodology in the *Flood Estimation Handbook* (FEH) for estimating flows in the UK should be used (CEH, 2018). Hydrological modelling is basically to estimate the run-off from the catchment due to rainfall. Flows and hydrographs are often estimated by following the key steps outlined below:

- The mean annual maximum flood (QMED) is calculated based on AMAX data provided on the NRFA website; the NFRA-UK database contains AMAX series from gauging stations located throughout the UK. EA may provide AMAX data for the most recent years which are not available on the NFRA website; the QMED is then updated accordingly.
- The FEH methodology recommends estimating QMED from gauged records based on both AMAX and POT series. It is recommended that POT data should be used where less than 14 years of AMAX data are available.
- At an ungauged location, a gauged site that has similar catchment characteristics to the subject site is normally selected as a donor site. A gauged donor site is normally selected from the gauges located downstream or upstream of the same river system, and at the minimum, from a catchment of similar hydrological parameters to the subject site, e.g. catchment area, annual rainfall, *base flow index* (BFI) values, etc.
- *Flood frequency analysis* is carried out.
- Storm duration affects the flood volume and the timing of the peak flows and how the flow hydrographs are combined when flood water propagates down the river system. Different locations along the river system will have different *critical storm durations*. The critical storm duration should be derived from observed data if available, otherwise through the rainfall and run-off method using the FEH or revitalised flood hydrograph (ReFH) approach as appropriate; if possible this should be calibrated against observed flood events.
- The *design hydrograph shape* is derived using observed data wherever possible, or via the use of FEH, ReFH or revitalised flood hydrograph 2.2 (ReFH2) methods as appropriate, if observed data are not available.

- Finally, design hydrographs for flood events of different annual exceedance probability (AEP) are derived by using a combination of QMED, flood growth curve, FEH, ReFH or ReFH2.

To assess the flood risk in the future, the climate change allowance should be applied according to the UK Government's online guidance issued in February 2016 ([EA, 2016b](#)).

4.5 Hydraulic modelling

Hydraulic modelling, which broadly couples both hydrological and hydrodynamic models, is applied for preparing flood risk maps, flood risk management, and appraisal/planning/design of flood alleviation schemes. EA and NRW, SEPA and DfI have developed numerous hydraulic models for fluvial flood risk assessment across the catchment of UK. For new flood risk assessment, existing models — if available — should be reviewed to assess suitability for use in the study or project.

The scope of work should describe the intended use of the model — whether it is to be for strategic flood risk assessment, a site-specific flood risk assessment, or to assist with the design and/or optimisation of a flood scheme.

The model development methodology should outline the expected accuracy of the model; for example, whether it is important that the model accurately represents the water levels, flows, flood volume or any combination of these. To ensure that all the key areas are represented and modelled correctly, competent hydrologists and hydraulic modellers (who have a good understanding of the locations of important flow paths and the performance of complex hydraulics, and who can make sound judgements) and a good representation of the reality in the model, should be used. Good quality topographical data and hydrometric data are also fundamental to the accuracy of the model. If there are specific key flood risk areas that need to be considered, these should be clearly highlighted. The benefits of [walkover surveys](#) should not be overlooked. Sensibility checks of the model results are an integral part of modelling.

Topographical data is needed to build hydraulic models. Topographical data (LIDAR) for the floodplain of some main river systems/watercourses is freely available from EA, NRW and SEPA. When topographical survey data for river channels, floodplains and hydraulic structures are required for modelling and flood risk assessment purposes, it is recommended to follow the latest topographical survey specifications produced by EA, NRW or SEPA as appropriate

4. Methodologies

depending on the site locations. The most commonly used datasets for building hydraulic models is summarised in [Table 6](#).

Table 6. Datasets commonly used in building hydraulic models. (Source: Mott MacDonald)

Data	Usage in model build
OS Master Map (vector), OS Land Line (vector), OS 1:10k (raster), OS 1:25k (raster), OS 1:50k (raster)	Understanding of the catchment, presentation of model results on top of maps; OS Master Map used in 2D models to assign no-flow areas around properties and in the application of Manning's 'n' to different areas
Aerial photography	Understanding of the catchment; presenting model results on top of aerial photographs; useful in public consultation exercises
Digital elevation data (bare earth and surface)	SAR or LIDAR model construction (elevation) in 1D and 2D, and in the flood mapping
Survey data of the channel and structures	Representing channel topography and structures in the model
Existing models and reports	Used or modified to provide all or part of a new hydraulic model; existing model reports useful to gain an understanding of how a catchment responds and operates
Historic data: water level, discharge, flood outline, photographs, etc	Model calibration and validation
Hydrological design flows	Used as inflows to model for prediction of flood risk
Defence data (including operational information)	Necessary to consider the standard of protection afforded by existing defences in the model

Flow data are required as inputs to run hydraulic models. Flows are put into the hydraulic model in a number of ways: point inflows at the upstream boundary of the hydraulic model; point inflows from tributaries; natural watercourses; lateral inflows. Inflows are distributed over a length of the model and combined with distributed areal rainfall to model surface water runoff (only in a 2D model).

The downstream boundary must also be defined for hydraulic modelling. Its location needs to be far enough away to ensure that model accuracy for the area of interest is not affected by the assumption and/or inaccuracy in the downstream boundary conditions. The impact of boundary conditions could be assessed through sensitivity tests which may lead to a revision of the model extent.

It is important that models are calibrated and verified to show that an appropriate level of accuracy is achieved ([Table 7](#)) prior to their use in predicting flood water flows, water levels, velocities, flood extent or flood hazard. Both hydrological and hydraulic models should be calibrated against a variety of historical events and verified against different sets of flood events. When selecting calibration and verification events, it is important to choose events covering a wide range of flow patterns and magnitudes, e.g. in-bank low flows, medium flows and out-of-bank high flows, single and multiple peak events, and hydrographs with different durations.

When using the model results, it is important to know the assumptions and the limitations of the models.

Table 7. Fluvial flood modelling – level of calibration accuracy on water level. (Source: EA (2009b))

Service level	Acceptable (mm)	Not worse than (mm)
Broad scale modelling (i.e. less detailed)	±500	±750
Flood defence	±250	±350

In addition to the peak water level, the rising and falling *limbs of the hydrograph* should also have a good match to those observed in magnitude, shape and timing wherever possible.

4.6 Flood forecasting and warning

In the UK, several types of models (see [Table 8](#)) are currently used for flood forecasting and warning purposes. The selection of model to be used normally requires consideration of a number of factors, including:

- technical feasibility;
- implementation costs;
- damage avoidance;
- model accuracy and uncertainty;
- data availability;
- operational constraints.

Existing types of flood forecasting model currently used in the UK range from simple relationships such as level correlations and time of travel relationships, through to rainfall runoff models, hydrological routing, and hydrodynamic models. An overview of different model types is

4. Methodologies

presented in [Table 8](#). Accuracy requirements for a forecasting model are given in [Table 9](#), and the colour-coded flood risk matrix of impacts versus likelihood is shown in [Figure 4](#).

Table 8. Flood forecasting model types in practice in the UK. (Source: Defra/EA (2003))

Model type	Calibration	Real time use
Correlation models	A calculator or spreadsheet is sufficient for single correlations, with a specialist package advisable for multiple correlations.	Simple enough to use manually, or to programme into the telemetry system (not all systems) or to use in a full 'shell'.
Transfer function models	Ideally requires a specialist statistical package to decide the appropriate structure and parameters of the model, but could be programmed in a spreadsheet.	Some versions simple enough to use in a spreadsheet although a 'shell' is required to take full advantage of updating, non-linear versions, etc.
Conceptual models	Requires a specialist package to decide the appropriate parameters of the model (and structure, where more than one configuration is possible).	Normally requires a 'shell' type environment.
Routing models	Fixed parameter versions could be calibrated by calculator or spreadsheet but a specialist package is generally advisable, and essential with variable parameters and when the reach is divided into sub-reaches.	Requires a 'shell' type environment.
Hydrodynamic models	Specialist package essential.	Requires a 'shell' type environment to calculate and display the results.

4. Methodologies

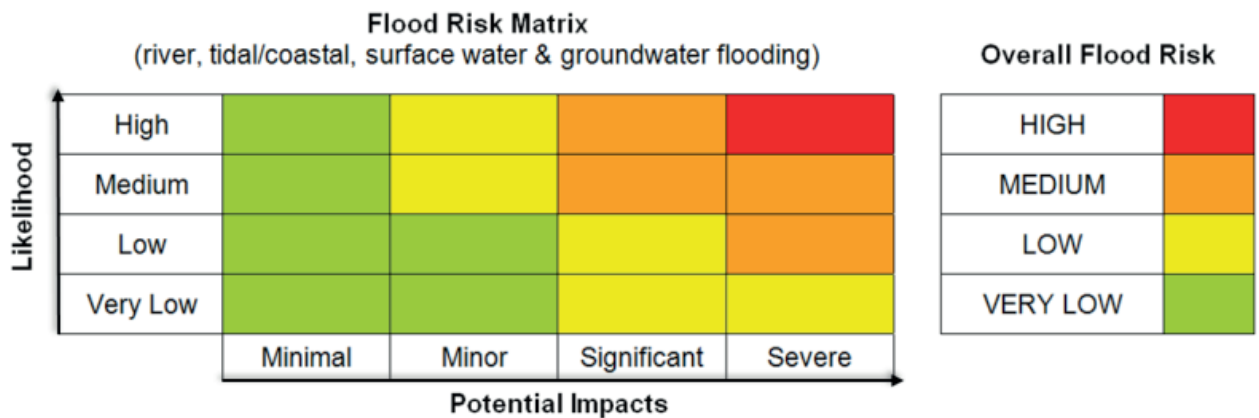


Figure 4. Flood risk matrix map – colour code practised in England and Wales. (Source: EA/Defra (2014))

In broad terms, a ‘shell’ or ‘full shell’ represents an operating system including computer servers for managing a database, running plugged-in forecasting models and issuing and disseminating forecasts. The National Flood Forecasting System (NFFS) has adopted the Delft Flood Early Warning System, Delft FEWS (Werner et al., 2004), as the forecasting shell at its base. The architecture of the NFFS is shown in Figure 5. The Delft FEWS system follows the open shell approach, where forecasting models are ‘plugged-in’ to the forecasting shell by means of a model ‘adapter’ that is developed by the model supplier. The NFFS adopted the strategy of a single software shell capable of using a standard set of EA-approved models.

Table 9. Fluvial flood forecast accuracy requirements. (Source: EA (2000))

Service level	Public	Emergency services	Agency staff
Accuracy of flood depth forecast	±0.5 m	±1.0 m	±2.0 m
Accuracy of flood duration estimate	±3 hrs	±3 hrs	±3 hrs
Accuracy of targeting	80%	100%	N/A
Reliability	75%	50%	50%

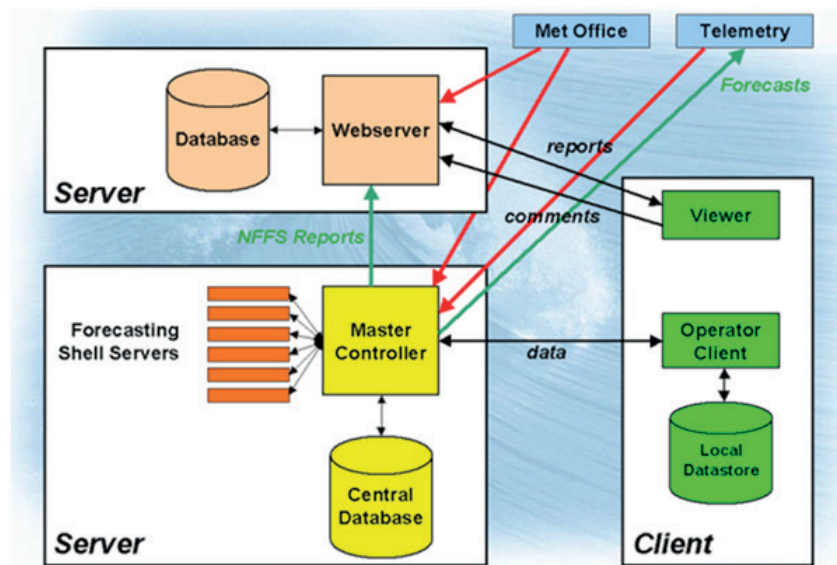


Figure 5. Architecture of EA's National Flood Forecasting System. (Source: EA (2007))

EA is currently in the process of updating the NFFS. It is expected that the new flood forecasting system will be in operation in 2019.

4.7 Climate change allowance

The National Planning Policy Framework (NPPF) sets out how the planning system should help to minimise flood risk and provide resilience to the impacts of climate change. NPPF explains when and how flood risk assessments should be applied, how flood risk should be managed now and over the lifetime of the development, and how to consider the effect of climate change. Guidance on flood risk assessment, and consideration of the latest climate change projections, can be found in [EA \(2016b\)](#).

To assess how fluvial and joint fluvial/tidal flood risk may change in the future, it is necessary to consider climate change allowances for:

- peak river flow;
- peak rainfall intensity;
- sea level rise.

These allowances are based on climate change projections and different scenarios of carbon dioxide (CO₂) emissions to the atmosphere. There are different allowances for different epochs or periods of time over the next century. EA, NRW, SEPA and DfI will use these allowances as benchmarks when providing advice on flood risk assessments and strategic flood risk assessments.

4. Methodologies

When assessing fluvial flood risk, in addition to considering the fluvial flow increase and rainfall intensity increase due to climate change, it is especially important to consider the sea level rise if the rivers are tidally influenced. Sea level rise will lead to a longer *tidal locking period*. Prolonged tidal locking will increase the fluvial flood risk of the river system. A summary of different climate change allowances is provided below:

- peak river flow allowances by river basin district in England are available in [EA \(2016b\)](#) and for Scotland are available at [SEPA \(2018c\)](#);
- peak rainfall intensity increase is presented in [Table 10](#) (this is also available in the references quoted above);
- sea level rise for England and Scotland is presented in [Table 11](#) (also available in the references quoted above).

Table 10. Peak rainfall intensity allowance in small and urban catchments (uses 1961 to 1990 baseline). (Source: EA (2016b))

Allowance category	Total potential change anticipated for the '2020s' (2015 to 2039)	Total potential change anticipated for the '2050s' (2040 to 2069)	Total potential change anticipated for the '2080s' (2070 to 2115)
Upper end	10%	20%	40%
Central	5%	20%	20%

[Table 11](#) provides a summary of the climate change allowance values for sea level rise across the coast of England and Scotland. These allowances also account for slow land movement due to *glacial isostatic adjustment* resulting from the release of pressure after ice that covered large parts of northern Britain melted at the end of the last ice age. The northern part of the country is slowly rising and the southern part is slowly sinking. Therefore, net sea level rise is less for the north-west and north-east than the rest of the country.

Table 11. Sea level allowance for each epoch in millimetres (mm) per year with cumulative sea level rise for each epoch in parentheses (uses 1990 baseline). (Source: EA (2016b))

Area of England	1990 to 2025 (mm)	2026 to 2055 (mm)	2056 to 2085 (mm)	2086 to 2115 (mm)	Cumulative rise 1990 to 2115 (m)
East, East Midlands, London, South East	4 (140)	8.5 (255)	12 (360)	15 (450)	1.21
South West	3.5 (122.5)	8 (240)	11.5 (345)	14.5 (435)	1.14
North West, North East	2.5 (87.5)	7 (210)	10 (300)	13 (390)	0.99

4.8 Joint probability

The occurrence of two or more conditions leading to a high water level (e.g. a large river flow and high surge or a higher fluvial event through one tributary inducing higher water level in another tributary due to backwater effect) can be modelled using a multivariate statistical distribution (often called joint probability analysis). There is often a degree of dependence between the variables and an assessment of this dependence is required to evaluate the flood risk due to these extreme events. Failure to consider joint probability in the design process can lead to significant under- or over-design.

When the area is affected by both fluvial and tidal conditions, it is important to provide realistic tidal conditions to correspond to the fluvial flood event. To do so, a joint probability desk-based approach can be adopted, as set out in [Defra/EA \(2005\)](#). The document outlines approaches for the following combined hazards:

- wave height and sea level;
- wave height and surge;
- tide and surge;
- river flow and surge;
- precipitation and surge;
- precipitation and sea level;
- wind generated waves and swell.

The general steps for river flow and surge are outlined below:

- Fit a marginal distribution (usually a generalised Pareto distribution above a threshold and an empirical distribution below the threshold).
- Fit a copula or multivariate extreme value model to the joint extreme values.
- Estimate the dependence between extreme river flow and surge. This can be illustrated using the extremal dependence measure χ (the probability of one variable being extreme given that the other is already extreme). A value of $\chi = 1$ signifies total dependence and $\chi = 0$ signifies independence of the extremes.
- Obtain confidence intervals for χ using bootstrapping.
- Construct a joint hazard curve using the copula or simulations from the multivariate extreme value model. This curve provides potential combinations for different AEPs.

4. Methodologies

For more detail on the approach outlined above see Volume 12 — Hazard Combinations. *Defra/EA (2005)* also presents the analytical approach as an alternative approach to joint probability analysis. The analytical approach requires the analysis of records of simultaneous occurrence of different variables. When there is not sufficient data, Monte Carlo simulation can be used to produce simulated joint data, effectively extrapolating the joint probability density to extreme values.

5. Related phenomena

There are uncertainties in flood level prediction relating to fluvial sediment transport. The present practices of flood risk assessment modelling in the UK are not sediment driven, they are pure hydrodynamic modelling. The Water Framework Directive EC 2000/60/EC (*EUR-Lex, 2000*) lists engineering/management activities regulated with respect to sediment management; there is increased awareness that sediment controls to floodwater conveyance are important for flood risk management. The collapse of the three bridges during the 2009 Cumbria flood (*NCE, 2009*) was primarily attributed to sediment transport and *morphodynamical* changes in the river bed. In future climate change scenarios, long-term channel conveyance may change in morphologically active rivers, particularly those flowing into estuaries. This may increase flood risk in some reaches due to *siltation*, alternatively it may decrease elsewhere due to erosion (*Pender et al., 2016*).

Thunderstorms thrive under certain conditions, with two of the most basic elements that cause a thunderstorm to develop being moisture and rapidly rising warm air. Flash flooding can occur as the result of thunderstorms. The UK had heatwaves in 2003, 2006 and 2013, with summer temperatures in 2013 more than 6 °C hotter than average (*EA, 2016a*). Heatwaves increase the likelihood of flash flooding.

The key regulations related to development in relation to fluvial flood risk are presented in this section. However, it should be noted that the regulations listed are by no means exhaustive. Regulations are updated and new regulations are also introduced. It is advisable to apply the most up-to-date regulations.

The Conservation of Habitats and Species Regulations 2017

The regulations came into force on 30th November 2017, and extend to England and Wales (including the adjacent territorial sea) and to a limited extent in Scotland (reserved matters) and Northern Ireland (excepted matters). In Scotland, the Habitats Directive is transposed through a combination of the Habitats Regulations 2010 (in relation to reserved matters) and the Conservation (Natural Habitats, & c.) Regulations 1994. The Conservation (Natural Habitats, etc.) Regulations (Northern Ireland) 1995 (as amended) transpose the Habitats Directive in relation to Northern Ireland. The regulations provide for the designation and protection of 'European sites', the protection of 'European protected species', and the adaptation of planning and other controls for the protection of European sites.

The Environmental Permitting (England and Wales) Regulations 2016

The new regulations came into force on 1st January 2017. Whilst there are no major changes because of the new regulations, they provide a consolidated system of environmental permitting in England and Wales and transpose provisions of fifteen EU Directives which impose obligations requiring delivery through permits or which are capable of being delivered through permits. The new regulations revoke the Environmental Permitting (England and Wales) 2007 (and amendments) as well as the Environmental Permitting (England and Wales) Regulations 2010.

The Environmental Damage Regulations 2015

The regulations oblige those who create environmental damage — whether by water pollution, adversely affecting protected species or sites of special scientific interest (SSSIs), or by land pollution that causes risks to human health — to not only cease the damage, but also to implement a wide variety of remedial measures to restore affected areas.

The Construction (Design and Management) Regulations 2015 (CDM 2015)

The regulations cover the management of health, safety and welfare when carrying out construction projects. CDM 2015 replaced the Construction (Design and Management) Regulations 2007. CDM 2015 aims to improve health and safety in the industry.

Flood and Water Management Act 2010

The Pitt Review looked at lessons learned from the widespread flooding in 2007. Extensive recommendations were made, including recommendations to prevent new buildings in flood risk areas and to increase the resilience of existing buildings in floodplains. The report also brought essential services to the forefront, with many recommendations for Government and infrastructure operators to work together on increasing resilience of those assets. The Government's response to the Pitt Review led to development of the Flood and Water Management Act 2010.

The Flood and Water Management Act (*HM Government, 2010*) aims to provide better, more sustainable management of flood and coastal risks for people, homes and businesses. This gives EA the power to undertake all necessary works for fluvial flooding, coastal flooding and coastal erosion works (Section Part 1 (13) and SCHEDULE 1 Section 30). Local authorities will have powers to undertake fluvial flooding, coastal flooding and coastal erosion works with EA consent (Section Part 1 (13) and SCHEDULE 1 Section 30). Regional Flood Defence Committees (RFDCs) will be replaced with Regional Flood and Coastal Committees (RFCCs). The Act provides EA with emergency power and power of entry (SCHEDULE 1, 12 (1) and 13(1)) if: (a) a person has contravened paragraph 5(1), and (b) the responsible authority thinks the contravention may immediately and materially increase or alter a flood risk or coastal erosion risk.

Flood risks include flooding from all sources; such as heavy rainfall, a river overflowing or its banks being breached, a dam overflowing or being breached, tidal waters, groundwater, or anything else including any combination of factors. But 'flood' does not include: (a) a flood from any part of a sewerage system, unless wholly or partly caused by an increase in the volume of rainwater (including snow and other precipitation) entering or otherwise affecting the system; (b) a flood caused by a burst water main (within the meaning given by section 219 of the Water Industry Act 1991).

The Act has amended some of the Sections within the Water Industry Act 1991, Environment Act 1995, Local Government Act 2000, Building Act 1984, New Roads and Street Works Act 1991, The Reservoirs Act 1975. Readers are advised to consult *HM Government (2010)* for further details for any specific requirement.

The Flood Risk Regulations 2009

These regulations require the Assessment and Management of Flood Risk.

Floods Directive

The European Directive on the Assessment and Management of Flood Risks, known as the Floods Directive, came into force in November 2007. The Directive requires Member States to assess whether watercourses and coastal waters are at risk from flooding, to map the flood extent and the assets and humans at risk in these areas, and to take adequate and coordinated measures to reduce this flood risk.

The Floods Directive will be implemented in coordination with the Water Framework Directive. The requirements of the Floods Directive are implemented in England and Wales through the Flood Risk Regulations 2009 and the Flood Risk (Cross Border Areas) Regulations 2010. These required the production of preliminary assessment maps and reports (by December 2011), the identification of significant flood risk areas, and for these areas, the development of flood hazard and flood risk maps (by December 2013) and flood risk management plans (by December 2015). However, we emphasise that this is an ongoing programme with future obligations for Member States to keep these plans current.

Environmental Act 1995

The Act provided for the formation of the Environment Agency in England and Wales, and the Scottish Environment Protection Agency in Scotland.

Water Resources Act 1991

The Act gives EA permissive powers to carry out flood risk management work (Section 165 within subsection (1D) (a) to (f) and (g) or (h)). Flood risk is defined as flooding from main rivers; also including lakes, ponds and other water areas which flow into main rivers, and the sea. Section 166 (Flood Warning) empowers EA to provide and operate flood warning systems.

Land Drainage Act 1991

The Act gives powers to local authorities to carry out works on watercourses which are not designated as 'main rivers' and are not within the area of an Internal Drainage Board.

The Civil Contingencies Act 2004

Requires Category 2 responders (utilities, telecoms) to have a business continuity plan in place. Furthermore, the Strategic Framework and Policy Statement 2010 outlines that the Critical Infrastructure Resilience Programme will seek to improve business continuity through best practice (BS 25999).

Town and Country Planning Act 1990

Section 57 of the Town and Country Planning Act 1990 creates a general requirement that development of land should not be carried out except with planning permission. Section 55 defines 'development' as the carrying out of building, engineering, mining or other operations in, on, over or under land, or the making of any material change in the use of any buildings or other land.

The Food and Environment Protection Act 1985 — FEPA licences

This covers the issue of licences for dredging and the disposal of material at sea.

Harbours Act 1964

Harbours in general sit outside of the lengths of coast covered under the Coast Protection Act 1949. These areas are covered under the Harbours Act 1964.

National Planning Policy Framework (NPPF)

The development of buildings in flood risk areas is controlled by the National Planning Policy Framework (March 2012) in England, Planning Policy Wales, Scottish Planning Policy SPP7 and Planning Policy Statement PPS15 in Northern Ireland.

The National Planning Policy Framework sets out government's planning policies for England and how these are expected to be applied. The framework acts as guidance for local planning authorities and decision-makers, both in drawing up plans and making decisions about planning applications. The planning practice guidance to support the framework is published online and regularly updated ([MHCLG, 2018](#)). Within English policy for example, development is steered to low flood risk areas and development within higher flood risk areas requires site-specific flood risk assessments. Site-specific flood risk assessments are an appropriate tool to future-proof the resilience of buildings. Hydraulic models considering climate change and sea level rise are required to provide site-specific evidence. Some guidance on flood risk is provided in BS 8533:2017.

Local planning authorities should adopt proactive strategies to mitigate and adapt to climate change ([HM Government, 2008](#)), taking full account of flood risk, coastal change and water supply and demand considerations ([DCLG, 2012](#)). Local Plans should take account of climate change over the longer term, including factors such as flood risk, coastal change, water supply and changes to biodiversity and landscape. New development should be planned to avoid increased vulnerability to the range of impacts arising from climate change. When new

development is brought forward in areas which are vulnerable, care should be taken to ensure that risks can be managed through suitable adaptation measures, including through the planning of green infrastructure (*DCLG, 2012*). Section 100 states that inappropriate development in areas at risk of flooding should be avoided by directing development away from areas at highest risk, but where development is necessary, making it safe without increasing flood risk elsewhere. Local Plans should be supported by strategic flood risk assessment and develop policies to manage flood risk from all sources, taking account of advice from EA and other relevant flood risk management bodies. Local Plans should apply a sequential, risk-based approach to the location of development to avoid where possible flood risk to people and property and manage any residual risk, taking account of the impacts of climate change, by applying the *Sequential Test*; and if necessary, applying the Exception Test. Each of the tests are specific flood risk assessment methodology; detailed scopes of the tests are provided between Article 100 and 104 (*DCLG, 2012*). Please also see *Table 3* for the specific conditions where Exception Tests are required for planning permission.

7. Emerging trends

Major floods often trigger policy changes due to public outrage and political pressure, e.g. the Pitt Review following the 2007 floods in the UK. Subsequently in April 2010, the Flood and Water Management Act became law. The Act, which applies to England and Wales, aims to create a simpler and more effective means of managing the risk of flood and coastal erosion. The Act also aims to help improve the sustainability of our water resources and protect against potential droughts. Through adaptive strategies, reactive response should be replaced by proactive behaviour and strategies, which need to be developed over time. Adaptive management is a systematic process for improving management policies and practices by learning from outcomes of implemented management strategies. Adaptive management regimes are defined as a range of technologies, institutions, environmental factors and paradigms that together form the basis of a functioning flood risk management system.

Authorities for flood risk management in the UK have been pioneering this approach. EA has published its second adaptation plan for climate change (EA, 2016a); the first was published in 2011 under The Climate Change Act 2008.

Despite having the Thames Tidal Barrier, Thames Estuary 2100 strategy pioneers an 'adaptation pathways' approach to account for climate uncertainty and ensure that decisions to upgrade or replace assets are made at the right time. In Oxford, a flood alleviation scheme will adapt incrementally to increased risk of flooding in the future. The scheme's key components are: building new flood wall, lowering of floodplain, making space for water, and creation of 5 hectares of new wildlife habitat. The Strategy Appraisal Report recommended options to split into immediate (0 to 9 yrs; i.e. from the current time to 9 years in the future), medium (30 to 70 yrs) and long-term (70 to 90 yrs) solutions to tackle flood risk. This approach will ensure future solutions are easily implemented as and when required, and can be regularly reviewed. River Basin Plans include climate change assessments for each management catchment in England. These use local judgement to consider which aspects of climate change are likely to pose a long-term risk for the catchment. Measures have been included in the plans to address the impacts from climate change that are flexible, or increase resilience to severe weather and a changing climate.

Sustainable drainage is the practice of controlling surface water run-off as close to its origin as possible, before it enters a watercourse or the ground. SUDS at The Dings, Bristol help to avoid aggravating existing or creating new flooding problems, either on the site or elsewhere, and protect water quality and resources. In England, the use of SUDS was recommended by the Pitt Review and since April 2015 are a requirement for all new developments of ten or more

7. Emerging trends

properties at risk of flooding under amended planning guidance ([DCLG, 2014](#)). However, the recent uptake of SUDS has been insufficient to mitigate increasing flood risk from surface run-off and the risk of sewer overload ([Defra, 2011](#)).

Based on the risk assessment, EA's priority adaptation actions ensure that all its new major plans and strategies are climate resilient by 2020. A detailed action plan by EA is available at [EA \(2016a\)](#).

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Acoustic Doppler Current Profiler (ADCP)

An instrument that uses acoustic signalling to measure water velocity, direction, depth and boat speed when undertaking a discrete discharge measurement (gauging).

Base flow index (BFI)

A measure of catchment responsiveness derived using the 29-class Hydrology Of Soil Types.

Critical storm duration

The critical storm duration within an hour is the one that gives the largest flow (or, for some design studies, the highest water level or greatest storage pond volume) at the site of interest.

Design flood

A flood of a given flow used in fluvial designs (e.g. height of an embankment or size of a bridge or culvert) is known as a design flood; it is usual to express how often floods could be larger than the design flood, which is known as flood frequency, often expressed as a return period. Flood frequency can alternatively be expressed in terms of an annual exceedance probability, which is the inverse of the return period.

Design hydrograph shape

The shape of a full hydrograph for a design flood when flood volumes and/or critical storm duration are important, for example in the design of flood storage areas or reservoir spillways.

Exception Test

A method of managing flood risk while still allowing necessary development to occur; this test is only appropriate for use when there are large areas in flood zones 2 and 3, where the Sequential Test alone cannot deliver acceptable sites, but where some continuing development is necessary for wider sustainable development reasons.

Flood frequency analysis

The relationship between flow and return period is known as the flood frequency curve. Common approaches to estimating flood frequency curves include: a) statistical analysis of flood peak data (single site or pooled analysis), b) the design event approach, which uses a rainfall-runoff model.

Gauging reach

A length of river surrounding a flow and/or water level gauging station; it is a characteristic reach length of the river, within which any disturbance on the bed, flow resistance or other human intervention can influence the existing relationship between discharge and water level.

Glacial isostatic adjustment

The ongoing movement of land that was once burdened by ice-age glaciers.

Hindcast modelling

A mathematical model adjusted with known inputs for past events to provide a model where the output matches known past observations.

Limbs of the hydrograph

The rising limb of the flood hydrograph is when a flood increases to the peak condition and the falling limb is when a flood decreases from the peak condition.

Morphodynamics

Refers to the interaction and adjustment of the river bed topography, fluid hydrodynamic processes, river bed morphologies and motion of sediment. Hydrodynamic processes include primary currents, secondary currents, bends and braids.

Ordnance datum

The mean sea level as defined by the Ordnance Survey; mean sea level is calculated from observations taken at Newlyn, Cornwall, and this is used as the official basis for height calculation on British maps.

Rating equation

An equation defining the relationship between discharge and water level; water level is independent variable, discharge is dependent variable.

Sequential Test

A flood risk assessment approach for ensuring new development in areas with the lowest probability of flooding, i.e. in flood zone 1. A sequential approach should be used in areas known to be at risk from any form of flooding.

Siltation

Deposition of sediment (e.g. sand, silt and clay) on a river bed.

Stage-discharge relationship

A mathematical relationship between water level and discharge based on observed data between water level and discharge; water level is the independent variable and discharge is the dependent variable.

Stilling well

A chamber, usually a tower of one or more steel or concrete pipe sections, connected to the water body by a much smaller diameter inlet pipe. The intake dampens the effect of waves and surge in the main flow so there is a still water surface in the chamber on which a float can ride.

Tidal locking period

A length of time when drainage from river flow is impeded (fully locked through a flapped sluice) due to rising tides in coasts and estuaries.

Velocity traverse

A line or path of travel in a river or in any water body across which velocity is measured at a series of fixed depths.

Velocity-discharge equation

A mathematical relationship between water level and discharge based on observed data between water level and discharge; velocity is the independent variable and discharge is the dependent variable.

Walkover survey

A reconnaissance of watercourses and floodplains to validate cross-sectional geometry, embankment condition, structure condition and various parameters, including roughness values used in hydraulic modelling.

ABI	The Association of British Insurers
ADCP	Acoustic Doppler Current Profiler
AEP	Annual exceedance probability
AMAX	Annual maximum
AOD	Above ordnance datum
BFI	Base flow index
CEH	Centre for Ecology and Hydrology
CDM	Construction Design and Management
CO ₂	Carbon dioxide
Defra	Department for Environment, Food and Rural Affairs
Dfi	Department for Infrastructure
EA	Environment Agency
emf	Electromotive force
FEH	<i>Flood Estimation Handbook</i>
FEPA	The Food and Environment Protection Act 1985
FRA	Flood risk assessment
FWMA	Flood and Water Management Act 2010
IDB	Internal Drainage Board
LIDAR	Light Detection and Ranging
LRF	Local Resilience Forum
mAOD	Metres above ordnance datum
NFF	National Flood Forum
NFFS	National Flood Forecasting System
NRFA	National River Flow Archive
NRW	Natural Resources Wales
NPPF	National Planning Policy Framework
POT	Peak over threshold
PPS15	Planning Policy Statement 15 for Northern Ireland
QMED	Mean annual maximum flood
ReFH	Revitalised flood hydrograph
ReFH2	Revitalised flood hydrograph 2.2
RFCC	Regional Flood and Coastal Committee
RFDC	Regional Flood Defence Committee
RSPCA	Royal Society for the Prevention of Cruelty to Animals
SEPA	Scottish Environment Protection Agency

Abbreviations

SFRA	Strategic flood risk assessment
SPP7	Scottish Planning Policy 7
SSSI	Sites of special scientific interest
SUDS	Sustainable Urban Drainage Systems



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