UK Centre for Ecology & Hydrology

Probabilistic impact-based approaches for flood forecasting and prediction

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Modelling Hydrology, Climate and Land Surface Processes
Lillehammer, Norway
19 September 2023

Overview

- International frameworks for calculating Disaster Risk
- Global and UK context for flood risk trends and climate change
  - Third UK Climate Change Risk Assessment (2022)
  - Emerging mapping methods for calculating flood risk
- Recent developments in UK Flood Risk Management and Forecasting
- Probabilistic and Ensemble Flood Forecasting
- Impact-based Forecasting

The Sendai Framework

The expected outcome of the United Nations Sendai Framework for Disaster Risk Reduction (2015-30) is:

> *The substantial **reduction of disaster risk and losses** in lives, livelihoods and health and in the economic, physical, social, cultural and environmental assets of persons, businesses, communities and countries*

United Nations Office for Disaster Risk Reduction (UNDRR)
www.undrr.org

Sendai Priority 1: Understanding Disaster Risk

Priority 1 of the Sendai Framework is Understanding Disaster Risk, which advocates member states to:

*Develop and apply methodologies and **models** to assess **disaster risks**, **vulnerabilities** and **exposure** to all **hazards***

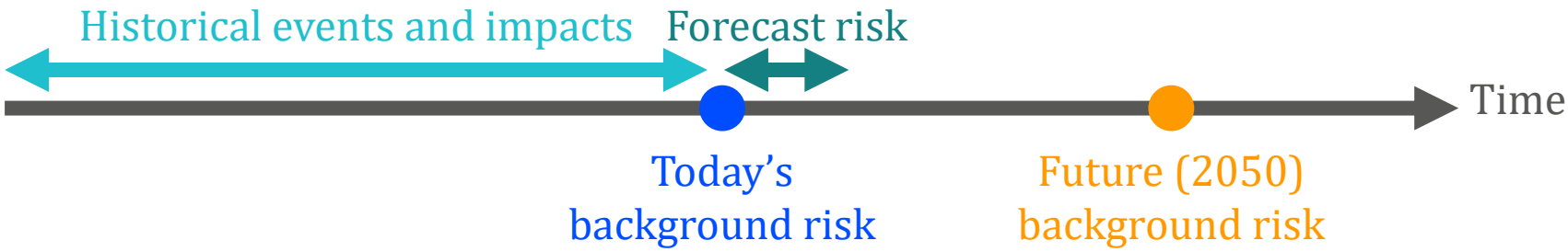
Need for Hazard <u>Impact</u> Modelling

Disaster risk can change with time

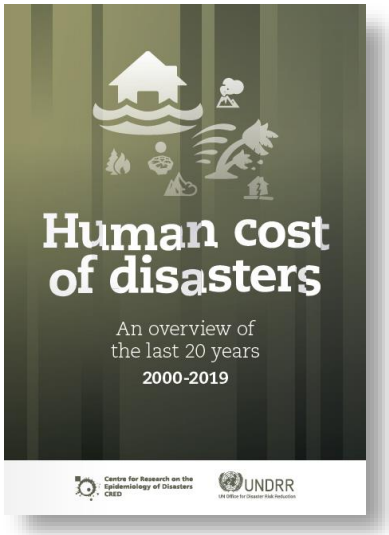
Examples of different time frames

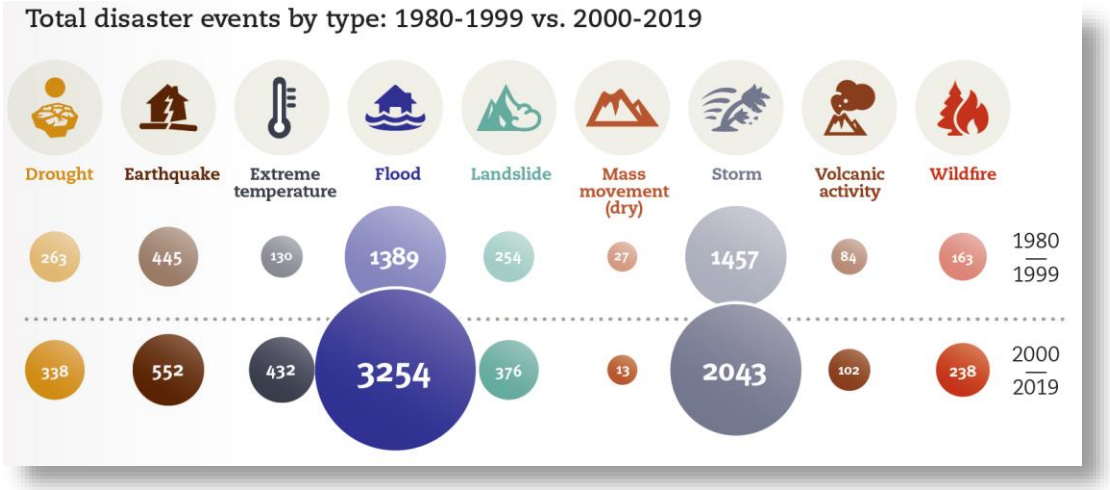
- Current background risk (e.g. average annual flood damage)
- Future background risk (e.g. expected annual flood damage in 2050)
- Forecast risk over the next few days/weeks/months (e.g. expected impacts)

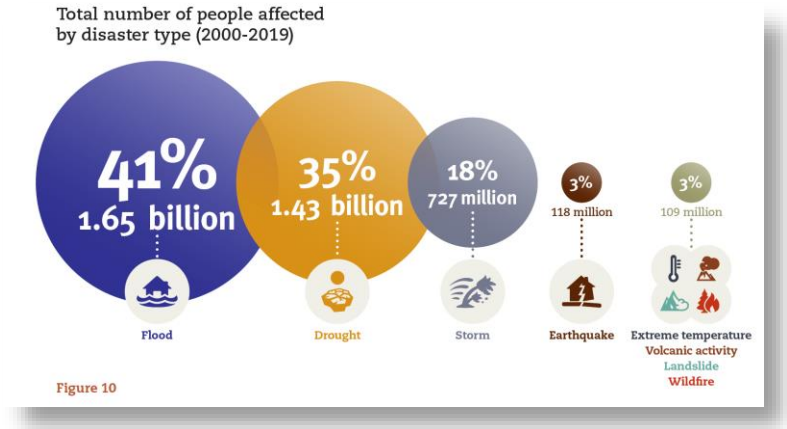
Historical events and impacts provides useful context



Flood Risk: Global Context



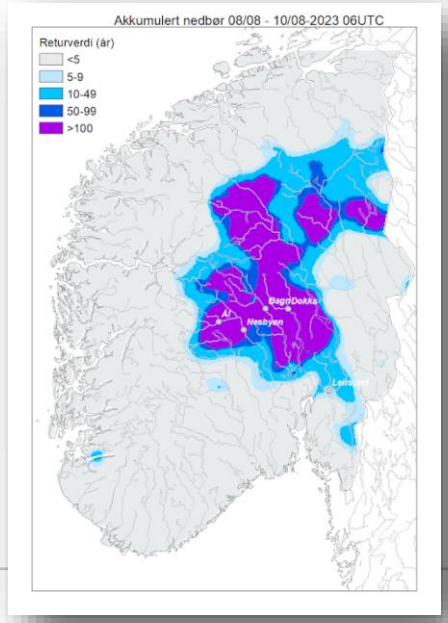




- Number of major floods in last 20 years (3,254) more than double previous 20 years (1,389)
- Floods affect more people globally than any other hazard
- 22% of disaster losses over 2000-19 were due to flooding ($651 billion)

Flood Risk: Recent Floods (2021-23)

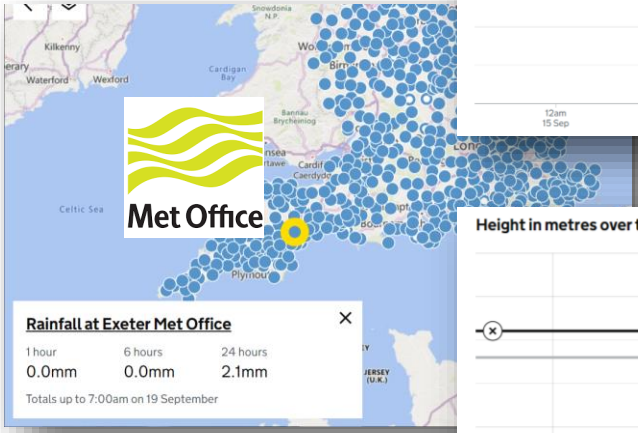
- Major floods in all continents, reminder why flood risk management needed
- 2021 European summer floods >10 inches in 48 hours, ~250 people died
- 2022 Pakistan flood: 33 million people affected, 1,739 deaths
- Norway, Storm “Hans”. Record widespread rainfall. Floods and landslides. NOK 1.8 b insurance estimate.

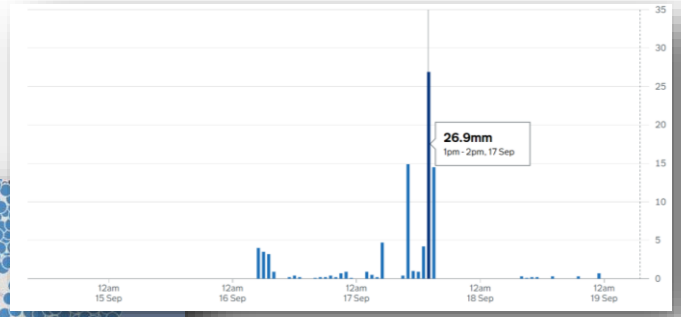


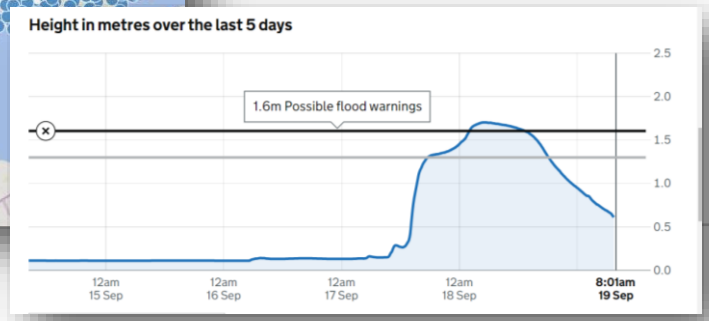
> 100 year return period rain

Flood Risk: Recent UK Floods

- Storm Franklin Feb 2022. Last of 3 named storms in 1 week. 24h Rainfall >120mm, 400 properties flooded, 40,000 protected. Wind and floods.
- UK, Exeter Met Office, **Sunday**! Localised rainfall, 37mm in 1h, 69mm in 24h. Airport closed, streets flooded.
  Rapid surface flooding.







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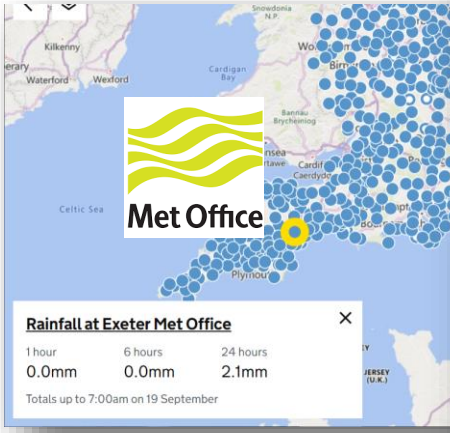

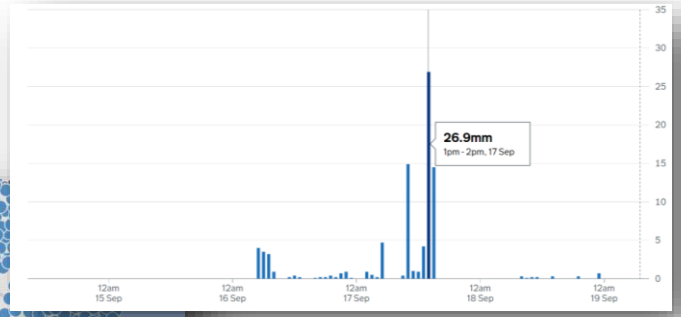

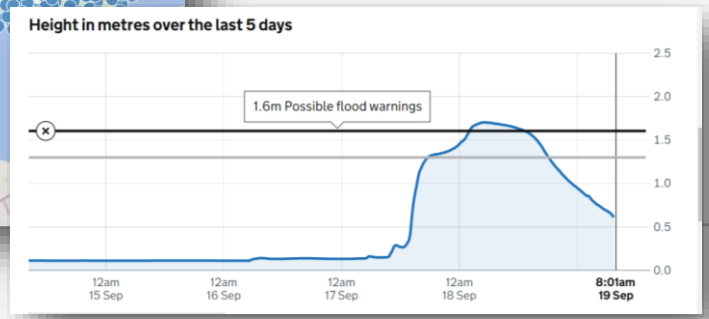

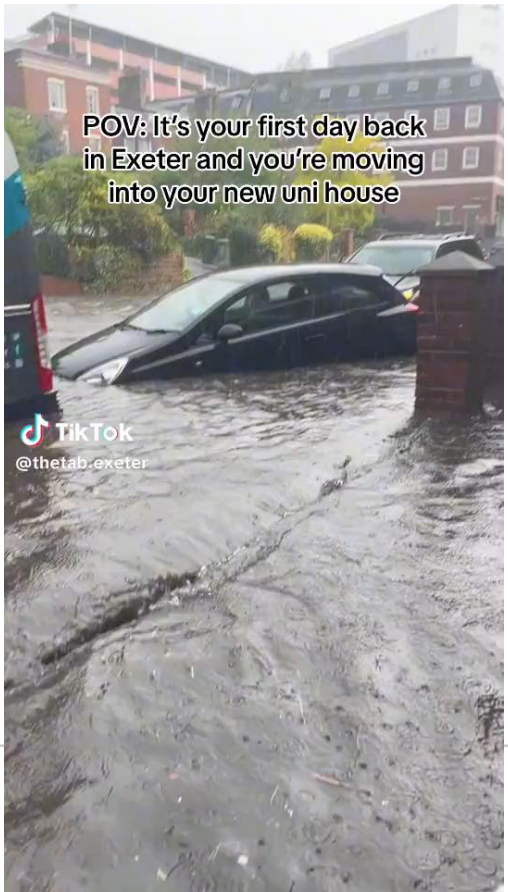

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Climate change

Climate Change: UK Context

- UK Climate Change Risk Assessment 3 (CCRA3) in 2022 supported by a technical report, advice report and detailed research and analysis reports
- National summaries and Sector Briefings also provided
- Example from flood study:

*"... unless we take further action, under a **2°C** by 2100 warming scenario annual damages **from flooding** for non-residential properties across the UK is expected to increase by **27% by 2050** and **40% by 2080**. At **4°C** this increases to **44%** and **75%** respectively."*

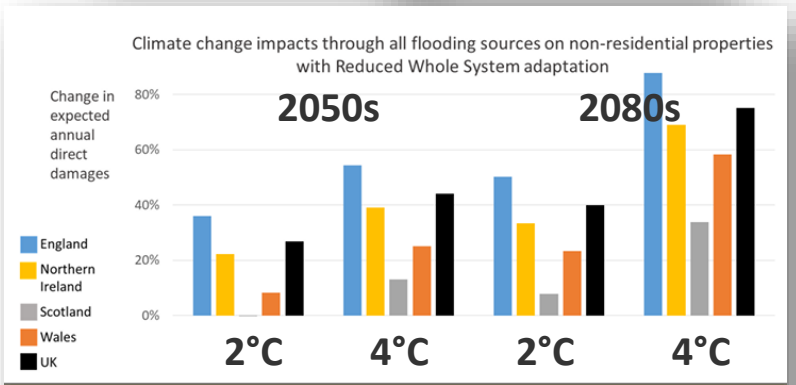
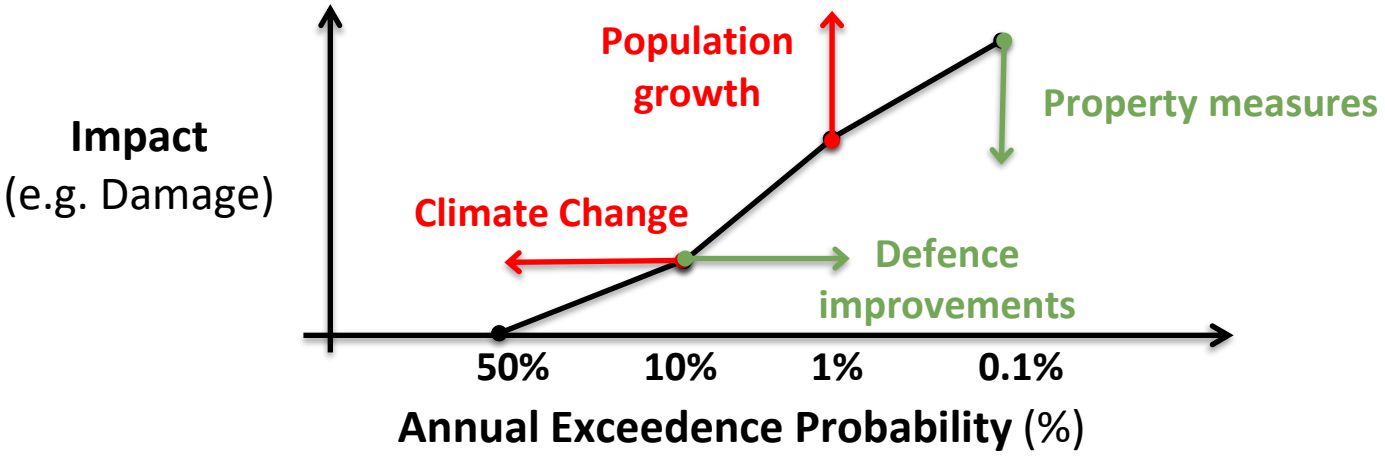


Figure 6.4 Percentage change in expected annual direct damages to non-residential properties from all sources of flooding for scenarios of global warming reaching 2°C and 4°C in 2100. Source: Sayers *et al.* (2020)

Climate Change: UK Context

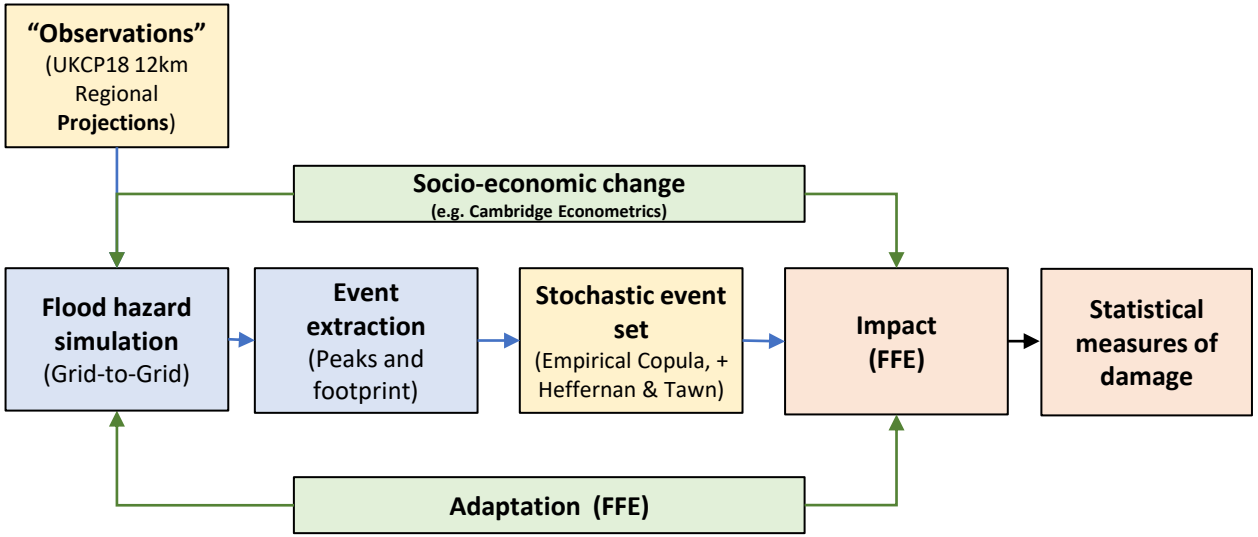
- CCRA3 method for flood risk estimation is the Future Flood Explorer - FFE
- Splits country up into ~840,000 Census Calculation Areas (CCAs)
- Derives Impact Curves for CCAs for a range of flood types and impacts
- Modifies Impact Curves to take account of climate & population changes, and adaptation strategies (e.g. current standard of protection, more or less)



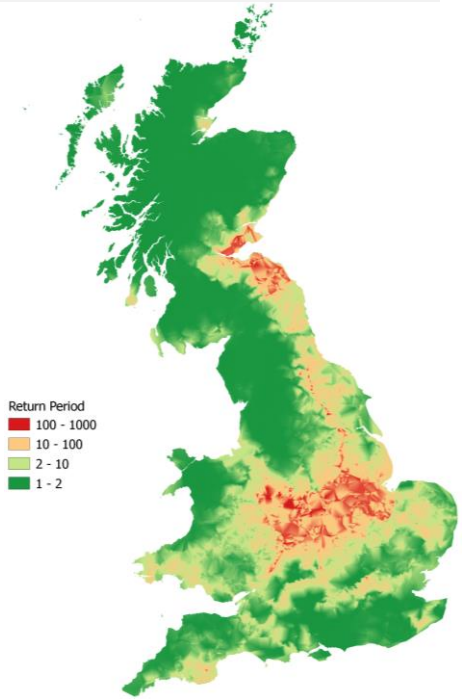
Climate Change: emerging methods

AquaCAT: Event-based climate risk assessment using UKCP18 data

Generate **spatially consistent** flood events for historical (1980-2010) and future (2050-80) time slices (100,000s of events!)



Example event with 20 year damage return period



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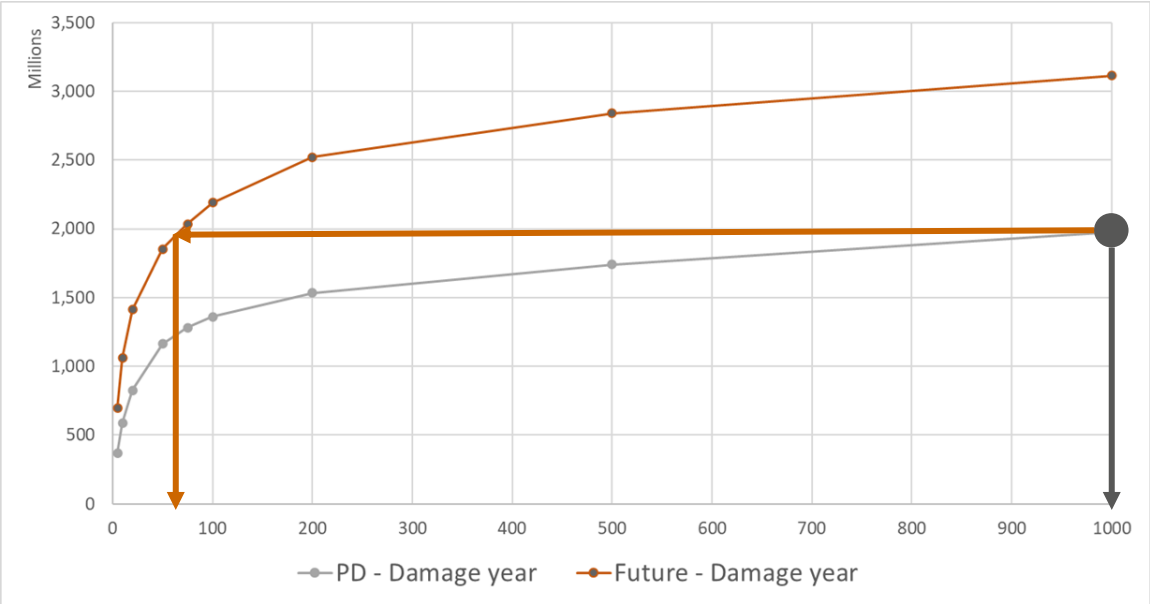
Generate **spatially consistent** flood events for historical (1980-2010) and future (2050-80) time slices (100,000s of events!)

Calculate impact and damage for each event. Assess how the **frequency** and **severity** of damage may change in the future.



A £2 billion flood event has a return period of 1000 years in current climate

In the future climate (2050-80) this has a return period of ~75 years!

Flood Forecasting

Move to Flood Risk Management

- UK (and many other countries) have moved from Flood Defence policies towards Flood Risk Management
  - Requires risk-based decision making

- Summer 2007 Floods and Pitt Review by UK Government
  - £3 Billion in insurance payouts
  - National-scale flood forecasting required

- National Flood Resilience Review (2016)
  - Further exploit probabilistic rainfall and flood forecasts
  - Improve flood risk communication

Flood forecasting Model Chain

Inputs

Flood models

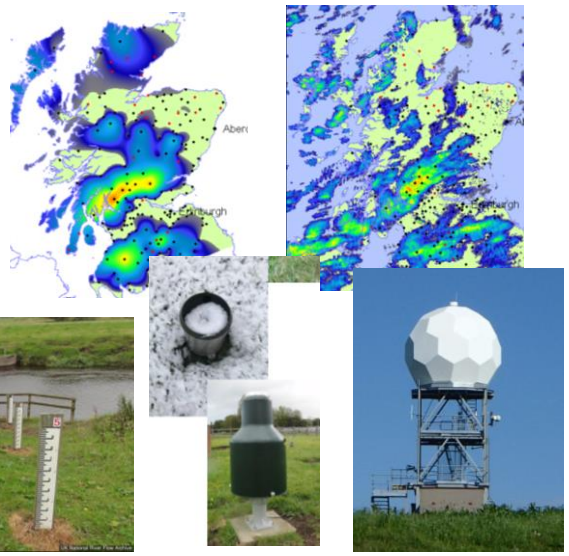
Outputs

Observation-based

Precipitation

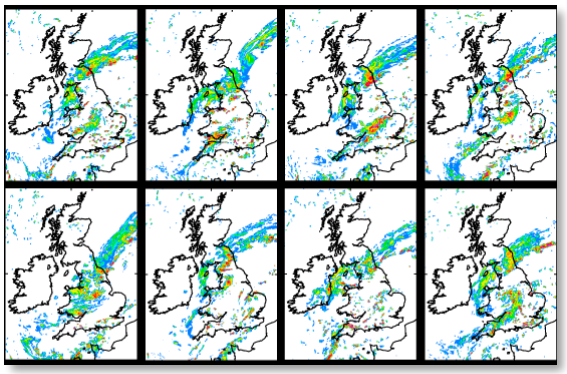
River Flows

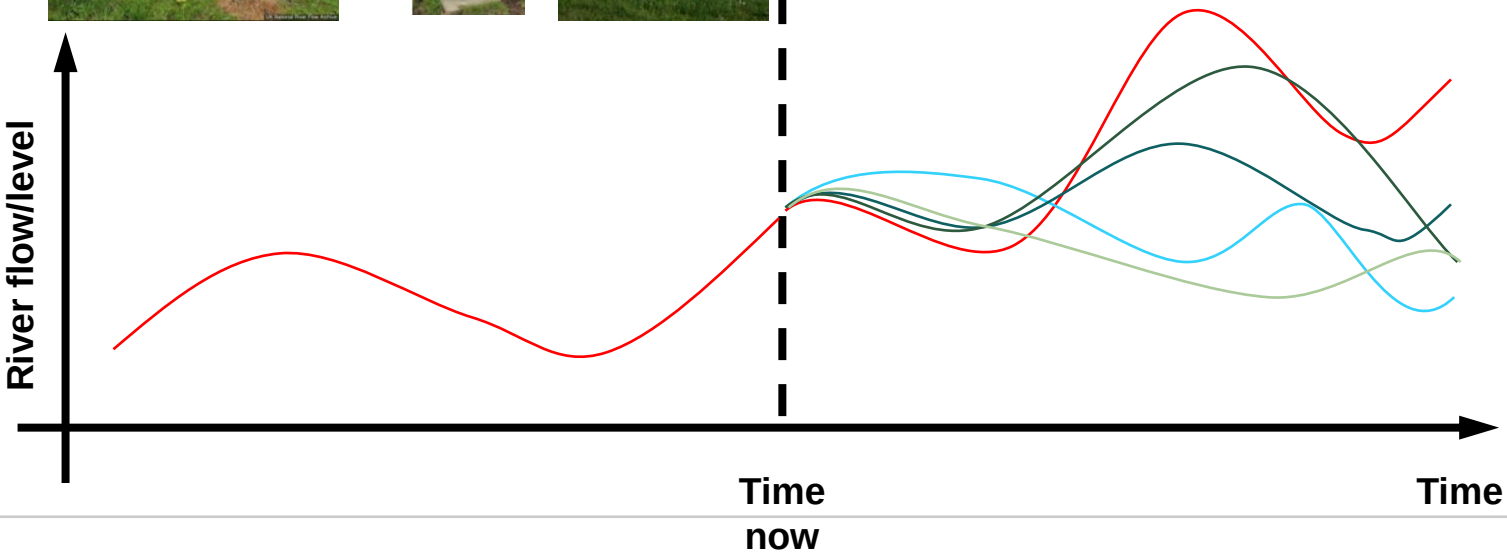
Potential Evaporation



Numerical Weather Prediction (NWP)

Deterministic and Ensemble





Benefits of probabilistic forecasting

- Even if forecast uncertainty has been reduced (e.g. high resolution NWP), uncertainty still remains and probabilistic forecasting is still required

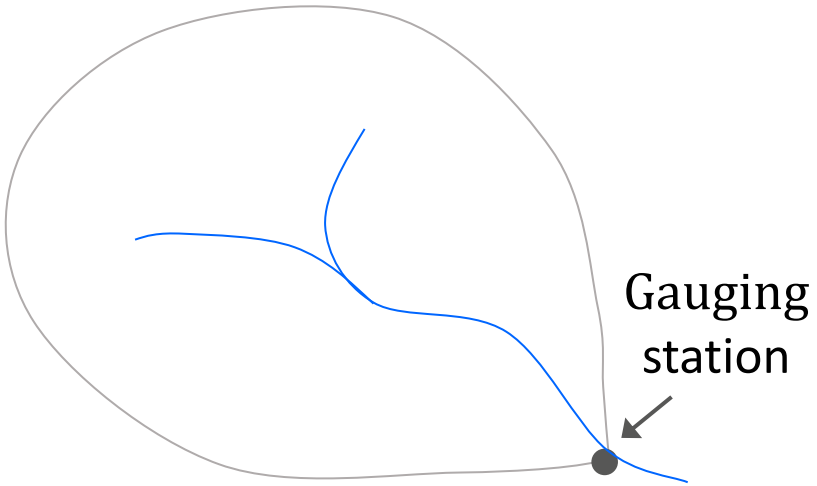
- Four potential benefits are
  - Scientifically more honest can express degree of uncertainty/certainty
  - Support risk-based forecasting and warning
  - Enable rational decision-making where users include uncertainty
  - Potential for economic benefits based on improved decision-making

- A truly probabilistic forecast system should quantify the *total uncertainty* in the forecast including *all sources.* Ensemble flood forecasts normally only account for the dominant source of uncertainty from NWP precipitation!

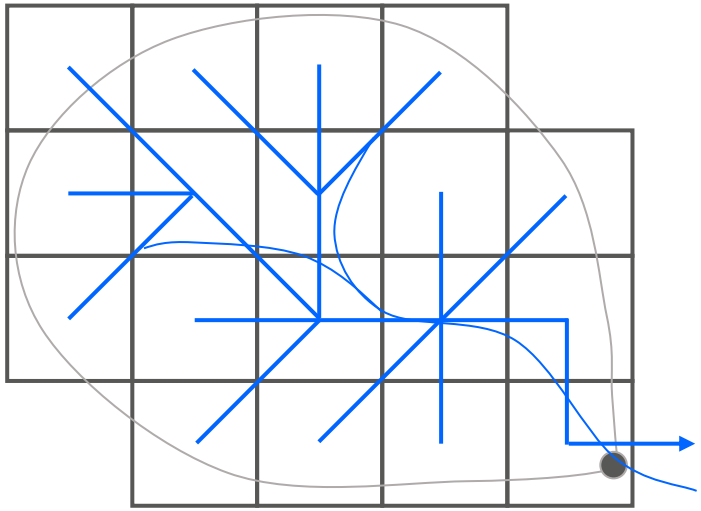
Krzysztofowicz (2001), Journal of Hydrology

Distributed hydrological modelling

Lumped Model
Traditional approach



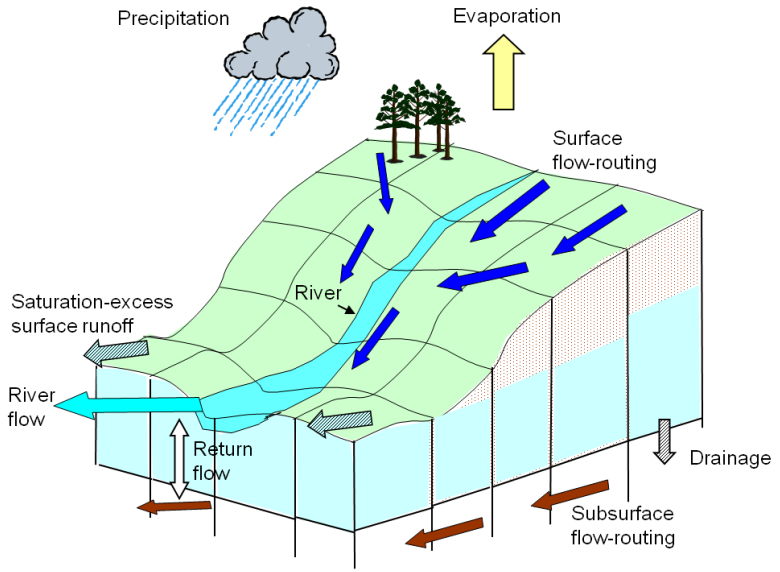
Distributed Model
Recent development

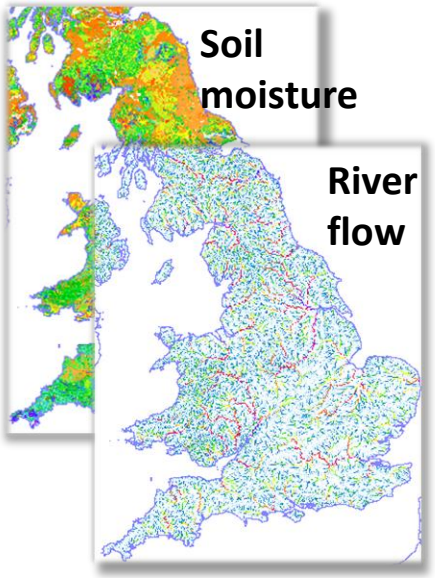


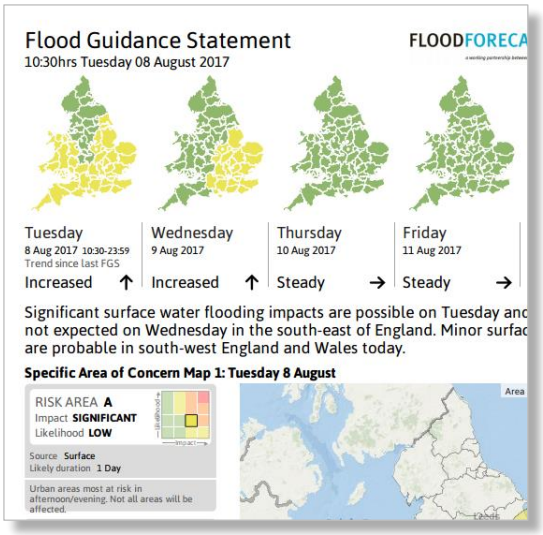
- One model for each gauging station ⟺ One model for large regions (UK)
- Many calibrated parameters ⟺ Few parameters, use spatial datasets
- Flow estimates for one location only ⟺ Flow estimates in each grid (1km^2)
- Uses catchment average rainfall ⟺ Uses gridded rainfall estimates

Potential for ungauged sites – national forecasting everywhere!

UKCEH Grid-to-Grid (G2G) Model







FLOODFORECASTINGCENTRE
a working partnership between Environment Agency | Met Office

Met Office | SEPA Scottish Environment Protection Agency | Scottish Flood Forecasting Service
Working in partnership

- G2G used for 24/7 Flood Forecasting across Britain at a 1km, 15 min resolution
- Uses spatial datasets on terrain, soil/geology, land-cover
- Responds to spatial variation of rainfall input
- Probabilistic forecasts inform Flood Guidance Statements

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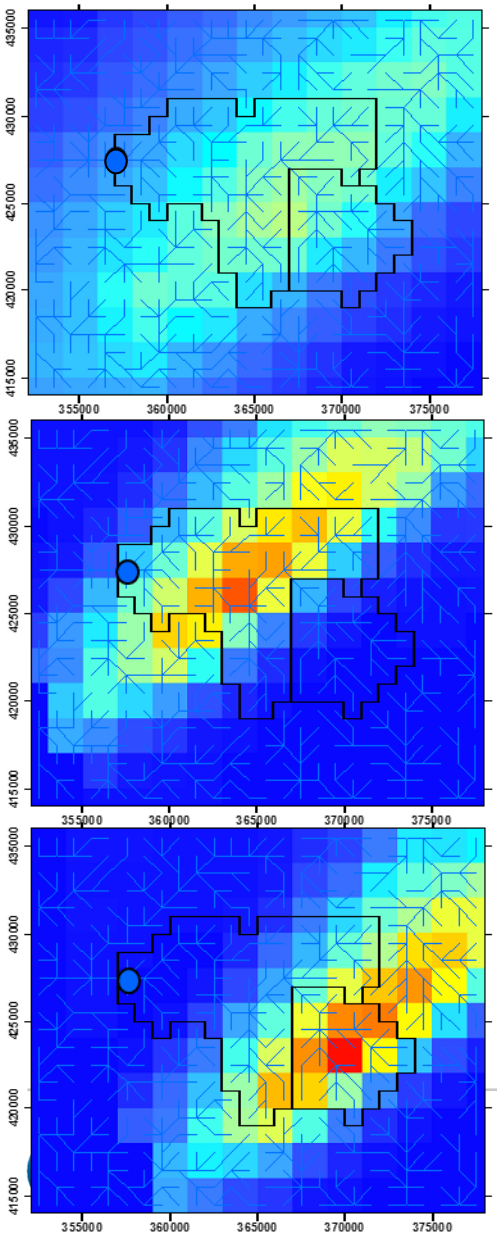
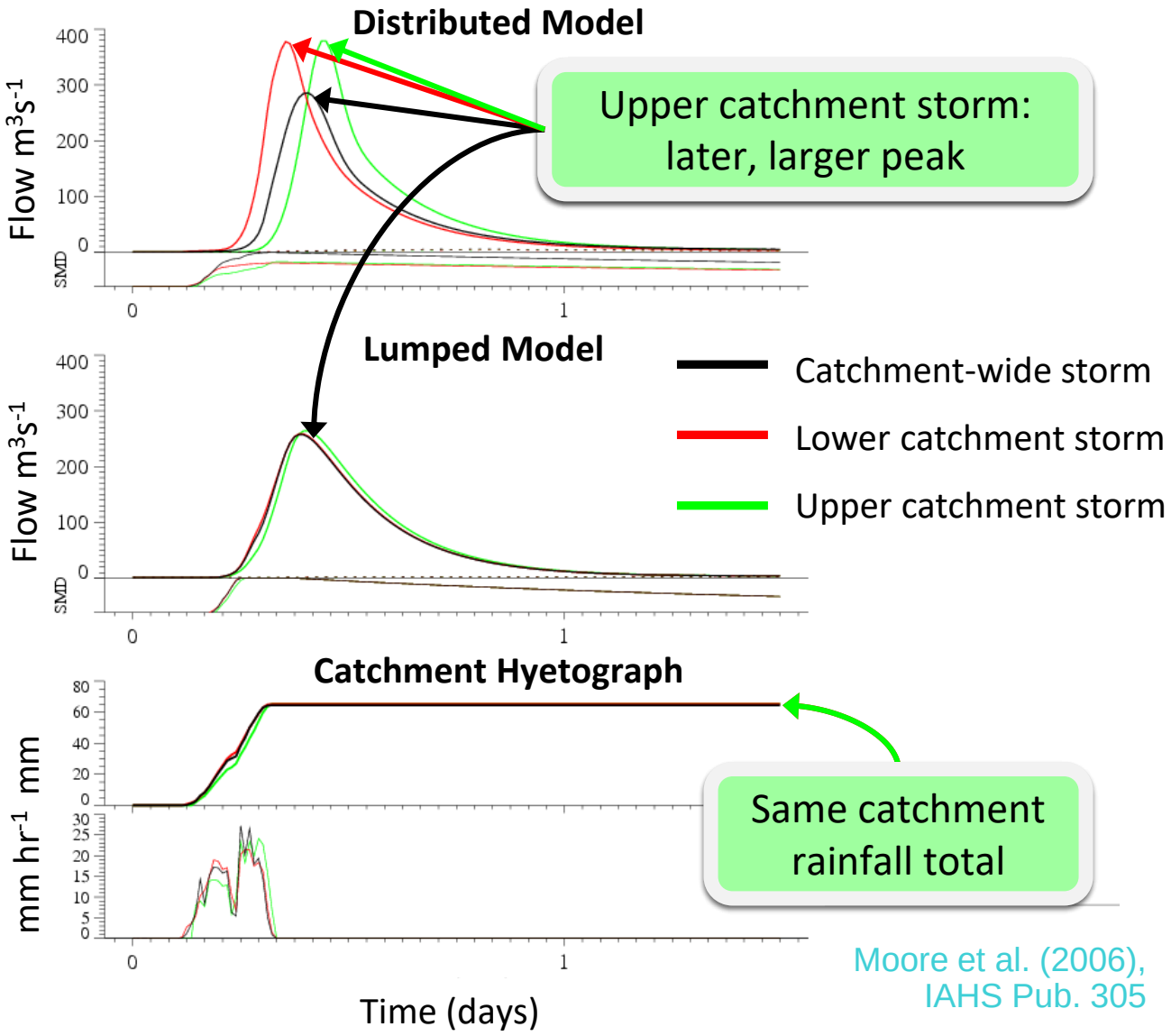
Price et al.; Cranston & Tavendale, Water Management (2012)
Moore et al., IAHS Publ. 305 (2006)

Extreme flood response

Storm rainfall total



Impact of spatial extent and location of storm on flood response?



Moore et al. (2006), IAHS Pub. 305

Rapid Response Catchments

- Rapid Response Catchments are typically small & ungauged
- Challenge to develop forecast/warning capability
- Needs rainfall forecast ensembles (~2km, 24h, 12 members)
- Case study experience (6-7 July 2012)

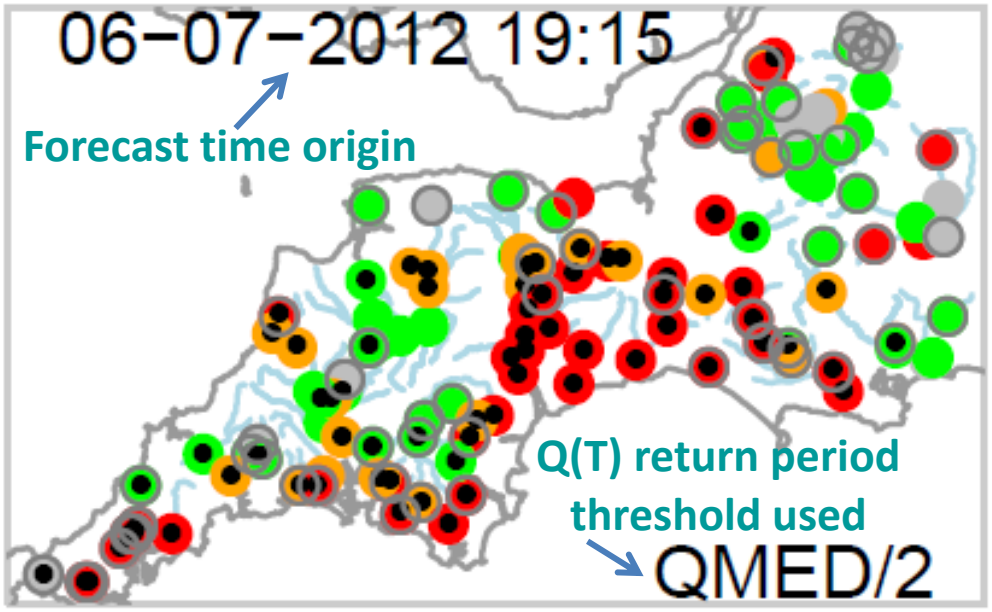
Met Office

Circles denote gauging stations

- Solid outline: area <50km^2
- Observed flow exceeds threshold during forecast

Percentage of ensembles that exceeded the Q(T) threshold at some point during forecast

0 | 0-33% | 34-66% | >67%



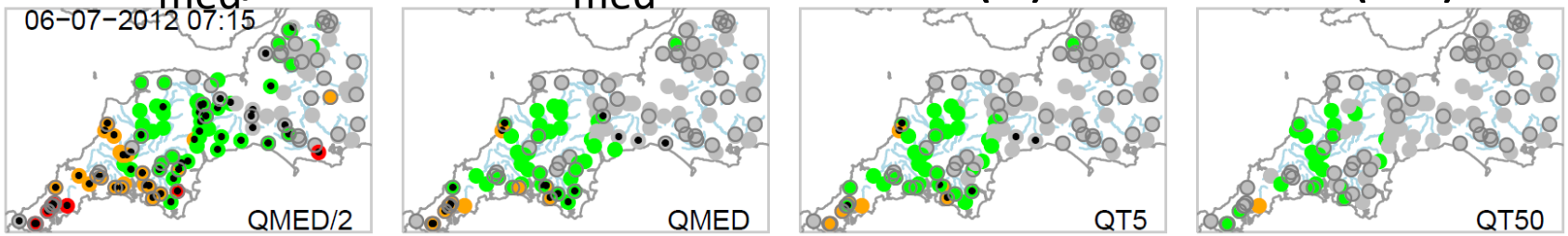
Case study: 6-7 July 2012

Threshold

Forecast Origin

06-07-2012 07:15

$Q_{med}/2$ | Q_{med} | Q(5) | Q(50)



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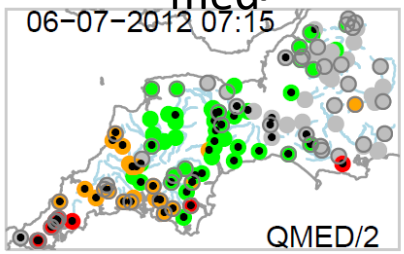
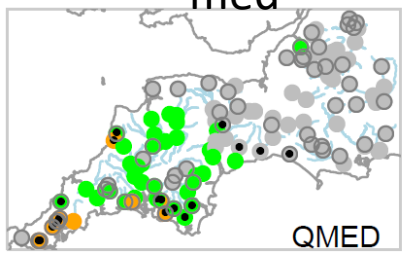
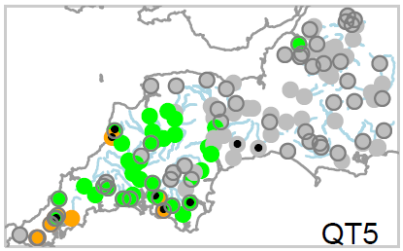
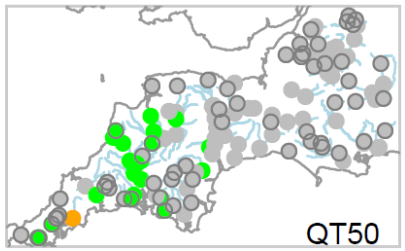
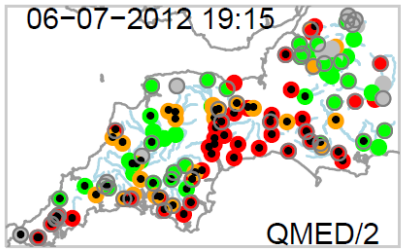
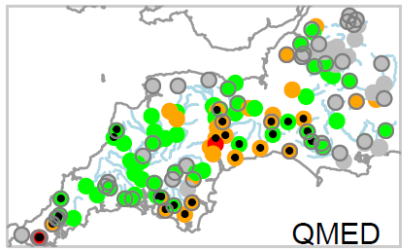
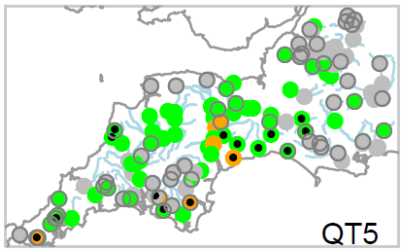
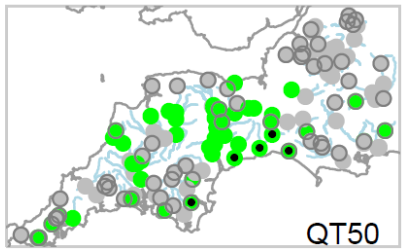
06-07-2012 07:15				
06-07-2012 19:15				

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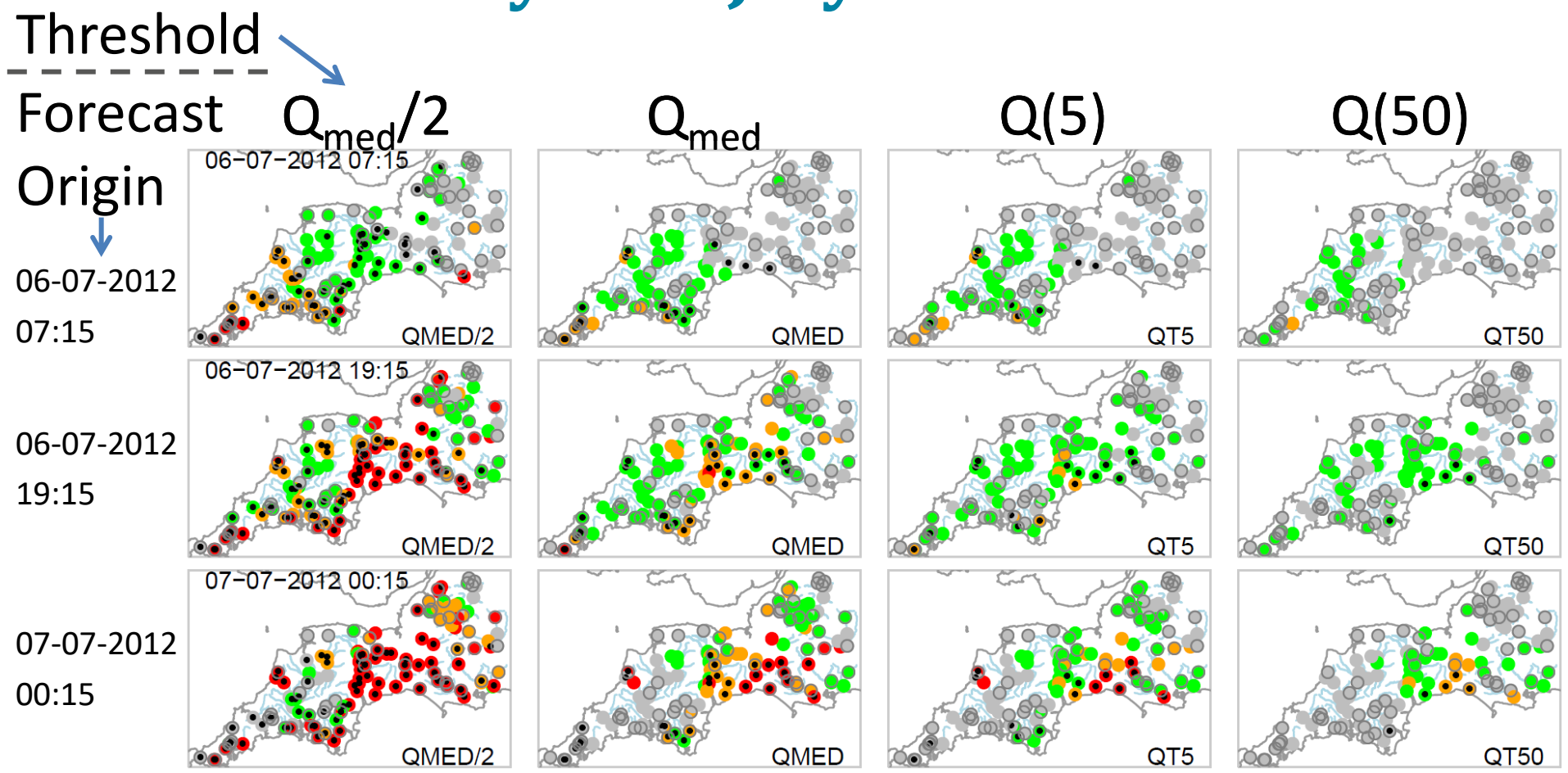

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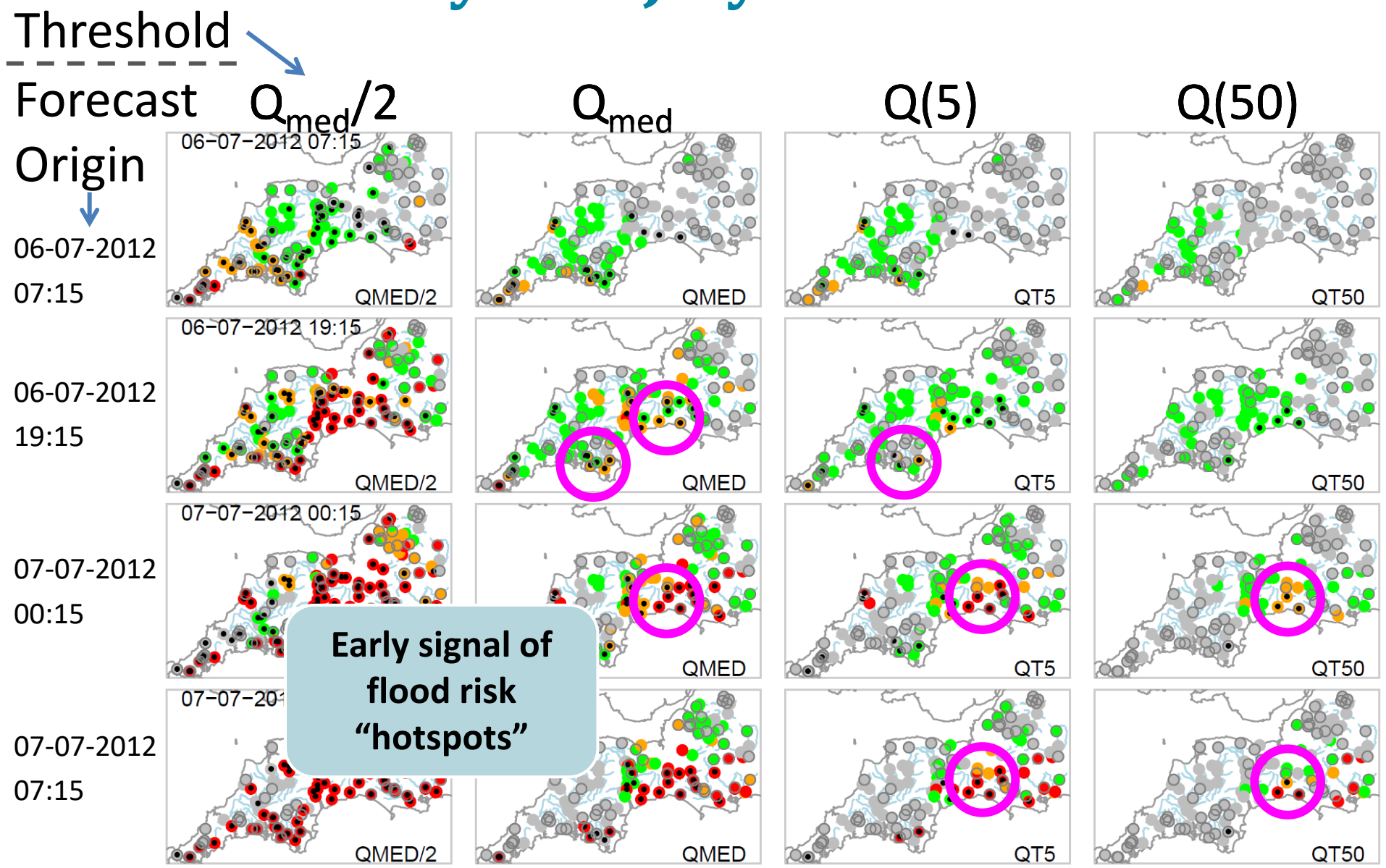


Real-world example, SEPA – Nov 2022

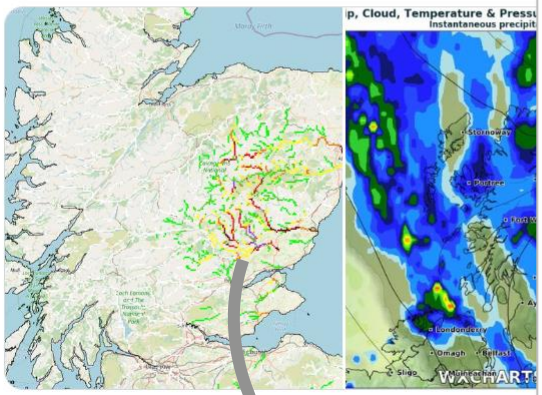
G2G Probabilistic Flood Forecasts

Public Flood Forecasts/Guidance

Triggered satellites to capture impact

⚠️ Potential for 100mm of rain across parts of east Scotland in the next 24 hours. Our hydrological forecasts showing strong response with significant flooding likely across the Grampian and Ang

Check the Scottish flood forecast 👉
scottishfloodforecast.sepa.org.uk/public



11:15 am · 17 Nov 2022

Michael Cranston @Michaelcranston · 18 Nov 2022

⚠️ The forecast has now been escalated to RED meaning flooding co pose a risk to life and severe disruption to transport.

Check live flood warnings 👉 floodline.sepa.org.uk/floodupdates/

SEPA Scottish Environment Protection Agency
Met Office

Scottish Flood Forecast

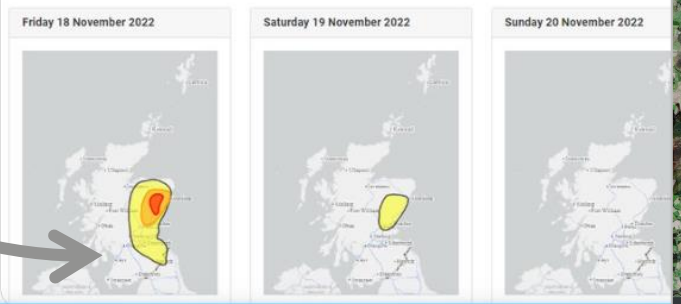
Feedback | Back to SEPA

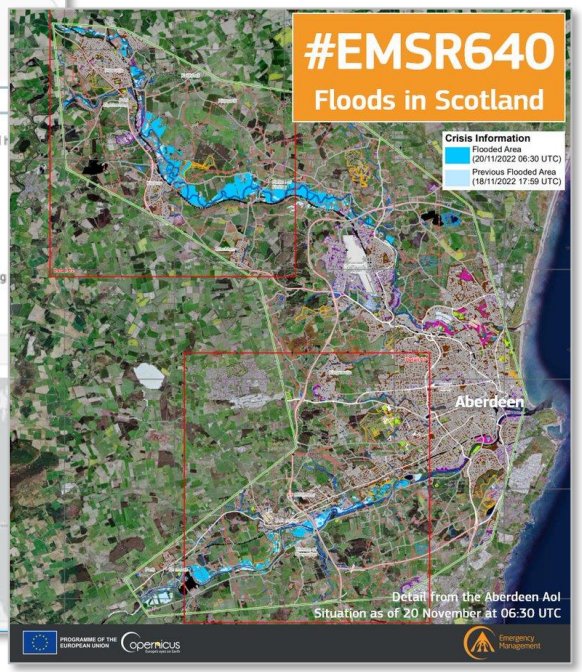
Last updated on 18/11/2022 @ 10:36

This is a BETA service - your feedback will h improve the service.

Summary

Extensive flooding from rivers is expected on Friday in Aberdeenshire and Angus due to very heavy rainfall. Danger to life, widespread property flooding, flooding to roads and disruption to infrastructure is expected, with the severest impacts being area coloured red.





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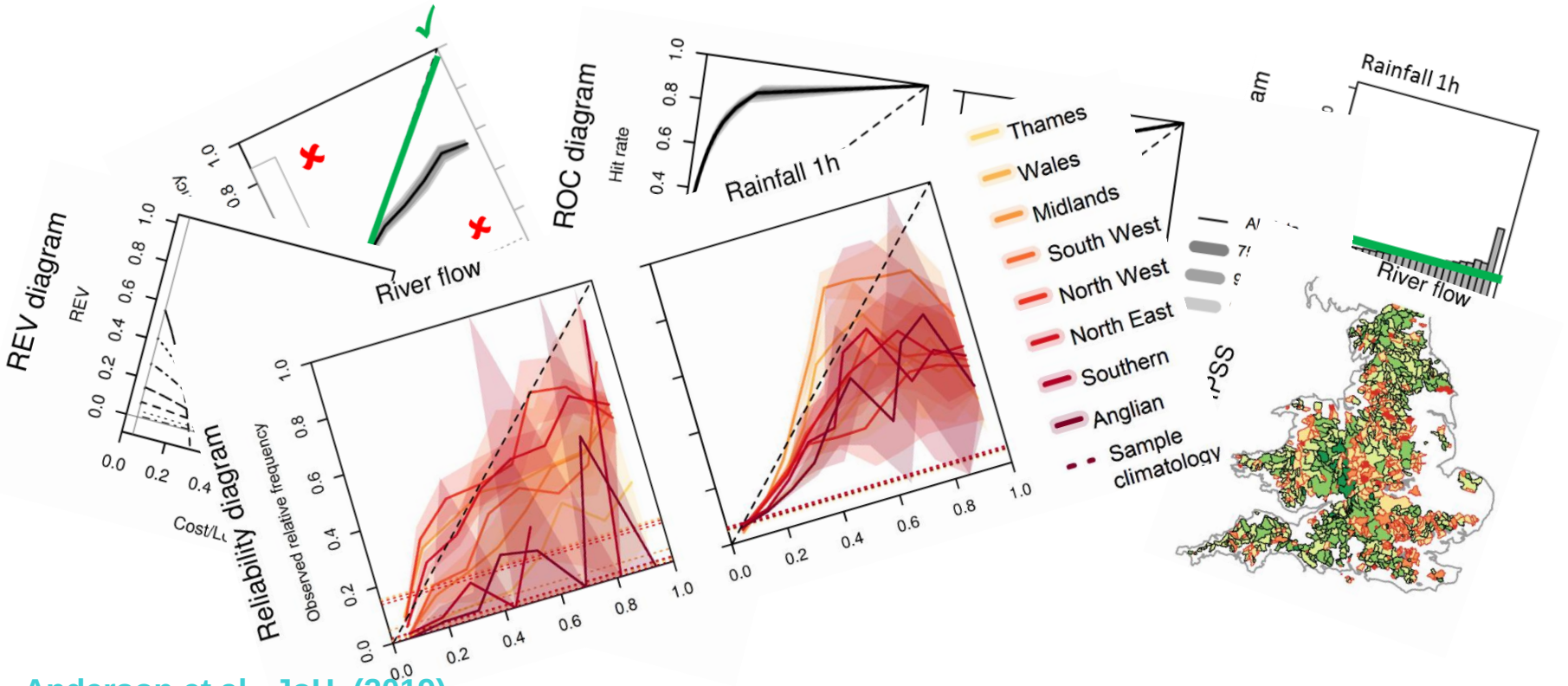
Rainfall & River Flow Ensemble Verification

- Generally accepted that probabilistic rainfall and flood forecasts ar needed BUT…
  - ❖ How well do forecasts perform? (ensemble verification)
  - ❖ How to assess? Metrics, robustness, thresholds,…



Anderson et al., JoH, (2019)

Rainfall & River Flow Ensemble Verification

- Generally accepted that probabilistic rainfall and flood forecasts ar needed BUT…
  - How well do forecasts perform? (ensemble verification)
  - How to assess? Metrics, robustness, thresholds,…

- Key is to be stakeholder and user focused:
  - Flood-producing events of interest
  - What does this mean for *today's* forecast?

- UKCEH/Met-Office project for Flood Forecasting Centre, Scottish Flood Forecasting Service, EA, SEPA, NRW. tinyurl.com/ensver

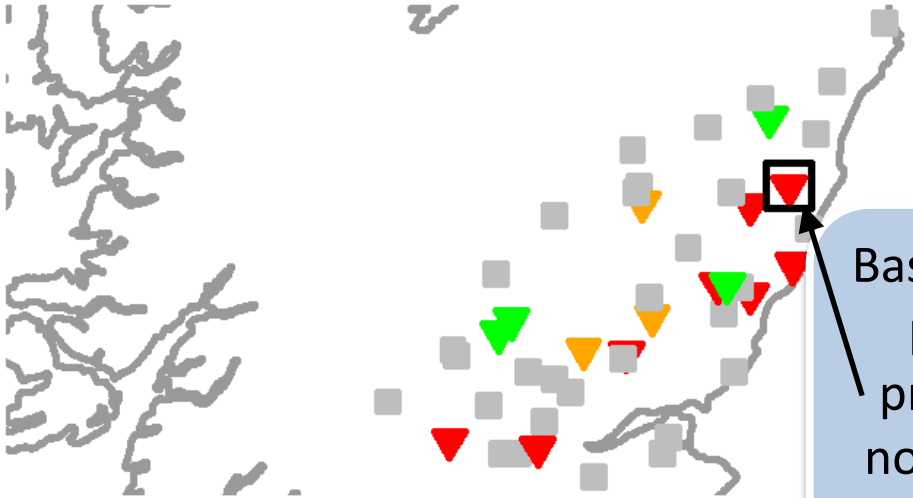
Anderson et al., JoH, (2019)

Rainfall & River Flow Ensemble Verification

What does this mean for today's forecast?

Day 1

Derive using >1 year of 5 day forecasts made 4 times a day



Based on historical performance, probabilities are normally too high at this location

QT(2)/2

Colours give probability of threshold crossing

Red: 16 to 24 of members

Orange: 8 to 16 of members

Green: 1 to 8 of members

Symbols give suggested tendency from verification

△ Upwards triangle: possible underestimation

▽ Downwards triangle: possible overestimation

□ Square: no suggested trend

◆ Diamond: not enough data for a trend

Rainfall & River Flow Ensemble Verification

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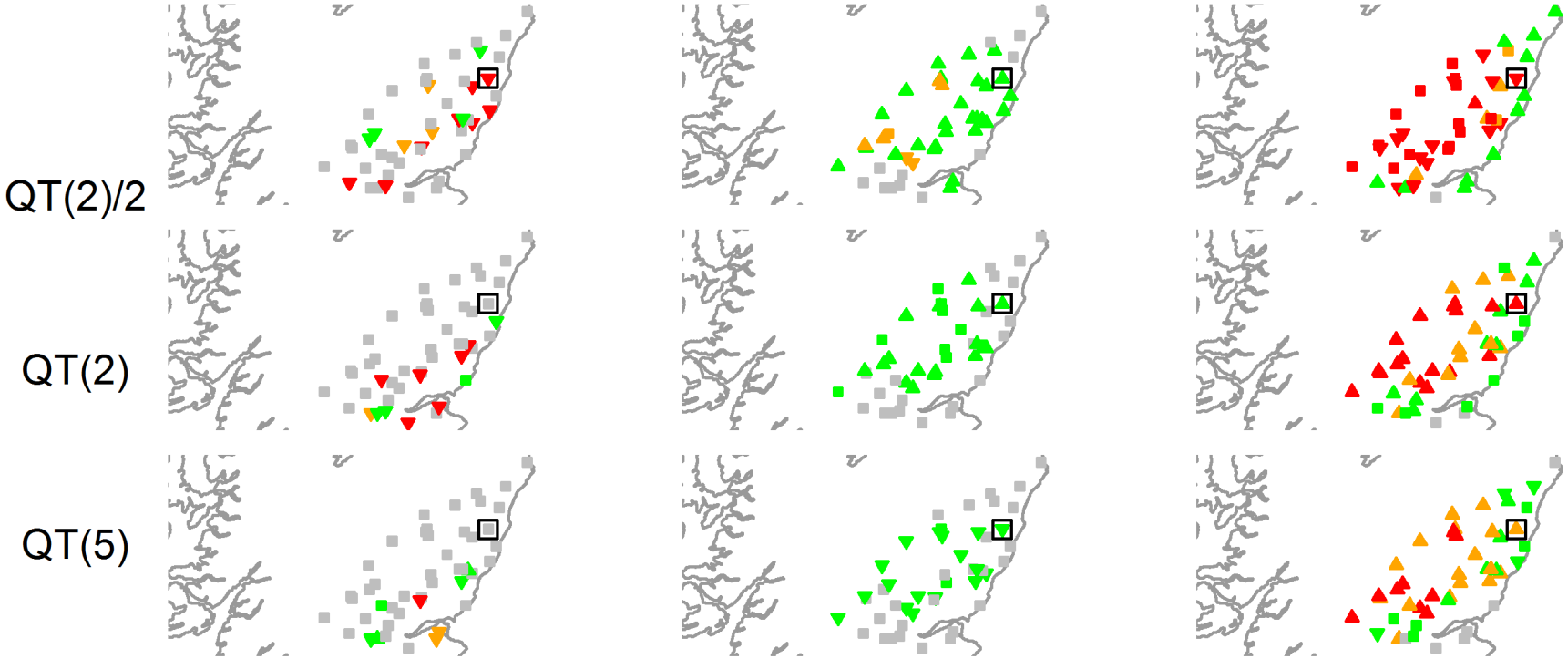

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Impact-based Forecasting

Why do we want impact-based forecasts?

"[People] want to know three things:

- **What does it mean to them?**
- **What does it mean to their family?**
- **What do they need to do right now?**

And so don't speak like a meteorologist. Tell me what we need to know."
(television meteorologist, quoted by Demuth et al. 2012)

Demuth et al. (2012), BAMS

Demand for impact-based forecasting

What the hazard will ***be*** ⟶ What the hazard will ***do***

Flood depth of 0.5m expected

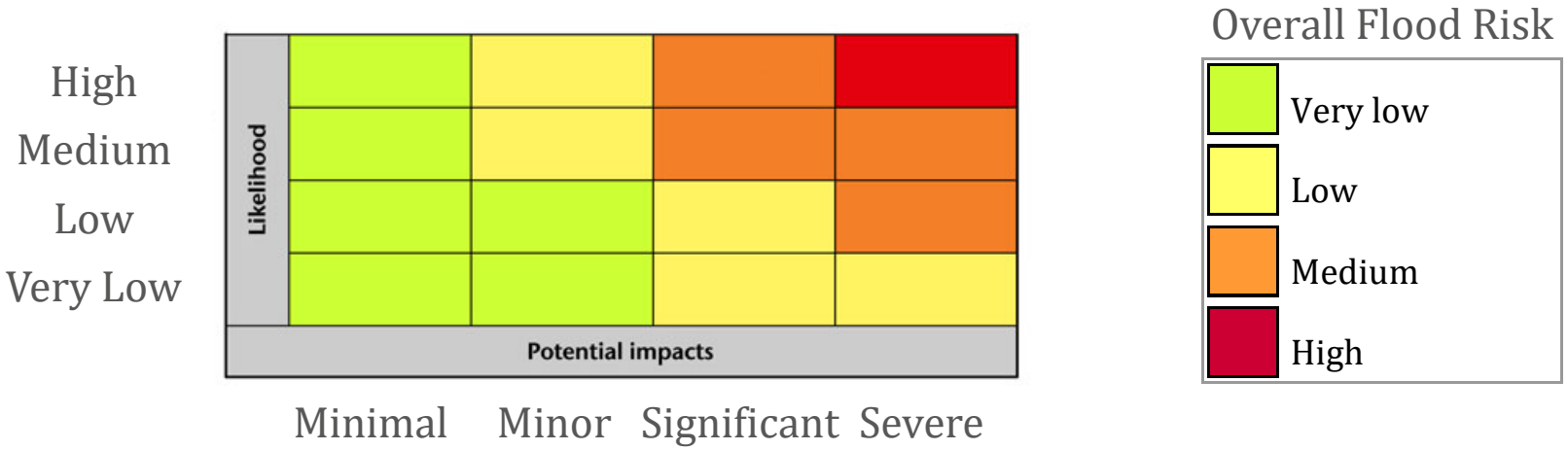
→ **Property flooding expected**

Some places will experience 60mph winds today

→ **60mph wind gusts will cause fallen trees and travel disruption**

Impact-based forecasting: risk matrix

- Many operational weather and flood forecasting centres are moving to Impact-based Forecasting and Warning – encouraged by WMO[1]
- Risk Matrix approach that combines uncertainty ***and*** impacts
- Important to acknowledge and account for uncertainty
  - ➢Make better, more informed, decisions

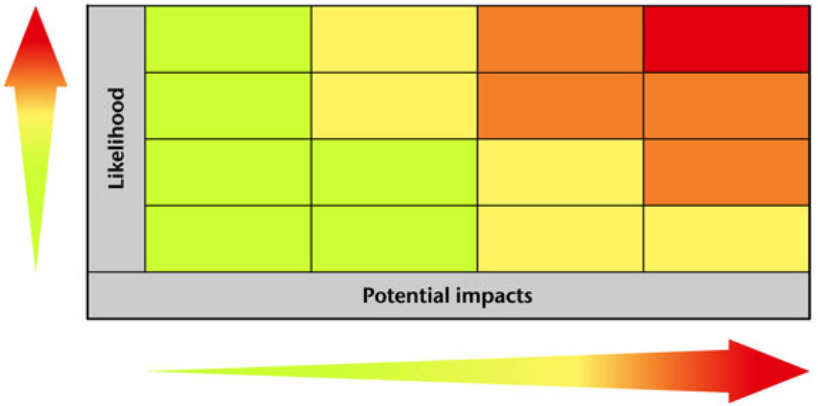


[1]WMO (2015, 2021) Guidelines on Multi-hazard Impact-based Forecast and Warning Services (WMO-No. 1150)

Hazard Impact Models (HIMs)

Automated Hazard Impact Models are becoming a common Impact-based Forecasting tool to help forecasters

WMO guidance recommends developing in partnership and using the **Risk Triangle** and **Flood Risk Matrix** approach



Recent HIM development in the UK

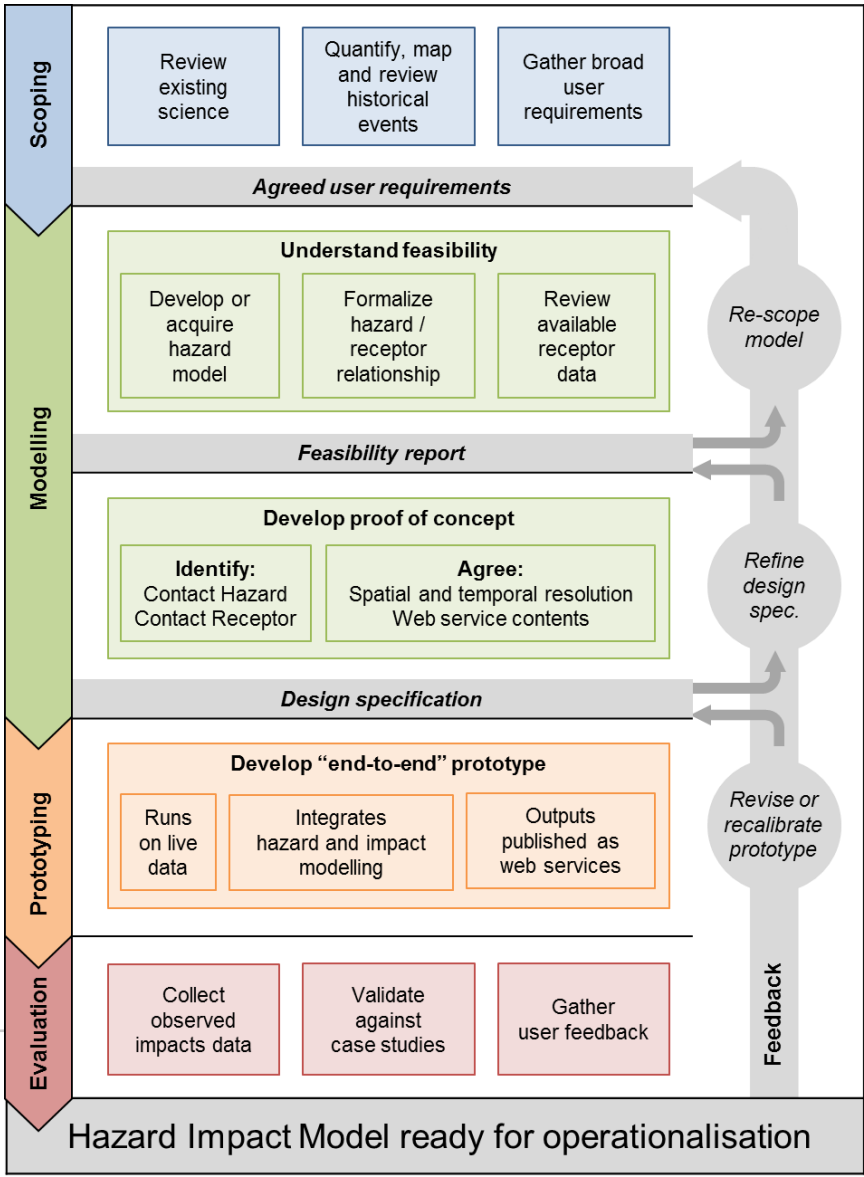
- Automatic HIMs developed under the Natural Hazards Partnership (NHP) of research and government bodies

- NHP aims:
  - Focus on Impacts
  - Emphasis on risk reduction and prevention
  - Develop new services

Hazard Impact Framework (HIF)

- How to build Hazard Impact Models?
- Natural Hazards Partnership have developed a Hazard Impact Framework (HIF)

"A common and consistent approach to modelling and forecasting natural hazard impacts"

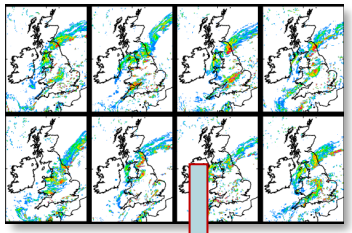


Gunawan *et al.* (2017), The Hazard Impact Framework

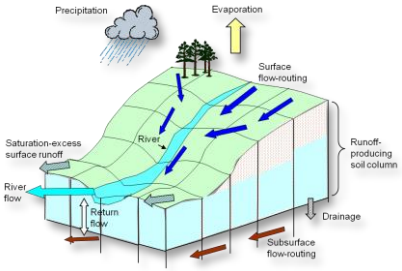
Impact-based forecasting: UK flooding example

- Surface Water Flooding Hazard Impact Model (SWF HIM)
- Builds on existing tools & models
- Operational 24/7 for the Flood Forecasting Centre since 2020

Rainfall ensembles (MOGREPS-UK)



Grid-to-Grid Hydrology

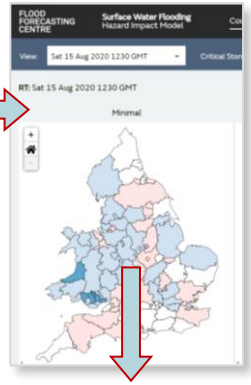


SWF Hazard Footprint

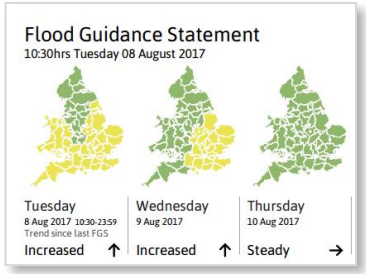
SWF HIM

Real-time SWF risk outputs

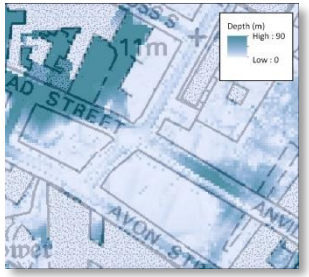
Visualisation



Dissemination

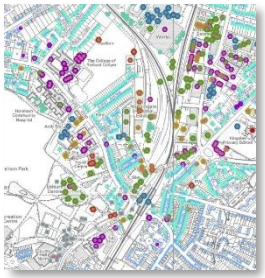


Impact Library



Updated Flood Map for Surface Water

National Receptor Database (NRD)



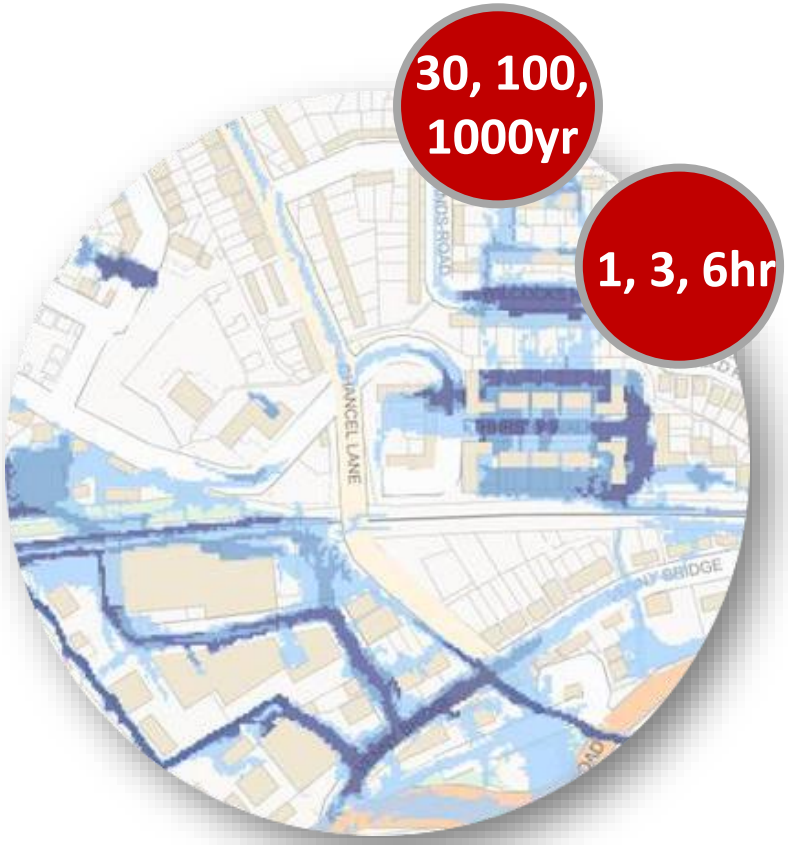
National Population Database (NPD)

FLOODFORECASTINGCENTRE
a working partnership between Environment Agency | Met Office

Risk of flooding from surface water

- Maps produced offline
- Use JFlow+ (2m resolution), 2D inundation model
- 9 maps available for 9 different rainfall scenarios

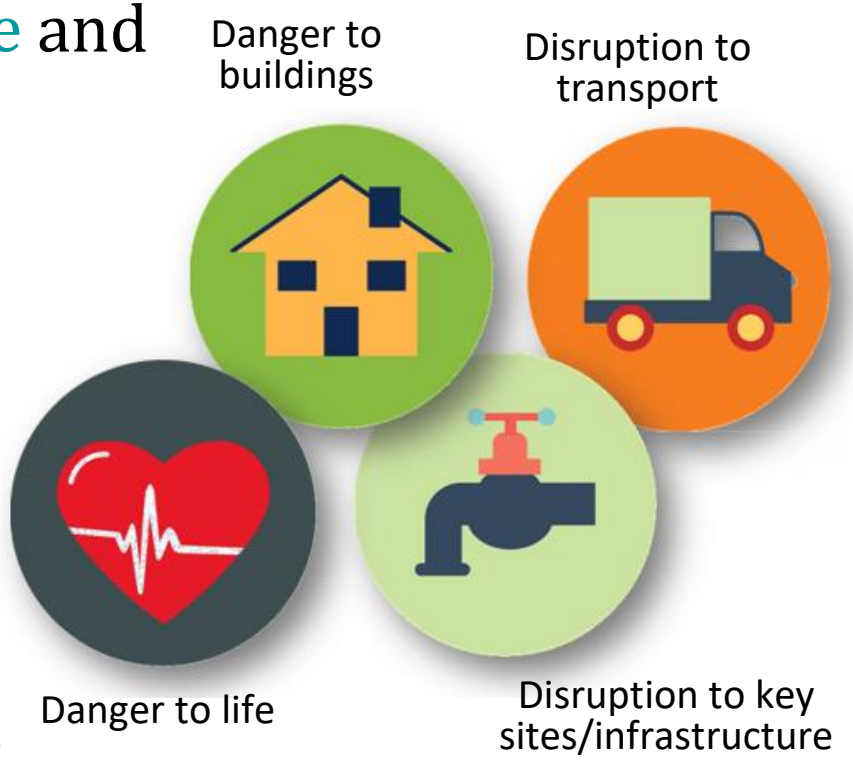
- Key assumption G2G Surface Runoff equates to "effective rainfall" input to maps



Example offline map

Impact Library

- Impact Library developed offline and accessed in real-time
- Four categories of disruption (impact criteria)
- Impact maps created for each flood map and impact criteria
- Judgements needed on counts of impacts per 1km^2

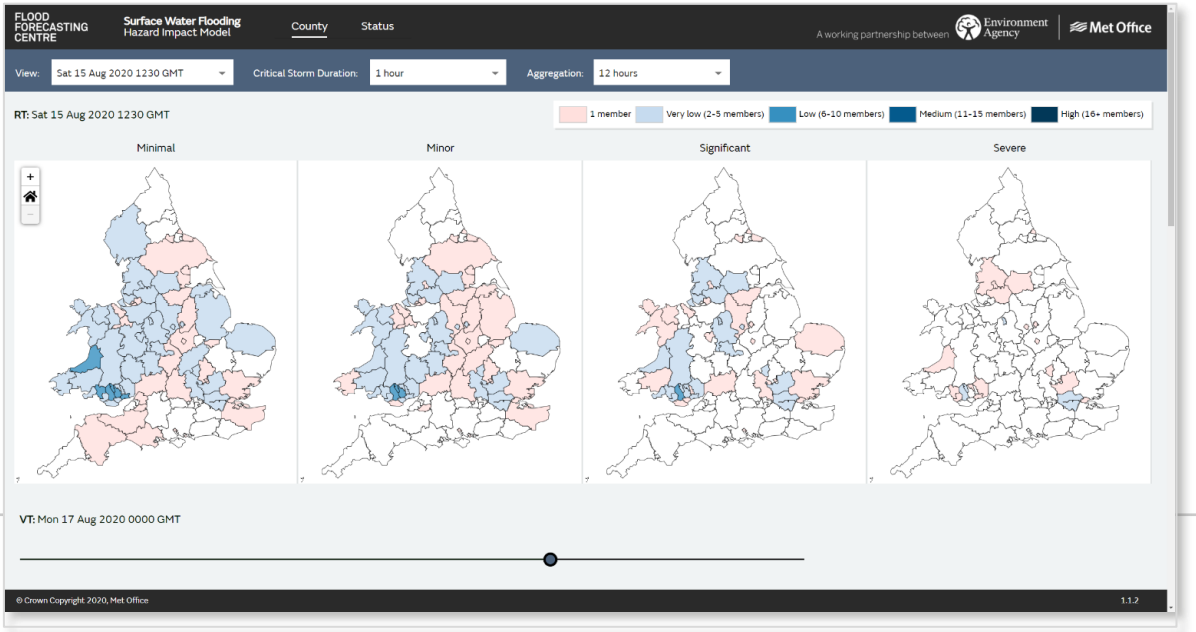


Cole et al., Aldridge et al., FLOODrisk2016

SWF HIM Visualisation

- Flood Forecasting Centre duty officers designed interface with User Experience consultant
- Easy-to-use in time-pressured decision-making process
- Cloud-based solution

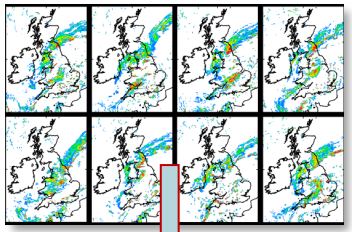
FLOOD FORECASTING CENTRE



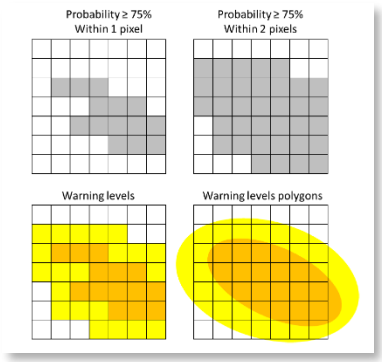
Scotland SWF IbF: PREDICTOR

New method trialled in Summer 2023. Based on rainfall ensembles.

Blended Ensembles
(Met Office)



"in vicinity" rainfall
exceedance probability

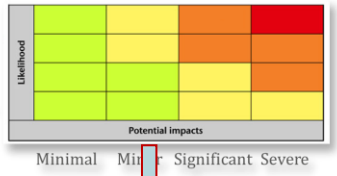


Hazard Footprint

PREDICTOR SWF IbF

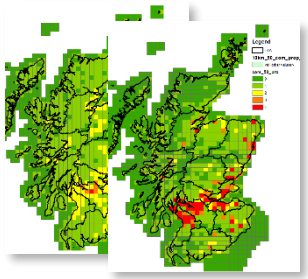
Real-time SWF risk outputs

Flood Risk Matrix

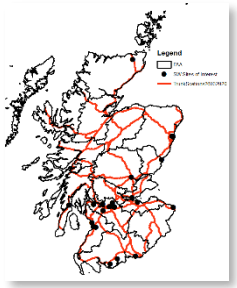


Web portal/
Decision Support Tool

Impact Library



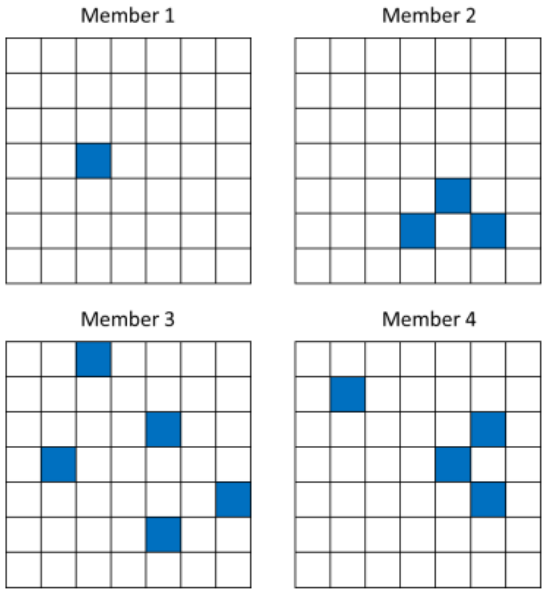
NFRA
(roads, property, …)



Scottish Water Sites
Trunk roads
Flood Alert Areas

Rainfall threshold exceedance: Neighbourhood Approach

- For each ensemble member, calculate the maximum rainfall total for a duration (e.g. 3h), and forecast window (e.g. 0-12h)
- 1 (blue) if it threshold exceeded, 0 if it isn't



Raw ensembles

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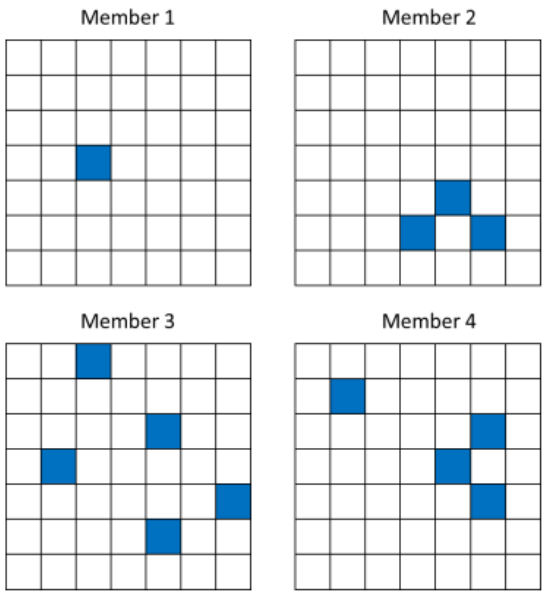

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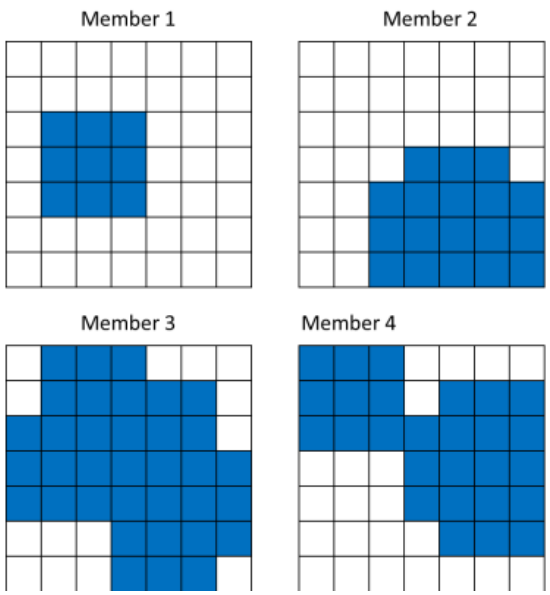

3 x 3 Neighbourhood

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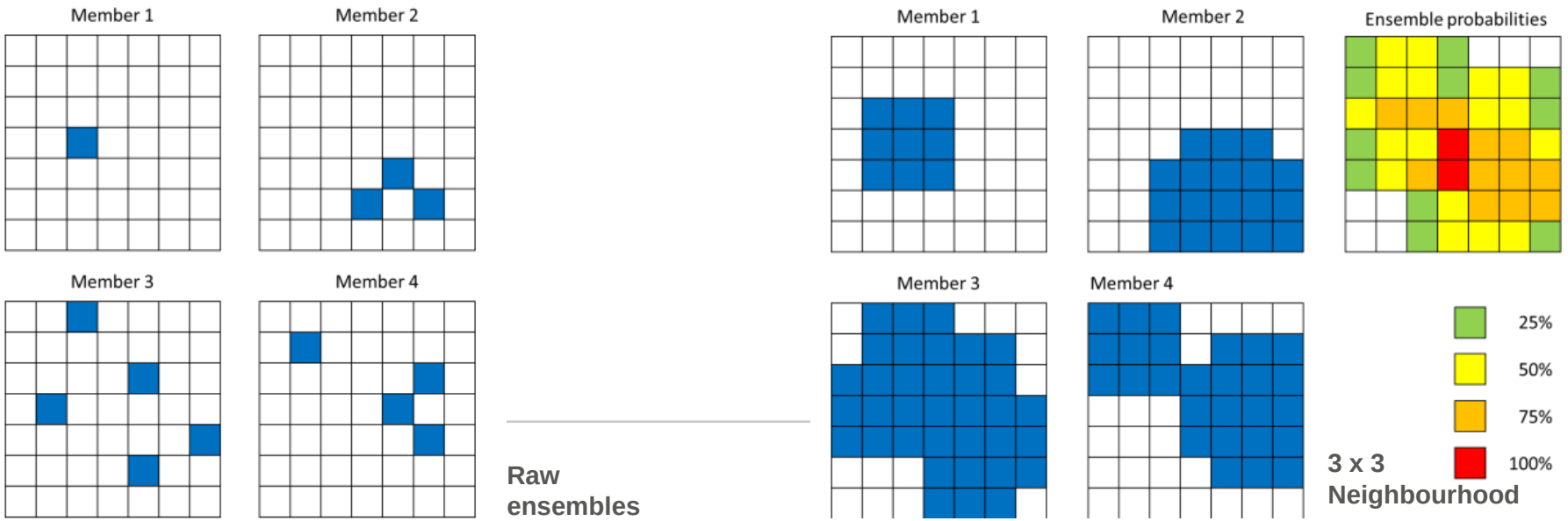
- Then combine all members to calculate probability of exceedance



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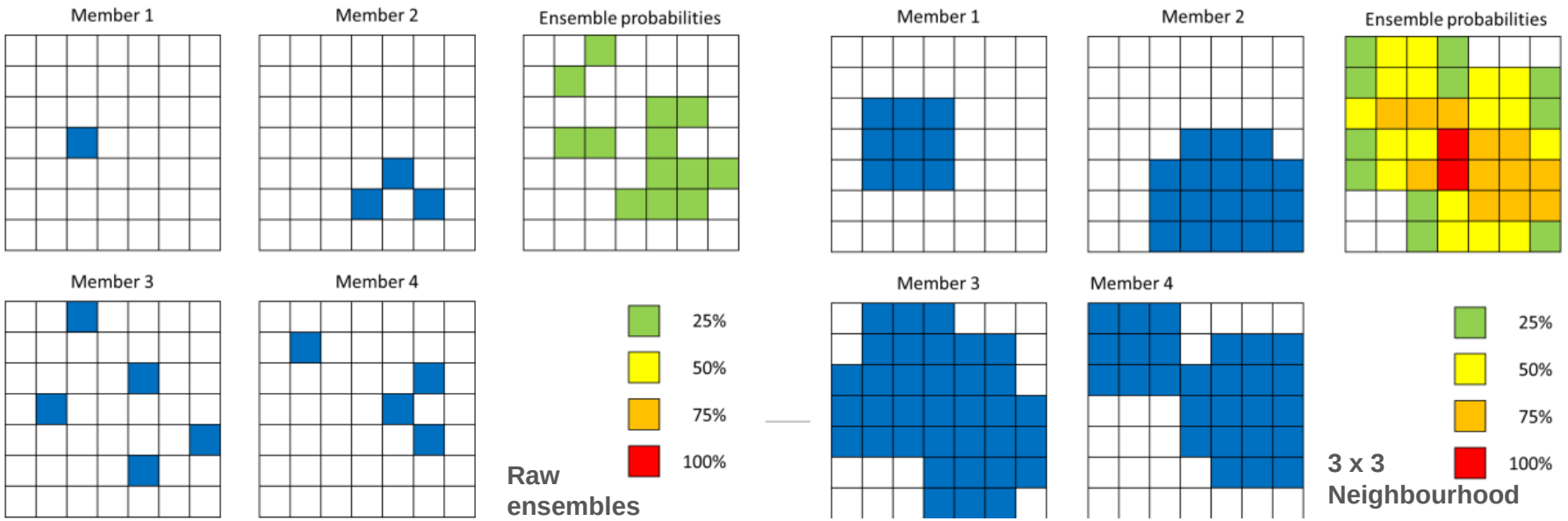
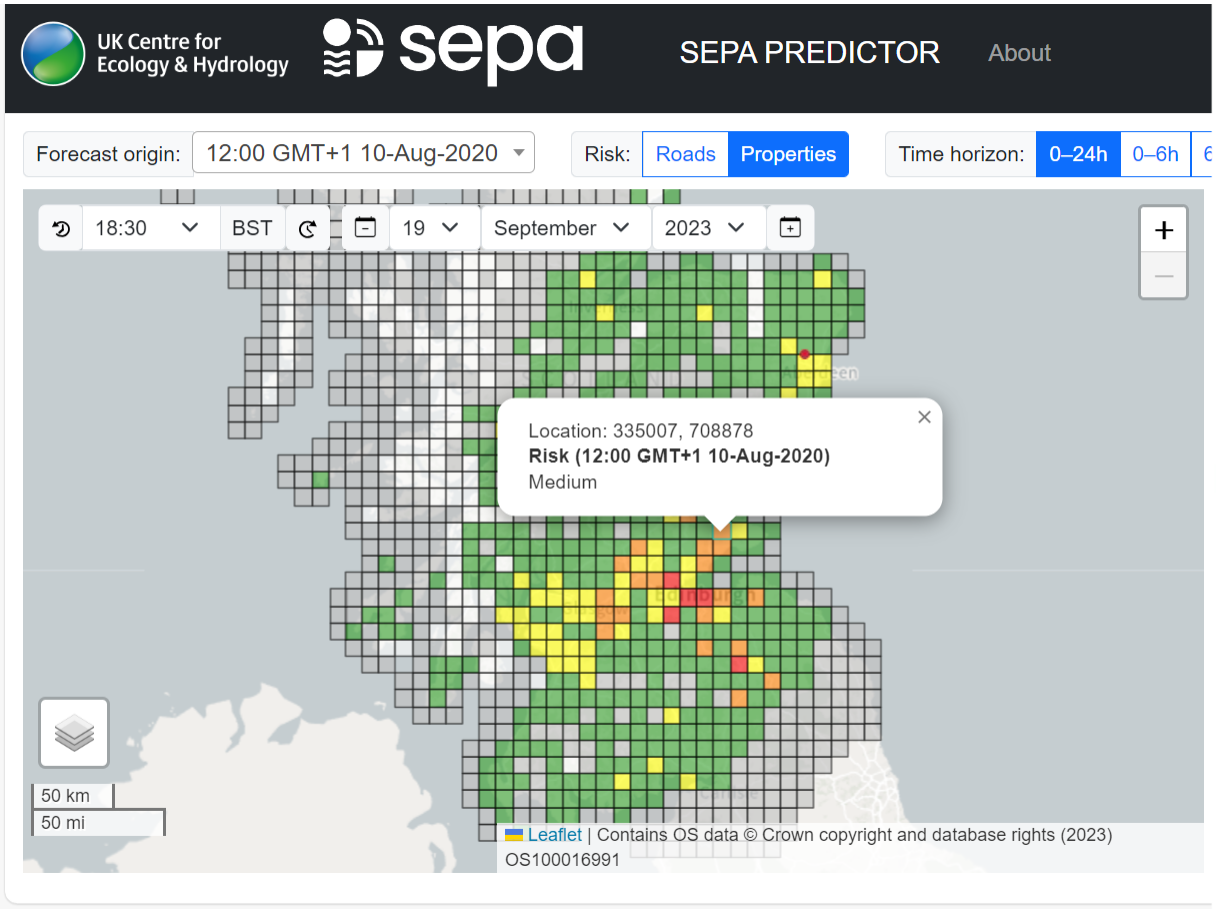
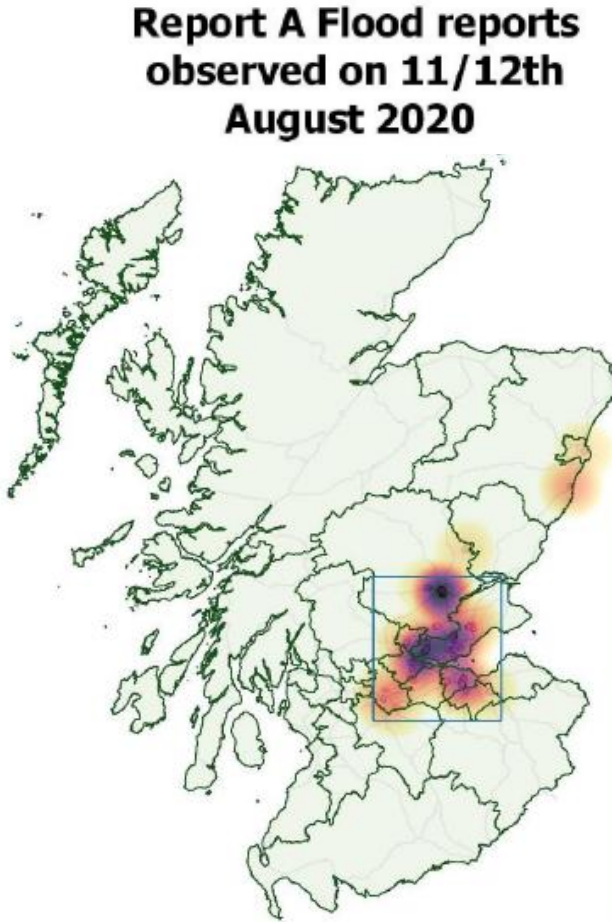


PREDICTOR – SWF live portal

- Outputs produced on a 10km grid for Roads and Property impacts
- 24 hour lead time, 24 member ensemble. Good forecast!





Summary

- Summarised flood risk mapping used in the UK's third Climate Change Risk Assessment (CCRA3), published in 2022
  - Method modifies impact curves for Census Calculation Areas
- Outlined new country-wide climate change flood scenario methods
  - Potential to better capture risk from wide-spread major floods
  - Verification of ensemble rainfall and flood forecasts is important
- Move to real-time Impact-based Forecasting
  - Risk = Hazard x Exposure x Vulnerability
  - Remember which uncertainty is (and isn't) included in forecasts!
  - Methods developed in UK are transferable (e.g. India)

Dr Steven Cole: scole@ceh.ac.uk

Current progress

- **UK.** Climate adaptation progress report to government in 2023
  - The second National Adaptation Programme has **not adequately prepared** the UK for climate change.
  - The impacts from extreme weather in the UK over the last year highlight the **urgency of adapting** to climate change
  - The next National Adaptation Programme must make a **step change** and be **more ambitious**
- **Norway.** Investigation into government authorities' effort to adapt infrastructure and built-up areas to a changing climate (2022)
  - The investigation reveals that the Norwegian government authorities **do not have the necessary overview** of the risks of natural disasters in a future climate.

Climate Change Committee

Office of the Auditor General of Norway

UK Centre for Ecology & Hydrology

Future steps

- **Partnership.** Improved partnership working across government and beyond (example Natural Hazards Partnership)
- **Better understanding of risk and vulnerability.** Including key infrastructure and under climate change (UK developing NAFRA 2)
- **Roles and responsibilities.** Clarity in responsibilities for climate adaptation
- **Monitoring progress.** Improved monitoring and reporting to government on adaptation progress (UK report every 2 years)
- **Impact-based forecasting and warning.** To better include uncertainty, impacts and multi/cascading-hazards
- **Communication and actions.** "Last mile" how effectively are warning used by the public, response community and more widely