STORMS: Strategies and Tools for Resilience of Buried Infrastructure to Meteorological Shocks

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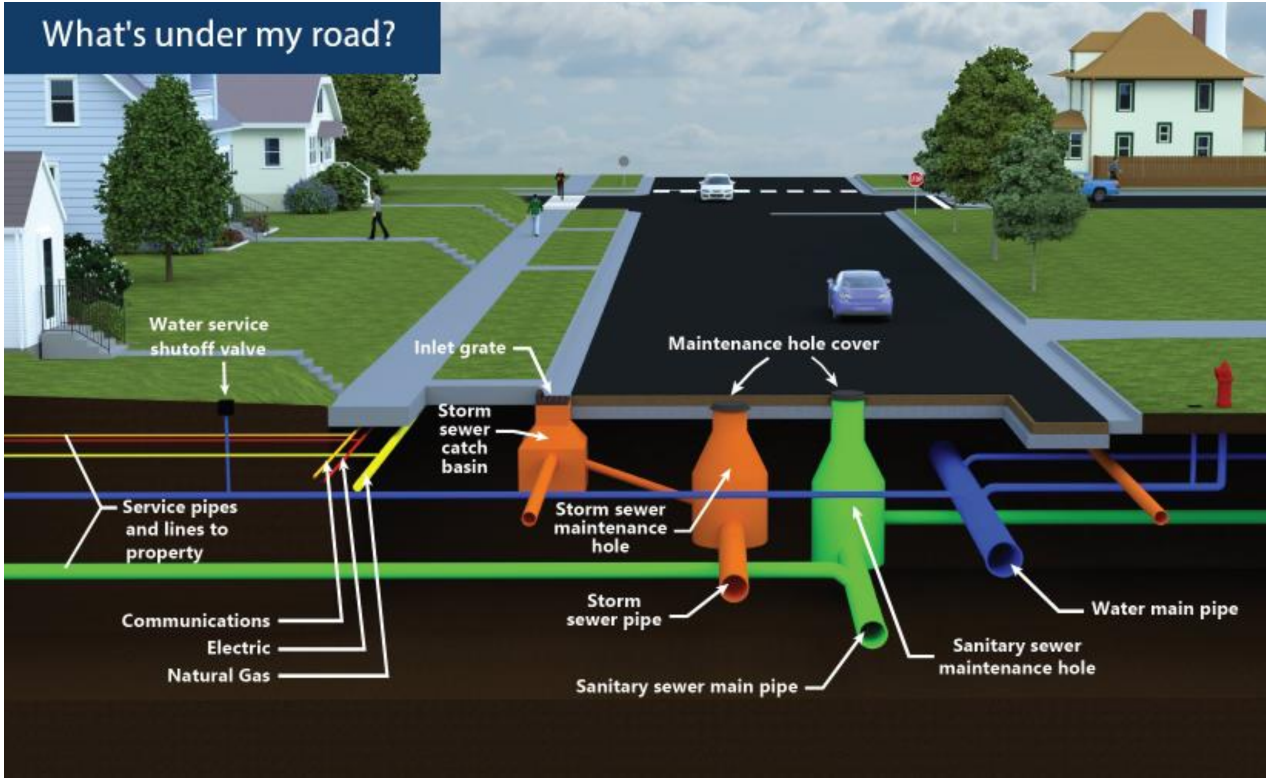
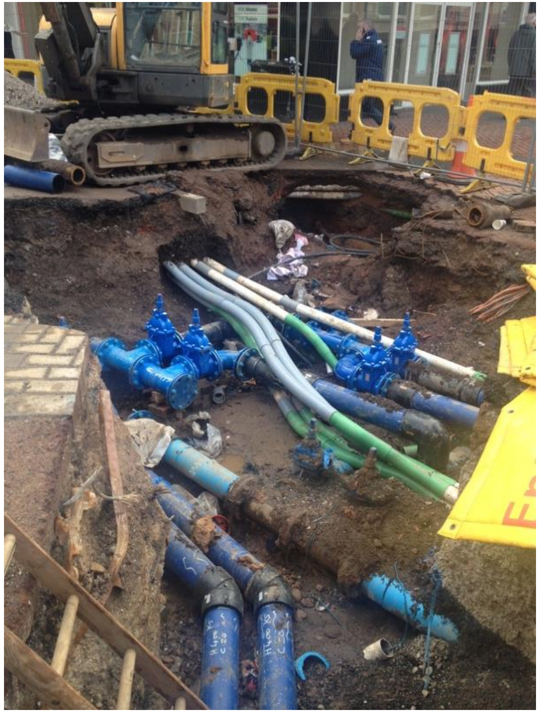
Why buried Infrastructure?





Buried infrastructure provides essential services: Water, Energy and Communication

Buried utilities in numbers

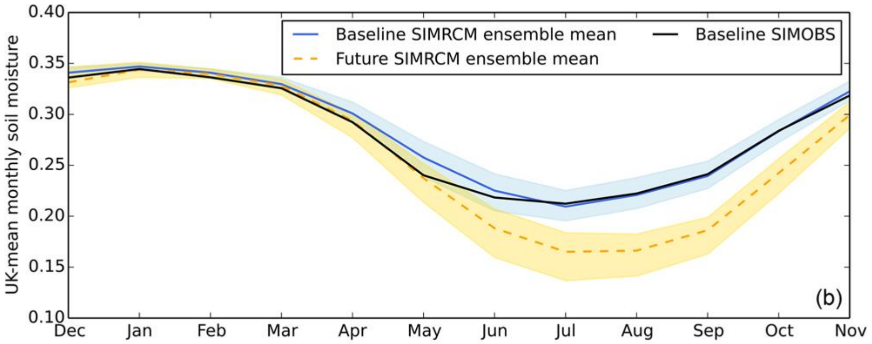
Asset	Approximate buried length
Water mains (England & Wales)	≈ 350,000 km
Public sewers (UK)	≈ 500,000 km
Gas distribution pipes	≈ 280,000 km
Electricity network	≈ 20,000 km high-voltage cables, plus ≈ 800,000 km lower-voltage distribution lines

£2.4 billion per year in direct and indirect costs is lost to utility strikes

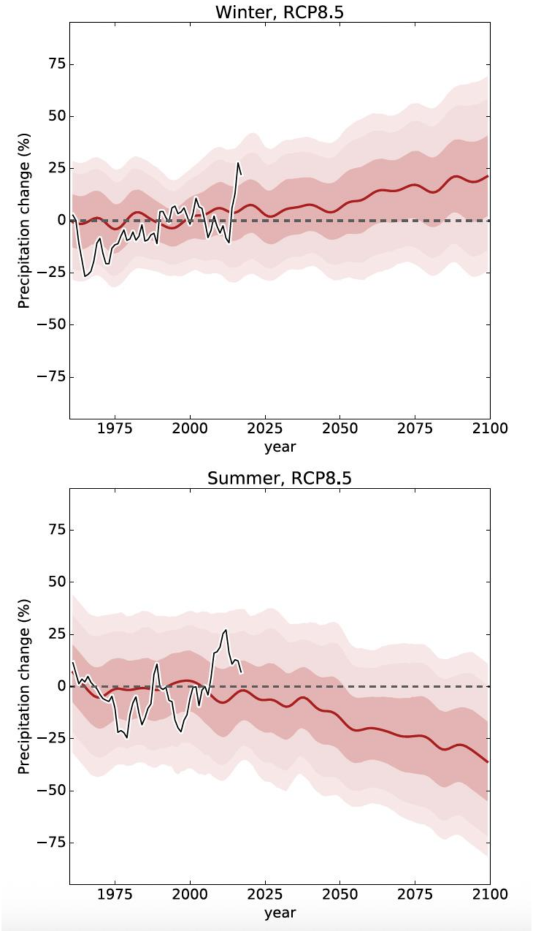
How the UK Climate is Changing

According to UK Climate Projections 2018

- **Warmer**, **wetter** winters and **hotter**, **drier** summers
- **Increases** in precipitation intensity on wet days in winter
- **More pronounced variability** of precipitation and soil moisture



Kay et al. (2023)



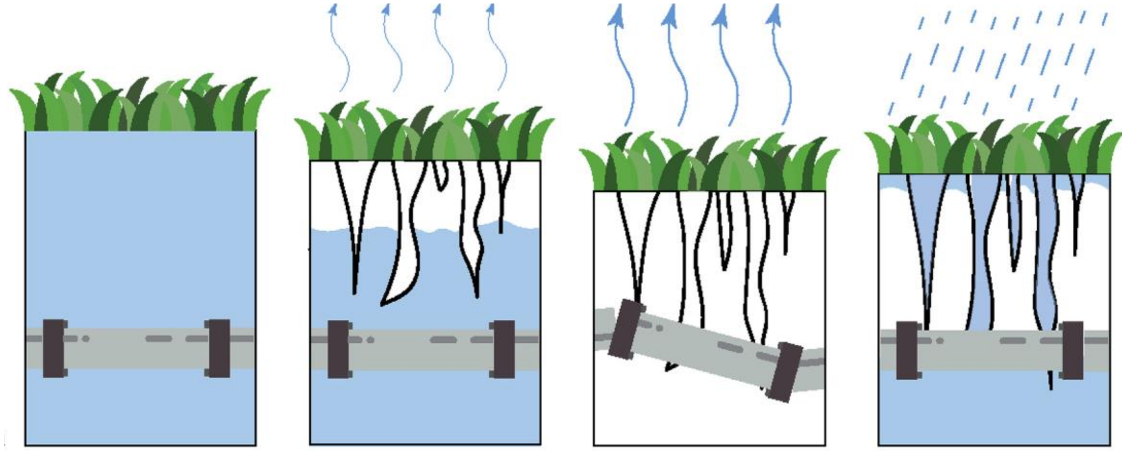
Met Office 2018

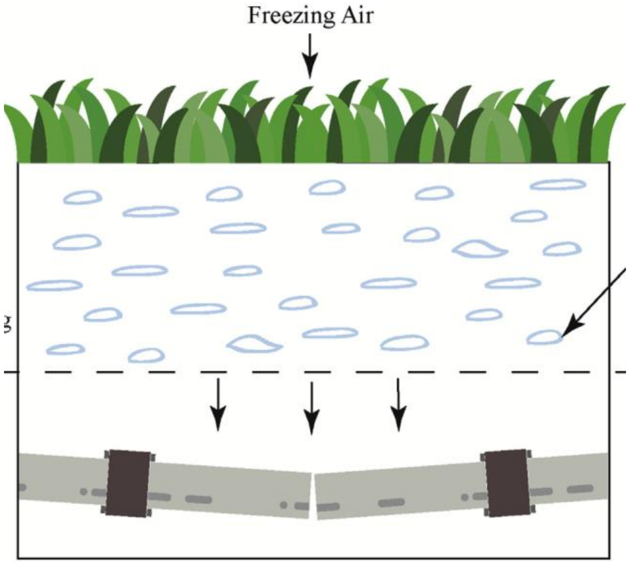
Impacts from Climate Change

- Extreme floods
  - Wash-off and erosion
  - Sinkhole
  - Uproot of trees
  - Loss of load bearing

Impacts from Climate Change

- Wet-Dry Cycle and Freeze-Thaw Cycle
  - Differential soil movement (Swelling and Shrinkage)
  - Breakage of rigid pipes





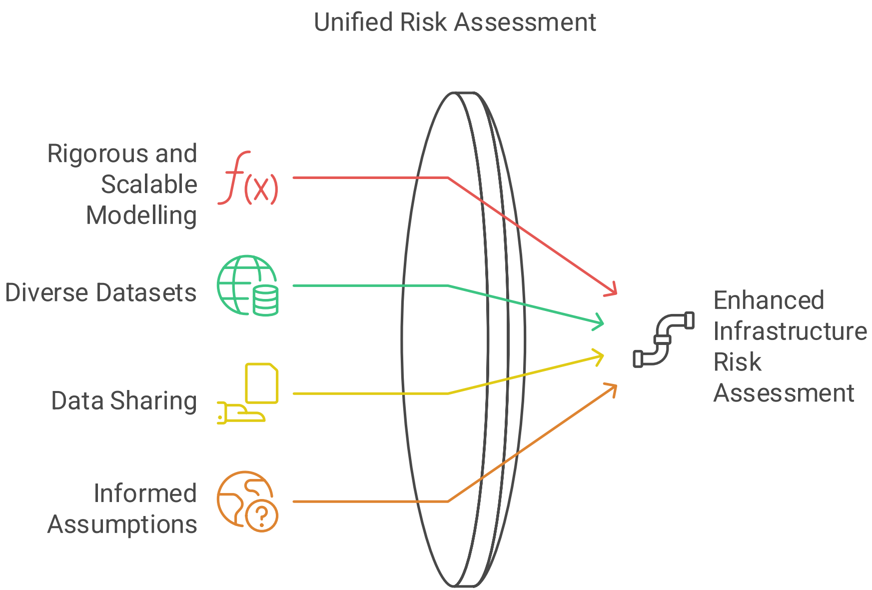
Barton et al. (2019)

Current status of climate risk assessment for buried infrastructure

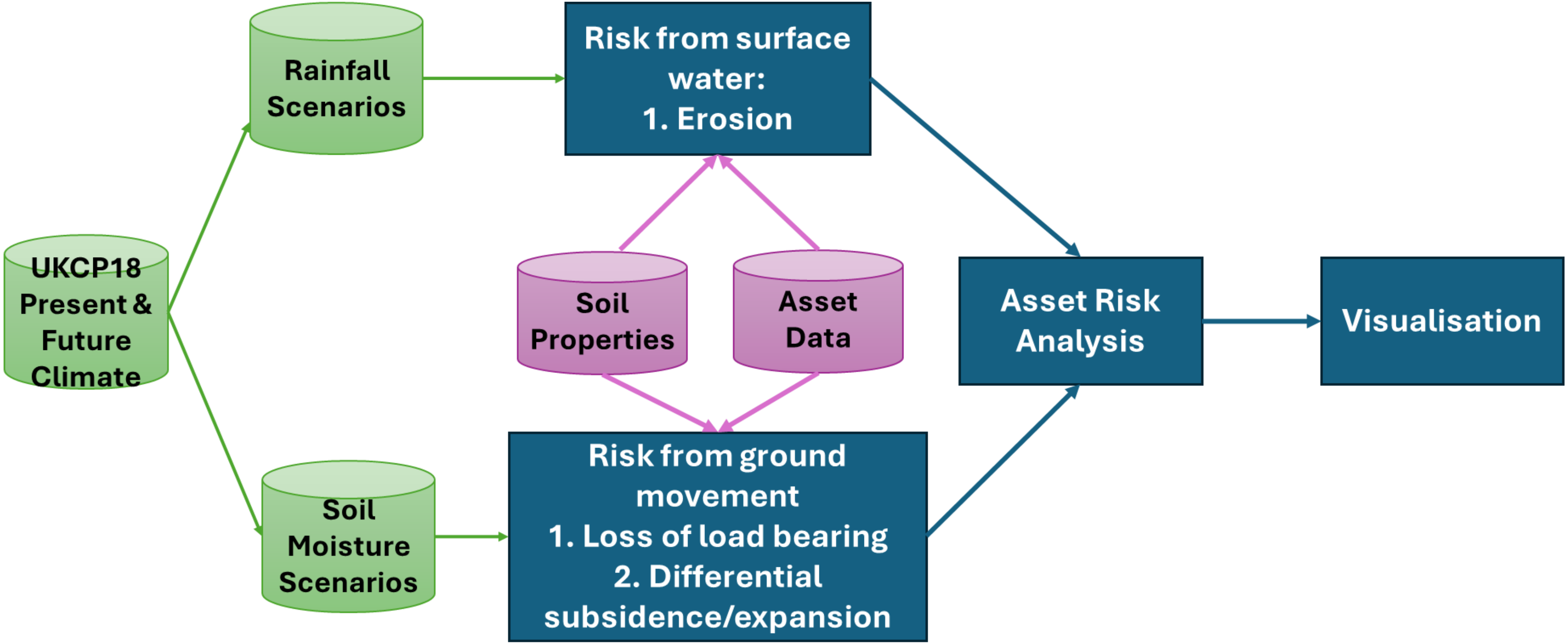
- The climate drivers and impacts are well-known, as reported by UK Climate Change Risk Assessment (CCRA3) and Adaptation Reporting Power (ARP) reports [suggesting **100s million** damage per year]
- Existing risk assessments are qualitative, high-level, mostly based on expert judgement
- National-scale quantitative risk assessment tool is urgently needed for water, energy and telecommunication sectors
- STORMS aims to develop a comprehensive risk assessment model to guide decision making for climate resilience

Challenges for developing a national-scale risk assessment model for buried infrastructure

- **New modelling technique** that is rigorous and scalable
- Integration of **diverse datasets** – climate, hydrology, geology and infrastructure
- Overcoming barriers for **data sharing** – how asset owners apply the model to their [sensitive] datasets about buried pipes
- Making **informed assumptions** where data are missing or incomplete, e.g., unknown buried depth of pipes

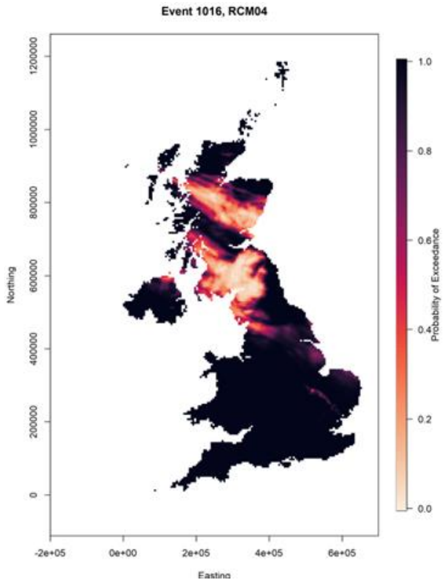


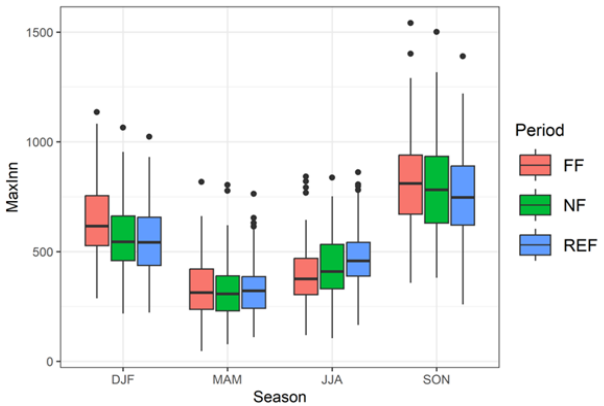
Climate Risk Assessment Model Overview



Rainfall scenarios

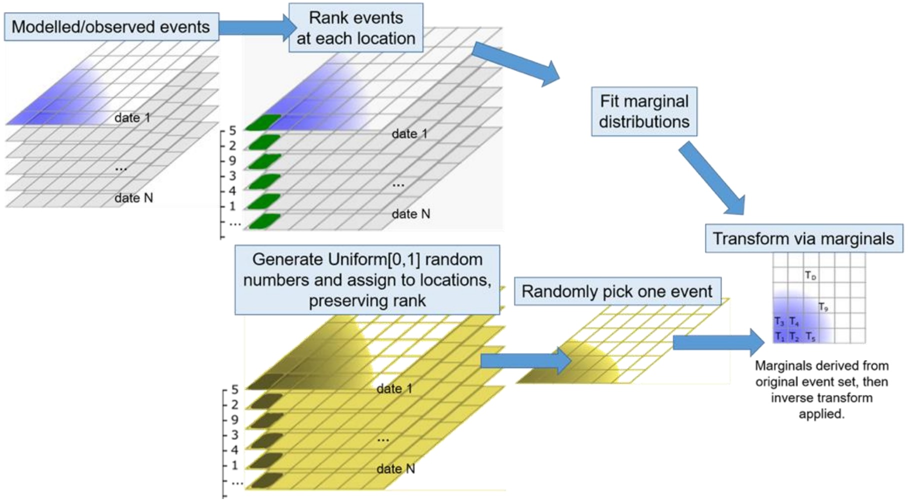
- Widespread multi-day precipitation events (daily depth)
  - At site annual probability less than 3/360
  - Extent greater than 1% of GB mainland
- Based on UKCP18 Convection Permitting models under RCP8.5
- Baseline (1980-2000), Central (2020-2040) and Future (2060-2080)
- Available on DAFNI and EIDC





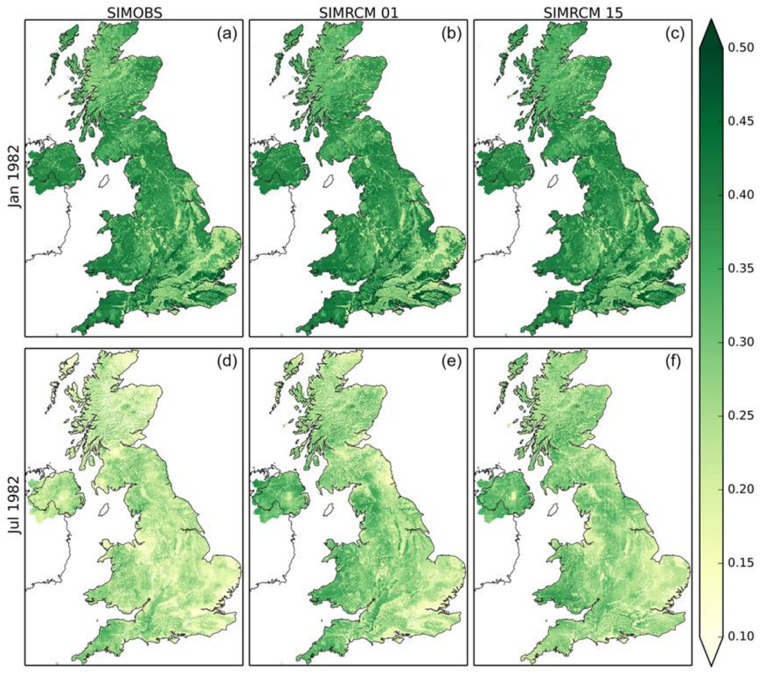
Expanding the event dataset

- To understand the diversity of the rarest events, we statistically simulate more events to supplement those directly modelled from UKCP18.
- The Empirical Copula method is very computation-time-efficient, and has more than doubled the event set.
- Has known applications in event-based CAT modelling (Climate Resilience Programme)



UKCP18 Soil Moisture Data

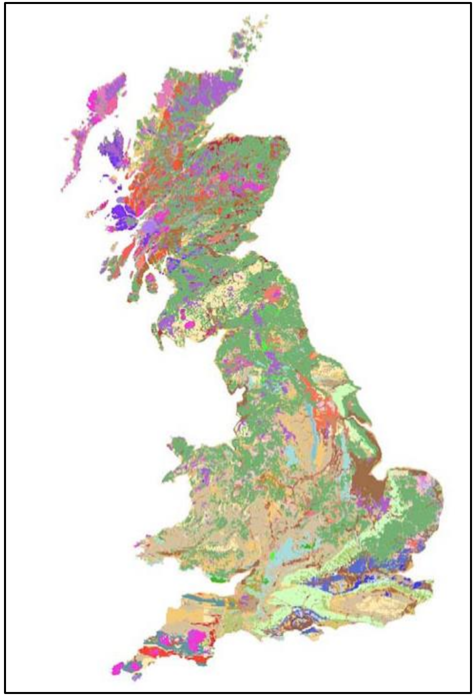
- Probabilistic Climate Projection for RCP 8.5 (UKCP18)
- Monthly mean soil moisture product (Kay *et al.*, 2023) from UKCEH, based on UKCP18
- Using Grid-to-Grid hydrological model with 12 ensemble member (1 km^2 resolution)
- Mean soil moisture data for Great Britain from 12 ensemble member stacked (a single GeoTIFF file per month for period 1980–2080, available on DAFNI)
- Working on an enhanced version with new data from Hydro-JULES programme, e.g., the British Groundwater Model (BGWM)



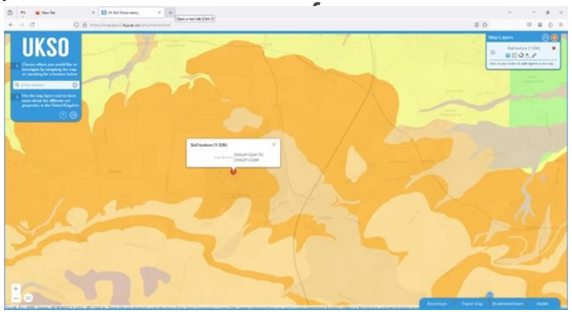
Maps of monthly mean soil moisture content (m water / m soil) for January and July 1982 from SIMOBS and two SIMRCM ensemble members. *(Figure and caption from Kay et al., 2023.)*

Soil Parent Material Model

- British Geological Survey product
- Soil Parent Material Model for the UK (1 km^2 resolution, 1:50k also available)
- Dataset includes “soil depth” and “Grain Size” that are used as hazard factors and inform parameterisation of pipe damage modelling
- Dataset is intersected with the desired soil moisture file (e.g. month and year)
- Final product contains risk levels for every grid-cell (1 km^2)
- Developed method for accessing the data from UK Soil Observatory (direct access from DAFNI in progress via web service)

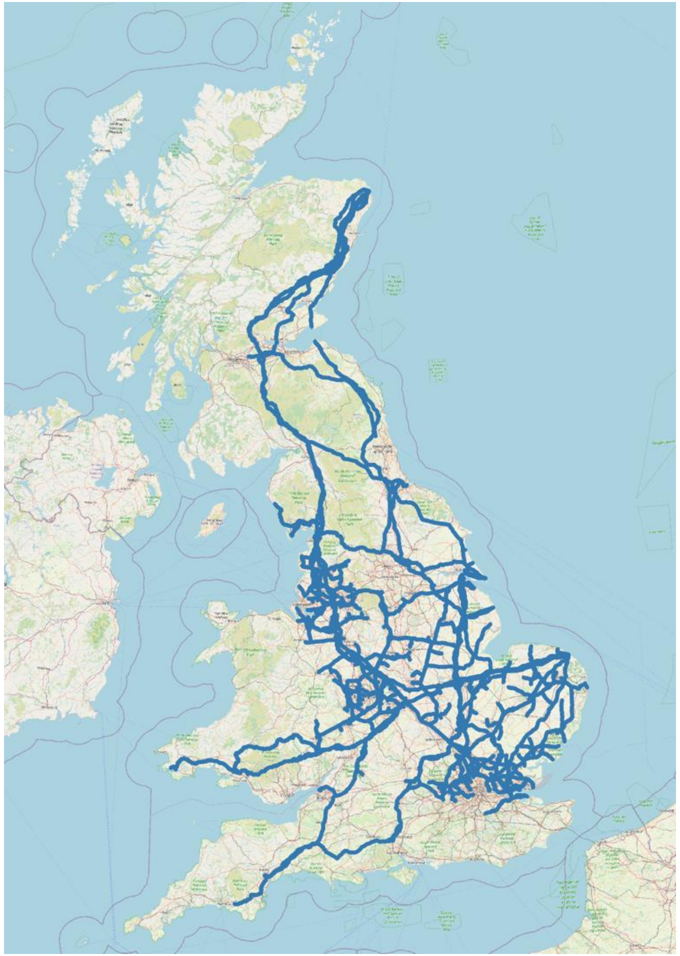


Overview of BGS Soil Parent Material map



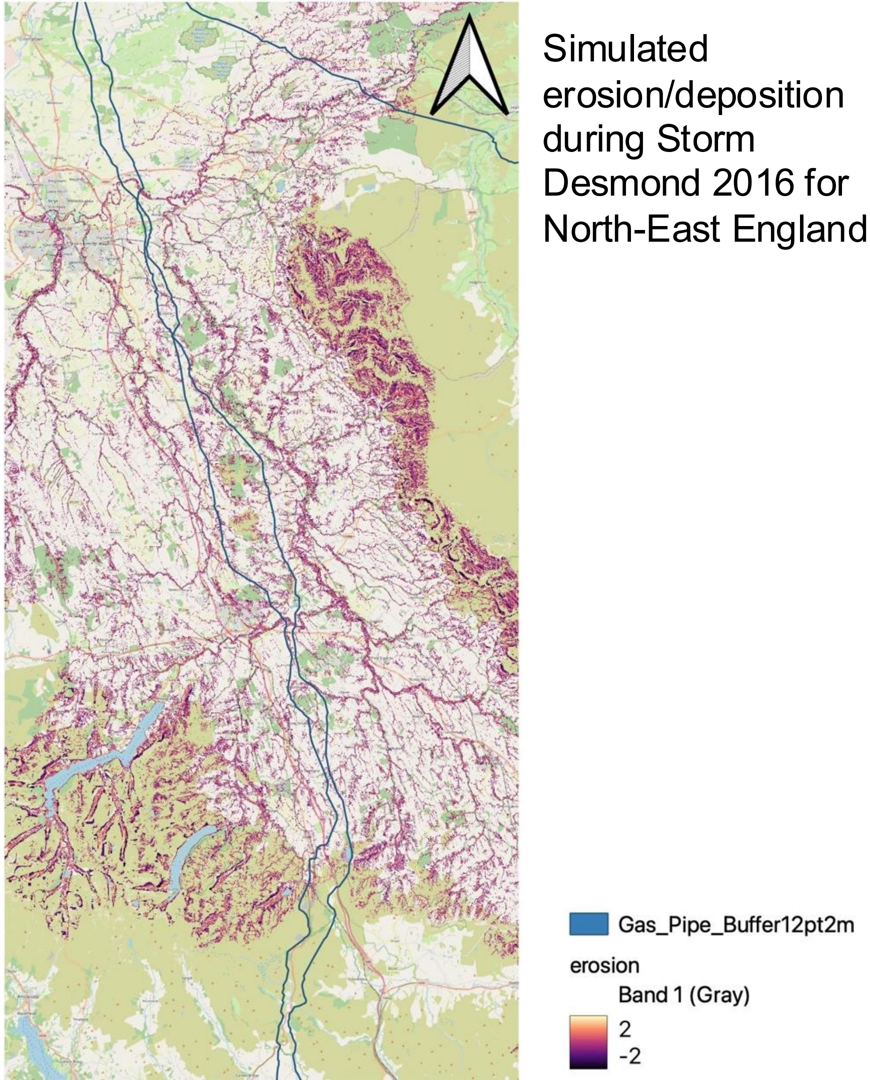
Natural Gas Networks

- Two networks including
  - National Gas (open data)
  - Cadent Gas
- Shapefile data containing
  - Pipe location
  - Pipe diameter
  - Pipe material
- Overlaid with other data layers for risk assessment



Risk from surface water

- Floods can cause:
  erosion – exposes pipelines
  accumulation – increases pressure, potentially damaging pipelines
- Rainfall scenarios are based on frequency analysis using UKCP18 climate projection
- Erosion/accumulation is calculated using open-source SynxFlow hydrodynamic model

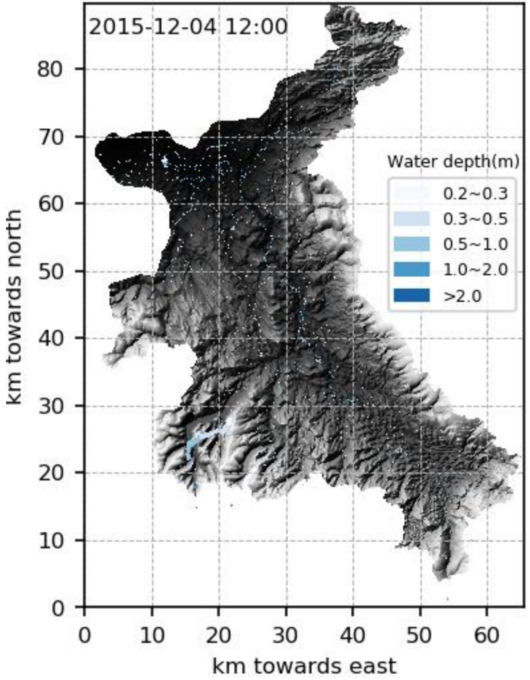


Simulated erosion/deposition during Storm Desmond 2016 for North-East England

SynxFlow: Synergising High-Performance Hazard Simulation with Data Flow

- A shallow water equations based hydrodynamic model for flood and other hazards (landslides, mud/debris flows)
- Open-source and on DAFNI
- Key development objectives
  - **Accuracy**: benchmark by real and theoretical test cases
  - **Performance**: scaling efficiently on supercomputers
  - **Robustness**: handling real-world simulations robustly
  - **Interoperability**: easy coupling among different solvers (flood/landslide/sediment) and with other models
  - **Ease of use**: straightforward to set up; easy to follow tutorials

Water hazard simulations by SynxFlow

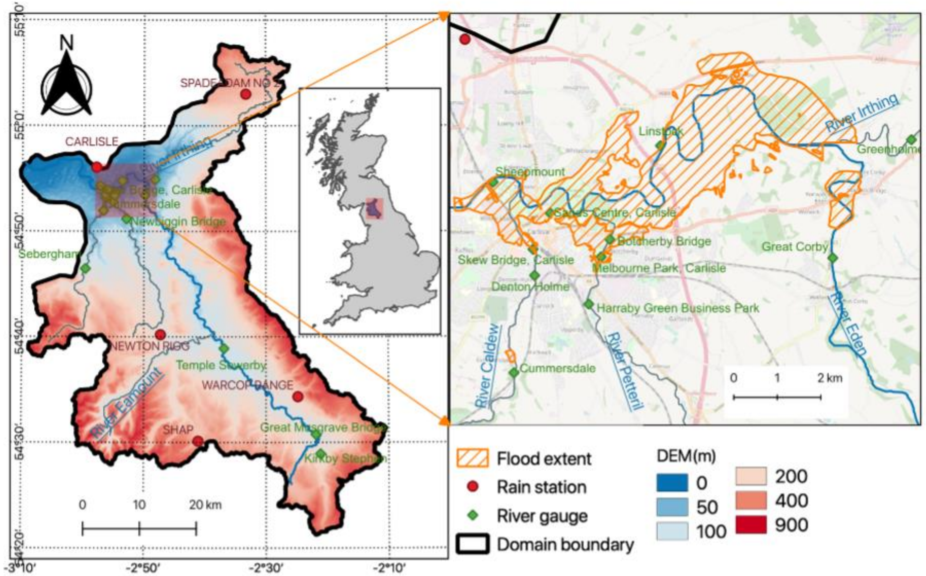


Flood modelling for Storm Desmond floods

Landslide – dam break simulations

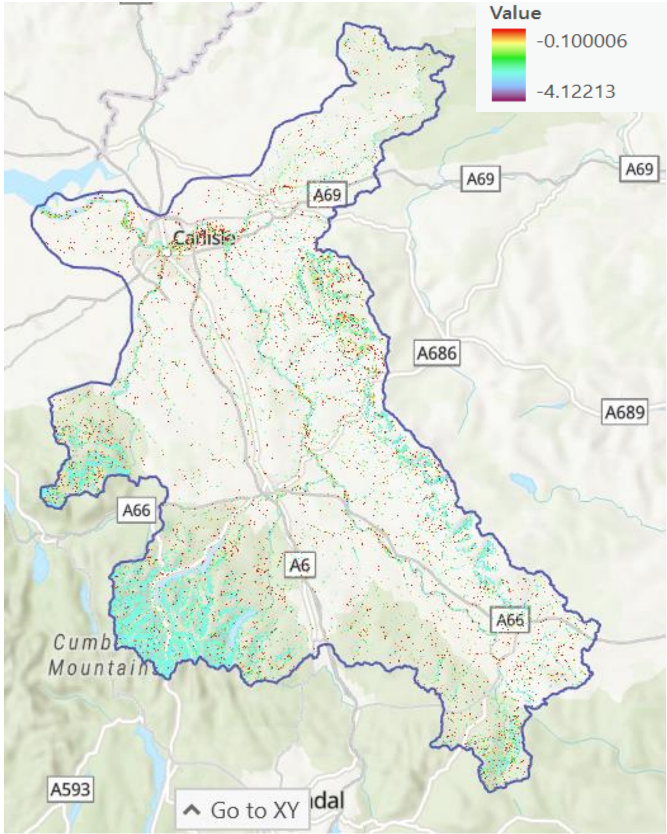
Input/output of flood and debris simulation

- Case Study: North-West England
- Input data:
  - DEM
  - Land type
  - Rainfall
- Output results:
  - **Surface elevation at different output time points**
  - **Maximum/minimum surface elevation during whole simulation process**



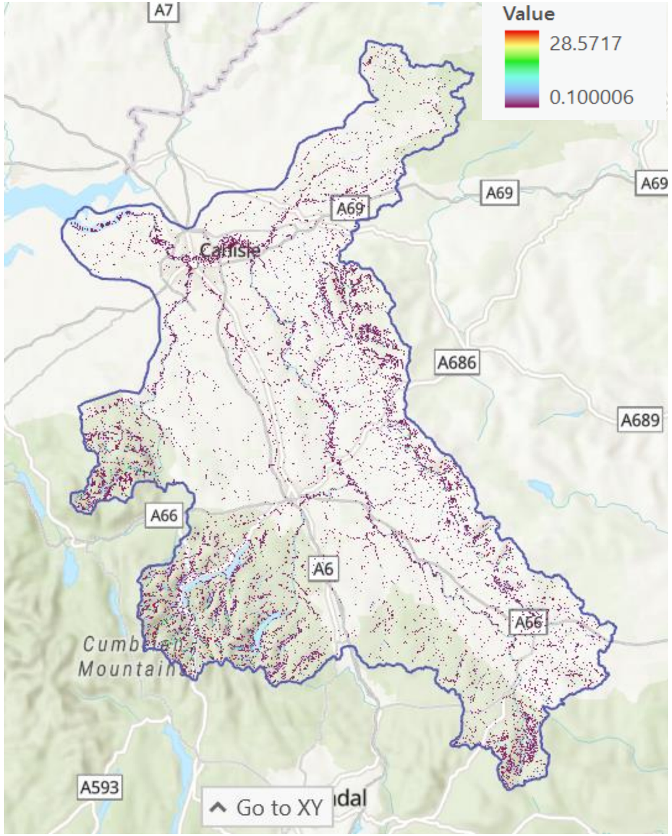
Ming, X., Liang, Q., Xia, X., Li, D. and Fowler, H.J., 2020. Real-time flood forecasting based on a high-performance 2-D hydrodynamic model and numerical weather predictions. *Water Resources Research*, *56*(7), p.e2019WR025583.

Soil erosion

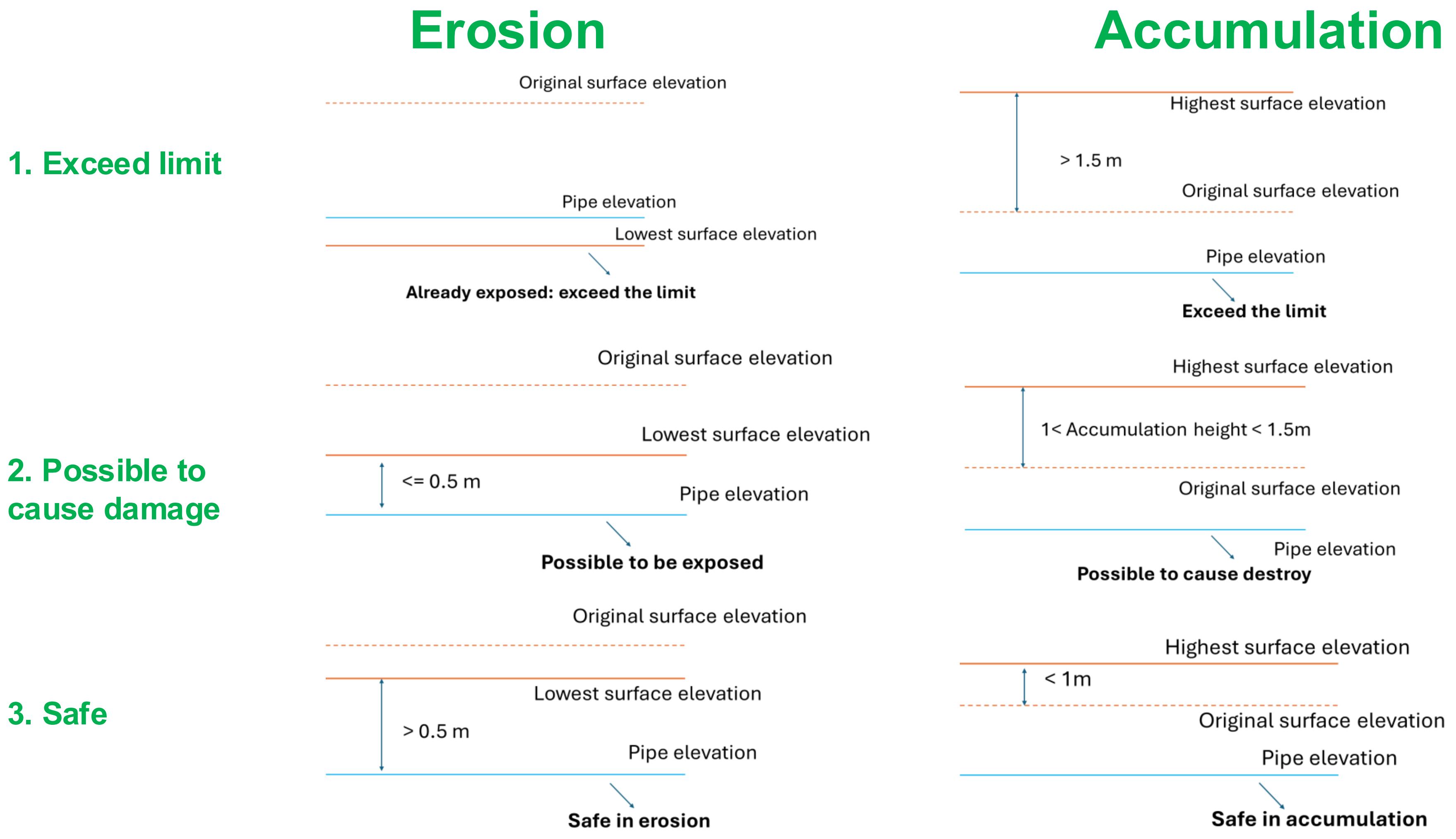


Minimum ground elevation – original DEM

Soil accumulation

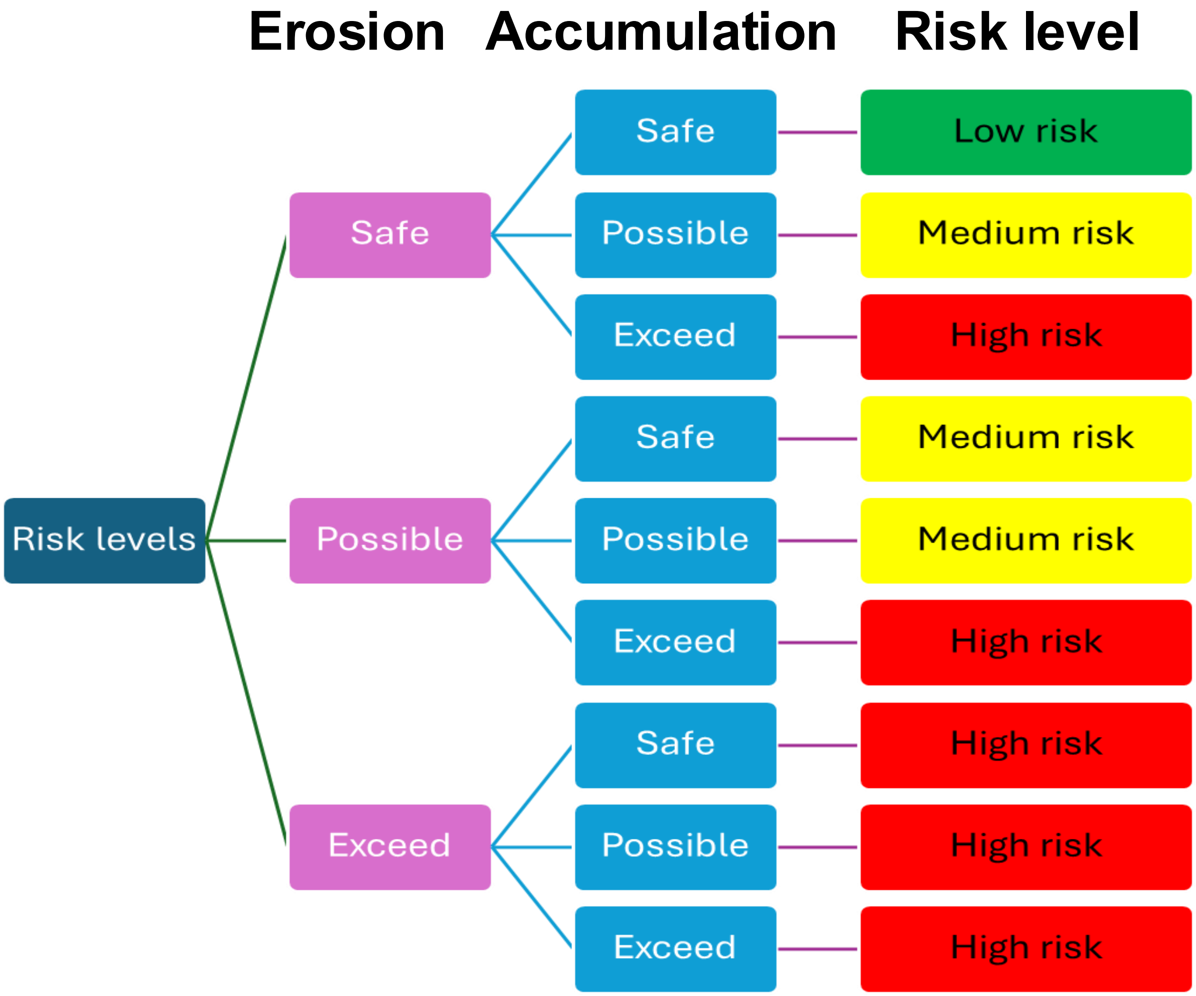


Maximum ground elevation – original DEM

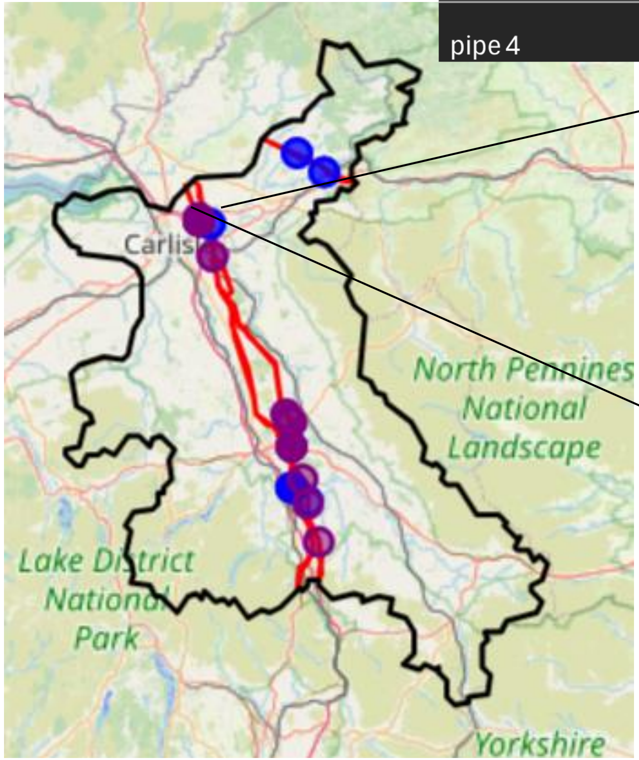


Erosion
Accumulation
1. Exceed limit
Original surface elevation
Pipe elevation
Lowest surface elevation
Already exposed: exceed the limit
Highest surface elevation
> 1.5 m
Original surface elevation
Pipe elevation
Exceed the limit
2. Possible to cause damage
Original surface elevation
Lowest surface elevation
<= 0.5 m
Pipe elevation
Possible to be exposed
Highest surface elevation
1< Accumulation height < 1.5m
Original surface elevation
Pipe elevation
Possible to cause destroy
3. Safe
Original surface elevation
Lowest surface elevation
> 0.5 m
Pipe elevation
Safe in erosion
Highest surface elevation
< 1m
Original surface elevation
Pipe elevation
Safe in accumulation

Underground pipe risk assessment based on erosion and accumulation levels



	burried_depth	max_erosion	erosion level	max_acculation	accumulation level	risk level
pipe 1	-2	-1.096939	safe	4.505023	exceed	high
pipe 2	-2.5	-1.040039	safe	1.77316	exceed	high
pipe 3	-1.2	-1.025479	possible	2.786937	exceed	high
pipe 4	-1	-1.253584	exceed	2.550079	exceed	high



Legend
Layer: historical_event_2016

Risk Level
- Low
- Medium
- High

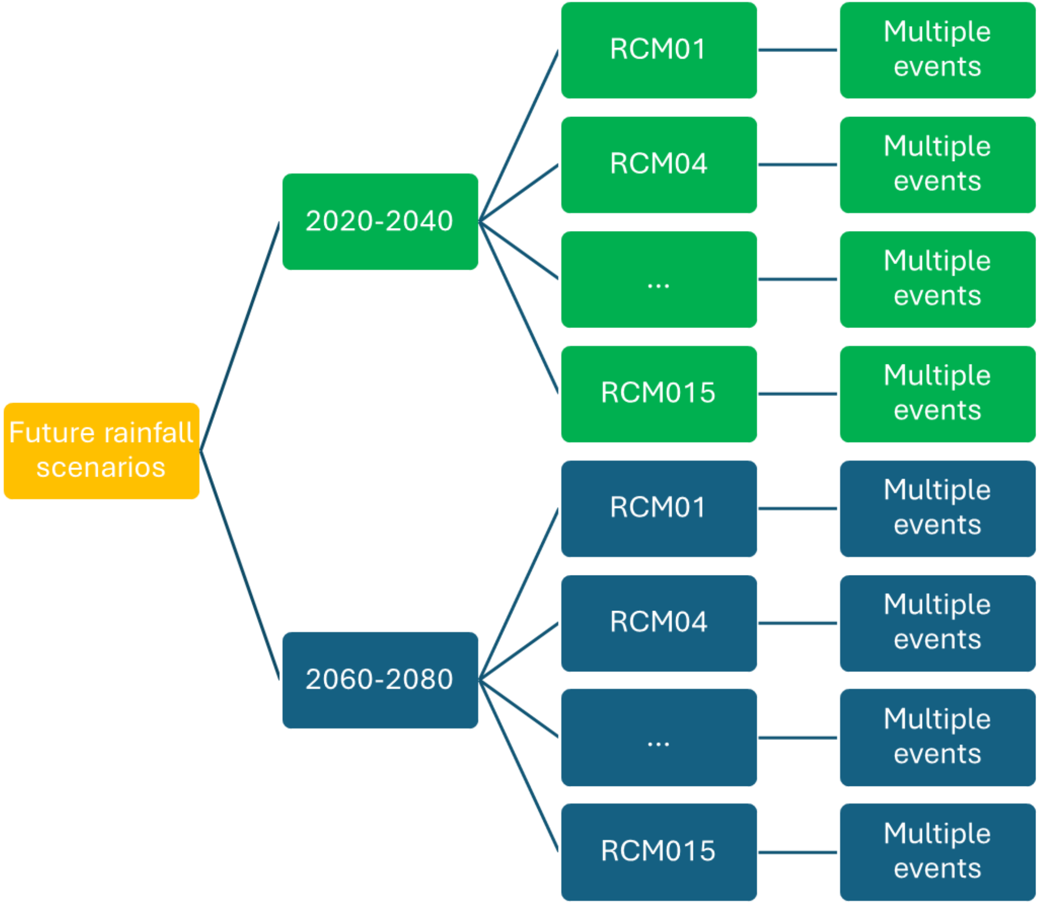
High Risk Locations
- accumulation
- erosion

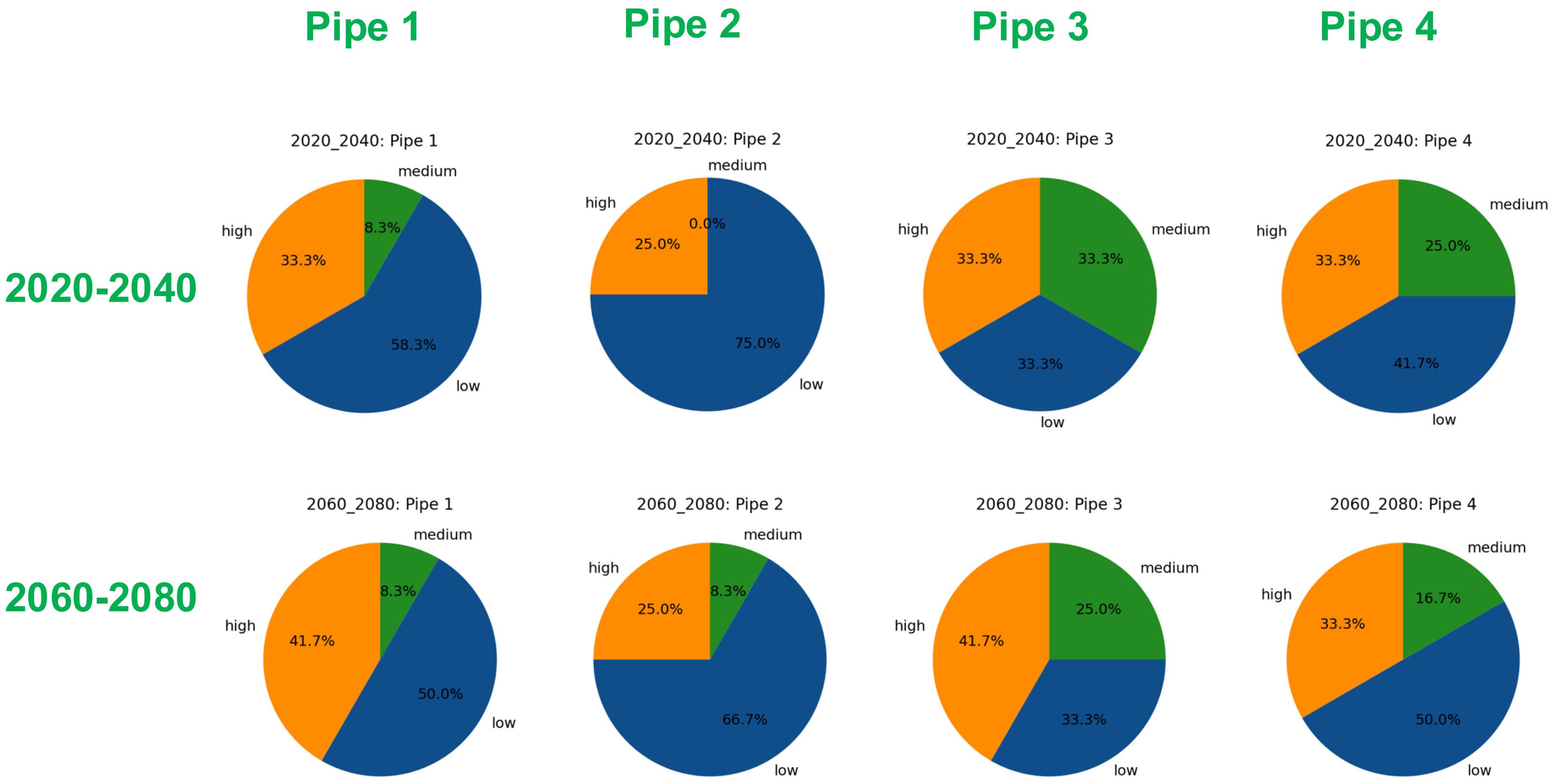
Test events:
A severe flood event induced by the 2015 Desmond storm in the Eden Catchment

This event may cause high risk to underground pipes within Eden catchment.

Pipe risk prediction due to climate change

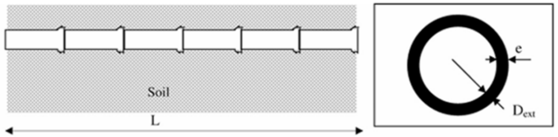
- **Future Rainfall Scenarios:** 2020-2040, 2060-2080
- **Event Generation:** different climate ensemble parameters produce events with varied peak daily depth and exceedance probability
- **Event Selection:** the most extreme two, two with moderate intensity, and the two least intense events are selected from each ensemble parameter set
- **Simulation:** 12 randomly selected events assess pipe risk

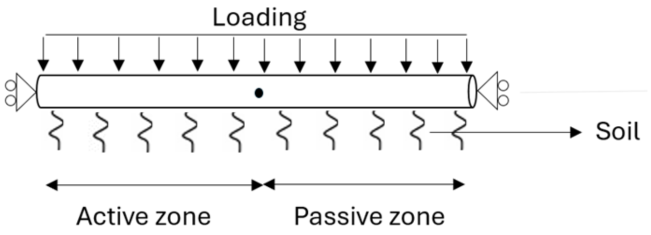


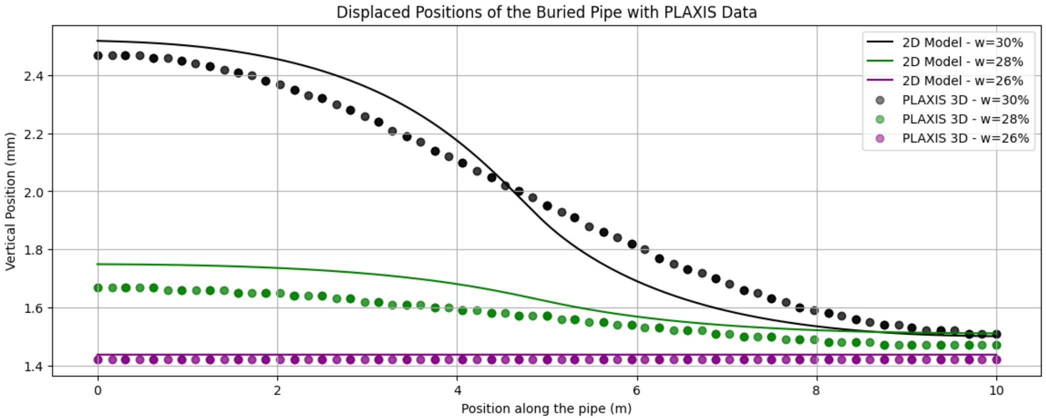

Pipe 1
Pipe 2
Pipe 3
Pipe 4
2020-2040
2060-2080
2020_2040: Pipe 1
medium
high
low
8.3%
33.3%
58.3%
2020_2040: Pipe 2
medium
high
low
0.0%
25.0%
75.0%
2020_2040: Pipe 3
medium
high
low
33.3%
33.3%
33.3%
2020_2040: Pipe 4
medium
high
low
25.0%
33.3%
41.7%
2060_2080: Pipe 1
medium
high
low
8.3%
41.7%
50.0%
2060_2080: Pipe 2
medium
high
low
8.3%
25.0%
66.7%
2060_2080: Pipe 3
medium
high
low
25.0%
41.7%
33.3%
2060_2080: Pipe 4
medium
high
low
16.7%
33.3%
50.0%

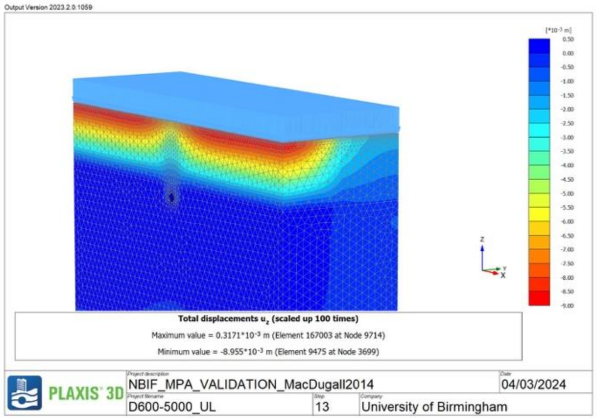
Damage Calculation for Buried Pipes – Finite Element

- 2D FEM model constructed to simulate soil-pipe interaction
- Soil moisture used to estimate soil stiffness and expansion/shrinkage volume
- Validated by a 3D PLAXIS model developed at National Buried Infrastructure Facility (NBIF)



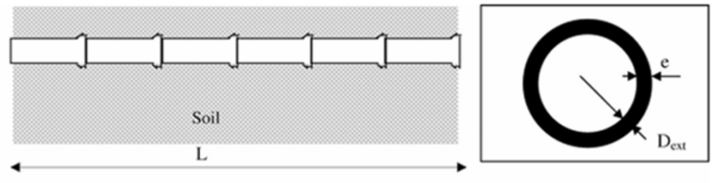


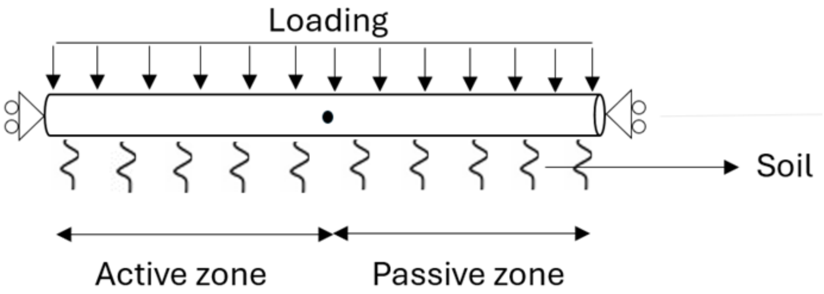




Key assumptions for the FEM model

- Solving the 2D Eulerian beam equation using finite element method
- Swelling and shrinkage applied as external loading
- Same model is applied to each individual pipe section but with varying parameters
- Dividing the pipe into active and passive zones to consider soil moisture variability





Risk Coding

Risk mapping using FEM

- **Low Risk->** Green colour

displacement/failure displacement < 40%

- **Medium Risk->** Yellow colour

40% ≤ displacement/failure displacement < 90%

- **High Risk ->** Red colour

90% ≤ displacement/failure displacement

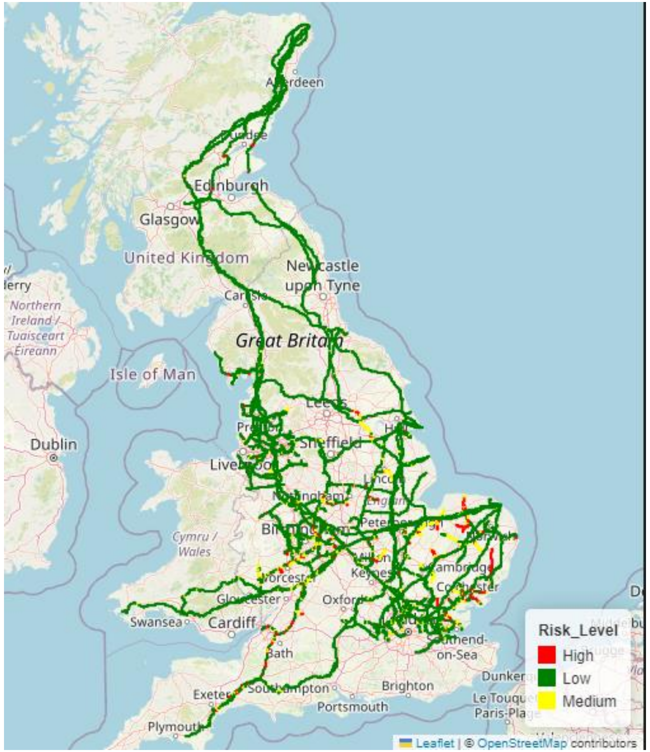
Risk mapping using matrix-based approach

RISK	LOW	MEDIUM	HIGH
Type of soil **Grain size class (Non- igneous parent):** **Grain size (igneous parent)**	Sand-rich subsoil Sand and gravel • Arenaceous • Arenaceous-Rudaceous • Medium (0.25 mm<x<2 mm) Low risks -> abrasion to pipes.	Sandy soils • Rudaceous • Argillic-Arenaceous • Coarse (> 2 mm) Good balance between drainage and support	Clay and Silt-rich subsoil Organic peaty subsoil • Argilic or Argillaceous • PEAT (organic soil-high moisture content) • Argillic-Rudaceous • Fine(< 0.25 mm) Retain water and can impose drainage issues.
Water Content	Lower than 20% Manageable and pose minimal risk to buried pipes (Chan, 2014)	20 to 35% Potential for increased soil pressure, settlement, and soil movement.	35% and above. Swelling of soils.
Soil Depth	Deep (h>0.8m)	Deep-intermediate Intermediate	Intermediate-shallow to shallow (h< 0.5 m)

Results: Matrix-based Risk Calculation vs FEM

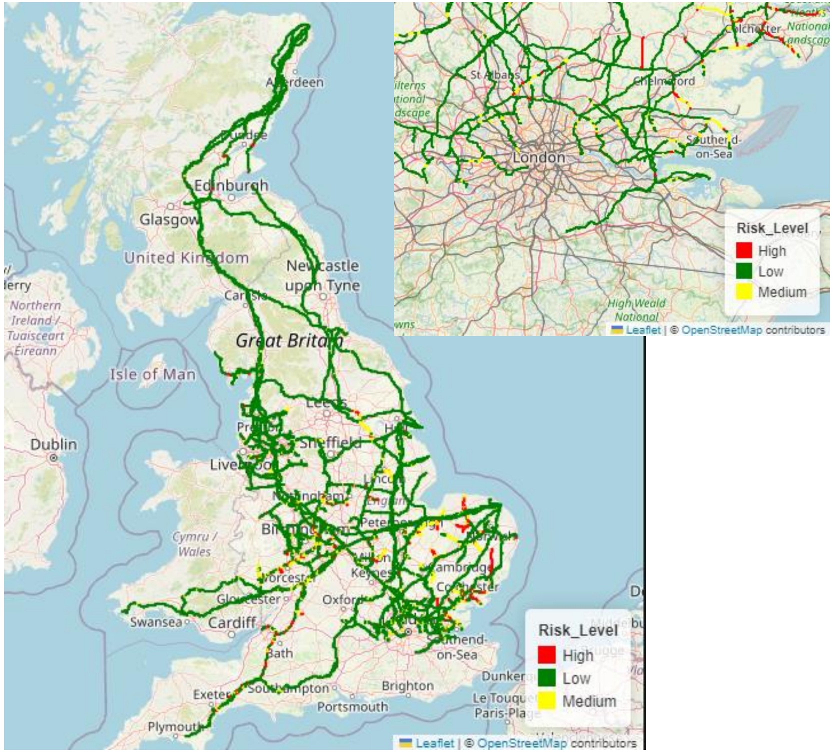
Risk mapping using matrix-based method
May 2020

Risk mapping using FEM
May 2020

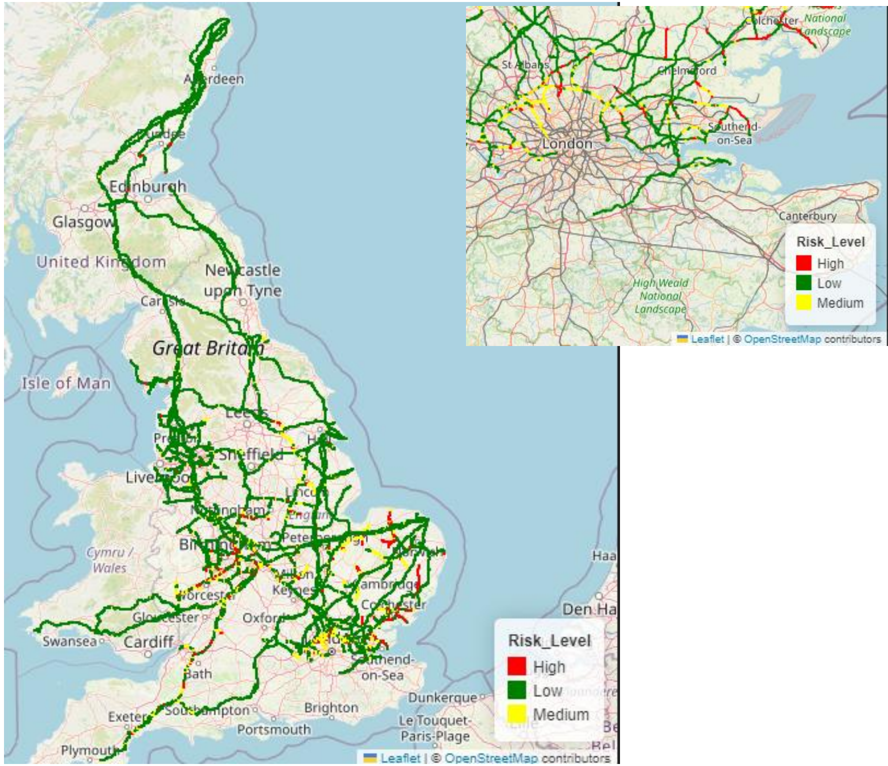


Results: Current vs Future Risk Coding for National Gas Transmission Pipeline

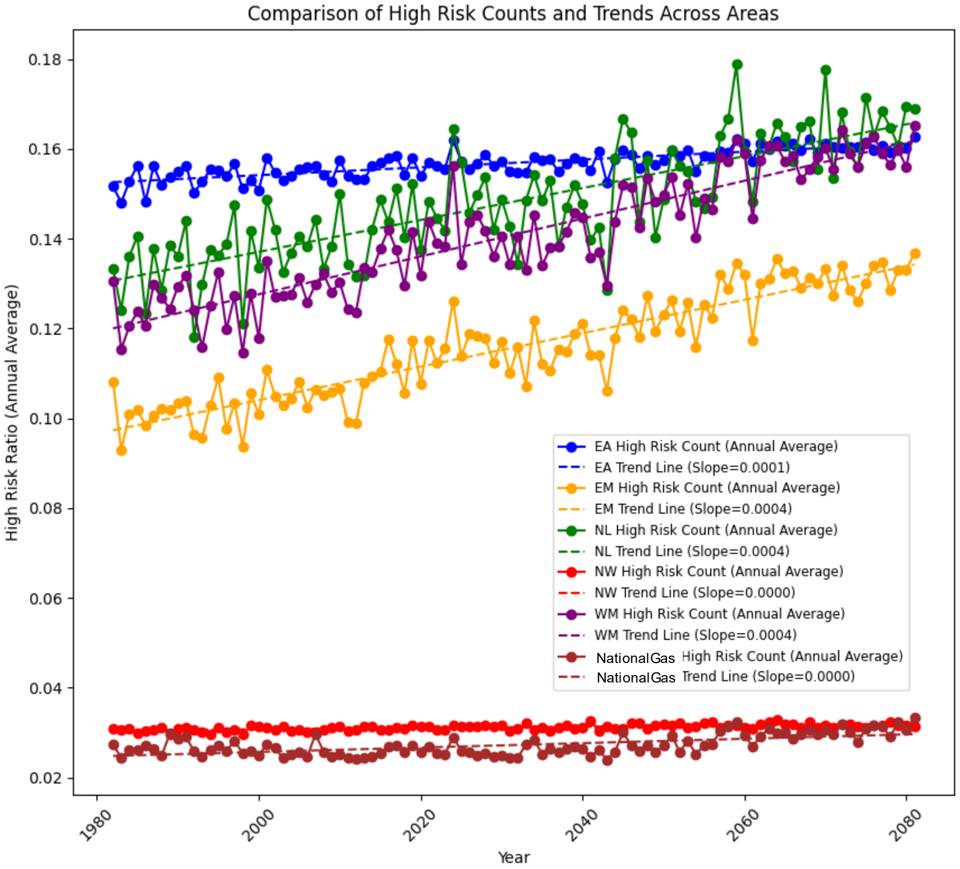
FEM risk model for May 2020



FEM risk model for May 2080



Results: High Risk annual trend through the years



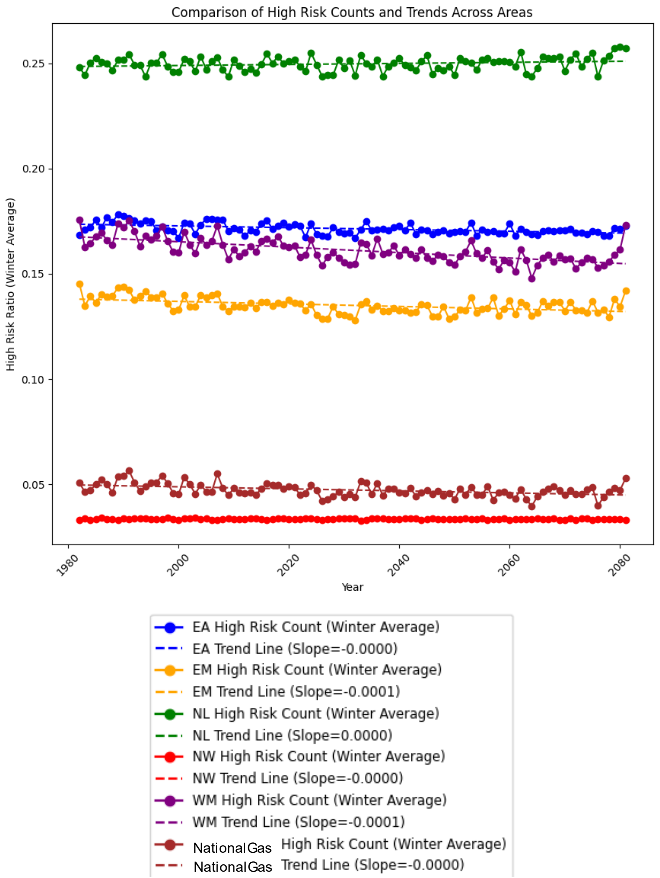
Comparison with Cadent data

Percentage of Pipe Failure according to Cadent per area				
EA	EM	NL	NW	WM
1.68%	1.28%	2.40%	1.01%	1.19%

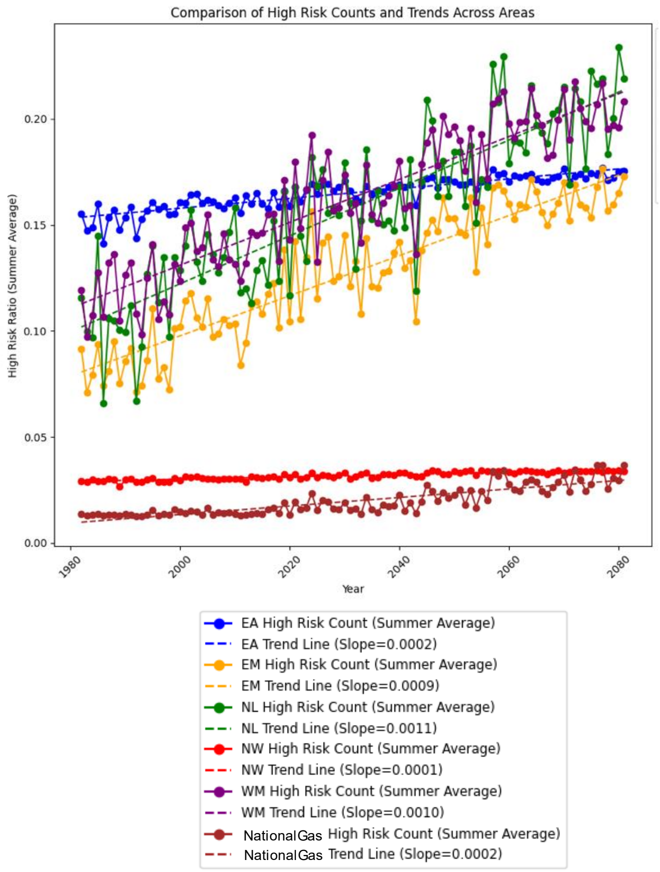
- **High-Risk Regions:** EA and NL areas exhibit the highest predicted risk
- **Low-Risk Regions:** NW and WM regions demonstrate lower risk percentages

Results: High Risk Seasonal trend through the years

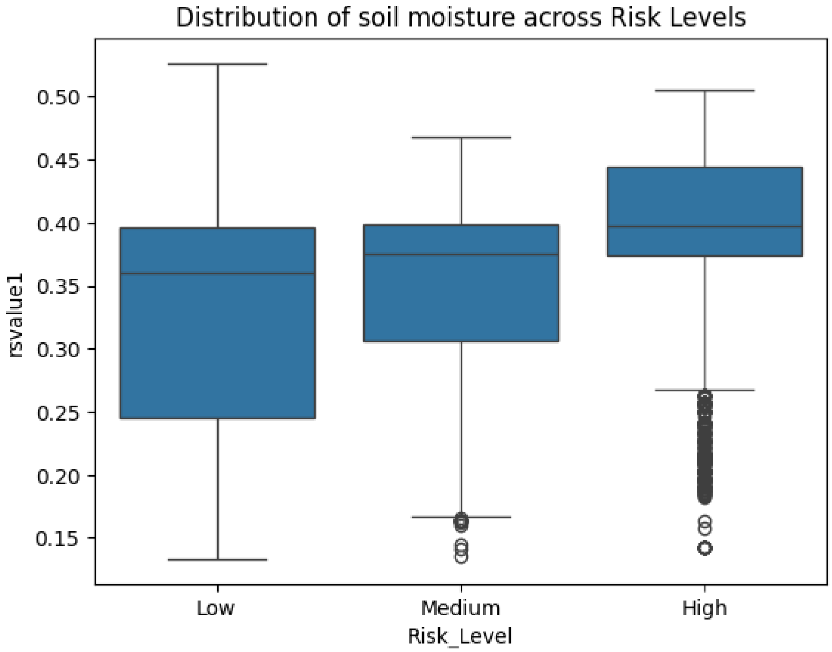
Winter



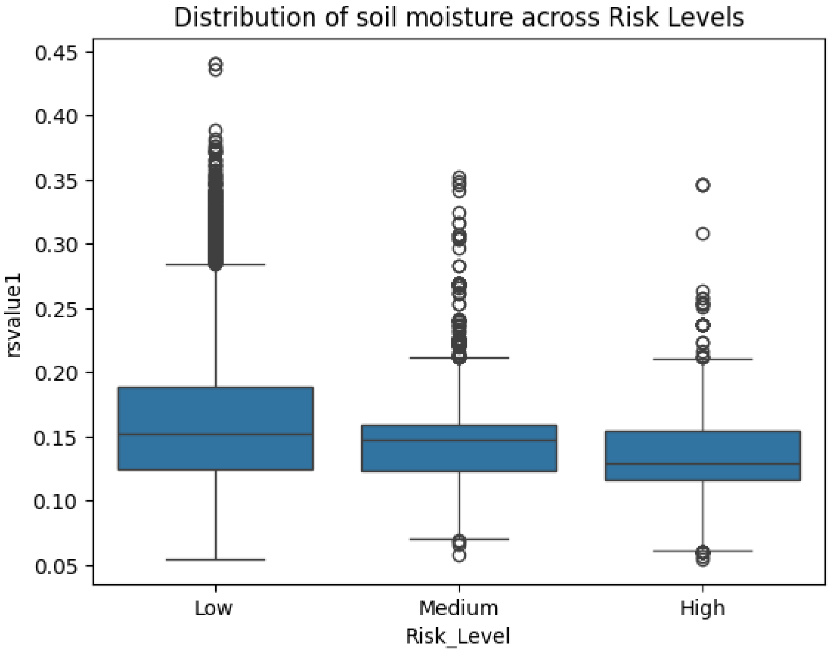
Summer



Results: correlation with soil moisture

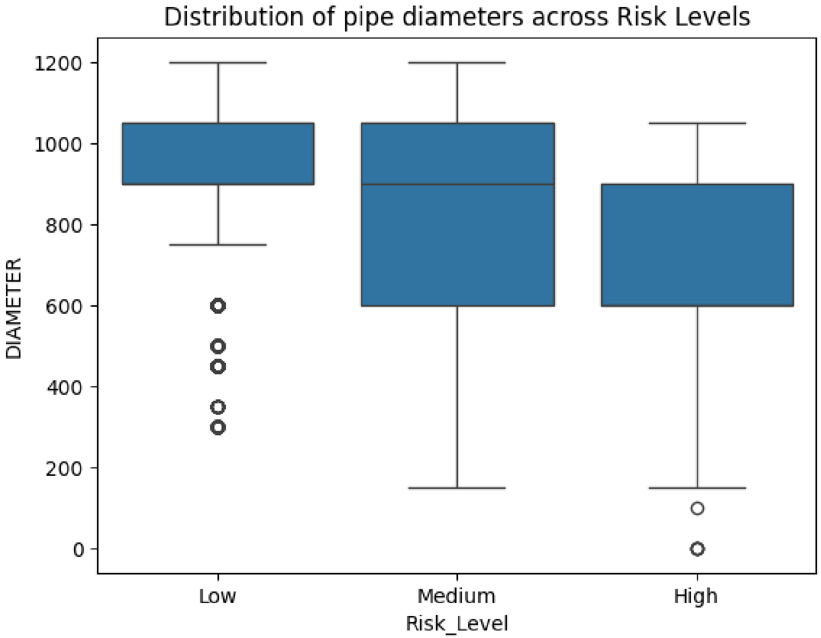


January 2020, *r = 0.2*

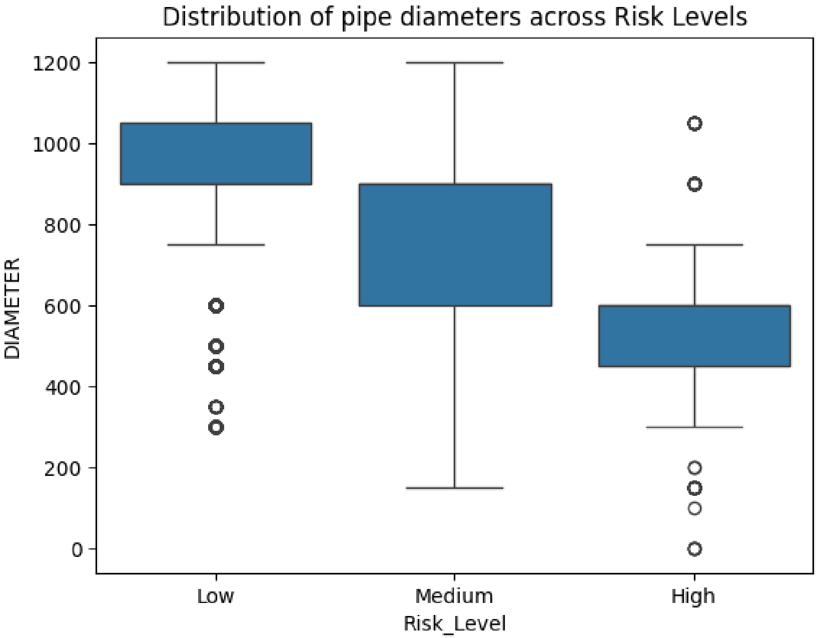


July 2020, *r = - 0.16*

Results: correlation with pipe diameter



January 2020, *r = - 0.21*

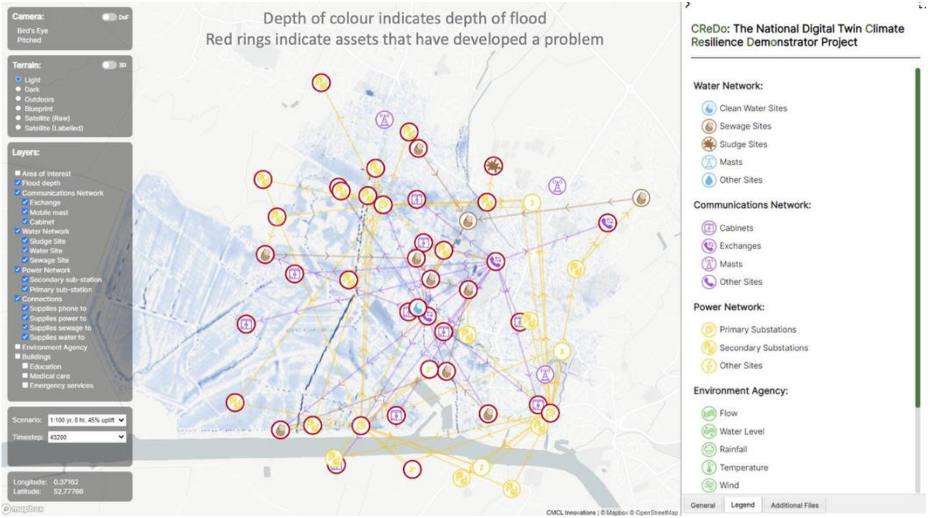


July 2020, *r = - 0.22*

DAFNI platform

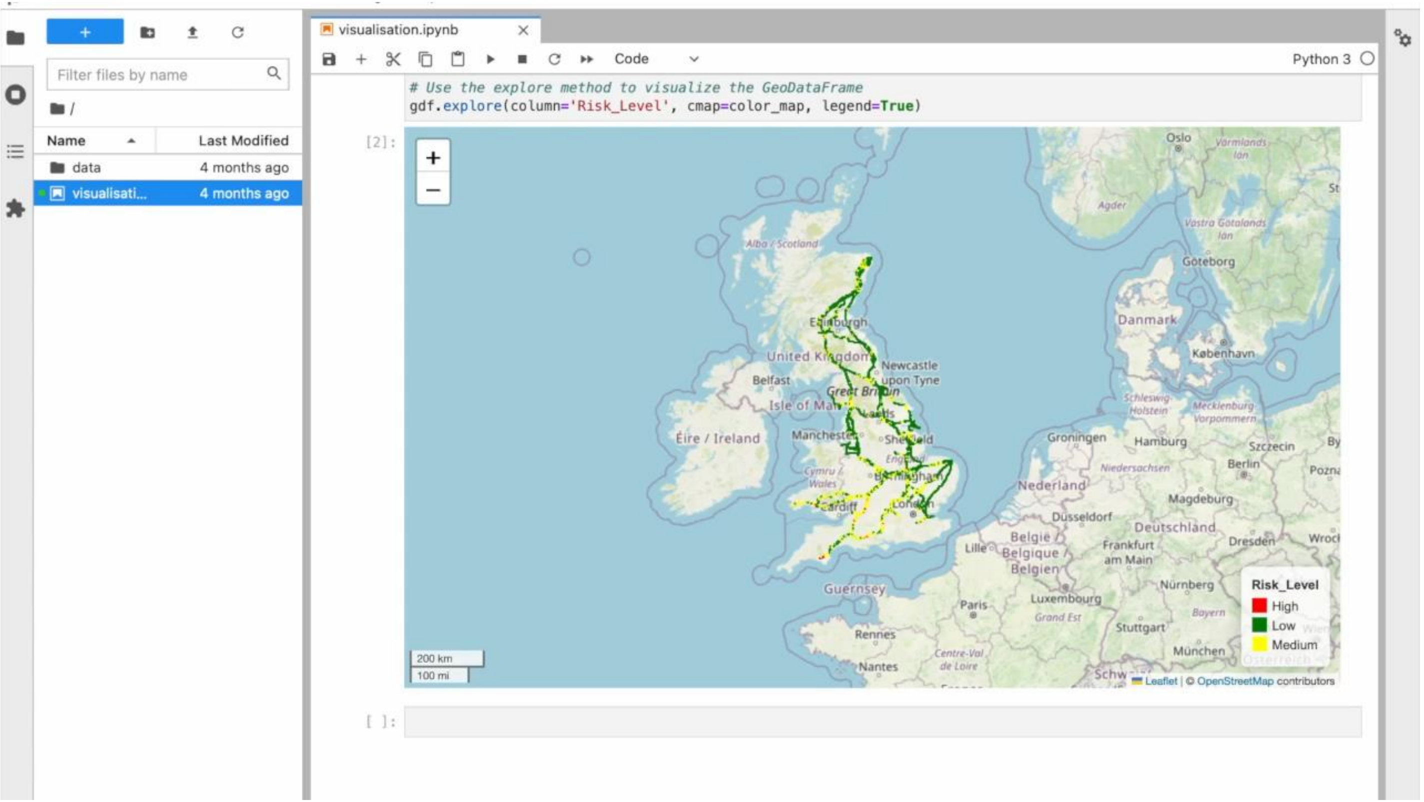
Data & Analytics Facility for National Infrastructure

- Data & Analytics Facility for National Infrastructure
- £8 million investment from the UK Collaboratorium for Research on Infrastructure and Cities (UKCRIC)
- Implemented and managed by the Science and Technology Facilities Council (STFC)
- Better sharing and use of data
- Exploitation of simulation and optimisation techniques
- Engagement with stakeholders through visualisation



Source: CReDo project report

Visualisation on DAFNI



Outcomes from the project

- Framework for quantifying climate change risk to buried infrastructure at UK national scale
  - New models (pipe damage assessment, hydrodynamic model for surface erosion)
  - New datasets (extreme rainfall events, soil moisture estimates)
- Quantitative risk assessment for gas networks
- Better understanding of the opportunities and barriers for cross-organisational data integration

Benefits, challenges and next steps

- Benefits – helping adapt to Climate Change and increase resilience
  - Understand network-wide and national-scale climate risk comprehensively, and inform national guidance, e.g., **CCRA**
  - Test different scenarios of adaptation measures (benefit of being a process-based model)
- Challenges
  - Uncertainty (i.e., attribution of pipe failure)
  - Data unavailable or non-existent
- Potential next steps
  - Explore linkage with other data portals, e.g., JASMIN and NUAR
  - Trial and adoption by industry
  - Consider interdependencies (energy/water/transport)
  - Further improve modelling methods

Thank you!

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