Risk analysis of levee systems
Analyse de risque des systèmes d'endiguement

National and regional flood risk analysis approaches in the United Kingdom

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Photo : Paul Royet

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Overview of physical systems in England (from EA)

- 7000 km of defences on main river
- 1000 km of defences on the coast
- 22,300* structures
- 36,000 km of main river on which we have permissive powers
- 2,000 major operating sites
- 212 reservoirs
- 73,000* EA and third party assets on main river
- Approx. 1 million Properties in areas benefiting from defences
- £25bn replacement value
- £15bn value of assets owned by others over which we have an oversight role

*Source - AIMS Inventory 9 November 2016

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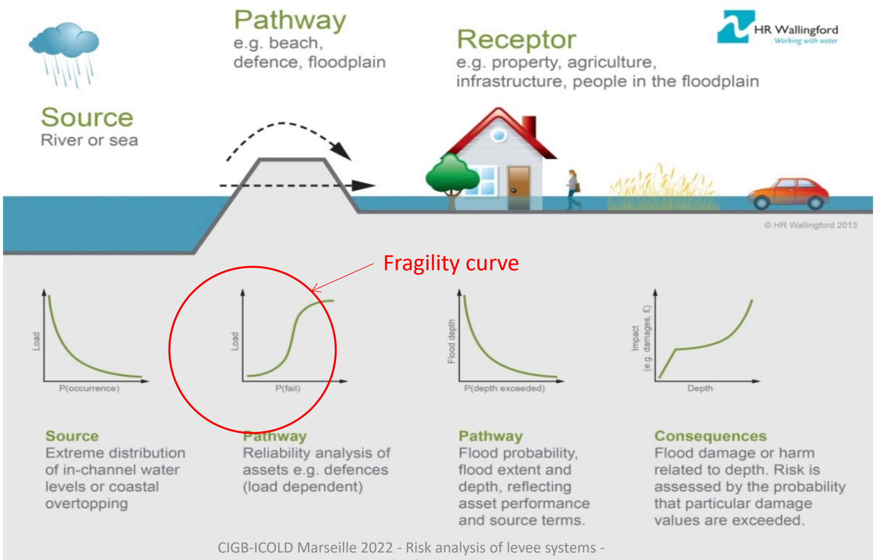
Overall approach to assessment of flood risk

Example features of English system that support the flood risk analysis

3

Source-pathway-receptor (SPR) concept for flood systems



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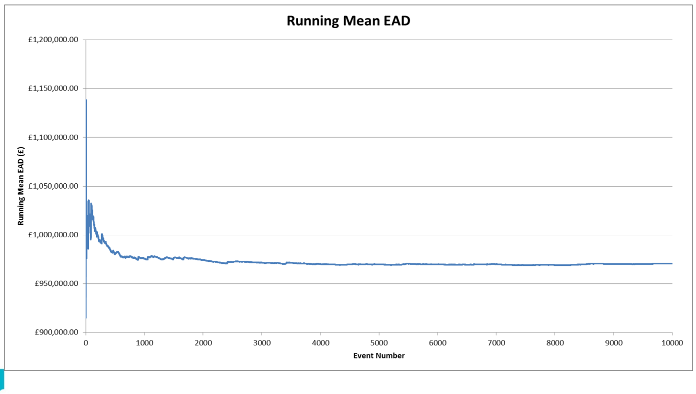
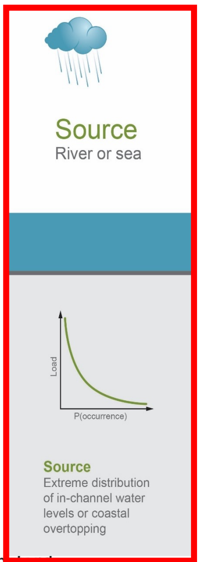
Flood risk and its calculation

Risk = probability of flood event (Source) x probability of levee breach (on Pathway) x consequences (£) (to Receptors)



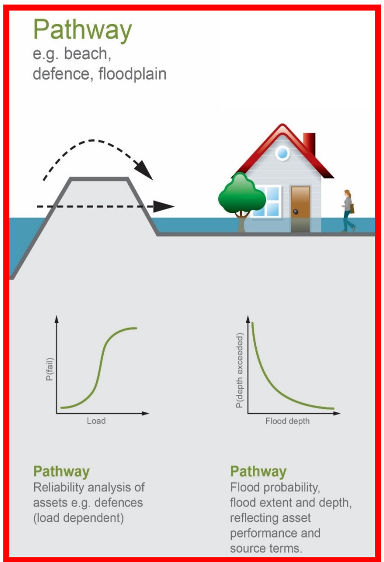
- Risk is calculated via thousands of simulations that explore the event and system state probability space
- Additional simulations are run until further exploration gives no appreciable change to the mean risk.

How is flood risk assessed? - Sources



- The events are known as sources
- The source information is:
  - Extreme rainfall events, flows or water levels (Fluvial and Tidal)
  - Extreme overtopping rates (Coastal)
  - Dependence
    - Yes but challenging
    - On the research agenda

How is flood risk assessed? – Pathways



- Flood defence reliability
- Inflows to the floodplain
- Hydraulically connected flood spreading

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How is *system* flood risk assessed? Defence State

- Flood defence assets operate as functional systems.
- It is possible for one or more breaches to occur in a system of defences
- For each event, the sampling framework selects a system state

Defence Assets:

Asset state: Failed Not failed Failed Not failed
System state: (1 0 1 0)

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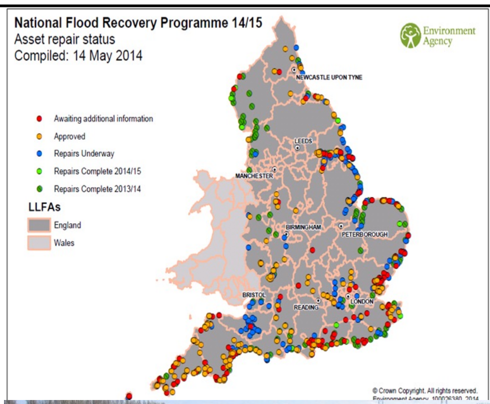
Why include breaches in flood risk models?

- Challenge:
  - Considering breach probabilistically differs from other methods which
    - ignore breaching altogether
    - or assume a small number of pre-defined breach locations
  - Considering breaches probabilistically adds considerable run-time overhead
- Response:
  - Determining residual risk associated with breach (structural issues) as well as overtopping (hydraulic issues) enables more focussed levee management
  - Breach risk is a significant proportion of the total risk (see next slide)



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Importance of breach in calculation of risk

- Approach taking account of breaching …

Scenario	Event Likelihood	Conditional scenario probability	Scenario likelihood	Consequence (£)	Risk (£)
0.02 AEP fluvial event (fail)	0.02	0.2	0.004	70,000	280
0.02 AEP fluvial event (non-fail)	0.02	0.8	0.016	35,000	560
Total			0.02		840

- Approach ignoring possibility of breach…

Scenario	Likelihood	Consequence (£)	Risk (£)
0.02 AEP fluvial event	0.02	35,000	700

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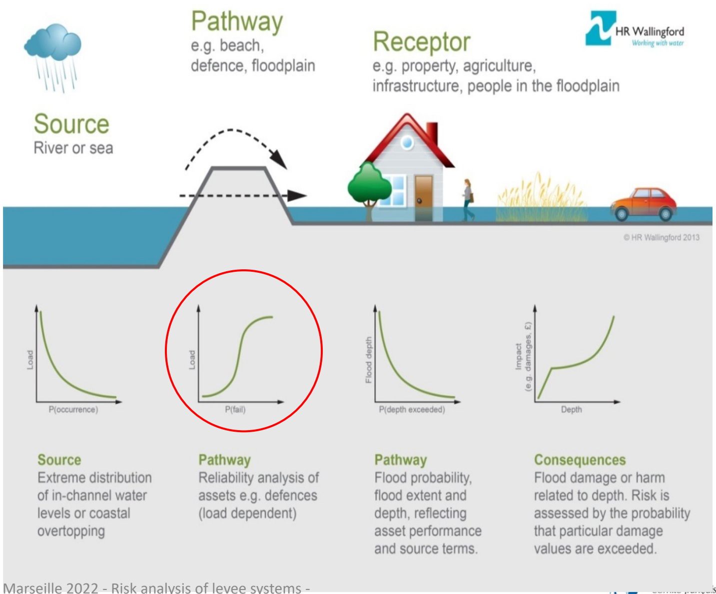
Fragility curves

- Express varying probability of failure with load
- Allow inclusion of defence performance in flood systems analysis
- Can be generalised for broad scale or bespoke for local system or individual defence segments
- Allow the inclusion of expert judgement



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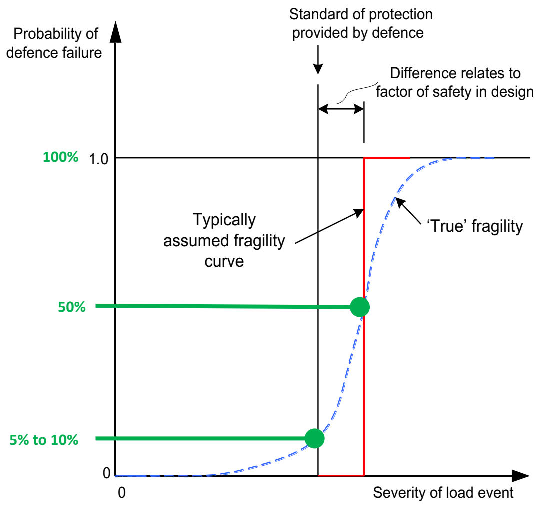
Fragility curve basics

A fragility curve is a curve which expresses the probability of failure of a defence as a function of the loading

Z (*reliability*) = *R* (*strength*) – *S* (*loading*)

KEY POINT:
Probability of failure:
for |load > design load| < 100%
for |load < design load| > 0%



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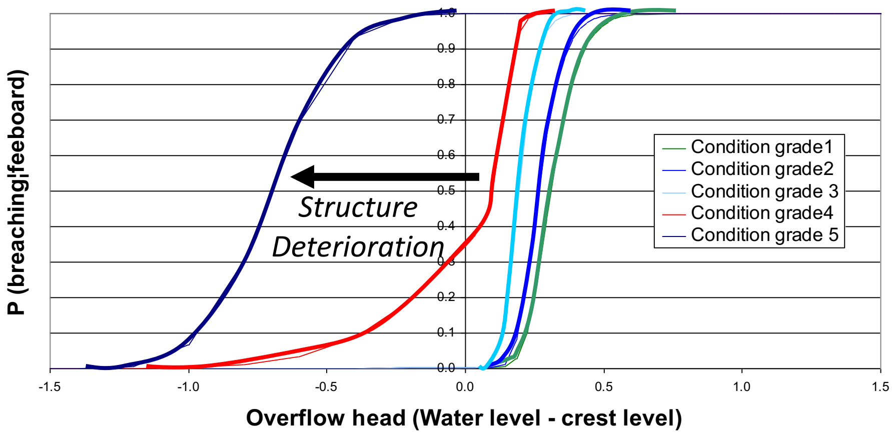
Fragility curves – the effect of defence condition



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Process to generate fragility curves by analysis

1. **Identification and analysis of all relevant failure modes**
2. **Identification of Limit State Equations (LSE's) or models for all failure modes (recast into reliability format: i.e. *Z* (*reliability*) = *R* (*strength*) – *S* (*loading*))**
3. Preparation of a schedule of engineering parameters (and their uncertainties)
4. Preparation of fault trees specifying the logical sequence of all possible mechanisms leading to defence failure
5. Performance of many reliability analyses, for a single hydraulic loading across a range of parameter uncertainties (i.e. Monte-Carlo sampling). For each loading analysed, the probability of failure is the proportion of times that Z<1. (Repeated for other hydraulic loadings and the resulting fragility curve plotted)

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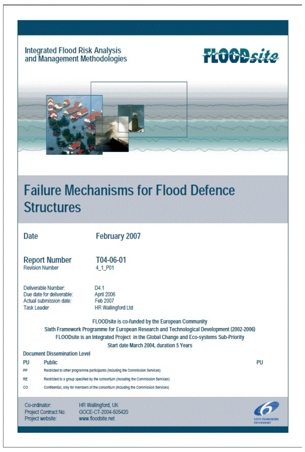
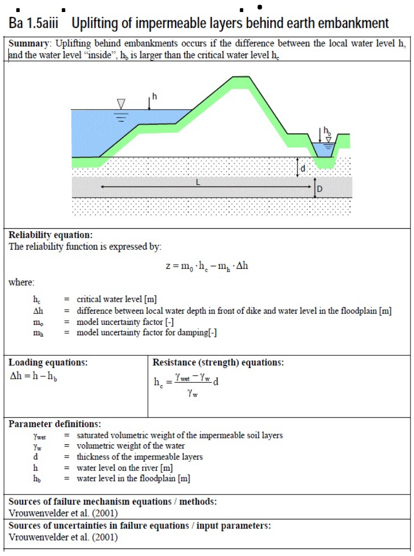
FLOODsite report - Source of inspiration for failure modes and limit s





Ba 1.5aiii Uplifting of impermeable layers behind earth embankment

Summary: Uplifting behind embankments occurs if the difference between the local water level h, and the water level "inside", h_b is larger than the critical water level h_c

Reliability equation:
The reliability function is expressed by:

$$z = m_0 \cdot h_c - m_h \cdot \Delta h$$

where:

h_c = critical water level [m]
Δh = difference between local water depth in front of dike and water level in the floodplain [m]
m_o = model uncertainty factor [-]
m_h = model uncertainty factor for damping[-]

Loading equations:
$\Delta h = h - h_b$

Resistance (strength) equations:
$h_c = \frac{\gamma_{wet} - \gamma_w}{\gamma_w} d$

Parameter definitions:
γ_{wet} = saturated volumetric weight of the impermeable soil layers
γ_w = volumetric weight of the water
d = thickness of the impermeable layers
h = water level on the river [m]
h_b = water level in the floodplain [m]

Sources of failure mechanism equations / methods:
Vrouwenvelder et al. (2001)

Sources of uncertainties in failure equations / input parameters:
Vrouwenvelder et al. (2001)

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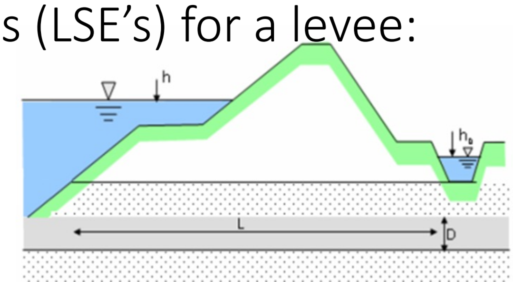
Identification of failure modes and Limit State Equations (LSE's) for a levee:



Failure mode	Failure mode description
External erosion	Erosion of rear face of an embankment due to overtopping, leading to down cutting and hence breach
Through-seepage	Seepage through levee in the embankment (based on steady state conditions) which could lead to piping.
Under-seepage	Piping under levee due to under seepage (based on steady state conditions), conditional on the following heave/uplift mechanism
Protected side heave	Heave/uplift behind levee due to under-seepage (based on steady state conditions)

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Process to generate fragility curves

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Parameter value identification

Reliability analysis is different from design

Strength — Load

$$\frac{R_{rep}}{\gamma_R} > \gamma_S S_{rep}$$

Partial load factors

Statistical variability reflected by setting design values a certain number of standard deviations away from the mean:

$$R_{rep} = \mu_R + k_R \sigma_R$$
$$S_{rep} = \mu_S + k_S \sigma_S$$

To generate fragility curves we must change approach and use the mean values. (Otherwise, for example, we would not get pf = 50% when FS=1)

Process to generate fragility curves

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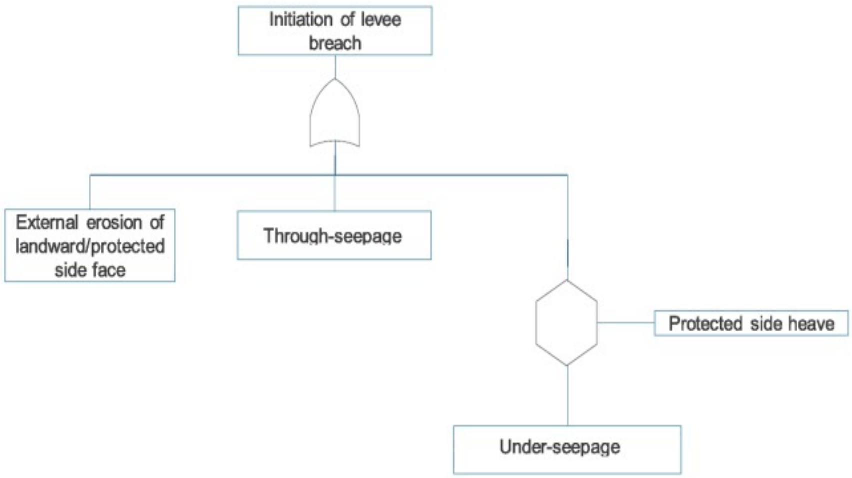
Simplified fault tree for assessment of a levee (excludes mass instability)



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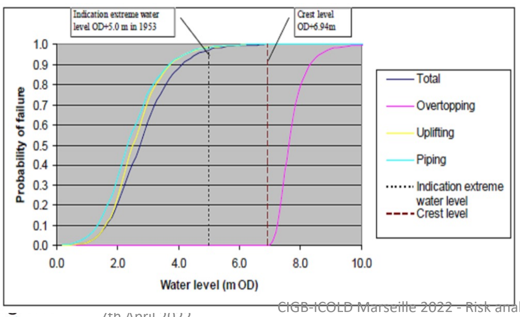
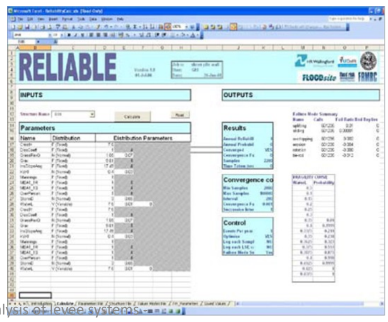
Combining fragility representations

- If failure modes are independent of each other then they can be combined to provide an overall probability of failure by using De Morgan's Law:

$$\Pr(f) = 1 - \{[1 - \Pr(f_r)] \times [1 - \Pr(f_s)]\}$$

- If they are dependent then it is better to use appropriate tools such as 'HR RELIABLE' which can deal with this complex issue. (source: FLOODsite and FRMRC projects)





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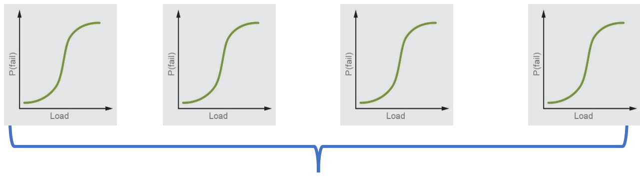
Role of *system state* in assessment of flood risk

The system state probability is given by:

- ***The product of all defence asset states***

Defence Assets:				
Asset state:	Failed	Not failed	Failed	Not failed
System state:	(1	0	1	0)

Fragility curves:



Asset state probability:	0.2	0.95	0.1	0.85
System state probability:	0.01615			

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Estimating floodplain inflow (breach inflow)

- Fixed width and simple inflow estimate weir equation
  - Eg broad-crested weir equation / OT rates and…

Defence Type	Maximum breach width
Earth embankment	200m
Barrier beaches	100m
Revetment/ vertical wall	50m
Flood Gate	Entire gate

- Width based on simplified methods (function of load and defence asset properties)
- Defence asset specific model giving breach growth and hydrograph

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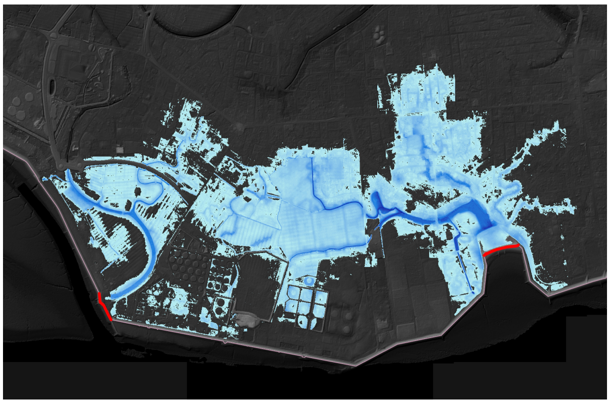
Flows over or through levees in flood risk calculation

- Loads and System state → the inflow volumes and locations
  - Includes overflow, overtop and breach
- Inundation model spreads the combined volume, with **hydraulic connectivity**



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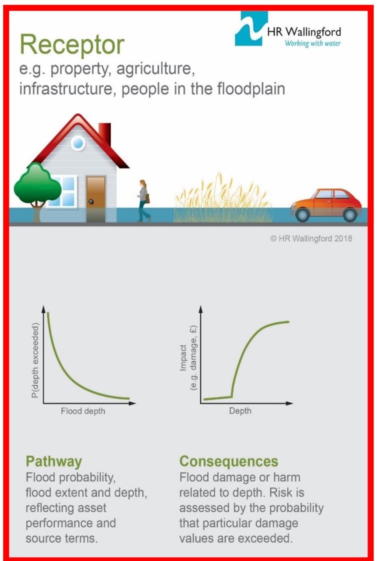
How is flood risk assessed? – Receptors



- Depth versus probability for each receptor
- Combined with damage functions
- →Expected Annual Damage

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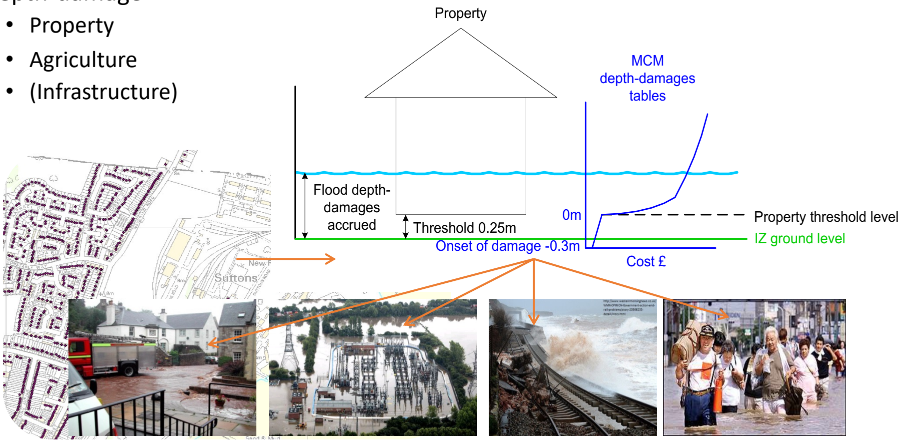
How is flood risk assessed – Receptors?

- For each simulation the receptor impacts are evaluated.
  - Number of people/property exposed
  - Depth-damage
    - Property
    - Agriculture
    - (Infrastructure)



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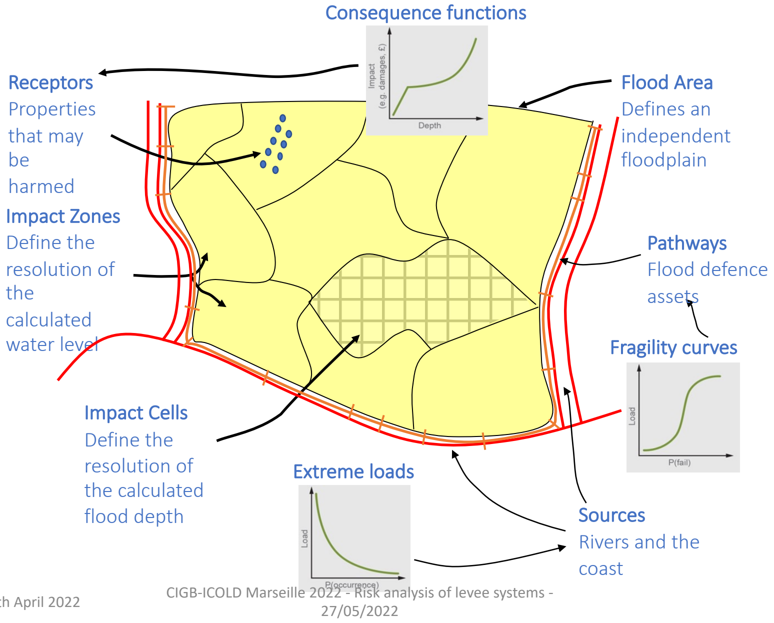
Risk modelling framework - model schematisation



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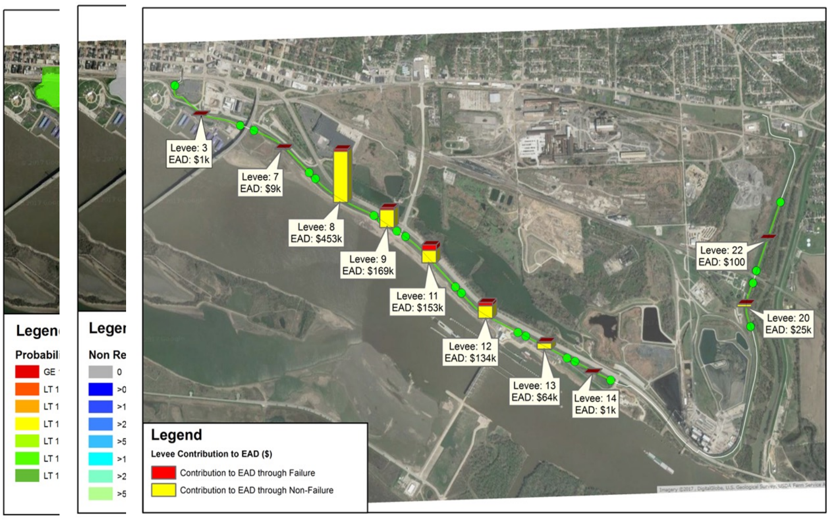
Typical system risk model outputs



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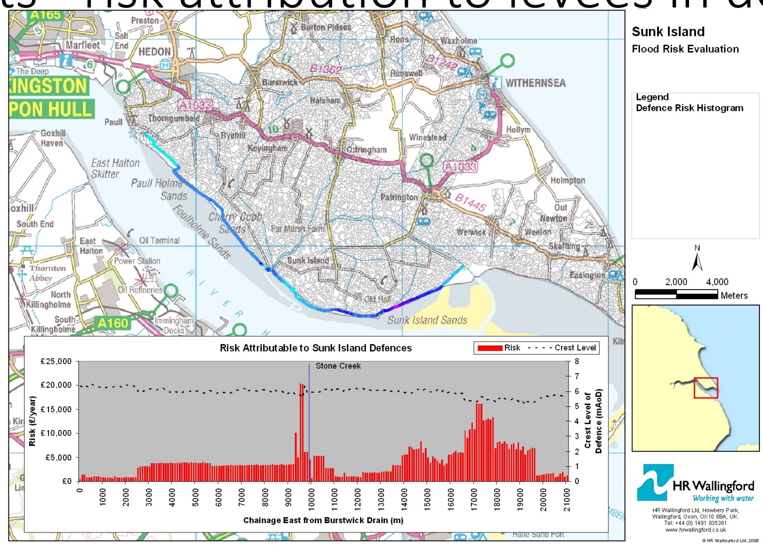
Outputs - risk attribution to levees in detail



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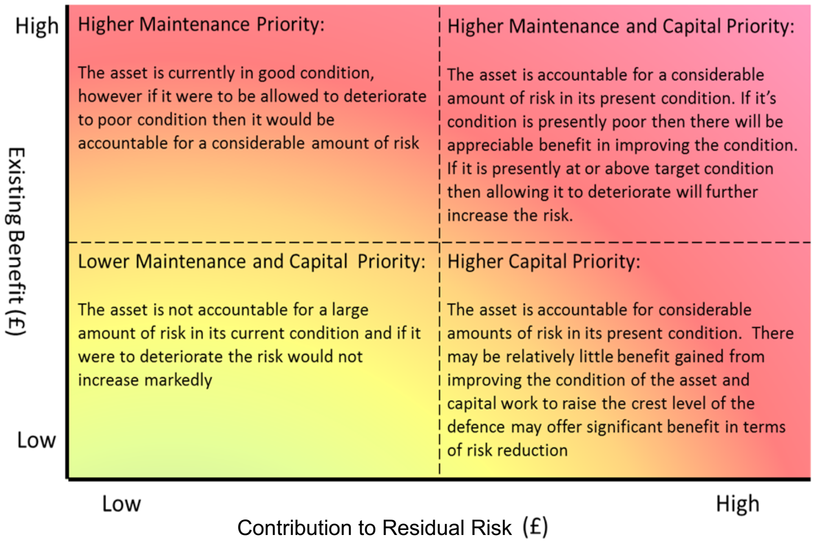
Contribution to Existing Benefit vs Contribution to Residual Risk



<u>Explanation of terms</u>

Total flood risk in undefended flood plain
=
Existing benefit provided by levee system (or segment)
+
Contribution to residual risk associated with levee system (or segment)

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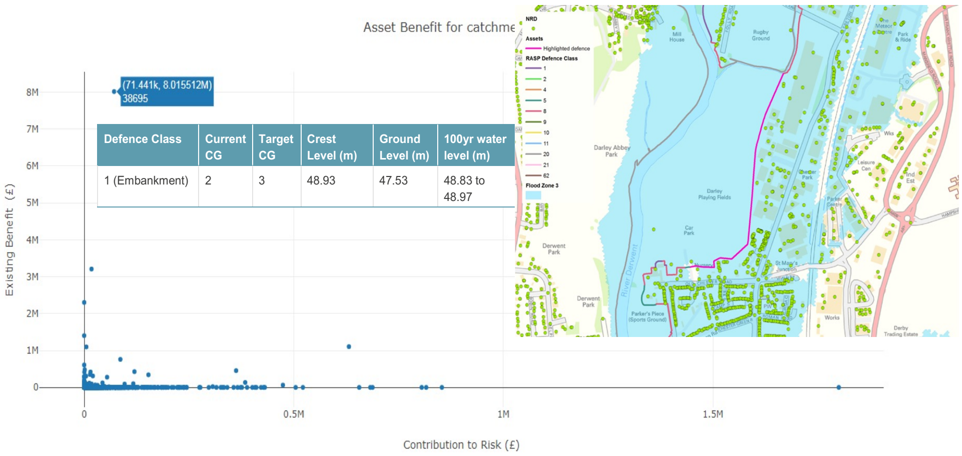
Levee with significant existing benefit



Defence Class	Current CG	Target CG	Crest Level (m)	Ground Level (m)	100yr water level (m)
1 (Embankment)	2	3	48.93	47.53	48.83 to 48.97

Catchment 2804, Asset 38695

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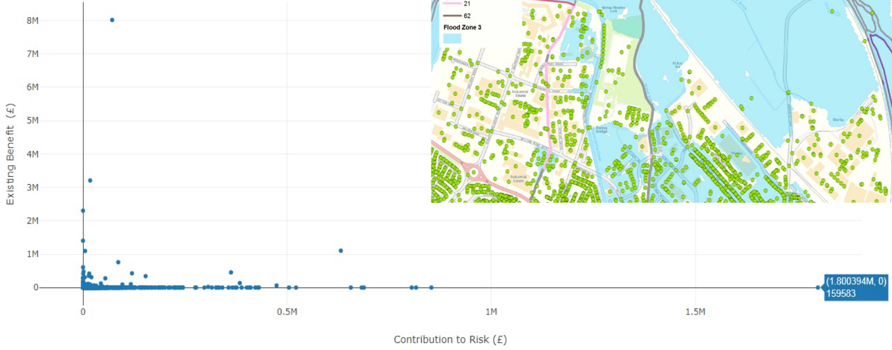
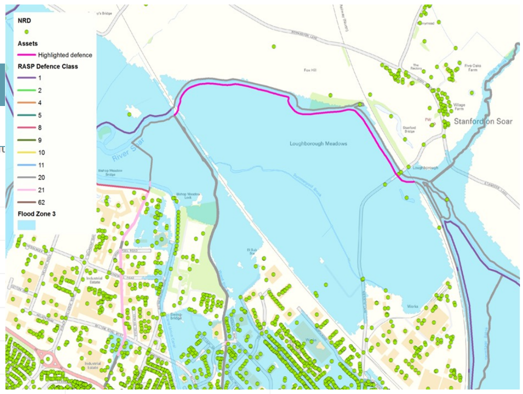
Levee with significant contribution to residual risk

Catchment 2804, Asset 159583

Defence Class	Current CG	Target CG	Crest Level (m)	Ground Level (m)	100yr water level (m)
20 (High ground)	3	3	36.13 to 37.05	36.13 to 37.05	36.95 to 37.72





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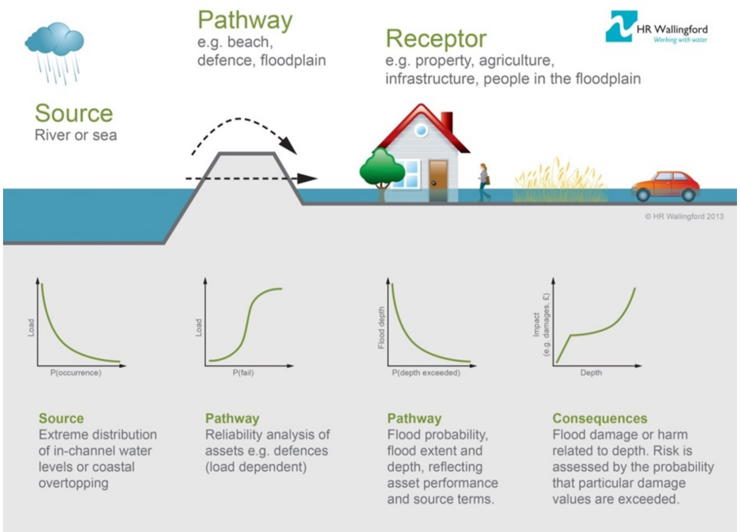
Whole life changes in flooding systems including levees

- Each component of system can change with time:
  - Source loadings can change,
    - e.g. sea level rise
  - Pathway components can change
    - defence deterioration
  - Receptors (people and property) can change
    - Development
    - Land use change
    - Social vulnerability changes



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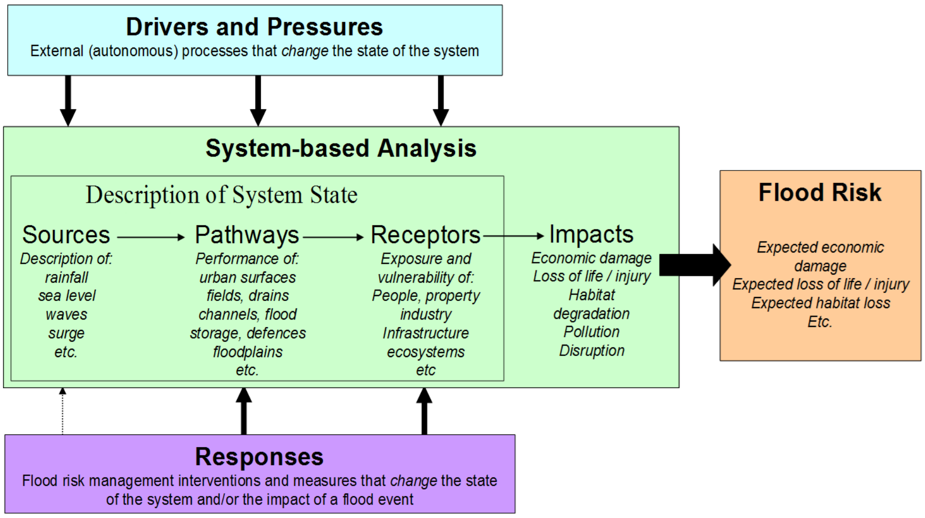
Pressures and responses on flooding system



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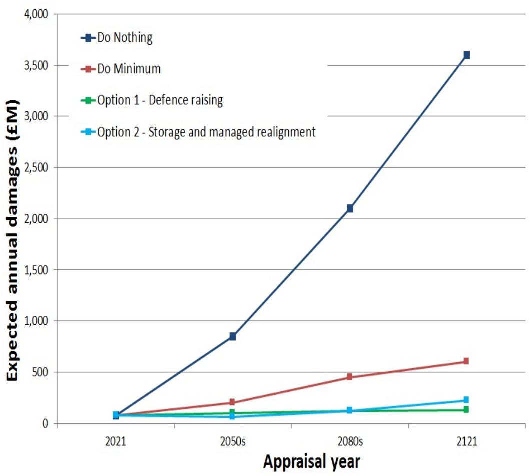
Option appraisal - Risk profile



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Overall approach to assessment of flood risk

Example features of English system that support the flood risk analysis

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Example features specific to English approach

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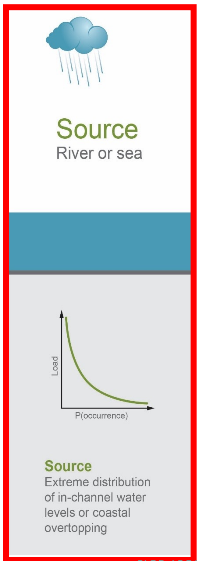
How is flood risk assessed for the English NaFRA? Sources

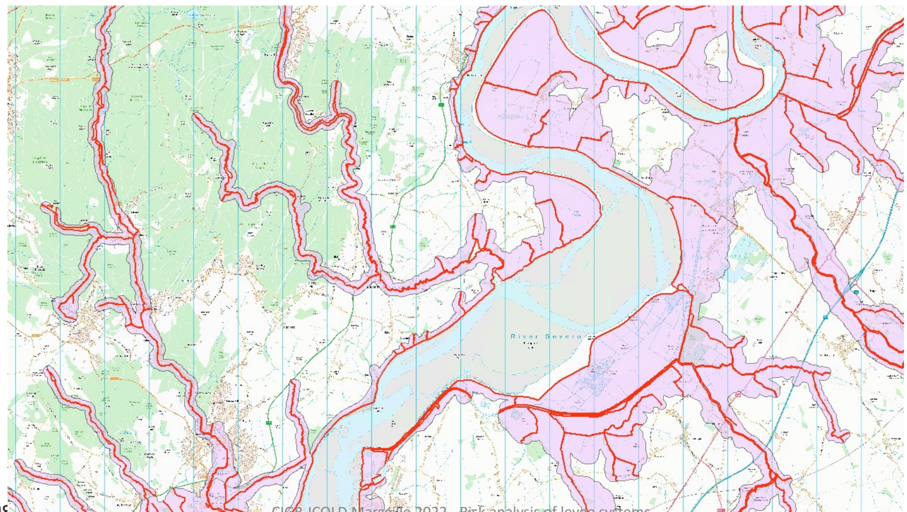


- The source information is:
  - Extreme water levels (Fluvial and Tidal)
  - Extreme overtopping rates (Coastal)
- Represented via a distribution of 40 return periods
- Sometimes referred to as 'loading conditions'.
- A distribution is used for every defence

Default Return Periods			
1	70	170	550
2	80	180	600
3	90	190	650
5	100	200	700
10	110	250	750
20	120	300	800
30	130	350	850
40	140	400	900
50	150	450	950
60	160	500	1000

Continuous Defence Line

- Consider every river bank, flood defence and length of coastline



Detailed river network

Consider every source of flooding.

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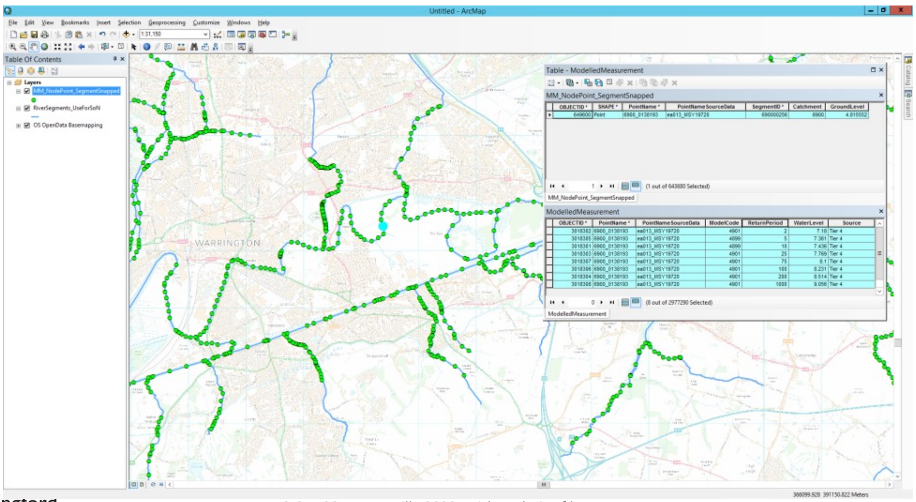
Extremes data
National Fluvial Loads Database



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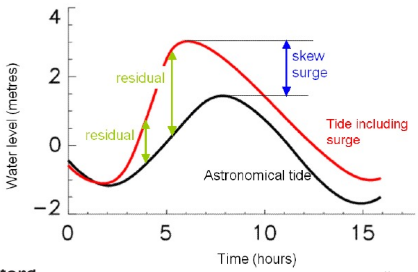
Coastal Flood Boundaries data

- Extreme sea levels
  - Provided at 2km intervals
  - RPs from 1 to 1,000
- Confidence intervals
- Skew surge shape



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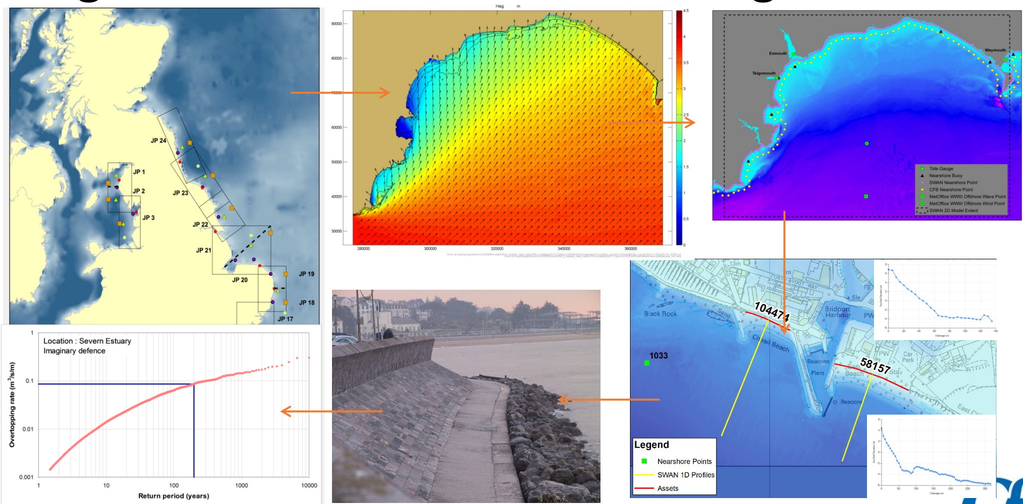
10,000 years of extreme events transformed through detailed process modelling chain



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Gouldby, B., *et al*., 'Multivariate extreme value modelling of sea conditions around the coast of England' *Proc. Institution of Civil Engineers - Maritime Engineering, vol 170, Issue 1, Mar 2017.*

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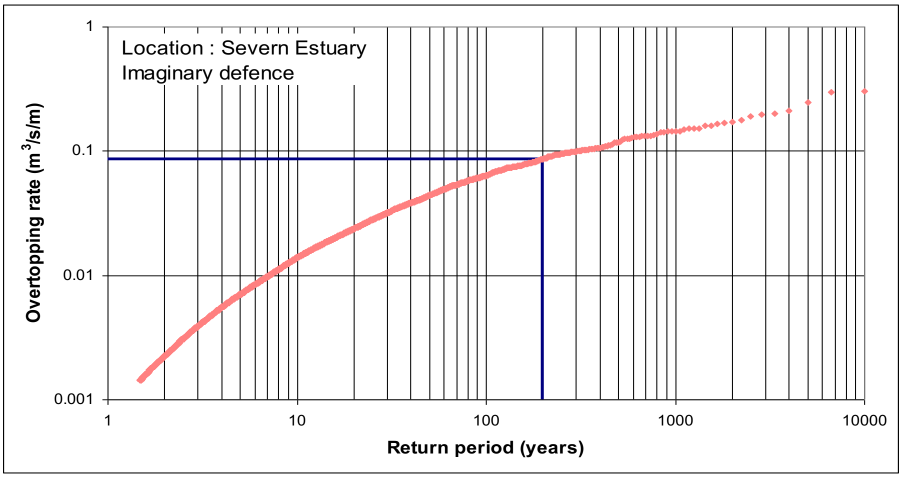
Coastal Loads



Return period of the response, not the event
Change the defence and the events take on a different ranking.

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Example features specific to English approach

Pathways

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"Generalised Fragility" curves

- Used in the UK for high level risk modelling
- Based on defence type and features - ***see next slides***
- Principal failure modes
- Defined condition inspection procedures
- Simplified approach to deterioration

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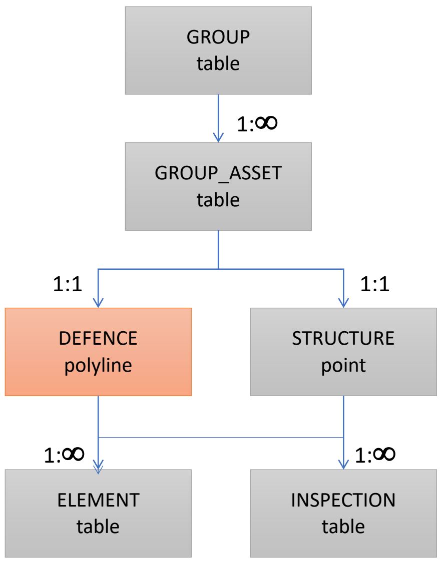
AIMS Inventory data model



- Linear defences
  - Embankments
  - Walls
  - Culverts
  - High ground
  - Demountable
- Type
- SoP
- Condition
- Maintainer
- Bank
- Protection Type
- Crest Level

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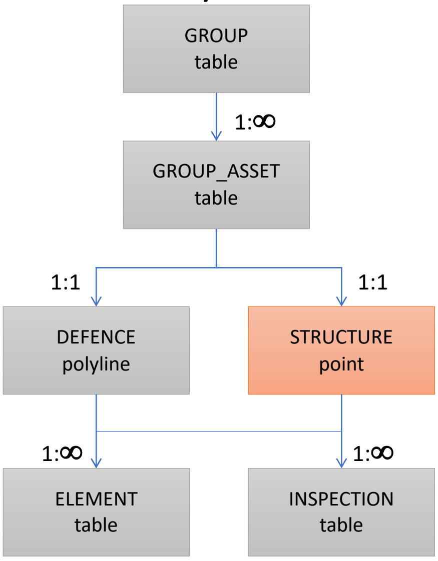
AIMS Inventory data model



- Point structures
  - Bridges
  - Weirs
  - Outfalls
  - Pumps
  - Control gates
- Type
- SoP
- Condition
- Maintainer
- Bank
- Protection Type
- Crest Level

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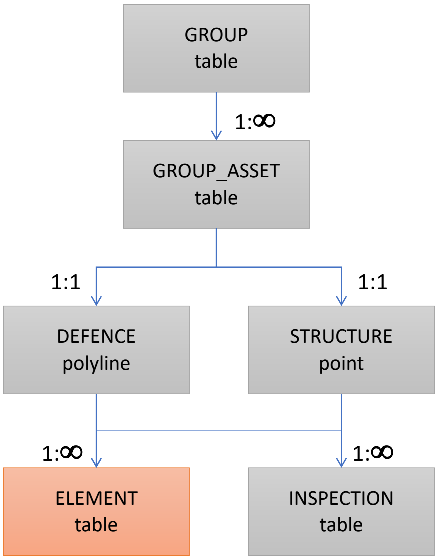
AIMS Inventory data model



- Component of assets
  - Crest
  - Front face
  - Channel
- Material
  - Earth
  - Masonry
  - Concrete
- Revetment
  - Turf
  - Blockwork
- Width

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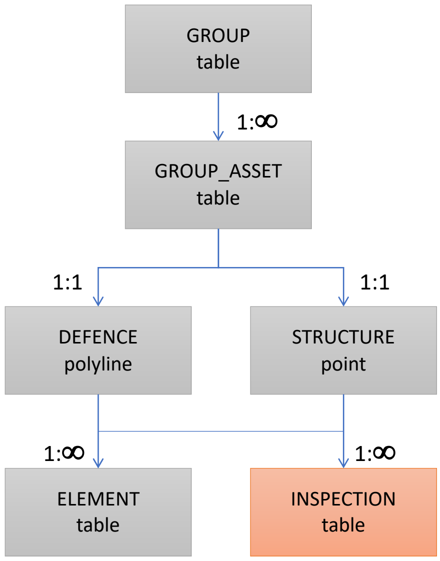
AIMS Inventory data model



- Date
- Condition Grade
- Urgency
- Residual Life

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Visual inspection – English condition grades

Grade	Rating	Description
1	Very good	Cosmetic defects that will have no effect on performance
2	Good	Minor defects that will not reduce the overall performance of the defence asset
3	Fair	Defects that could reduce performance of the defence asset
4	Poor	Defects that would significantly reduce the performance of the defence asset. Further investigation needed
5	Very poor	Severe defects resulting in complete performance failure

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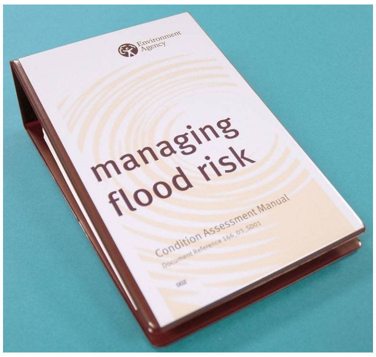
Defence asset condition grades



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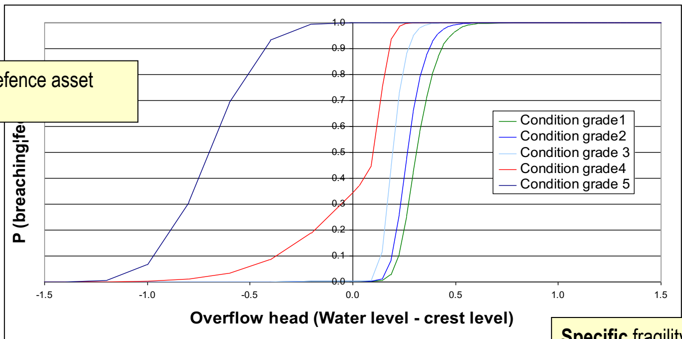
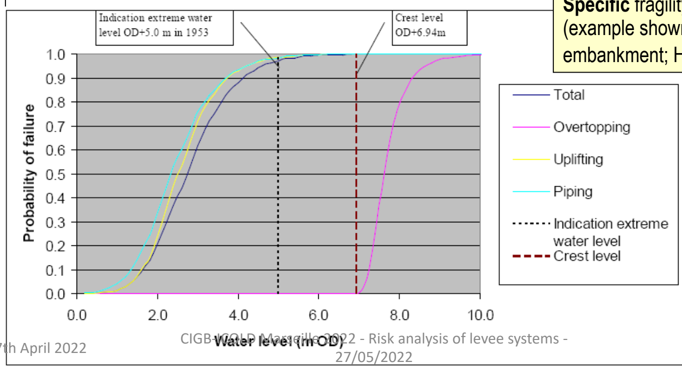
Generic' curves linked to defence asset type and condition grade



Specific fragility curves for a specific assets (example shown is for Dartford Creek embankment; HR Wallingford, 2006)



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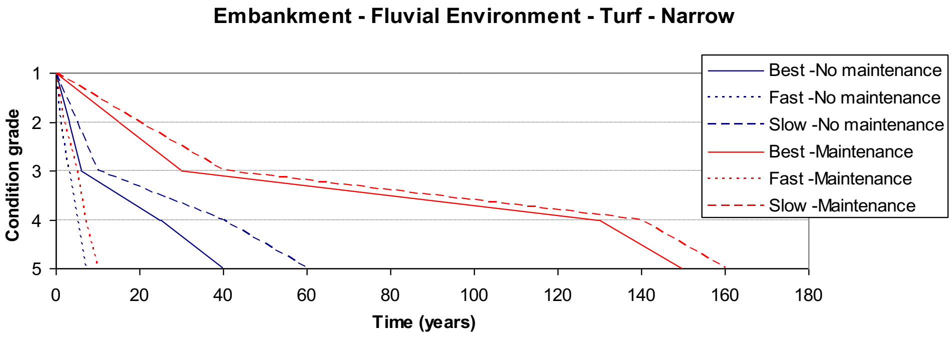
Deterioration curves



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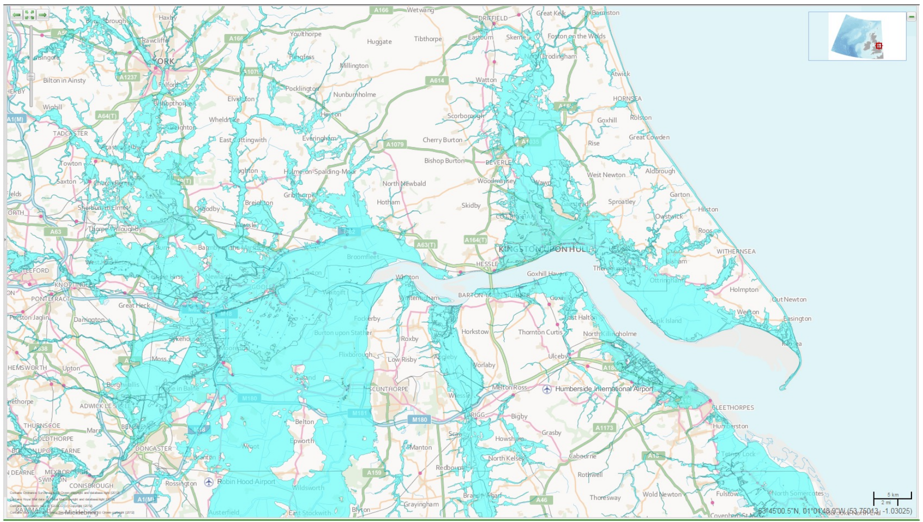
Considers all possible floodable locations

Consider every region of floodplain within the undefended 1:1000yr extent



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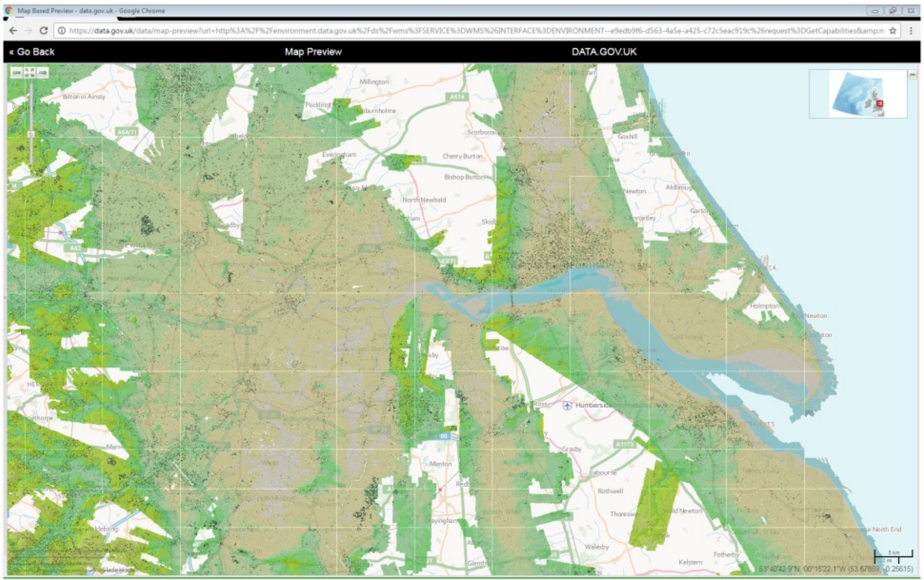
LiDAR DTM (2m)



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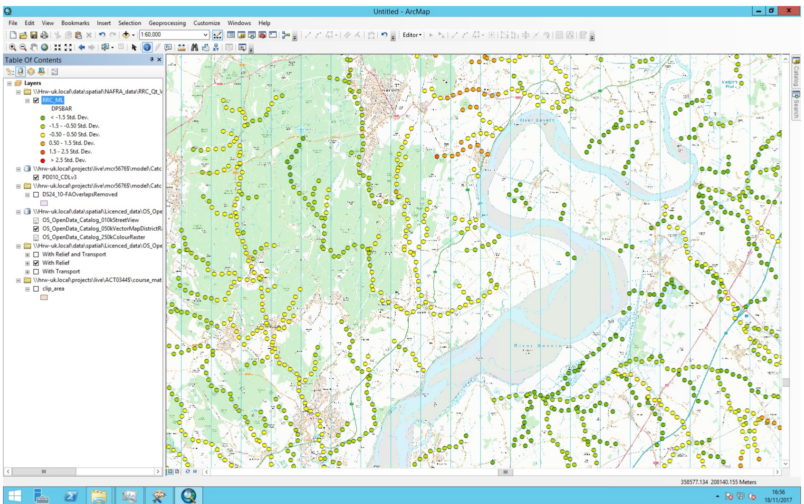
Flood Estimation Handbook
Qt data and catchment descriptors

Catchment properties used to estimate fluvial inflow duration → inflow volumes



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Examples of features specific to UK approach

Receptors

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Damage to property

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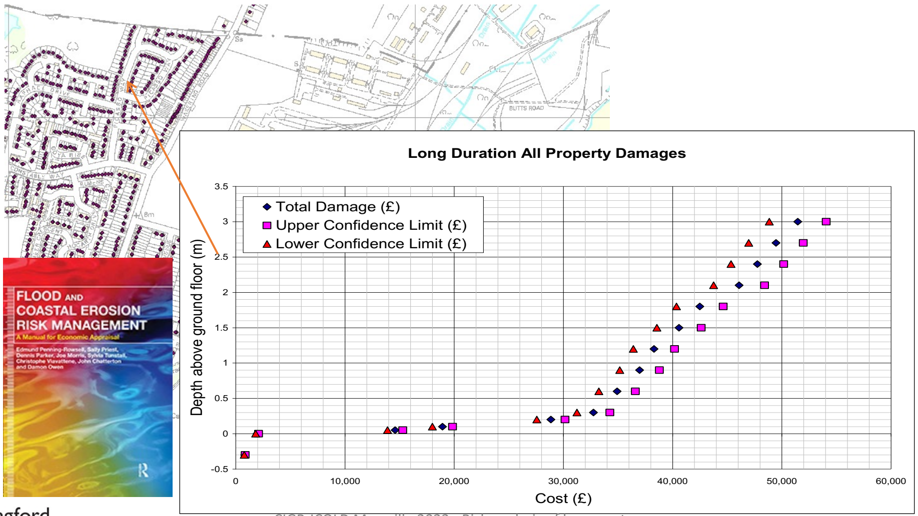
Depth damage curves (MCM)

Curves (£ per metre) for residential and 8 types of non-residential properties.



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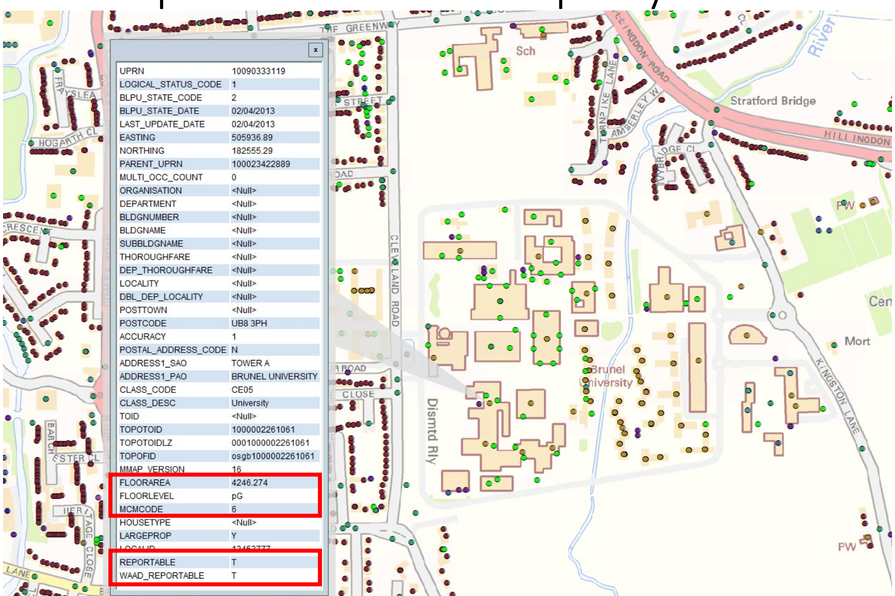
National Receptor Database: Property



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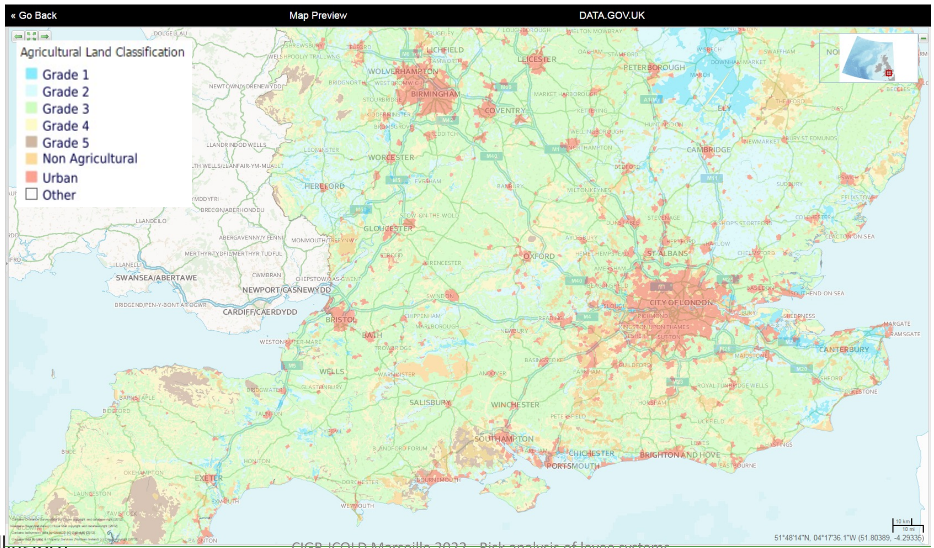
Other receptors
Agricultural Land Classification



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Key references

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- *Reliability Analysis of Flood and Sea Defence Structures and Systems, (2009). T07-08-01. FLOODsite. Available at https://www.floodsite.net/html/news.asp*
- Simm, J. and Tarrant, O. (2018) *Development of fragility curves to describe the performance of UK levee systems.* Proc. 26th Congress ICOLD, Vienna, Austria

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