APPENDIX F: **THE FUTURE FLOOD EXPLORER: OVERVIEW**

Contents

F.1 Introduction

This Appendix sets out the approach the emulation of the UK Flood Risk System and its representation within the Future Flood Explorer (FFE). The approach consists of five steps (Figure F1). Steps 1-2 focus on marshalling input datasets and developing a series of Impact Curves (which represent impact as a function of storm return period) for each unit area. The emulator is developed in Step 3 and the outputs verified and validated in Step 4. The FFE is then used to explore alternative futures in Step 5.

Each of these steps are discussed in more detailed in the following sections.

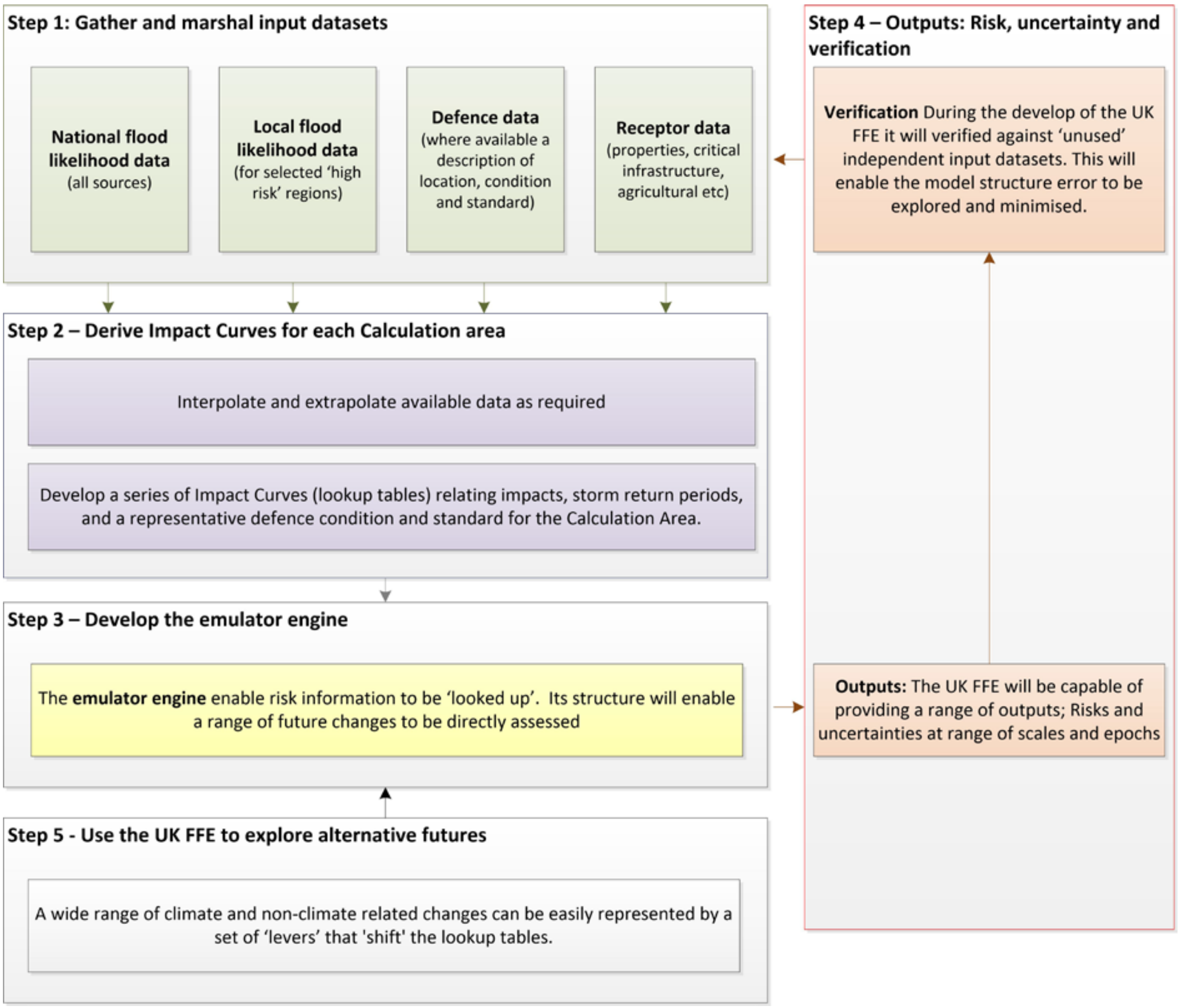


Figure F1 Overview of the steps in the method

Each step in the process is discussed in more detail below.

F.2 Step 1: Gather input datasets and aggregate by Calculation Area

The first step involves bringing together data representing sources, pathways and receptors from England and the Devolved Administrations.

The datasets used within the FFE have been previously set out in Appendix A.

F.3 Step 2: Develop impact curves

The Impact Curves provide a summary of the input data for each *Calculation Areas*. The Calculation Areas are defined as follows:

- For fluvial and coastal flooding, areas related to the river network and coastline are used. For England and Wales, these are Flood Areas used in NaFRA. For Scotland and Northern Ireland, the equivalent polygons are derived from GIS data representing the river network, floodplain extent and coastline. Flood Areas typically cover a few km of river reach (with a flood area on each side of the river) or coastline, and cover all areas at risk of flooding from fluvial and coastal sources.
- For surface water flooding, 1km squares are used

These definitions of Calculation Area give a few hundred thousand areas over the UK, defined consistently for all flood sources. Where the Calculation Area definitions produce very small polygons (e.g. “slivers” of 1km grid squares) these are merged with neighbouring Flood Areas.

Impact curves are developed for each receptor type, each Calculation Area and each source of flooding. Impact curves are compiled by calculating the number (for points), length (for lines), or area (for polygons) of receptors lying within flood extents for different return periods. Some point receptor information does not include a specific geographical location (e.g. for some social infrastructure receptors); in this case the postcode is used and linked to the OS Code-Point or OSNI equivalent. For property counts based on polygon data (e.g. using OSNI Large Scale Vector mapping), the centroid of the building is extracted and used to count properties.

An example Calculation Area and resulting impact curve is shown in Figure F2.

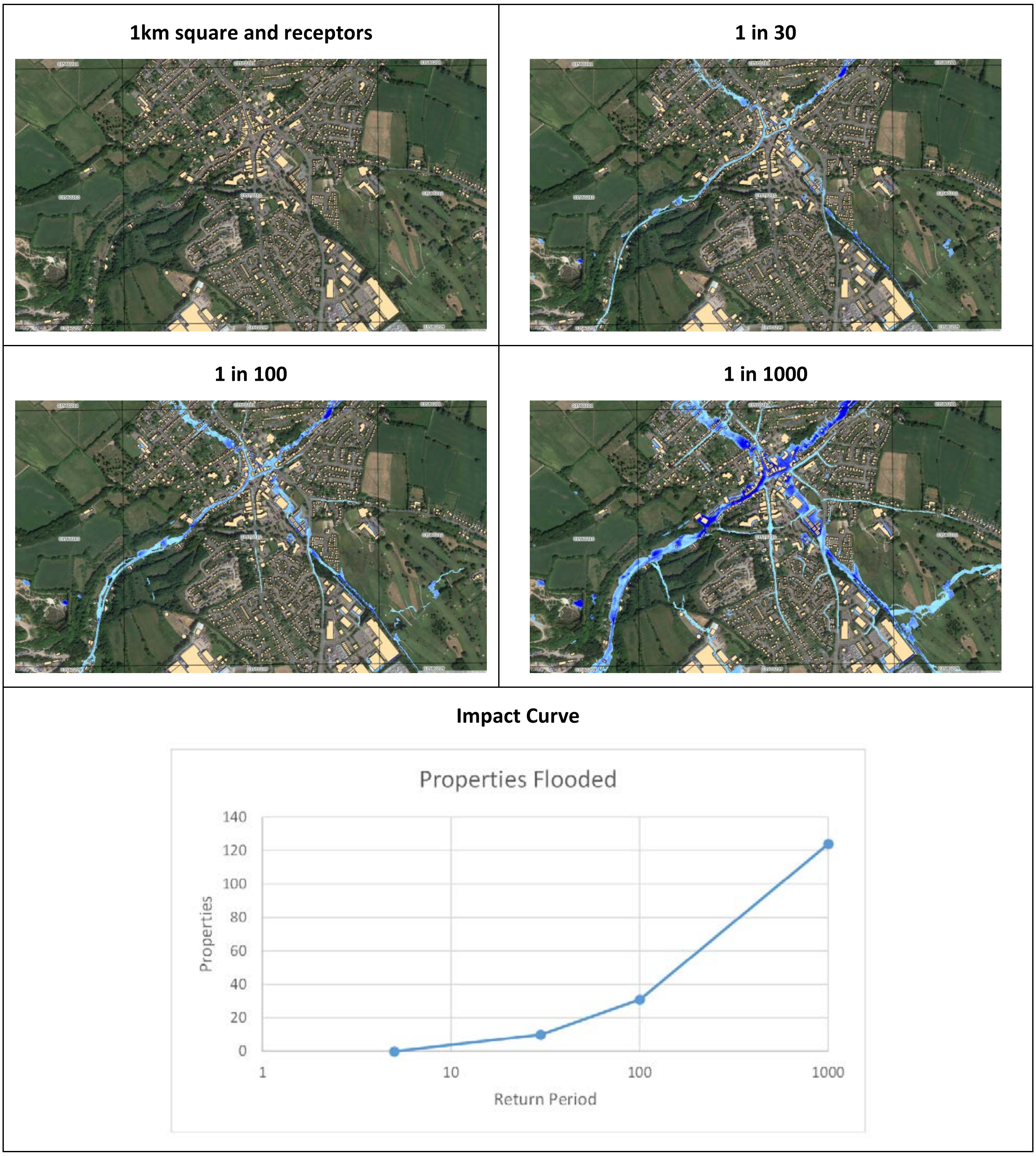


Figure F3 Example of development of property count impact curve from surface water hazard information (illustration only)

To allow for sensible extrapolation to return periods above and below the values associated with the hazard data, extra points above and below the available return periods will be added:

- At extremely high return periods (1 in 1 million), the impact is set to the total number of receptors in the Calculation Area.
- At a return period of 1, the impact is set to zero.

Initial testing has indicated that some metrics may be sensitive to these assumptions; sensitivity analysis issued to quantify this and feed into the confidence rating as part of the FFE verification process.

One case requiring special treatment is property counts for surface water hazard data sets. The hazard data can include the effects of buildings, meaning it is impossible for receptor points to be flooded because buildings produce holes in the flood extent (see Figure F4 for an example). In this case the property counting method first fills any holes in the flood extent associated with a building, by identifying any building footprints in contact with the flood extent; properties within these footprints are also flooded. This gives a relatively quick method that can be applied to data sets which give flood extent only (i.e. if no depth information is supplied). According to testing of property counting methods undertaken for the Environment Agency uFMfSW project, this approach will tend to overestimate the number of properties when compared with observed numbers of properties flooded. Testing of these different approaches undertaken for the uFMfSW and Communities at Risk workpackage 5 projects indicates that a correction factor of 1/6 needs to be applied to the "raw" property counts to align with the Environment Agency's recommended method for surface water property counts. In practice, a factor of 1/5 is applied to ensure property counts in England match those in LTIS 2014.

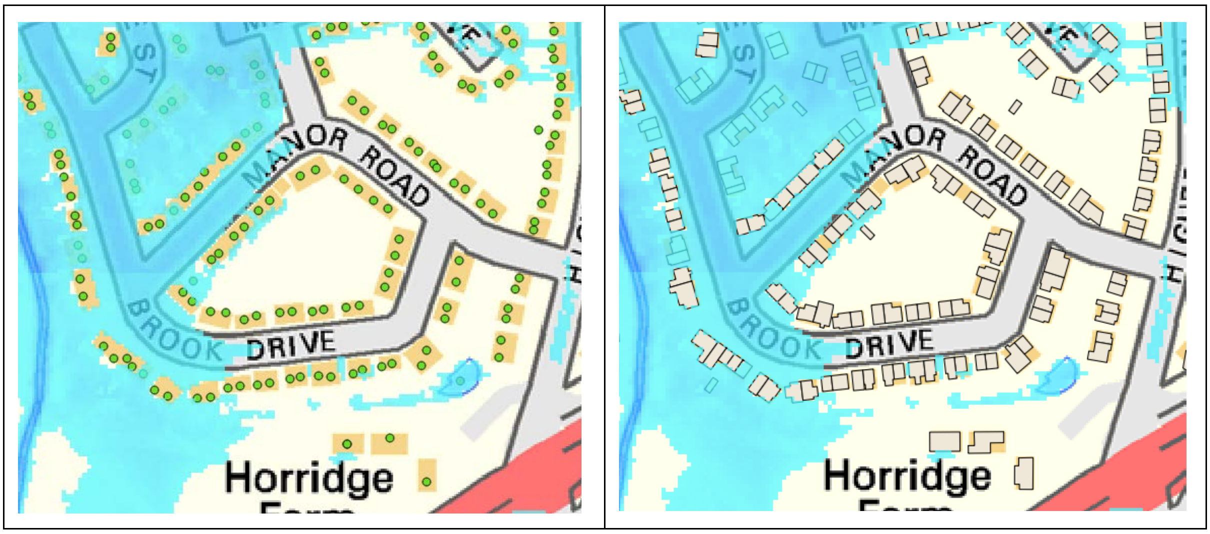


Figure F4 Property counts based on centroids for surface water hazards could generate no flooded properties (left); the perimeter of building footprints must be used (right).

A further special case is the treatment of point infrastructure, as there may be so few of these sites that there is only one in a Calculation Area. In this case, the impact curve looks like those shown in Figure F5, depending on whether the infrastructure is behind a defence or not. The difficulty here is in determining where the step in the impact curve occurs. For probabilistic hazard data like NaFRA, then the impact cell in which the receptor sits gives us the probability with some precision; but for flood extent data then the receptor can only be assigned a fairly broad probability band (e.g. the probability of flooding is somewhere between 0.1% and 1%). The probability of flooding could be assigned to the middle of the band, but then when the curve is shifted to represent climate change uplifts, then it is unlikely to change bands; the increase in risk is therefore not represented.

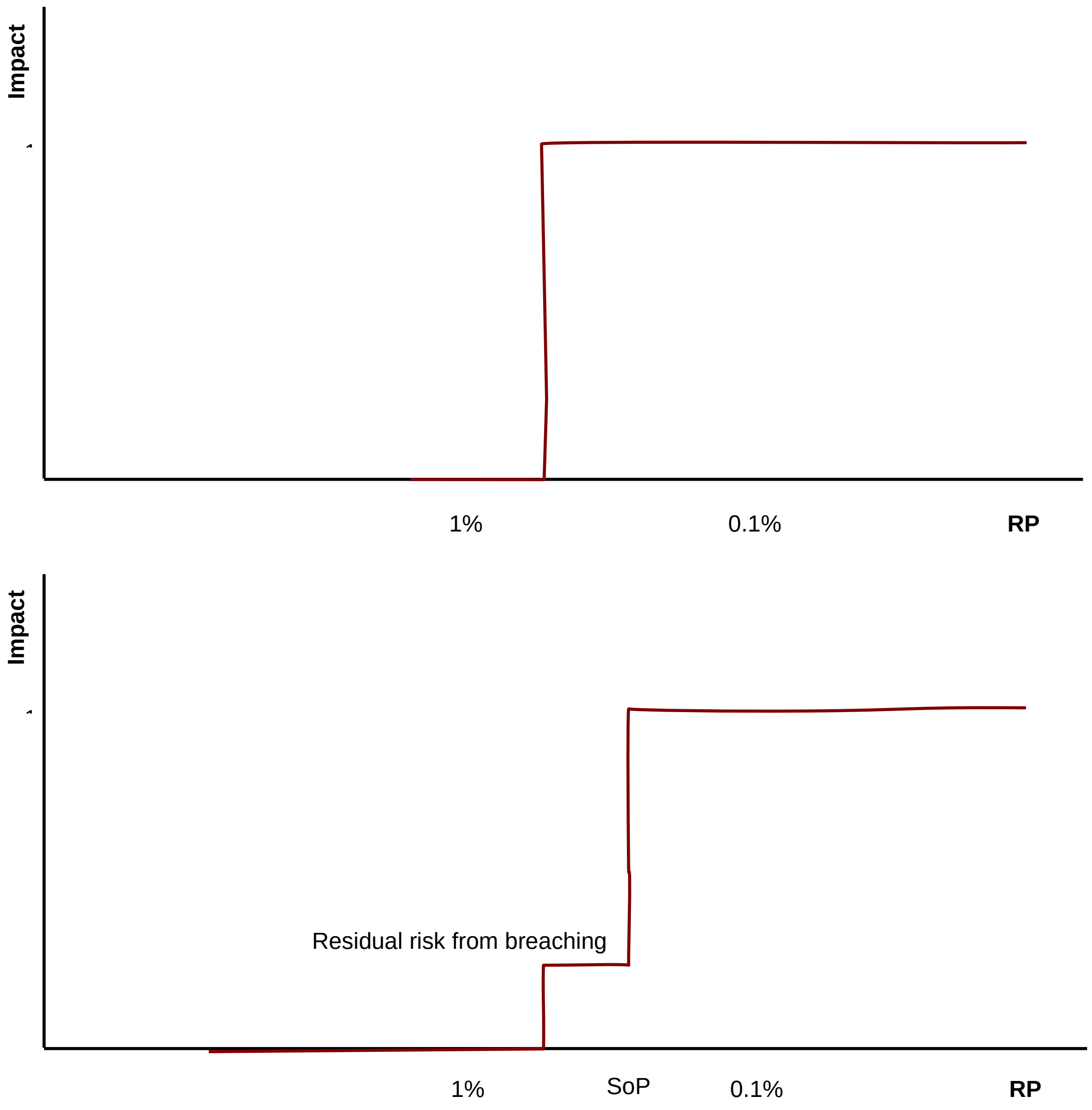


Figure F5 Impact curves for a single receptor, on an undefended floodplain (top). With defences in place, the receptor is protected up to SoP, but with a small residual risk from defence breaching.

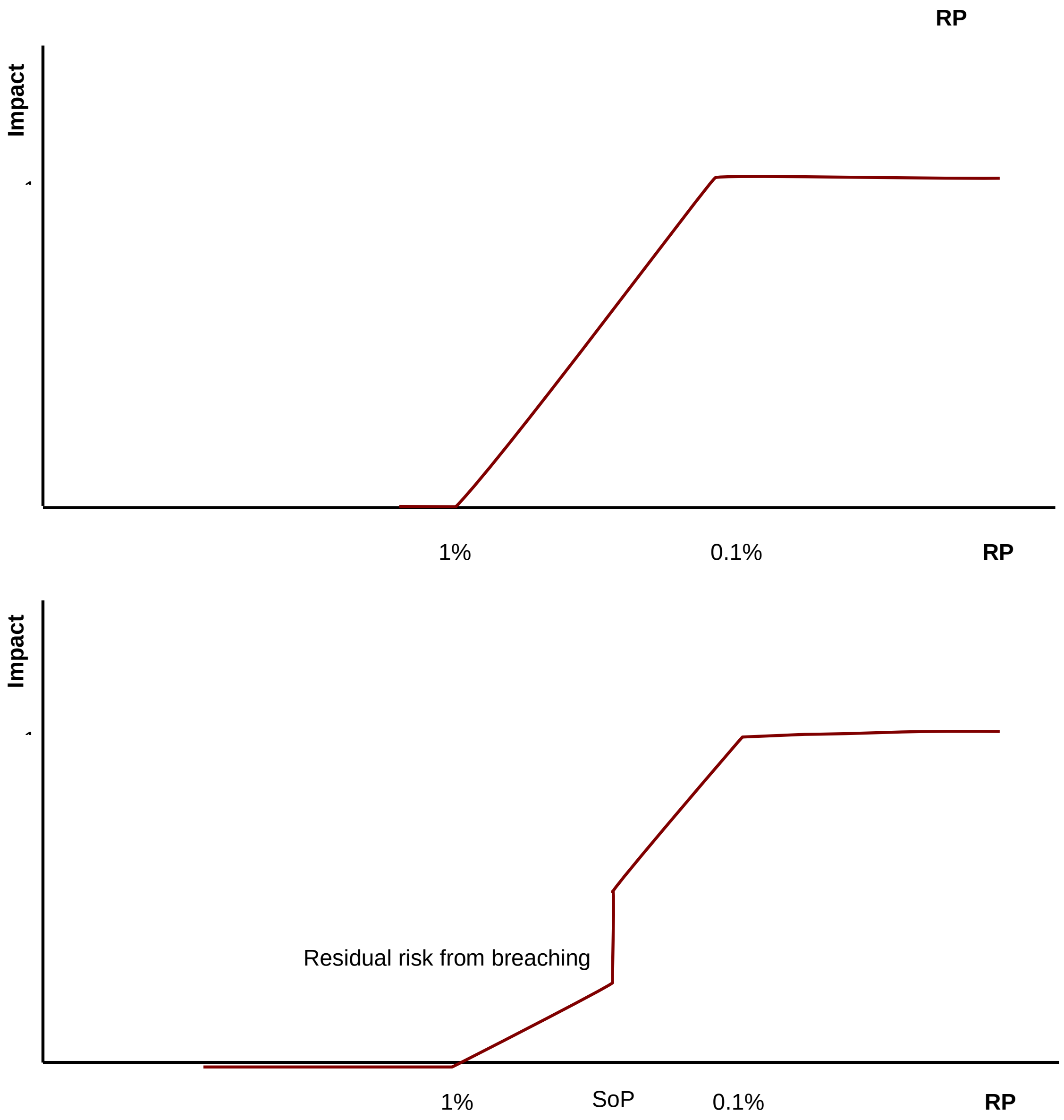


Figure F6 "Fuzzy" impact curves for a single receptor, on an undefended floodplain (top) and with defences (bottom).

This problem is solved by using impact curves as shown In Figure F6. In the undefended case, the step function is changed to a slope over the probability band in which the receptor sits. This is like spreading the receptor over the whole band, or treating the probability of inundation as a fuzzy value across the band. When a climate change shift in return period is applied, this will result in increased risk as some of the curve moves into a different probability band. The curve for a defended scenario is also shown, where the fuzzy impact below SoP is scaled by the probability of failure (or by its CG proxy).

This approach to representing point infrastructure also means that metrics which count the number of sites in a probability band can generate non-integer values (for both present day and in future epochs). These non-integer values can be interpreted probabilistically: for example, if the number of receptors in an output probability band is 0.5, this means that there is a 50% chance of the number of receptors in the band actually being 1. For most receptors this will not be a significant issue, as when aggregating to regional or national scale, there are enough receptors for any fractional parts to not be a significant proportion of the total risk. When there are only a small number of receptors, this fractional part may be a significant proportion of the total risk.

As well as using hazard data sets representing current conditions, there may also be hazard data sets representing future, climate change affected, scenarios. For these, the uplifts given in section 4 are used to calculate an equivalent current return period for the hazard data. For example a 200 year plus climate change scenario could be equivalent to a 500 year present day storm, and therefore can be used to give an extra point on the impact curve. This makes best use of available hazard data and add more detail to the impact curves.

For fluvial and coastal sources, the impact curves need to represent the effects of defences and breaching. This is done by developing a number of impact curves for each source, representing:

- An undefended scenario, equivalent to very fragile or non-existent defences
- A perfectly defended scenario, equivalent to defences with a zero probability of breaching
- A current scenario, somewhere between the two, which includes residual risk behind defences from breaching

Impact curves for these scenarios are illustrated in Figure F7. For storms well above SoP (i.e. defences are totally overwhelmed), the three scenarios converge; it is assumed that this happens at 5 x SoP. Where the "with breaching" scenario sits between the other two depends on the probability of breaching within the Calculation Area.

There is a complex relationship between defence type, fragility, loading water levels (or overtopping rates for coastal defences) and probability of breaching. A simplified approach is therefore adopted, where the condition grade (CG) of defences is taken as a proxy for defence fragility. For defences with CG1, defences are assumed to function perfectly, with zero probability of failure; for defences with CG5, defences will assume to fail, which is equivalent to the undefended scenario; other CGs will give scenarios somewhere between these two extremes. Condition Grade can therefore be used to represent changes to defence performance, by interpolating between defended and undefended scenarios.

Some Calculation Areas will include a range of defence types, conditions and standards of protection; these need to be summarised as a single condition grade. This is done by determining a dominant defence type for each Calculation Area (likely to be limited to classification as embankment or wall), along with a dominant condition grade.

Dominant defence type, condition grade and standard of protection within a Calculation Area are defined as follows. For standard of protection, the representative value is taken as the upper 80%ile of the values in the Calculation Area. This definition excludes lower outliers (which are likely to be associated with undefended or poorly defended areas but with correspondingly few receptors), and biases the value toward the better defended areas where the risk is likely to be. Representative condition grade is taken as the average from the defences used in the calculation of representative standard of protection. Representative defence type is taken as the majority of types for the same defences. After applying these calculation rules, the results are reviewed to check for unrealistic results.

A detailed description of the treatment of impact curves and defence performance in terms of probability theory is given in Annex C of this appendix.

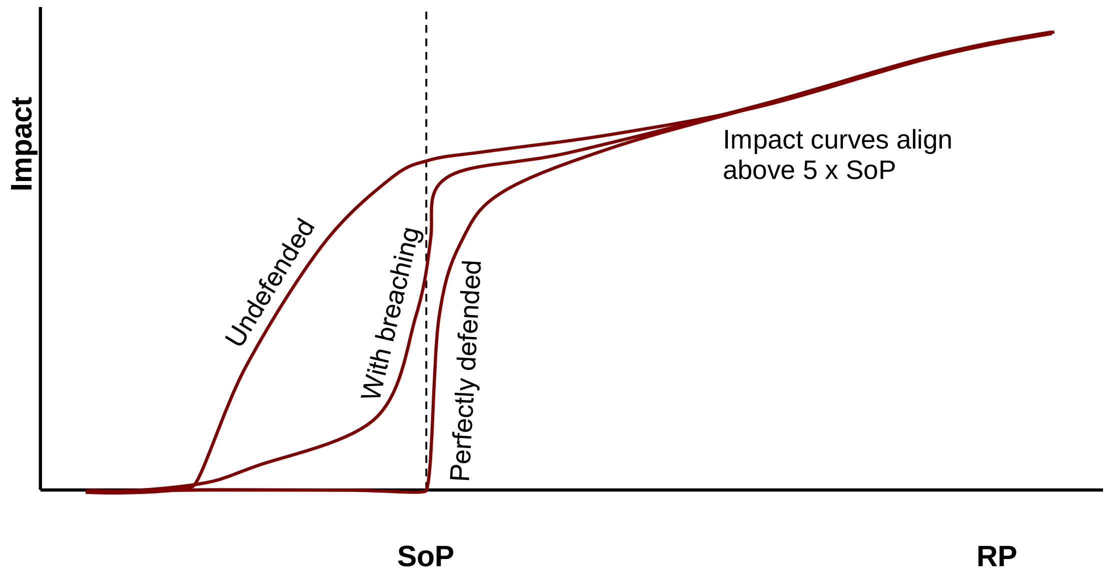


Figure F7 Illustrative impact curves for undefended, perfectly defended and breaching scenarios.

The practical application of this approach for defences and breaching differs across countries because of the different data sets available:

- In **England and Wales**, current impact curves are taken from NaFRA POI (probability of inundation) grids, and will therefore include the risk from breaching. SoP and condition grade are taken from the AIMS database (explained in more detail below). The perfectly defended scenario is produced by taking the current scenario and removing all risk below the SoP. The undefended scenario curve are produced using Flood Zones data (which represents flood extents without defences) scaled so that it matches the NaFRA curve above SoP (see Figure F8 for an example). The theoretical basis for deriving impact curves from NaFRA data which includes breaching is discussed in Appendix C.
- In **Scotland** and **Northern Ireland**, both defended and undefended flood extents are available, and impact curves are derived from these. There are some limitations (for example, only 2 defended scenarios are available for Scotland), so similar assumptions are made as with the NaFRA data. Defence SoP and condition grade are derived from national data sets.

With this approach in place, which calculation areas are defended and undefended, and a representative standard of protection, condition grade and defence type (for coastal defences, as changes to standard of protection in response to climate change differs for walls, embankments and beaches) need to be defined. Calculation areas are defined as defended if they intersect with any part of the defence. The definition of other parameters varies between countries:

- For England and Wales, the AIMS database provides information on defence type, SoP and condition grade. SoP is taken as the average of the *current_sop* field (this defines the SoP of the defence based on crest level, without allowing for freeboard). Where no valid *current_sop* values are present in a calculation area, the average *design_sop* is used (this may be lower than *current_sop* as it allows for freeboard). Where no valid *design_sop* values are present, the national average of *current_sop* is used (80 years for fluvial, 170 years for coastal). The representative condition grade is taken as the average of non-null values in the calculation area; where there are no non-null values, a value of 3 is used. Where available, the *Target Condition Grade* is assumed to be a better proxy of case for investment in those defences than the actual present day condition grade. The representative condition grade is therefore based on the higher of the present day actual or target condition grade (where known).

- Defence type is taken directly from the AIMS database, with embankment taken as the default type.
- For Scotland, a similar process has been used with the DESIGN_SOP and SOP fields of the Scottish Flood Defence Asset Database (SFDAD). In SFDAD, the SoPs are attribute to a set of points (one points per flood protection scheme) rather than the defence lines themselves; the SoPs for a defence line are sampled from the nearest points. Now condition grade is included in SFDAD, so a representative value of 3 is used. Defence lines in SFDAD are separated into walls and embankments, and the defence type is assigned accordingly; no beaches are defined.
- For Northern Ireland, a similar process has been applied using defence data provided by the Rivers Agency (which includes SoP, condition grade and defence type).

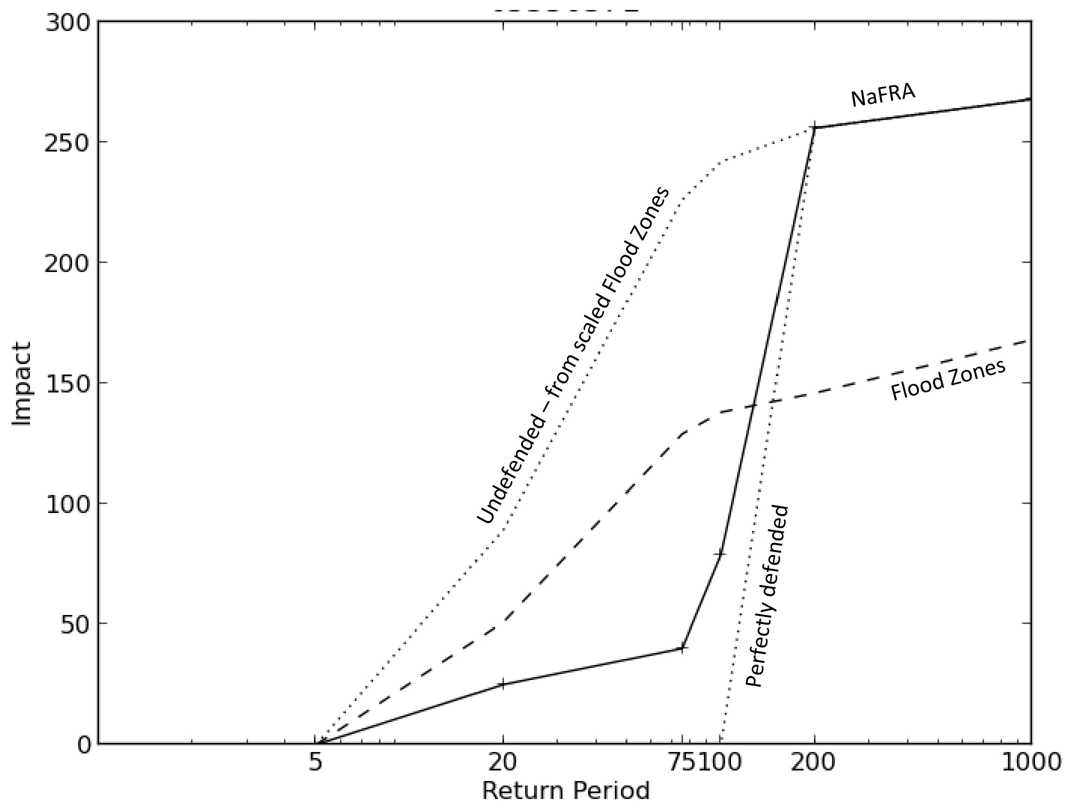


Figure F8 Impact curves for undefended, perfectly defended and breaching scenarios derived from NaFRA and Flood Zones data.

Once the impact curves are developed, they can be used to generate the risk metrics described in chapter 7. Impacts which refer to counts or receptors in probability bands are a simple lookup from the impact curves, with interpolation and extrapolation as necessary. Annual average values are calculated by treating the impact curve as a probability distribution and integrating to give the expected value.

F.4 Step 3: Deploy Emulator Engine

The impact curves described in the previous section contain all the information representing current risk. The emulator engine takes these impact curves and manipulates them to represent future epochs with the effects of climate change and adaptation.

To produce an impact curve for a future epoch, the current impact curve is shifted along the return period axis, using the uplifts described in chapter 4.. Risk metrics can then be calculated for future epochs as for the present day. The same approach of shifting the return period of impact curves is also used to represent other changes to the probability of storms resulting from catchment and stormwater management levers.

Future standard of protection for fluvial and coastal sources are represented as follows. If there is no change to defence crest levels, then future SoP will change solely due to climate change, and this will automatically be represented in the shifted impact curves representing future climate. An increase in SoP is represented by scaling the impact curve below the SoP, as illustrated in Figure F9. This can be used to represent defences being improved to keep pace with climate change (crest levels raised, but SoP stays the same), or defences improved to improve SoP overall.

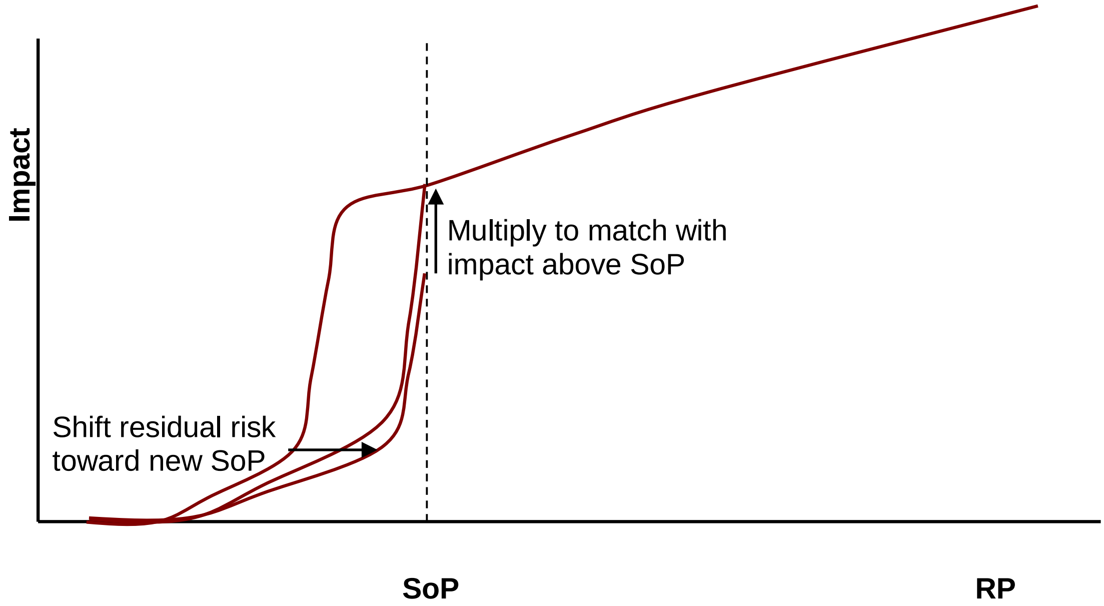


Figure F9 Representing increased SoP by scaling impact curve below SoP.

Changes to condition grade (e.g. deterioration, improvements to defences) are represented by shifting the impact curves between the perfectly defended and undefended cases, using CG as a proxy for breach probability. A linear relationship between CG and impact is proposed; if a Calculation Area has a CG of 3, for example, this is treated as being halfway between the perfectly defended (CG=1 equivalent) and undefended (CG=5 equivalent) impact curves.

The verification process described in the following chapter is used to confirm, as far as possible, that this is a reasonable assumption, by testing whether the emulator outputs match those from LTIS (which includes a full treatment of defence loading, fragility and breaching). If the correspondence is not acceptable, then simple calibration will be used to improve the outputs. This calibration will involve applying different weightings to the condition grades when interpolating between impact curves; the relationship between probability of failure and CG will no longer be linear.

Changes to receptors, either from adaptation, future population or development, are represented by scaling the impact curve along the impact axis.

F.5 Step 4: Outputs: risk, uncertainty and verification

At a low level, the emulator generates risk metrics at Calculation Area scale, and these will be aggregated to the output area scale before being output.

F.6 Step 5: Use FFE to explore future risk

The FFE is then used to estimate future flood risks for the range of climate, socio-economic and adaptation scenarios as summarised in Chapter 6.

F.7 Estimating economic damages

Economic damages within the FFE are calculated using the concept of a Weighted Annual Average Damages (WAAD); the same approach as applied for LTIS 2014. This following sections outline that approach and the assumptions made.

F.7.1 Background to the MCM Weighted Annual Average Damage Method

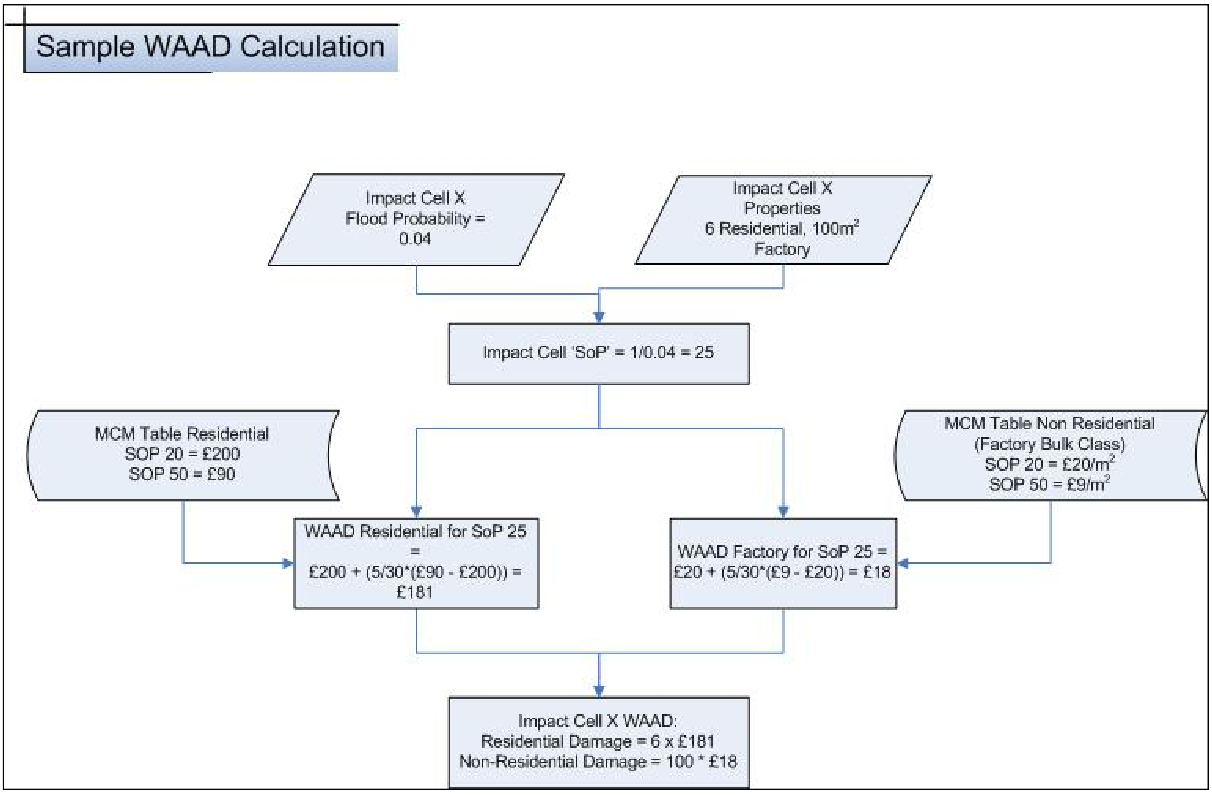
The Multi-Coloured Manual (MCM) method for WAAD calculation is aimed at Strategy Study level where knowledge of flood depth and return period is poor but where the Standard of Protection (SoP), property type and numbers are known. The tables in the MCM do not provide a distinction of damages to flood depth, but reports typical damages based on Standard of Protection. Therefore, the depth/probability curves generated in the NaFRA Models for each Impact Cell cannot be fully used for the WAAD analysis. The impact of changing flood probability is represented but it is not possible to directly link to the impact on flood depths due to climate change or intervention strategy using the depth/probability curves.

Instead, the reciprocal of the probability of exceeding flood depths > 0m for each Impact Cell is used as a proxy of the Standard of Protection provided in that Impact Cell. The probability of flood depth exceeding 0m for each Impact Cell will increase with Climate Change as well as increase/decrease with each LTIS Intervention Option. Using the flood probability also ensures that the manual adjustments made to these by Area Reviews can be incorporated easily (see section 4.4.1 above).

The MCM Handbook gives typical damages for a relatively small number of Standard of Protection values, especially so for residential properties. The WAAD calculation tool developed does interpolate the typical damages between them. Typical damages for probabilities smaller than the given upper SoP band in the MCM tables have been set to typical damages of the highest SoP reported in the table. This may need to be reviewed, though there is no known evidence base to which extent to adjust the typical damages with increasing SoP. For example for Table 5.1 from the MCM Handbook below, the typical damages from SoP 200 to 1000 (low probability) for Factory Bulk Class are set to 0.32/m2. This results in an overestimation of damages for the low probabilities. It should be noted that the 200 year typical damages are half the 100 year typical damages, suggesting that the analysis underpinning the MCM tables is reliable up to a return period of 100 years.

A brief review was carried out to estimate the potential differences between using the WAAD method and using a full depth/ damage method. A number of potential factors were identified that could lead to WAAD giving different results and these were evaluated – see section 8.

Below a worked example of the calculation of WAAD for a fictional Impact Cell X which has 6 residential properties and 100m2 of non-residential (MCM factory bulk class).


Sample WAAD Calculation
Impact Cell X
Flood Probability =
0.04
Impact Cell X
Properties
6 Residential, 100m2
Factory
Impact Cell 'SoP' = 1/0.04 = 25
MCM Table Residential
SOP 20 = £200
SOP 50 = £90
MCM Table Non Residential
(Factory Bulk Class)
SOP 20 = £20/m2
SOP 50 = £9/m2
WAAD Residential for SoP 25
=
£200 + (5/30*(£90 - £200)) =
£181
WAAD Factory for SoP 25 =
£20 + (5/30*(£9 - £20)) = £18
Impact Cell X WAAD:
Residential Damage = 6 x £181
Non-Residential Damage = 100 * £18

F.7.2 Estimating the associated annual damages (Direct)

The calculation of the annualised damage has been based on the Weighted Annual Average Damage (WAAD) approach for both residential and non-residential properties (Multicoloured Manual, 2013) but with some modification as outlined below. The WAAD approach assigns an annual average damage to each property (or damage per unit floor area for non-residential properties), which varies with the annual exceedance probability of flooding for that property.

Eight WAAD tables covering the four sources of flooding (fluvial, coastal, surface water and groundwater) and residential/non-residential properties are used. The values in the WAAD tables are populated data as follows:

Fluvial and coastal flooding

- For residential damages for fluvial and coastal, the from Multi-Coloured Manual (MCM) WAAD values are used
- For non-residential damages for fluvial and coastal, the sector average MCM WAAD values are used

For surface water flooding

- A multiplier of 0.33 is applied to the residential and non-residential WAAD values. This value is based calibration of the FFE surface water damages for England with those estimated within the LTIS (Environment Agency, 2014). This is also consistent with the difference in depth-damage curves for short shallow depth floods typical of surface water flooding.

For groundwater:

- Within the fluvial floodplain (PSD flooding): All properties are assumed to flooded at the equivalent fluvial flood return period. All properties within the PSD area an enhancement is applied to the fluvial residential and non-residential WAAD value (a multiplier of 1.5) to account for the longer duration of flooding typically associated with groundwater flooding.
- Outside of the fluvial floodplain (PSD): Flooded properties are 3% of those properties identified as 'susceptible' to flooding and experience damage at 50% of the fluvial WAAD value. This reflects the longer duration but shallow depth of groundwater flooding. The evidence for this is much less and an active area of research within FHRC. In the absence of other evidence the assumption of 50% has necessarily been made.
- Outside of the fluvial floodplain (Clearwater Chalk): Flooded properties are 10% of those properties identified as 'susceptible' to flooding and experience damage at 50% of the fluvial WAAD value. The same rationale for the WAAD damage as PSD is made here.
- Outside of the fluvial floodplain (Clearwater Non-Chalk): Assumed not to contribute to flood risk.

The WAAD values are summarised in Table A1-2.

Table A1-2 WAAD (no warning) tables for the different sources and residential/non-residential properties.

Flood Return Period at property location (years)	WAAD Look-up values used within the FFE							
	Residential (£)				Non-residential (£/m^2)			
	Fluvial	Coastal	Surface	Ground (outside of fluvial floodplain)	Fluvial	Coastal	Surface[1]	Ground (outside of fluvial floodplain)
1	4,815	4,815	2,408	2,408	66	66	22	33
2	4,815	4,815	2,408	2,408	66	66	22	33
5	2,880	2,880	1,440	1,440	35	35	12	18
10	1,426	1,426	713	713	26	26	9	13
25	623	623	312	312	14	14	5	7
50	266	266	133	133	6	6	2	3
100	66	66	33	33	2	2	1	1
200	34	34	17	17	1	1	1	1

For calculating risk profiles, a damage needs to be assigned to a specific event (e.g. the 1 in 100 year). The WAAD calculation gives an EAD value per property (residential) or per unit floor area (non-residential), and this means assigning damages to specific events is not straightforward. An example is given in Table 1-1, which shows the residential property WAAD table, along with the WAAD value multiplied by the return period. This represents an average damage per inundation event; for example, a property that floods every 10 years, with a WAAD value of £1,426, must have an average damage of £14,260 for each flood event that does happen. This average damage does not tell us about what kind of floods generate that average damage, as there could be large contributions from extremely rare events.

The average WAAD x RP value from Table 1-1 is £11,000, and this is used as a representative figure for damage per property in calculating damages for the risk profile. For example, to calculate the damage from the 1 in 100 year event, we will simply take the number of properties in the >1% flood likelihood band and multiply by £11,000. A similar calculation is used for non-residential properties.

To ensure the risk profile and EAD metrics are consistent, the EAD is also calculated from the risk profile, and the damage per inundation event calibrated so that these values are the same. The calibrated value is checked to ensure it reflects a sensible damage per inundation event.

Table 1-1 Residential WAAD values and the implied damage per property per inundation event (example taken from 2010 residential table).

Return period of flooding	Residential WAAD value	WAAD x RP
1	£4,815	£4,815
2	£4,815	£9,630
5	£2,880	£14,400
10	£1,426	£14,260
25	£623	£15,575
50	£266	£13,300
100	£66	£6,600
200	£34	£6,800
	Average	~£11,000

F.7.3 Determining the number and location of most deprived households

Property counts (annual average and in each probability bands) and Expected Annual Damages (EAD) are reported for the 20% most deprived areas. The 20% threshold is chosen to be the same as used in LTIS (Environment Agency, 2014).

The 20% most deprived areas from been derived from the Census Output Areas (COA) with the highest deprivation indicators as indicated by the following sources:

- The English Index of Multiple Deprivation, 2010
- The Welsh Index of Multiple Deprivation 2011
- The Scottish Index of Multiple Deprivation 2012
- Northern Ireland Multiple Deprivation Measure 2010

These data sources may not be the latest available (for example there are 2011 census tables for England and Wales which include other deprivation measures), but have been chosen as being: reasonably recent; with available geographies; capable of summarising/ranking deprivation in a single measure; consistent with other studies such as LTIS; giving a reasonably consistent picture of deprivation across all nations. EAD for deprived areas are calculated using the same WAAD tables as for other areas.

It should be noted that because the deprivation statistics are compiled country-by-country, the 20% most deprived areas in the constituent countries do not necessarily represent the 20% most deprived for the UK as a whole. Direct comparison between countries is difficult because of the different methodologies used; nevertheless the approach described here is considered suitable for the purpose of showing whether changes in future risks could disproportionately affect poor communities.

F.7.4 Estimating the Expected Annual Damages (indirect)

Indirect damages are calculated as a function of the direct damage estimates. Indirect damages include impacts not directly related to flooded properties, and are quantified as follows (based on the 2014 LTIS report):

- 11% indirect losses associated with emergency services and provision of temporary accommodation; this is applied to residential losses only in accordance with the method adopted in LTIS
- 16% for risk to life
- 43% for impacts on infrastructure, transport, schools and leisure

These figures give a total multiplier of 1.7 to account for indirect damages.

F.8 People related counts

Annual average and within probability band counts of people are based on the residential property counts described in the previous section. The property counts are multiplied by an occupancy factor, which gives an estimate of the number of people occupying each residential property. These are taken from the 2011 Census table QS406 Household Size (KS403NI in Northern Ireland), which gives the number of households with 1, 2, 3 etc. normally resident people, at different output areas. This data has been processed to give an average number of residents per household, for the lowest level data readily available. This is LSOA (Lower Layer Super Output Area) for England and Wales, SOAs (Super Output Areas) for Northern Ireland (both covering around 700 households per output area) and Data Zones for Scotland (around 350 households).

F.8.1 Occupancy rates

An overview of the occupancy values is given in the table below, derived from 2011 census data.

Table 1-2 Statistics of occupancy rates for households derived from 2011 census data

Country	Mean	Standard deviation	10%ile	90%ile
England and Wales	2.38	0.29	1.94	2.69
Scotland	2.22	0.30	1.82	2.58
Northern Ireland	2.56	0.32	2.12	3.00

The census derived occupancy rates show a variation between census areas of around ±15%, which warrants treating these in a spatially variable way. The occupancy rates are therefore sampled to Calculation Areas (see section F.1 for a definition of these) using the area weighted mean of the census reporting areas which lie within each Calculation Area. This allows the method to represent different occupancies in different areas, for example reflecting different household characteristics in urban and rural areas.

Note:

For counts of people in deprived areas, the same occupancy rates are used, and applied to property counts in those areas. This ignores potential correlations between deprivation and occupancy as they vary across a calculation area.

F.8.2 Natural Capital related counts: Defining SPAs, SACs and Ramsar sites

SPAs and SACs - A Special Protection Area (SPA) is a designation under the European Union Directive on the Conservation of Wild Birds. Under the Directive, Member States of the European Union (EU) have a duty to safeguard the habitats of migratory birds and certain particularly threatened birds. Together with Special Areas of Conservation (SACs), the SPAs form a network of protected sites across the EU, called Natura 2000. The Conservation (Natural Habitats etc.) Regulations 1994 implement the terms of the Directive in Scotland, England and Wales. In Great Britain, SPAs (and SACs) designated on land or in the intertidal area are normally also notified as Sites of Special Scientific Interest (SSSIs), and in Northern Ireland as Areas of Special Scientific Interest (ASSIs). For example, the Broadland SPA in eastern England is a conglomeration of some 28 SSSIs. SPAs may extend below low tide into the sea, and for these areas SSSI notification is not possible. In Scotland, some SPAs have been classified without any underpinning designation by SSSI.

Ramsar sites - The Ramsar Convention (formally, the Convention on Wetlands of International Importance, especially as Waterfowl Habitat) is an international treaty for the conservation and sustainable utilization of wetlands, recognizing the fundamental ecological functions of wetlands and their economic, cultural, scientific, and recreational value. It is named after the city of Ramsar in Iran, where the Convention was signed in 1971.

F.9 References

Environment Agency (2014). Flood and coastal erosion risk management long-term investment scenarios (LTIS).

Penning-Rowsell et al. (2013). *Flood and Coastal Erosion Risk Management: A Manual for Economic Appraisal*. Routledge.

Annex A Development of nationally representative rainfall-runoff curves

This appendix describes how nationally representative rainfall-runoff relationships are derived for rural and urban areas, for England and Wales, based on the infiltration model used in uFMfSW modelling. When information on the methods used in Scotland and Northern Ireland becomes available similar relationships will be developed for these countries.

A.1 Rural runoff

The uFMfSW rural infiltration model is the same as is used in ReFH rainfall runoff modelling, which estimates runoff based on a soil moisture retention model, parameterised through catchment descriptors. The total runoff coefficient (i.e. runoff integrated over the storm duration) depends only on the parameters C_{max} and C_{ini}:

$$\frac{q}{P} = \frac{C_{ini}}{C_{max}} + \frac{P}{2C_{max}} \quad [B1]$$

q is the runoff and *P* is the total rainfall depth. The parameters are defined from catchment descriptors BFIHOST (base flow index) and PROPWET (catchment wetness index or proportion of the catchment that is wet):

$$C_{max} = 596.7\ BFIHOST^{0.95}\ PROPWET^{-0.24} \quad [B2]$$

$$C_{ini} = \frac{C_{max}}{2}\ (0.90 - 0.82\ BFIHOST - 0.43\ PROPWET) \quad [B3]$$

The runoff coefficient in [B1] depends on the total rainfall, which varies across the country, as well as on the catchment descriptors BFIHOST and PROPWET.

A simpler relationship between rainfall and runoff would be more useful in allowing rapid assessment of climate change uplifts appropriate for the FFE. To parameterize a rainfall runoff relationship, the following method is used:

1. BFIHOST and PROPWET values are taken from the National River Flow Archive station catchment descriptor data set. These give a representative set of values showing how these vary across the country.
2. For each station, the 30, 100 and 1000 year rainfall depth is calculated for 1, 3 and 6 hour storm durations. This is calculated from the station median annual 1 hour rainfall multiplied by a growth factor and duration factor based on FEH DDF curves.
3. For each station, return period and storm duration, the runoff for that rainfall depth is calculated using [B1]
4. This gives around 9000 rainfall-runoff points, spread across different locations, storm durations and return periods. These are representative of the rainfall depths used in surface water modelling. A linear regression relationship between percentage runoff and rainfall depth is fitted.

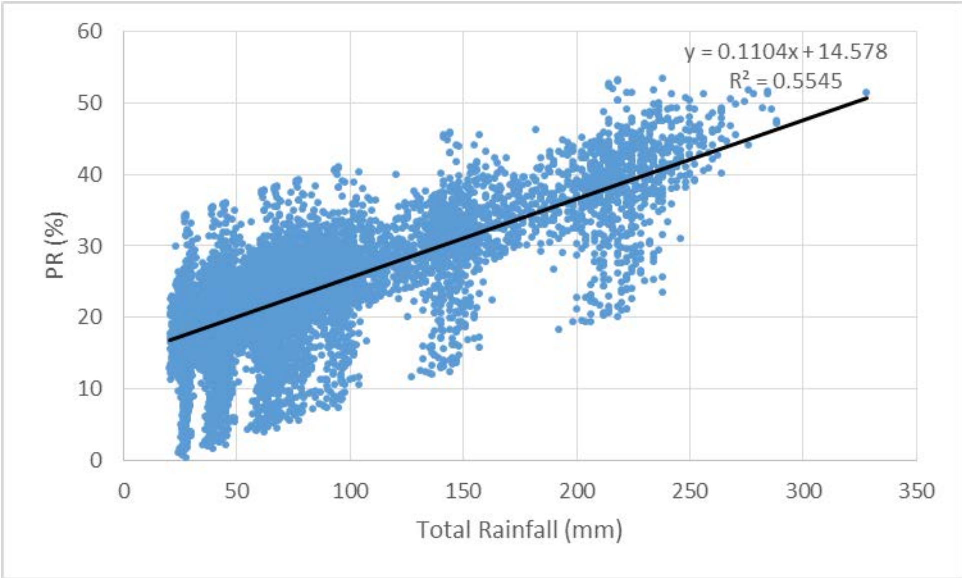


Figure FA-1 Relationship between percentage runoff (PR, in %) and total rainfall depth (mm) parameterised for ~9000 storms.

The results of applying this method are shown in 1. For small rainfall depths, PR is small (15%), and approaches 40% (the single value used in previous national surface water mapping studies) only for high rainfall values.

A.2 Urban runoff

The runoff model for urban areas is based on a single runoff coefficient of 70% and a sewer capacity of 12 mm/hr. In uFMfSW modelling, this is applied at all modelling time steps to the input rainfall hyetograph: 70% runoff is calculated, and 12 mm/hr subtracted from the runoff rate to give the runoff entering the surface model.

To generate a simplified rainfall-runoff relationship, this method of calculating runoff was applied to 6 storms, with depths ranging between 50 and 300mm, and 3 hour duration (calculated using FEH DDF curves). The resulting percentage runoff values are plotted against input rainfall, with the results shown in Figure FA-2. For small rainfall depths, the runoff coefficient is around 20% (because most rainfall is carried away by the sewer system); for large storms, the runoff asymptotically approaches 70% as the sewer capacity become less significant.

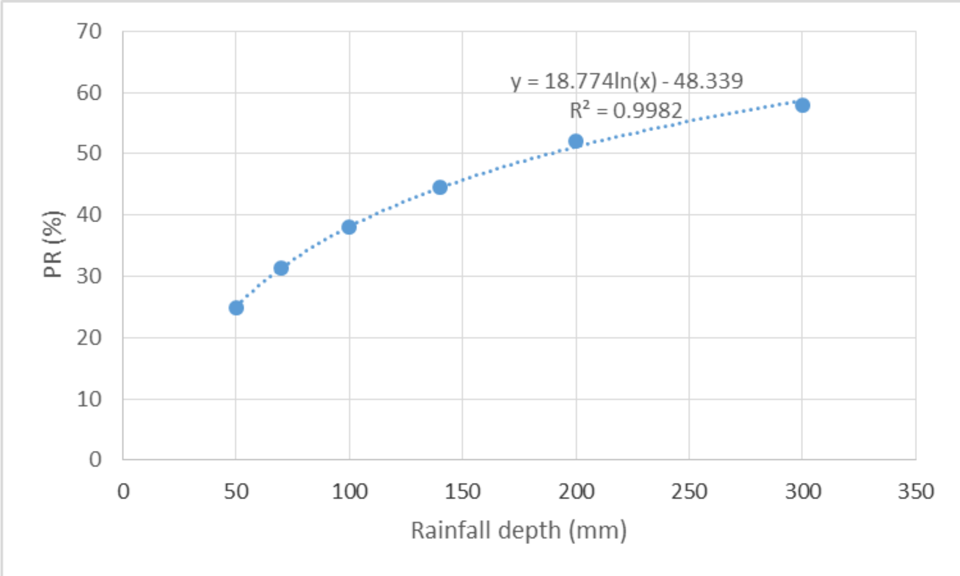


Figure FA-2 Relationship between percentage runoff and rainfall depth for urban areas

Annex B - Agricultural land classification (ALC)

B.1 England

STRATEGIC MAP INFORMATION – *LIKELIHOOD OF BMV AGRICULTURAL LAND* DATASET

Agricultural Land Classification (ALC) Strategic Map information is based on predicting the likelihood of 'best and most versatile' agricultural land (ALC Grades 1, 2 and 3a) when surveyed at the local level. This is important in a land use planning context as described in the National Planning Policy Framework[1], particularly where large tracts of Grade 3 land are indicated on published Provisional ALC maps and the extent of 'best and most versatile' agricultural land is currently uncertain. The predictions use soil associations (which are the mapping unit[2] of the published 1:250 000 scale national soil map) as the main basis of the assessment. The map is intended for strategic planning purposes only and is **not** suitable for use below scale 1:250 000 or for the definitive classification of any local area or site.

The methodology involves each soil association being systematically assessed on a regional basis in accordance with the current classification criteria (MAFF, 1988[3]) using a combination of ALC data derived from site surveys (post 1988), provisional ALC map data, climatic data and published Soil Survey and Land Research Centre (now National Soil Resources Institute) information, to give an assessment for each of the likely proportion of 'best and most versatile' agricultural land to be encountered, according to the following categories

- Areas where more than 60% of the land is likely to be 'best and most versatile' agricultural land. **(High likelihood of 'best and most versatile' agricultural land)**
- Areas where 20-60% of the land is likely to be 'best and most versatile' agricultural land. **(Moderate likelihood of 'best and most versatile' agricultural land)**
- Areas where less than 20% of the land is likely to be 'best and most versatile' agricultural land. **(Low likelihood of 'best and most versatile' agricultural land)**

In order to maintain consistency with the published series of 1:250,000 scale Provisional ALC maps land shown as Grades 1 and 2 are automatically placed in the high likelihood category. Land which cannot be 'best and most versatile' agricultural land due to overall climatic limitations is placed in the low likelihood category.

The resulting assessments are mapped using GIS techniques to produce predictive land quality information at 1:250000 scale. The method is designed to allow improvements to the predictions as new data becomes available, for instance new digital datasets (e.g. geology or topography) or ALC site data. It should therefore be viewed as an evolving GIS based system rather than a single one-off map. **The user should ensure that the most up to date version of the mapped data is used. For further information on this matter refer to the contact given below.**

The data can be used as a companion to the published provisional ALC map series, as the latter will provide a guide to individual ALC grades within each category.

[1] National Planning Policy Framework (March 2012) .

[2] There are 296 soil associations in England and Wales. These are shown on a series of 6 regional soil maps produced in 1983 by the Soil Survey of England and Wales (now National Soil Resources Institute, Cranfield University)

[3] *Agricultural Land Classification of England and Wales* (MAFF, 1988)

The Strategic Map data has a number of limitations which make it best suited for strategic planning rather than detailed site assessment purposes. These are:

- The soil association data at 1:250,000 scale is a relatively crude indicator of agricultural land quality
- The relative lack of (post 1988) ALC site data for some soil associations and its uneven spatial distribution means the allocation to 'best and most versatile' agricultural land categories cannot be completely objective.
- The combination of different data in the production of the Strategic Map, some with different resolutions, means that there may be some compromises with the presentation

Where post 1988 field survey data is available, allocation to one of the three categories of 'best and most versatile' agricultural land likelihood is depicted on the basis of actual grades determined from the field survey work. In these areas the 'best and most versatile' agricultural land category is not a prediction of the likelihood of 'best and most versatile' agricultural, but a generalized representation of the actual land quality in the surveyed area.

Where recent (post 1988) MAFF ALC field survey data is available, this is the most reliable source of information on land quality. Where this is not available the predictive data provides the best available information on land quality. The data will be most useful at national and regional levels for indicating the general disposition of land quality within that region (e.g. comparing counties and districts with each other.) It will also enable an appreciation of the relative land qualities within districts and around major settlements at a crude level. **It is not suitable for site specific appraisals.** Site specific studies, including new ALC field surveys, will be needed to obtain definitive information on ALC grades for individual sites.

Taken from Natural England June 2012

B.2 Scotland

System of Land Capability for Agriculture Classification, Hutton Institute

B.2.1 The classes

Land suited to arable cropping

Class 1 Land capable of producing a very wide range of crops

Cropping is highly flexible and includes the more exacting crops such as winter harvested vegetables (cauliflowers, brussels sprouts, leeks), The level of yield is consistently high. Soils are usually well-drained deep loams, sandy loams, silty loams, or their related humic variants, with good reserves of moisture. Sites are level or gently sloping and the climate is favourable. There are no or only very minor physical limitations affecting agricultural use.

Class 2 Land capable of producing a wide range of crops

Cropping is very flexible and a wide range of crops can be grown though some root and winter harvested crops may not be ideal choices because of difficulties in harvesting. The level of yield is high but less consistently obtained than on Class I land due to the effects of minor limitations affecting cultivation, crop growth or harvesting. The limitations include, either singly or in combination, slight workability or wetness problems, slightly unfavourable soil structure or texture, moderate slopes or slightly unfavourable climate. The limitations are always minor in their effect however and land in the class is highly productive.

Class 3 Land capable of producing a moderate range of crops.

Land in this class is capable of producing good yields of a narrow range of crops, principally cereals and grass, and/or moderate yields of a wider range including potatoes, some vegetable crops (e.g.

field beans and summer harvested brassicae) and oil-seed rape. The degree of variability between years will be greater than is the case for Classes I and 2, mainly due to interactions between climate, soil and management factors affecting the timing and type of cultivations, sowing and harvesting. The moderate limitations require careful management and include wetness, restrictions to rooting depth, unfavourable structure or texture, strongly sloping ground, slight erosion or a variable climate. The range of soil types within the class is greater than for previous classes.

- **Division 3.1 -** Land in this division is capable of producing consistently high yields of a narrow range of crops (principally cereals and grass) and/ or moderate yields of a wider range (including potatoes, field beans and other common root crops. Short grass leys are common.
- **Division 3.2 -** Land in this division is capable of average production but high yields of barley, oats and grass are often obtained. Other crops are limited to potatoes and forage crops. Grass leys are common and reflect the increasing growth limitations for arable crops and degree of risk involved on their production.

Class 4 Land capable of producing a narrow range of crops

The land is suitable for enterprises based primarily on grassland with short arable breaks (e.g. barley, oats, forage crops). Yields of arable crops are variable due to soil, wetness or climatic factors. Yields of grass are often high but difficulties of production or utilization may be encountered. The moderately severe levels of limitation restrict the choice of crops and demand careful management. The limitations may include moderately severe wetness, occasional damaging floods, shallow or very stony soils, moderately steep gradients, erosion, moderately severe climate or interactions of these which increase the level of farming risk.

- **Division 4.1 -** Land in this division is suited to rotations which, although primarily based on ley grassland, include forage crops and cereals for stock feed. Yields of grass are high but difficulties of utilization and conservation may be encountered. Other crop yields are very variable and usually below the national average.
- **Division 4.2 -** The land is primarily grassland with some limited potential for other crops. Grass yields can be high bit the difficulties of conservation or utilization may be severe, especially in areas of poor climate or on very wet soils. Some forage cropping is possible and, when the extra risks involved can be accepted, an occasional cereal crop.

Class 5 Land suited only to improved grassland and rough grazing

Land capable of use as improved grassland. The agricultural use of land in Class 5 is restricted to grass production but such land frequently plays an important role in the economy of British hill lands. Mechanized surface treatments to improve the grassland, ranging from ploughing through rotation to surface seeding and improvement by non-disruptive techniques are all possible. Although an occasional pioneer forage crop may be grown, one or more severe limitations render the land unsuited to arable cropping. These include adverse climate, wetness, frequent damaging floods, steep slopes, soil defects or erosion risk. Grass yields within the class can be variable and difficulties in production, and particularly utilization, are common.

- **Division 5.1** - Establishment of a grass sward and its maintenance present few problems and potential yields are high with ample growth throughout the season. Patterns of soil, slope or wetness may be slightly restricting but the land has few poaching problems. High stocking rates are possible.
- **Division 5.2** - Sward establishment presents no difficulties but moderate or low trafficability, patterned land and/or strong slopes cause maintenance problems. Growth rates are high and despite some problems of poaching satisfactory sticking rates are achievable.
- **Division 5.3** - Land in this division has properties which lead to serious trafficability and poaching difficulties and although sward establishment may be easy, deterioration in quality is often rapid. Patterns of soil, slope, and wetness may seriously interfere with establishment and/ or

maintenance. The land cannot support high stock densities without damage and this may be serious after heavy rain even in summer.

Class 6 Land capable only of use as rough grazing

The land has very severe site, soil or wetness limitations which generally prevent the use of tractor-operated machinery for improvement. Some reclamation of small patches to encourage stock to range is often possible. Climate is often a very significant limiting factor. A range of widely different qualities of grazing is included, from very steep land with significant grazing value in the lowland situation to moorland with a low but sustained production in the uplands. Grazing is usually insignificant in the arctic zones of the mountain lands but below this level grazings which can be utilized for five months or longer in any year are included in the class. Land affected by severe industrial pollution or dereliction may be included if the effects of the pollution are non-toxic.

- **Division 6.1 -** Land in this division has high proportions of palatable herbage in the sward, principally the better grasses, e.g. meadow grass-bent grassland and bent-fescue grassland.
- **Division 6.2 -** Moderate quality herbage such as white and flying bent grasslands, rush pastures and herb-rich moorlands or mosaics of high and low grazing values characterize land in this division.
- **Division 6.3 -** This vegetation is dominated by plant communities with low grazing values. Particularly heather moor, bog heather moor and blanket bog.

Class 7 Land of very limited agricultural value

Land with extremely severe limitations that cannot be rectified. The limitations may result from one or more of the following defects: extremely severe wetness, extremely stony, rocky land, bare soils, scree or beach sand and gravels, toxic waste tips and dereliction, very steep gradients, severe erosion including intensively hagged peat lands and extremely severe climates (exposed situations, protracted snow-cover and short growing season). Agricultural use is restricted to very poor rough grazing.

B.2.2 The divisions

A division is a ranking within a class; the approach to it however needs to be selective. Because the requirements of the crops suited to Classes 1 and 2 are fairly stringent, land in these classes has inherently low degrees of internal variability. The requirements of crops grown in the remaining classes are less rigorous, consequently land included is more variable in character and covers larger areas. For purposes of strategic and regional planning, it is quite clear that some further guidance is necessary in these areas, although for detailed planning the variability of the class dictates that on-site inspections must always be made. Classes 3 and 4 each have two divisions based on increasing restrictions to arable cropping. These are principally climate, in particular the reliability of suitable weather conditions and interactions between soil properties and climatic features. Qualities of land such as workability and droughtiness are particularly affected. Relatively small amounts of rain upon clayey topsoils may equal or exceed in their effect upon farming, that of large amounts upon coarser topsoil textures for example. Site criteria and erosion play relatively small parts. Class 5 land has three divisions based on potential for successful reclamation and Class 6 three based upon the value of the existing vegetation for grazing purposes.

The divisions of Class 3

The definition of Class 3 incorporates land which has a good capability for the production of a moderate range of crops, that part of the British farmscape which is usually regarded as 'average arable land'. For economic reasons it is devoted principally to cereal and grass farming, but the land is often capable of producing in addition, potatoes, oilseed rape, field beans or some vegetables. The picture throughout the class is one of variability so that it is possible that, in anyone year, the situation may differ drastically from the mean. It is against this background that the farmer has to plan the long-term investment on his farm and decide the kinds of enterprise he wishes to practice and thus the actual farming patterns found reflect social as much as physical conditions. In dividing any class, the choice of limits is difficult and their significance to agricultural operations more tenuous. This is particularly so in Class 3 and for this reason only two divisions are proposed.

- **Division 1** - Land in this division is capable of producing consistently high yields of a narrow range of crops (principally cereals and grass) and/or moderate yields of a wider range (including potatoes, field beans and other vegetables, and root crops). Short grass leys are common.
- **Division 2 -** This land is capable of average production but high yields of grass, barley and oats are often obtained. Other crops are limited to potatoes and forage crops. Grass leys are common and reflect the increasing growth limitations for arable crops and degree of risk involved in their production.

The divisions of Class 4

The class comprises land marginal for the economic production of crops and usually confined to types suitable for winter feeding to livestock. Farming enterprises on this land are based primarily on livestock production, as with Class 3, year to year variability in crop yield is large, but the risks of crop failure or poor weather interfering with harvests are higher. Class 4 land is principally found where the deleterious effects of many types of limitation combine. Foremost among these are high rainfall causing wetness limitations, particularly in central and western Scotland. In southern and eastern Scotland, however, shallow or sandy soils and low rainfall are responsible for some areas being included in the class because of drought limitations. As with Class 3, the critical parameters are climate, wetness and droughtiness.

- **Division 1** - Land in this division is suited to rotations which, although primarily based on long ley grassland, include forage crops and cereals for stock feed. Yields of grass are high but difficulties of utilization or conservation may be encountered. Other crop yields are very variable and usually below the national average.
- **Division 2** - The land is primarily grassland with some limited potential for other crops. Grass yields can be high but the difficulties of conservation or utilization may be severe, especially in areas of poor climate or on very wet soils. Some forage cropping is possible and, when the extra risks involved can be accepted, an occasional cereal crop.

The divisions of Class 5

By definition, land included in Class 5 is capable of use as grassland and to improvement by mechanized means. Improvement may take the form of regeneration (reseeding of previously sown swards which have deteriorated in quality through time) or reclamation (the production of new grasslands from previously uncultivated natural or semi-natural vegetation). By ‘mechanized means’ is understood all techniques for the production of grassland from full ploughing to surface seeding without the disruption of soil. Class 5 land is broadly constrained by climate limitations to hill areas where risks are too great for arable cropping. Other limitations are usually subsidiary in determining the overall pattern of class distribution but become important in intra-class ranking and in determining the boundary between Classes 5 and 6. The assumption regarding level of management is significant in determining what land is to be considered improvable, since it involves a favourable balance in input output relationships. This latter criterion should not be carried too far however, for it is the physical qualities of the land which are diagnostic. Many other characters, such as the pattern of land ownership, farm structure, availability of roads and the farmer’s preference may determine the actual areas selected for improvement within the class. The allocation of land to Class 5 only indicates a potential for some improvement, which is attainable within a very short time scale compared with the slower improvements which result from careful grazing management within Class 6. It is useful, therefore, to know whether the improvement results in valuable grassland with long term potential or grassland with only short term potential and requiring constant maintenance. Sward quality of improved grasslands and their levels of production are always high compared with the semi-natural grasslands found in hill areas. The important factors to be considered in improvement are (a) the ease or otherwise of establishment of the sward, (b) the persistence of the sown species, (c) the costs of maintenance and (d) whether the resultant sward can be used for grass conservation or whether it must be grazed.

- **Division 1 -** Land well suited to reclamation and to use as improved grassland Establishment of a grass sward and its maintenance present few problems and potential yields are high with ample growth throughout the season. Patterns of soil, slope or wetness may be slightly restricting but the land has few poaching problems. High stocking rates are possible.
- **Division 2 -**Land moderately suited to reclamation and use as improved grassland Sward establishment presents no difficulties but moderate or low trafficability, patterned land and/or strong slopes cause maintenance problems. Growth rates are high and despite some problems of poaching, satisfactory stocking rates are achievable. Division 3 Land marginally suited to reclamation and use as improved grassland Land in this division has properties which lead to serious trafficability and poaching difficulties and although sward establishment may be easy, deterioration in quality is often rapid. Patterns of soil, slope or wetness may seriously interfere with establishment and maintenance. The land cannot support high stock densities without damage and this may be serious after heavy rain, even in summer.

The divisions of Class 6

Land included in Class 6 is unsuited to improvement by mechanized means but has some sustained grazing value. The grazing must be available for five months or more in any year. Improvements to sward quality and quantity have been practiced in these areas for many years and include stock control by fencing, encouragement to the grazing animal to range (mosaic improvements of small areas « 40%) by limited mechanical means) and by burning. In general, such improvement techniques are slow compared with those available on Class 5 land and often achieve their more striking successes only on the best land of the class. With such a wide range of sward quality included, attention has been given to developing a technique of assessing relative grazing values of different swards. In this, the use of adequately described and defined plant communities (e.g. Birse and Robertson 1976) was invaluable. The number and type of plant communities in any area can be determined and the value of each to the grazing animal assessed. Communities dominated by grasses are usually of high relative value; those by dwarf shrubs and mosses of low value. Management of hill and mountain areas has often resulted in the modification of the original plant communities, sometimes fairly substantially. The resultant replacement communities have a relationship with the original communities and, if the particular form of management ceases, will revert to them within a short period. In the broad sense there is a relationship between the semi-natural and replacement communities and the underlying soil types, and both are related to climatic zones in mountainous areas which allow useful suitability groups to be identified. It must be stressed that rarely does one plant community cover a large enough area to map individually, but mosaics of plant communities are found which are averaged to give values for the area.

- **Division 1 High grazing value -** The dominant plant communities contain high proportions of palatable herbage, principally the better grasses, e.g. bent-fescue or meadowgrass-bent pasture.
- **Division 2 Moderate grazing value -** Moderate quality herbage such as white and flying bent grasslands, rush pastures and herb-rich moorlands, or a mosaic of high and low grazing values characterises land in the division.
- **Division 3 Low grazing value -** The vegetation is dominated by plant communities with low grazing values, particularly heather moor, bog heather moor and blanket bog.

B.2.3 Data Attributes

The dataset contains 1 attribute:

Lccode: The numerical classification code

B.2.4 Further Information

GIS and Data Services, The James Hutton Institute, Craigiebuckler, Aberdeen, AB15 8QH. Contact names: David Donnelly.

Tel 01224 395265. Email: david.donnelly@hutton.ac.uk http://www.hutton.ac.uk/

Annex C- Theoretical basis for representation of breaching in impact curves

C.1 Introduction

This section provides a theoretical basis for the use of impact curves to represent risk for current and future epochs. The main body of the text relies on heuristic arguments to demonstrate use of impact curves in estimating risk; this section provides a theoretical justification for this treatment.

For the case with no defences, or with zero probability of breaching, the impact curve as a function of loading storm return period is directly equivalent to the probability distribution of the impact. Taking the fluvial case as an example, the number of properties affected is a monotonic function of loading water level, which is in turn a monotonic function of storm return period. The probability of an impact being below a certain number of properties is therefore the same as the probability of the water level being below the level required to flood those properties:

$$P(n \leq N) = P(wl \leq WL) \qquad \text{[C1]}$$

We can use the same logic for coastal, surface water and groundwater sources; as long as the loading event is defined suitably (coastal still water level, rainfall depth for a suitable storm duration), there will be a direct link between the impacts estimated from hazard grids and the probability of those impacts occurring.

When breaching is taken into account, the situation is more complex: the direct link between loading water level and probability of the impact occurring is lost. We simplify the analysis by assuming a single, representative value of defence failure probability; in practice we will use condition grade as a proxy for this.

An intuitive interpretation of the impact curves is that it represents the damage conditional on a loading return period, and averaged over defence states (breached/non breached). This interpretation allows us to easily represent the effects of climate change (which changes the return period of loading events) by scaling the curve along the return period axis. Formally, the impact curve with breaching can be written as a linear combination of the defended and undefended impact curves:

$$Impact(WL) = P_{Breach} \times N_{Undefended}(WL) + (1 - P_{Breach}) \times N_{Defended}(WL) \qquad \text{[C2]}$$

$N_{Defended}$ here represents the impact curve for the perfectly defended scenario. The impact, averaged over defence states, at a given water level (and hence loading return period) is an average of the defended and undefended damage, weighted by probability of breaching; alternatively, we can think of this as interpolating between curves along the vertical axis. This curve, however, does not represent a probability distribution, as discussed below.

An alternative interpretation of the impact curve is that it represents a probability distribution of the impacts. The probability that the impact does not exceed *N* properties is given by the sum of the probabilities for the exclusive breach and non-breach scenarios:

$$P(n \leq N) = P_{Breach} P_{Undefended}(N) + (1 - P_{Breach}) P_{Defended}(N) \qquad \text{[C3]}$$

Again this is an average weighted by breach probability, but now interpolating between curves along the probability or return period axis, and represents the true probability distribution of impacts.

The number of properties (or other receptor measure) in each probability band can be calculated by considering the probability of inundation of individual properties. The probability of inundation is the sum of the probabilities for the breached and unbreached probabilities:

$$P_{Breach} \times P_{Flood}^{Undefended} + (1 - P_{Breach}) \times P_{Flood}^{Defended} \qquad \text{[C4]}$$

If the properties are ranked by probability of inundation, then [C4] becomes an equation for the number of properties with a probability of inundation greater than a threshold and is directly equivalent to [C3]. This type of impact curve thus represents both a probability distribution for the number of receptors flooded, but also gives us the number of receptors in probability of inundation bands.

The two curves produced by interpolating along the impact axis and along the probability axis are not the same, as illustrated in Figure FC-1.

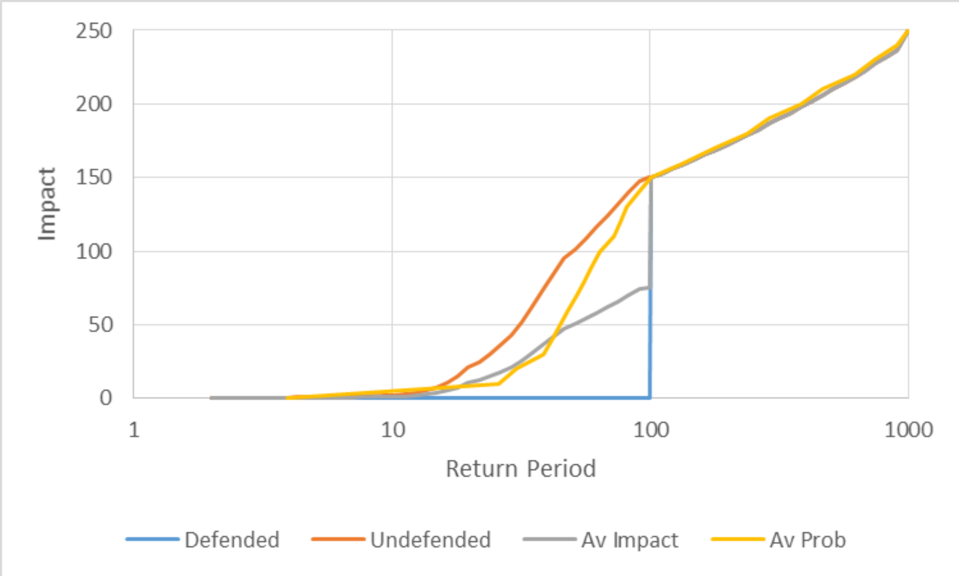


Figure FC-1 Impact curves illustrating the difference between averaging along the impact axis (in grey) and averaging along the return period axis (in yellow). The yellow curve represents the true probability distribution of impacts. The breach probability for this example is 0.5.

These two types of curves may need to be treated differently when calculating impact metrics or applying climate change shifts:

- Annual averages can be calculated from either type of curve ([C2] and [C3] when integrated give the same equation but with a change of variable of integration from *WL* to *N*)
- Scaling along the return period axis to represent climate change can only be applied to the impact curve for loading water level (except for a special case of a uniform multiplicative scaling applied to the return period; in this case either curve can be used)
- Calculating properties (or other receptor measures) in probability bands can only be done using the impact curve for probability

The emulation method therefore needs access to both types of curve; furthermore some hazard information will be in the form of a probability impact curve (e.g. from NaFRA) which will need to be transformed to a loading impact curve before climate change scaling can be applied.

Some method of transforming between curves is therefore required. A simple approach (illustrated for transforming a probability curve into a loading water level curve) runs as follows:

1. Determine the probability impact curve and the perfectly defended and undefended scenarios from the hazard data
2. Use the defended and undefended curves to generate a probability curve using an assumed representative probability of failure (using [C3])
3. Calibrate the assumed representative probability of failure so that the curve generated in [2] and the one derived from hazard data have the same expected annual average
4. Use the calibrated assumed representative probability of failure to derive a loading impact curve using [C2]

This process can also be used to transform curves in the other direction, for example after climate change scaling has been applied.

Annex D - Estimating receptors affected by groundwater flooding

D.1 Data on potential occurrence

BGS has prepared GB-wide groundwater flood susceptibility maps – on a 50 metre grid, with a nominal resolution of 1:50k. The maps are effectively an amalgamation of datasets on permeability and on groundwater level (either observed or estimated) to identify shallow groundwater.

Susceptibility doesn't mean that flooding will occur, and it is recognized that the susceptible areas cover a greater area and number of properties than will be affected by groundwater flood events. This is due to several factors.

- Limited resolution of geological mapping and water level datasets.
- Hydrogeological heterogeneity imposing local controls on groundwater emergence.
- Extensive adaptation in the existing landscape and built environment. This adaption includes agricultural land drainage, urban drainage and sewers as well as property level adaption, such as raised floor levels.

D.2 Data on actual occurrence

Data on actual occurrence of groundwater flooding comes from 3 sources.

- Recorded information. This includes incidents logged by the Environment Agency in England and Wales at household level. Some data may also be collected by Department of Transport (for roads), water companies (for sewers), the fire service, local authorities and insurance companies. At local level this may be complemented by reports from flood wardens and other local groups. With the exception of the Environment Agency data, these reports are not centrally collated.
- Systematic survey. This may include mapping during flood events, either on the ground or using remote sensing/aerial photography.
- Reports. Published and unpublished reports and literature on groundwater flooding and local hydrogeological conditions.

D.3 Estimating Affected Properties

To estimate the number of properties that may be affected by groundwater flooding the number of receptors in the various classes of groundwater susceptibility mapping can be compared to the recorded incident data.

This approach works well on outcrop Chalk where the flooding process is straightforward, and good observations are available, on other geologies there will be greater uncertainty.

Estimating the total number of properties affected from reported incidents requires expert judgement.

No account is taken of differences in occurrence and reporting between urban and rural areas. This may lead to an over estimate of affected properties in urban areas where more adaption through denser drainage and sewer systems are expected to reduce receptor vulnerability.