HM Government

National Flood Resilience Review

September 2016

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Ministerial foreword

Last winter we saw the devastating impact of record rainfall and extreme flood events across wide areas of the country. The Government took swift action to provide direct support to those affected and make sure that communities could get back on their feet as soon as possible. We also set up this review, to assess how the country can be better protected from future flooding and extreme weather events.

Although the events we saw last winter are rare, we must recognise that extreme weather and flooding events do happen and that we need to be well equipped to respond. The stress testing of our modelling and flood risk maps carried out as part of this review has provided reassurance that we know the areas of the country which are at risk of flooding. Our next task is to make sure we improve how we let people know where they could be at risk and encourage them to take action.

Last winter we saw how disruptive flooding can be for homes and businesses, as well as for key local infrastructure. As part of this review we have secured commitments from the water and telecommunications industries to make their infrastructure more resilient. In addition, this year the Environment Agency will be able to deploy four times more temporary barriers to protect our communities than last winter.

As these plans are completed, we are confident that our communities will be better protected. They can have confidence that the essential services they rely on will be even more resilient to the kind of extreme weather we saw last December.

Rt Hon Ben Gummer

Minister for the Cabinet Office and Paymaster General

Rt Hon Andrea Leadsom

Secretary of State for Department of Environment, Food and Rural Affairs

Executive Summary

Over recent years the UK has been hit by a number of extreme flood events, in Somerset, Cumbria, Yorkshire and elsewhere. Record rainfall and river levels have led to widespread floods severely affecting cities and communities, bringing misery to the lives of thousands and seriously disrupting businesses and livelihoods. Communities have lost power, water and telecoms during the flooding, and have then had to deal with the lengthy process of recovery. We need to recognise that there is a non-negligible chance that we will see further events of a similar, or maybe even greater, scale over the next decade.

The Government has already taken action to improve our protection from and resilience to flooding. We are spending £2.3 billion over the next six years from 2015-2021 to strengthen the country's flood and coastal defences, better protecting 300,000 homes. We are prepared to respond swiftly and effectively to events as and when they happen, and to support communities in the recovery phase.

Overseen by a Ministerial Recovery Group, we have put in place a recovery package for homes, businesses and farms in those areas of Northern England affected by last winter's floods to help get communities back on their feet and to strengthen defences in places such as Leeds, York, the Calder Valley and Cumbria. Flood Re has now been established to ensure that households can continue to obtain flood insurance at affordable cost.

But, in the light of the severity of recent events, and the risk that these or similar events will occur again, it is appropriate to reconsider our approaches to assessing flood risk, to reducing the likelihood of flooding, and to making our nation as resilient as possible to flooding.

One important area for improvement is better management of rainfall in the natural environment. Water is a precious resource that at many times and in many places is in increasingly short supply. There are obvious benefits to managing water in a way that reduces both flood risk and water stress, and that delivers wider environmental benefits, by slowing the flow of water from the land into our rivers and smoothing the flow of the rivers themselves.

The Government's future 25 year plan for the environment will aim to achieve these effects by managing whole river catchments intelligently, developing sophisticated modelling to work out what can be done in each part of the catchment to minimise flooding. A 'pioneer' pilot project in Cumbria will test and demonstrate the power of this approach across the different river catchments there.

The reduction in current flood risk that could be achieved through the future 25 year plan for the environment will complement the work on long term risks caused by climate change, which the Adaptation Sub-Committee of the Climate Change Committee has been considering. Integrated catchment management will not, however, deliver flood risk reductions overnight.

The magnitude of events in recent years means that it is important to reassure ourselves that we understand the scale of risk that the country is currently facing from river and coastal flooding and to take more immediate steps to improve the resilience of the country to such flooding. We set up the National Flood Resilience Review to look at these questions, chaired by the Chancellor of the Duchy of Lancaster and overseen by a cross-government National Flood Resilience Review Group (see Annex 1 for the group's membership).

This report explains how we have been conducting the review and sets out our findings.

Our first programme of work has been to improve our understanding of the fluvial and coastal flood risk in England. As a result of recent events, we have become clear that describing flood risk in traditional terms such as a '1% chance of flooding' or '1 in a 100 year risk' is not helpful because it is so likely to be misinterpreted. These terms describe the flood risk at a specific location. They do not describe the chance of one of these events happening somewhere in the country or region in a given year – which is much greater. Nor do they describe the impact on people and on the economy when events that have previously been regarded as very unlikely do sometimes happen (as this winter's rain showed).

In order to test the resilience of the nation's infrastructure to flooding from rivers and seas, we began by asking the Met Office to develop new plausible extreme rainfall scenarios. The Met Office based these on recently recorded extreme events, and added substantial but plausible additional uplifts, of between 20% and 30% for each of the six standard climatological regions of England and Wales, determined from modelling and analysis of monthly rainfall records for these regions. The Met Office has a 90% confidence that monthly rainfall in any of the six regions will not exceed these modelled levels at any time over the next ten years.

When we used a selection of the Environment Agency's detailed models to predict the flooding associated with these extreme rainfall scenarios, we discovered (unsurprisingly) that it, too, was worse than anything we have seen to date. Crucially, however, our models suggest that even this plausible extreme flooding remains overwhelmingly within the areas and depths defined by the current Environment Agency Extreme Flood Outlines. We have also looked at scenarios involving extreme tidal surges – and these too produce flooding which is within the Extreme Flood Outlines, even when the tidal surges are combined with extreme rainfall scenarios.

This gives us confidence that the Environment Agency Extreme Flood Outlines constitute a good representation of plausible severe fluvial and tidal flooding.

The second part of our work has involved using these Extreme Flood Outlines to test the resilience of key local infrastructure assets (such as energy, water, health, transport and telecommunications) on which services to our communities and businesses depend. We have completed preliminary assessment of the resilience of each piece of key local infrastructure around the country on which substantial numbers of people depend.

The third part of our work has focused on making this key infrastructure resilient to the level of flooding portrayed in the Extreme Flood Outlines. We have also examined the potential for industry to buy and use temporary defences to defend a significant proportion of this key local infrastructure rapidly and effectively against extreme flood conditions before it is made as resilient as is feasible.

Working with the relevant utilities, regulators and government departments, we have agreed that, by Christmas 2016, the water and telecoms sectors will develop and implement plans for temporary improvements to resilience in line with those already available in the electricity supply industry. These plans will ensure that the utilities obtain stock-piles of temporary defences in advance, and have ready site-specific plans for deploying them where appropriate and possible, if and when serious floods occur this coming winter.

In addition, we have agreed that (where not in place already) the water, telecoms and electricity utilities will develop over the remainder of this year, and will thereafter implement, longer term plans for permanently improving the resilience of service provision to significant local communities from the flooding defined by the Environment Agency’s Extreme Flood Outlines. This could be delivered by increasing interconnectivity to enable service provision to be rerouted in the event of asset loss, or by the installation of permanent defences at significant local infrastructure asset sites, or (in cases where permanent defences are not cost-effective) through other measures where this is feasible.

While we are monitoring the improvements in resilience and the implementation of the temporary improvement plans for key local infrastructure, we are also using the Extreme Flood Outlines map to test the resilience of our Core Cities and other communities, in order to ensure that decisions about the next (post-2021) round of investment in flood defences are taken on the basis of the best possible evidence. We are working with Sheffield to develop and pilot a new model of self-financing investment which could bring together flood defence, aesthetic improvement and urban development to make our cities more beautiful, more prosperous and more resilient. We envisage that this work will continue in 2017. If it yields the benefits for which we hope, we will then begin work with other cities.

Finally, in parallel with this review and the ongoing development of the 25 year plan for the environment, we continue to learn lessons on emergency response and recovery. We set out in this report a series of actions that we will be taking to improve flood incident response, to conduct a long-term rolling programme of improvements in our modelling and to improve our communication of flood risk. As part of their review of the winter 2015 flooding, the Department for Communities and Local Government is re-evaluating the package of support made available to communities and businesses, so that government can be ready to respond swiftly if necessary.

At Budget 2016, the Chancellor of the Exchequer announced a £700 million increase in flood defence and resilience spending and signaled that he would use part of this funding to respond to this review. The findings published today commit an investment of £12.5 million to increase the Environment Agency's stock of temporary flood defences and other incident response equipment. The review's work is ongoing and additional funding support will be considered as further findings emerge. In 2017, we will also be considering issues relating to surface water which, although an important source of flooding, has causes and mitigations different from those encountered in the fluvial and coastal flooding with which this report is concerned.

The review has benefitted greatly from the responses to our Call for Evidence, and from the challenge and assurance provided by the review's Scientific Advisory Group. We would like to thank all those who have contributed so generously of their time and expertise.

1 Generating extreme flood scenarios

The succession of severe floods in recent years has given rise to a perception that the country is facing an increase in flood risk, and that new approaches may be needed to strengthen the nation's resilience against flooding.

The review therefore began with a reassessment of the current river and sea flood risk to test the accuracy of our understanding of that risk. Until now, the Environment Agency assessments of fluvial flood risk have been primarily based on historical records of river levels and flows during previous floods rather than on Met Office modelling of extreme rainfall.

Thanks to the advances made in weather and climate modelling in recent years, this review has been able to use plausible extreme rainfall scenarios from the Met Office as a basis for more sophisticated analysis of the risk of coastal and fluvial flooding over the next ten years. For the first time, we have linked Met Office projections of extreme rainfall with Environment Agency modelling of the flooding that these rainfall scenarios might cause, through a set of case studies in locations around the country. We also developed tidal surge scenarios to extend this approach to coastal flooding.

In all the case studies, the flooding predicted lay overwhelmingly within the Environment Agency's existing published Extreme Flood Outlines which define the areas of England at risk from river or sea flooding. We have therefore concluded that these currently remain a robust planning tool for fluvial and tidal flood risk.

In this chapter we set out: the approach we have taken to modelling the three components (extreme rainfall, tidal surge, and river flow/flood extent); the results of bringing these together in a set of 'stress test' case studies; and the assurance and advice provided by the review's Scientific Advisory Group, including on communicating risk and the uncertainties in our estimations.

1.1 Extreme rainfall scenarios

The Met Office was asked to develop extreme rainfall scenarios that are scientifically valid and plausible. This is a challenging task given the high natural variability of UK weather and the underlying dynamics of our climate, and has been made possible only by recent advances in global climate modelling.

The approach taken by the Met Office has been to base the scenarios on recent extreme rainfall events (to capture any current underlying climate trends) and add a plausible uplift (to account for natural variability, which is expected to be the main driver of extreme rainfall over the next ten years). The challenge then becomes estimating the scale of a plausible uplift – estimating how much worse the next record breaking rainfall event is likely to be.

Because the UK weather is so variable, we cannot do this with confidence simply using the historical records – they are not long enough for us to be sure that they contain chance examples of very unlikely extreme events (an assessment borne out by the fact that we regularly see record-breaking events).

Fortunately, the Met Office's high resolution global climate model is now good enough to be able to generate 'virtual' weather simulations that are so realistic that they can pass for actual, observed, weather patterns (see Annex 2 for more details). The Met Office have used their model to generate simulations of 11,000 months of weather – a much larger set than the observed dataset, so containing more very unlikely events. They have searched this dataset for rainfall events that are worse than any ever recorded, but which are still plausible for our current climate. With a dataset of this size and quality, the Met Office has been able to identify plausible events down to a 1% annual likelihood threshold. (The dataset does contain a few even lower likelihood events, but there are not enough of them to be sufficiently statistically significant to assess their plausibility: an even larger dataset would be required to probe lower probabilities.)

Based on this analysis, the Met Office have concluded that winter monthly rainfall totals could plausibly be 20% higher than recent past extremes in some parts of the country and up to 30% higher than recent past extremes in other parts. These results from the Met Office have been corroborated by results from European Centre for Medium-Range Weather Forecasts. They used a similar methodology, but applied it to their independent modelled estimates of the maximum possible daily rainfall, based on UK weather patterns over the last 20 years.

Rainfall is heavily influenced by the geography of the land. The west of the country receives ten times more rain than the east because the prevailing UK weather pattern is of wet air moving in from the west, which falls as rain as it is forced up over western hills. This means that plausible extreme rainfalls will be different across the country (typically wetter on the west) so the Met Office determined the appropriate uplift for each of the six climate regions of England and Wales. The percentage uplifts for each region were then applied to detailed kilometre-scale simulations of recent extreme rainfall events to generate detailed extreme rainfall scenarios for input to the Environment Agency's catchment models.

There are of course many causes of uncertainty in these estimates – and there is always the possibility that next year will see a supremely unlikely event. Nevertheless, the Met Office are 90% confident that, over the next ten years, we will not see levels of winter monthly rainfall in any of the six climate regions of England or Wales that are greater than the amounts they have modelled.

Figure 1: Met Office climate regions.

Although the Met Office climate modelling is not yet sufficiently fine-grained to provide an equal level of statistical confidence about the maximum monthly rainfall in sub-regions, such as Cumbria, the Met Office takes the view, based on atmospheric behaviour, UK geography and observational records, that the same broad conclusions are likely to apply at this sub-regional scale.

Annex 2 provides more detail on generation of these extreme rainfall scenarios and the evidence underpinning this level of confidence.

1.2 Extreme tidal scenarios

Extreme tidal surges happen when a high astronomical tide coincides with a storm tidal surge driven by factors such as wind and atmospheric pressure. Since the nature and scale of tides also depend strongly on the location, the Environment Agency and Met Office generated plausible extreme tidal scenarios for the specific case studies locations, rather than broad regions. In consultation with the Met Office and the National Oceanographic Centre, it was decided that a plausible extreme scenario would be to combine a recent storm surge with the highest recorded astronomical tide.

The Environment Agency therefore first analysed the worst recent recorded tidal surge in the test case locations, to separate the storm surge element from the underlying astronomical tide. They then combined this ‘residual’ storm surge with the highest astronomical tide recorded at that location to provide an extreme, but plausible, tidal scenario.

1.3 Modelling extreme floods and river flows

The third component of our stress tests consisted of modelling the fluvial and tidal flooding that results from extreme rainfall scenarios and extreme tidal surges. All models are, to a greater or lesser extent, simplified representations of reality, focusing on the aspects that are of particular interest in particular circumstances – so we often need different models for different purposes. The Environment Agency has a range of different models to predict different types of flooding and the effect of flood defences.

Since the review set out to stress test our understanding of the inherent fluvial and tidal flood risk (in the absence, or failure, of any flood defences), we used the Environment Agency models that underpin the maps of the Extreme Flood Outlines, which give a broad view of the possible flood extent from rivers and sea in any given location, assuming that there are no defences in place.

1.3.1 Environment Agency Extreme Flood Outlines

In order to map areas at risk from flooding from rivers and sea, the EA have developed around 2000 ‘local detailed models’ ranging in size from a few kilometres of a river or coast up to a model for a whole catchment.

All local detailed models share broadly the same type of input data and basic physical principles but are built up (and updated) from detailed observations. For example, a model focusing on a particular river catchment will combine three main components: survey information on the shape of the river channel and surrounding landscape; a hydrological model to estimate the influx of water; and a hydraulic model that calculates where the inflowing water goes, enabling flood extent and depth to be mapped.

These local detailed models provide the most fine-grained modelling available for potential flooding in particular locations. Outputs from these models are combined with national level broad scale modelling, to give a national map of areas at risk from flooding from rivers and sea.

The outer boundary of an area mapped as having a 0.1% chance of fluvial or tidal flooding in any year at any location is known as the Extreme Flood Outline. (The risk of surface water flooding from heavy localised rainfall, which is not the focus of this review, is covered in separate maps.) Around 12% of the land area in England lies within the Extreme Flood Outlines. Further detail on the Environment Agency Extreme Flood Outlines and the underpinning modelling is given in Annex 3.

1.3.2 Stress tests results

The review has provided a stress test of the current Extreme Flood Outlines by using selected Environment Agency local detailed models to estimate the floods that would be caused by the extreme rainfall and tidal scenarios described in sections 1.1 and 1.2, to see whether these floods would extend beyond the areas shown in the Extreme Flood Outlines map. In modelling the predicted floods, we took a ‘worst case’ approach to other parameters (such as prior soil saturation).

We selected four inland flood risk areas (Carlisle, Calder Valley, Oxford and Exeter) and two coastal areas (Great Yarmouth, tidal Thames in London) for the case studies. These areas were selected on the basis of the quality and availability of data (in particular recent severe flooding data) and models, and because they are representative of the differing hydrology across the country.

The Met Office high resolution rainfall scenarios modelled the rain falling in each 2km square every fifteen minutes. This input sequence was used to generate modelled river flows and the resulting flood extents.

The modelled results were compared with the Extreme Flood Outlines map. The flood extents and depth lay overwhelmingly within, or very close to, the Extreme Flood Outlines. In drawing conclusions from these results it is important be aware of the inherent uncertainties in predictions around extreme rainfall and flood conditions, and in the boundaries defined by the Extreme Flood Outlines. Nevertheless, the results from these case studies show there is a credible scientific basis for the robustness of the Extreme Flood Outlines now and over the next decade and for their current use as a planning tool for assessing flood risk, including in our assessment of the defences required to give us a high level of confidence that key local infrastructure will be resilient over at least the next ten years.

Further detail on the stress testing of the Extreme Flood Outlines map is provided in Annex 4.

1.4 Scientific advice

Validation of science in the National Flood Resilience Review

It is important that scientific evidence and analysis which informs policy stands up to challenges of credibility, reliability and objectivity. Through a well-established system of peer review, the academic community ensures that new research is scrutinised by experts in the field before it is more widely discussed and accepted. A Scientific Advisory Group made up of respected individuals from universities and industry provided this function for the review. It examined the meteorological and hydrological evidence underpinning the review and ensured that the complexities and limitations of this evidence were identified and understood. The group also provided advice on the principles of communicating flood risk and on how flood modelling might be improved.

1.4.1 Membership of the Scientific Advisory Group

The group was chaired by Sir Mark Walport, Government Chief Scientific Adviser and the Deputy Chair was Professor Charles Godfray, who leads the Science Advisory Council to the Department for Environment, Food and Rural Affairs. It comprised a number of independent experts across the natural and social sciences who brought a breadth of knowledge and perspective spanning many aspects of meteorology, hydrology and flood risk management. The Met Office and the Environment Agency attended meetings of the advisory group and took its advice forward on an iterative basis as they conducted their work on the review. Full details of the group's membership can be found in Annex 5.

1.4.2 Approach taken by the Scientific Advisory Group

The group's focus was to challenge and assure the scientific methods and evidence that underpinned the review's assessment of the river and sea flood risk facing England. It examined the Met Office's assessment of what extremes of rainfall accumulation are meteorologically plausible but still unlikely to be exceeded over the next 10 years. In support of this examination, the group asked the Met Office to extend its analysis with further statistical evidence from the observational record. The European Centre for Medium-Range Weather Forecasts was commissioned to provide its own analysis of plausible extreme rainfall in the UK with comparable findings to those of the Met Office. The group scrutinised the approach taken by the Environment Agency to model the flood extents associated with these rainfall scenarios (where applicable in combination with peak high tides) using case study areas that represented specific flood characteristics. It reviewed the finding that these modelled floods fall largely within the current Extreme Flood Outlines and recommended additional testing to ensure the robustness of this conclusion.

In further work, the group assessed whether there was evidence that climate change may have a role in recent extreme rainfall and flooding. The group also commissioned work to assess the likelihood of extreme flood events happening anywhere in the country over particular time periods, using statistical analysis of the observed record of river flows. And finally in another work strand, the group brought a wide range of expertise together to consider the challenge of communicating flood risk effectively.

1.4.3 Advice from the Scientific Advisory Group

The group's key conclusions were that:

1. the Environment Agency's Extreme Flood Outlines are a reliable way to identify areas at risk from extreme river and coastal flooding over the ten year time horizon considered by this review; and
2. while the probability of an extreme river flow that could result in a severe flood at any given location is very small, such flows are not unusual when considering the whole country.

How this advice was reached

The group considered several lines of evidence in drawing its conclusions:

1. the Extreme Flood Outlines were originally developed by the Environment Agency and its partners using statistical analysis of measured floods and computer models of flood flows. Those computer models have been well-validated by comparison with measurements of flood depth and extent;
2. the Met Office used a global climate model that has been shown to simulate realistically large scale weather patterns, and a high resolution UK weather model shown to simulate realistically local weather and rainfall patterns. These were used to produce extreme rainfall scenarios that lie outside recent observations but are meteorologically plausible. Computer simulations by the European Centre for Medium-Range Weather Forecasts showed a similar range of rainfall over regions of the UK. The Environment Agency then used its well-calibrated flood forecasting models to simulate the extent of flooding that would occur during the simulated extreme rainfall; and
3. the river flow records at 916 sites across England and Wales were analysed statistically. This used a method developed at Lancaster University and JBA Consulting, through the Environment Agency's Research and Development

programme. It has been published in the peer reviewed literature and is well validated against observations.

The group decided that the rainfall scenarios were a sufficiently extreme test for the ten year scope of the review. Based on the additional work undertaken, climate change over this same period was not identified as a factor, with natural variability dominating extreme rainfall. The group thought that this innovative technique should be developed further given its potential for exploring a fuller range of events that have not yet been experienced across the country but remain possible.

The group noted that the extent of flooding is impossible to forecast precisely and the possibility of floods that extend beyond the Extreme Flood Outlines could not be excluded. The variable nature of regional and local weather and rainfall, combined with the varying terrain and complexity of catchments, meant that the results could only be indicative and could not describe all settings. It was also noted that catchments vary in their capacity to absorb extreme rainfall, influencing the potential for exceeding the Extreme Flood Outlines. Nonetheless, the group considered the Extreme Flood Outlines to have passed a reasonable stress test for the review. The group noted that the review considered flooding from rivers and sea only: the group believes that surface water and groundwater flood risk should also be assessed as part of subsequent work.

The statistical analysis of observed river flows assumes that the probability of flooding has not changed significantly over time, for example due to climate or land use change or due to decadal-scale climatic variations. It involves extrapolating beyond the range of these observations based on well-established statistical theory that is subject to uncertainty, though an assessment of this was not possible in the time available and is recommended.

The group noted that there was scope to improve the UK's competency in fully integrated modelling from weather and rainfall scenarios through to likely flood extents, depths and impacts at the local and national scale. The group also noted that assessment of flood risk is dependent on observed records of river flows which typically go back only 30 to 40 years (although pooling of data from similar locations means good statistical estimates of the likelihood of high river flows can be made). Therefore there remains some uncertainty in taking a long-term view. The group recommended that statistical and modelling methods to quantify and reduce this uncertainty, and allow for trends in the data, should be explored in subsequent work, and that the option of adding other, novel sources of data such as from the historical or prehistorical record should also be considered.

The Scientific Advisory Group also provided advice on communicating flood risk (details in Annex 6) and on longer-term options on modelling extreme flooding (details in Annex 7).

2 Identifying key local infrastructure at risk

2.1 Why focus on infrastructure?

Our economy and society depend on a secure supply of services such as electricity, telecommunications, water, healthcare and transport. In the UK, many of these essential services are delivered by the private sector (with the exception of healthcare), within regulatory frameworks set out by Government These frameworks specify the responsibilities of private sector operators to deliver a reliable and resilient service.

Government, sector regulators and industries have worked together over many years to ensure security of supply by improving the resilience of these services to a range of disruptive risks. Infrastructure sectors employ a wide range of measures to strengthen resilience including: enhancing physical protection of assets; relocating critical equipment on sites; increasing interconnectivity so that service provision is no longer dependent on a single asset; and deploying mobile back-up equipment. The choice in any particular case is determined by a number of factors including risk, benefits, economic and commercial considerations.

To date, attention has been focused on those sites within our national infrastructure that are most vital to the provision of services to the nation. This 'Critical National Infrastructure'[1] (CNI) is what underpins the essential services on which the UK relies, the loss or compromise of which would have the greatest impact on society and the nation. As a result of many years of working with infrastructure operators across the thirteen CNI sectors, the nation's CNI is largely protected against a wide range of hazards and threats, including flooding.

Although it is clearly right to focus first on ensuring the resilience of the most critical infrastructure assets, the lives of communities can still be heavily impacted by the loss of other infrastructure assets. The impact of loss of local services was seen most recently in the floods of last winter, adding to the misery of being flooded and to the challenge of recovery. This review has therefore focused on the locally significant infrastructure on which the lives and livelihoods of communities depend, and has considered individual assets sector-by-sector.

1 http://www.cpni.gov.uk/about/cni/

Working closely at a national level with infrastructure operators (many of whom have worked closely with local responders over recent years to improve understanding of local impacts of loss of service), we have identified key local infrastructure assets at risk from flooding (those lying within the Extreme Flood Outlines) and assessed their resilience against flooding from rivers and the sea. As the work of the review continues through 2016 and 2017, we will consider further the interdependencies between sectors.

2.2 Key local infrastructure at risk in extreme flood scenarios

The immediate impact on local communities of losing certain services (such as electricity and hospitals) is particularly acute.

For some of the services where the impact is most serious, in-depth studies of resilience have been, or are being, conducted. Most notably, in 2014 the Department for Transport commissioned Richard Brown, former Chair of Eurostar, to review the resilience of the transport network in England to extreme weather[2]. The then-Government endorsed Mr Brown's recommendations, and organisations across the transport sector have been taking action to improve their resilience. For example:

- Network Rail has developed route-based weather resilience and climate change adaptation plans[3], and is planning to spend £900 million between 2014 and 2019 to improve the rail network's resilience;
- Highways England plans to invest £78 million over the next five years as part of its Flood Risk Management Plan to reduce the risk of flooding on major roads, and is investing a further £300 million through an environment fund as part of its Road Investment Strategy;
- Gatwick Airport has invested £20 million in flood resilience measures but following flood-related disruption in December 2013, the airport commissioned an independent review of its vulnerability to flooding[4] and as a result is investing a further £10 million over the next 2 years; and
- the Department for Transport has promoted closer working between ports and Local Resilience Forums to improve overall awareness of, and preparation for, severe flooding. Port resilience groups are being set up along the East Coast

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2 https://www.gov.uk/government/groups/review-of-the-resilience-of-the-transport-network-to-extreme-weather-events-expert-panel

3 http://www.networkrail.co.uk/publications/weather-and-climate-change-resilience/

4 http://www.gatwickairport.com/globalassets/publicationfiles/business_and_community/all_public_publications/2014/mcmillan_report_feb14.pdf

where appropriate, and the ports sector has come together to discuss risks and action planning. The Port of Immingham is investing in improving its defences to defend against extreme flood.

This review has focused its attention on those sectors which deliver critical local services through local assets, to initiate (or, where already undertaken, provide assurance of) comprehensive in-depth studies of the resilience of such assets.

These have included:

- water (where we have focused first on clean water assets serving more than 25,000 people and will continue with smaller and wastewater assets in the autumn);
- fixed and mobile telecommunications;
- energy (electricity transmission and distribution, gas transmission and distribution and oil distribution); and
- medical facilities which are significant on a regional or national basis, including regional trauma centres serving very large areas.

Within these sectors, the task of assessing every single piece of infrastructure providing a service to someone would be enormous. For example, there are several hundred thousand small electricity sub-stations, some of which provide electricity to no more than a street or a few properties. We have focused on those assets which, if flooded, would deprive large numbers of people of a critical service. For pragmatic reasons we have set different population thresholds (ranging from 10,000 to 25,000) for different sectors, taking into account the thresholds already in use within specific industries.

Determining which assets meet the threshold is not an exact science. In highly networked services, if one asset is lost, the service may be supplied by another without the consumer even being aware. For mobile telecoms, particularly during working hours, those in the impacted location may not be those whose phones are registered there. Nevertheless, working closely with the sector operators, we have identified in table 1, those utility infrastructure assets which serve populations above the threshold size and which lie within the Environment Agency's Extreme Flood Outlines – so putting the services they provide at risk, unless adequate defences or alternative types of resilience are in place.

Table 1: Assets above relevant population threshold within Extreme Flood Outlines (EFO) (* to nearest 10).

	Total number of potentially vulnerable asset sites (above pop. threshold and within EFO)
All sectors (clean water, electricity, gas, oil, telecoms, health)	1640

2.3 Existing and planned permanent defences

For each of these assets lying within the Extreme Flood Outlines, and again working closely with the sector operators, we have assessed current levels of protection against Extreme Flood Outlines flooding. For those assets within the Extreme Flood Outlines that are currently inadequately or un-defended, we have also collated information on planned resilience improvements. The results of our analysis show that some sectors are more flood-resilient at a local level than others.

We have concluded that the gas network is resilient against flooding, mainly because it is a sealed system that is largely isolated from the environment. The oil (fuel) distribution sector has a wide range of potential supply routes which serves to mitigate the impact of any individual site being lost to flooding. Oil and gas infrastructure asset numbers have therefore not been included in the number of potentially vulnerable assets shown in table 2.

Table 2: Current levels of protection of assets against Extreme Flood Outlines (EFO) flooding (*to nearest 10).

	Total number of potentially vulnerable sites (above pop. threshold and within EFO)	Number of sites defended against flood extent in EFO	Net number vulnerable to flooding to extent identified in EFO
Sectors assessed as potentially vulnerable (clean water, electricity, telecoms, health)	820*	290*	530*

As table 2 shows we have identified a large number of potentially vulnerable assets which are already defended against Extreme Flood Outlines flooding.

In reviewing the vulnerability of health facilities to flooding, the Department of Health and NHS England identified only a small number of locations where service provision could not be diverted to another nearby facility in the event of flooding interrupting services at a particular location. A detailed review of these facilities concluded that they are either protected by Environment Agency defences (specifically the Thames Barrier in London) to the level of an extreme flood or have been protected to a (lower) level consistent with the fact that transport routes to and from the hospital would be blocked in any case by flooding above this level.

Setting health aside, this leaves us with around 530 sites around the country where key local infrastructure is still vulnerable to flooding in the circumstances pictured by the Extreme Flood Outlines. It is to these sites that we have turned our attention.

3 Assessing the potential for temporary defences to protect key local infrastructure

Permanent defences or permanent network solutions are clearly preferable to the ad hoc deployment of temporary defences as a means of protecting key local infrastructure. In some instances, however, permanent solutions either do not offer value for money or cannot improve the situation before next winter. We have therefore investigated the scope for temporary defences to play an immediate role in strengthening the resilience of our local infrastructure.

3.1 Types and general use of temporary defences

Temporary flood defences are systems that are brought to a site to provide a flood defence for a limited period. They are then removed until required again. They have no fixed foundation other than the natural ground on which they are based (with perhaps minor modifications to ensure proper stability or performance of the temporary barriers).

Temporary barriers can provide a relatively quick and easy means to protect assets against floodwater in some situations and for short periods. There is a variety of commercially available products, most of which are re-usable. Temporary barriers can be classed into four broad types:

- tubes of prefabricated membrane which are either air- or water- filled to form dams;
- filled containers - cellular barriers or baskets that often have a wire frame or are made from impermeable plastic that provides stability and are filled on site with aggregate or water;
- freestanding barriers made of impermeable free-standing sections joined together to form a barrier that is self-supporting; and
- frame barriers which use a system of metal frames to support impermeable sections spanning between them.

Safe and robust deployment of temporary barriers requires reliable flood forecasts far enough ahead to provide sufficient lead time for deployment. Such forecasts are more often available for the lower reaches of large rivers and are rarely available for steep fast-responding upper catchments. The best option in any specific situation depends on a range of variables (including location, ground conditions, flood scenario, water depth, flow rate, duration) as well as operational factors such as site access and availability of resources, including suitable skilled staff and installation equipment.

Temporary barriers do not provide the same level of protection as permanent defences and typically have failure rates of 20-30%, although these rates of failure can be reduced by good advanced planning. No type of temporary barrier is universally deployable in all situations, and generally they cannot withstand large wave action. All leak to a certain extent and therefore need to be accompanied by pumps.

Once installed, successful ongoing deployment of temporary barriers requires additional support including security (to protect barriers and in some cases the protected installation from theft and vandalism) and health and safety measures such as lighting and maintaining access to surrounding homes and businesses.

Thorough site-specific pre-planning is critical to successful and timely deployment. A typical plan for deployment would include details of the site to be protected, the equipment, people and plant required, the access route, transportation arrangement, utility plans, local arrangements with authorities, traffic management plans and pre-prepared key communications messages, along with assessments of risk and environmental constraints. Alongside advanced planning, availability of sufficient numbers of trained staff is of vital importance for successful deployment.

Annex 8 contains illustrations of the types of barriers and a summary of their strengths, weaknesses and costs.

3.2 Pilot study to assess the potential use of temporary defences

In order to assess at a high level the potential for temporary defences to protect key local infrastructure sites before a programme of permanent defences is fully implemented, the Environment Agency was asked to undertake a pilot feasibility study, to include site visits and assessment of costs, benefits and logistics.

Based on the pilot study (together with previous research and experience of actual flood events), the Environment Agency assesses that 30-40% of locally important infrastructure sites might be suitable for protection using an appropriate form of temporary defence.

Infrastructure sites vary greatly is size, but in order to estimate costs we assumed a typical site perimeter of 300 metres, based on the pilot study sites. For the purposes of the pilot study we have estimated that the cost of purchasing, storing and transporting rigid frame barriers and ancillary equipment is £800/metre, so the estimated cost for one typical site is £240,000. The cost of protecting an equivalent site using sandbags (£200/metre) is £60,000 but the standard of protection offered is considerably lower, re-use is limited, and the Environment Agency does not recommend the use of sandbags for this purpose. The revenue cost per deployment of the recommended types of temporary defence is estimated to be between £10,000 and £30,000 per site. This can be an important factor in determining whether temporary defences offer value for money as a long term strategy, or are only cost effective as a short-term measure before permanent defences are built.

3.2.1 The suitability of temporary defences to protect locally important infrastructure

In order to assess and cost the use of temporary barriers, the Environment Agency commissioned case studies where experienced engineers visited a selection of potentially defendable infrastructure sites in different geographies. The detailed results are in Annex 9.

The type or sector of infrastructure was found to be less of a determining factor than the size of the site and available space for barriers; the requirement for access; the depth and flow rate of flooding; the ability of flood forecasting to provide lead time for deployment; and the ground conditions. Sites requiring continuous access in order to operate were found to provide particular challenges but there can be opportunities to protect specific parts of these sites.

Different types of temporary barrier have different technical and operational features. The best option in any specific situation depends on a range of factors, especially the space available and the availability of suitable skilled staff and equipment. Frame barriers offer the most protection but require space and skilled people. There are currently no tested temporary defence products available that protect to a flooded depth of more than 2 metres (such as was experienced in Carlisle in December 2015) and very few are tested above 1 metre.

3.2.2 Deployment logistics

The current ownership and logistical model for temporary defences for infrastructure assets is a sectoral one, where individual utility sectors have (to a greater or lesser extent) developed and funded the use of temporary defences. The electricity sector companies hold 8.9km of temporary flood barriers and these are managed on a company-wide basis, with well-developed mutual aid arrangements in place between companies. Other sectors and local authorities have some provision. All users emphasise that having enough lead time to enable the logistics of transportation and deployment is essential and a key challenge. The importance of pre-deployment planning is also stressed.

The Environment Agency has depots in its 16 Areas and is looking at seven further strategic storage sites across the country, enabling temporary barrier deployment anywhere in England within 12 hours (3 hours driving and 9 hours loading and unloading). They also hold nationally significant equipment such as ultra-high volume pumps.

Strategic Coordination Groups manage incidents within the boundaries of the 38 Local Resilience Forum (Police) boundaries in England. Local Resilience Forums bring together each organisation and sector to determine their state of readiness, and whether they are able to offer support to others. It is the primary responsibility of operators to have arrangements in place to protect their assets in an emergency, but the Environment Agency will also endeavour to protect infrastructure where possible. There are also recent examples of the electricity sector providing equipment to other sectors.

4 Next steps

4.1 Improving the resilience of local infrastructure

As discussed in Chapter 2, over the last six months Government has worked with the infrastructure industries to identify the facilities which are at risk from flooding and which could disrupt services to a large number of people if flooded. We are committed to increasing the resilience of this key local infrastructure: on a temporary basis ahead of the coming winter and on a permanent basis in the longer term.

Some sectors have already achieved significant resilience, including by having robust plans for deploying temporary defences where that is practical. However, infrastructure sectors are at different stages of this process and some have still to complete their analysis of assets within the scope of this review in order to develop a full picture of the defences that might be appropriate. There are particular challenges to overcome in some industries such as telecoms where the infrastructure is complex and interconnected, and assets are often located on sites that are not owned by the operators concerned.

All the sectors with infrastructure that the review has found to be at risk have agreed to develop or expand existing medium term plans to increase the resilience to an extreme flood of service supply to significant populations, either through adequately defended assets or via some other means such as interconnections or back-up supplies.

Between 2015 and 2021 the electricity industry will invest £250 million in increasing the resilience of the electricity network against flooding. All electricity sites serving more than 10,000 people which are not protected against an extreme flood have been surveyed and have a plan in place to deploy temporary barriers if required and feasible.

To improve the resilience of our infrastructure in the short-term, the water and telecommunications industries have agreed to complete a detailed assessment of each of these key local infrastructure sites which are not yet resilient to an extreme flood event. This will build on the action they are already taking to manage the flood risk to their assets. These assessments will provide a more detailed understanding of the flood risk to those assets and will identify any measures (e.g. temporary defences) which could improve the resilience of the site in the short term. The two industries have committed to deliver these temporary improvements to resilience before Christmas 2016 where this is the appropriate solution to protect service provision.

The Government has also agreed with the utilities that we will work together to improve the mechanisms for cooperation and information sharing between the Government (e.g. Met Office and Environment Agency flood forecasts) and infrastructure operators on resilience, both in relation to flooding and more broadly. In particular, we are proactively working with the utilities to establish a national infrastructure resilience council or forum to:

- sponsor inter-industry cooperation and information sharing;
- develop suitable proposals on resilience;
- carefully examine and document interdependencies between different sectors; and
- in an emergency make the link between different industry sectors and the relevant local LRFs and the Government COBR machinery.

In the second half of this year we will also work with the water industry to extend the review's analysis to cover all relevant water assets (clean and waste) serving more than 10,000 people.

We will continue to improve our knowledge of infrastructure resilience. Following this winter's storms and floods, the Department for Transport has commissioned research to identify communities which are at risk of becoming isolated due to a severe flood event (i.e. one making all access roads impassable) and will share its research with Local Highways Authorities to ensure that the communities identified are prioritised for temporary and permanent flood resilience measures.

As a first step to tackle the challenge of assessing interdependencies, the Department for Transport and the utilities will work together to identify those bridges which are a single point of failure for other infrastructure operators (for example by carrying telephone or power cables) and could be at risk in a severe flood event, so that sectors can develop mitigating actions to protect services.

4.2 Improving incident response

The Environment Agency will significantly expand its capabilities to respond to a flood emergency by investing £12.5 million in temporary flood barriers, mobile water pumps and incident command vehicles. These will be stored in strategic locations across the country, so that they can be quickly deployed wherever there is a need.

We will also make sure that national assets like the rescue boats operated by the Fire and Rescue Services and other organisations are at peak capacity in time for this winter by investing £0.75 million to provide maintenance grants to enable nationally deployable flood rescue teams to maintain their equipment.

Just as it is crucial to have a good stock of well-maintained equipment, it is also crucial that people have a clear understanding of what equipment is available and where it is located so that it can be deployed quickly to where it is needed. To enable this to happen, departments will work together to draw up a single register of national flood response assets which will be kept up to date and will be viewable through ResilienceDirect. Additionally, as part of the improvements to the national emergency management machinery identified in the National Security Strategy and Strategic Defence and Security Review (2015)[5], we will establish an operations centre to bring together relevant organisations to improve situational awareness and the timely deployment of national assets, including the armed forces.

Local planning and response is a critical part of any flood response. We will continue to look at actions to improve the Government's overview of operational readiness of local responders and identify good practice in planning locally for flood resilience and response. Defra in collaboration with other government departments will establish a standard operating model for local responders and the Environment Agency will work with Local Resilience Forums to identify opportunities to embed good practice in their flood response plans. Many local responders already use Resilience Direct to plan and prepare for incidents and it is increasingly used to record and keep track of what is happening during a response, but we want to increase adoption of this vital application. We will drive forward improvements to make ResilienceDirect as user friendly as possible and develop new capabilities in line with responders' requirements. The aim is to have a tool which will make it possible for all of those involved in a response to know what others are doing.

The Environment Agency will be conducting a resilience exercise this autumn to test its readiness to deploy its new stock of emergency equipment. The Department for Environment, Food and Rural Affairs and the Cabinet Office Civil Contingencies Secretariat will take the opportunity to exercise arrangements alongside the Environment Agency. Many local emergency responders have similar plans to test their readiness for the coming winter.

4.3 Pilot for innovative flood defence and urban development in the Core Cities

Through the course of this review, we have identified a clear need to think more strategically about how we plan the defence of our cities from fluvial and coastal flooding. Given the scale of the challenge, and the significant economic impact of major flooding when it does occur, it is clear that we must consider more creative

[5] https://www.gov.uk/government/publications/national-security-strategy-and-strategic-defence-and-security-review-2015

solutions to deliver new flood defences, without a significant additional burden being placed on the taxpayer. We have been looking in the first instance at the Core Cities in England, and starting with one in particular – Sheffield – in order to explore and demonstrate what can be achieved. Our ultimate aim should be to deliver flood defence levels for the Core Cities similar to that of London. With Sheffield as an example, we hope other urban areas will adopt the principles of building resilience into the design of their urban development and regeneration, creating additional social and economic value from flood defences.

To support this challenge, we are drawing together a group of senior business leaders and experts from a range of sectors and disciplines including the flooding and water industry, engineering, architecture, development, infrastructure, finance, technology and commerce.

The group will focus specifically on how we can design new defences which will deliver, and be financed from the proceeds of, economic value for the local area. We will be working with Sheffield to enable the city to identify development of a type that will beautify the city-scape, unlock opportunities for urban regeneration and fit with local development priorities. Our aim is for Sheffield, and thereafter the other Core Cities, to own and lead this resilient (re)development. The group will also consider international examples where significant economic value has been created through flood defence schemes, such as in the Netherlands.

We are delighted that Sheffield itself has welcomed this new partnership approach and the opportunity to access the advice of the group. Sheffield offers great potential, both for improving defence from flooding from its many rivers and for regenerating the urban environment in general, via an integrated programme which can unlock the economic, aesthetic and ecological value of the city's water at the same time as making Sheffield an even nicer place to live. There are already exciting development plans under consideration by and for the city, but this will also provide the opportunity to consider how the programme could be hugely expanded, with effective flood defence at its heart.

If this pilot approach proves to be successful, our intention is to broaden it out to those other Core Cities where the level of flood protection is below that of London. Looking further ahead, we will also consider how communities and neighbourhoods can take the approach in larger urban areas and extend it to their own smaller cities and towns.

4.4 Rolling programme of long-term modelling improvements

The review and the scientific assurance within it have confirmed that existing approaches are robust. However, through the course of undertaking the review some areas have been identified which would benefit from improvement. These are:

- develop a more integrated flood risk modelling approach to allow simulations to be run which link meteorology, hydrology and flooding across England. This will make it easier and quicker in future to assess the probability of given levels of flooding to identify the impacts and to evaluate a range of flood management measures;
- undertake further work, including using information from historic sources (for example newspaper reports, photographs, and sediments) to extend flood records and allow recent flood events to be set in a longer-term context, so as to improve assessments of the likelihood of extreme flood events happening somewhere in the country over different time periods;
- develop further the statistical methods to reduce uncertainties in flood estimation, including taking account of long term variability and trends; and
- flood risk and the associated impacts should be reviewed on a regular basis to take account of the latest science, the results of the next set of UK Climate Projections in 2018, and reflect any changes in the underlying assumptions.

The Environment Agency is taking forward work to improve and enrich modelling of flooding from all sources, as part of existing plans to update the National Flood Risk Assessment. The Environment Agency is also procuring an upgraded Flood Forecasting System which will be fully able to exploit the probabilistic weather forecasting products developed in conjunction with the Met Office, providing much closer integration between meteorology and flood forecasts.

The Met Office and Environment Agency will work closely to scope and investigate the benefits of an ambitious longer term approach, integrating meteorology and flood risk modelling more closely still, to build on the ongoing work that both organisations are carrying out separately and on the approaches set out in the Joint Flood Forecasting Plan.

Delivering this longer term approach, and the other recommended actions, will require new science and analytical techniques, and we will be encouraging the UK research community to engage with the Met Office and the Environment Agency in the development of the next generation of integrated flood risk assessments.

4.5 Environment Agency flood risk communication

The review has identified that improvements are needed in how flood risk is communicated and the Scientific Advisory Group have provided advice on the core principles of good flood risk communication (see Annex 6).

Building on previous work to improve public engagement on the risk of flood undertaken by Sciencewise, the Environment Agency, working with others, will therefore develop different approaches to expressing the scale and likelihood of severe flooding. These will be trialled in, and refined after, the flood awareness and engagement campaign described below.

Using the new approaches, the Environment Agency will run an autumn awareness campaign that is locally delivered to communities at risk of flooding, especially those at high risk who have not experienced a flood in their lifetime. The aim will be to encourage cities and communities to plan for and take action should their city or community flood and support them in doing this.

In addition, the Department for Environment, Food and Rural Affairs, through its Science Advisory Council, will work with the Environment Agency and the Met Office to develop further advice on how to communicate flood risk to different audiences.

4.6 Surface water flooding

This review has concerned itself with the greatest flood risks facing the country—flooding from rivers and seas. Surface water flooding is also an important source of flooding so we will be taking action to consider this type of flooding, which has different causes and mitigations to those of river or sea flooding.

Every two years the UK Government carries out a National Risk Assessment[6] of the major risks of civil emergencies facing people in the UK over the next five years. This risk assessment serves as the basis of emergency planning at both national and local level. A risk is assessed both on the likelihood of it happening over the next five years and on the consequences or impacts that people will feel if it does. To enable this assessment to be made, a 'reasonable worst case' scenario is used, which represents a challenging manifestation of the risk after highly implausible scenarios are excluded.

[6] https://www.gov.uk/guidance/risk-assessment-how-the-risk-of-emergencies-in-the-uk-is-assessed

We publish a version of the National Risk Assessment, which is a confidential document, as the National Risk Register[7].

The 2014 National Risk Assessment considered two flooding risks: coastal flooding and inland flooding, summaries of which can be found in the 2015 National Risk Register. The inland flooding risk focused almost exclusively on the risk of fluvial (river) flooding, with some potential combined or additional impacts from surface water flooding. In the course of reviewing these risks for the 2016 NRA, new modelling has confirmed the potentially severe consequences of surface water flooding and the different distribution of risk across the country for fluvial and surface water floods, with surface water flooding being a particular risk in large urban areas.

The 2016 National Risk Assessment will therefore include separate fluvial and surface water flood risks in place of a single 'inland flood' risk. This recognises the different characteristics of surface water flooding and river flooding, which will allow a more targeted approach to planning for and managing the risk of surface water flooding at both the national and local level.

In addition, the Department for Communities and Local Government, working with the Department for Environment, Food and Rural Affairs, the Environment Agency and key stakeholders will be carrying out a review of planning legislation, government planning policy and local planning policies concerning sustainable drainage in relation to the development of land in England, as set out in the Housing and Planning Act 2016. This review will make a constructive contribution to the work of the Adaptation Sub-Committee of the Committee on Climate Change and inform their 2017 progress update on the National Adaptation Plan.

4.7 Long term (post-2021) strategy

The Government has prioritised investment in maintaining and improving flood defences in England over this parliament with a record level six-year commitment to 1,500 schemes. This is set to drive down total risk by 5%, better protecting 300,000 homes and providing £30 billion in economic benefits by 2021. On top of this Budget 2016 included an additional boost to spending on flood defence and resilience of over £700 million up to 2021. Funding from this uplift has already been committed to provide additional support for schemes in areas of high risk that were affected by the winter floods and an increase in spending on maintaining defences.

With the evidence of this review in hand, the Department for Environment, Food and Rural Affairs (Defra) will now turn its attention to investment after 2021 and the Government's role in supporting the resilience of communities and the wider

[7] https://www.gov.uk/government/publications/national-risk-register-of-civil-emergencies

economy. Building on progress made through this review to improve the resilience of local infrastructure, Defra will work with the Environment Agency, HM Treasury and the National Infrastructure Commission to consider long term investment needs and funding options. It will take account of the resilience of Core Cities, including any lessons learned from the Sheffield pilot to develop new models of self-financing which could compliment Government investment after 2021. The Defra work will consider the balance between protection and resilience, will look closely at flood risk in England's cities and will consider the role of both government and wider society in reducing flood risk.

Defra will work with the Environment Agency to enhance its analysis of long term investment options, ensuring that Government funding is balanced to support communities at highest risk as well as maximising wider economic benefits. We will assess how Government investment can be most effectively targeted to achieve these goals while providing the best possible information to allow others to manage their risks.

As part of the evidence gathering for this work, we have collated information on approaches to flood risk mitigation in a global selection of nations in Annex 10.

The Government's six year funding commitment and partnership funding approach has already provided much greater certainty around funding, allowing risk management authorities to plan, gain greater efficiencies and leverage more contributions. We will consider how these improvements can be built upon after 2021 with a rolling government commitment to driving down flood risk and improving defences over clear and effective planning horizons.

Engineered hard flood defences can only ever be part the solution. We have seen the benefits of natural flood management in places like Pickering, North Yorkshire and Holnicote in Somerset. The Government's future 25 year plan for the environment will look at strengthening the role of local partners, bring them together to integrate flood management with water planning at a catchment level.

Catchment leaders will coordinate planning, taking an integrated approach to the environment, valuing interventions, such as natural flood management, as part of natural capital accounting. Government will continue to base its funding for flood management on reduction in risk rather than type of intervention to ensure that new approaches, such as land management to slow the flow, can compete on an equal value for money basis with conventional engineered defences.

Annexes

Annex 1 - Membership of the National Flood Resilience Review Group

Chair: Chancellor of the Duchy of Lancaster

Cabinet Office

Department for Communities and Local Government

Department for Culture, Media & Sports

Department for Environment, Food & Rural Affairs

Department for Transport

Department of Energy & Climate Change

Department of Health

HM Treasury

Prime Minister’s Office, 10 Downing Street

The Government Chief Scientific Adviser

Environment Agency

Met Office

Annex 2 - Generating plausible extreme rainfall scenarios for England and Wales

Summary

This annex describes how the Met Office generated plausible extreme rainfall scenarios with a 10-year forward look, to use to stress test the Environment Agency's flood modelling, and summarises the current evidence for the role of climate change in recent extreme rainfall and flooding events,

So far there is limited evidence that climate change is affecting rainfall over England and Wales, and therefore we expect that natural variability will continue to dominate extreme rainfall for the next 10 years. Our approach to generating plausible extreme rainfall scenarios has therefore focused on natural variability and whether there are plausible weather patterns that could drive extreme rainfall in excess of current records, but that have not so far been observed – 'black swan' events.

The latest version of the Met Office high-resolution climate model has been used to generate a large event set of simulated monthly rainfall scenarios for 6 standard climatological regions covering England and Wales. This 'virtual' event set consists of over 11,000 monthly scenarios, which is many times larger than the set available from observations for the same period (420 months). This means that it contains many more 'black swan' extreme events than current existing rainfall records: we have identified several hundred monthly virtual rainfall events that are worse than any in the observed records but are regarded as meteorologically plausible for the current climate. This enables us to estimate how much worse than past records a low probability plausible extreme rainfall event might be.

We have used a 1% annual probability threshold to define a plausible extreme scenario. This is the lowest probability that we consider robust based on the size of the event set.

Based on our analysis of these simulations, and combined with other evidence from observations, natural climate variability, climate change scenarios and our understanding of climate model performance, we have concluded that uplifts of between 20-30% should be added to recent record-breaking rainfall events to generate plausible extreme rainfall events that have a 1% annual probability of occurrence within each region. In other words, over the next decade, there is a 10% chance that monthly regional rainfall will exceed existing records by more than these uplifts - or conversely, we can have a 90% confidence that they will not.

Our analysis also indicates that on average there is a 10% likelihood of a region experiencing rainfall that breaks the existing record (by any amount) in any year. It is therefore likely that there will be one or more monthly regional rainfall record event,

smaller than our plausible extreme scenarios but similar to those observed in recent years, in the coming decade.

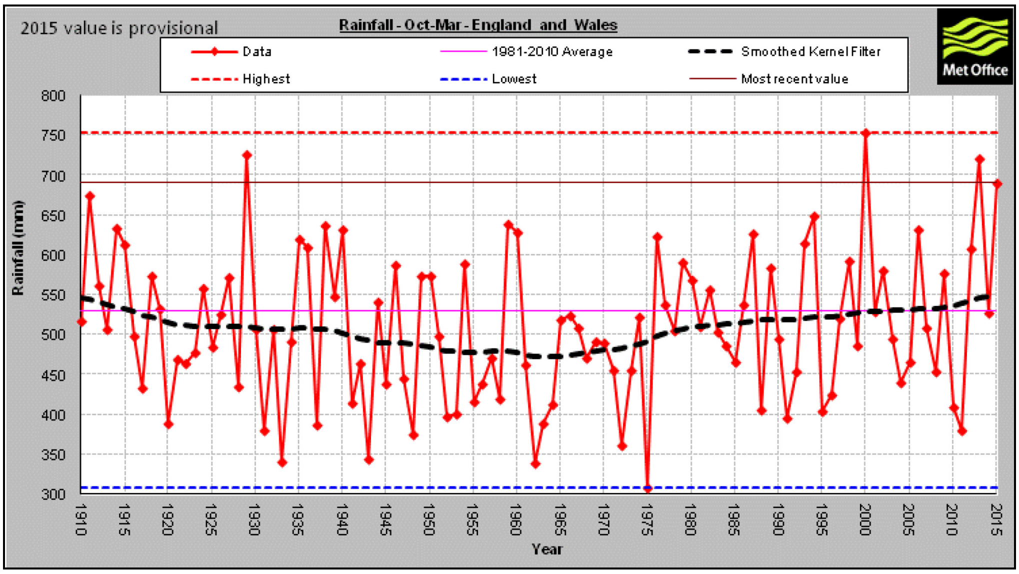
Role of climate change in past extreme rainfall and flooding events

The Met Office, through its National Climate Information Centre (NCIC), and the Environment Agency hold detailed observational records of meteorological variables and river flows. These have been combined with other measurements, such as sea level rise, and with published evidence to make an assessment of the influence of climate change on past events.

The observational record of monthly accumulations since 1910[1] suggests some detectable changes in the rainfall distribution across the UK and across seasons, particularly in the northern and western parts of the UK. However the attribution of those changes to climate change continues to be challenging because of the large natural variability of the UK's climate[2,3].

- Although the last 50 years has shown a trend of increasing winter rainfall, in the longer context of the last 100 years values being observed now are close to those in the early part of the 20th century (figure 1, upper panel).
- However, the observational record up to 2014 shows that 7 of the 10 wettest years in the UK have occurred since 1998[4]. The cluster of flood events through the early years of the 21st century, and the duration of recent runoff and recharge patterns are near to the extreme range of historical variability over the past 100 years[4].
- Extreme rainfall is often related to very intense events occurring on daily or even hourly timescales. Observations on these timescales are much more limited, and comprehensive UK daily rainfall records are currently only available back to 1960. These show a clear signal of more heavy daily rain events in the most recent decade. This is consistent with the thermodynamic effects of climate change; increases in rainfall intensity have been documented world-wide and are recognised as being one of the most detectable signals of climate change in rainfall characteristics[5].

In summary, signals of a role for climate change in recent extreme daily rainfall events are emerging, but the inherent natural variability in the UK's climate means that it will probably be some time before a definitive answer on longer period (e.g. monthly and seasonal) accumulations will be obtained.



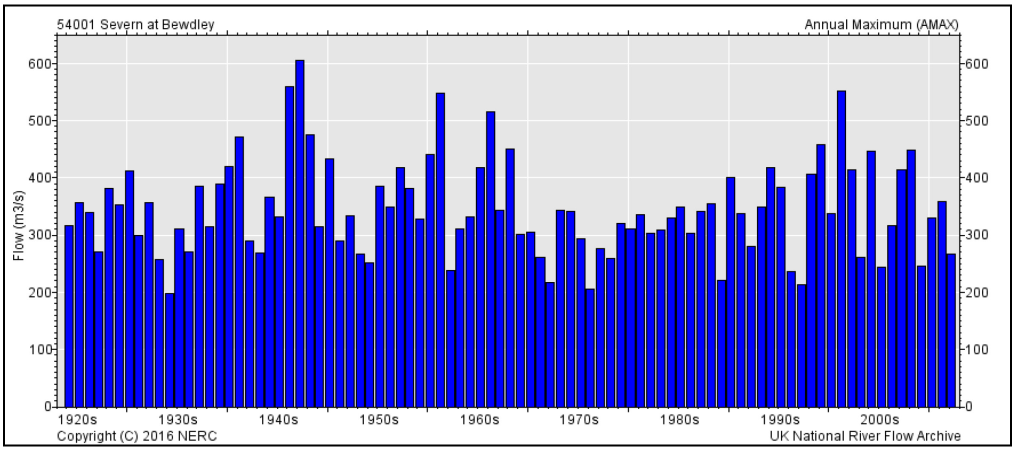


Figure 1: Time series of annual rainfall totals for England and Wales (upper panel), and maximum flow rates for the Severn at Bewdley (lower panel) showing the long term natural variations in rainfall patterns.

The UK's rainfall derives from the prevailing weather patterns and so the fundamental driver of extreme rainfall is the meteorology. The UK's weather is notoriously variable and so detection of any change in the behaviour of the meteorology (e.g. storminess) is particularly challenging. Severe storms have always affected the UK and are documented in many historical records. The intensity of recent storms is unusual, but not necessarily unprecedented.

- A comprehensive study of trends in storminess[6], for the period 1871-2010 shows a robust signal of increasing numbers of strong winter storms and with increasing intensity for the high latitude North Atlantic. This is associated with a reduction in storminess further south and supports a wide body of evidence for a northwards shift of the Atlantic storm track.

- However, analysis of changes in storminess further south over the mid-latitude North Atlantic – the path of the storms that affected the UK in winter 2013/14, for example – suggests a more complex signal. Although the number of strong winter cyclones has not increased since 1871, the mean intensity has. Notably, for very strong storms, the mean intensity has increased significantly. However these results are not conclusive and there remains substantial debate about the behaviour of the North Atlantic jet stream and the storms that form along it.

In summary, finding evidence for increased storminess over the UK, in terms of frequency or intensity, is currently very challenging and is a topic of active research.

Most of the reliable high flow records in the UK start in the 1960s. In line with changes in rainfall over the same period, annual average flow has increased over the last 50 years in Scotland, Wales and parts of Northern and Western England; in contrast, no pronounced changes have occurred in the lowlands of South East England. Over the same period, winter flows have increased in upland, western catchments. Autumn flows have increased in Central England and parts of Eastern Scotland. There is no apparent pattern of change in summer flows across the UK[7].

- High winter flows have increased over the last 30 years and there has been an increase in the frequency and magnitude of flooding over the same period, particularly in the West and North[7]. However, as with rainfall, longer records demonstrate that there are flood-rich and flood-poor periods in the hydrological record (figure 1, lower panel), and the recent decade is not very different from the early part of the twentieth century. Reconstruction of floods from sediment records suggests some very large floods in the 18th and 19th centuries[8].
- Changes in UK river flows have so far not been attributed robustly to man-made climate change; there are periods of high and low flows throughout the UK flow record which make this challenging.

In summary, the existing observational record is too short to provide a detectable signal of climate change in river flows, and the current capabilities of meteorological and hydrological models are not robust enough to attribute recent flooding events to climate change.

Sea level along the English Channel has already risen by about 12cm during the 20th century[9]; this is over and above the increases associated with sinking of the southern part of the UK due to isostatic adjustment from the last Ice Age.

- These rises in sea level elevate the risk of coastal flooding during a storm surge event and also increase the tidal locking in rivers, such as in the Somerset Levels.

- In terms of storm surge and extreme sea levels, UKCP09[10] reported that trends in extreme high water levels were dominated by changes to mean sea level and that there is no observational evidence for regional trends in either storm surge frequency or magnitude over recent decades.

In summary, rising sea levels have been detected which increase the risk of coastal flooding and tidal locking.

Generating plausible extreme rainfall scenarios

This is the first time that fluvial flood risk has been based on realistic rainfall scenarios and considered extreme events that are meteorologically plausible but lie outside existing observational records. Previous assessments have used peak river flows based on historical records[11,12]. This means that this study is breaking new ground on how flood risk is assessed; however it is important to be clear about the scope of the study.

- The focus has been on large-scale fluvial flooding events, typically related to large accumulated rainfall and associated with persistent weather regimes, typical of recent severe floods.
- Flash flooding events, related to extreme sub-daily and localised rainfall, are out of scope.
- Plausible worst case rainfall accumulations can only be produced on monthly timescales and on large regional scales due to time limitations and the suitability and availability of model simulations. However, the majority of serious fluvial flooding events with large impacts on property and infrastructure tend to be associated with record monthly rainfall accumulations.
- Only a few catchments have been stress tested due to time limitations; these have been chosen to be representative of differing hydrological regimes across the UK.
- The variable nature of the UK's regional and local weather, the UK's varying terrain and the hydrological complexity of its catchments, mean that although the results of from this limited number of case studies provide a good indication of the validity of the Environment Agency's flood modelling, they are not exhaustive and further work would be valuable.

Extreme flooding is driven primarily by the meteorological conditions[13] and therefore the focus is on whether there are plausible weather patterns that could drive extreme rainfall in excess of current records, but have not so far been observed – 'black swan' events. Plausible uplifts for extreme rainfall scenarios for England and Wales are based on an assessment of the potential for rainfall accumulations to exceed those already observed in the recent past; this is derived from simulations with the Met

Office Hadley Centre's high-resolution climate model (50km atmosphere, 25km ocean).

- Over 11,000 months of climate model simulations are used to produce events sets of extreme monthly regional rainfall for all months of the year. This event set is many times larger than the set available from observations (420 months) for the same period.
- These simulations form part of our latest decadal prediction system. This system predicts potential global weather patterns over a 10-year period based on real-world initial conditions and, as part of the validation of the system, we produce multiple forecasts of past conditions (known as hindcasts).
- The use of the decadal prediction system means that these simulations are constrained to sample the same large-scale forcings as the real world (e.g. greenhouse gas concentrations, phase of the Atlantic Multi-decadal Oscillation), but still have the freedom to evolve away from their initial state to climate regimes that lie outside what has been observed.
- The simulations cover the period, 1980-2014, which covers the 30-year period, 1981-2010, set by the World Meteorological Organisation to define the current state of the climate.
- The resolution of the Met Office Hadley Centre (MOHC) climate model is higher than any used previously in climate prediction, with demonstrable improvements over previous models in synoptic weather patterns of relevance to the UK[14,15], such as cyclonic storms and their related weather fronts. This is the first time that the resolution of the MOHC climate model has been considered high enough for a study of this nature.
- The climate model performance has been tested against observations using a range of statistical tests and shown to be generally valid. The only exception is in mountainous regions where the spread in the distribution of modelled rainfall accumulations has had to be adjusted. This is because mountains are not adequately represented in coarser resolution global models leading to well-documented under-predictions of rainfall amounts[16].
- Noting that there is a large rainfall gradient from east to west across the country, the Met Office has conducted an assessment using the six standard National Climate Information Centre (NCIC) climatological regions of England and Wales to provide an assessment of the uncertainty in changes in extreme rainfall accumulations across the country.
- For each region an ensemble (or model event set) of monthly mean rainfall accumulations was produced from the climate model simulations. These were compared with the observed event set for each month and model events that lie outside the observed rainfall records were identified (see figure 2 as an

example). To increase the sample size the months have been aggregated into those for winter (October to March) and summer (April to September).

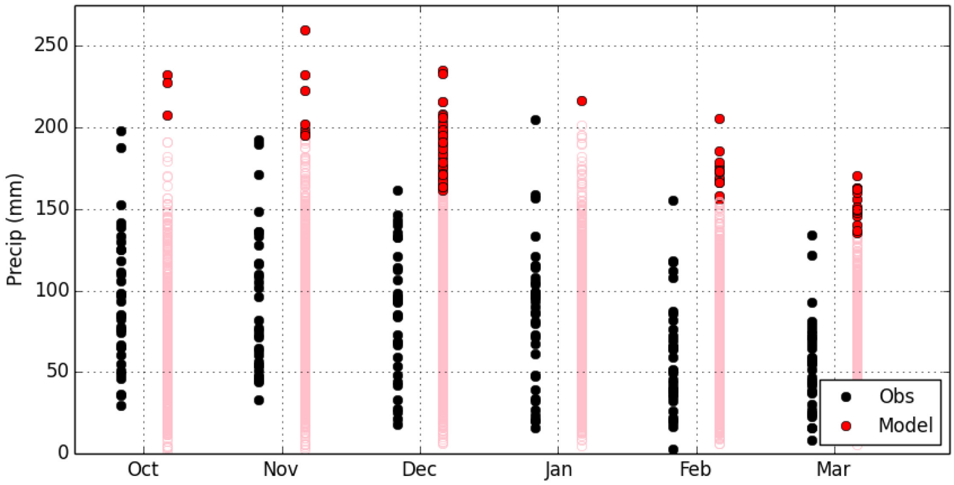


Figure 2: Example of the identification of 'black swan' events (those that lie outside the range of the observations) for the winter months (October to March) based on 7000 months of simulation for the current climate, representative of the period 1980 to 2014, for the England South East & Central South climate region. Black dots indicate the observed monthly totals for 1980 to 2014, red dots indicate model monthly totals; red filled dots indicate unprecedented wet months in the model.

- Based on this set of modelled 'black swan' events , the range of probabilities across England and Wales of exceeding certain rainfall thresholds, in excess of current observed rainfall records, has been calculated for winter (October to March; figure 3, left panel) and summer (April to September; figure 3, right panel).
- A probability threshold of 1% per annum has been used to define a plausible extreme scenario for the monthly rainfall in a region. The model event set is not large enough to provide a robust estimate of risk for probabilities smaller than 1% (e.g. an even worse but less likely 0.1% scenario (1 in a 1000 year)).
- Figure 3 indicates that for extreme events with a 1% likelihood of occurrence each year, plausible uplifts on existing monthly mean records for the winter (October to March) are in the range 15-35%. In summer (April to September) the range of plausible uplifts is 25-50%, at the 1% probability level. These uplifts are valid for regional averages typical of large catchments and for monthly accumulations only.
- The results shown in figure 3 also indicate that there is around a 10% chance in any given year of existing monthly rainfall records over a large region being matched and/or broken. It is therefore likely that there will be one or more record rainfall events in the coming decade that could lead to large-scale accumulations and potentially flooding.

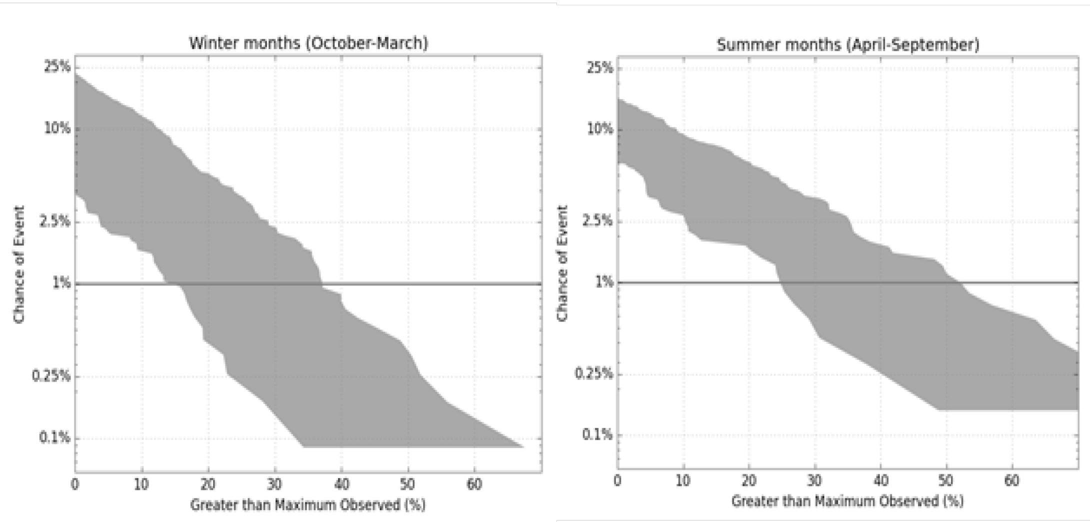


Figure 3: The risk of an unprecedented month of rainfall occurring in a given region during a given winter (left panel) or summer (right panel) across England and Wales (shaded region shows the range). Note that on average there is a 10% risk of unprecedented regional rainfall in any year (upper left of each diagram). Across England and Wales, there is a 1% risk of exceeding the observed regional monthly maximum rainfall amounts by approximately 15-35% for each winter, and by 25-50% for each summer (centre of diagram). These results are representative of the current climate (1980 - 2014).

- The percentage uplifts from the Met Office event set are consistent with results from the European Centre for Medium-Range Weather Forecasts based on model estimates of the maximum possible daily rainfall from the weather patterns that the UK has experienced in the last 20 years in both winter and summer.

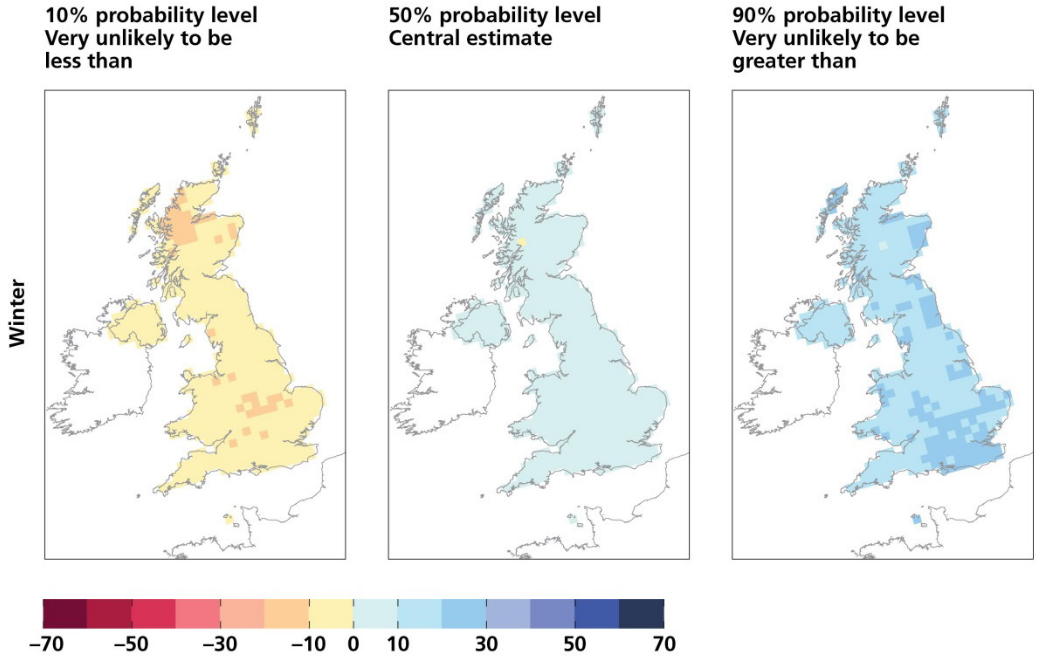


Figure 4: UKCP09 assessment of the % change in rainfall for the wettest day in winter for the 2020s from the high emission scenario. Note that the largest changes are in SE England and ‘very unlikely to be greater than’ 20-30%. Taken from maps available at www.ukclimateprojections.metoffice.gov.uk.

- The percentage uplifts used are also in line with the scale at which previous records have been broken in the observed records, and with UKCP09 assessments of the change in the wettest winter day for the 2020s (figure 4)[17].
- These percentage uplifts apply to a large region and for the whole month. Based on past observations we know that on smaller, more local space scales the percentage exceedance of existing rainfall records may be higher; however, it is not possible at this stage, with existing model data, to provide that level of detail. Nevertheless, the evidence suggests that severe fluvial flooding is linked to extreme monthly rainfall accumulations over a large area (see figure 5 as examples of recent severe flooding events), which supports the approach used in this study.

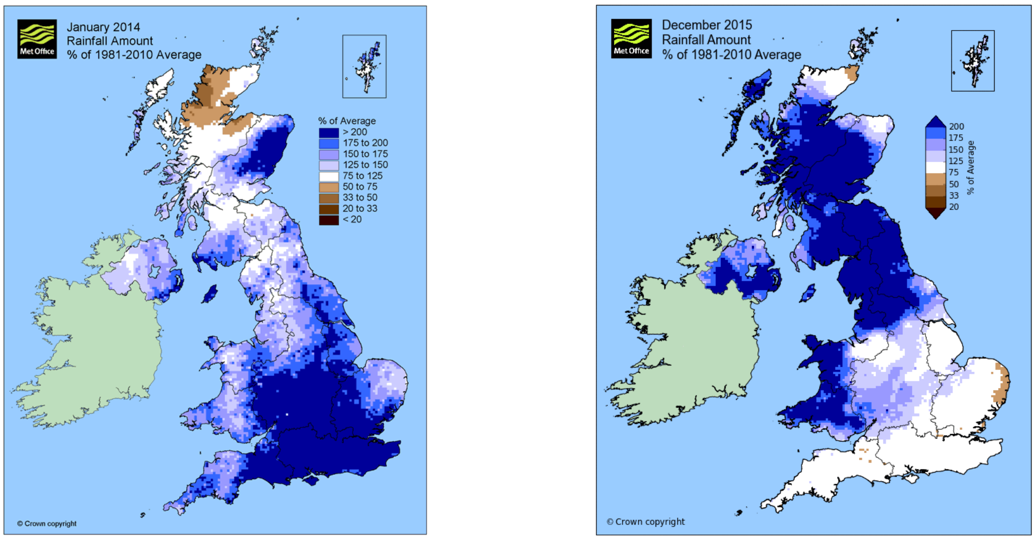


Figure 5: Monthly rainfall accumulations expressed as a % of the climatological average for 1981-2010 for the severe fluvial flooding cases of January 2014 (left panel) and December 2015 (right panel). Both months broke existing rainfall records and the figures emphasise the large scale nature of the extreme rainfall accumulations.

Stress tests of the Environment Agency's Extreme Flood Outlines, based on plausible extreme rainfall scenarios, have been conducted for selected real cases with differing hydrological environments. These cases were chosen based on the record-breaking nature of the rainfall and/or the high impact of the flooding.

- The main focus has been on very recent events so that the potential impacts of past climate change have already been factored in. These events have also occurred in the rain-rich/flood-rich periods associated with long-period variations in UK climate linked to the Atlantic Multi-decadal Oscillation (figure 1). The one exception is the 1960 Exe case study, where a higher uplift factor of 30% was agreed accordingly.

- For each of the stress test case studies, expert judgement based on an understanding of model limitations and climatological observational datasets has been used to define the appropriate percentage uplifts. These range from 20% for North-West England to 30% for cases in Southern England.
- High resolution rainfall scenarios have been produced for each event using output from the UK kilometre-scale weather forecast model as the 'base case'. The UK kilometre-scale model performance has been evaluated extensively[18] and is used operationally in the Flood Forecasting Centre. We chose to use model output rather than direct observations because of the sparseness of the rain gauge network, and also because radar measurements over complex terrain, such as the Cumbrian Fells, and also during very strong events, tend to underestimate the rainfall (figure 6).

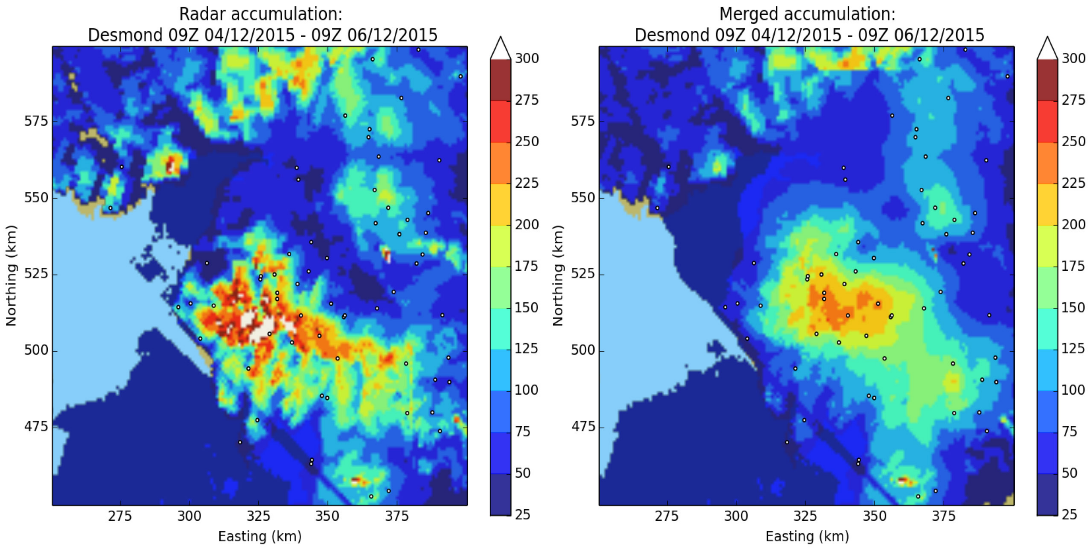


Figure 6: Example of the observational uncertainty in the 48-hour rainfall accumulations from radar and a merged radar and rain gauge product for Storm Desmond. The positions of the EA rain gauges are shown as circles. Note the loss of the rainfall enhancement over elevated terrain in the merged product and the lack of rainfall to the north-east of the Cumbrian Fells in the radar product.

- The percentage uplift is applied uniformly in space and time to the whole period of the high resolution rainfall scenario. This represents a substantial increase in the volume of water entering the catchments. The resulting accumulations for the plausible extreme rainfall scenario can be compared with the 'base case' rainfall accumulations (see figure 7 as an example).
- The high-resolution 'base case' and the percentage uplift rainfall scenarios have been supplied to the Environment Agency as input to their catchment models, with a spatial resolution of 2km and a temporal sampling of 15

minutes. This is the same space and time sampling that is used operationally in the Flood Forecasting Centre to produce flood warnings, and the consistency of approach provides additional confidence in the methods we have used to stress test the Environment Agency flood models.

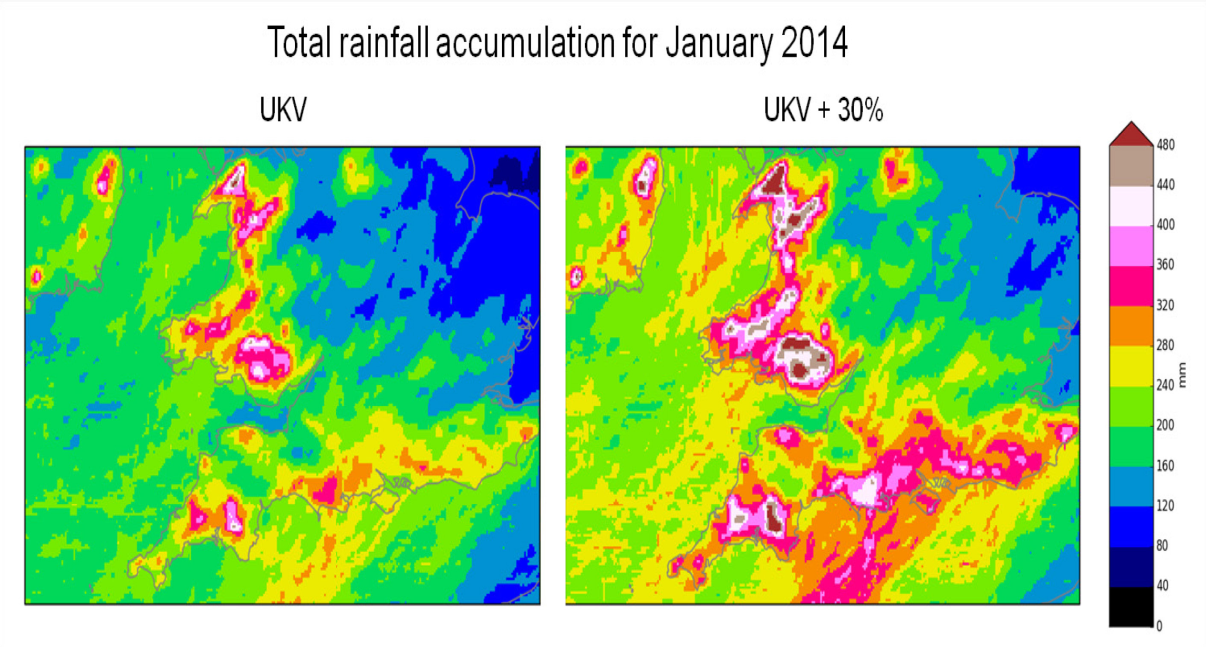


Figure 7: Example of monthly rainfall accumulations from Met Office's 1.5km resolution model (UKV) for the 'base case' (left panel) and the plausible worst case scenario based on a 30% uplift (right panel) for the southern England case study for January 2014.

We have also considered the potential for climate change over the review's 10-year time horizon to contribute to record breaking rainfall, but have concluded that no further uplift needs adding.

- With the exception of the Exe (see above), the scenarios have been based on very recent events, so that the potential impacts of past climate change have already been factored in, and the scenarios are consistent with current greenhouse gas concentrations. These events have also occurred in the current rain-rich/flood-rich period associated with long-period natural variations in UK climate (figure 1).
- Natural weather and climate variability dominates the UK's rainfall and flooding and will continue to do so for the review's time horizon of the next 10 years. The trend in rainfall due to climate change over this period is very small in comparison[19] (figure 8 and figure 9), and contained within the proposed percentage uplifts in rainfall used to stress test the Extreme Flood Outlines.

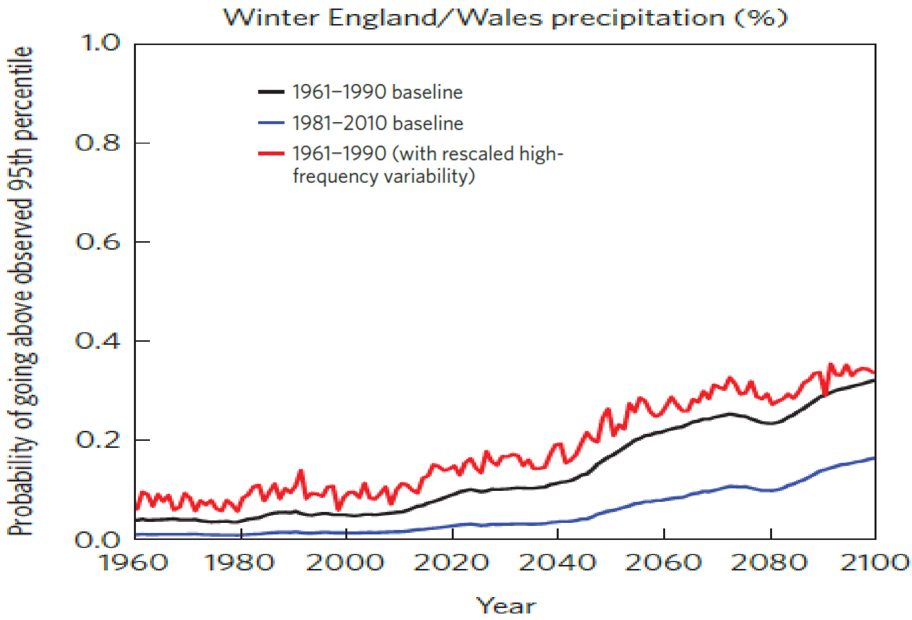


Figure 8: Probability of exceeding the 95th percentile of the observed baseline distribution for England/Wales winter precipitation. The black and blue lines use the conditional 1-year cumulative PDFs, but for two different baseline periods that reflect multi-decadal variability in UK rainfall. The red line is an estimate of the fraction of realizations that exceed the 95th percentile of the observed 1961–1990 distribution at each time point after adjustment to reflect the deficiencies in the amplitude of natural variability in the UKCP09 model data. Taken from Sexton and Harris (2015)[19].

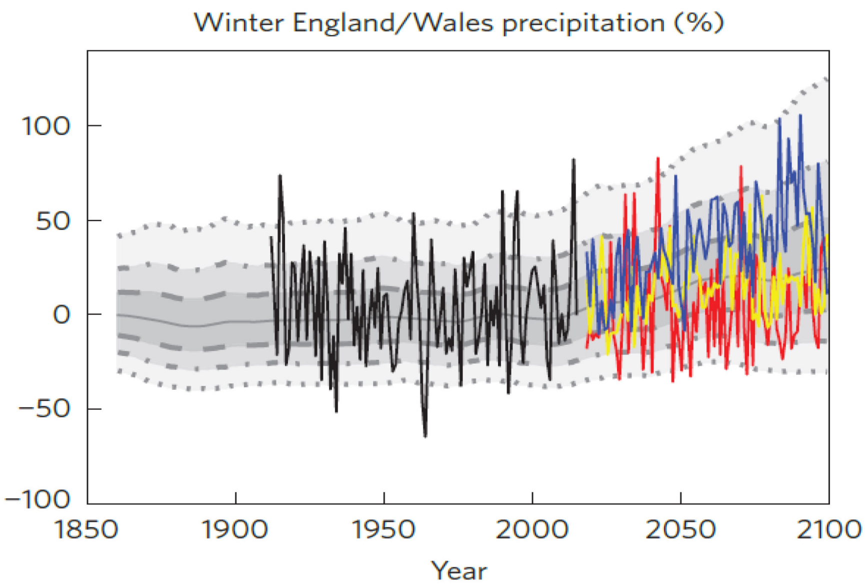


Figure 9: Natural variability and climate change in UK rainfall. Projections for winter rainfall in response to historical forcings, followed by the A1B scenario from the UKCP09 regional model simulations. Grey shading and lines show percentiles of anomalies in the variables relative to 1961–1990, calculated from 1-year mean probability distribution functions for every year between 1860 and 2100. Coloured lines show three individual realisations of year-to-year variation. Thick black lines show observed annual global and England/Wales precipitation time series up to winter 2014/15. (Taken from Sexton and Harris (2015)[19]).

Longer term future climate change

Current assessments of future climate risk are based on past climate records and on future climate projections derived from UK Climate Projections produced in 2009 (UKCP09)[16]. UKCP09 provides an assessment of the likelihood of possible future UK long-term (30-year) averages based on large ensembles of climate simulations that explored various sources of uncertainty. The headline message based on these projections is for a trend towards ‘hotter, drier summers and milder, wetter winters’ by the end of the century.

- High flows and flooding are expected to increase over the century because of increased rainfall, particularly in winter. Increased sub-daily rainfall intensities would lead to more flash flooding.
- In terms of sea level rise, with the warming we are already committed to over the next few decades, a further overall 11-16cm of sea level rise is likely by 2030, relative to 1990, of which at least two-thirds will be due to the effects of climate change[10]. In terms of extreme sea levels and storm surge these will continue to be dominated by natural variability and with little evidence of any trends.
- Recent events have emphasised that it will be the volatility of the UK’s weather at the regional and local level that will be critical for determining future climate risk. This will increasingly be a juxtaposition of natural variability and climate change. The next set of UK Climate Projections due to be published in 2018 (UKCP18) is designed with this in mind and will deliver a more robust approach to assessing the impacts of climate change and in particular changes in the frequency and intensity of extreme rainfall and in storminess. This information is essential for assessing the UK’s future risk from flooding to underpin actions to mitigate that risk and make us more resilient and better prepared.

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Annex 3 – Modelling for flood risk management

Overview

Flood risk modelling provides key evidence to understand risk and the potential impacts of flooding on people and communities. Flood risk modelling allows us to raise awareness of risk in advance of flooding, and to plan for, forecast and warn of impending flooding. Modelling is used to design new defences to reduce flood risk, prioritise spending on maintenance, and manage flood risk to future development.

Models are a simplified representation of reality and are never perfectly accurate. They are limited by the data that we use to build them, and by the way that they represent reality. But if we use them carefully, understanding the way that the uncertainties affect the decisions that we are making, then they can be extremely powerful and informative.

Models may reflect risks from different sources of flooding – for example flooding from rivers, the sea, surface water or reservoir breach. They may cover the whole of England, a catchment, or a single settlement. The outputs from models are often used – separately or together – to develop datasets, such as flood maps, to make the information easier to understand and use.

Our models

The Environment Agency has many kinds of models for different purposes, with some overlaps in use. They can however broadly be split into hydrological and hydraulic models.

Hydrological models generally take rainfall or river flows, together with catchment information, as inputs, and can provide information on the resulting river flows downstream. These models allow us to take account of the many factors that influence river flows, such as catchment size, land use, steepness, roughness and catchment saturation. They help us to understand the complex non-linear relationship between rainfall and river flow and are often used to provide inputs to hydraulic models.

Hydraulic models generally use river flows, and river and ground surface information (as well as information on flood defences and other structures such as bridges) as inputs, and enable us to assess the extent, depth and velocity of flooding that would result from a given flow. The Environment Agency hold over 2000 local detailed models, covering nearly 70% of all properties at risk of flooding from rivers and sea; each of these models covers an area from a few kilometres of river to a catchment.

These models are used individually to understand flood risk in the local area – for example, for flood warnings or for flood defence scheme design – but they are also used in combination to produce a number of national products; best known are the national flood maps described in table 1 below.

Table 1: National flood maps.

Map name	Shows
Flood Map for planning (rivers and sea)	The chance of flooding in any given year from rivers and the sea, without defences, used primarily for development and spatial planning decisions
Risk of flooding from rivers and sea (also known as the National Flood Risk Assessment (NaFRA)	The chance that any location will flood from rivers and/or sea, taking account of flood defences, in any given year
Risk of flooding from surface water	The chance that any location will flood from surface water, in any given year
Risk of flooding from reservoirs	Areas that could be at risk of flooding in the realistic worst case scenario of a major breach of a reservoir

Modelling flood extremes

Sometimes we need to understand *what* would flood in a given scenario – for example, as a result of particular rainfall conditions – so we can understand the impacts and identify how to respond.

At other times we want to understand *how likely it is* that a given location will flood in any year, irrespective of the rainfall coverage or whether the rainfall driving the flood is persistent and heavy or shorter in duration but very intense. Examples of such models are those that we use to design and assess the cost benefit ratio of new flood defences, or the residual risk if a flood defence is overtopped by an extreme flood. The outputs from these models are included in our national flood maps to raise awareness of flood risk and help identify locations suitable for development.

When we want to assess what extreme flooding looks like we typically model the effects of a scenario with a nominal 0.1% chance of occurring in a year at any given location, using local detailed models. These local flood extents are combined with less detailed broad scale modelling and observed flood data to create a national Extreme Flood Outlines (EFO) map, showing the extent of extreme floods at any specific location. This Extreme Flood Outlines map is not a single scenario, but is used in understanding flood risk at local and national levels (including allowing comparison of flood risk in different locations) and raising awareness of flood risk. For example, it is used with planning guidance to assess whether a location is suitable for development, or to understand the benefits of measures to reduce the risk of flooding.

The EFOs form the limit of flooding on the Risk of Flooding from Rivers and Sea maps. The EFO mapping is are available at: http://maps.environment-agency.gov.uk/wiyby/wiybyController?x=357683&y=355134&scale=1&layerGroups=default&ep=map&textonly=off&lang=_e&topic=floodmap

The EFOs show river and sea flooding: extreme flooding from other sources such as surface water can arise outside the EFOs. Separate Risk of Flooding from Surface Water maps show areas with a nominal 0.1% chance of flooding in any year from surface water and are available at: http://watermaps.environment-agency.gov.uk/wiyby/wiyby.aspx?topic=ufmfsw&scale=1&ep=map&layerGroups=default&lang=_e&y=355132&x=357681#x=357681&y=355132&scale=1

Testing the Extreme Flood Outlines: case studies

The case studies for the review used extreme rainfall scenarios supplied by the Met Office, together with other appropriate parameters such as catchment parameters, to derive flows using hydrological models. Hydraulic models were then used to assess the flood extents and depths that would result from these flows.

The case studies showed that the vast majority of the flooded extent under these scenarios would be expected to remain within the EFOs. Although this does not mean that the EFOs cannot be exceeded (and indeed, statistically it is expected that they will periodically be exceeded) it confirms that the EFO maps provide a good extreme flood extent for the purposes for which it was developed, and also for the review's infrastructure risk assessment.

Mapping the flood risk

The following pages provide more detail on key Environment Agency models and products derived from modelling. All of these are updated as new local detailed modelling becomes available.

Local detailed flood modelling (rivers and sea)

Primary purpose

Used for the design of flood defence schemes, or to assist in developing strategies to manage flood risk where more accurate flood mapping is needed. Often includes modelled flood levels.

Key assumptions

The local detailed modelling produced by the Environment Agency is our best assessment of flood risk, based on the information available at the time of modelling, such as information about previous floods for comparison, water level records from river and rain gauges, and other information about the area such as the topography.

What to look for

As well as flood extents based on range of potential scenarios, depth and velocity data may also be available.

Used for

Supporting the design of resistant and resilience measures

Testing the performance of assets against a wide range of 'what if' scenarios

Considering options for managing flood risk in the future.

Caution

Local detailed flood models are not available for all parts of England.

Need specialist flood modelling and mapping experts to use and interpret data.

Even though these models are detailed, they may not be detailed enough for a specific site and so may need further development for specific site assessments to understand potential flooding mechanisms and test potential mitigation measures.

Flood Map for planning (rivers and sea)

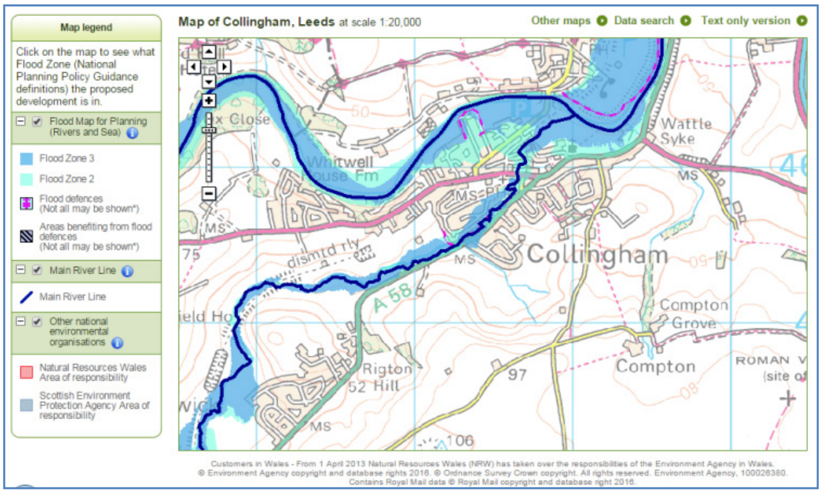
Primary purpose

Support the National Planning Policy Framework and the work of Local Planning Authorities when considering planning applications.

Key assumptions

Ignore the presence of flood defences.

What to look for



Zone 3 - is shaded dark blue and shows areas where the chance of flooding in any one year is greater than or equal to 1% for river flooding and greater or equal to 0.5% for flooding from the sea.

Zone 2 - is shaded light blue and shows the area between zone 3 and zone 1. This represents an area where the chance of flooding in any one year lies between 0.1% and 1% (for rivers) or between 0.1% and 0.5% (for the sea). The outer edge of this zone is referred to as the Extreme Flood Outline (EFO).

Zone 1 - is un-shaded and shows areas where the chance of flooding in any one year is less than 0.1% from rivers and the sea.

Used for

High level screening – for example, use to identify infrastructure assets potentially at risk of flooding from river or sea flooding, ignoring the presence of flood defences.

Caution

Flood defences will significantly reduce the risk of flooding in many locations

Data is not of sufficient resolution to design resistance or resilience measures to reduce flood risk.

Risk of flooding from rivers and sea

Primary purpose

Provides an assessment of the chance of flooding in any given year, taking into account flood defences. It is sometimes also referred to as the National Flood Risk Assessment (NaFRA).

Key assumptions

Assessment includes flood defences and their condition, and the chance and effects of breach and overtopping.

What to look for

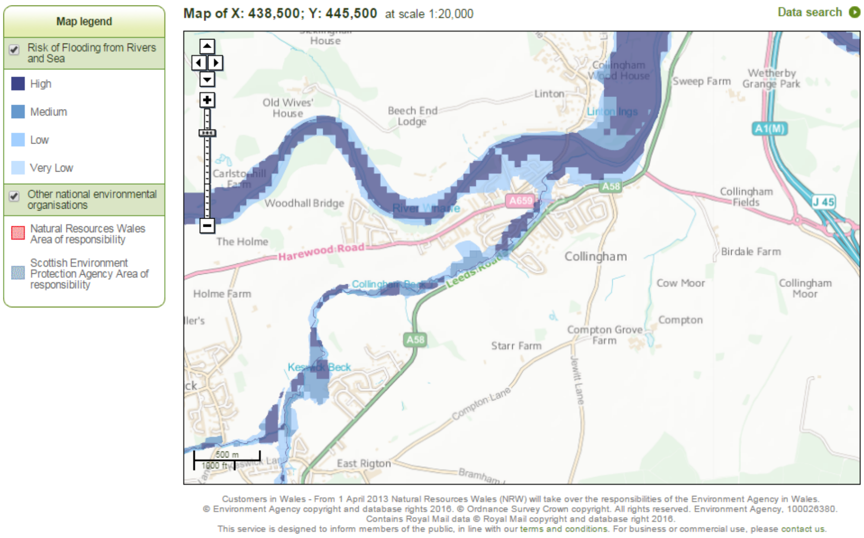
There are four flood likelihood categories:

High - Greater than or equal to 3.3% chance in any given year (darkest blue)

Medium - Less than 3.3% but greater than or equal to 1% chance in any given year

Low - Less than 1% but greater than or equal to 0.1% chance in any given year

Very Low - Less than 0.1% chance in any given year (lightest blue)



Used for

Prioritisation and ranking of residual flood risk (taking account of the benefits of flood defences) within the Extreme Flood Outlines. For example, important infrastructure at high likelihood of flooding should be considered first.

Caution

Flood defences reduce, but do not completely stop the chance of flooding as they can be overtopped, fail to operate as designed, or their capacity can be exceeded.

Not all flood defences types are directly included in the assessment.

It is important to understand the impact of flooding on an infrastructure asset: high likelihood of flooding may not mean high impact.

The modelling is not site specific, so is an indicator of risk but would need more detailed information to design or develop resilience measures.

Risk of flooding from surface water

Primary purpose

An assessment of where surface water flooding may occur when rainwater does not drain away through the normal drainage systems or soak into the ground, but lies on or flows over the ground instead. It is sometimes also referred to as the updated Flood Map for Surface Water (uFMfSW).

Key assumptions

Drainage is taken into account in urban areas, but drainage rates have generally not been validated.

Some data has been supplied by Lead Local Flood Authorities, from their local modelling and mapping.

What to look for

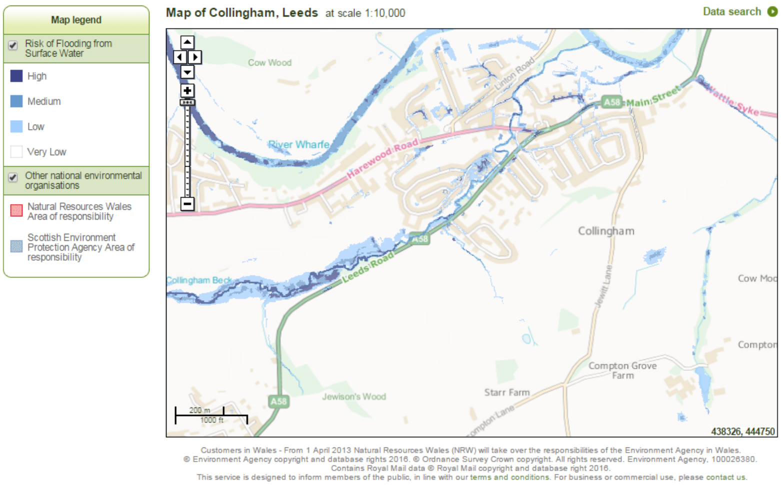
There are three categories showing the chance of flooding in any given year:

High means that each year, this area has a chance of flooding of greater than 3.3%.

Medium means that each year, this area has a chance of flooding of between 1% and 3.3%.

Low means that each year, this area has a chance of flooding of between 0.1% and 1%.

There is also information on the modelled depth and velocity of flooding for each of the different categories.



Information on estimated flood depth is available in the ranges: below 300mm, 300mm-900mm; and over 900mm

Information on velocity and flow direction is also available.

A separate layer shows the source of data, indicating whether from national or local detailed modelling.

Used for

High level screening – for example to identify infrastructure assets potentially at risk of flooding from surface water or near to an area identified as being at risk of flooding from surface water.

Caution

Additional investigation and discussions with the relevant Local Authority would be essential before designing any flood resistant or flood resilience measures.

Areas at risk of surface water flooding can be much more difficult to predict than river or sea flooding, because it is hard to forecast - or even record - exactly where or how much rain falls in any storm. Surface water flooding can be highly localised, and in some places the extent of flooding may be larger or smaller than shown.

Although the mapping appears very detailed, the majority of data is derived from a national model. Surface water flooding is particularly sensitive to obstacles and small changes in ground level, so consideration needs to be given to sites adjacent or near to an area shown at risk, as the flooding may occur in a slightly different location.

Annex 4 - Case studies

Overview

Six stress test case studies were undertaken in order to assess the likely extent of flooding under plausible extreme conditions, worse than any observed. The case study areas (Carlisle, Calder Valley, Oxford, Exeter, Great Yarmouth, tidal Thames in London) were selected to cover a range of different river types as well as coastal situations. This work also enabled the performance of the Environment Agency models used in the tests to be evaluated under such extreme conditions. For the river case studies, extreme rainfall scenarios were provided by the Met Office, based on recent extreme records together with a plausible uplift. In addition, the models were set up with the river catchments being fully saturated from the outset in order to provide as stringent a test as possible. For the coastal case studies, recent storm surges were combined with highest astronomical tides.

Case study 1: Carlisle study area

Figure 1: Carlisle – December 2015.

Introduction

Flooding in Carlisle has a long history, with major floods recorded in 1771, 1822, 1856, 1925, 1931, 1968, 2005, and recently December 2015 (figure 1). Studies after the January 2005 event assigned it a return period of around once in 200 years (0.5% annual probability), and the historical record appeared to support this. Flood alleviation schemes built after the 2005 event prevented flooding from a new highest event on record on the Caldew in June 2012.

The December 2015 event was chosen as the basis for this case study as it is the largest known flood event. Rainfall totals were exceptional, though highly variable spatially. The rain gauge at Honister recorded the highest 24 hour rainfall recorded in the UK at 341.4mm, and although this is not in the Eden catchment, a rain gauge within the catchment, at Brotherswater, recorded 293.4mm in 24 hours. At the start of the event the ground was saturated and river and lake levels were high. More than 2,100 properties were flooded in the area of Carlisle City Council, and over 400 properties were flooded in the Eden catchment upstream of Carlisle. As in many of the previous events, flooding in Carlisle (figure 2) occurred from both the Eden itself as well as from the lower reaches of the tributary rivers of the Caldew and Petteril, which were backed-up by the Eden.

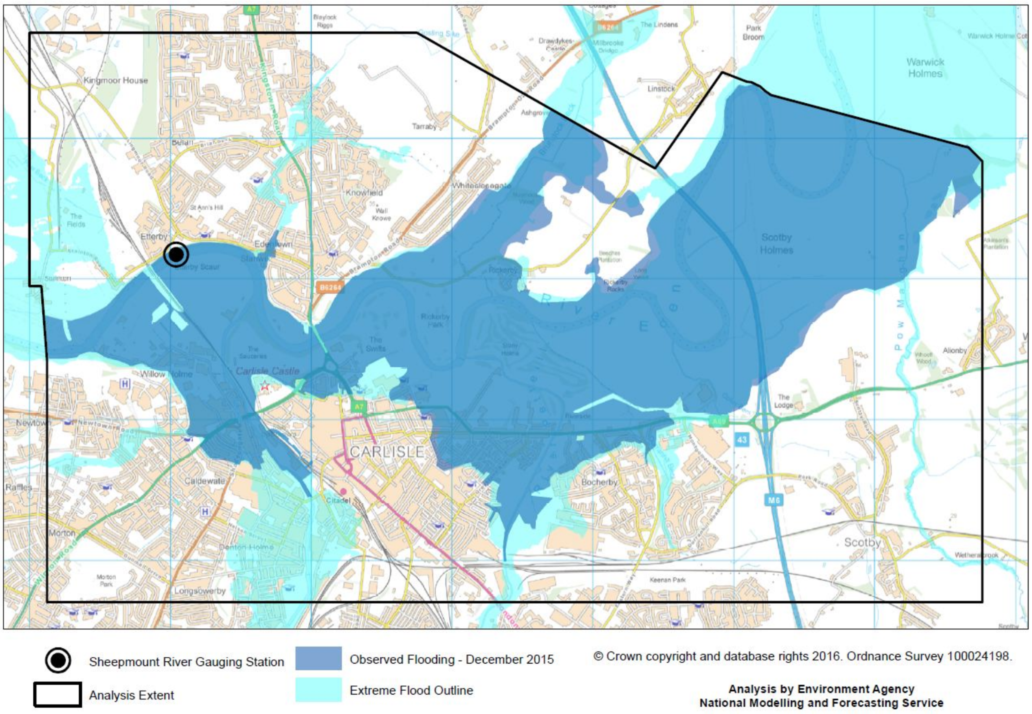


Figure 2: Carlisle case study – observed December 2015 flood extent and the Extreme Flood Outlines.

Scenario Used

The plausible extreme rainfall scenario generated by the Met Office added a 20% uplift to the heavy rainfall experienced in early December from Storm Desmond. The rainfall was used as a stress test input to the local detailed model developed for Carlisle as part of designing the flood alleviation scheme in the City.

Results

For the Carlisle study area, flood levels would increase between 0.2m (Cummersdale) and 0.8m (Sheepmount) compared with the observed flood levels in December 2015, as shown in Table 1.

Table 1: Results for the Carlisle study area (*mAOD – metres Above Ordnance Datum).

Gauging station location	Dec 2015 flood levels (mAOD)*	Modelled flood levels based on extreme rainfall scenario (mAOD)	Difference between observed and extreme rainfall scenario (m)	Modelled flood levels for the published Extreme Flood Outlines (mAOD)	Difference between extreme rainfall scenario and Extreme Flood Outlines (m)
Sheepmount	14.58	15.40	0.82	15.51	0.11
Cummersdale	25.30	25.48	0.19	25.85	0.37
Great Corby	25.63	26.02	0.39	26.63	0.61

At 3%, the increase in flood extent between the December 2015 event and the stress test is comparatively small, due to the shape of the flood plain in this location (figure 3). Should a flood of this magnitude happen, it would mean an additional 280 properties would flood in the Carlisle study area compared to the December 2015 floods.

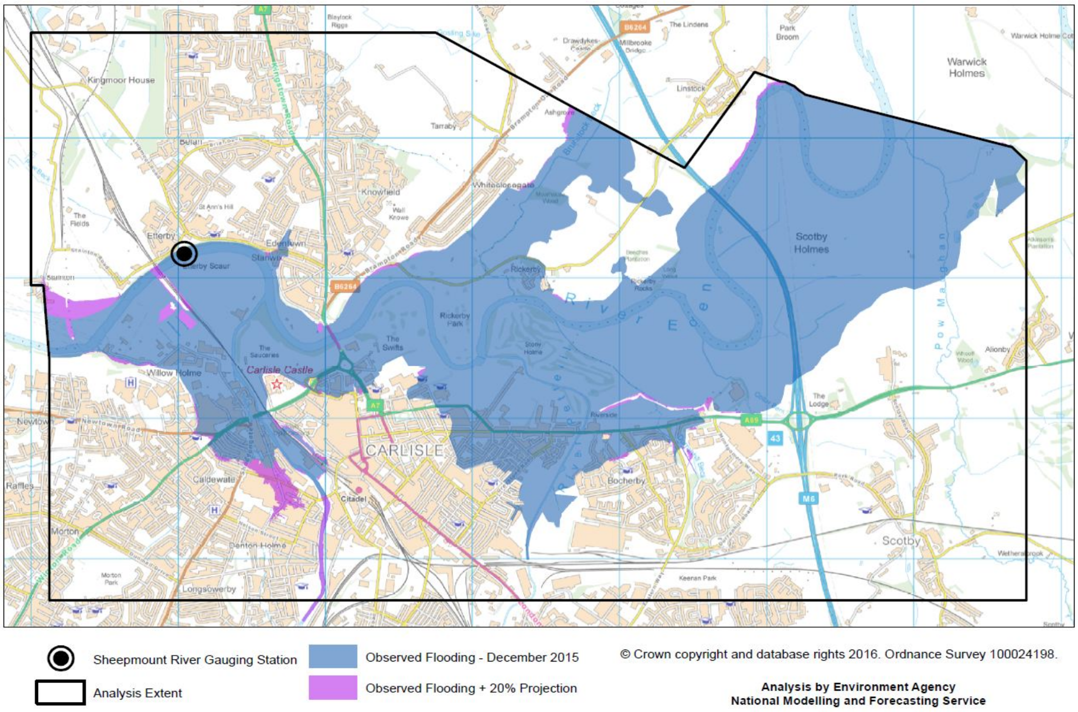


Figure 3: Carlisle case study – observed December 2015 flood extent and the modelled stress test scenario. Note that due to the shape of the flood plain, the differences in extent are very small.

Findings suggest, however, that even with this increase in flood depth, modelled flood levels remain 0.1 to 0.6m below those in the published Environment Agency Extreme Flood Outlines. If a flood of this magnitude happened, an estimated additional 3000 properties would be at risk of flooding in the wider Carlisle area.

Conclusions

For the Carlisle case study, the plausible extreme rainfall scenario would result in increased river flows and a larger flood extent. Additional property flooding would also be likely as a result.

The extent of flooding would remain within the Extreme Flood Outlines for Carlisle. In many places the flood extent would be at, or very close to, the Extreme Flood Outlines.

Case study 2: Calder Valley study area

Figure 4: Mytholmroyd – January 2016.

Introduction

The River Calder is a predominantly urban river, set in relatively steep and narrow valleys on the southeast edge of the Pennines. Serious flooding risks exist and have been addressed in part by a considerable number of channel improvements and flood defence schemes along the river, including those at Todmorden, Mytholmroyd, Sowerby Bridge, Copley, Elland and Brighouse.

However, significant areas on the Calder remain at risk from flooding. The River Calder has a very long history of notable floods: 1615, 1673, 1722, 1775, 1866, 1891, 1901, 1920, 1935, 1938, 1944, 1945, 1946, 1947, 1962, 1965, 1967, 1975, 1978, 1982 (June, Aug, Dec), 1986, 1989, 1990, 1991, 1992, 1995, 2000, 2006, 2008, 2012 (June, July), and 2015 (Nov, Dec).

Before the 26th December 2015 event, the Calder Valley had experienced a number of heavy and prolonged periods of rainfall throughout November and December leading to saturated catchments. Over Christmas and Boxing Day, Pennine areas had over 60mm of rainfall in 24 hours and some locations had over 100 mm. The saturated catchments and the heavy rainfall led to a rapid river rise in the Calder Valley with many river level stations recording their highest levels ever.

Over 2,200 homes and 1,600 businesses were seriously affected with a building being washed away in Mytholmroyd and Elland Bridge being seriously damaged. In addition to this a number of substations, schools, roads and bridges were also damaged. The communities of Todmorden, Hebden Bridge and Mytholmroyd (figure 4), Sowerby Bridge, Elland and Brighouse were all seriously flooded.

Scenario Used

The plausible extreme rainfall scenario generated by the Met Office added a 20% uplift to the heavy rainfall observed in late December 2015. This rainfall was used as an input into a local detailed model. Because of the complex arrangement of man-made structures in the area, for example bridges and canals, the model is calibrated to water depths, rather than flows to give a more accurate representation.

Results

For the three locations in the Calder Valley study area, flood levels would increase between 0.2m (Wakefield) and 0.9m (Mytholmroyd) under the stress test scenario, compared with the observed flood levels in December 2015, as shown in table 2.

Table 2: Results for the Calder Valley study area.

Gauging station location	Dec 2015 flood levels (mAOD)	Modelled flood levels based on extreme rainfall scenario (mAOD)	Difference between observed and extreme rainfall scenario (m)	Modelled flood levels for the published Extreme Flood Outlines (mAOD)	Difference between extreme rainfall scenario and Extreme Flood Outlines (m)
Hebden Bridge	103.70	104.13	0.43	104.28	0.15
Mytholmroyd	93.36	94.23	0.86	95.18	0.95
Wakefield	23.61	23.83	0.21	24.52	0.30

The difference in flood extent between the Dec 2015 extent and the stress test extreme rainfall scenario is an increase of 31% (0.8ha) for Hebden Bridge and 43% (1.7ha) for Mytholmroyd, reflecting the shape of the flood plain in this location (figure 5). Under this scenario up to 400 more properties would be flooded in the Mytholmroyd area and a similar number in Hebden Bridge.

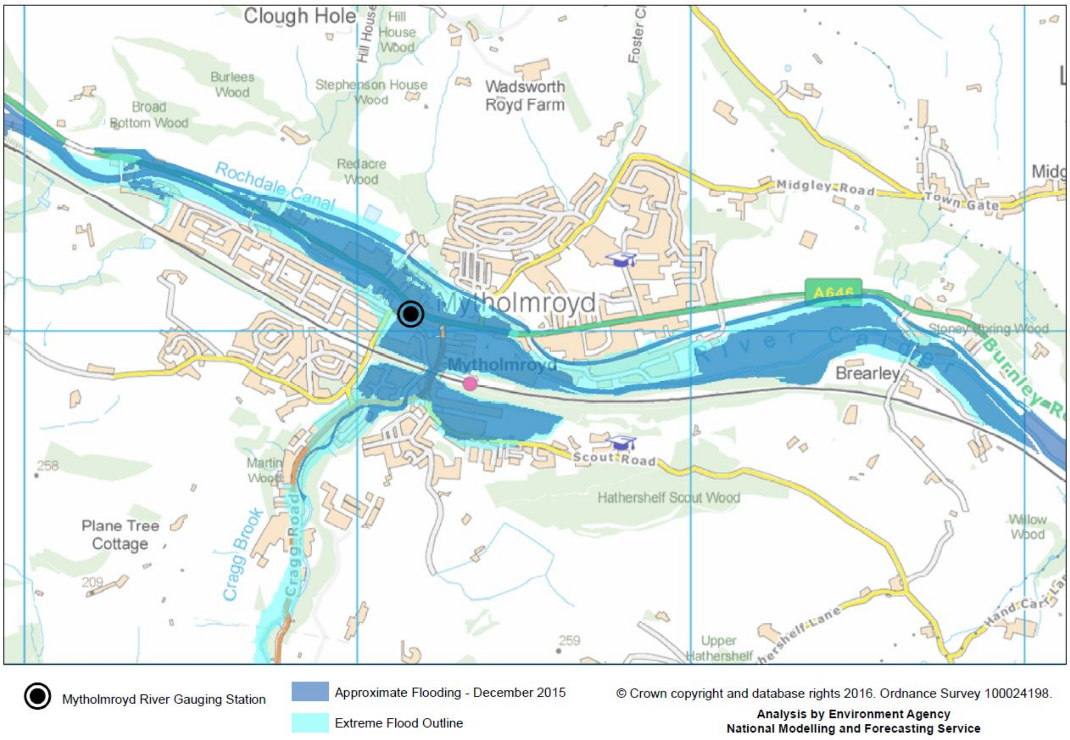


Figure 5: Mytholmroyd (Calder) – approximate observed December 2015 flood extent and the Extreme Flood Outlines. The extent of flooding under the stress test scenario is so close to the Extreme Flood Outlines that it has not been mapped separately.

For Wakefield, further downstream on the river Calder, flood levels would also increase, but to a lesser extent. This highlights that changes in flood extent will always be affected by the duration, intensity and distribution of the rainfall but also on the nature and size of the catchment.

Even with this increase in flood depth, the modelled stress test flood levels remain 0.15 to 0.95m below those in the published Environment Agency Extreme Flood Outlines. Consequently the areas that would be affected by this plausible extreme rainfall scenario in Hebden Bridge and Mytholmroyd are likely to be within existing areas known to be at flood risk.

Conclusions

The stress text plausible extreme rainfall scenario would increase the area of flooding in the Calder Valley with additional properties being flooded as a result. Flooding under this extreme scenario would be expected to be very close to or at the Extreme Flood Outlines.

Case study 3: Oxford study area

Figure 6: aerial view of the Thames floodplain at Oxford, January 2014.

Introduction

The River Thames has one of the longest-running archives of water levels in the UK, with records stretching back to the late 19th century. Documentary evidence for flooding extends further still and gives a unique insight into the behaviour of the catchment. Notable floods were recorded in the Oxford area in 1852, 1894, 1903, 1947, 2000, 2003, 2007, 2012 and January 2014.

For this case study the January 2014 event (the most recent notable flooding in the city) was chosen as the basis for the plausible rainfall scenario. River Thames levels rose steadily from mid-December onward, driven by heavy rainfall from a succession of deep Atlantic low pressure systems. The highest levels in Oxford were recorded between 8 and 10 January 2014. Homes and businesses were flooded internally, and key road and rail links were affected for up to a week.

Water naturally drains slowly in the Thames catchment and it can be 3 to 5 days after the rainfall that the highest levels are recorded at Oxford. Levels then take 1-2 weeks to return to normal, which makes the catchment vulnerable to successive storms. Repeated rainfall events generate flood peaks on the tributaries that then add additional water to an already inundated Thames floodplain (figure 6).

Scenario Used

The Met Office plausible extreme rainfall scenario added a 30% uplift to modelled rainfall estimates for December 2013 and January 2014. This extreme rainfall scenario was then fed into the Environment Agency's 'Oxford Thames' flood forecasting model.

This operational model is the primary tool used to predict flood levels in and around Oxford. Predictions from the model are used to support flood warning and resource planning decisions. Normally the inputs are observed rainfall data from Environment Agency rain gauges and weather forecasts from the Met Office. For the purposes of this stress test the model was reconfigured to use the extreme rainfall scenario as the primary input. The model outputs were then analysed and compared to what was actually recorded in at Environment Agency monitoring stations in the study area.

Results

Under the stress test scenario, the flood levels in the Oxford study area would increase by between 0.07m (Godstow Lock) and 0.31m (New Botley) compared with the observed flood levels in January 2014, as shown in table 3 below. Upstream of Oxford (Godstow Lock) there is an extensive floodplain so the increase in water levels in this area is relatively low. The floodplain narrows at Oxford, and it is also further constricted by urban development. As a result the change in water levels is greater (as indicated by levels at Osney Lock and New Botley).

Table 3: Results for the Oxford study area.

Gauging station location	Jan 2014 recorded flood levels (mAOD)	Modelled flood levels based on extreme rainfall scenario (mAOD)	Difference between observed and extreme rainfall scenario (m)	Modelled flood levels for the published Extreme Flood Outlines (mAOD)	Difference between extreme rainfall scenario and Extreme Flood Outlines (m)
Godstow Lock	57.90	57.97	0.07	58.08	0.11
Osney Lock	56.34	56.58	0.24	56.63	0.05
New Botley	56.92	57.23	0.31	57.43	0.20

Should a flood of this magnitude happen, it could mean several hundred additional properties could be affected in the Oxford study area compared to the January 2014 floods. The modelled flood extent is shown in figure 7 and the additional area affected in figure 8. Property counts are in table 4.

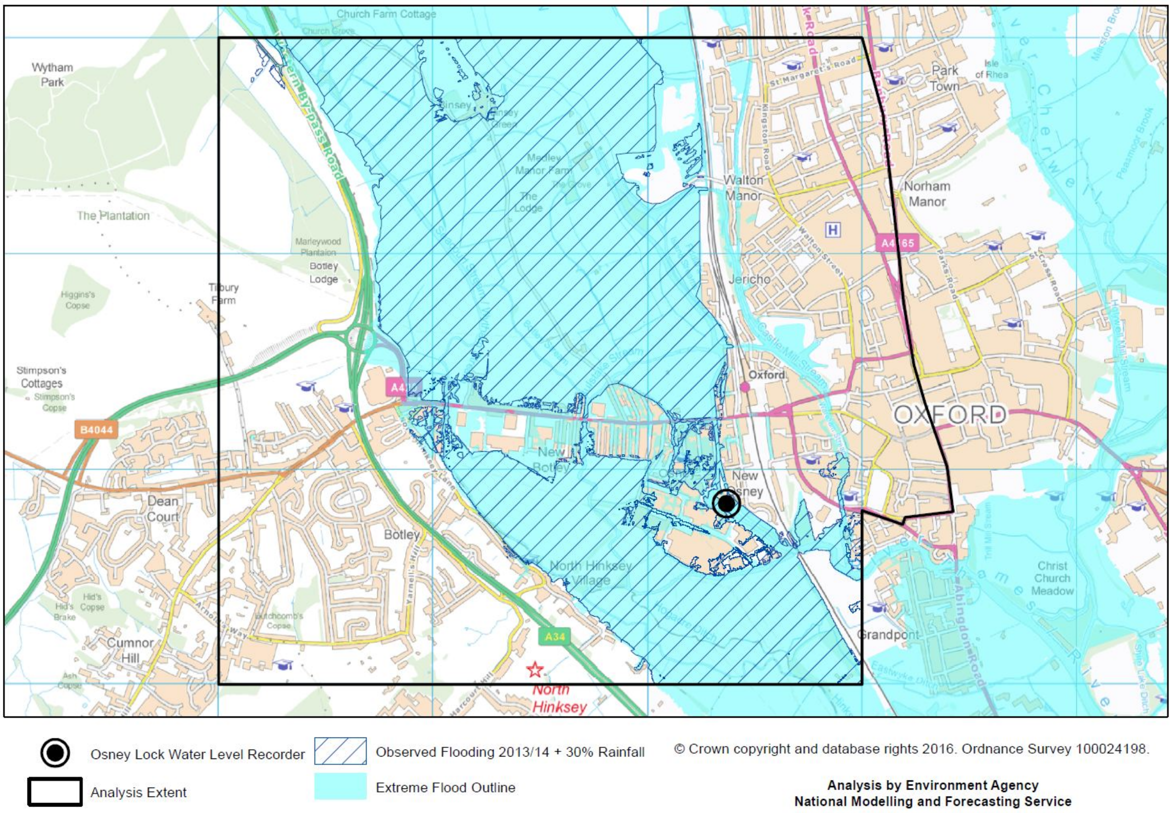


Figure 7: Oxford case study – modelled stress test scenario and the Extreme Flood Outlines.

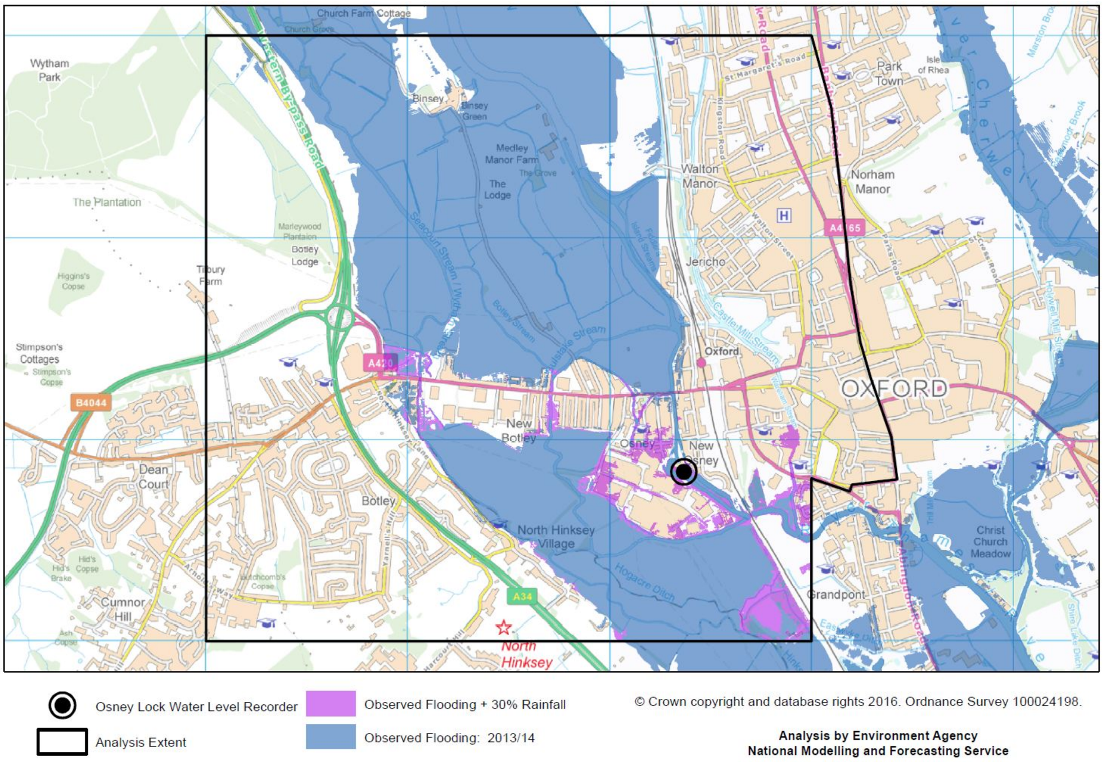


Figure 8: Oxford case study – observed January 2014 flood extent and the stress test scenario.

Table 4: Number of properties affected.

	Properties within analysis extent	Properties within Extreme Flood Outlines	Properties flooded internally in Jan 2014 flood event	Modelled properties affected in Jan 2014 flood event	Modelled properties affected in extreme rainfall scenario (2013/4 +30%)
Residential	10,150	900		150	300
Non Residential	2,750	250		50	150
Total	12,900	1,150	21	200	450

In January 2014 and other recent floods, temporary defences and pumps were deployed to help reduce the impact of flooding in high risk areas (figure 9). The effects of such defences were not considered in this analysis, but they could help reduce the number of additional properties affected.

Under the extreme rainfall scenario, modelled flood levels range from 0.05m to 0.20m below those in the published Environment Agency Extreme Flood Outlines.

Figure 9: Temporary defences deployed in Oxford in January 2014.

The number of properties that were reported as flooded internally differs significantly from those modelled to have been affected in this analysis. As mentioned above actions taken by the Environment Agency to help alleviate flooding were not included in this analysis. Assumptions also had to be made when counting properties as flooded in this study – a simple approach was used that does not capture the full complexity and detail of the situation. These counts are therefore likely to be an overestimate and should be treated as indicative only.

Conclusions

For the stress test case study, a plausible extreme rainfall scenario of a 30% uplift to the January 2014 event would lead to increased river flows and a larger flood extent. The analysis shows that additional property flooding would also be likely.

Temporary flood defences have been deployed in Oxford in recent events and these have helped reduce the impact of flooding in high risk areas. Options for a permanent scheme to alleviate flooding are currently under consideration. These measures may help reduce the impact of future flooding.

Under the extreme scenario the flooded extent would be expected to remain within the Extreme Flood Outlines. In some areas the difference would be close enough that it is difficult to draw a clear distinction between the two. However, there are no signals suggesting that an area significantly larger than the EFO would be affected.

Case study 4: Exeter study area

Figure 10: Exeter – December 1960.

Introduction

The Exe catchment has suffered a long history of extreme flood events since as early as 1286 (from historical records). The urban area of the city of Exeter was affected by serious flooding six times within 50 years between 1910 and 1960. Two extreme flood events in October and December 1960 (figure 10), which resulted in over 1000 properties flooding during each event (figure 11), and led to the construction of the Exeter flood alleviation scheme, which was completed in 1978.

Since the completion of the scheme, January 1999, October 2000, December 2000 and December 2012 were the most recent notable events that occurred on the River Exe, however none of these events led to flooding of the low-lying areas of Exeter and the flood alleviation schemes operated successfully.

Further improvements to the Exeter flood alleviation scheme, which are currently in progress, will further reduce the risk of flooding to the city (figure 12).

For this case study, the rainfall causing the December 1960 flood event has been used as the basis for this stress test as it is the largest recorded flood on record, and affected a significant number of properties.

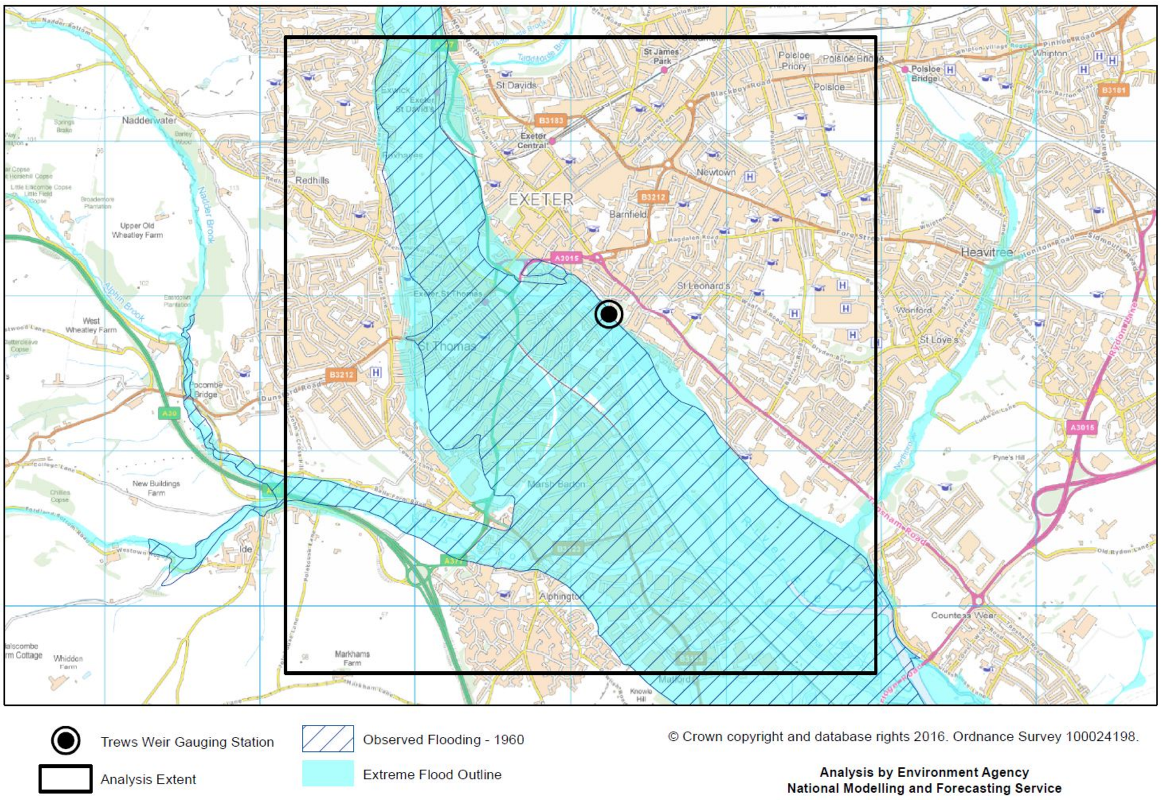


Figure 11: Exeter case study – observed December 1960 flood extent and the Extreme Flood Outlines.

Scenario Used

Because detailed weather modelling was not available in 1960, rain gauge data from representative gauges on Exmoor were used to calculate a suitable scaling factor in order to derive a detailed rainfall scenario for the December 1960 flood event, to which a 30% uplift was added. This scenario was used to provide inflows for the EA's detailed, calibrated 1D-2D hydraulic model of the River Exe.

There are no recorded (gauged) flood levels or flows for the December 1960 flood event, however historic reports suggest a flow of around 700 cubic metres per second (cumecs) in the River Exe through Exeter. Using our calibrated hydraulic flood model we can calculate that this flow would equate to a water level of around 6.9mAOD at Trews Weir Gauge in Exeter.

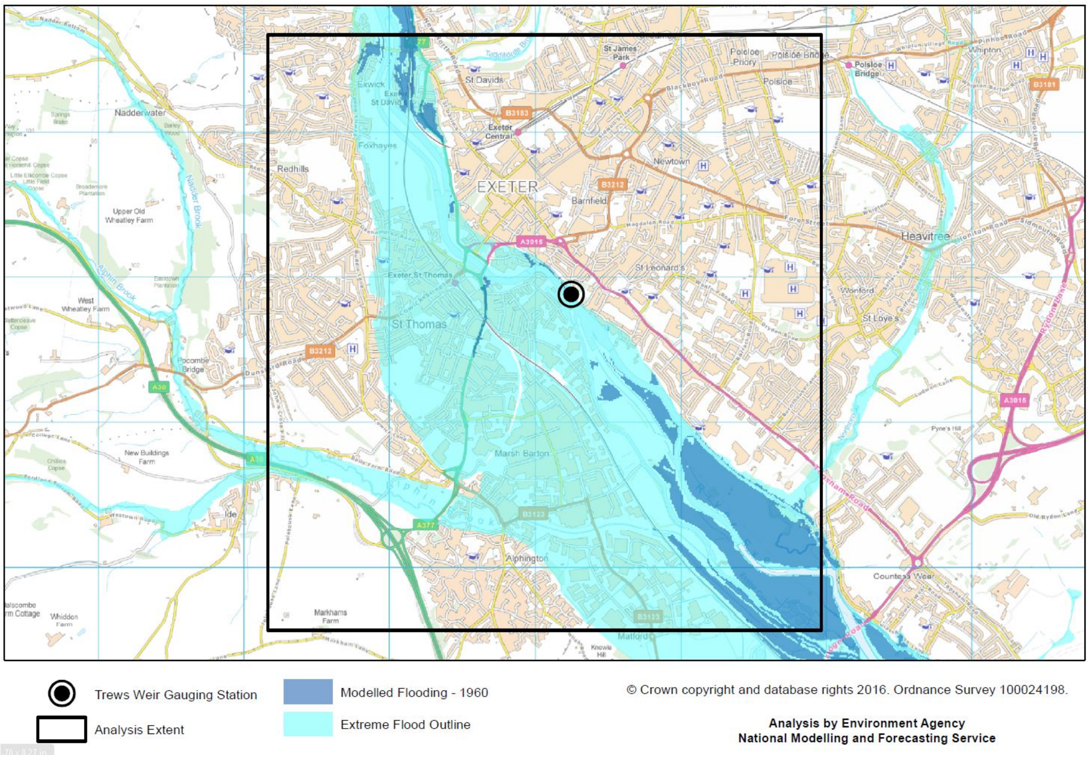


Figure 12: Exeter case study – modelled December 1960 flood extent with present day alleviation scheme and the Extreme Flood Outlines

Results

Our model runs have shown that the stress test extreme rainfall scenario would increase flood depth levels in Exeter by only 0.06m (table 5). The difference in flood extent between the modelled 1960 event and the stress test scenario is however significantly different – with an increase of 185% (figure 13). In an event of this magnitude a large proportion of the flow would be out-of-bank and so a small increase in water levels in-channel would lead to a much larger increase in the number of properties at risk of flooding.

Table 5: River level results for the Exeter study area.

Gauging station location	Modelled Dec 1960 flood levels (mAOD)	Modelled flood levels based on extreme rainfall scenario (mAOD)	Difference between observed and extreme rainfall scenario (m)	Modelled flood levels for the published Extreme Flood Outlines (mAOD)	Difference between extreme rainfall scenario and Extreme Flood Outlines (m)
Exwick	12.08	12.43	0.35	13.45	1.02
Trews Weir	6.85	6.91	0.06	7.41	0.50

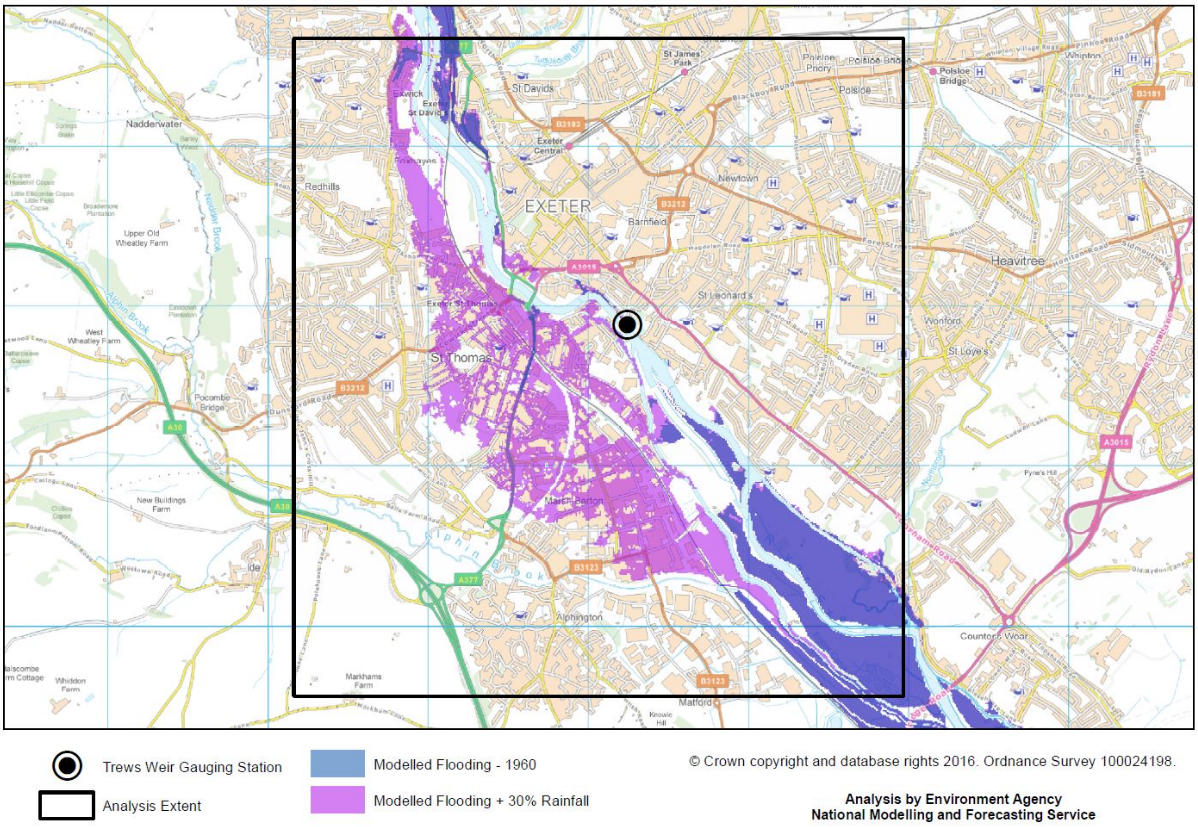


Figure 13: Exeter case study – modelled December 1960 flood extent and the modelled stress test scenario (both with present day alleviation scheme in place).

Should a flood of the same magnitude of December 1960 occur today, only circa 200 properties would flood in the Exeter study area, thanks to the flood defences built since then (table 6). If the extreme rainfall scenario occurred today circa 2,250 additional properties would flood in Exeter.

Table 6: Flooded property results.

	Properties within analysis extent	Properties within Extreme Flood Outlines	Properties flooded in Dec 1960 flood event	Modelled properties affected in Dec 1960 flood event	Modelled properties affected in extreme rainfall scenario (1960 +30%)
Residential	30,200	5,800		200	2,050
Non Residential	400	1,000		0	400
Total	30,600	6,800	1,200	200	2,450

However findings suggest that even with this increase in flood depth, modelled flood levels remain 0.5m below those in the published Environment Agency Extreme Flood

Outlines for Exeter. If a flood of the same magnitude as the EFO occurred today, (approximately) an additional 4,350 properties would flood in the Exeter study area when compared to the stress test scenario.

It is important to note that the property numbers quoted for 1960 and the stress test scenarios are based on the modelled scenario which is based on present day infrastructure and flood alleviation scheme which was constructed after the 1960 floods. Historic records state that circa 1,200 properties flooded in Exeter during the December 1960 flood event, our modelling predicts that this number would be reduced to circa 200 if the same event occurred in the present day.

Conclusions

Flood events since 1960 have led to few properties being inundated, in part due to the flood alleviation scheme which was built following the 1960 floods. Flooding from an event of the same magnitude of December 1960 event today would be significantly reduced (85% less properties) due to the Exeter flood alleviation scheme.

The stress test scenario would lead to flooding of around 2,500 properties; however the flood extent would still be well within the published EFO.

The Exeter flood alleviation scheme has been improved further in the past 2 years reducing flood risk further. The modelling used for this case study does not take account of these latest improvements and so provides a conservative outlook.

Case study 5: Great Yarmouth study area

Figure 14: Bridge Road, Great Yarmouth – December 2013.

Introduction

Great Yarmouth has a history of flood risk: in the 1953 East Coast floods around 3500 homes were damaged in Yarmouth and 10 people lost their lives. The December 2013 (figure 14) surge reached a slightly higher level in Great Yarmouth than that recorded in 1953, however, due to improved tidal defences and flood warnings the impacts were much lower (figure 15). Twenty properties were flooded in the area adjacent to the River Yare, caused by seepage and overtopping of defences. Since 2013 there has been ongoing work to improve flood defences in Great Yarmouth.

Great Yarmouth is primarily at tidal flood risk, with the highest risk being from the effect of the tidal surge on levels in the River Yare. During more extreme events, some exposed parts of the town are also at flood risk from the open sea.

Scenario Used

In discussion with the Met Office and the National Oceanography Centre (NOC) it was determined that a plausible stress test scenario would be for a storm surge similar to December 2013 to coincide with a recent Highest Astronomical Tide (HAT).

Figure 15: Great Yarmouth case study – observed December 2013 flood extent and the Extreme Flood Outlines.

The Environment Agency analysed the observed data from the December 2013 event to separate the storm surge residual (the part of the tide resulting from meteorological factors including wind stress and atmospheric pressure) from the astronomic tide at that time. This was then combined with the gauged record of the most recent HAT, in September 2015, ensuring that the surge residual was phased correctly against the HAT to maximise the peak total water level. The resulting total tide curve, which peaks at 3.58m, is shown in figure 16 below.

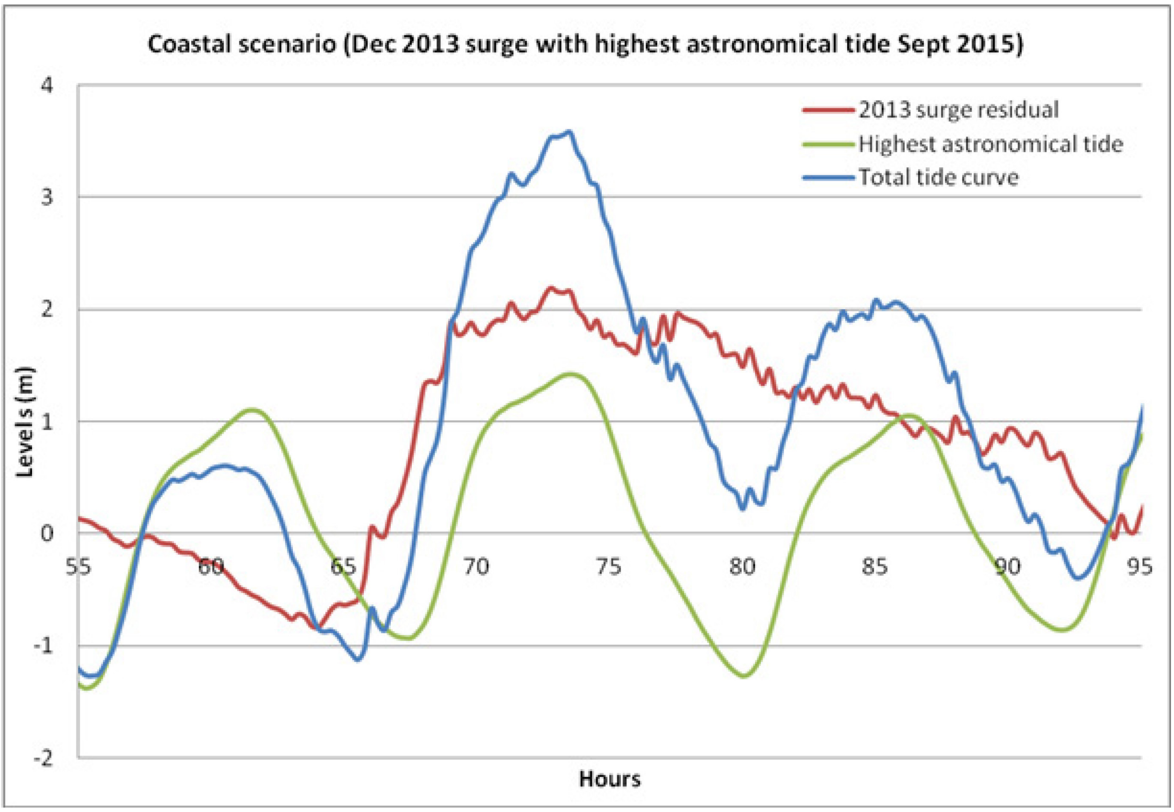


Figure 16: Elements used to create the stress test tidal surge scenario.

In order to assess the impact of this stress test coastal scenario, its peak level was compared to a set of detailed modelled ‘design scenarios’ generated from the detailed local model for the Great Yarmouth coast. The closest match was to a slightly more stringent scenario, with a peak tide level of 3.65m, which is 0.07m higher than that required for the stress test coastal scenario. The modelled design tide curve has a more prolonged peak than the stress test scenario tide curve, with a higher preceding tide, causing higher water levels in the Yare prior to the peak.

Consequently the results from using this slightly more stringent scenario in the case study provides a precautionary view of the impact of the stress test scenario.

Results

For the Great Yarmouth case study, the flood levels would increase by 0.26m, compared with the observed flood levels in December 2013, as shown in Table 7. The difference in flood extent between the December 2013 extent and the increased surge level in the case study is significant (figure 17). Due to increased overtopping of defences it more than doubles the area of the flood extent, covering an additional $2km^2$.

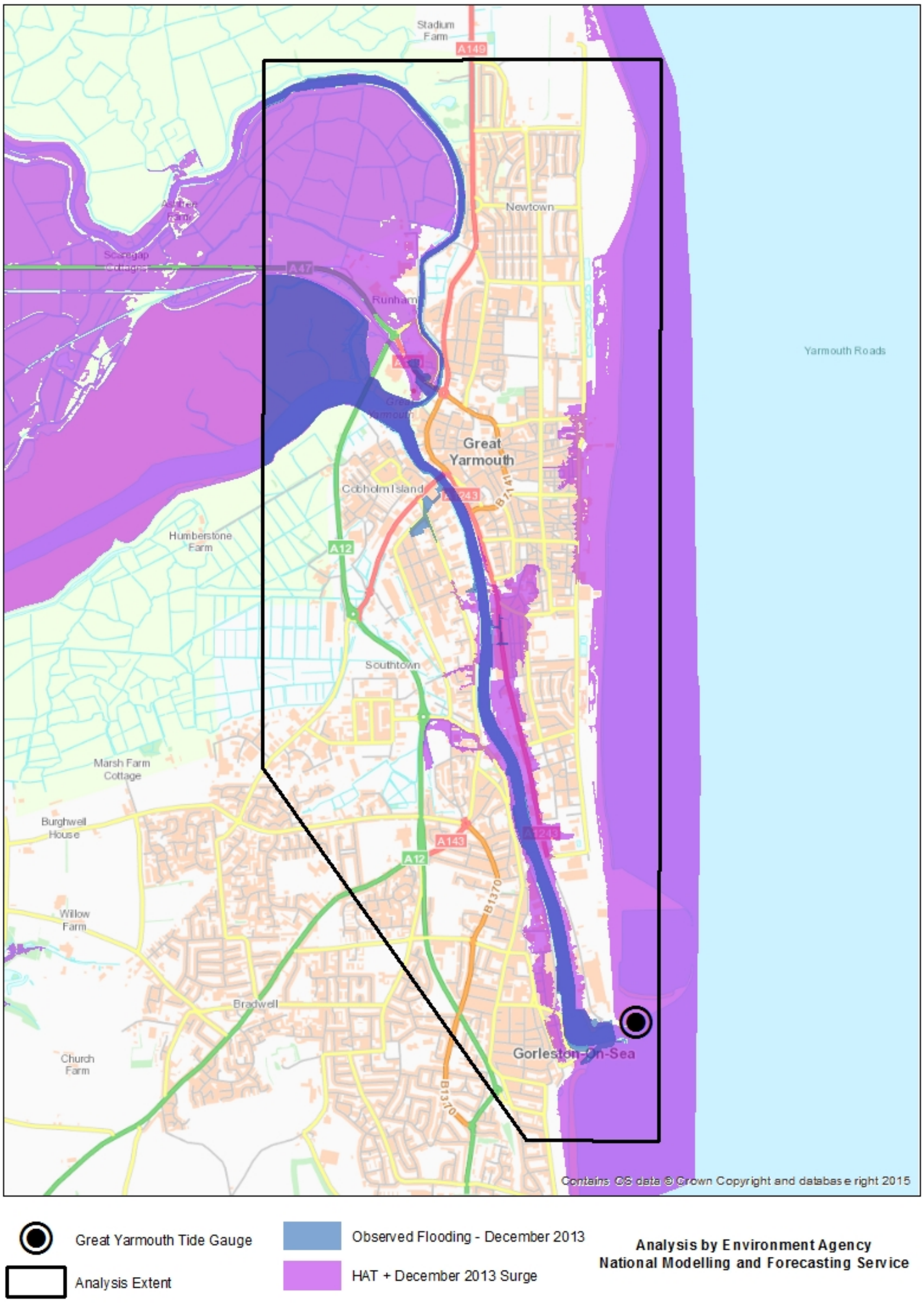


Figure 17: Great Yarmouth case study – observed December 2013 flood extent and the modelled stress test scenario. Note that some differences are due to seepage through defences in December 2013, which is not modelled.

Table 7: Results for the Great Yarmouth study area.

Gauging station location	Dec 2013 flood levels (mAOD)	Scenario Flood Level: December 2013 surge peak coinciding with HAT (mAOD)	Difference between observed and extreme surge scenario (m)	Modelled flood levels for the published Extreme Flood Outlines (mAOD)	Difference between extreme surge scenario and Extreme Flood Outlines (m)
Great Yarmouth	3.32	3.58	0.26	3.59	0.01

Should a flood of this magnitude happen, it would mean an additional 1700 properties would flood in the Great Yarmouth study area compared to the December 2013 tidal surge, when 20 properties were flooded.

The levels from this case study are very similar to those used in the Extreme Flood Outlines (figure 18). However, the Extreme Flood Outlines excludes the effect of flood defences, so more flood water can inundate the floodplain hence its extent is much greater as a result.

Conclusions

The stress test case study scenario would lead to a significantly larger flood extent than that seen in December 2013. The analysis shows that additional property flooding would also be likely.

Although the stress test case study flood extent is much smaller than the EFO in total, there are areas adjacent to the seafront where the extent is slightly greater. The results show that a small number of additional properties (0 – 100) which are currently outside the existing EFO may potentially be affected by flooding. However, since the modelled scenario is slightly worse than the stress test scenario as originally defined, the impact on the ground is likely to be overestimated and should be seen as a conservative estimate.

The predominant risk of flooding is due to the tidal surge propagating up the channel of the River Yare. There is currently a scheme to reduce the consequences of this effect underway to improve the flood defences through Great Yarmouth.

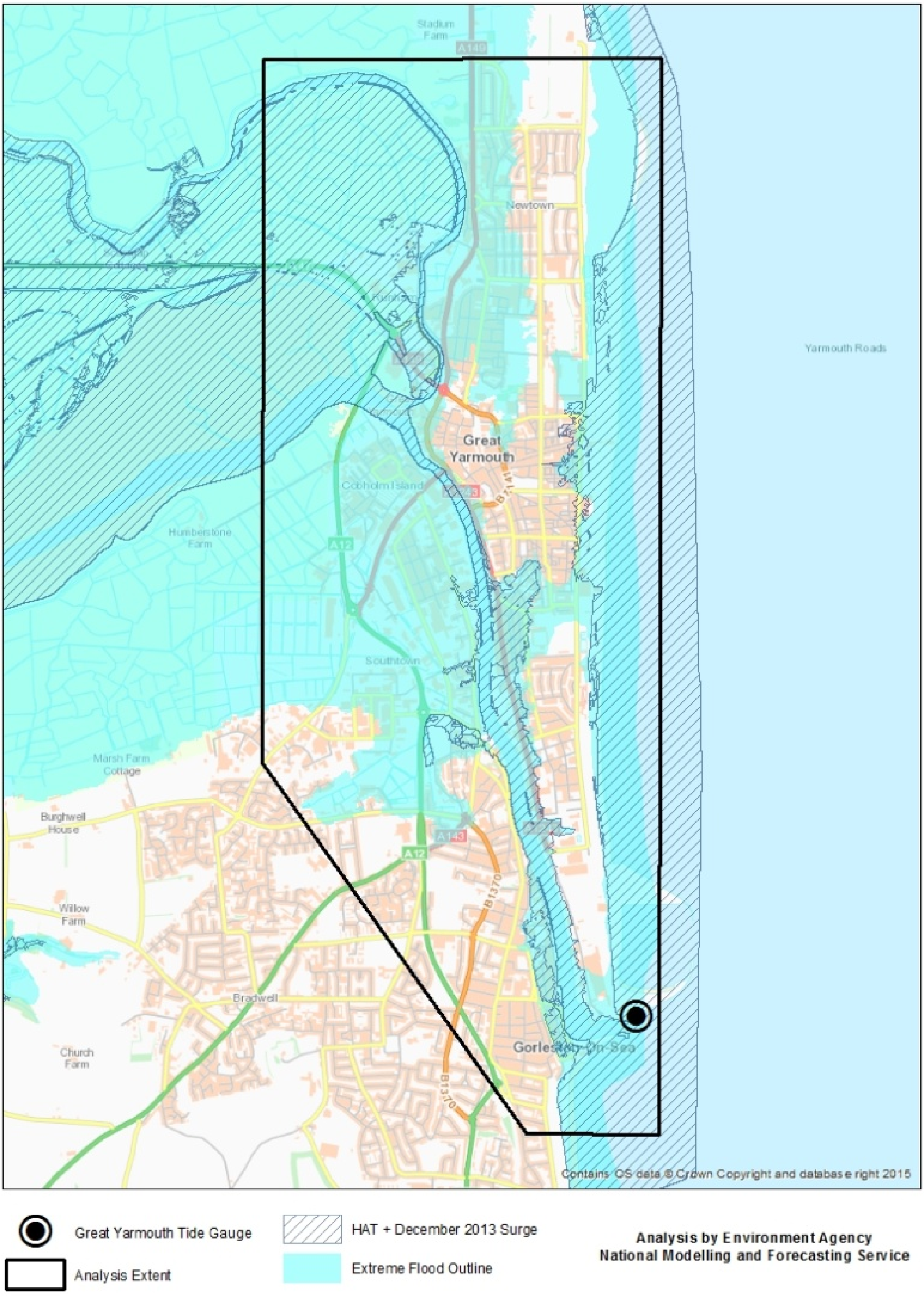


Figure 18: Great Yarmouth case study – modelled stress test scenario and the Extreme Flood Outlines.

Case Study 6: Tidal Thames in London study area (Thames Estuary between Teddington and the Thames Barrier)

Figure 19: The Thames Barrier, Thames Estuary.

Introduction

The flood risk to the tidal Thames floodplain is managed by a combination of walls, embankments and barriers, most notably the Thames Barrier (figure 19). The Thames Barrier and associated walls and embankments have been designed to contain, at a minimum, tidal water levels that have a 0.1% chance of occurring in any one year. This minimum standard of protection is currently estimated to continue up to 2070 even with considerations of projected sea level rise. The standard of protection now is considerably higher.

The storm surge of 6th December 2013, combined with the astronomical tide, formed the highest tidal levels at Southend (4.1mAOD) since the construction of the Thames Barrier in 1982. This level has been exceeded six times since 1911, most notably in 1953 when the tide reached 4.6mAOD. This is quite an outlier, with the second highest level being 4.24mAOD in 1949.

Downstream of Teddington there is also a risk of flooding from the fluvial flows in the Thames. During February 2014 the flow immediately upstream of Teddington reached 507 cumecs. This peak flow has been exceeded only seven times since 1883, most notably in 1894 when the discharge was reported as 806 cumecs.

Scenario Used

The stress test scenario used was a combination of extreme fluvial flow and tidal peak based on ‘worse versions’ of recent extreme events, to test whether the current flood risk management system across the case study area (figure 20) would prevent flooding.

The combination of extreme rainfall and tidal surge was agreed in discussion with the Met Office and the National Oceanographic Centre (NOC). The rainfall scenario would be based on winter 2013/14 records with a 30% uplift. This would be taken as coinciding with the storm surge that caused the December 2013 peak tide, superimposed on top of the highest recorded astronomical tide (HAT).

Fluvial

Firstly, the increase of flows due to extreme rainfall was derived using previous work undertaken for the Oxford case study. Using statistical methods the increased flows were seen to translate to a 27% average increase at Kingston which pushes the peak flow up to 644 cumecs which has a 2.86% chance of occurring in any one year.

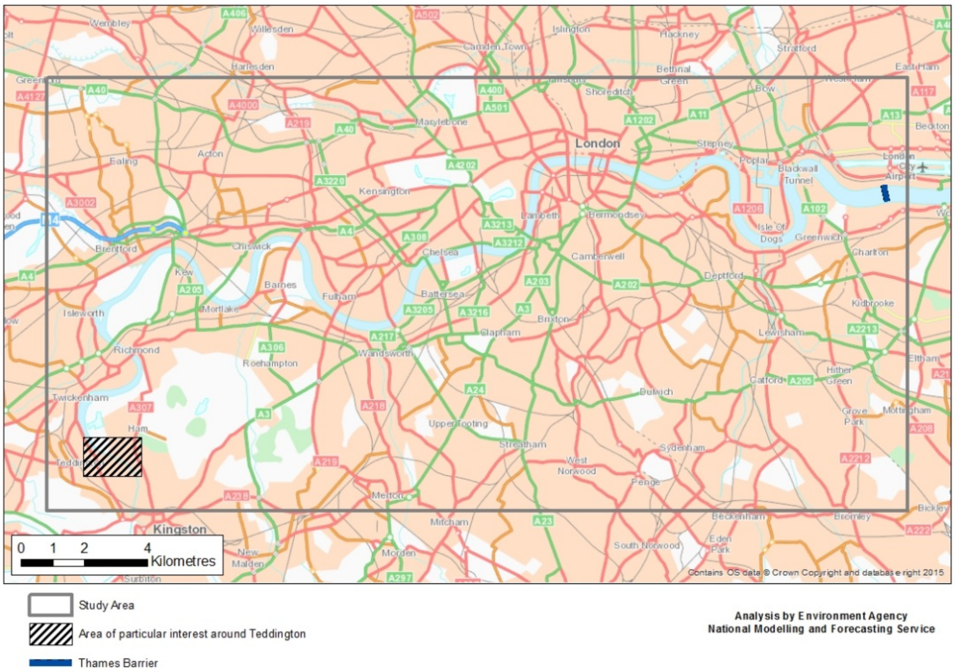


Figure 20: Thames case study area.

Tidal

The astronomical peak on the 6th December 2013 was 3.13mAOD at Southend. The storm surge raised the peak tidal level to 4.1mAOD (figure 21). If the same storm surge had occurred on the highest astronomical tide (3.52mAOD) the tidal level would have reached 4.5mAOD (approximately 1% chance of occurring in any one year at that location) (figure 22).

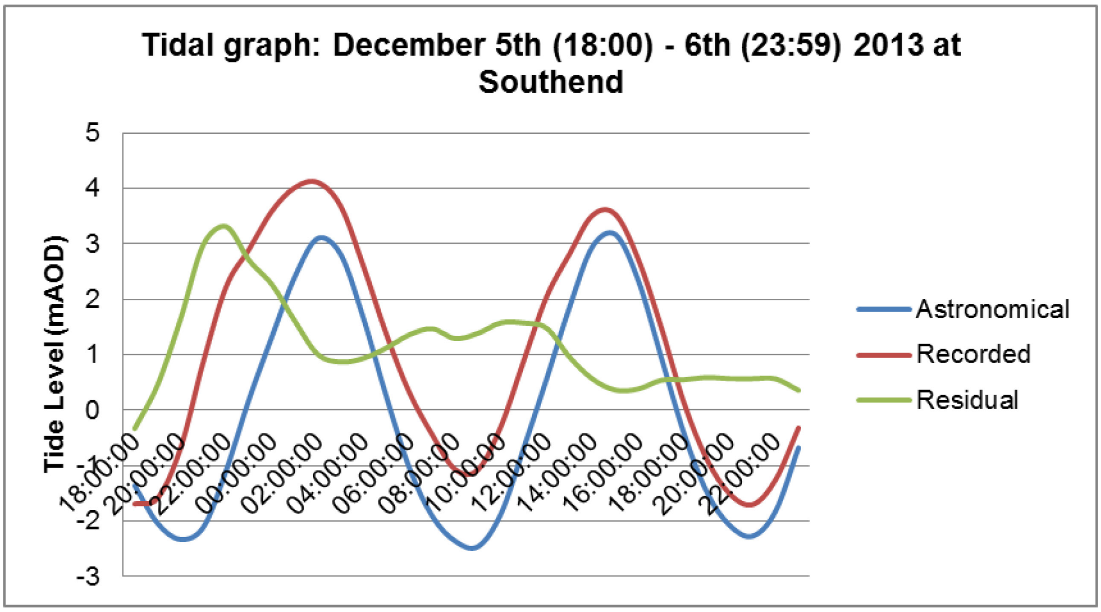


Figure 21: Observed tide at Southend 5th to 6th December 2015.

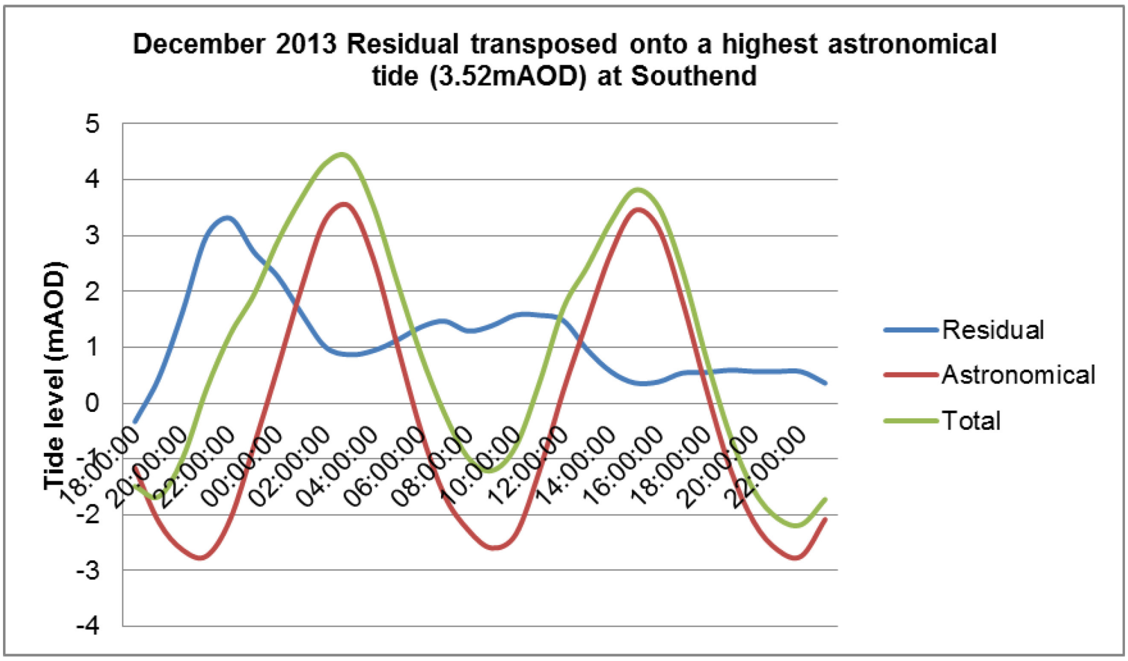


Figure 22: Combined tide and surge used for test scenario.

Hydraulics

To model the flow and the tide in the estuary, the Thames tidal flood forecast model, (based on the Flood Modeller Pro software) was used with a steady state discharge of 644 cumecs and the tidal boundary of the 2013 residual surge transposed onto the highest astronomical tide. A barrier closure was modelled when the tide reached 1mAOD after the first low tide at the Thames Barrier.

Results

Any tide above 3.7mAOD would most likely precipitate a Thames Barrier closure given an above average river discharge at Teddington. For this reason a closure was modelled and the resulting water levels can be seen in table 8.

Table 8: Water level results comparison.

Location	Observed event	Stress test scenario	Difference between stress test & observed	Modelled flood levels for the published EFO (mAOD)	Difference between stress test and EFO (mAOD)
Teddington	4.78 Feb 2014	5.67	0.89	7.10	-1.43
Thames Barrier U/S	2.96 Dec 2013 surge	2.10	-0.86*	6.20	-4.10**
Thames Barrier D/S	4.50 Dec 2013 surge	5.40	0.90	6.20	-0.80
Southend	4.10 Dec 2013 surge	4.50	0.40	4.95	-0.45

*The level is lower because of closure timing. It is desirable to re-open as soon as possible for river traffic. For this reason later closures are often used to 'take the top of the tide'. For a combined high flow and tide the barrier would most likely be closed earlier.

**The difference here is very large because the EFO excludes the effects of flood defences, such as the Thames Barrier.

Under this scenario, there is no overtopping within the tidal Thames between Teddington and the Thames Barrier. However, there is likely to be some flooding upstream around the Teddington area, possibly with flows coming around the defences on the land side and flowing into the study area. The stress test flood extent is illustrated in figure 23.

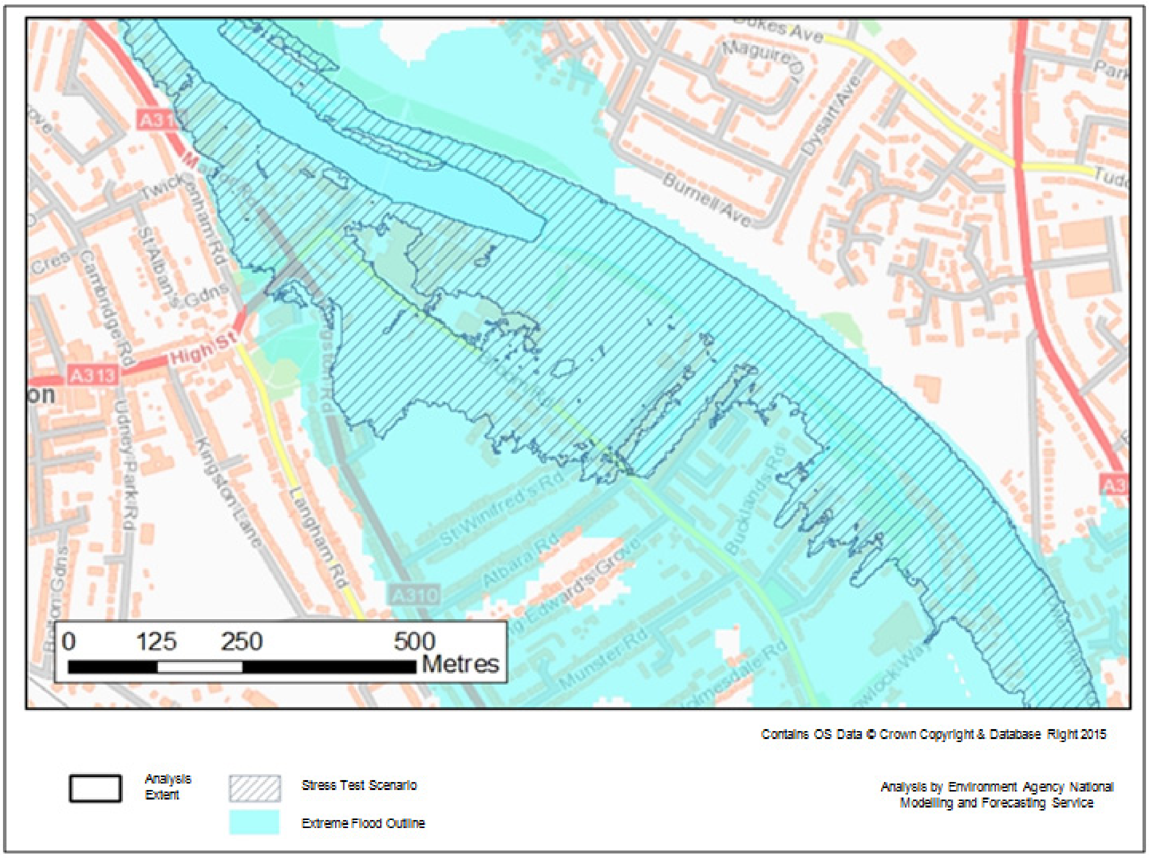


Figure 23: Thames case study – modelled stress test scenario and the Extreme Flood Outlines.

Conclusions

For this stress test the water level at Southend reaches a level of 4.5mAOD and precipitates a routine Thames Barrier closure just after the low tide before the peak. Due to the high standard of protection provided by the Thames Barrier and associated defences there is no overtopping in the study area. Low lying areas would be inundated with between 66 and 521 properties at risk (table 9). To put this into perspective; there has been no flooding to the properties on this area since the Thames Barrier was operational.

Table 9: An upper and lower estimate of properties flooding in this scenario.

	Properties within Extreme Flood Outlines	Stress test: upper projection	Stress test: lower projection
Residential	1,644	436	34
Non-residential	179	85	32
Total	1,823	521	66

The area at flood risk under the stress test scenario would be well within the published Extreme Flood Outlines.

Annex 5 - Membership of the Scientific Advisory Group

Professor Sir Mark Walport (Chair)	Government Chief Scientific Adviser
Professor Charles Godfray (Deputy Chair)	Chair of the Science Advisory Council, Department for Environment, Food and Rural Affairs and Hope Professor, University of Oxford
Professor Myles Allen	Professor of Geosystem Science, University of Oxford
Professor David Balmforth	Executive Technical Director, MWH Global and Visiting Professor, Imperial College London
Professor Paul Bates	Professor of Hydrology and Head of School in Geographical Sciences, University of Bristol
Professor Ian Boyd	Chief Scientific Adviser at the Department of Environment, Food and Rural Affairs and Professor in Biology, University of St Andrews
Dr Justin Butler	Managing Director, Ambiental
Professor Hannah Cloke	Professor of Hydrology, University of Reading
Professor Roger Falconer	Professor of Water Management, Cardiff University
Giorgis Hadzilacos	Divisional Director, Willis Towers Watson
Professor Jim Hall	Director of the Environmental Change Institute, University of Oxford and member of the Committee on Climate Change Adaptation
Professor Alan Jenkins	Deputy Director, Centre for Ecology and Hydrology (CEH), Honorary Professor, Lancaster University and Visiting Professor, University College London

Professor Rob Lamb	Director of JBA Trust and Honorary Professor, Lancaster University
Dr David Lavers	Scientist, European Centre for Medium-Range Weather Forecasting (ECWFM)
Professor Robert Nicholls	Professor of Coastal Engineering, University of Southampton
Professor Susan Owens	Professor of Environment and Policy, University of Cambridge
Professor Tim Palmer	Royal Society Research Professor in Climate Physics, University of Oxford
Nick Reynard	Science Area Lead for Natural Hazards, Centre for Ecology and Hydrology (CEH)
David Richardson	Head of Evaluation, European Centre of Medium-Range Weather Forecasting (ECMWF)
Professor Jon Tawn	Professor of Statistics, Lancaster University
Professor Sarah Whatmore	Professor of Environment and Public Policy, University of Oxford

Representing the National Flood Resilience Review at the meetings of the Scientific Advisory Group

Dr Fiona Harrison	Deputy Director, National Flood Resilience Review, Department for Environment, Food and Rural Affairs

Representing the Met Office and Environment Agency at the meetings of the Scientific Advisory Group and its subgroups

Sir James Bevan	Chief Executive, Environment Agency

John Curtin	Executive Director for Flood and Coastal Risk Management, Environment Agency
Paul Davies	Met Office Chief Meteorologist
Phil Evans	Government Services Director, Met Office
Dr Tony Grayling	Director, Sustainable Business and Development, Environment Agency
Shirley Greenwood	Expert Advisor, Flood Mapping, Modelling and Data Team, Environment Agency
Dr Sarah Jackson	Head of Strategic Engagement with Defra, Met Office
Stefan Laeger	Improvements and Resilience Manager, National Flood Modelling and Forecasting Service, Environment Agency
Dr Sean Longfield	Lead Scientist, Flooding and Communities Research, Environment Agency
Professor Dame Julia Slingo	Chief Scientist, Met Office
Dr Glenn Watts	Acting Deputy Director, Research, Environment Agency and visiting Senior Research Fellow, Department of Geography, Kings College, London
Professor Doug Wilson	Director, Scientific and Evidence Services, Environment Agency and Visiting Professor, Nottingham Trent University

Annex 6 - Principles and advice to inform communicating about flood risk

The Communication Sub-group of the Scientific Advisory Group has been involved during the National Flood Resilience Review in offering guidance on the communication of the science underlying the estimation of flood risk. This document summarises some of the general advice it provided and its intended audience is groups that in the future may be involved in the communication of flood risk.

Think carefully about the audience for any communication and do not address 'the public' as an undifferentiated aggregate of individuals

Estimates of flood risk will be anticipated and received by different public constituencies with greater or lesser degrees of flood experience and specialist knowledge. In any communication a decision should be made on which 'public' to prioritise as the target audience, whilst not losing sight of others who might be attentive to the findings. Communications should be comprehensible to an intelligent non-specialist. This requires a logical structure, clear articulation, arguments expressed without (or with clear explanations of) 'in house' language (specialist terminology, acronyms etc.), and with critical reflection on disciplinary norms and presumptions, for example about what constitutes valid evidence or how flood risks are interpreted and understood.

Avoid implying that target audiences are ignorant and simply require 'education'

In the past much communication has concentrated simply on information transfer and 'educating' the public[8]. However, the most engaged publics are likely to be those individuals, businesses and communities that have experienced flooding first-hand and therefore have heightened concerns and knowledge about the management of flood risk. These '*flood active*' publics tend to be highly aware, well informed, and motivated to help themselves and others ahead of, or in conjunction with, flood management agencies. 'Flood active' publics are particularly likely to want to know

[8] Often referred to as the 'knowledge deficit' model of communication, best practice today is to take a more sophisticated approach about knowledge interchange with different audiences

how any analysis and proposals improve or make a difference to the management of the flood risk with which they live.

Make data public and collect as well as disseminate information

Enable communities affected by flooding to themselves engage in exploring flood risks by making rainfall and flow gauge data publically available at an appropriate level of granularity. Facilitate their becoming 'citizen scientists' and collecting data helpful to future flood risk estimation and planning, including both scientific data and experiential information.

Provide an early explanation of the logic and structure of the central tenets and argument of any communication

Offer a clear account of connections between rainfall, river flows, and floods (and tides, where relevant). Provide information about the various sources that have been used, individually or in combination, in reaching conclusions. Diagrams and images (including photographic images) when used appropriately can assist in communicating these complex relationships more effectively. Be clear about the different components of flood risk, for example the probability of an extreme weather event and the chance that it has damaging consequences. Be explicit about whether flood risk estimates take into account existing flood defences.

Don't overclaim

Be clear and precise about the scope of any flood risk estimate and the types of flooding that it does and does not cover (for example: river, coastal, surface water and groundwater). Be aware that insurance contracts may use definitions of flooding that differ from common usage.

It is also important to convey clearly and consistently that flood risk estimation, like any other forecasting exercise (e.g. weather forecasting), has to deal with uncertainties. These uncertainties are inherent to the exercise and not (necessarily) the product of deficient techniques. This is best communicated by consistently using appropriate verbs (e.g. estimate, forecast, simulate) to describe the scientific techniques used in the management of flood risk. This helps to focus minds on what makes flood risk estimates reliable *as estimations* rather than undermining their utility by a misplaced and misleading emphasis on their empirical precision.

Express estimations of the likelihood of events in intuitive, consistent and unambiguous ways

The technical literature often uses highly specific quantitative measures such as one in a thousand year return rate. In the context in which they are used (assuming disciplinary norms), these are often appropriate; the specialist reader understands the underlying assumptions, for example that the probabilities will not change over time (stationarity), that they are based on a model incorporating our current understanding of the world (which may change), and that they apply to a single geographical location. Other readers will not necessarily make such assumptions; so model-based quantitative measures should be avoided or used with great care when seeking to communicate flood risk.

It is often helpful to frame the likelihood of a flooding event over timescales that are relevant to particular audiences. For example the probability of one in a hundred year flood occurring during the extent of a typical mortgage (30 years) is about one in four.

Agree on appropriate terminology—choosing, for example, whether to use probability, chance, or likelihood. Explain (at the beginning) what this means and how it relates to different spatial and temporal scales. Once chosen, the terminology should be used consistently throughout.

Events that are rare at any one location may still occur quite frequently somewhere in the country, depending on the degree to which they are spatially correlated. Non-technical audiences are frequently confused by, for example, 'one in a thousand year floods' occurring somewhere every few years. It is particularly important if quantitative estimates are used to be very clear about their spatial context, and the aggregate likelihood of such events occurring over larger geographic areas.

Make uncertainties and levels of confidence in the estimations transparent

There are a great many uncertainties associated with component elements of flood risk estimation. These estimates typically rely on models, and uncertainties can arise due to (i) our inability to estimate all the inputs to the model, (ii) our choice of the particular structure of the model which may not be the most appropriate because of our limited knowledge of the system, and (iii) our failure to anticipate everything that might occur in the future. Different types of model (for example meteorological, hydrological or economic) are affected to different degrees by the three types of uncertainty. Be clear what uncertainties are and are not included in any risk estimates.

The likelihood of flooding is not purely a product of rainfall, river flows and geography. There are uncertainties about the likelihood that a rainfall event of a given magnitude will trigger flooding in any particular locality that relate to the influence of human–environment interactions on the impact of that rainfall (e.g. preparedness; the effectiveness of flood defences and management agencies etc.). The extent to which estimations take into account human–environment uncertainties should be made clear.

Probability estimates may include precise statements (e.g. tossing a fair coin will come up heads half the time) or judgements (e.g. a statement about who is likely to win the next general election). Expressions of judgement are the only way to deal with some categories of uncertainty, and formal ways of summarising the judgements of groups of people with differing expertise are available. Both modelling and expert opinion can valuably be used to estimate flood risk, though it should always be made clear how estimates are obtained

A valuable way to communicate estimates of events subject to multiple uncertainties is to use a 'reserved vocabulary' or a consistent set of terms. An example of this approach is that taken by the Intergovernmental Panel on Climate Change (IPCC), which includes both numerical estimates and verbal interpretations of the degrees of uncertainties and levels of confidence that attach to different of its key statements (see Tables 1 and 2 below).

Take particular care with terminologies that have a more vernacular use

Many terms and concepts have both specialist and more vernacular uses and should therefore be used with caution. For example, the concept of a 'realistic scenario' has a specific meaning in the insurance and disaster risk avoidance communities but is likely to be interpreted differently by other groups. Use of the term 'realistic' might even alienate communities with experience of flood events by pitting first-hand realities against the abstractions necessary to any form of flood risk estimation. (There is nothing so real as wading through water up to the tops of your wellington boots.) In this case, 'plausible' might be a better choice. A further example is the term 'climate model', which, after several decades of media attention, might be assumed automatically to have something to do with climate change.

Any document seeking to communicate flood risk should be carefully proof read to identify such ambiguities. Where they exist, either different words should be chosen (and used consistently) or the meanings of the words in the context of the document should be clearly articulated.

Table 1: Likelihood scales used by IPPC Working Group

Terminology[9]	Likelihood of occurrence/outcome
Virtually certain	> 99% probability of occurrence
Extremely likely	> 95%
Very likely	> 90%
Likely	> 66%
More likely than not	> 50%
About as likely as not	33 to 66%
Unlikely	< 33%
Very unlikely	< 10%
Extremely unlikely	< 5%
Exceptionally unlikely	< 1%

*Note: The ‘extremely likely,’ ‘more likely than not,’ and ‘extremely unlikely’ categories are not included in the IPCC guidance. See *the simpler table at:* *https://www.ipcc.ch/pdf/supporting-material/uncertainty-guidance-note.pdf*

Table 2: Confidence scales used by IPPC Working Group

	Degree of confidence in being correct
Very high confidence	At least 9 out of 10 chance of being correct
High confidence	About 8 out of 10 chance
Medium confidence	About 5 out of 10 chance
Low confidence	About 2 out of 10 chance
Very low confidence	Less than 1 out of 10 chance

[9] Source: Interacademy Council 2010, Climate Change Assessments: Review of the Processes and Procedures of the IPCC <https://www.ipcc.ch/pdf/IAC_report/IAC%20Report.pdf>)

Annex 7 - Advice on longer term improvements to modelling extreme flooding

The Scientific Advisory Group confirmed that existing modelling approaches are robust, but it noted a number of areas where development would be beneficial to improve our understanding of flood risk. This annex summarises the advice provided by the Scientific Advisory Group on longer term improvements to modelling and associated developments.

Develop a more integrated flood risk modelling approach

Build on available tools and the work done for the review, by closer linking of global and regional weather models to hydrological and flood models, along with other relevant factors, to provide a more robust probabilistic assessment of potential impacts, as shown in figure 1.

There are compelling scientific arguments for fully coupling the atmosphere-land-ocean system to deliver robust evaluations of the risks from natural hazards. Such an approach would allow flood risk management strategies to be tested under different scenarios. By combining with the latest generation of climate models it would allow the simulation of a range of future scenarios and help to improve understanding of how flood risk may change in response to climate change. This approach would need to work across the national, catchment, and local scales to ensure that a comprehensive picture of flood risk is created. This work is an ideal opportunity for collaboration and shared learning across academic disciplines and between Government bodies and industry.

A significant amount of work has been undertaken or is underway in these areas. Some aspects of the integrated approach are in place already for operational flood forecasting through the Flood Forecasting Centre, and greater alignment of flood forecasting and future flood risk assessment approaches would be optimal. Before progressing this recommendation it would be necessary to refine the needs more fully. It will also be important to ensure that this approach fits with, for example, early work by the Environment Agency to update the National Flood Risk Assessment (NaFRA2), and developments in coastal and estuarine modelling

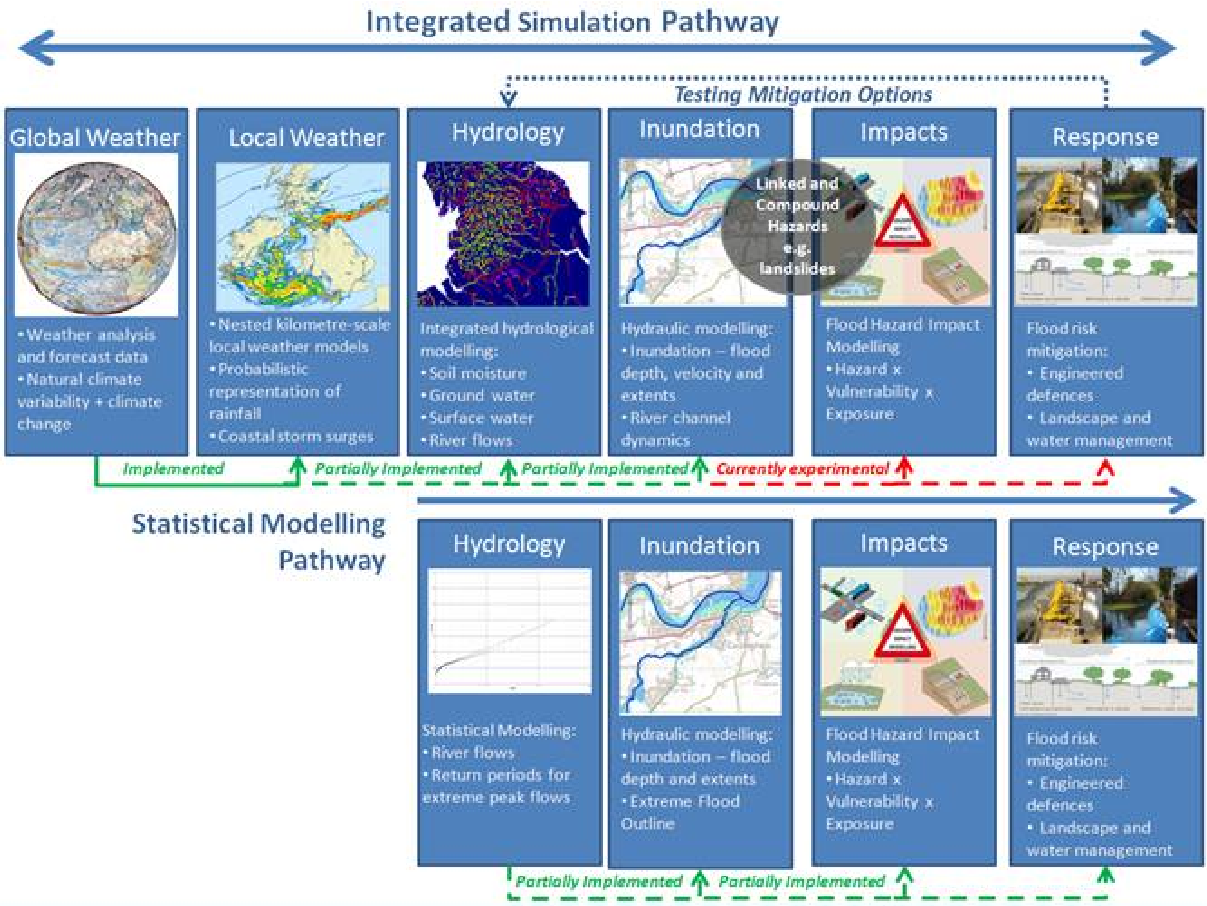


Figure 1 - Schematic showing the key elements of an integrated flood risk approach.

The arrows indicate status: implemented (solid green), partially implemented (dashed green) or currently experimental (dashed red).

Undertake further work to assess the likelihood of extreme flood events happening anywhere in the country, as likelihood is generally only expressed at the local level

Analysing information about rainfall, flows and floods will enable a better understanding of the national level of risk posed by flooding at a local and distributed level. Whilst extreme floods are rare at individual locations there is a higher probability that they will happen somewhere in the country. Understanding the confidence in these assessments is essential for them to be used as part of decision-making.

Use information from historic sources to extend flood records

This can have an impact on flood estimates but it is rarely used in the UK. Using data from historic sources, for example newspaper reports, photographs, and sedimentary records, will supplement the observed record of flooding. Making greater use of this information would improve planning and management of extreme events in the future. Collating, storing and accessing this information in a way which enables it to be accessed by a wider range of users will be a key consideration.

Develop further the statistical methods to reduce uncertainties in flood estimation

There is scope for improvement by combining the latest statistical methods with modelling approaches. There is a high degree of natural variability in the nature and frequency of flooding in the UK. Methods should be developed to better understand this variability and how it may alter due to future climate change.

Flood risk and the associated impacts should be reviewed on a regular basis, and a programme for undertaking this on a five year basis should be established

This will enable the latest developments in scientific understanding (such as the 2018 UK Climate Projections), newly-available techniques (including those developed in other sectors), and any changes in underlying trends, to be taken into account. This programme should also examine whether the necessary skills, IT capability, and data are available.

Annex 8 - Temporary defences

Illustrations of barrier types and summary of strengths, weakness and purchase costs of temporary barriers

Example temporary barrier types


Tube


Filled container


Frame barrier


Filled container


Flexible free-standing barrier


Rigid free-standing barrier

Summary of strengths, weaknesses and costs of temporary barriers (capital costs of barrier only)

Barrier Type	Strengths	Weaknesses	Typical purchase cost for 100m of 1m high barrier[10]
Tubes	Quick and easy to deploy Reusable Require small storage space	Very vulnerable to vandalism Can move under extreme load or when overtopped Need to source and dispose of water Need constant supervision once in place	£30k
Filled containers	Relatively unskilled labour required Small storage space Height can be increased whilst in service Can adapt to uneven terrain Can use locally available fill material Low security requirement	High pressure on bedding surface, especially when stacked Need to source and dispose of fill material Some can be re-used but only a limited number of times	£4k - £35k
Frame barriers	Adapt well to various terrain conditions (except hard surfaces). Easily cleaned and reusable. Minor repairs to membrane can be made under service conditions.	Membrane is susceptible to strong winds (especially before flood peak). High bearing pressure on soil. Susceptible to leakage at low water levels. High transportation and storage requirement. Membrane susceptible to accidental tear damage.	£12k - £50k
Flexible free-standing barriers	Quick and easy to install (usually requiring only hand tools) No equipment or machinery required for installation Small storage space required Easily transportable in cars and small pick-up	Susceptible to leakage at low water levels Skirt may twist or flap under heavy winds and current Susceptible to vandalism and accidental tear or puncture Membrane is susceptible to heavy winds (especially before flood peak)	£19k - £35k

[10] Source: Environment Agency (2011) Evidence report SC080019 Temporary and Demountable Flood Protection Guide

Barrier Type	Strengths	Weaknesses	Typical purchase cost for 100m of 1m high barrier[10]
	trucks		
Rigid free-standing barriers	Quick and easy to install. Most products do not require large equipment or machinery for installation Low mobilisation, demobilisation and clean-up requirements Easily cleaned and reusable	Significant seepage may occur under the barriers in uneven terrain due to their rigidity Some units require large storage areas Some units have high bearing pressure on bedding surface.	£15k - £47k

Annex 9 - Temporary defences pilot

General assessment of the applicability of temporary barriers to protect different types of local infrastructure

Type of infrastructure	Temporary barrier suitability
Data centre	Temporary barriers can be used if there is sufficient area around the building to build a barrier. Most of the communication centres will be located in urban areas. Therefore it will not be possible to use this method much of the time.
Drinking water treatment works	Temporary barriers can be placed around the plant to prevent flooding of the installations and the buildings.
Waste water treatment works	Temporary barriers can be used to prevent flooding of the installations and the buildings.
Electricity	Temporary barriers can be used. Surface substations have a large space demand. The flexibility of electricity connections should be taken into account especially in cases when high flood levels are expected.
Energy storage (tank farms)	Permanent barriers are needed because of the high risk when one of the fuels would leak. Because of this, temporary barriers are not an obvious choice.
Hospitals	Temporary barriers are not the preferred option because they close off the hospital and make it impossible for vehicles to enter or exit the premises. It could be an option if the access is located on higher ground or to protect specific departments where access or encirclement is not a danger to patients or staff.
Ambulance/fire stations	Temporary barriers are not feasible if it would block access to vehicles. They may be used to protect buildings and assist recovery.
Airports	Temporary barriers are a feasible option if the entire airport is enclosed. For example, in 2009 a $24million system has been implemented at the airport of Saint Paul (USA). It is 1km long and takes about 48 hours to install.

Further information can be found in FloodProBE co-funded by the European Community Seventh Framework Programme for European Research and Technological Development (2009-2013) http://cordis.europa.eu/project/rcn/93521_en.html

Table: Temporary barriers pilot - results of site assessments to verify the general assessment.

Asset Type	Type of critical infra-structure	Technical assessment					Size		Type of temporary barrier			
		Access to site	Width of deployment area	Obstructions	Topography	Ground surface	Length m	Max depth defended m	Frame barrier	Sandbag	Filled container or basket	Water filled tube
Data Centre	Communi-cations	green	green	green	green	green	220	0.75	green	red	green	red
Power substation	Electricity	green	green	green	green	green	40	1.50	green	red	green	red
Power substation	Electricity	green	green	green	green	green	336	0.75	green	red	red	red
Care Centre	Health	green	green	green	green	green	155	0.50	green	green	green	green
Health Centre	Health	green	red	red	green	red	n/a	n/a	grey	grey	grey	grey
Electricity Distribution substation	Electricity	green	green	green	green	green	3	1.00	red	green	green	red
Telecoms mast	Communi-cations	green	green	green	green	green	50	1.00	green	red	green	red
Waste Water Treatment Plant	Water and Sewage	green	red	green	red	red	n/a	n/a	grey	grey	grey	grey
Pumping station	Water and Sewage	green	red	green	red	red	n/a	n/a	grey	grey	grey	grey
Hospital	Health	green	green	green	red	green	n/a	n/a	grey	grey	grey	grey
Electricity Distribution substation	Electricity	green	red	red	green	green	n/a	n/a	grey	grey	grey	grey
Waste Water Treatment Plant	Water and Sewage	green	green	green	green	green	1600	1.50	green	red	red	green
Ambulance station	Emergency Services	green	green	green	green	green	195	1.50	green	red	green	green
Electricity substation	Electricity	red	red	red	red	red	n/a	n/a	grey	grey	grey	grey
Telecoms mast inc building	Communi-cations	green	green	green	green	green	60	1.00	green	red	green	red

green: passes technical assessment / acceptable type of barrier; red: fails technical assessment; grey: not assessed for type as failed the technical assessment

Annex 10 - Comparison of international approaches to flood resilience

Overview

National approaches to fluvial and coastal Flood Risk Management (FRM) vary for many reasons including differing geography, infrastructure and governance arrangements as well as differing experience and perceptions of flooding.

This report summarises some of the similarities and differences in approach across a selection of countries. It is aimed at informing the development of the approach in England. Information has been drawn primarily from flood risk management research and other publicly available information. The report does not draw conclusions, nor does it make judgements about approaches in England or other countries.

Structure

The countries examined in this report are England, France, the Netherlands, Australia, Japan and the USA. A summary of findings is presented in the main body of the document. Further, more detailed, information has been provided in a tabular format for ease of access. There are many different ways of categorising flood risk management approaches. This annex uses the following structure:

1. **country overviews** – information about flood risk, flood experience and overall approach;

2. **funding and allocation** – how flood risk management is funded (where that information has been made available);

3. **mapping flood risk and use of spatial planning** – how countries map flood risk and minimise exposure to flooding through controls on development in areas at risk of flooding;

4. **defence and mitigation** – measures to minimise the likelihood or severity of flooding by managing (flood) water, including controlling water with physical or engineered defences, working with natural processes, use of green infrastructure and property-level protection measures;

5. **preparing for and responding to floods** – measures which aim to minimise the consequences of flooding through societal or individual action. This includes flood prediction and dissemination of flood warnings, flood preparation and flood response;

6. **flood recovery** – measures to aid recovery from the consequences of flooding, including insurance, rebuilding and buyback of flood-affected land.

Challenges in comparing different countries

Differences in financial, social and geographical contexts make comparison of flood risk management strategies between countries challenging. Additionally, the absence of common definitions mean that terms that appear comparable at face value may not actually give the same information. For example, a flood with a 1% annual chance of occurring in the Netherlands, may not have the same impact as a flood with the same categorisation in England[1].

We have tried to provide this national context where possible and have added caveats whenever direct numerical comparisons are made.

Common Substitutions

In order to keep consistency within this annex and support a comparative approach, a number of language substitutions have been made:

- where 'municipality', 'provincial government', or 'local authority' have been used by the countries examined, we have used the more general term 'local government';
- where the term 'levee' has been used, we have used the term 'dyke' except when 'levee' has been used as part of a name (e.g. 'super-levee'). We take both 'levee' and 'dyke' to be interchangeable and to mean a constructed or naturally-occurring embankment that runs parallel to a watercourse or coastline and is raised above the most common (i.e. non-flood) water level; and
- where foreign language words have been used, we have given the best approximate translation, unless it is part of a name. In the case of names of organisations and initiatives, we have provided the name in the original language and an approximate translation in the first instance so that the purpose of the organisation or initiative can be seen (e.g. Department of Waterways and Public Works (Rijkswaterstaat).

Currency Conversion

In order to facilitate the comparison of costs of and savings or income generated by initiatives, monetary values have been quoted in the original currency. A pound-sterling equivalent has been given, using conversion rates as of 1 April of the year the figures are from.

Flood Risk Quantification

Return rates (e.g. 'a 1-in-50 year flood') are often used to describe flood risk/defence levels. In most instances, except where the use of return rates is essential to the point of the statement, we have converted return rates to percentage annual chance of flooding:

Return rate	% annual chance	Return rate	% annual chance	Return rate	% annual chance	Return rate	% annual chance
1-in-2	50%	1-in-25	4%	1-in-50	2%	1-in-100	1%
1-in-200	0.5%	1-in-500	0.2%	1-in-1000	0.1%	1-in-10,000	0.01%

1. Country Overviews

In England, around 8% of the population (and around 16% of the land area) has at least a 0.1% annual chance of flooding from rivers or the sea[2]. The public in England are not legally entitled to a specific level of flood protection but the government aims to optimise the benefit from every pound spent on flood risk management. In the last 20 years, there have been a number of severe floods, with few fatalities but economic impacts in the billions of pounds (table 1a). England implements a wide range of approaches to flood risk management, as set out in the National Flood Risk Management and Coastal Erosion Strategy[3]. This strategy was shaped by major flooding in England 2007 and the Pitt Review[4] that followed. Figure 1 compares the extent of the populations at risk of flooding from rivers and the sea in the countries examined.

In contrast, over half (59%) of the land area of the Netherlands, including the major economic and business centres, is at risk. Flooding could be catastrophic and the vast majority of the area at risk (98%) is protected by dyke rings[5]. These offer a level of protection ranging from a 0.4% to a 0.01% annual chance of flooding to over 11 million people (65% of the population). The flood risk arises from the Netherlands' position on the deltas of the Rhine and Meuse, along with the low lying nature of its reclaimed land. Floods have a relatively long response lead time[6].

Unlike in England, there is a legal standard of protection in the Netherlands and FRM activities focus on meeting this standard. This approach was developed in response to the coastal flooding in 1953 that caused the loss of 1,835 lives[7] and is implemented through the Dutch Delta Programmes. After near-flooding in 1995, the 'Room for the River' programme[8] was introduced. It focuses on accommodating flood water to prevent flooding, in addition to the long standing approach of building defences to keep flood water out. The concept of multi-layer safety (defence; spatial planning; response) was introduced in 2009[7] and the legal protection standards, which are currently based on resisting a given height of water, are due to change in 2017 to be based on an acceptable individual mortality rate from flooding[9].

France is exposed to diverse flood risks: river flooding (including rapid and slower response flooding) and coastal flooding. At least 8% of the population have a 1% annual chance of flooding and 28% of the population have a 0.1% annual chance of coastal or river flooding[10]. As in England, there is no specific legal level of protection. In the last sixty years, flooding in France has been largely local, often resulting in multiple fatalities and an economic cost of hundreds of millions of Euros (table 1a). France has adopted a wide range of FRM approaches, with state-imposed restrictions on development in areas at risk of flooding and a state-controlled fund for flood compensation. The different approaches are brought together at the local level in 'Action Programmes for Flood Prevention' (Programme d'Action de Prevention des

Inondations - PAPI) which are used to secure partnership and central government funding. These are supplemented by the newer 'Rapid Flooding Plans' (Plan Submersible Rapide) developed in response to flooding in 2010 and focusing on individual's safety. France is undergoing a process of decentralisation and the responsibility for FRM is moving to local governments, supported by legislation introduced in 2014[11].

Japan comprises a series of mountainous islands bordering the Pacific Ocean. Its flat, low-lying, coastal areas are densely populated. Rivers are short and steep, so flood response lead times are short[12]. Nearly half (49%) of Japan's 127 million people and 75% of properties are in flood prone areas[12,13,14]. Japan is also prone to typhoons and tsunamis originating in the Pacific Ocean. Flooding is frequent and sometimes catastrophic, such as in 2011 following an earthquake and tsunami, and in 2015 when floods in the city of Joso forced 90,000 people to abandon their homes. Japan mitigates its vulnerability to flooding through a combination of physical defences, warning and evacuation, and coordinated recovery efforts.

Australia is the world's driest inhabited continent, but also has the greatest annual rainfall and runoff variability[15]. Its east coast is particularly vulnerable to flooding caused by cyclones, such as in the Queensland floods of 2010 and 2011. FRM best practice principles for Australia are set out by central government[16]. However, implementation is at the state level and at the state's discretion. Flood warning is provided centrally by the Bureau of Meteorology [15,16,17].

The USA is susceptible to flooding associated with tropical storms on its Gulf coast, hurricanes on its Atlantic coast, and tsunamis and cyclones on its Pacific coast. Two percent of the population has a 1% annual chance of coastal flooding[18]. Additionally, there is a significant flooding threat from its rivers. The Mississippi drains nearly 40% of the landmass of the continental United States, and river floods can become very extensive. One percent of the population has a 1% annual risk from river flooding[19]. Recent floods have been significant both in terms of fatalities and economic consequences (table 1b). The USA's approach comprises a mix of physical defences and the National Flood Insurance Program (NFIP) which drives controls on construction and provides state-subsidised flood insurance[20,21,22]. Relocating communities out of the floodplain is also a recognised approach.

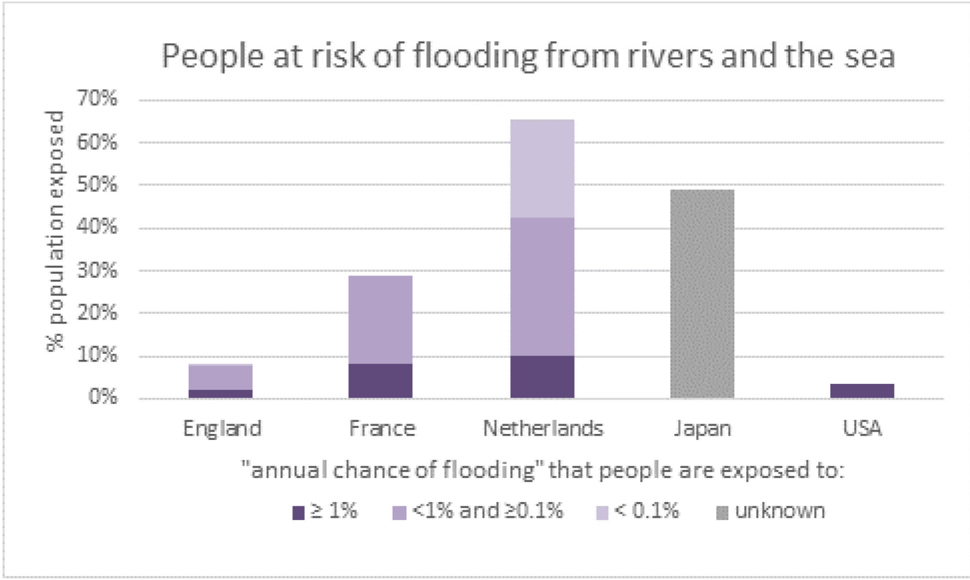


Figure 1: Indicative percentages of population at risk of flooding from rivers and the sea. It is based on the figures quoted by each country which may not be calculated on a like-for-like basis.
Sources: England 2015[2]*, France 2011[10], Netherlands 2010[7]* (number of people behind defences), Japan estimate[23], USA coastal estimate[18]* and inland estimate[19] (* indicates that figures take into account existing defences).

2. Funding and allocation

In England, FRM activity is primarily funded by the taxpayer. Expenditure for 2014/15 totalled £690 million, if specific funding for recovery from 2013/14 flooding is excluded: £623 million (90%) of this was from central government, £24 million (3%) from local levies and £43 million (6%) from other sources, including partnership funding. 53% of central government FRM funding was spent on schemes to deliver flood defence and mitigation measures, and another 27% (£171 million) on maintaining existing schemes[24,25].

Decisions on England's overall level of funding for FRM are supported by Long Term Investment Scenarios which model the impact of different funding scenarios to support investment decisions[26]. Decisions on the allocation of funding for individual flood defence schemes are informed by a cost benefit analysis, which takes into account societal and environmental benefits.

A six year capital programme was put in place in 2015/16, supported by central government funding of £2.3 billion. At least 15% additional funding will be provided through partnership contributions from the public and private sectors. In spring 2016, an additional £700 million in funding through to 2021 was announced, including a £160m boost to maintenance, taking the maintenance budget to over £1 billion for 2015/16 to 2019/20. The overall benefit-cost ratio of England's capital programme for flood defence schemes was 9.8 to 1 between April 2011 and March 2015[24]. The six year capital investment programme is expected to deliver better protection to 300,000 households and an additional £30.3 billion benefits to society[27,28]. Figure 2 provides an indicative view of flood risk spend in England, France and the Netherlands.

In the Netherlands, FRM is also primarily funded by the tax payer. In 2013 investment totaled £1 billion (€1.2 billion): £730 million (€870 million, 74%) from central government, £37 million (€44 million, 4%) from local government and £220 million (€260 million, 22%) from water boards. The 24 regional water boards responsible for both water management and managing flood defences can raise funds through local water taxes, ranging from under £360 to over £520 (€420-€620) per household per year. These taxes also contribute to sewerage, water resource and water quality[29,30]. Allocation is determined by the need to provide a statutory level of protection and there is a high degree of certainty around funding. The new protection standards coming into force in 2017 take into account the economically optimum level of protection for each dyke ring. The core programmes of work to deliver this are focused on improvements to dykes, coastal erosion control and river widening. The Netherlands describes its expenditure as an ‘excellent insurance policy’ – investing around 0.2-0.3% of GDP in flood defence protects around £1500 billion (€1800 billion) benefit to the economy[9].

In France, estimates of annual FRM expenditure range from £250 million to £380 million (€300 million to €450 million)[31]. In contrast to England and the Netherlands, French FRM activities are funded primarily (~60%) through public sector partnership funding, with the PAPI acting as a contract tool between local and central government. The rest is provided by the state through a combination of general taxation and income raised through a flat-rate tax on home insurance policies known as the Barnier Fund. Allocation decisions have not historically been risk-based although this is the direction of travel, with cost benefit analysis obligatory for projects over £1.7 million (€2 million)[11]. Legislation underpinning the transfer of responsibilities to local governments (MAPAM Act 2014) provides the possibility of a tax of £34 (€40) per inhabitant per year[11].

It has not been possible to get a full picture of the funding and allocation arrangements in Japan, the USA and Australia.

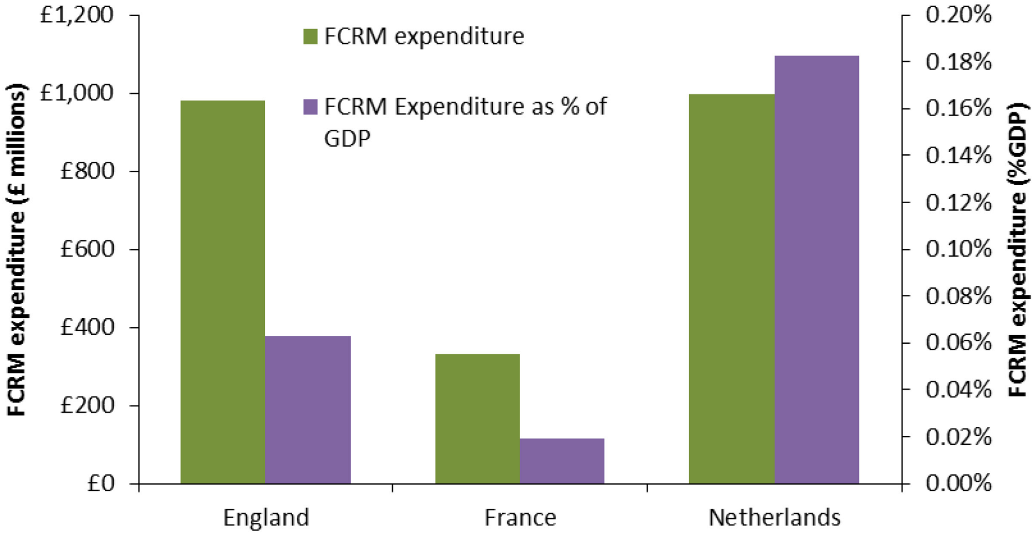


Figure 2 - Indicative view of flood risk spend. This chart is based on the figures quoted by each country; they may not be calculated on a like for like basis and are for different years *(England 2014/15 less recovery funding*[24]*, France indicative*[11]*, Netherlands 2013*[29]*)*

3. Mapping flood risk and use of spatial planning

In England, flood risk from rivers and sea is modelled and mapped nationally, using local knowledge and data. This national picture of flood risk supports the risk based approach to FRM. Environment Agency flood risk mapping products are described in more detail in Annex 3, and include the Flood map for planning (rivers and sea), which maps three zones of flood risk in the absence of defences. Areas in Zone 3 (~10% of the land area of England) have an annual chance of flooding that is greater than or equal to 1% from rivers or 0.5% from the sea. Areas in Zone 2 (~2% of the land area of England) have an annual chance of flooding between 0.1% and 1% (for rivers), or between 0.1% and 0.5% (for the sea). The outer boundary of Zone 2 is referred to as the Extreme Flood Outline. Areas outside the Extreme Flood Outlines lie in Zone 1, with an annual chance of flooding of less than 0.1% from rivers and the sea. National planning policy aims to steer development away from the highest risk Zone 3[32], and in 2014/15, 8% of new homes were built in Zone 3[33]. Where development in high flood risk areas is approved, planning conditions are set to mitigate flood risk. The Environment Agency is a statutory consultee in planning applications in areas at risk of flooding.

France and the Netherlands also map their flood risk at the national level. The Netherlands has recently carried out an in-depth national flood risk assessment which informs its approach to flood risk management[7]. In both France and the Netherlands there are legislative tools which can be used to prohibit development on the floodplain. In France, restrictions are imposed by the state through ‘Flood Risk

Prevention Plans' (Plan de Prévention du Risque Inondation). Local governments must ensure they adhere to these restrictions, although some negotiation is allowed. This approach is reinforced through the legal requirement to make all property purchasers/tenants aware of their flood risk[11].

The Netherlands' approach is less centralised. Local governments develop their own spatial zoning plans, which can also be used to set flood resistance/resilience standards. Integration between spatial planning and FRM is achieved through the 'water effect assessment' (water toets) whereby water boards must comment on the water implications of any development. These comments can lead to design changes or the implementation of mitigation measures elsewhere, but there is no requirement for the advice to be taken forward. Spatial planning has been used to move forward some of major 'Room for the River' projects, such as the dyke relocation in Lent[8].

In Australia, flood risk is mapped at the state or municipal level. The Australian government provides guidelines for planning development on the floodplain[16], but they do not have the force of law and different states have different regulations for development on the floodplain[34,35,36]. Australia has a comprehensive building code for building at risk of flooding, provided by the Australian Building Codes Board[37]. These are intended to prevent injury or death to people during a flood, not to prevent flooding.

In the USA, the Federal Emergency Management Agency (FEMA) models and maps flood risk to produce 'Flood Insurance Rate Maps'[38]. These indicate 'Special Flood Hazard Areas' where there is a 1% or greater annual chance of flooding. Flood insurance is a pre-requisite for many mortgages for properties in a Special Flood Hazard Area. This can be purchased through the National Flood Insurance Programme if the local government joins the scheme and commits to using local law to implement minimal levels of floodplain management, including development controls[22]. Regions behind dykes designed to protect against a 1% annual chance of flooding are not included within Special Flood Hazard Areas and mortgage flood insurance requirements do not apply. Federal law requires that federally constructed buildings are constructed above the flood hazard level, as defined by the National Flood Insurance Programme[39,40].

4. Defence and mitigation

All the countries studied use flood defence structures such as dykes, dams, floodgates and pumps to a greater or lesser extent. In Japan and the Netherlands, where flooding events can have the most catastrophic impacts, protection standards are highest and dyke rings are used to keep flood waters out of low-lying areas. Densely-populated Japan is building a series of 'super-levees' which are high, broad, gently sloping dykes that can accommodate construction on top. These ensure that overtopping is gradual rather than catastrophic[41]. Storm surge barriers, such as the Thames barrier and Maeslandkering are particularly important. Large-scale dams are seen in France, the USA and Australia[42,43,44].

Mechanisms for funding new defences, and the standards of protection offered, vary by country. In Australia this is managed at state level. In the USA, federal dykes must receive 35% of their funding from local government and must demonstrate their contribution to national economic development. These requirements lead to defences usually being built to protect against a 1% annual chance of flooding. Sections one and two of this annex provide further information on defences for France, the Netherlands and England.

Maintenance and improvement of existing, ageing, defences is an acknowledged challenge. England has a risk-based inspection and maintenance regime and like most countries studied is investing in IT systems to help manage flood defence asset maintenance and management more efficiently. Maintenance responsibilities are shared between the Environment Agency (responsible for 8,000km of defences) and other flood risk management authorities (responsible for the remaining 1,700km)[24]. Responsibility for the Netherlands' flood protection programme, which delivers dyke improvements to ensure that primary defences meet legal standards, is shared between Rijkwasterstaat (funded 100% from central government) and the regional water boards (funded 50% by central government and 50% by local taxes)[9]. In the USA, 35,000 miles of dykes have federal oversight and these are considered to be significantly more reliable than the 100,000 miles that do not[15].

Working with nature provides a complementary approach to more structural engineered methods. The Netherlands has the 'Room for the River' programme which focuses on making space for water in a collaborative and consultative way. France and England have introduced similar strategies[45,11,8]. Floodplain restoration is seen in the USA, and Japan's 'comprehensive flood control measures' approach also includes the restoration of green areas. In the Netherlands, sand plays an important role in coastal flood defence. The Sand Engine is a 1 km spit which has been put in place to 'naturally' nourish beaches. It is an experimental approach which will be scientifically evaluated[46]. A similar approach, on a much smaller scale, is being trialled in Poole, in England[47].

Whole catchment management is a particular focus for planning FRM activities in England and elsewhere. Japan's river law provides a legal framework for whole catchment management. This approach is also seen in France, for example in the 'Loire plan for the grandeur of nature' (Plan Loire Grandeur Nature) which covers FRM, environmental protection and economic development for the whole of the Loire Valley[48]. Given its geographical setting, whole catchment management and upland natural processes in the Netherlands requires international cooperation and there are mechanisms in place to facilitate this.

Blue-green infrastructure is acknowledged as playing a role in flood risk mitigation. This is generally implemented at a local level. Examples from the USA include the Staten Island Blue Belt project that uses slow-release water retention areas to provide effective flood mitigation[49]. In England, Newcastle provides a well-studied example[50].

England's approach to managing residual risk includes Property Level Protection (PLP) which covers measures such as flood boards (to prevent water entering individual properties) and raised electric sockets (to minimise its impact). PLP products are commercially available in both England and France, but uptake is low. European research has identified several reasons for this, including property owners not wanting to accept responsibility (or costs) and a lack of trust in PLP products[51]. To address these barriers, England has introduced a kitemark for PLP products and provided resilient repair grants[52] to support uptake of PLP by property owners affected by the floods of winter 2015/16. There are some examples of property level resilience through floating/amphibious homes in the Netherlands[53] and the US approach of raising houses above the flood level can also be seen as a property level resilience measure.

The Environment Agency participates in many international networks to exchange best practice on flood defences. For example, with partners from the USA, the Netherlands, Germany and France, the Environment Agency has produced an international best practice guide for levee design, and has also developed a Memorandum of Understanding with the US Army Core of Engineers to foster exchange of research and best practice.

5. Preparing for and responding to floods

In England, France and the Netherlands, preparation for, and response to, flooding fall under wider civil protection policy. Within England's general emergencies framework, there is a specific 'National Flood Emergency Framework for England' which sets out roles and responsibilities in relation to flooding, whereas in France and the Netherlands it is managed alongside other risks. The Netherlands lacks recent experience of significant floods to test their approach and Rijkswaterstaat (and its water boards recognise that there are lessons they might learn from England on this).

Forecasting and warning is provided by the state in most of the countries studied here. In Australia the Bureau of Meteorology provides forecasts and warnings for all floods except those with a lead time of less than six hours, when local governments are responsible and the role of private bodies such as dam operators is under development. In England, the Flood Forecasting Centre (a joint venture between the Environment Agency and the Met Office) provides a comprehensive flood forecasting service. The Environment Agency provides coastal and river flood warnings based on local interpretation of the forecasts. Warnings are made publicly available and issued to individuals at risk through an opt-in service. In 2013, England was the first country in Europe to start to use twitter alerts for a major flood. The Netherlands also provides central forecasts to managers of flood defences who then determine the best course of action[8]. In France, the state provides forecasting and 'vigilance' (an indication of flood risk) for rivers in the public domain, through 22 regional forecasting centres. The private sector provides services directly to local councils for smaller rivers[8,11,45,54]. In contrast to England, Australia uses its 'Emergency Alert' system is to send messages to all landlines and mobile phones within the area at risk[17].

Effective flood preparation requires community awareness and engagement. As set out in section 4.5 of the review, the Environment Agency, working with others, will be developing new and different approaches to risk communication, building on previous work undertaken by Sciencewise. In Australia a pilot scheme in the Calide Valley is experimenting with innovative means of educating residents likely to be affected by floods, using maps and fridge magnets to raise awareness of the potential impacts of flooding.

In terms of response, French legislation holds citizens responsible for their own safety. This incentivises individuals to take note of information provided and make their own provision. In the Netherlands citizens are also officially responsible for their own safety[7], but have limited awareness of flood risk[30]. Initiatives such as the website 'Do I flood?' (overstroomik.nl) provide information about flood risk and actions to take[55]. Evacuation plays a key part of Japan's flood preparation strategy: evacuation centres are distributed around many cities and are clearly signposted to enable people to find them quickly[12]. Regular drills are conducted by local governments and an annual 'disaster reduction day' is held to run emergency response simulations[14]. Australia uses its volunteer 'State Emergency Service' to support the flood response effort[56]. The Netherlands use mainly voluntary 'dyke guard' teams to survey the condition of flood protection infrastructure during critical periods. Arrangements vary between water boards, but there is a particularly active flood brigade in Kampen[57]. Volunteer flood wardens and community flood groups also play a part in England. Their role varies locally with actions ranging from raising flood awareness to providing emergency coordination.

6. Flood recovery

There are significantly different models for flood recovery funding. In England, flood insurance for individuals and businesses is bundled with standard building and contents insurance. Market penetration is high and the new Flood Re scheme ensures that affordable insurance is available even for those at significant risk of flooding, through cross-subsidisation. It is intended as a transitional arrangement in a move to risk-reflective pricing by 2039.

Japan provides flood insurance as an add-on within a broader natural risk policy that also includes volcanoes, earthquakes and storms. Uptake is at least 35%[58]. There is an expectation that individuals will take on some of the financial risk associated with flooding.

The USA's National Flood Insurance Program provides insurance to those within areas prone to flooding (see section three above). The NFIP requires properties that are substantially damaged by flooding to be raised or removed from the flood risk area[16].

France has a state-backed fund for natural disaster compensation. It is funded through a fixed rate levy on property insurance[59]. This levy also funds the Barnier Fund (see section two above).

In the Netherlands, private insurance against flooding from rivers and seas has been explored and ruled out[59]. There is state compensation in the event of major disasters including floods, which provides compensation for a given proportion of the damages, determined after the event.

France, the Netherlands and England have access to the EU solidarity fund for recovery work. In addition, the Bellwin scheme in England provides funding for local, public sector recovery costs. Awards are capped and aimed to encourage resilient rebuilding[45]. In the USA 15% of Federal disaster relief must be spent on reducing future flood risk, which can lead to elevation or relocation of properties[15]. Relocation is also a recognised approach in the Netherlands, where the 'Room for the River' programme has offered compensation for relocation on a voluntary basis, and in Australia, where Brisbane City Council offers to purchase homes that have an annual chance of flooding of over 50%, if there are no other methods of flood control available. Purchased land is given over to green space or parkland[60].

Following the devastation wreaked by Hurricane Sandy in the Northeast United States, the US Housing and Urban Development department launched the 'Rebuild by design' competition[61]. Its purpose was to develop innovative, implementable solutions to respond to the region's most complex needs. Six entries were selected in July 2014 and are currently being taken forward.

Tabulated information

The following tables provide more detailed information for each of the six countries studied, under the same headings as used in the structure as above, but with the first two sections (country overview, and funding and allocation) covered together in the first table.

Table 1: country, funding and allocation overview

Table 2: mapping flood risk and use of spatial planning

Table 3: defence and mitigation

Table 4: preparing for and responding to floods

Table 5: flood recovery

For ease of reading, each table is split into two parts, with tables a covering the three EU countries and tables b covering the international ones.

In most cases, the tables summarise: basis of approach (what is done); funding (how much is spent); allocation (how that money is distributed); actors and implementation (who is responsible); and impact (what the result is, where this information is available). We have used best available information and attempted to provide quantitative information wherever possible.

Table 1a: Country, funding and allocation overview – Europe.

	England	France	Netherlands
Country statistics	Population: ~54.3 million in 2014. Population density (average): ~400 people/km^2. GDP: £1,769 billion for 2014.	Population: ~66 million in 2014. Population density (average): ~120 people/km^2. GDP: £1,710 billion for 2014.	Population: ~17 million in 2014. Population density (average): ~500 people/km^2. GDP: $520 billion for 2014.
Flood risk	**Scale:** 12% of the land area, ~8% of the population and 2.4 million (8%) properties (residential and non-residential) are at risk of sea/river flooding. **Type:** sea flooding, particularly tidal surges on east coast; **r**iver flooding including rapid response flooding; surface water flooding (~3 million properties at risk of surface water flooding, of which ~0.6 million also at risk of sea/river flooding)[24]. **Coastline:** England's coastline is ~ 32% of the UK total ~ 4,000km (Ordnance Survey). **Largest rivers:** • Thames – average discharge rate at London 65.8m^3/s, basin 12,935km^2; • Humber – average discharge rate 250m^3/s, basin 24,240km^2; • Severn – average discharge 61.17m^3/s, basin 11,420km^2.	**Scale:** 15% of the land area, 18.4 million people (26% of the population) and 9 million jobs located in flood-prone areas. **Type:** sea flooding, particularly tidal floods & storm surges in the northwest; slow response river flooding along main rivers and rapid response flooding in the south[11]; surface water flooding in most cities. **Coastline:** continental France has a coastline of approximately 3,430km. Including overseas territories, its coastline is approximately 4,850km. **Largest rivers:** • Loire – average discharge at Montjean-sur-Loire 835m3/s, basin 117,000km^2; • Seine – average discharge at Le Havre 563m^3/s, basin 79,000km^2; • Rhone – average discharge 1,710m^3/s, basin 98,000km^2.	**Scale:** 59% of the land area is susceptible to flooding (55% is protected by embankments or dunes, 4% is unprotected). At least 11 million people (65% of the population) are at risk of flooding. The 'Randstad', where 70% of the GDP is produced and population density is highest, is susceptible to flooding. **Type:** sea flooding, particularly along the west coast; slow response river flooding (the Netherlands is situated downstream on several major European rivers, but has no rapid response flooding due to flatness of land); increasing risk of surface water flooding. **Coastline:** approximately 450km. **Largest rivers:** • Rhine – average discharge 2,900m^3/s, basin 185,000km^2; • Meuse – average discharge 350m^3/s, basin 34,548km^2.
Flood history	1952 Lynmouth flash flood – 34 fatalities; 1953 East coast flood – 308 fatalities; 1998 Easter floods – 5 fatalities, £400 million damages; 2000 flooding – 10,000 properties flooded; 2007 flooding – 13 fatalities, 48,000 residential	1958 flooding in Gard and Herault – 35 fatalities; 1959 flooding on the Argens and failure of the Malpasset dam – 423 fatalities; 1987 Grand Bornand disaster – 27 fatalities, £89 million (~€107 million) damages; 1988 flooding in Gard – 10 fatalities, £420 million	1916 Zuiderzeestorm; 1925/1926 flooding of the rivers Rhine and Meuse; 1953 storm surge – 1,835 fatalities , 2,000km^2 land flooded[62]; 1993/ 1995 high river discharges in Rhine and

	England	France	Netherlands
	properties flooded, 7,300 commercial properties flooded, £3 billion damages; 2013/14 east coast surge and southern England floods – 11,000 properties flooded, £1.3 billion damages; 2015/16 – 20,000 properties flooded across Cumbria, Lancashire and Yorkshire (preliminary estimate of damages~£1.5 billion).	(~€500m) damages; 1992 flooding in Vaucluse, Ardeche and Drome – 47 fatalities, £420 million (~€500 million) damages; 1999 flooding in Aude, Tarn, Pyrenees-Orientales and Aveyron – 36 fatalities, £469 million (~€533 million) damages; 1999 flooding in Lothar and Martin – 17 fatalities; 2002 flooding in Gard – 23 fatalities, £1 billion (~€1.2 billion) damages; 2003 country-wide flooding – 10 fatalities, £1.3 billion (~€1.5 billion) damages ; 2010 Xynthia storm surge – 47 fatalities, damages over £890 billion (€1 billion).	Meuse – mass evacuations took place; 1998 intensive rainfall event; 2003 dyke breach by Wilnis due to drought.
Basis and evolution of approach	The focus is on reducing the impact on communities, by optimising investment benefits. There is no legal level of flood protection that English citizens are entitled to. The current approach has evolved from a historic focus on land drainage, through flood defence and working more with nature (‘Making space for water’ strategy in 2004) to a diversified and joined up approach to FRM, including considering flood risk in land use planning[45]. (National strategy following 2007 flooding[3] & Pitt review[4].)	The aim is to: reduce vulnerability; improve the safety of exposed populations; stabilise (short term) and minimise (medium term) the costs of flood damage; and reduce the recovery time for affected areas[63]. There is no statutory duty for government to protect land or property from flooding. There is a precedent for compensation in the event of natural disasters[11].	The aim is to minimise the loss of life. There are legal safety standards for dyke rings, which provide protection against a flood water level ranging between a 0.4% to 0.01% annual likelihood of flooding[7]. The approach has evolved from land drainage, through flood defence (following the catastrophic 1953 floods) and working more with nature (1996 ‘Room for the river’ programme) to a broad approach to FRM (2009 ‘multilevel safety’ concept). In 2017 new risk-based protection standards are being introduced that aim to ensure everyone behind a dyke ring has a probability of less than 0.001% of dying from flooding, in any given year[62].
Funding and allocation	Figures are for 2014/15, excluding the £180 million related specifically to recovery from winter 2013/14 flooding[24, 25]. **Central government:** 90% (£623 million), through general taxation. £602 million from Defra	Figures are for 2012[11]. **Central government:** 40% (~£130 million (~€155 million)) from a combination of general taxation and the Barnier Fund, which is funded from a premium on home insurance. The proportion	Figures are for 2013 [29]. **Central government:** 74% (~ £732 million (€868 million)) from general taxation. The Delta Fund is the primary central government fund for FRM. Funding is confirmed until 2028, averaging ~£505

	England	France	Netherlands
	and £21 million from DCLG. Long term commitment of £2.3 billion for the six year capital investment programme from 2015/16 to 2020/21, and £171 million for maintenance in 2015/16 and then £211 million p.a. from 2016/17 to 2019/20. Local levies: ~4% (£24 million). **Other, including partnership funding:** ~6% (£43 million) from local government and the private sector. This will increase to at least 15% of the capital programme by 2021. The overall allocation of funding to FRM activities is informed by an economic assessment of the consequences of investment choices, to allow optimisation[26]. Allocations to flood defence schemes are based on multi-criteria analysis which takes into account flood risk, deprivation, and environmental improvements. Flood defence maintenance spend allocation is risk-based.	coming from the Barnier fund increased by 30% between 2012 and 2013. **Local/regional authorities:** 60%, (~£200 million (~€240 million)) partnership funding from local governments. Partnership funding is secured through contracts with the state such as PAPIs and large river plans[31]. Historically not risk-based, but moving in that direction[31]. Cost -benefit analysis is required for infrastructure over ~ £1.7 million (€2 million)[11].	million (€600 million) p.a. for FRM. **Provinces:** 4% (~£36 million (€44 million)). **Water boards:** 22% (~£217million (€257 million)), through local water levies **Partnership funding:** has been raised in some cases, but only once from the private sector. The approach is driven by maintaining defences to meet set standards. In 2017 the standards are changing from absolute to risk-based standards, informed by an analysis to find the 'economically optimal' level of protection for each system[62].
Governance/ roles and responsibilities	Roles & responsibilities are set out in the National Flood and Coastal Erosion Risk Management Strategy for England[3]. **Central:** Department for the Environment Food and Rural Affairs (Defra) – FRM policy; Department for Communities and Local Government (DCLG) – spatial planning policy; Cabinet Office – civil contingencies**;** Environment Agency – overview, coordination and delivery; national Flood Forecasting Centre – flood warnings. **Local/regional:** Lead Local Flood Authorities; coastal erosion risk management authorities; district councils; Internal Drainage Boards and riparian land owners/managers; water companies; reservoir owners; highways	Roles & responsibilities are set out in the National FRM Strategy[63,64]. **Central state authorities:** Ministry of the Environment – prevention and defence**;** Ministry of the Environment together with Ministry of the Interior – preparation. **Regional state services**: 6 water agencies – implementing water management at the basin level; mayors represent the state in implementing the civil security response organisation plan **Local/Territorial authorities:** 13 regional council – strategic planning & economic development; 36,700 municipalities, often operating through inter-municipal bodies.	Roles & responsibilities are set out in the 2011 Administrative agreement on Water[62]. **Central:** Ministry of Infrastructure and the Environment – water policy; Rijkswaterstaat – operation and maintenance of main water system; Deltares - applied research institute which works closely with the public sector; Delta commissioner – oversees delivery of the Delta programme for FRM and freshwater supply. **Regional:** 24 Water Boards – flood defence maintenance supported by STOWA (foundation for applied water research) which acts as their knowledge centre through coordinating research and sharing information, improvement and operations; Safety Regions – emergency

	England	France	Netherlands
	authorities and other organisations; Regional Flood and Coastal Committees (RFCCs).		planning & management.
Impact	The overall cost-benefit ratio of England's capital programme for flood defence schemes was 9.8 to 1 between April 2011 and March 2015[24]. The six year capital investment programme is expected to deliver an additional £30.3 billion benefits to society[27].	No information found.	No recent experience of significant flooding, but potential flood damages estimated at £1,500 billion (€1,800 billion)[9].

Table 1b: Country, funding and allocation overview – International.

	Australia	Japan	USA
Country statistics	Population: 23.4 million in 2014. Population density (average): ~3 people/km^2. GDP: £866 billion for 2014.	Population: 127 million in 2014. Population density (average): ~349 people/km^2. GDP: £2,760 billion for 2014.	Population: 319 million in 2014. Population density (average): ~35 people/km^2. GDP: £10,420 billion for 2014.
Flood risk	**Scale:** %age of population and total area at risk are difficult to ascertain, but 170,000 residential properties are at a 1% annual risk of flooding, and 'tens of thousands' of commercial properties. The total value of property at risk of flooding exceeds £55 billion (Au$100 billion)[66]. **Type:** east coast is prone to typhoons from the Pacific; arid climate but prone to sudden downpours so both fluvial flooding (including rapid response flooding) and surface water flooding risks. **Coastline:** approximately 25,760km. **Largest rivers**: • Murray-Darling – average discharge 767m^3/s, basin 1,061,469km^3; • Lake Eyre – the 1,200,000km^3 basin is significant, though the rivers that flow into it are often dry.	**Scale:** 62 million people, and 75% of property located in flood-prone areas. **Type:** typhoons and tsunamis from the Pacific; short and steep rivers are prone to rapid response floods; surface water flooding. **Coastline:** approximately 29,750km. **Largest rivers**: • Shinano – average discharge 514 m^3/s, basin 11,900 km^3. Elevation at source: 2.5km. Japanese rivers are short and steep. • Tone – average discharge 256m^3/s, basin 16,840 km^3. Elevation at source 1.8km.	**Scale:** 6.7 million people have a 1% annual chance of coast flooding[18], and an estimated 3.9 million people live within an area at risk of a 1% annual chance of fluvial flooding[19]. Indication of the value of property defended: £88 billion ($141 billion) in flood damages prevented in 2011[20]. **Type**: large land area and a varied climate make the USA vulnerable to all types of flooding; Pacific coast is vulnerable to storm surges and tsunamis; Atlantic coast is vulnerable to hurricanes; Gulf Coast is vulnerable to tropical storms; rivers with large catchments are vulnerable to flooding. **Coastline:** approximately 19,920km. **Largest rivers**: • Mississippi – average discharge 1,956m^3/s, basin 1,371,017km^2; • Yukon – average discharge 6,340m^3/s, basin 870,000km^3.
Flood history	2015 south east Queensland flash floods – 5 fatalities; 2015 Hunter Valley floods – 8 fatalities, £66 million (Au$129 million) in insurance claims; 2013 Cyclone Oswald eastern Australia floods – 6 fatalities, £1.56 billion (Au$2.28 billion) in damages; 2012 eastern Australia floods – 2 fatalities; 2011 Victoria floods – 2 fatalities, £1.2 billion	2015 Tropical storm Etau/Joso floods – 8 fatalities, 2.8 million evacuated, 19,000 homes flooded; 2014 Hiroshima landslides and floods – 36 fatalities; 2013 northern Japan – 6 fatalities; 2012: south west Japan tsunami – 28 fatalities, 250,000 evacuated, 4,300 homes and 20 bridges in Fukuoka prefecture damaged;	2016 Houston Texas heavy rainfall – 4 fatalities; 2015 separate floods in Missouri, Utah, Lousiana, and Texas caused at least 102 fatalities and more than £810 million ($1.2 billion) in damages; 2012 Hurricane Sandy – 233 fatalities, £50 billion ($75 billion) in damages; 2011 Mississippi river floods – 20 deaths related to the floods, damages estimated at £1.3-2.7 billion ($2-4 billion);

	Australia	Japan	USA
	(Au$2 billion) in damages; 2010/11 Queensland floods – 38 fatalities, £1.53 billion (Au$2.38 billion); 2007 Hunter Valley floods – 9 fatalities, 105,000 homes impacted; 1974 Brisbane floods – 14 fatalities, ~£40 million (Au$68 million) in damages, 8000 homes destroyed.	2011 Tohoku earthquake and tsunami (40m high waves) – 16,000 fatalities, 127,000 fully collapsed buildings; 2008 Typhoon Jangmi – 4 fatalities, £466,000 (¥62 million) in damages; 1999 Typhoon Bart – 36 fatalities, £96 million (¥12.8 billion) in damages, £186 million (¥35.6 billion) in insurance claims, 80,000 homes damaged.	2005 Hurricane Katrina ~1,500 fatalities, £57 billion ($108 billion) in damages; 1993 'The Great Flood' – 32 fatalities, £10-13 billion ($15-20 billion) in damages; 1965 Hurricane Betsy – 81 fatalities, £11 billion ($20 billion) in damages.
Basis and evolution of approach	The focus is on prediction, warning, and recovery. Dams have been built in response to particularly severe floods, for example Wivenhoe Dam was built as a direct response to the 1974 Brisbane floods. Most effort has gone into early detection and warnings of flood events, although in response to the spate of floods in 2010/2011, many state and city governments are now including other actions (such as provision of dykes or green infrastructure) as part of their resilience plans.	Approach founded on extensive physical defences, well-defined authority over river management, and coordinated evacuations. The constant and unpredictable risk of earthquakes has led to a focus on structural measures. The 1964 River Law (still in effect, though with minor updates) assigns responsibility for river management to River Administrators, whose seniority depends on the importance of the river. Provision is made for evacuation routes and well-signposted shelters in new construction.	Focus is on physical defences and comprehensive insurance to aid recovery. The national Flood Insurance Act (1968) was developed in response to Hurricane Betsy and made flood insurance available through the National Flood Insurance Programme (NFIP). This programme still provides insurance to those at risk of flooding, if their community adopts minimum floodplain management standards. Executive orders 11988 and 13690 (mandates from the President) set standards for federally funded development in the floodplain
Funding and allocation	Taxes, allocation varies by state.	Ministry of Land, Infrastructure, Transport and Tourism raises funds of £3.9 billion (¥698 billion) pa through local and national taxes.	NFIP, public-private partnerships.
Stakeholders	Bureau of Meteorology (BOM); Australian Building Codes Boards (ABCB); state and territorial governments.	Ministry of Land, Infrastructure, Transport and Tourism (MLIT); Japan Meteorological Agency; Cabinet Office; River Administrators.	National Oceanic and Atmospheric Administration (NOAA); United States Geological Survey; United States Army Core of Engineers (USACE); Federal Emergency Management Agency (FEMA); state governments, communities.

Table 2a: Mapping flood risk and use of spatial planning – Europe.

	England	France	Netherlands
Context and basis of approach	The Environment Agency produces and publishes a number of national flood risk maps (further details in Annex 3). These include the National Flood Risk Assessment (NaFRA) and the Extreme Flood Outlines flood map for planning (rivers and sea). Development on land that is at risk of flooding is not prohibited. However, the National Planning Policy Framework steers development away from areas at highest risk of flooding and requires developers to demonstrate that development within areas at high risk of flooding will be safe for its lifetime and will not increase flood risk elsewhere. This approach aims to balance economic development and housing needs with flood risk[32].	Risk mapping is carried out by the state. Flood zoning, which prohibits building and imposes flood resilience standards, is centrally imposed and must be adhered to by local governments.	The Netherlands completed an extensive assessment of national flood risk in 2014. This informs the revised protection standards[7]. There are legal mechanisms for restricting development on land at risk of flooding and setting flood resilience standards. The positioning of the Netherlands' main economic and business hubs ('The Randstad') in the flood-prone land in the west of the country means that there is significant pressure to develop on land at risk of flooding[8].
Governance and Implementation	The Environment Agency's NaFRA covers flooding from river and the sea. It takes into account flood defence height and condition and estimates economic impacts of floods. It uses local data and expertise. This information enables the adoption of a risk-based approach to FRM. The Department for Communities and Local Government (DCLG) sets planning policy through the National Planning Policy Framework and is responsible for its enforcement. There are two key 'tests' in the planning policy framework, in relation to managing flood risk[32]. - the 'Sequential test' which aims to steer new developments to the area with the lowest risk of flooding; - the 'Exception test' which applies to development in areas at risk of flooding	Flood risk mapping/modelling is carried out by the Department for Risk Prevention in the Ministry for the Environment. It also sets out building restrictions for flood-prone land, in its Flood Prevention Plans (PPRIs). The mapping is sometimes challenged by local stakeholders[11]. Local governments are responsible for local land planning and issuing building permits. They must ensure these adhere to the PPRI. The law allows for dialogue between the state and local governments about the PPRI restrictions. In exceptional circumstances the state and local governments may work together on a development plan that goes against the PPRI land designations but includes FRM measures. An example is the 'Eco Valley' along the river Var in Nice, where land pressure has led to a development plan that allows development in an	The Netherlands' national flood risk assessment covers flooding from rivers and the sea. It takes into account flood defence failure modes and economic, societal and personal impacts of flooding. It underpins the new protection standards[6]. Responsibility for spatial planning is decentralised. Municipal councils develop 'strategic spatial development plans' (structuurvisies) and legally binding 'spatial zoning plans' (bestemmingsplannen) to steer where development can take place and to set flood resilience standards. State and provincial governments can set legally binding FRM instructions / standards within the zoning plans. The 'water effect assessment' (water toets) is the key instrument for bringing together spatial planning and FRM activities. Through it, Water

	England	France	Netherlands
	and aims to ensure that the development's sustainability benefits outweigh its flood risk that it will be safe for its lifetime that it will not increase flood risk elsewhere. Local Planning Authorities (LPAs) implement planning policy. This includes developing Strategic Flood Risk Assessments and determining planning applications. The Environment Agency provides advice to support this and there is a statutory requirement for LPAs to consult the Environment Agency for proposed developments at risk of flooding[45].	area at risk of flooding, but incorporates FRM measures[11].	Authorities advise municipal councils on all water-related aspects of their spatial zoning plans. Their advice is not legally binding. Spatial zoning plans may be used to take forward flood defence work, as has been the case in several 'Room for the River' projects (such as the dyke relocation work in Nijmegen[8]). The local government is responsible for costs of adjustments to the water management system resulting from development. The 'development initiator' is responsible for the costs of additional water management measures, but provision is made for them to pass these onto the developer[30].
Impact	It is estimated that without effective planning controls, pressure to build more homes could add up to 16% to the cost of optimal flood protection[26]. In 2014/15, 8% of new homes were built in flood zone 3, which has 1% annual chance of flooding from rivers or a 0.5% annual chance of flooding from the sea, if defences are not taken into account[33]. Where the environment agency is aware of a planning decision notice, 97.8% of residential units in those planning decisions were in line with Environment Agency advice.	A 2013 OECD report on FRM along the Seine identified that 1,500 hectares of development and major infrastructure had been situated in the floodplain[31] over the last 20 years.	Although the mechanisms for preventing flood risk are in place, development in the flood risk zones is rarely prevented due to competing pressures between economic development and flood prevention[8]. The OECD has identified development in flood-prone areas as a key risk to the future financial sustainability of flood defences and a barrier to the adoption of a broader range of FRM approaches[30].

Table 2b: Mapping flood risk and use of spatial planning – International.

	Australia	Japan	USA
Context and basis of approach	Building on floodplains is not subject to national-scale controls, but buildings in floodplains must be built to be flood-resistant.	Spatial planning is considered alongside other measures, including defence.	Federally-constructed buildings must be built outside the floodplain. Communities involved in the National Flood Insurance Programme must use municipal laws to manage the floodplain to minimum standards.
Governance and Implementation	Mapping of areas that are prone to flooding is carried out by local governments[44].Guidelines for floodplain planning are laid out in a central document that does not have the force of law[16,67]. Australia has a permissive approach to building, with zoning laws set by individual states or local governments. In Queensland, for example, State Planning Procedure 1/03 applies to the whole state[34], whereas in Victoria local councils set their own controls[68]. Building standards set by the ABCB are designed to protect the lives of occupants by ensuring that buildings in areas identified to be at risk of flooding do not collapse[34]. ABCB standards require that the height of the floor of habitable rooms and all electrical sockets be above the flood hazard level. Non-habitable rooms (such as bathrooms, garages and hallways) that are built below the flood hazard level must possess two openings of height and width of at least 75mm to allow the free flow of water through the room. The ABCB does not set standards for building in areas with a less than 1% annual chance of flooding.	Under the National River law, regional River Administrators are responsible for planning any river improvements or flood defences[69]. Disaster hazard zones are identified by local governments and new construction may be prevented by local municipal laws[13]. Buildings in sediment or tsunami disaster hazard zones must be built to resist damage related to those disasters or be relocated[70]. A catchment approach is being adopted in areas where significant urbanisation has taken place. This approach is also referred to as “comprehensive flood control” and includes land use planning measures such as the preservation of green areas and incentives for flood resilient building[23]. Local government can designate areas that are at risk of flooding and that lie outside of flood defences as ‘disaster hazard zones’ and use byelaws to prevent the construction of new houses in these zones. Planning that affects riparian areas must be approved by the local River Administrator,	Flood risk hazard zones are identified by FEMA[71]. Federal law (through Executive Orders 11988 and 13690) sets minimum standards for publicly-funded building projects located in the flood plain[39, 40]. To participate in the National Flood Insurance Programme (NFIP) communities must implement minimum floodplain management standards through their municipal laws (ordinances)[15,72]. Federal investments in water resources are advised to avoid: use of floodplains and flood-prone areas; having an unreasonable adverse effect on public health and safety; any actions that adversely affect one or more floodplain function[21].

	Australia	Japan	USA
		appointed according to the provisos of the River Law[69].	
Impact	Building on floodplains is not universally prevented and planning and mapping of floodplains is not universally applied. For example in Queensland most towns and cities are on floodplains but only 37% of planning schemes included any flood mapping. Most mapping does not comply with the relevant policy guidelines[15].	17 of the most urbanised river catchments have been subjected to the 'comprehensive flood control' measures.	Building in floodplains is not prohibited, except by local zoning laws, nor does the standard set by EO 13690 standard apply to private investments in structures or homes. It does not affect flood insurance premiums[71]. The NFIP has been criticised for providing a 'perverse incentive' to build just outside the 1% annual risk region, and in flood-prone areas protected by dykes[15].

Table 3a: Defence and mitigation — Europe.

	England	France	Netherlands
Context and approach	The key output aim is that '300,000 homes across the UK will be better protected from flooding and coastal erosion by 2021'[28]. This will be achieved through the implementation of FRM schemes, which range from the repair of existing structures to the implementation of new flood defences such as the 'Boston Barrier' which will protect over 20,000 residential properties[28].	The primary objective of France's National FRM Strategy[63] is to increase the safety of the exposed populations, in particular by ensuring the existing protection systems are secure[64]. The competence for this transferred from central government to local governments/public bodies for inter-city cooperation on 1 January 2016. The national strategy identifies the development of governance and project management around this as a key challenge[63].	Current protection standards specify water levels that each of the 95 dyke rings must withstand. New risk-based standards are coming into force in 2017, which will be implemented by 2050, and will provide everyone behind a dyke ring with an annual flood mortality risk of less than 0.001%[62]. The new standards are underpinned by analysis of dyke failure mechanisms and economic impact analysis to determine optimum levels of protection[7]. They will set more granular standards for individual dyke stretches (rather than whole rings), ranging between 0.33% and 0.001%[62] annual chance of flooding.
Governance and implementation	The Environment Agency's seven FRM Plans, published in 2016, set out the approach to managing flooding for each river basin district[74]. Twenty two Shoreline Management Plans (SMPs) set out the approach to managing coastal flooding and erosion[75]. This includes managed realignment such as at Medmerry[76]. The Environment Agency runs the six year capital investment programme for FRM schemes. Schemes are delivered by the Environment Agency and others[28]. The Environment Agency also maintains 8,000 km of flood defence on main rivers and the coast and 22,600 supporting structures (e.g. sluice gates, pumps). Improvements are underway to enable better planning and programming of maintenance work. Local flood authorities are	The Ministry of the Environment and Energy's National FRM Strategy[63] sets out the overall approach and the role of water management measures. FRM Plans set out the approach to managing flood for each river basin. Flood defences are owned by the owner of the land which they are on, although around 1,000km of dyke are managed by the state. A 2007 Decree on defence structure safety was intended to provide a technical framework for dyke classification, ownership and assessment. The 2014 MAPAM act, which transfers responsibility to the local level, also sets out norms and obligations for dyke maintenance and makes provision for an (optional) tax to fund this work[11]. Dams play an important role in flood defence. For example, the 4 main rivers in the Seine Basin are	The Ministry of Infrastructure and the Environment and the Ministry of Economic Affairs' joint National Waterplan[62] sets out the overall strategy for water management, including FRM, from 2016 to 2021. It includes the Coastal Strategy and FRM Plans in its appendices. The Delta Commissioner's Delta programme[9] provides an overview of all major FRM schemes that are planned or underway. This includes the rolling six year maintenance programme. The current programme is based on the results of primary flood defence testing carried out between 2011 and 2013. It is 50% funded by regional Water boards, 50% by central government. The next round of testing will be based on new criteria to deliver the new standards of protection and to allow better scheduling[9].

	England	France	Netherlands
	responsible for maintenance of 1,700 km of defences and 9,600 structures on ordinary watercourses[3, 24]. Between 2007 and 2015, government grants funded the installation of Property Level Protection in around 3,400 properties. A British Standards Institution (BSI) kitemark scheme to give consumers confidence has also been introduced. It is estimated to have the potential to encourage installation at 190,000 properties[78].	controlled by dams built between the 1950s and 1980s and managed by the public territorial basin authority (EPTB) Seine Grands Lacs (SGL)[42]. In 2014, 19% of PAPI funding went on upstream flow management[11]. The integrated coastal management strategy[79] sets out the ambition to use coastal realignment and relocation in some areas. Property Level Protection is used to some extent[51].	The Delta programme also includes the 'Room for the River' programme[9] which seeks to increase the capacity of rivers and/or reduces the height of peak flows, partly through working with nature. Management and maintenance of regional waterways, along with 18,000km of primary and regional flood defences, is carried out and funded by regional water boards through water management taxes[9]. Sand plays a key role in coastal defences and is replenished at the rate of 12 million m³ per year[62]. The Coastal Genesis II research programme will inform decisions on developing this strategy. Sustainable innovations include the 'Sand Engine' where a manmade spit is intended to 'naturally' regenerate the beaches for 20 years[46]. There are some examples of innovative flood resistant building, such as14 floating houses in Maasbommel[53], part of a government-sponsored opportunity to explore flood resilient building in 15 locations.

Table 3b: Defence and mitigation – International.

	Australia	Japan	USA
Context and approach	Defences and their funding are handled by local governments and private individuals, with no national coordination.	Defences form the primary strategy for Japanese FRM. National government provides subsidies for building defences and relocating individuals affected by those building plans.	The National Flood Insurance Programme (NFIP) drives dams and dykes being built to protect against at least a 1% annual chance of flooding. Mitigation measures are not widely used, although there are several local governments that have adopted some form.
Governance and implementation	Local governments are responsible for building their own flood defences and produce their own plans[80]. FRM dams exist: for example the Wivenhoe dam in Queensland was built to store 1.45 million litres of flood water[44]. Other dams, such as those in Victoria, do not have flood mitigation as their primary purpose. The extent of dyke use in Australia is hard to gauge due to the absence of regulation[15]. A dyke database is maintained by Victoria, and New South Wales is producing one, but Queensland does not have one[81]. Funding mechanism vary from state to state. New South Wales (NSW) allocates grants through its Floodplain Risk Management Grants Scheme (jointly funded with the federal government through the Natural Disaster Resilience Program) and the NSW Floodplain Management Program (£14m (Au$20.82m) in 2013-14)[82]. Queensland also provides grants.	Japan possesses approximately 13,400 km of embankments, and some 10,000 flood gates, sluice ways, sluice pipes, drainage pump stations, weirs and other structures. Ring dykes and temporary embankments are used as well as larger-scale engineering works such as super-levees and flood tunnels in areas (e.g. Tokyo) where flooding would not be tolerated[70,23]. Renewal of ageing flood defences is a challenge and the cost of renewal of flood defences has been projected to double over the next ten years. In response, funding allocation is now based on individual monitoring, which is expected to deliver savings to reduce the growth in expenditure to 30% above the current budget. National government subsidies are available to assist the construction of secondary embankments[23]. This includes subsidies for resettlement/relocation of housing if this reduces the scale of the embankment (thus making it more economical). Management priorities for riparian areas are decided by River Administrators[69]. Assistance is	The NFIP exempts building owners/tenants from buying insurance when protected by dykes that protect against a 1% or more annual chance of flooding[22]. The USA possesses an estimated 230,000km of dykes and 'levee-like' structures, of which 56,000 km are federally owned and managed[20]. Defences are partially paid for through public-private partnerships. Private owners cover 20% of the cost of maintenance and repair of physical defences[20], and the construction of new federal dykes is funded 65% by the federal government. Prioritisation of physical defences for maintenance and repair is based on a USACE 'Dam Safety Action Classification rating' that takes into account the cost of repair, and the likelihood and consequences (to life and the economy) of a failure[43]. Non-structural measures must be given full and equal consideration in federally-funded flood defence decisions[21].

	Australia	Japan	USA
	Blue-green infrastructure is used by some local governments. For example, 'rain gardens' are used in Melbourne and cost £17,000-£24,000 (Au$25,000-Au$35,000) for every 100m of road along which they are installed[83]. Citizens are also encouraged to create their own rain gardens.	provided for the costs of resettlement (including house removal, relocation, and the costs of temporary dwellings) when a River Administrator plans the construction of a ring dyke.	Some local governments have opted to include blue-green infrastructure. Examples include New York's Staten Island 'blue belt' project[49] and Philadelphia's ambitious 'Green City, Clean Waters' campaign which has a committed budget of £1.6bn ($2.4bn) for its projects over 25 years[84].

Table 4a: Preparing for and responding to floods - Europe.

	England	France	Netherlands
Basis of approach	Emergency preparation and response is a key part of England's diversified FRM strategy. Flooding is treated as part of broader civil protection 'emergency' policy, but Defra also maintains the 'National Flood Emergency Framework for England[45].	Flood preparation and response is part of the overall planning for risks and is part of civil security policy.	Preparation is a relatively new FRM strategy. It is a key area in which Rijkswaterstaat and the Dutch Water boards have identified that they wish to learn from England.
Governance and implementation	A study carried out after the 2009 flooding in Cumbria reported that around 40% of respondents felt homeowners should take responsibility to reduce flooding and 80% of respondents felt the government should – some people saw both parties as having a degree of responsibility. Approximately half of those who flooded expected to flood again in the next 5 years[85]. A number of FRM information products are published by the Environment Agency[86] covering all sources of flooding. For surface water flooding, velocity and depth are shown as well as likelihood of flooding. Category one responders (those who lead the response action) are required to form Local Resilience Forums, which facilitate multi-agency joined up working, including the development of multi-agency plans and community risk registers. The principle of subsidiarity applies for response, with the Cabinet Office ultimately responsible. In England, the Flood Forecasting Centre (a joint venture between the Met Office and the Environment Agency) provides a comprehensive flood forecasting service, which includes the	French civil security law (2004) states that 'citizens are responsible for their own safety'[11]. Nevertheless, the French do not treat flood risk as a high priority, are not concerned about the problem, are unwilling to take measures to adapt or change their behavior and consider themselves to be poorly informed.[11] Regional Department Prefects lead regional planning through the 'Rescue Organisation' (Organisation des Secours - ORSEC) plan, which covers all risks and the organisation of emergency exercises. Mayors lead municipal planning through 'Local Municipal Crisis Plans' (Plan communal de Sauvegarde), which are mandatory for local governments that have a PPRI in place. The subsidiarity principle applies for response, with the Ministry of the Interior ultimately responsible. The Departmental Council is in charge of rescue operations. The state provides forecasting and information for rivers in the public domain, through 22 regional Flood Forecasting Centres. This information is provided to the general public on a map, showing risk level. For rivers not owned by the state, private	At an individual level there is an expectation that the state will protect people from flooding and a perception that flooding will therefore not occur[62]. In general FRM is seen as an official responsibility but in terms of emergencies[30] the official expectation is that individual should be self-reliant[62,8]. FRM information is published by the by central government. It shows maximum flood depth and provides information on what that means for individuals in terms of impact and action. There are also apps available providing local information. The Boards of Security Regions, which include local governments and chairmen of relevant regional Water Boards, are responsible for planning. They develop 'Policy Plans' (beleidsplannen), based on concrete risk profiles, and 'Crisis Plans (crisisplannen), setting out operational policy and roles and responsibilities. These have to be aligned with the relevant Water Board's 'Emergency Plan' (calamiteitsplannen), which covers emergencies in general. However, their use is still limited[8]. Depending on the scale of the flood, mayors of

	England	France	Netherlands
	provision of coastal and river flood warnings. It is supported by category one responders and the media, who have contractual obligations to relay flood warnings. Targeted messages are sent to landlines, mobiles, faxes and pagers, and simultaneously broadcast on digital channels such as Twitter. Local flood wardens and flood action groups can also provide warnings[45]. Response activities include operating and maintaining flood defence structures, deploying demountable and temporary barriers to protect properties and infrastructure, pumping water and evacuating residents. Voluntary organisations such as the Red Cross support the response effort[87].	companies offer a service directly to local governments. Mayors are also responsible for informing the population of a risk and broadcasting warnings. They have police powers and can use the police force to spread flood warnings There is a national information system for national rivers[88].	local governments or chairmen of Security Regions may have supreme command over all parties involved in emergency management. If the flood impacts multiple local governments a regional policy team is set up to consult on all decisions. There is a tendency towards centralisation and the Ministry of security and justice is ultimately responsible. The storm surge warning service and regional river warning systems provide Security Regions, Water Boards and others with flood warning information. The public are informed by air raid sirens, the crisis.nl website and opt-in mobile phone messaging[89]. Response activities include operating and maintaining flood defences, deployment of temporary defences as well as forced evacuations and street bans[90]. Volunteers may be involved in this, such as the Kampen Flood Brigade[57].
Impact	In March 2015 direct warnings covered 55% of the properties that could benefit most from early warnings[22].		Recent research has found limitations in the capacity and knowledge of both emergency management authorities and individuals[8].

Table 4b: Preparing for and responding to floods – International.

	Australia	Japan	USA
Implementation	**Flood warnings** The Centre for Australian Weather and Climate Research works with the Bureau of Metrology (BOM), Geoscience Australia, and the Australian National University to collect and assess climate and meteorological data. Imperfect coverage (from automated rain gauges and water level measuring stations and manual stations in more isolated areas) has led to some disasters not being predicted[90]. The BOM provides forecasts and warnings for all floods except those with a lead time of less than six hours, when local governments are responsible and the role of private bodies such as dam operators is under development. Warnings are provided to all people in at-risk regions about both likely and ongoing emergencies[16] by phone and text by the nationally-run Emergency Alert System. Forecasting was funded with a total investment of £34m (Au$50m) from 2008 to 2013. In 2013, the government announced an additional £40m ($58.5m) to improve the BOM's capacity to respond to extreme weather events and natural disasters. Geoscience Australia has been provided with £8.2m (Au$12m) over four years to establish the National Flood Risk Information Project[91].	**Flood warnings** Warnings are issued by the Ministry for Land, Infrastructure, Transport and Tourism and the Japan Meteorological Agency. Flood data is collected using multiple methods, including RADAR and CCTV[92] alongside automated rain gauges and water level measuring stations. Warnings are broadcast on multiple channels, including sirens, emails, text alerts and online[92,93]. **Preparation** Evacuation centres are built around cities and regular drills are conducted to ensure that people are able to evacuate quickly and safely[14]. **Flood response** Japan makes use of flood-fighting teams, primarily made up of volunteers [12,70]. These were traditionally comprised of people from rural areas, and increasing urbanisation has led to declining levels of volunteers[70].	**Flood warnings** The national Oceanic and Atmospheric Administration (NOAA) publishes flood forecasts online. Rain gauges and sensors are used to detect water levels. The Corps Water Management System (CWMS) has over 700 reservoir and lock-and-dam projects from which precipitation, river stage, gate settings and other data from field sensors are retrieved, validated, stored in a database run by USACE. **Flood response** USACE and FEMA are involved in recovery and clean-up operations, including the provision of temporary accommodation, tarpaulins, and the restoration of critical infrastructure[94,95]. The National Response Framework[96] and the National Incident Management System[97] provide guidelines on how the different federal agencies are to interact during an emergency of any scale[71].

	Australia	Japan	USA
	Flood response Disaster management groups include emergency services and utility companies[68]. The voluntary State Emergency Services receives equipment and training from the fire and rescue services and through government grants[44,56]		
Evaluations	'The Brisbane Review' discusses a significant breakdown of communications when the web portal it was using became overwhelmed. SMS alerts were also delayed due to network congestion and reduction in capacity of mobile towers due to power loss[15].		

Table 5a: Flood recovery – Europe.

	England	France	Netherlands
Basis of approach	Private insurance against flood risk damage, bundled with general insurance, with 95% coverage and with cross-subsidy of high risk properties. Central government scheme for public sector recovery, funded through general taxation.	State-managed natural disasters fund, funded through a levy on compulsory private home insurance.	No private insurance for river or sea flooding. There is a largely untested state compensation scheme. Relocation has been used under the 'Room for the River' programme.
Implementation, funding and allocation	Private sector flood insurance is included as standard with building and contents cover[45]. Basic structural flood insurance is a pre-requisite for a mortgage, resulting in 95% market penetration[58]. The Flood Re re-insurance fund was introduced in April 2016. It offers re-insurance to private sector insurers, funded by a levy taken from all policy holders, to enable those insurers to provide people living in high flood risk areas with affordable flood insurance (based on their council tax band). Flood Re is intended to help manage the transition to risk-reflective pricing by 2039[45]. £5,000 grants for individuals to make their homes more flood resilient have been offered for victims of December 2015's Storm Desmond[52]. The Bellwin scheme provides emergency response funding for local governments, police and fire authorities and National Park Authorities. It is administered by DCLG. Payouts are capped and intended to encourage local governments to have their own emergency financial reserves, and to encourage flood risk reduction[45].	The state supported 'National Disaster Compensation Scheme' (CAT-NAT) was created in 1982. Policy holders hold private insurance and are bound by a private contract. Each insurance contract includes a risk premium (currently set at 12%) which funds the CAT-NAT scheme. It covers private and commercial losses when a state of disaster is declared by inter-ministerial decree (from the Ministry of the Environment, the Ministry of Finance and the Ministry of the Interior), and has a cap on individual payouts. Market penetration is close to 98%[11]. The CAT-NAT is ultimately a state-guaranteed public reinsurance scheme through the state-owned Caisse Centrale de Réassurance (CCR) re-insurance company. The state will make up any shortfall in pay-outs from tax revenues. Part of the CAT-NAT funding is channelled into the Barnier Fund for FRM activities[11]. The state guarantee applies to direct flood damages, but not indirect costs such as re-housing[73]. Since 2001 an insurer can legally refuse to cover flood risks in an area of a PPRI, if the property was built after the plan. Excesses can also be increased in the event of recurrent	Insurance for surface water flooding has been bundled with standard insurance since 1998, with high market penetration[8]. Risk-based insurance for fluvial flooding is expensive, has limited availability and market penetration is very low[8]. The introduction of compulsory public-private insurance was explored repeatedly between 2006 and 2013 but rejected on the basis of incompatibility with competition law[73]. Under specific circumstances state compensation can be provided under the Ministry of Security and Justice's Calamities and Compensation Act, . However, the act specifically excludes damages from seawater flooding. Funding for this scheme has not been established[58]. There is provision for compensation to be granted to individuals if a disproportionately large burden or loss is caused through lawful activities. For example, an individual could be compensated if their house was impacted by a dyke relocation[8].

	England	France	Netherlands
		natural disasters[11].	
	European Union Solidarity Funding is available for major natural disaster under certain circumstances. The funds are intended for essential public emergency and recovery operations[74].		
Impact		Annual CAT-NAT pay-outs for flooding: £340 million pa (€400 million). Estimated annual economic damages: £550-680 million (€650 - €800 million), over period from 1980-2010. Estimated annual economic impact of a major flood: £0.84 - 1.2 billion (€1 – €1.4 billion)[11].	There was a payout under the Calamities and Compensation act for a small flood at Wilnis in 2013[8].

Table 5b: Flood recovery - International.

	Australia	Japan	USA
Basis of approach	Insurance is limited, relocation plays a part.	The cost of disasters is shared between individuals, the government and the insurance industry.	The National Flood Insurance Programme (NFIP) plays an important role in funding flood recovery. Relocation plays a part.
Implementation, funding and allocation	Insurance for coastal, storm surge and river flooding is rarely available/affordable. Flash flooding insurance is widely available and market penetration is 60%. The Australian government is investigating the use of catastrophe bonds and other measures to improve coverage[73]. The Voluntary House Purchase Scheme in Brisbane, worth £2.6 million (Au$5 million), aims to purchase houses in regularly flooded areas. It is available to those whose home has a >50% annual chance of flooding[60]. The Victorian government has offered a buyback scheme of £6.2 million (Au$12 million) to irrigators in the Lower Loddon. The Inquiry into the 2011/12Queensland flooding report notes that the cost of a land swap is to be offset by the sale of land ballots at a later stage in the process[15].	Flood insurance is available as an optional add-on to comprehensive fire insurance. Fewer than half of households are covered, but 70% of potential damages are estimated to be covered[73]. Individuals often carry an important part of the economic loss of disasters[98]. Local public bodies are required to set aside a disaster relief fund which is managed by the prefecture[98]. There is financial assistance for reconstructing livelihoods available under the 'Act concerning support for reconstructing the Livelihoods of Disaster Victims'[98].	The NFIP is administered by FEMA and provided through a public-private partnership[71]. It offers flood insurance to property owners/tenants if their community participates in the NFIP[100]. To participate, communities have to adopt minimum building standards for new and existing developments, as set out by FEMA. They are encouraged to adopt higher standards, which can earn up to 45% discounts[101]. Pricing is currently based on multiple factors[71], but due to become risk-based for new developments. The average annual cost of insurance is £470 ($700), but costs vary depending on risk and level of protection[100,102]. All homeowners in areas with a 1% or higher annual chance of flooding, with mortgages from federally regulated or insured lenders, are required to buy flood insurance[71]. Uptake is 75% of those legally required to hold cover[73]. Damages are capped at £170,000 ($250,000) per property and private insurance is available to supplement NFIP cover. The Community Development Block Grant-Disaster Recovery (CDBG-DR) Program run by the Department for Housing and Urban Development provides disaster recovery resources such as mortgage insurance for lenders. The State of New Jersey allocated £0.74 billion ($1.1 billion) from the CDBG-DR to help homeowners repair or rebuild their Hurricane Sandy-impacted homes[103].

	Australia	Japan	USA
			States may also have their own disaster recovery assistance programs, for example the Rehabilitation, Reconstruction, Elevation and Mitigation (RREM) Program provided grant awards to the primary residences of homeowners in New Jersey to restore their storm-damaged homes after Hurricane Sandy[103]. New Jersey also launched a scheme to buy out up to 1,300 storm damaged homes, using up to £200 million ($300 million) federal funding[104]. Following Hurricane Sandy building standard codes are being revised and being aligned with the NFIP requirements[105]. Recovery after Hurricane Katrina has focused more on rebuilding homes and dykes than relocation. Although grant aid to relocate homes was made available, full compensation was only provided if the damage was assessed to be >51%, or the cost of repair was more than the cost of the home[106]. The National Disaster Recovery Framework (NDRF) was developed after Hurricane Katrina to set out recovery principles, define roles and responsibilities, enable communication and support coordinated, resilient recovery[71].
Impact		Penetration rates for flood insurance are approximately 49% and 35% for homes and household property respectively, but 70% of potential damages are estimated to be covered[73]. Recovery along the north-east coast after the tsunami of March 2011 has fallen behind schedule because of a building boom in Tokyo. Construction companies are focusing on projects in the cities where profits are higher[10].	Approximately £0.88 billion ($1.3 billion) worth of coverage was protected by the NFIP in 2014[107], with a total of 5.4 million policies in effect. About half of damages occur outside the high risk area and only 1% of these are covered by insurance[73]. The costs of the NFIP amount to a government subsidy of homes in flooded areas of $17.5 billion over the 40 years of the programme's life[73].

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Commonly used acronyms

Acronym	Phrase	Country
ABCB	Australian Buildings Code Board	Australia
BOM	Bureau of Meteorology	Australia
CATNAT	CATastrophes NATurelles (national disaster compensation scheme)	France
CCR	Caisse Centrale de Réassurance (central reinsurance agency)	France
CDBG-DR	Community Development Block Grant-Disaster Recovery	USA
CFMP	Catchment Flood Management Plan	England
CIA	Central Intelligence Agency	USA
CWIMS	Corps Water Management System	USA
DCLG	Department of Communities and Local Government	England
Defra	Department for the Environment, Food and Rural Affairs	England
EA	Environment Agency	England
EPTB	Établissement Public Territorial de Bassin (public territorial basin authority)	France
FCRM	Flood and Coastal Risk Management	-
FEMA	Federal Emergency Management Agency	USA
FIRM	Flood Insurance Rate Map	USA
FRM	Flood Risk Management	-
FWD	Floodline Warnings Direct	England
GDP	Gross Domestic Product	-

HUD	Housing and Urban Development department	USA
LPA	Local Planning Authority	England
MAPAM	Modernisation de l'Action Publique territoriale et d'Affirmation des Métropoles (modernization of territorial public action and affirmation of the metropolis)	France
MLIT	Ministry for Land, Infrastructure, Transport and tourism	Japan
NDRF	National Disaster Recovery Framework	USA
NFIP	National Flood Insurance Program	USA
NOAA	National Oceanographic and Atmospheric Administration	USA
OECD	Organisation for Economic Co-operation and Development	-
ORSEC	Organisation de la Réponse de SÉcurité Civile / ORganisation des SECours (organisation for the response of civil security / rescue organisation – these are the same organisation)	France
PAPI	Programme d'Action de Prevention des Inondations (flood prevention action program)	France
PCS	Plan Communal de Sauvegarde (community protection plan)	France
PPRI	Plan de Prévention du Risque Inondation (flood risk prevention plan)	France
RFCC	Regional Flood and Coastal Committee	England
SFHA	Special Flood Hazard Area	USA
SGL	Seine Grands Lacs (Seine grand lakes)	France
SPP	State Planning Procedure	Australia
USACE	United States Army Corps of Engineers	USA