Compound coastal-fluvial floods in urban environment

Indiana A. Olbert (UG), Sogol Moradian (ATU), Mohammad J. Alizadeh (UG), Tomasz Dabrowski (MI) Thomas McDermott (UG), Michael Puchley (UG) Martin Serano (UG), Vinoop Sanil (UG) Ciaran Broderick (Met Eireann) Amir AghaKouchak (UC Irvine, CA) Alexander Shchepetkin, Niall Madden (UG)

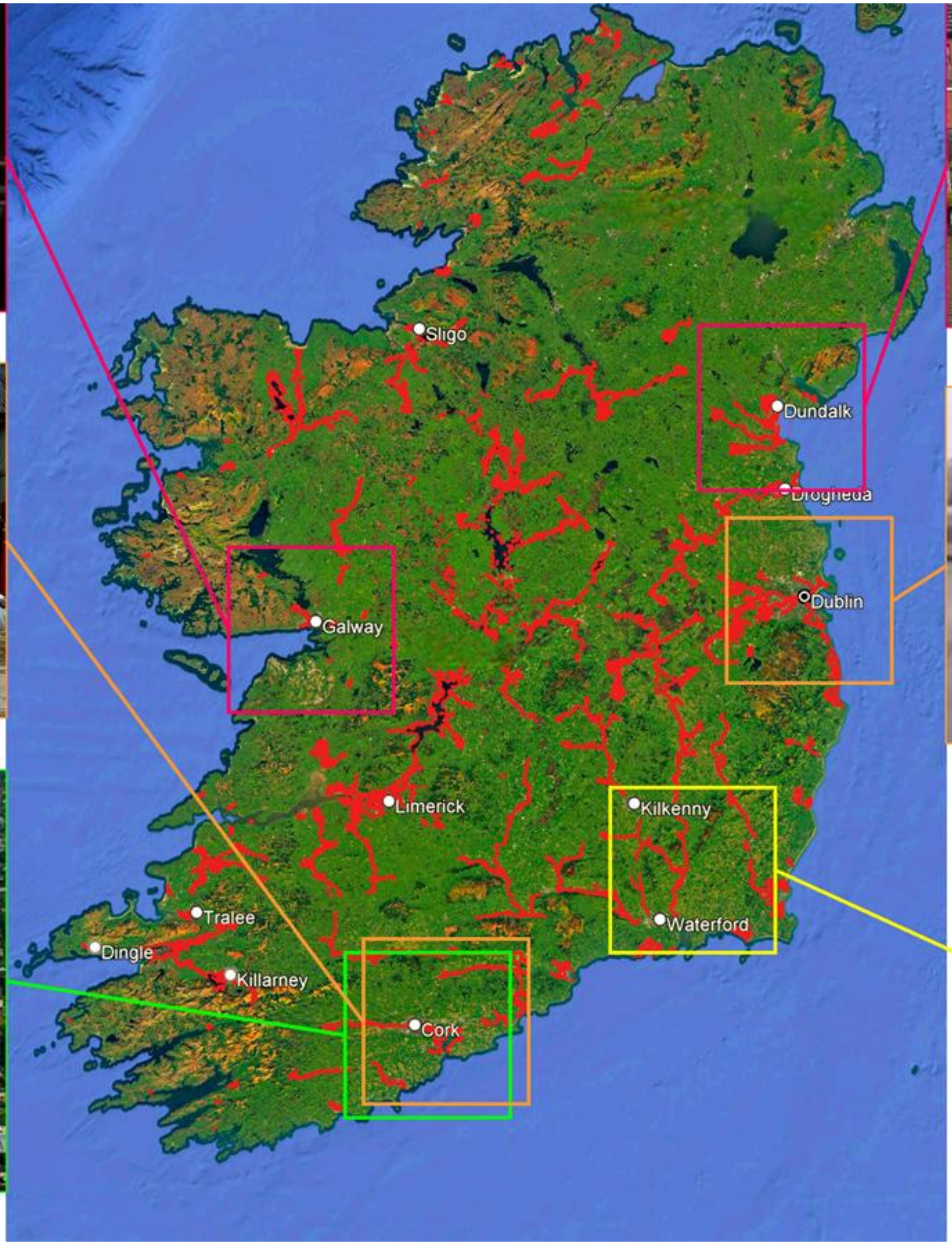
The Societal Challenge – Building Resilience to Flooding

If you are in insurance __________, you are affected.

November 2023, Galway

October 2023, Midleton

November 2009, Cork



July 2023, Dundalk

June 2016, Dublin

October 2023, Co. Kilkenny

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Floods are the costliest and most pervasive natural hazard

Societal Challenge

Globally:

- 1.8bn people (1-in-4) exposed

In Ireland:

- 750,000 people
- 300+ communities

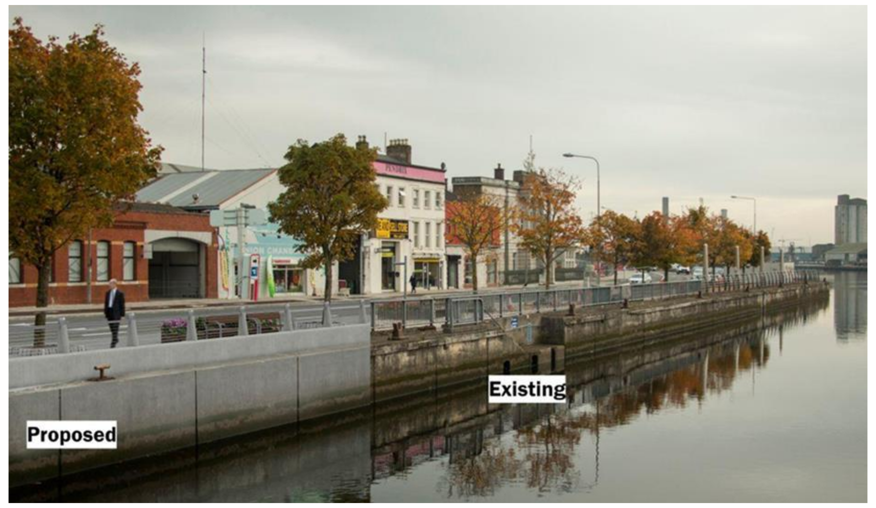
Perfect storm → imperfect flood defences

"We can't keep building our way out of trouble"

Climate adaptation + impact mitigation=
Hard & soft engineering+
early warning

September 2023

October 2023



Floods are the costliest and most pervasive

MET éireann The Irish Meteorological Service

Forecasts Latest Reports Climate Education Science Podcasts About

Warnings Weather Marine

Status red - Status Red - Wind warning for Carlow, Kilkenny, Wexford, Cork, Kerry, Limerick, Waterford

Met Éireann Weather Warning

Red Storm Éowyn: Gale to storm force southerly winds becoming westerly with extreme, damaging and destructive gusts in excess of 130km/h

Close x

Warnings explained

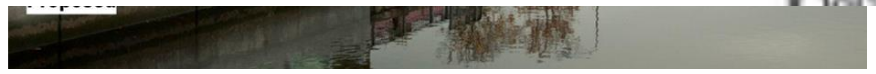
Mace Head Atmospheric Research Station

- **highest wind gust 184 km/h**
- **highest 10-minute wind speed 142 km/h**

- Many fallen trees
- Significant and widespread power outages

More severe storms =? more severe floods

- Structural damage
- Wave overtopping



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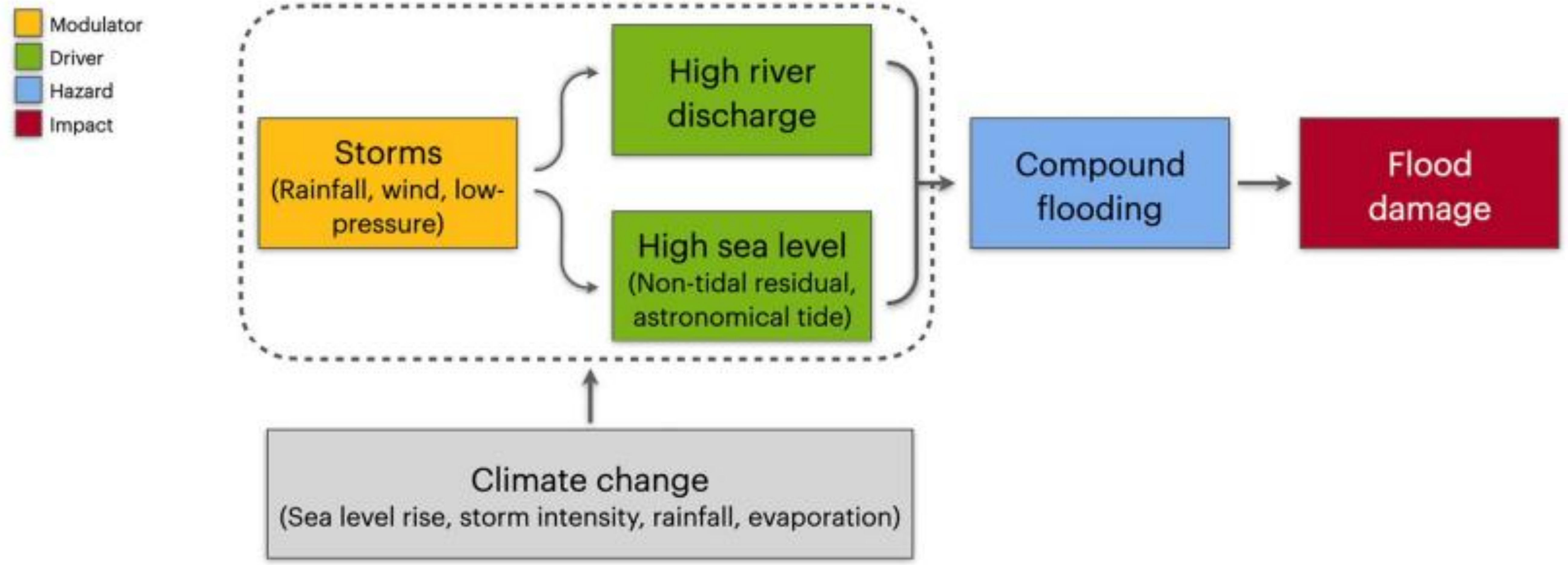
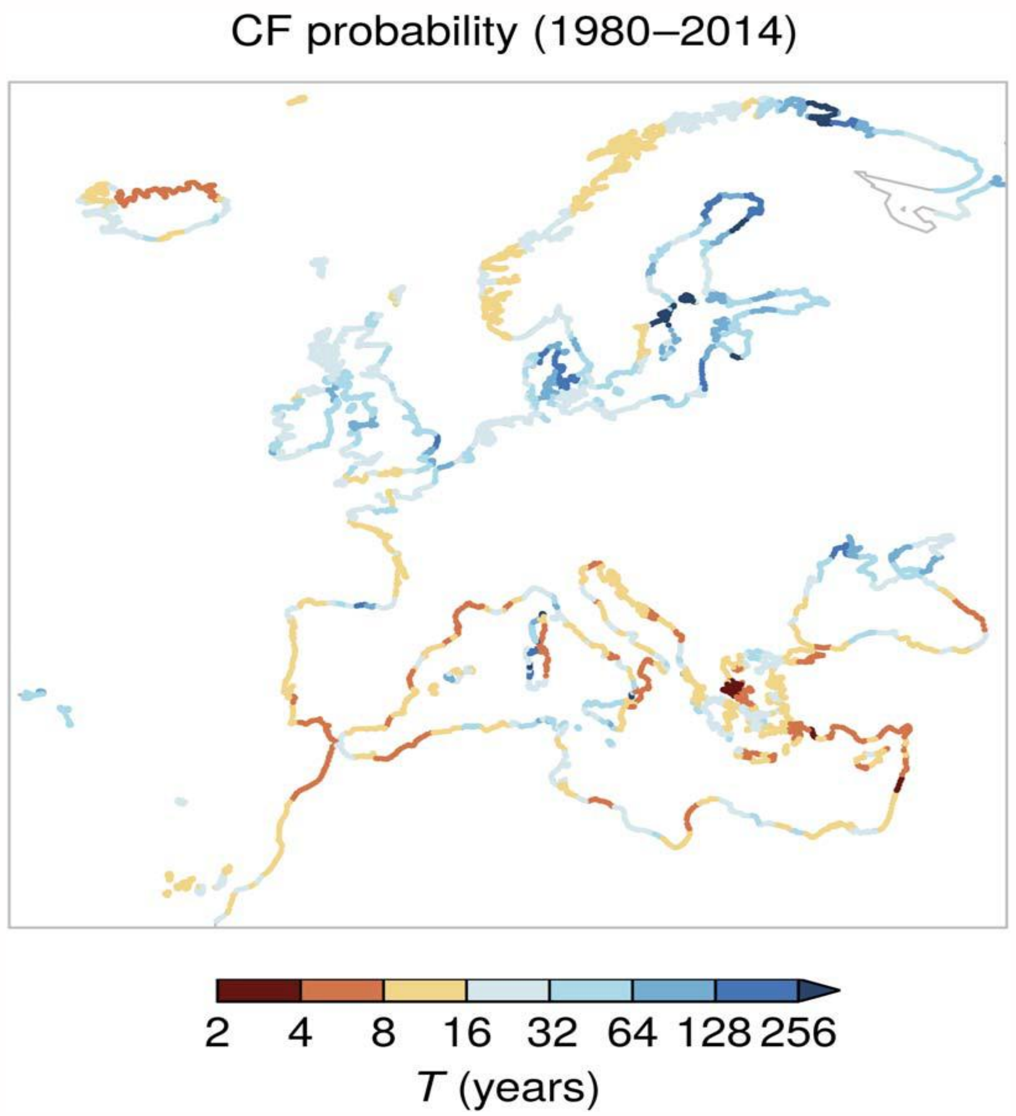
Floods are tricky to forecast!

Motivation

Compound events are combinations of drivers and/or hazards that contribute to societal or environmental risk and impact



Bevacqua et al. 2022



Bevacqua et al. 2019

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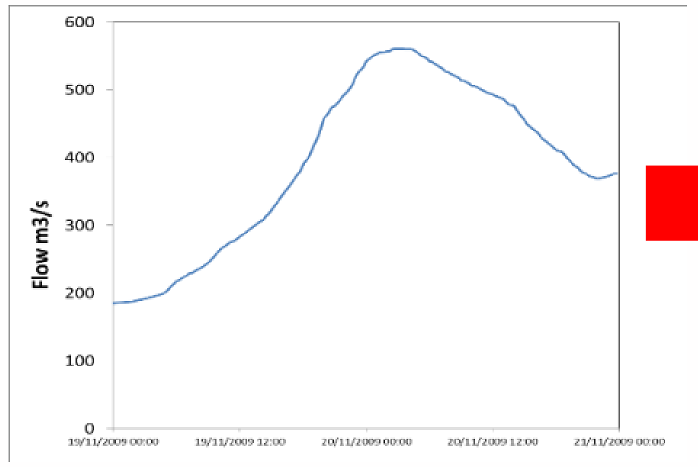
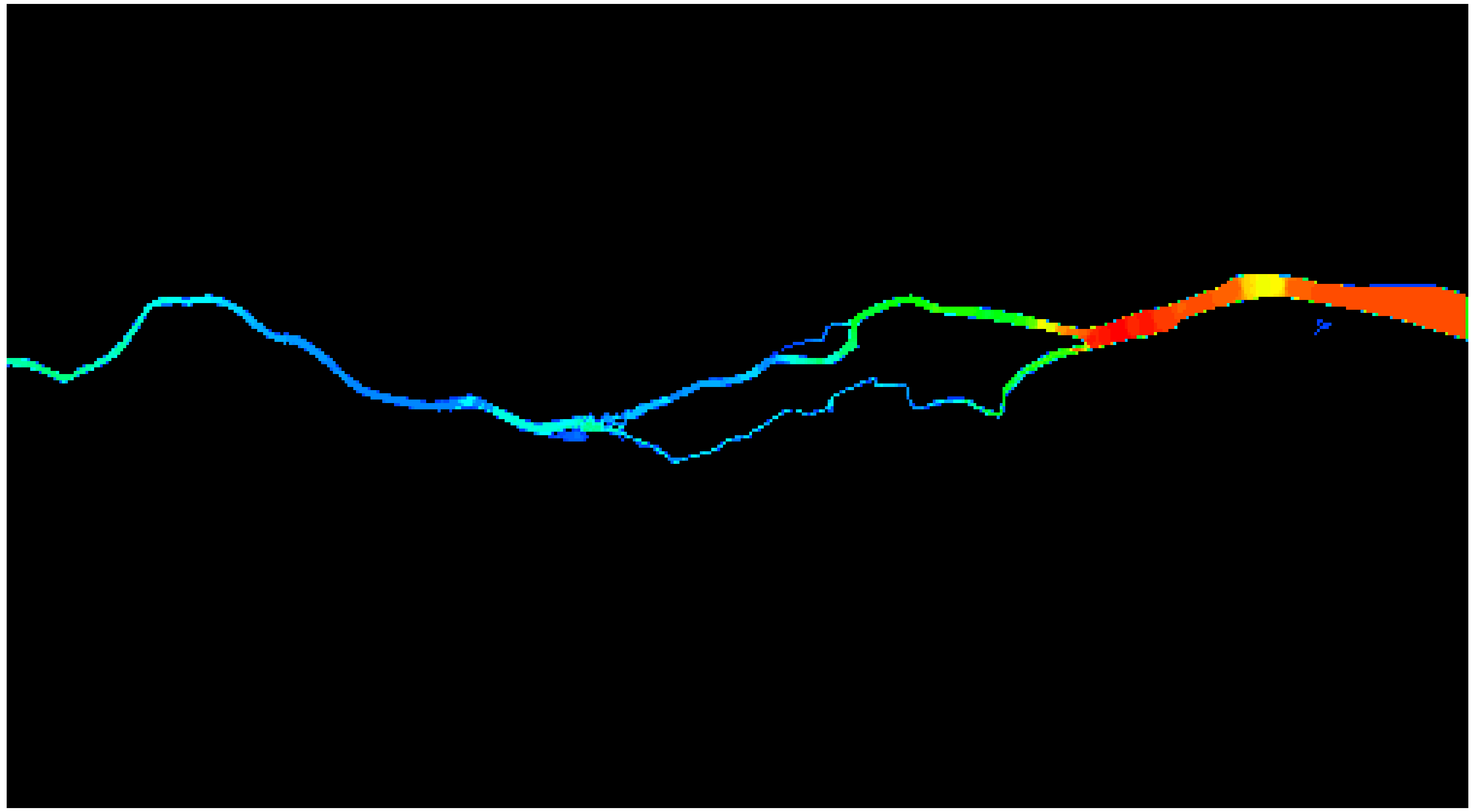
Coastal-fluvial flooding

Motivation

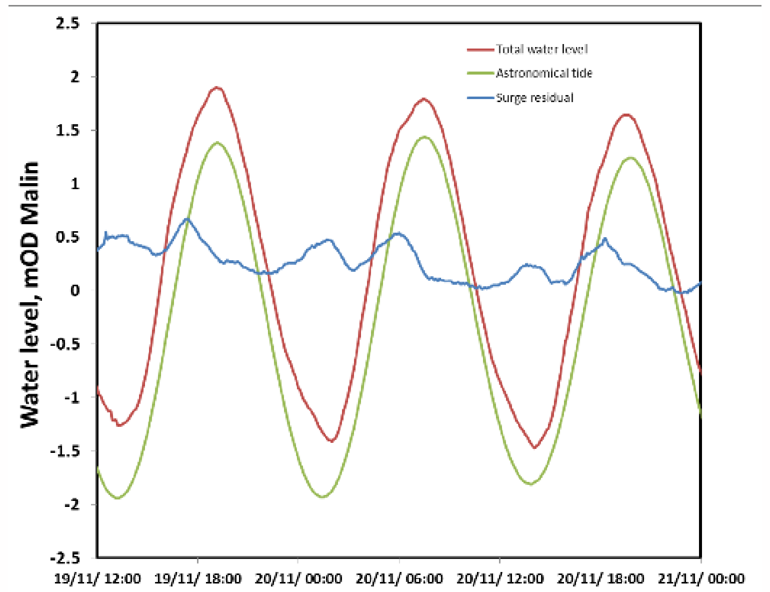
Compound events are combinations of drivers and/or hazards that contribute to societal or environmental risk and impact

Fluvial driver





Coastal driver



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Coastal-fluvial flooding

M

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How do we determine coastal flood risks?

Motivation

THE IRISH TIMES

Ireland

Thousands living in coastal areas ‘narrowly’ avoided devastating flooding during Storm Éowyn, research finds

Low tides meant many areas avoided flooding and inundation during Storm

Expand

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- Champions League final: Two dead and more than 500 arrested during PSG celebrations

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Ireland 'lucky' to escape devastating floods during Éowyn

Updated / Tuesday, 22 Apr 2025 19:56

During the storm in January, record-breaking wind gusts of 184km/h were recorded, causing an estimated €200m in damage

The country was "incredibly lucky" to avoid devastating flooding

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‘It’s hard to imagine how narrowly we avoided it’ – how luck of timing saved cities and airport from catastrophe here during Storm Éowyn

Storm Éowyn brought huge waves when it hit here in January. Photo: Getty

Caroline O'Doherty
Tue 22 Apr 2025 at 02:30

Tens of thousands of people and properties narrowly escaped disaster by luck of timing when Storm Éowyn hit the country.

Had it happened a week earlier, tidal conditions combined with Éowyn's hurricane-force winds would have created storm surges more than five metres high in densely

How we determine coastal flood risks?

Motivation

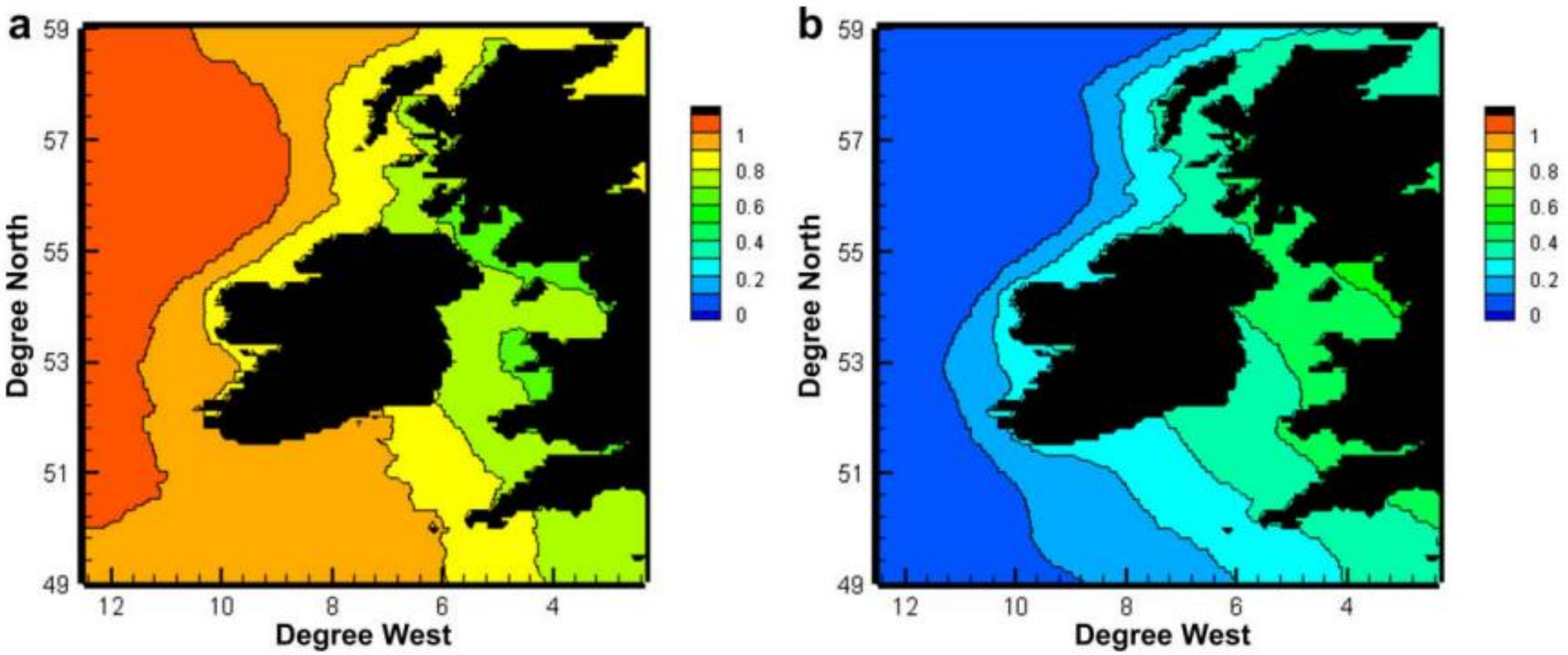
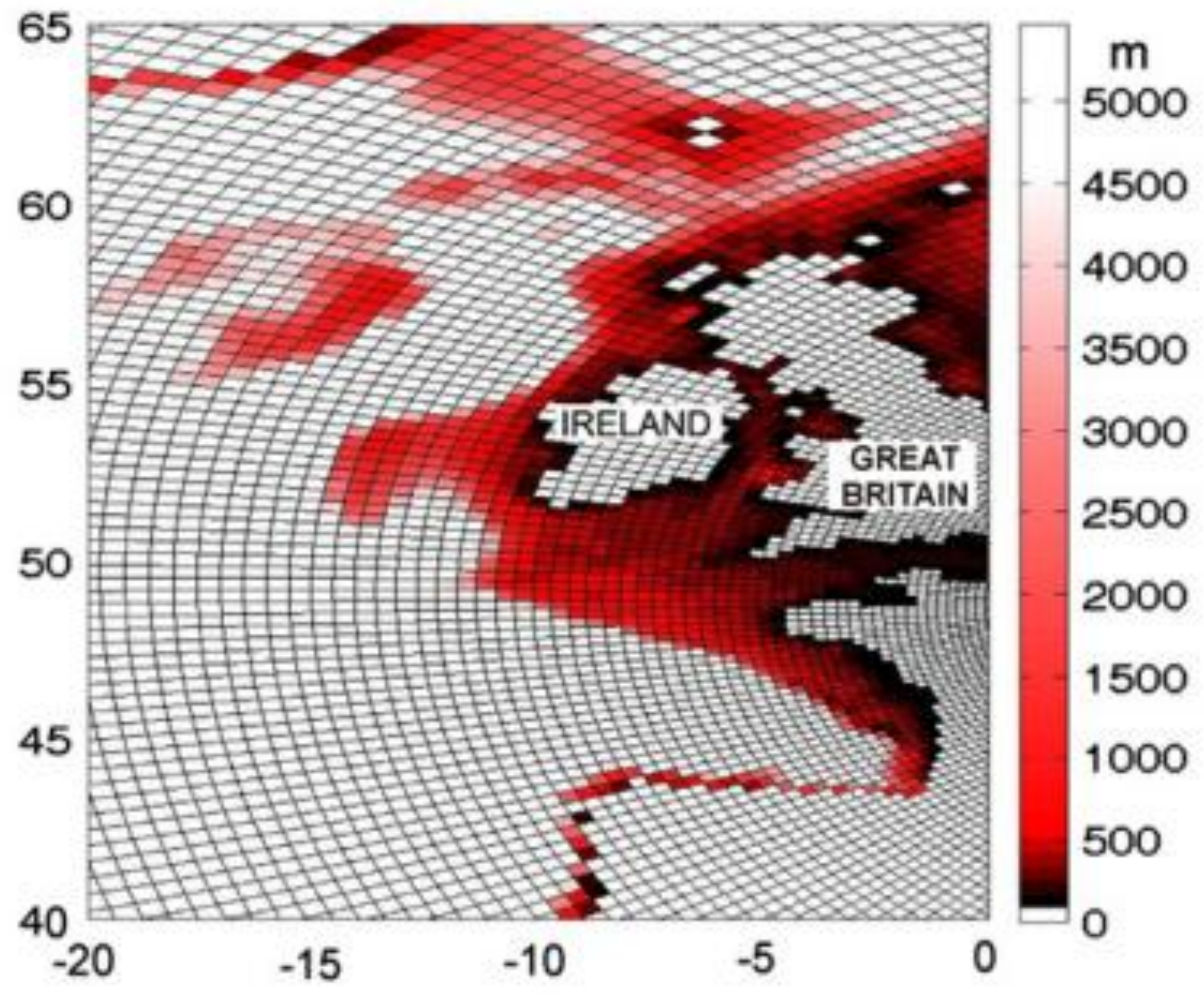


Fig. 5. Ratio of (a) S_P/S and (b) S_W/S. See text for definition of variables.

Results



A.I. Olbert, M. Hartnett / Ocean Modelling 34 (2010) 50–62 5

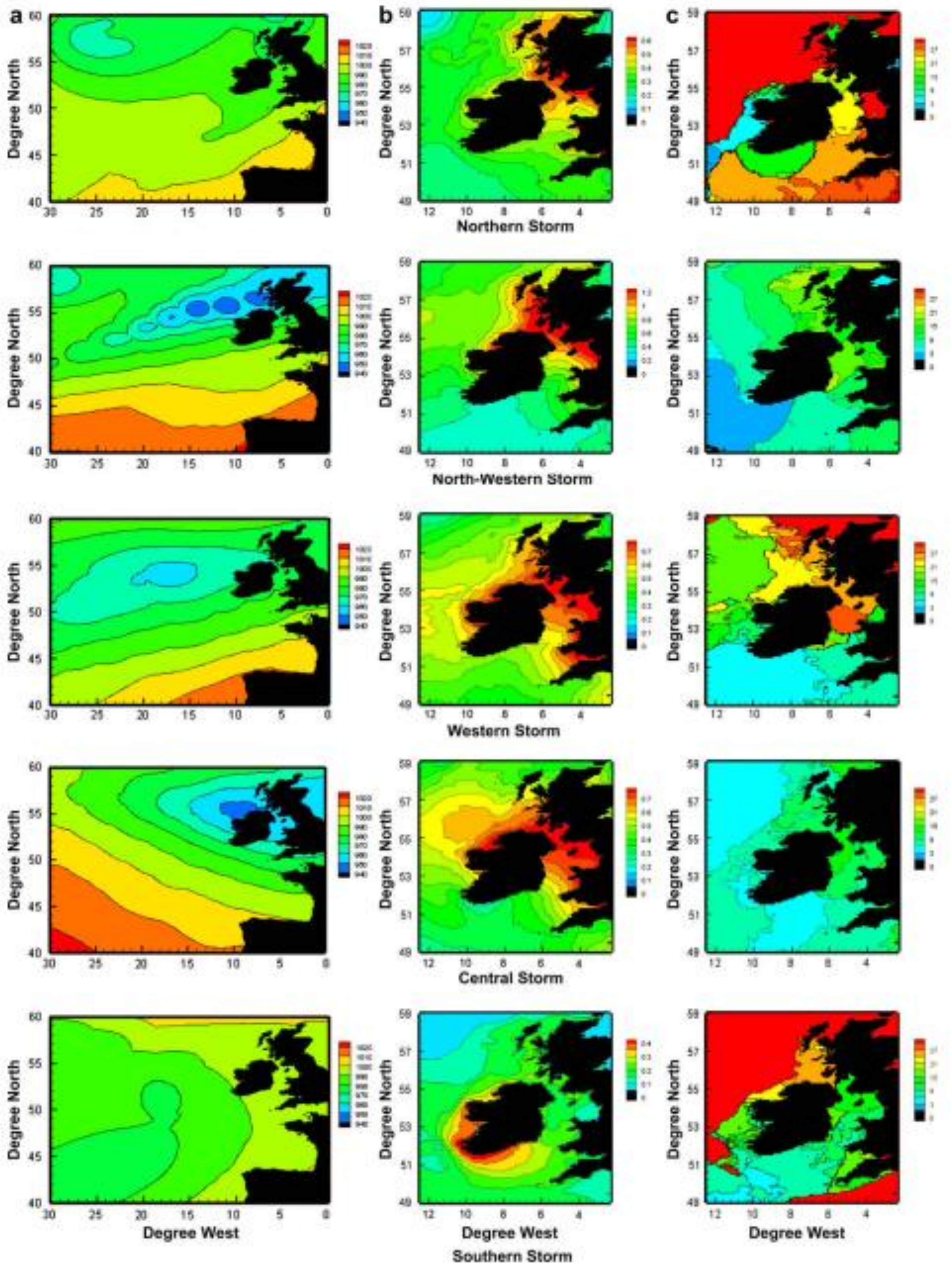


Fig. 4. (a) Depression system tracks, (b) maximum surges generated by these storms and (c) timing of occurrence of maximum surge. Pressure values in hPa, surges in meter

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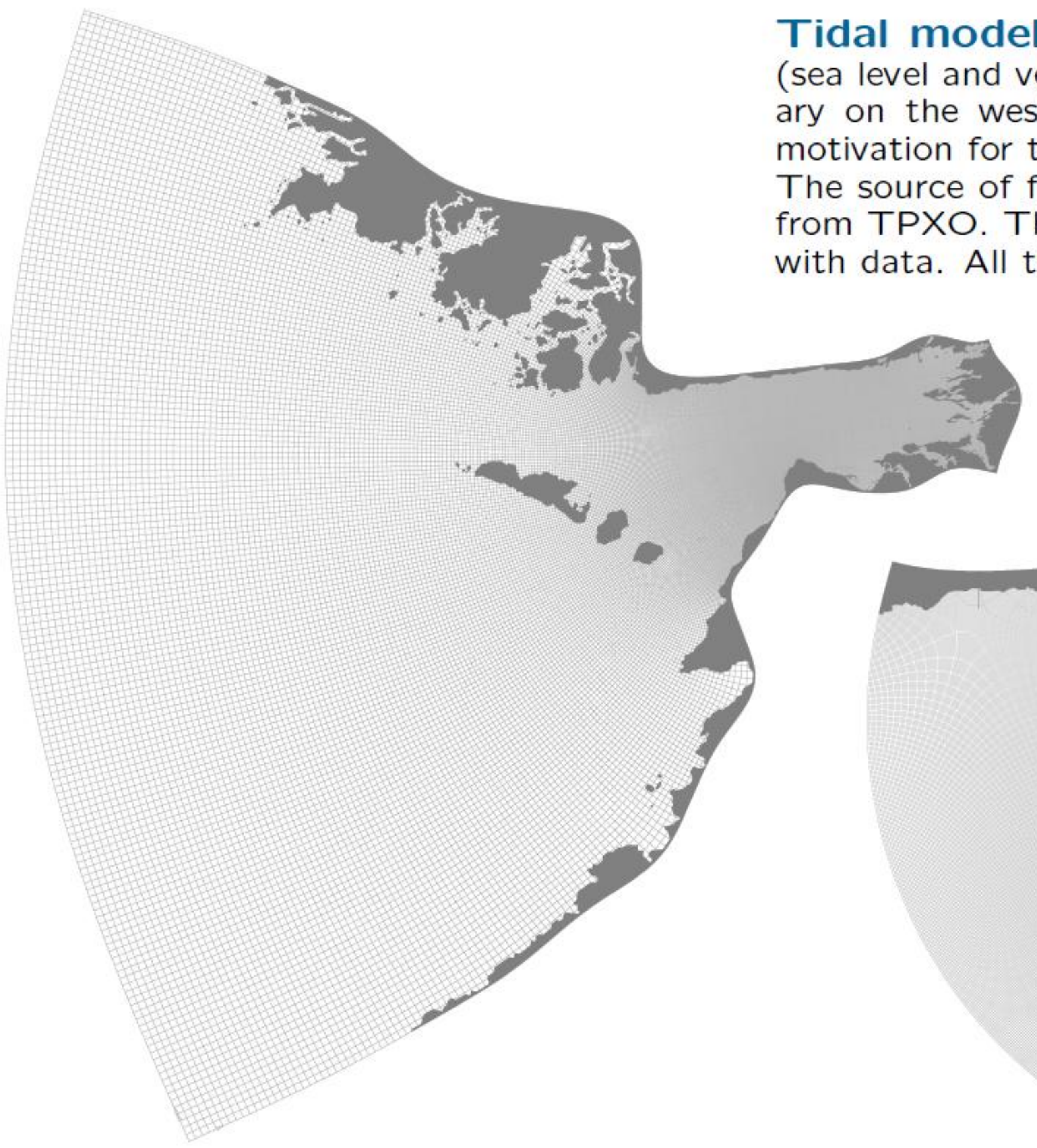
How do we determine coastal flood risks?

Storm Éowyn: What Can be Learned from Irish Tidal Gauges?

Storm Éowyn was not planned. Neither does this study. It just happened. Work in progress.



Tidal modelling in regional configuration: Tidal forcing (sea level and velocity components) is applied along the open boundary on the west, as off-shore as possible in deep area (hence the motivation for the shape of the grid). Focus of interest is inner Bay. The source of forcing data is from the parent model, and eventually from TPXO. There are no measurements offshore to compare model with data. All tidal gauges are near the coast.

left: Galway Bay model grid: 1117×322 points
below: close up on inner portion the Bay.
This part contains > 50% of all grid points.

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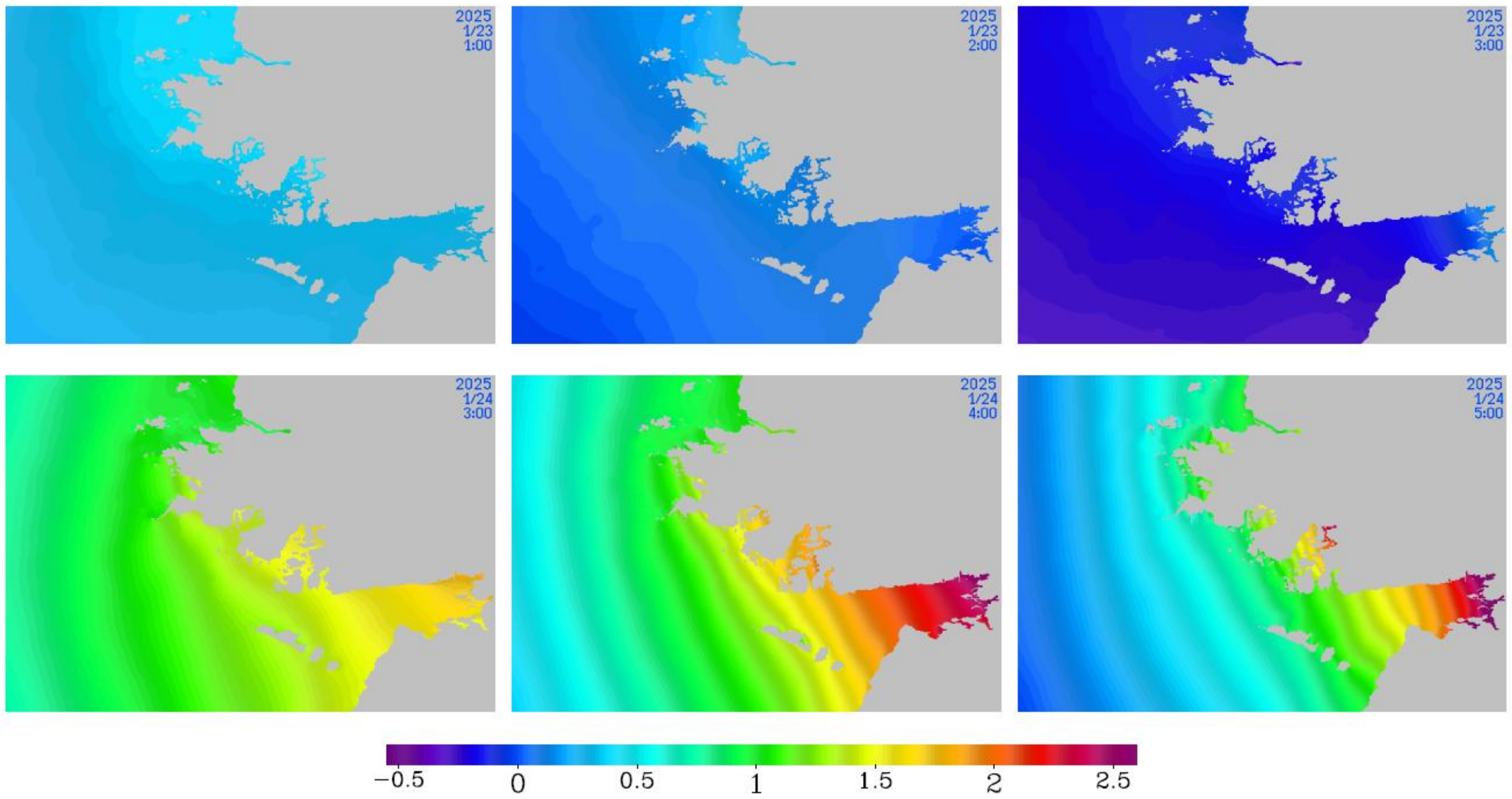
Marine Institute
Foras na Mara

How do we determine coastal risk?

Storm Eowyn, January 2025

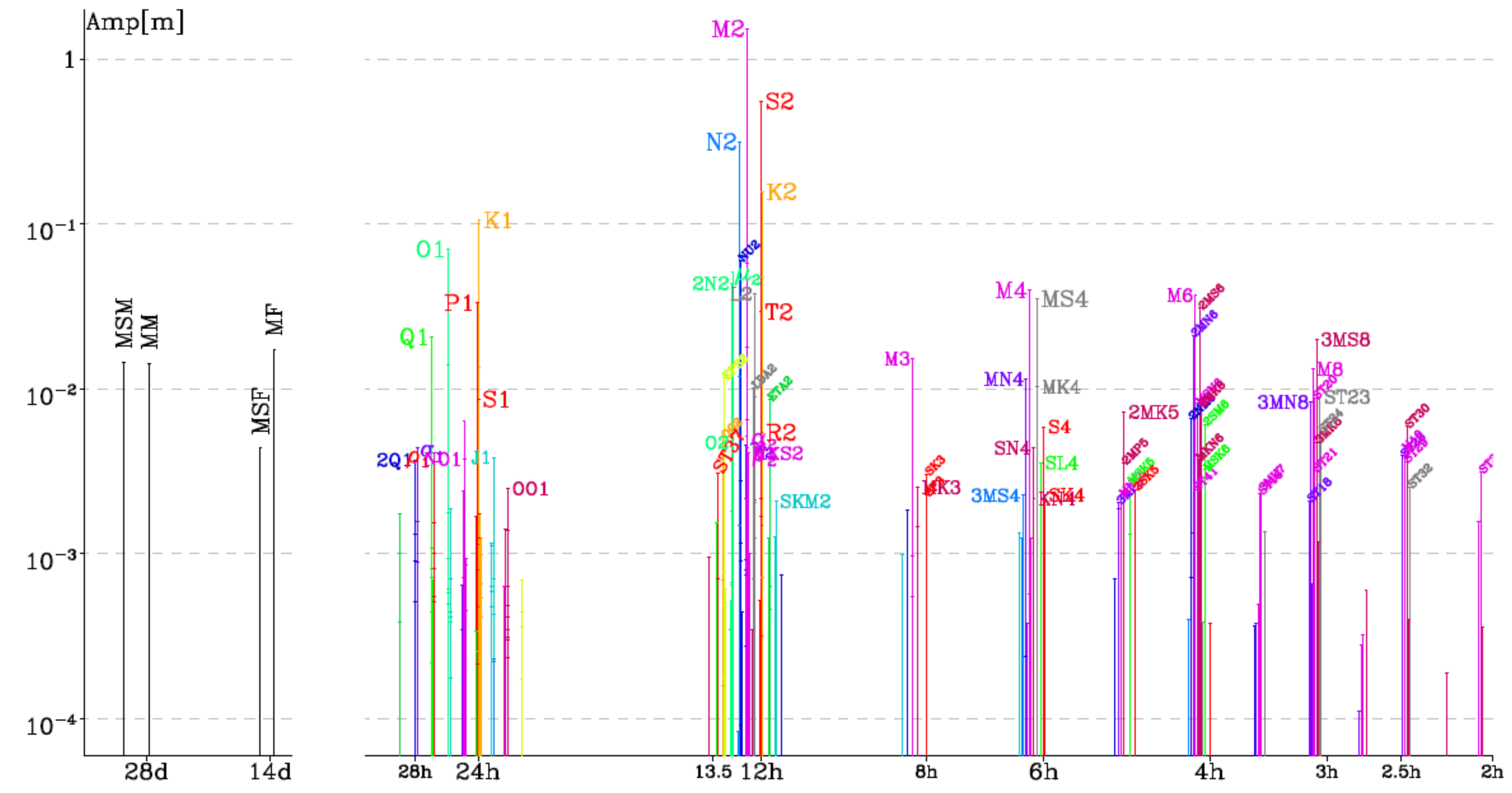


Upper row — three consecutive snapshots, one hour difference, approximately 24 hours before storm Éowyn, where the wind conditions were relatively calm. *Bottom* – three consecutive snapshots most affected by the storm. Note that 2025-1/23 3:00 (*upper-right*) is nearly exactly two M2 cycles ahead of 2025-1/24 4:00 (*bottom-middle*).

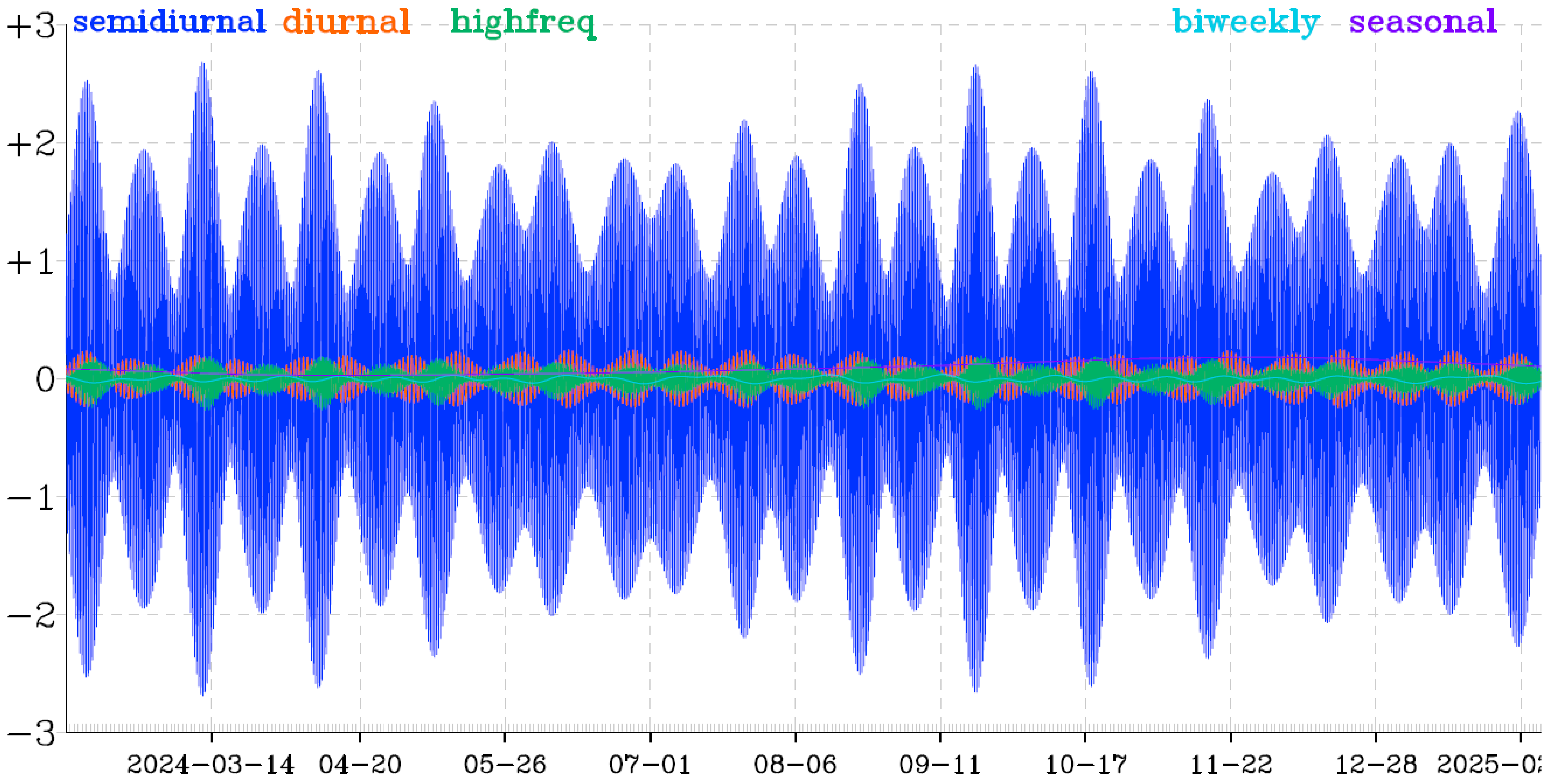
How do we determine coastal flood risks?

Storm Eowyn, January 2025

Real-world data tidal time series analysis



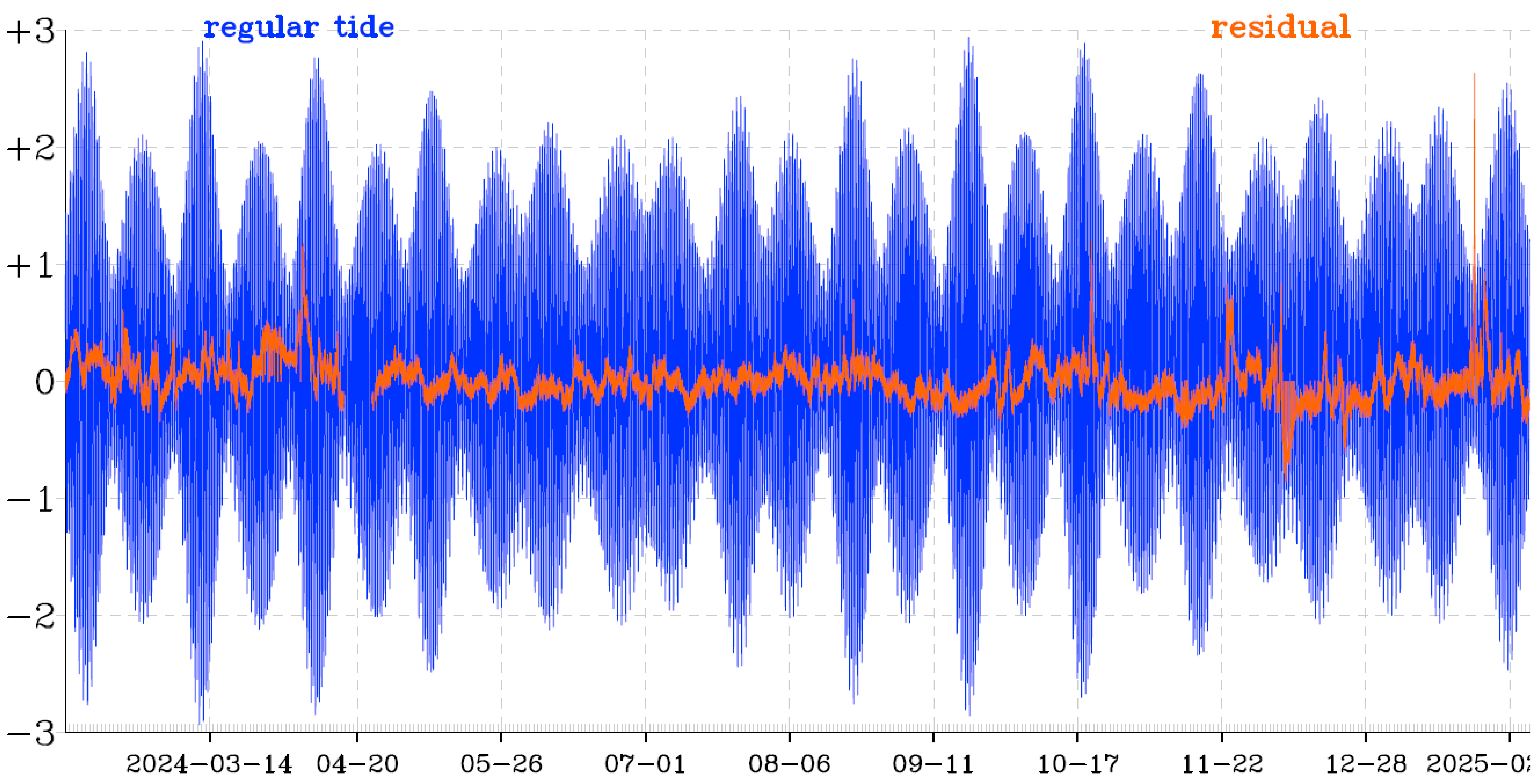
Tidal spectrum computed from Galway Port tidal gauge data. The data was collected from February 2007 to May 2025 (present time) as 6-minute, later 5-minute time series are available for approximately 95% of time for the entire period, $\approx 1.96 \times 10^{+6}$ samples overall. All were used to compute this spectrum. This spectrum consists of 46 main (*astronomical*, incl. 18.6-year MN) constituents, 101 *shallow-water*, and 123 *satellites* (hence 270 total).



Decomposition of regular tidal signal into spectral bands (plotted in the same scale), based on the spectrum above. Exactly one year is shown.

How we determine coastal flood risks?

Storm Eowyn, January 2025



Decomposition of the observed signal into regular tidal cycle (blue) and residual (orange). Storm Éowyn appears on this plot as the 2.6 meter spike in residual on 24 January 24 2025 (close to the right end of the plot).

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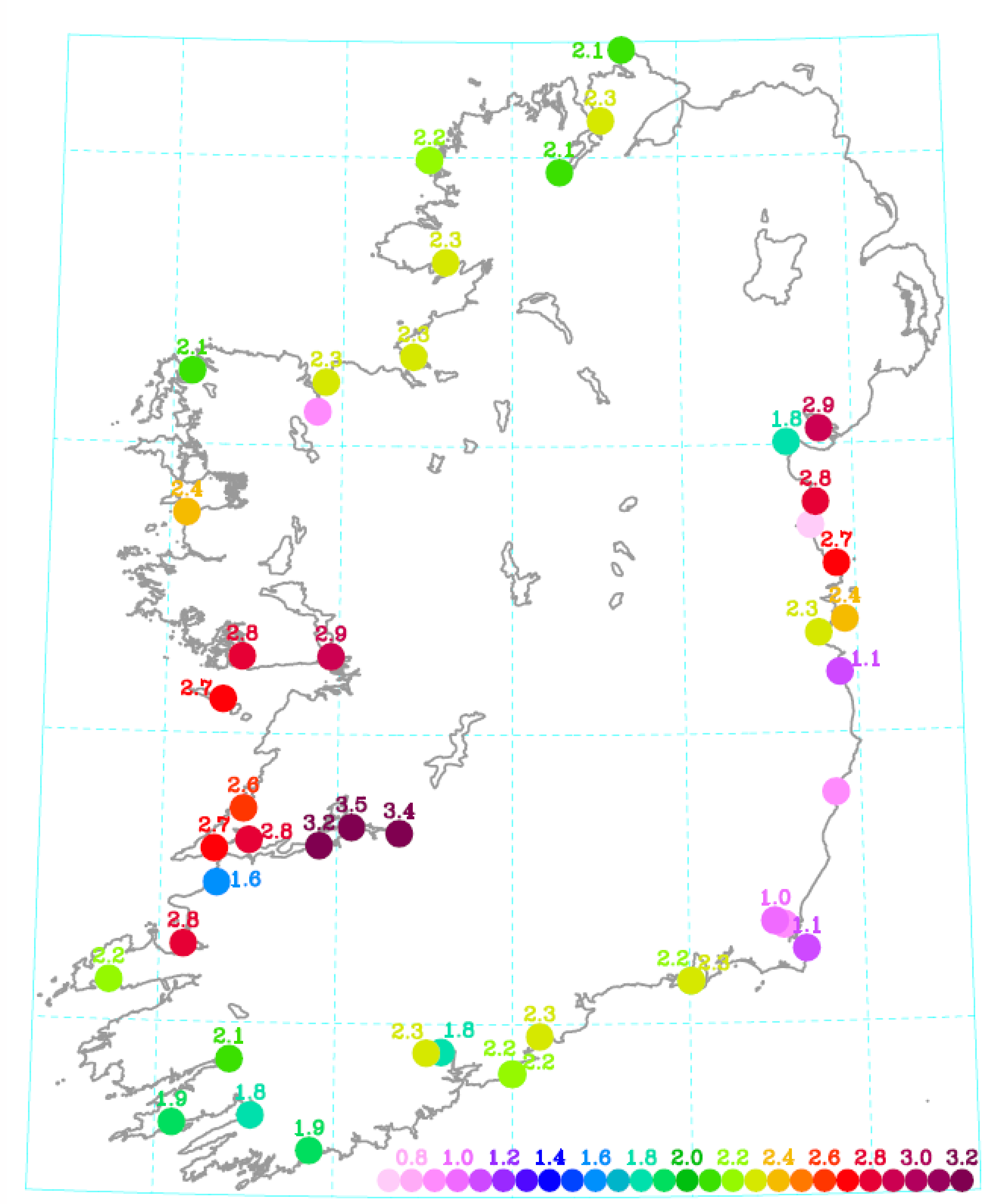
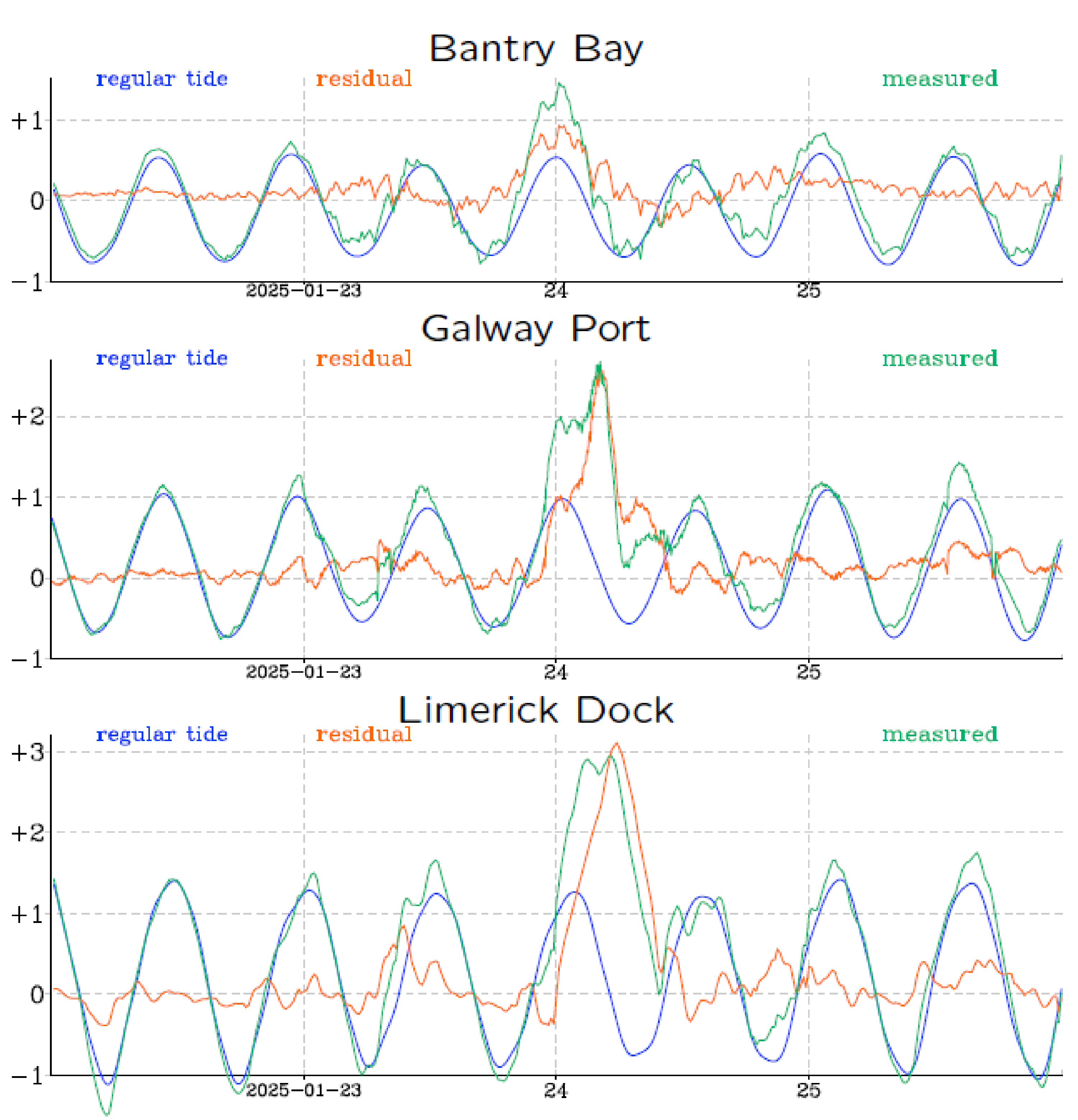
How do we determine coastal flood risks?

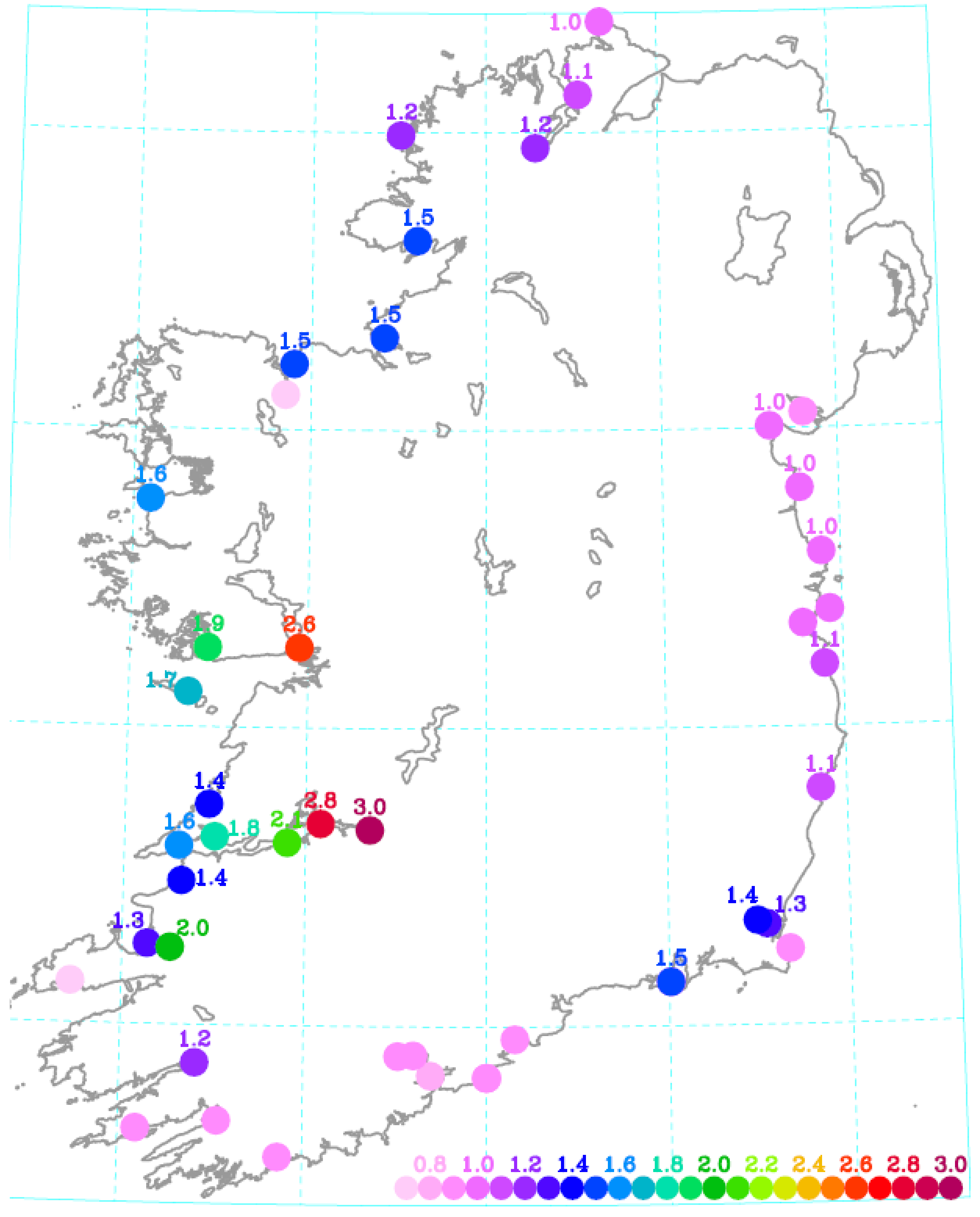
Storm Eowyn, January 2025

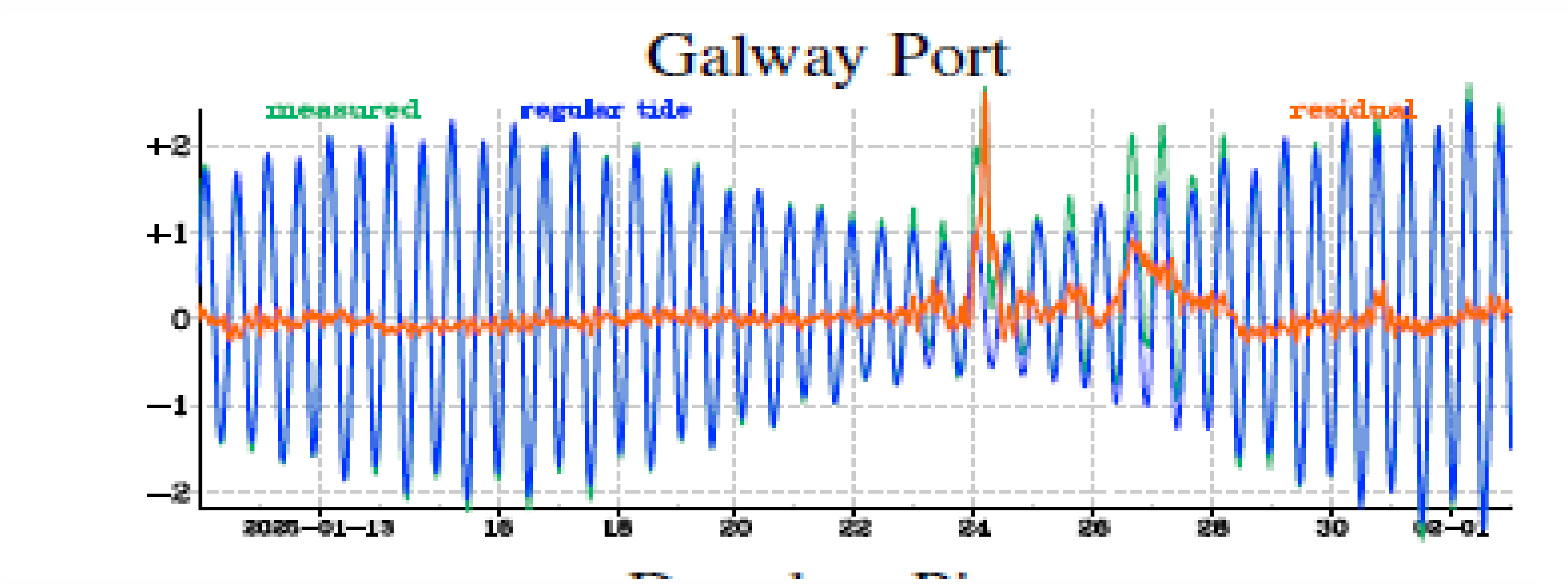
Max amplitude tide

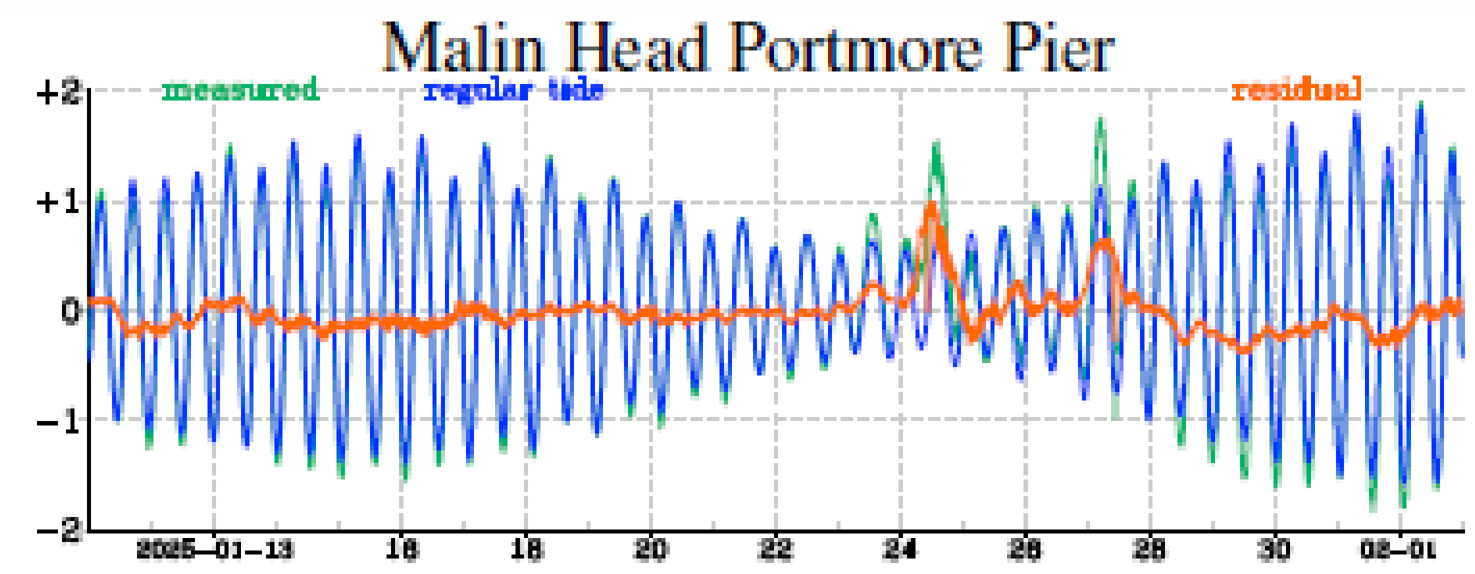


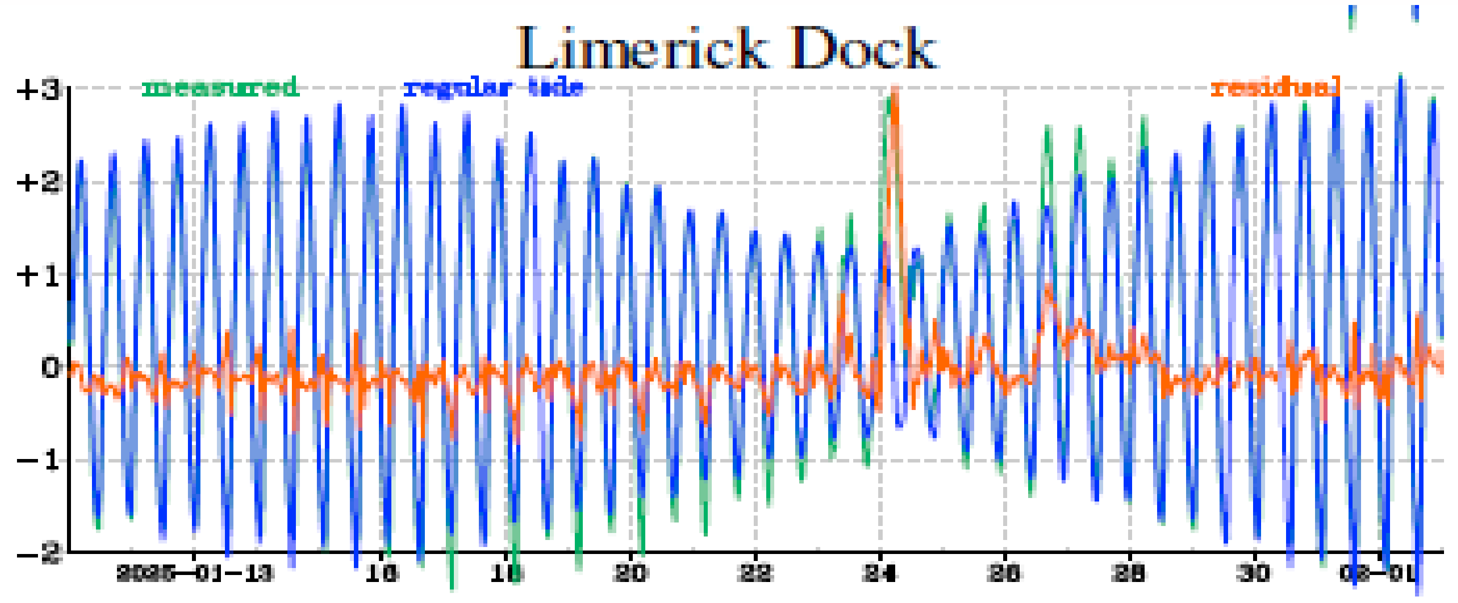


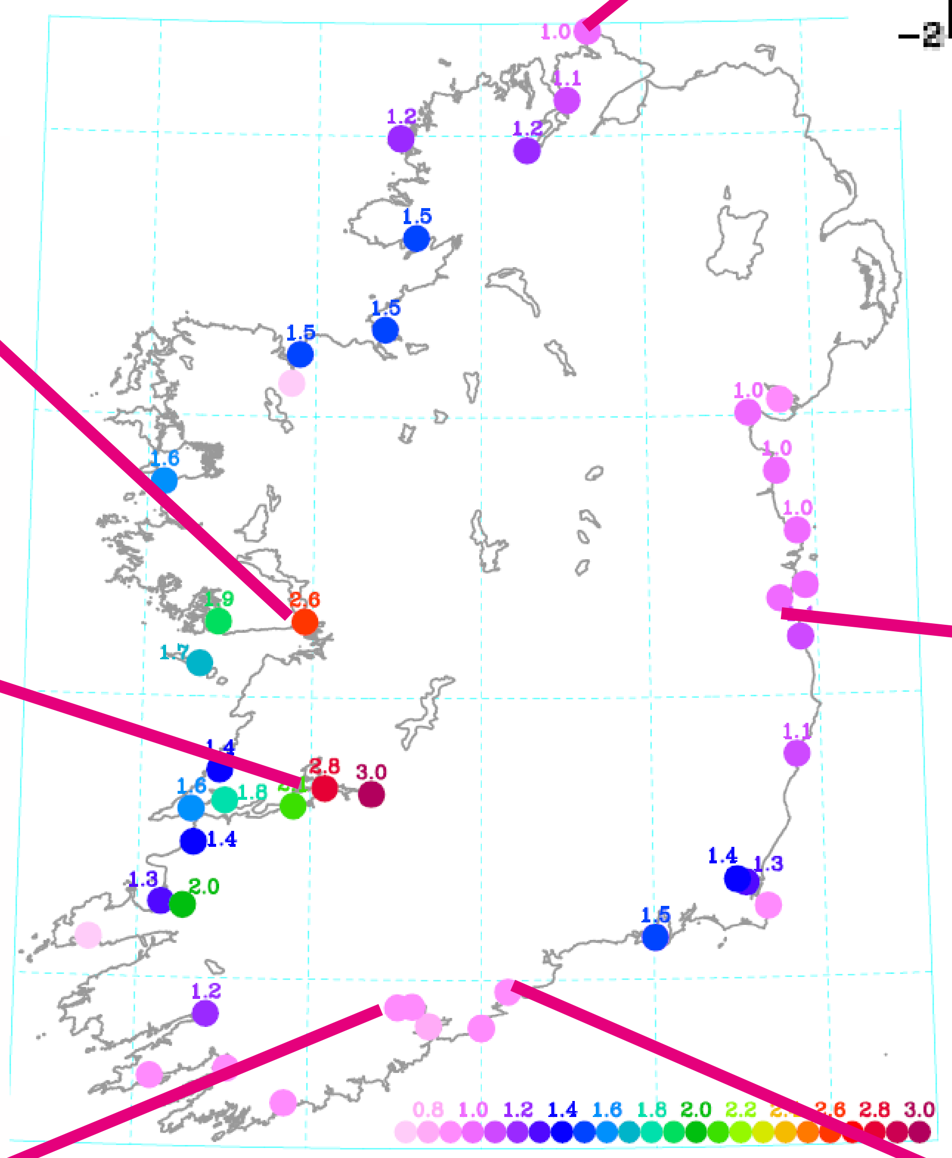
Storm surge residual

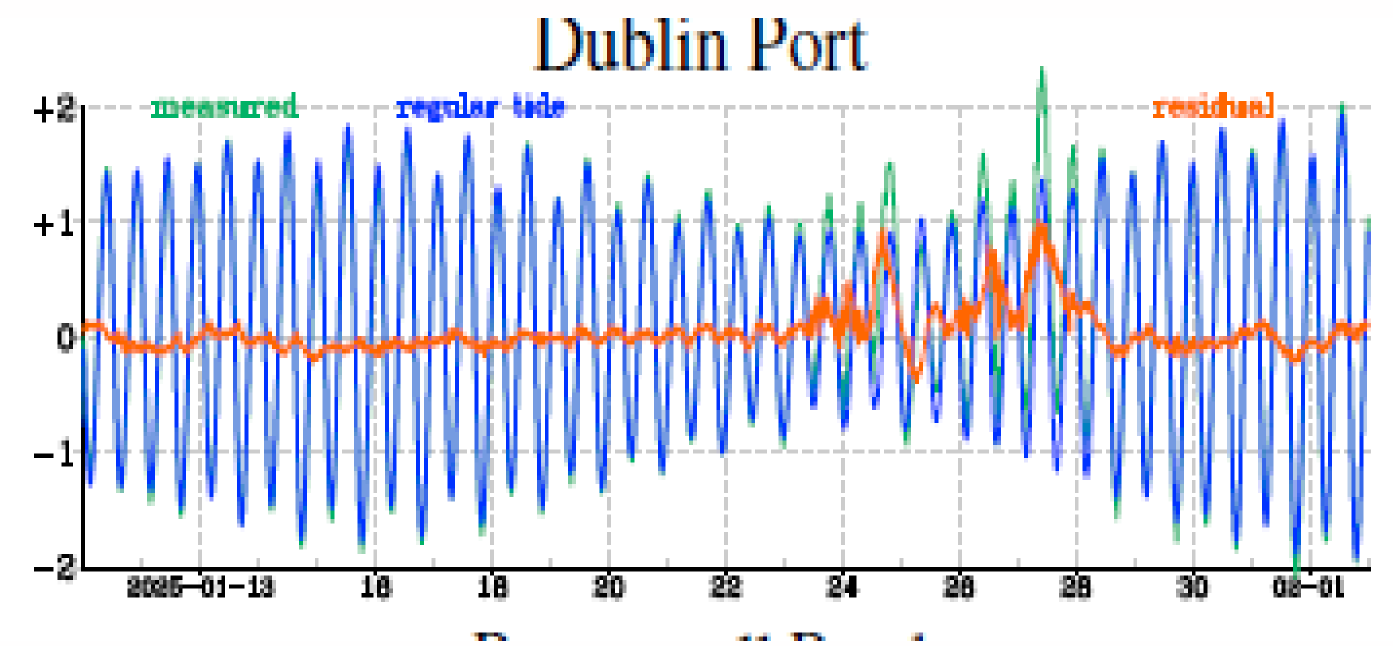


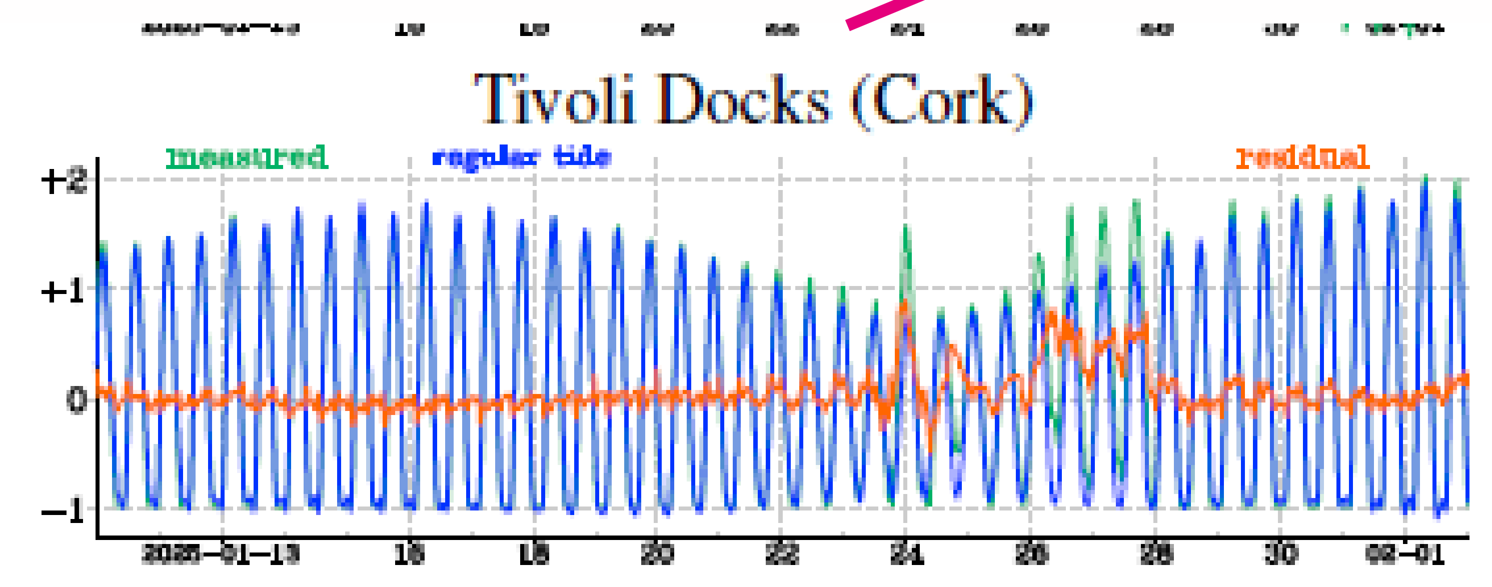

Galway Port
measured
regular tide
residual
+2
+1
0
−1
−2
2025−01−13
16
18
20
22
24
26
28
30
02−01

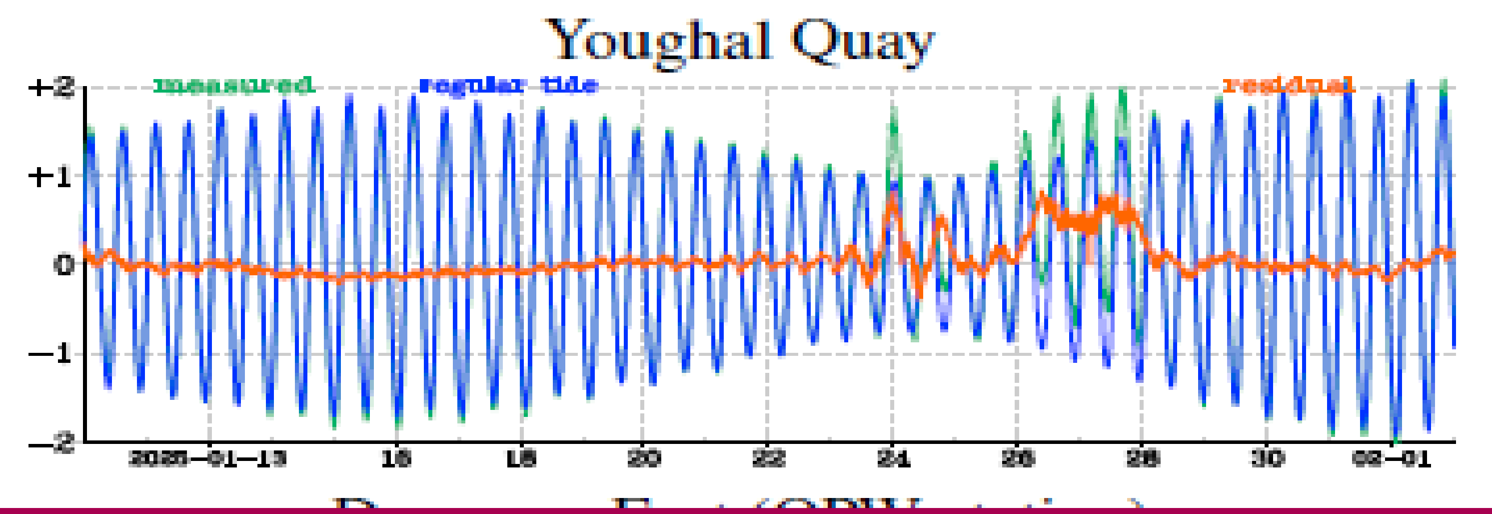

Malin Head Portmore Pier
measured
regular tide
residual
+2
+1
0
−1
−2
2025−01−13
16
18
20
22
24
26
28
30
02−01


Limerick Dock
measured
regular tide
residual
+3
+2
+1
0
−1
−2
2025−01−13
16
18
20
22
24
26
28
30
02−01


0.8
1.0
1.2
1.4
1.6
1.8
2.0
2.2
2.6
2.8
3.0


Dublin Port
measured
regular tide
residual
+2
+1
0
−1
−2
2025−01−13
16
18
20
22
24
26
28
30
02−01


Tivoli Docks (Cork)
measured
regular tide
residual
+2
+1
0
−1
2025−01−13
16
18
20
22
24
26
28
30
02−01


Youghal Quay
measured
regular tide
residual
+2
+1
0
−1
−2
2025−01−13
16
18
20
22
24
26
28
30
02−01

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Tide-surge interactions

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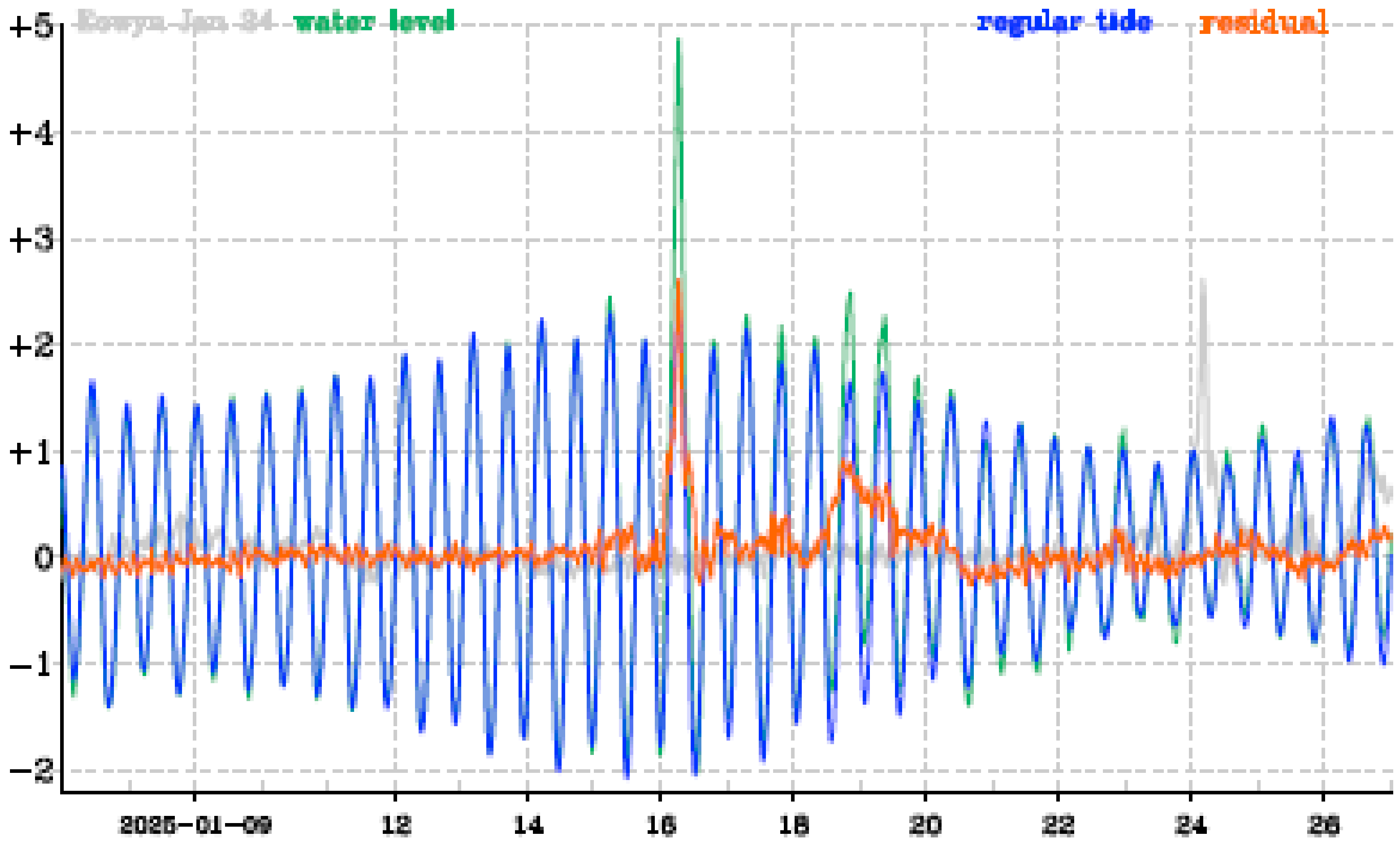
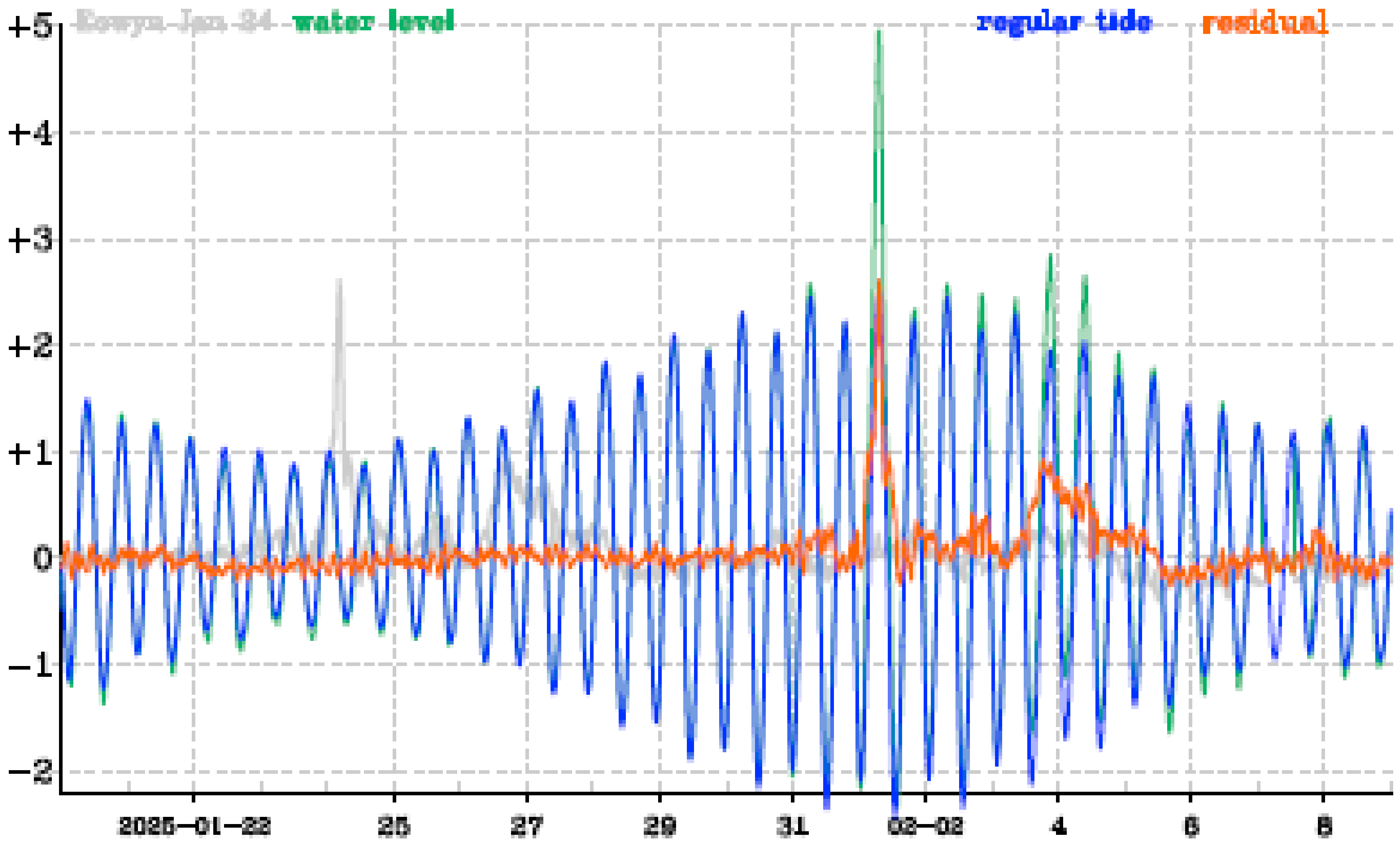
How do we determine coastal risks?

Worst-case scenario





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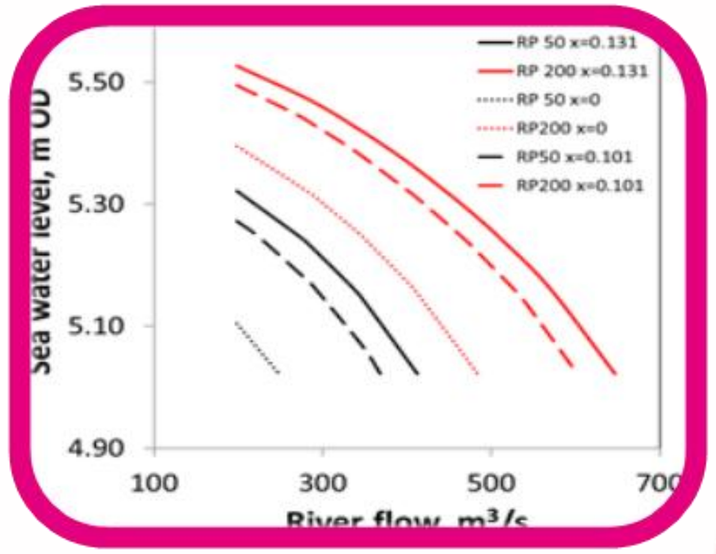
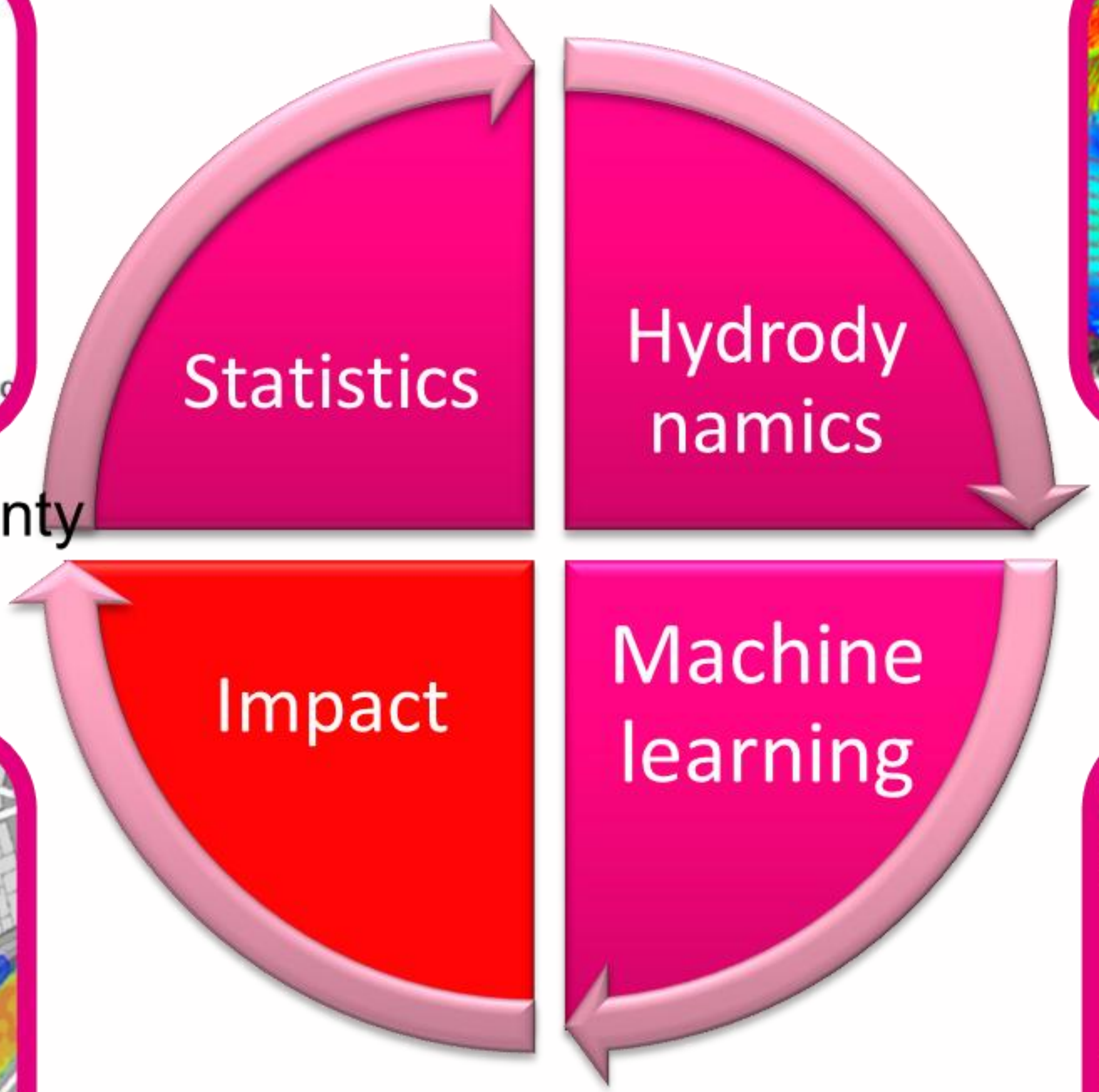
How we determine coastal flood risks?

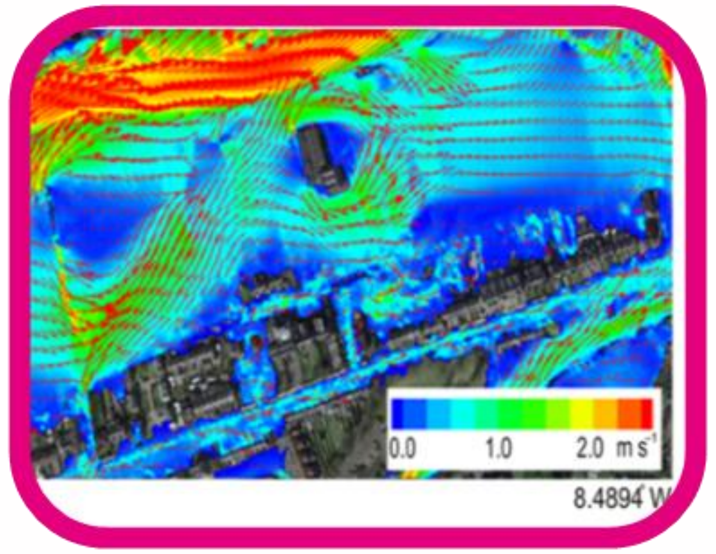
Compound floods are complex so they need complex analysis

Methodology



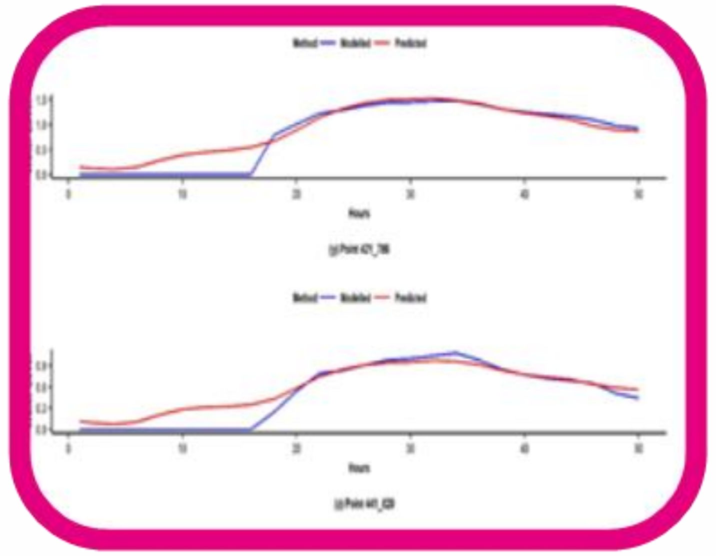
Probability + uncertainty





Flood mechanisms + inundation

Damage assessment



Flood forecasting

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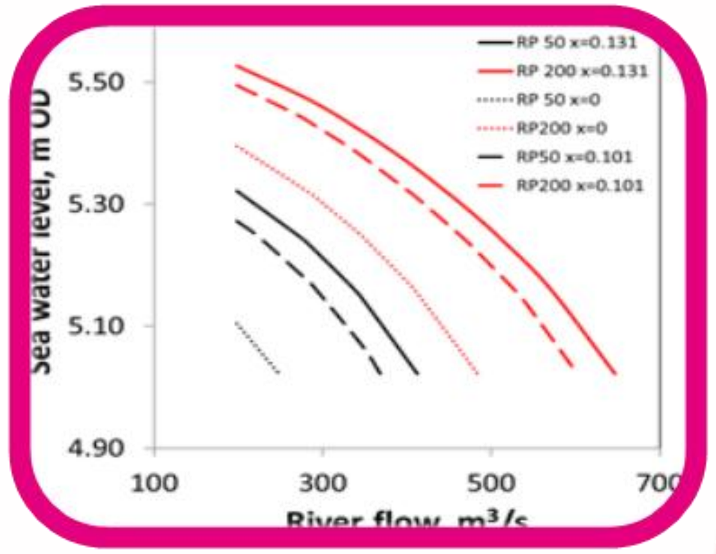
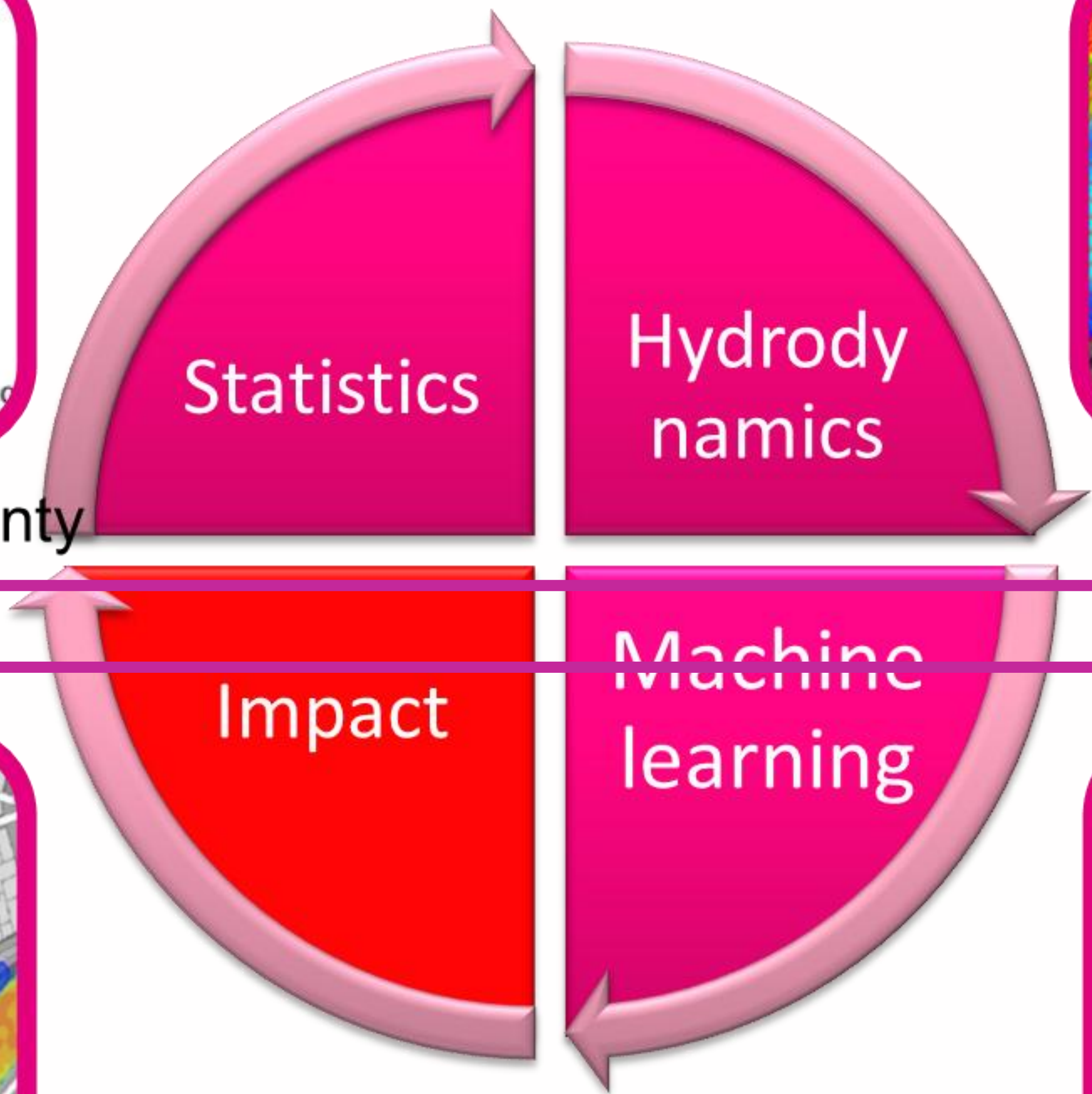
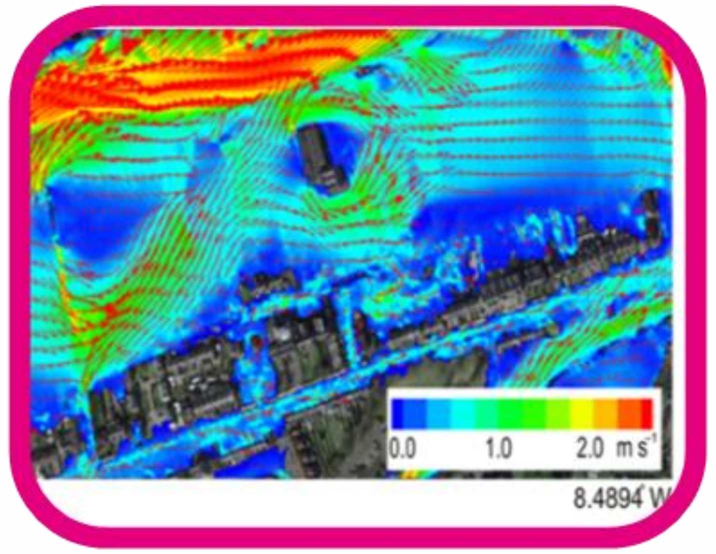
How do we determine coastal flood risks?

Flood risk assessment and hazard mapping



Probability + uncertainty

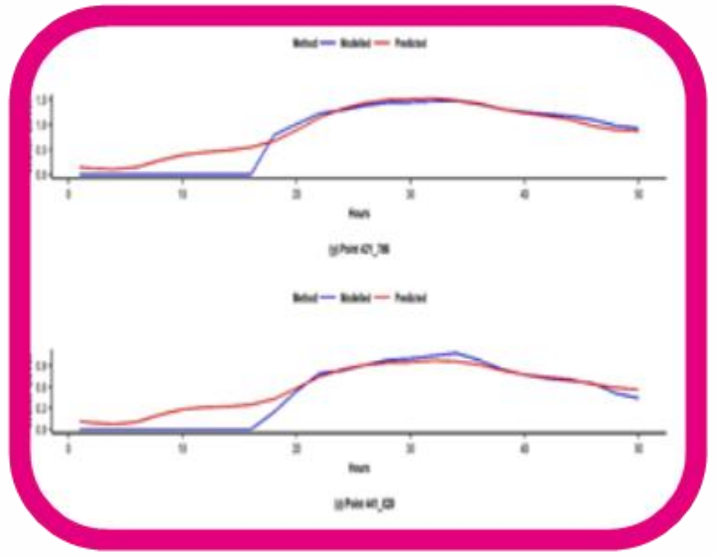




Flood mechanisms + inundation

Climate adaptation: Grey infrastructure, Early warning

Damage assessment



Flood forecasting

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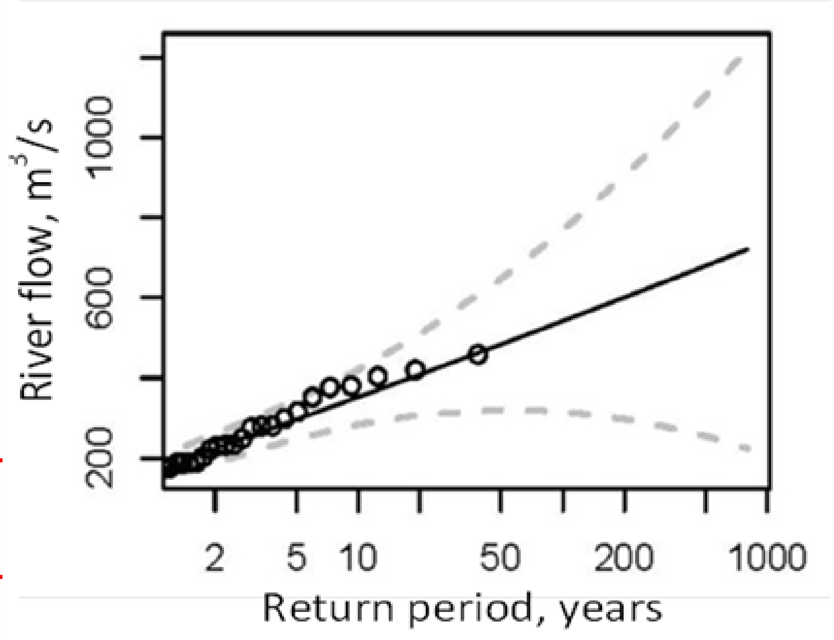
How do we determine coastal flood risks?

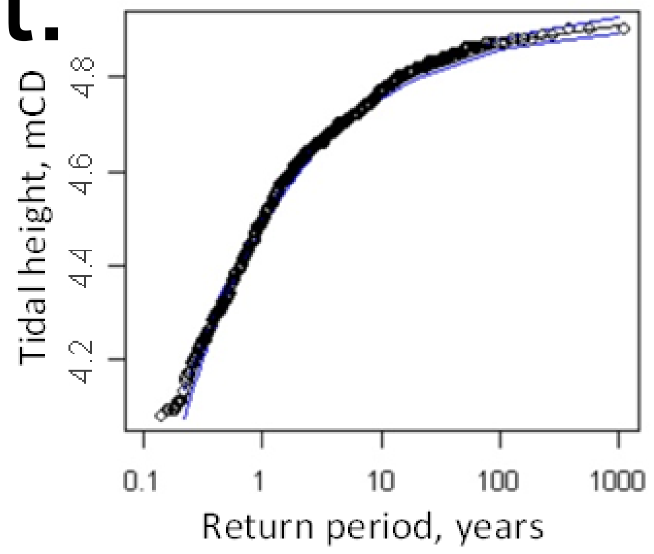
1. Statistical model

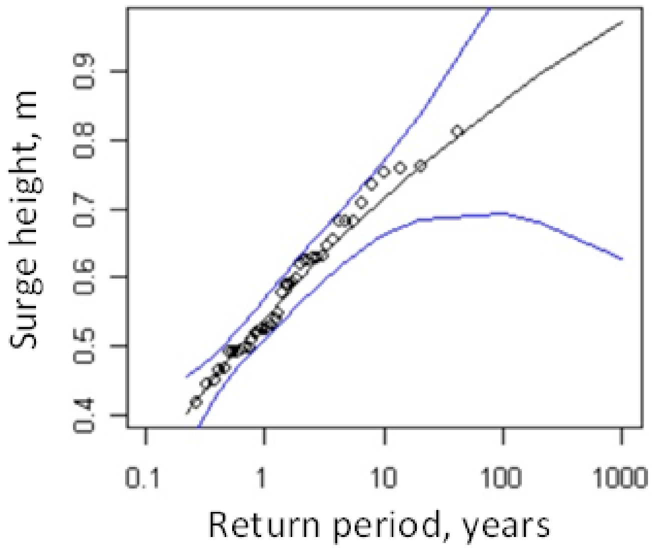
1. Data Collection
2. Extreme value analysis
3. Multivariate dependence analysis
4. Joint probability of extremes



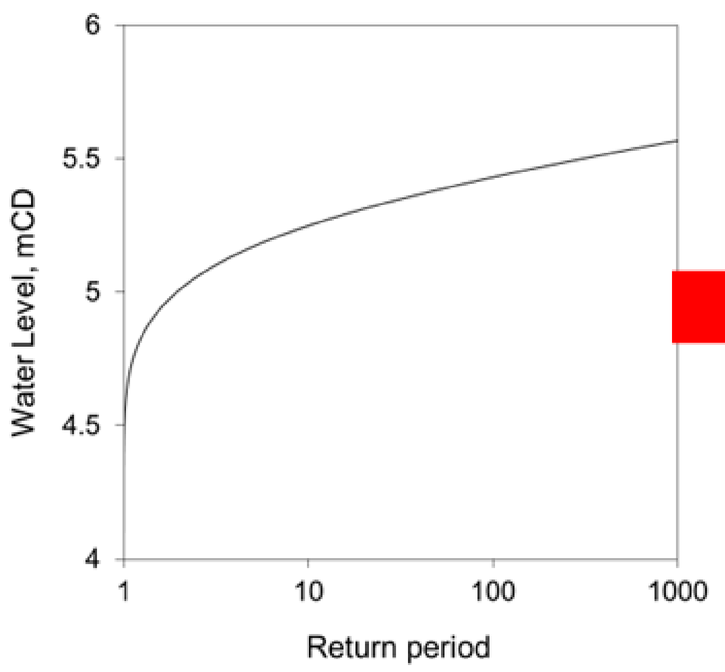
Flood risk assessment:

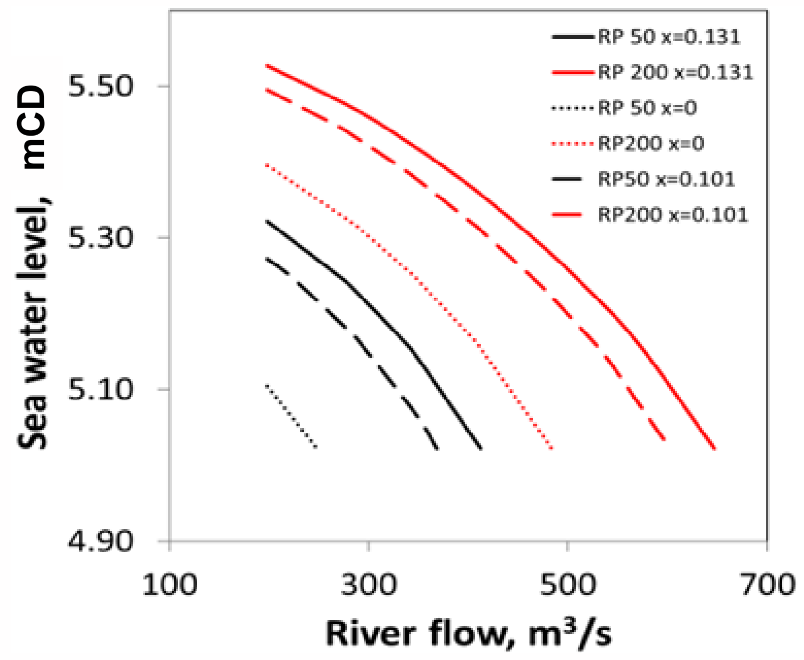
- Dependencies
- Interactions
- Marginal RPs
- Joint Probabilities





Trivariate joint probability





How do we determine coastal risks?

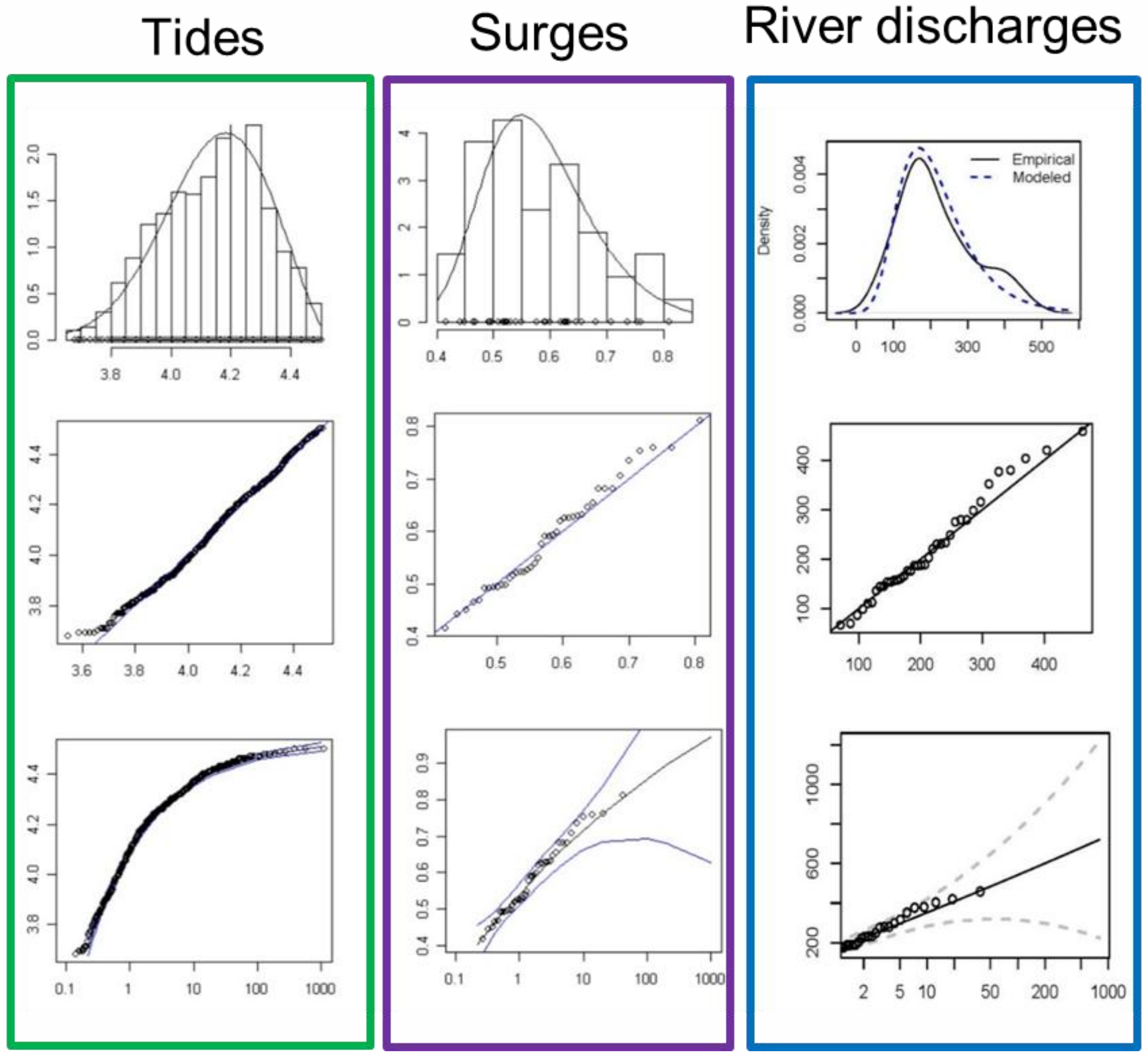
1. Statistical model

1. Data Collection

2. Extreme value analysis

Coastal drivers

Fluvial driver



How do we determine coastal risks?

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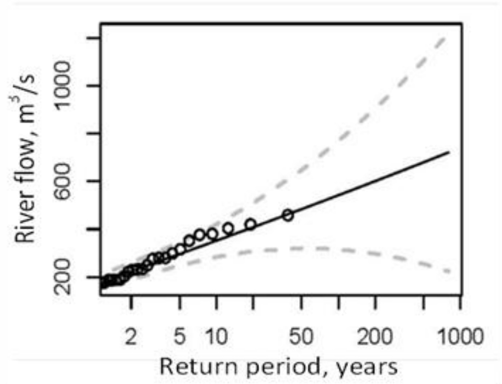
1. Statistical model

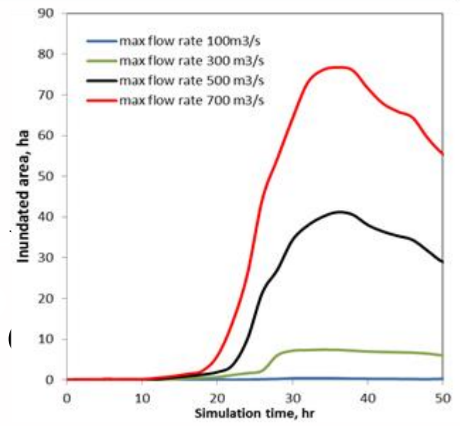
Univariate marginal analysis

1. Data Collection
2. Extreme vale analysis

Fluvial flooding

River discharge

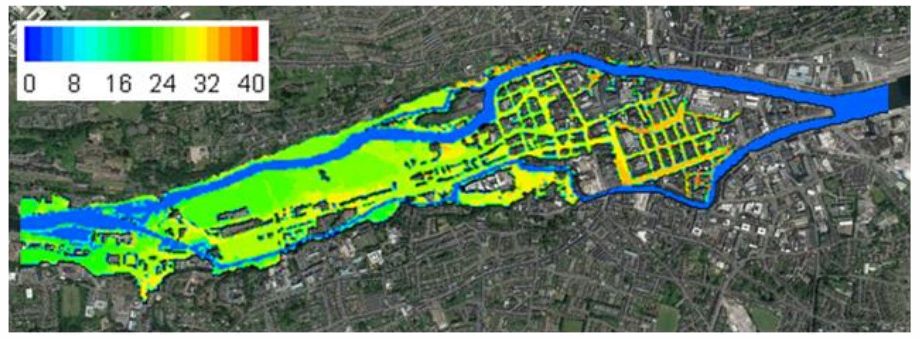




300m³/s

500m³/s

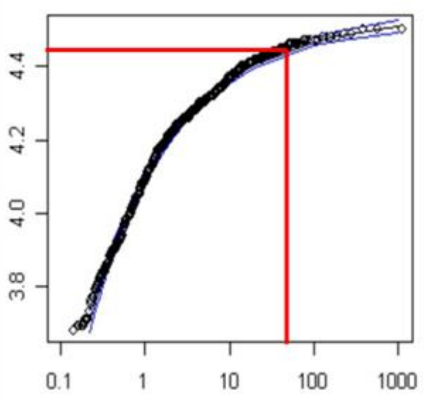
700m³/s



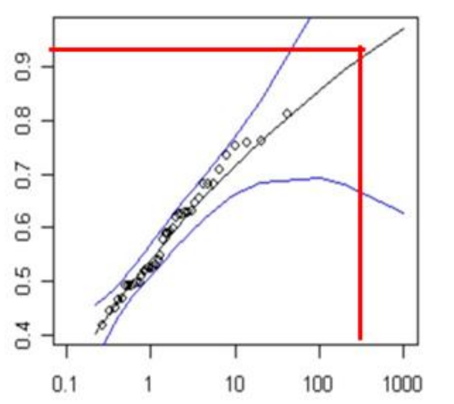
1. Data Collection
2. Extreme vale analysis

Coastal flooding

Tide

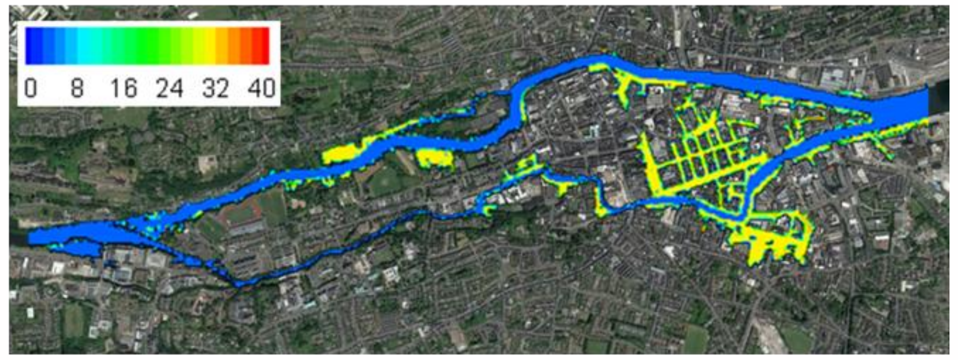


Surge



50RP tide +200RP surge MF

50RP tide +200RP surge HW



How do we determine coastal risks?

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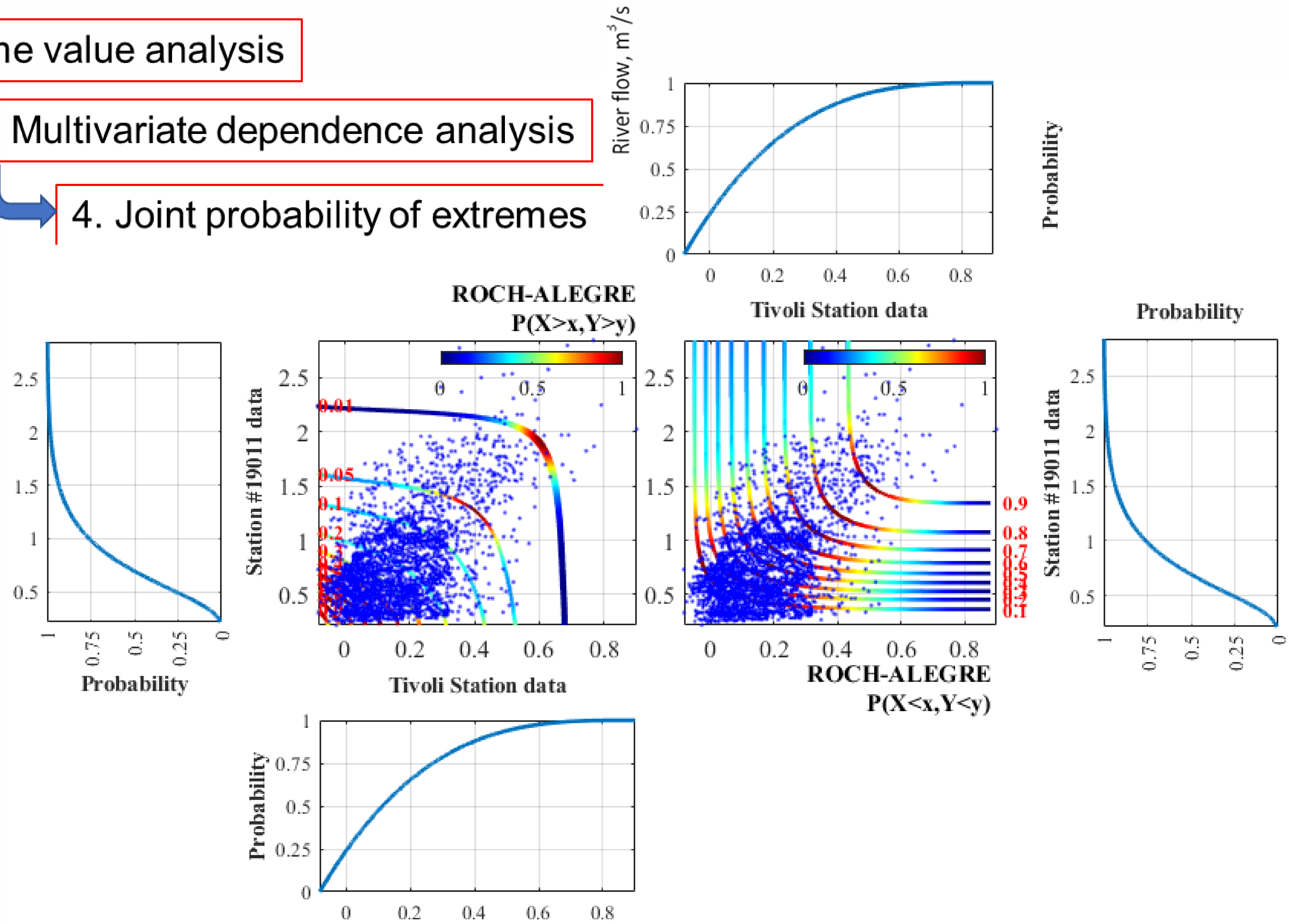
1. Statistical model

1. Data Collection
2. Extreme value analysis
3. Multivariate dependence analysis
4. Joint probability of extremes



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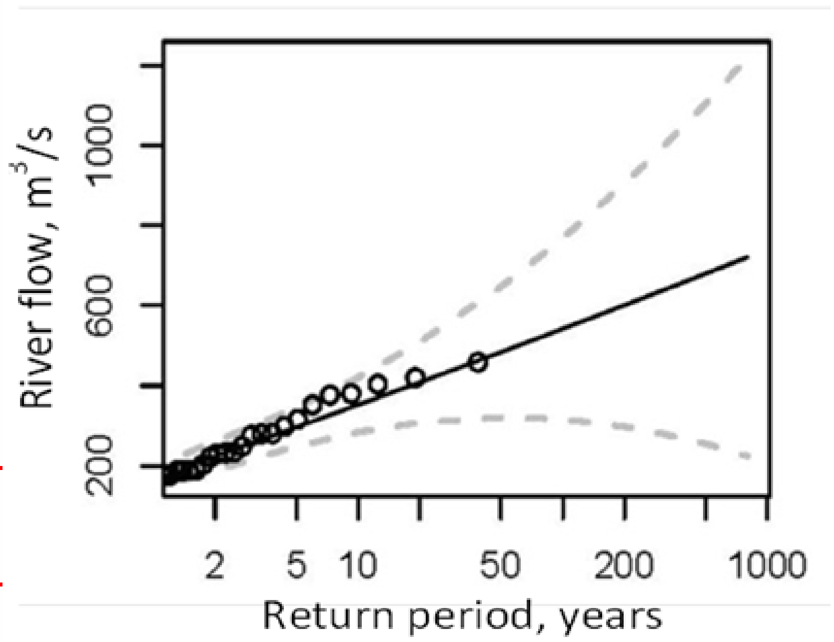
How do we determine coastal flood risks?

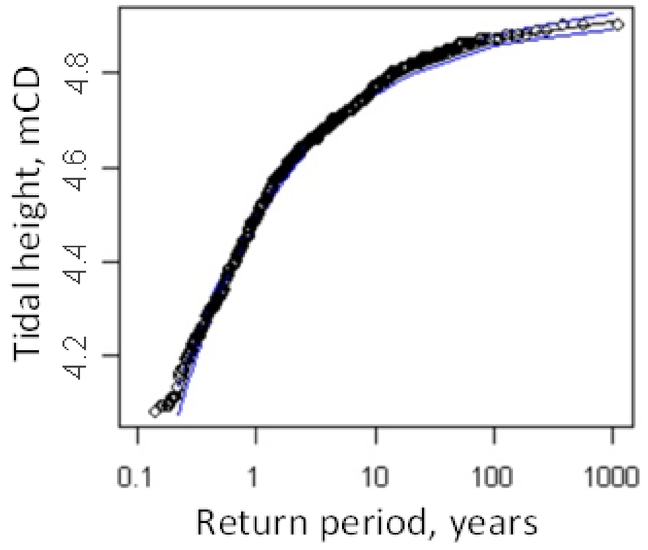
1. Statistical model

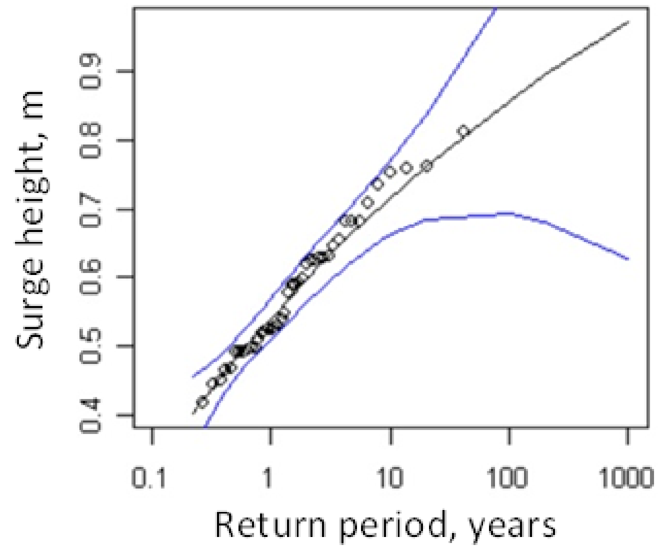
1. Data Collection
2. Extreme value analysis
3. Multivariate dependence analysis
4. Joint probability of extremes



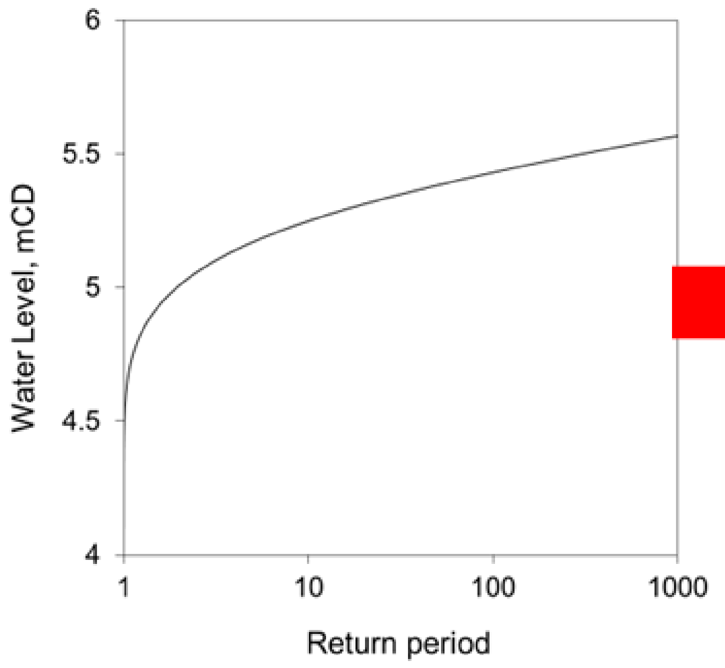
Flood risk assessment:

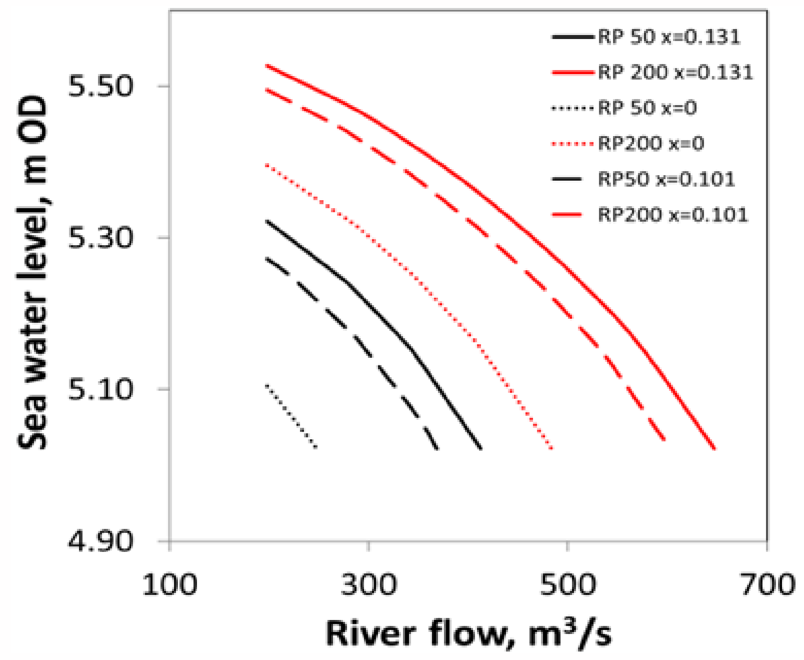
- Dependencies
- Interactions
- Marginal RPs
- Joint Probabilities





Trivariate joint probability





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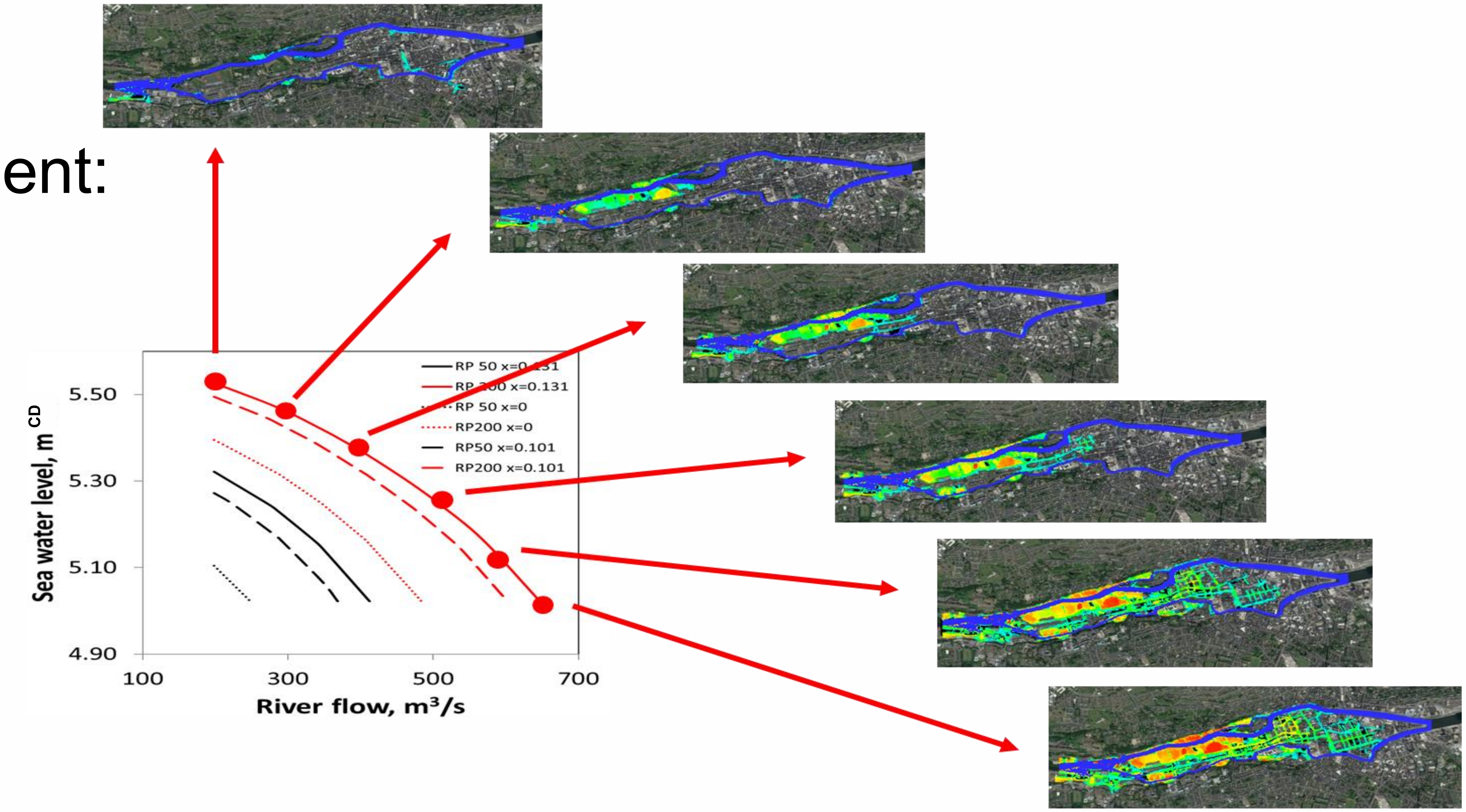
How do we determine coastal flood risks?

2.Hydrodynamic Model

Need to consider a range of scenarios

Flood risk assessment:

- Dependencies
- Interactions
- Marginal RPs
- Joint Probabilities



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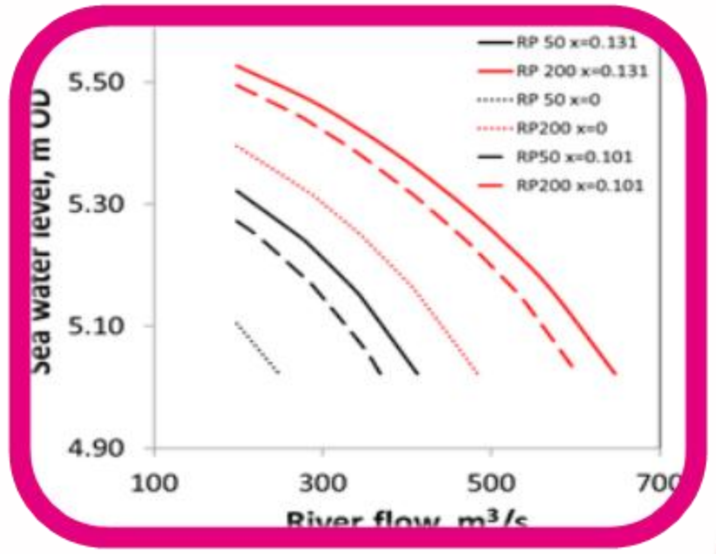
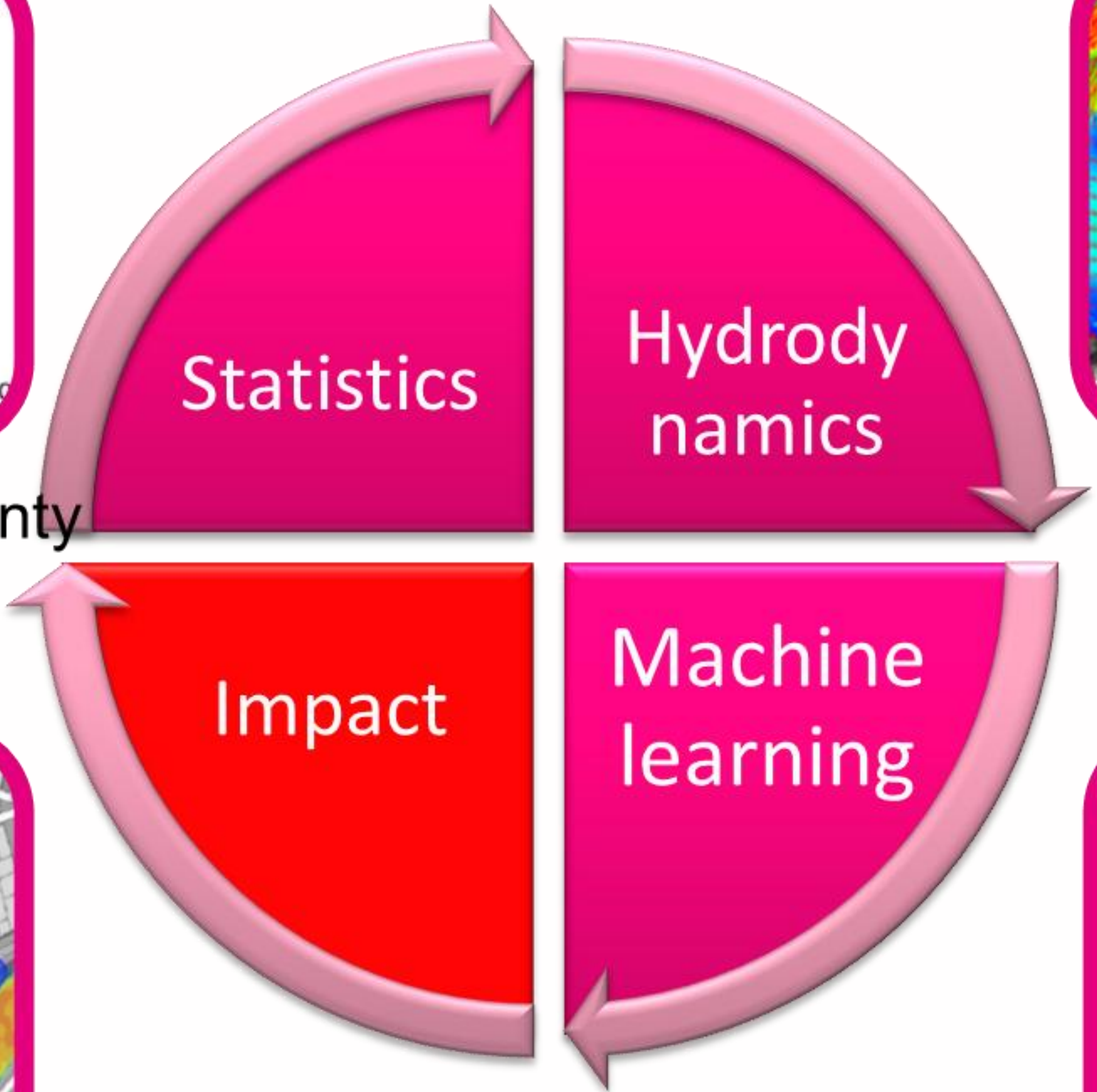
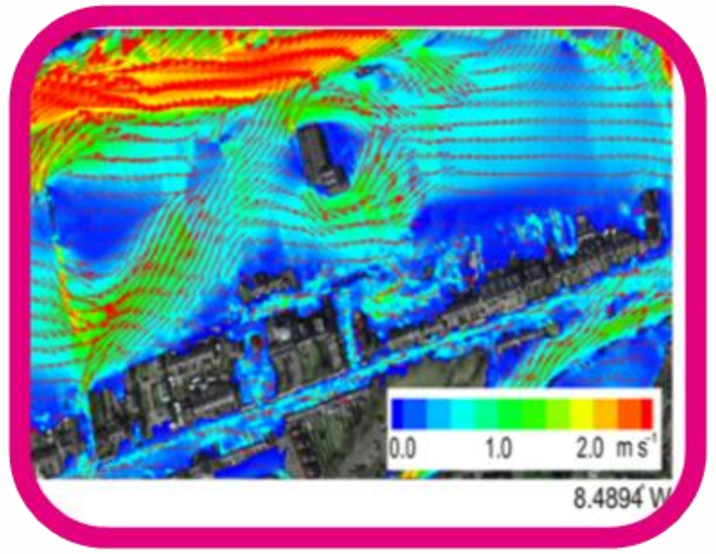
Methodology



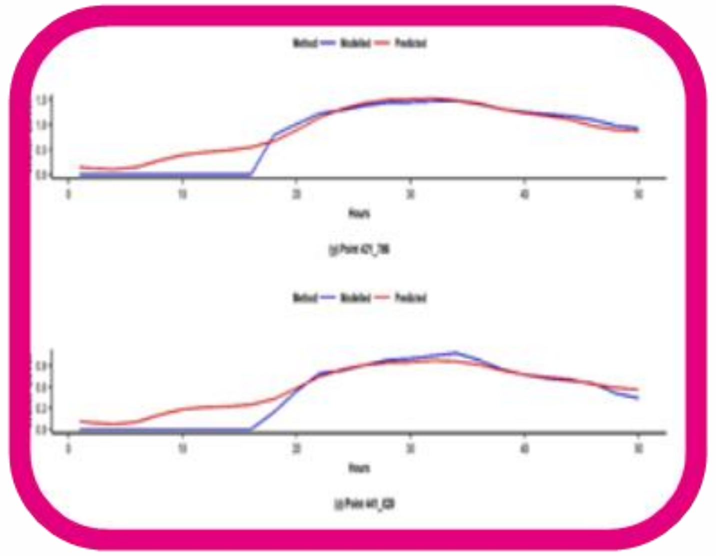
Probability + uncertainty





Flood mechanisms + inundation

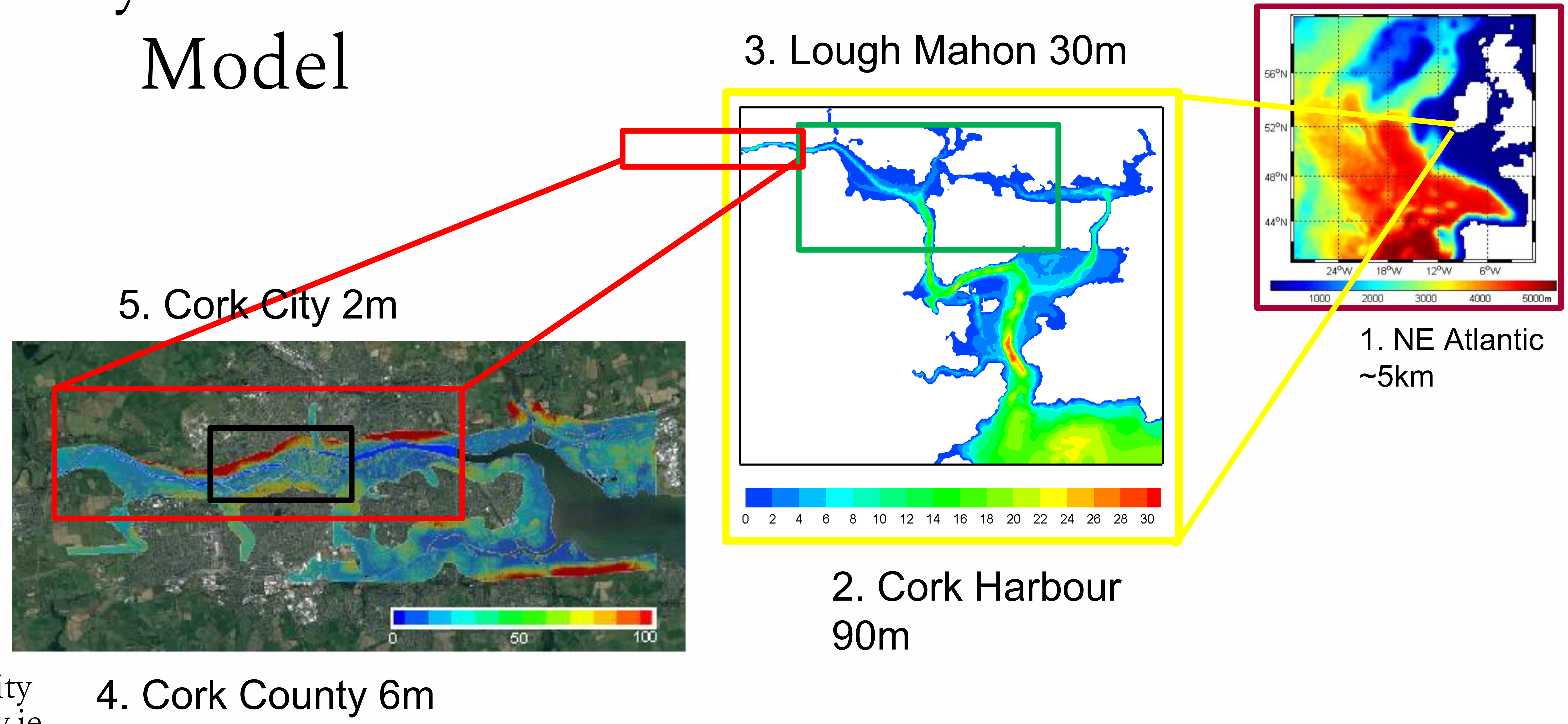
Damage assessment



Flood forecasting

2.Hydrodynamic Model

MPIOM → POM→ MNS_Flood



2.Hydrodynamic Model vs bathtub models

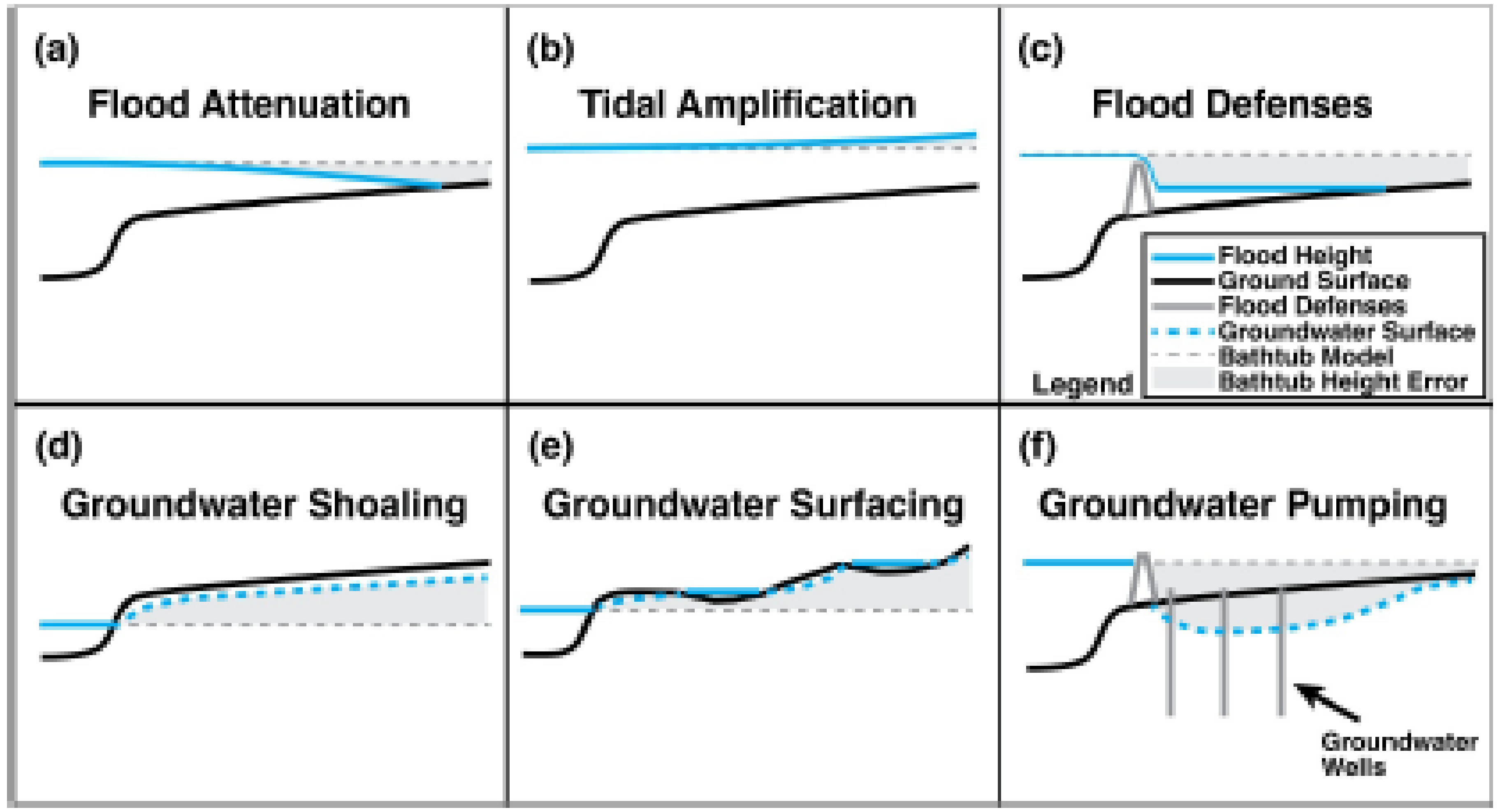
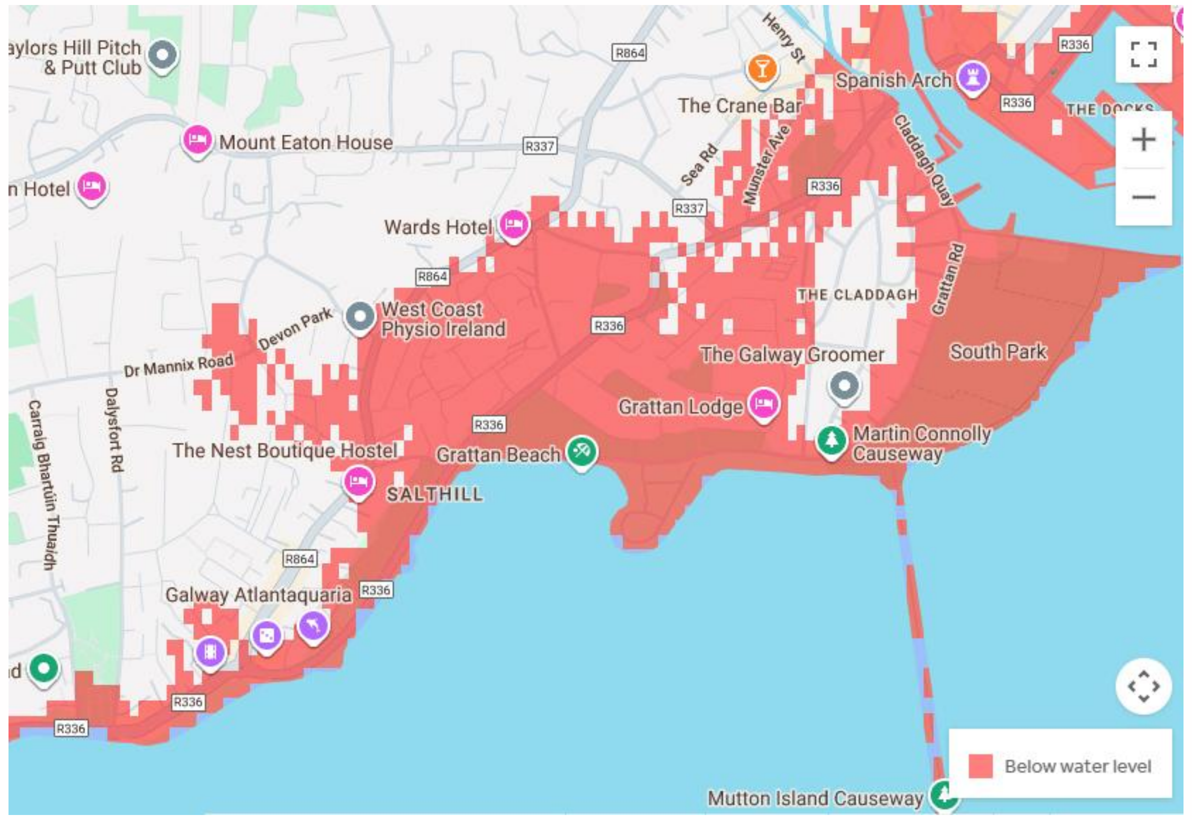


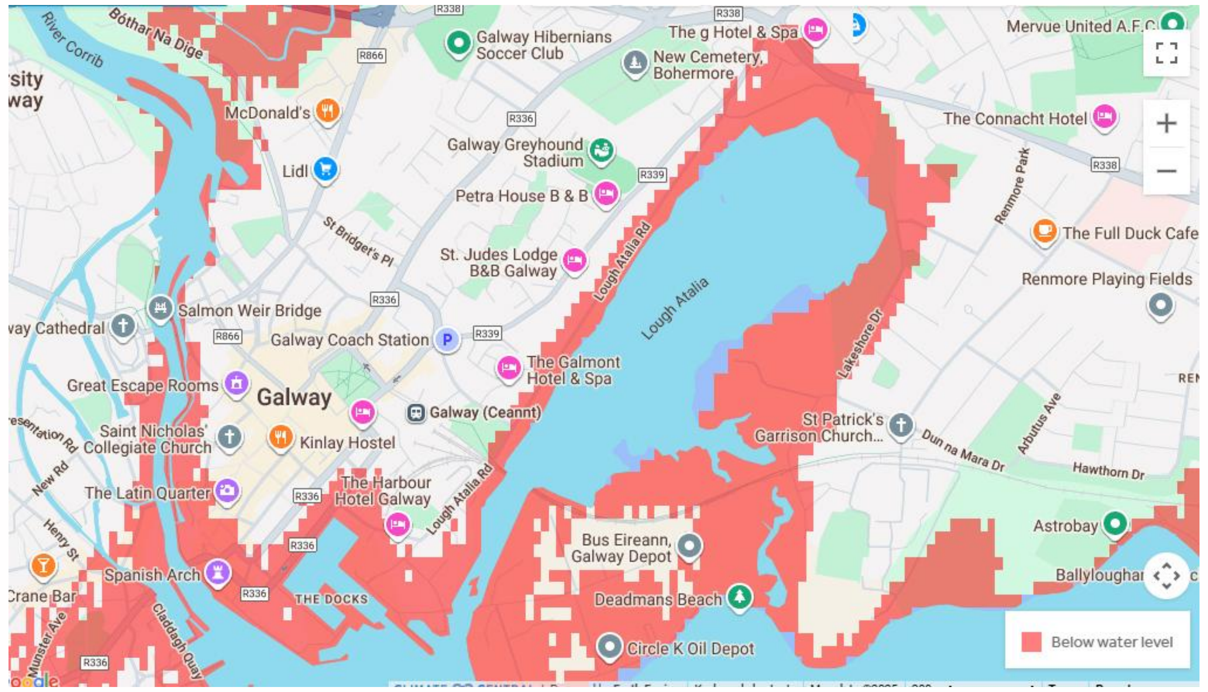
Figure 1. Examples of the limitations arising from bathtub modeling include the inability to capture: (a) flood attenuation from the effects of event dynamics and friction on flood spreading, (b) tidal amplification associated with the resonance of ocean tides within coastal embayments (e.g., Gallien et al., 2011), (c) flood defenses such as levees and flood walls that may overtop during an extreme event but still restrain the degree of inland flooding (e.g., Sanders et al., 2023), (d) shoaling of the groundwater table and (e) surfacing groundwater from the combined influence of rising sea levels and changing hydrologic budgets (Befus et al., 2020), and (f) pumping of groundwater within lands below sea level to mitigate inundation by rising groundwater.

Sanders et al. (2024)

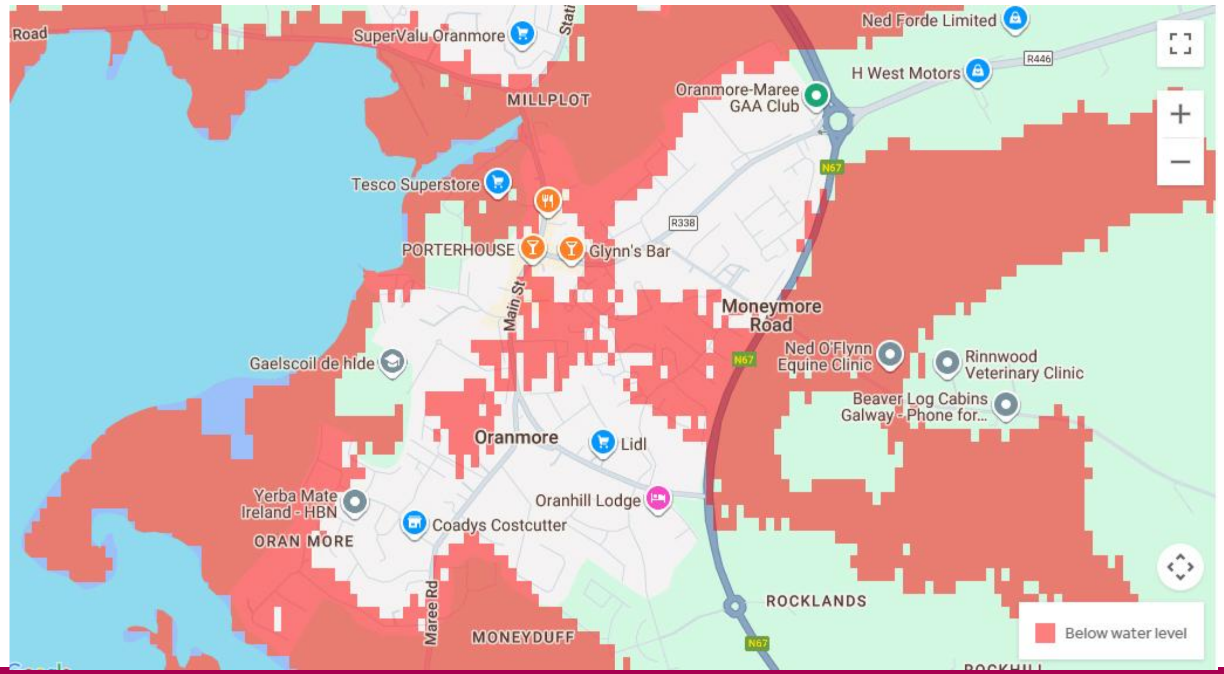
The Claddagh



Galway City



Oranmore

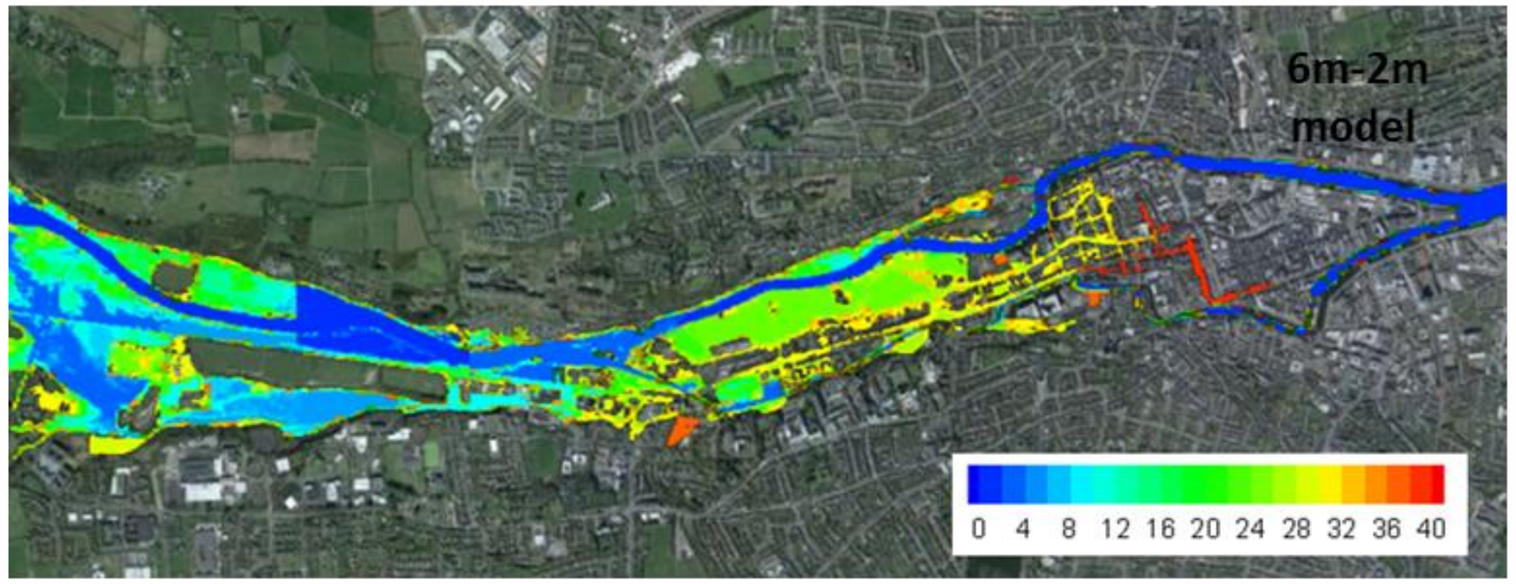


2.Hydrodynamic Model

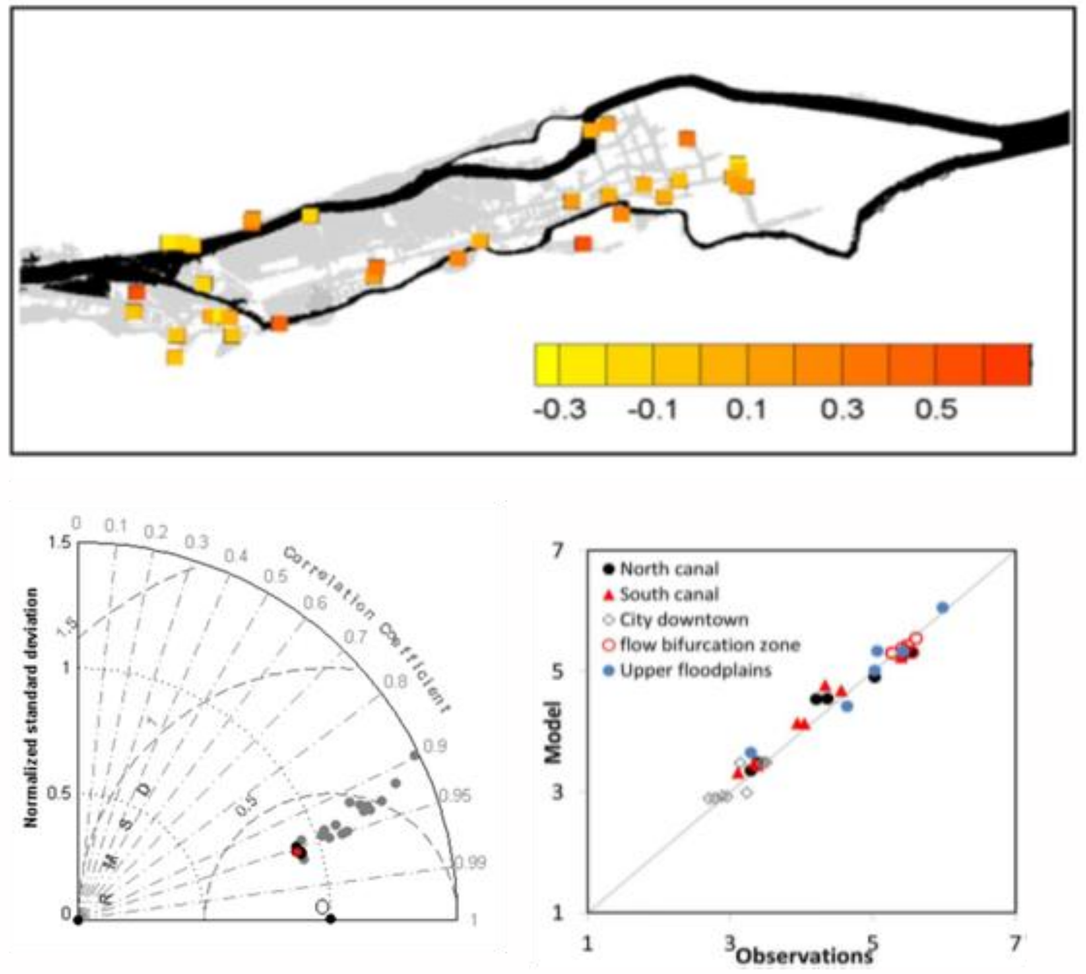
Model Validation

Cork City flood 19th/20th November 2009

Flood extent



Flood water height



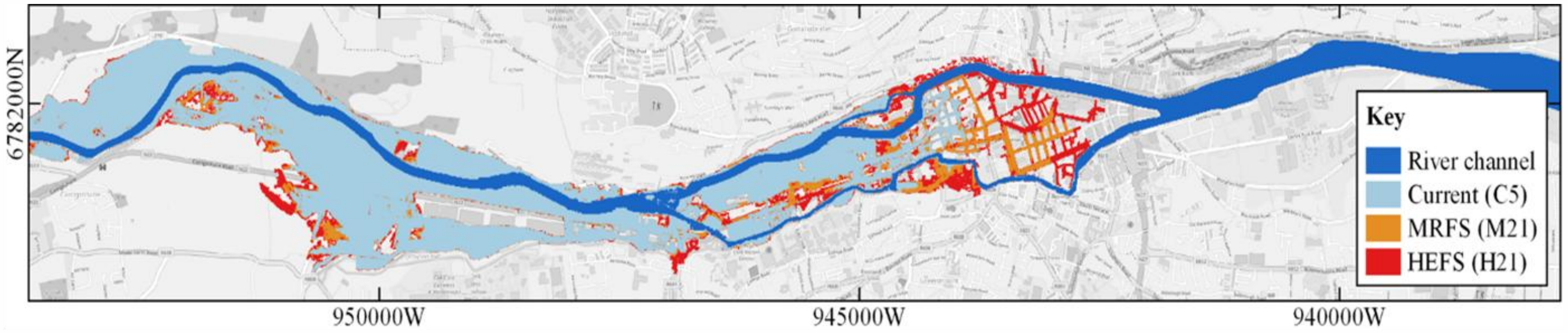
Coastal-fluvial flooding

2.Hydrodynamic Model

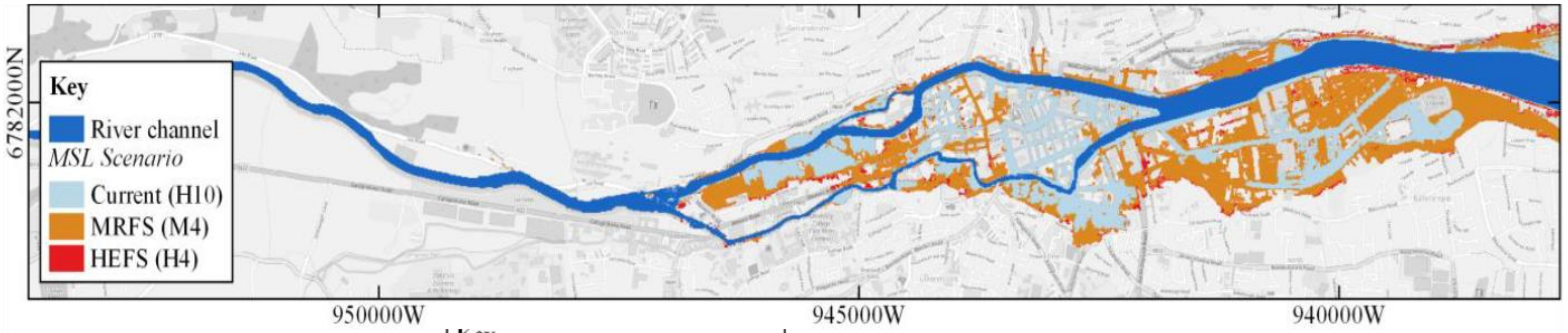
Flood mapping:

- **Water depth**
- **Inundation area**
- **Flood evolution**

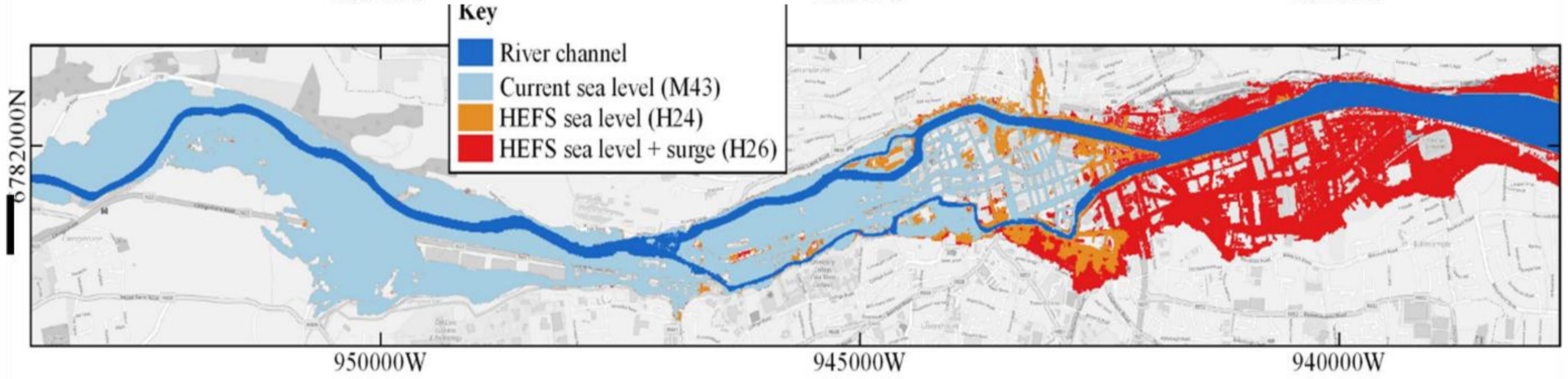
Fluvial



Coastal



Coastal-fluvial



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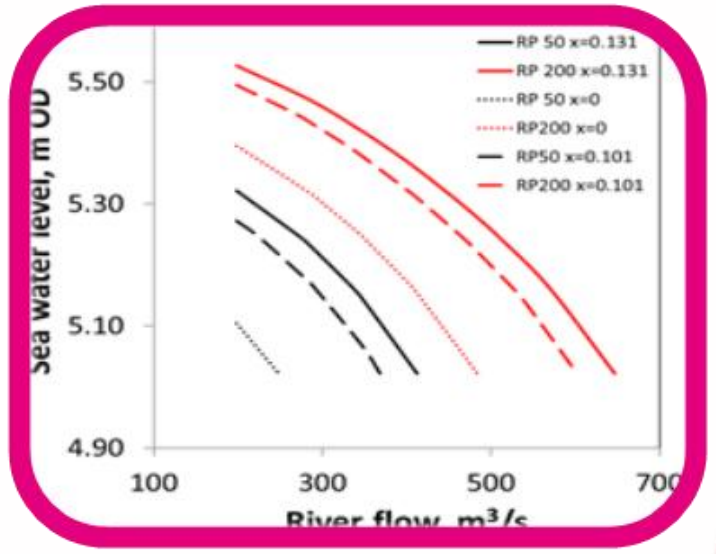
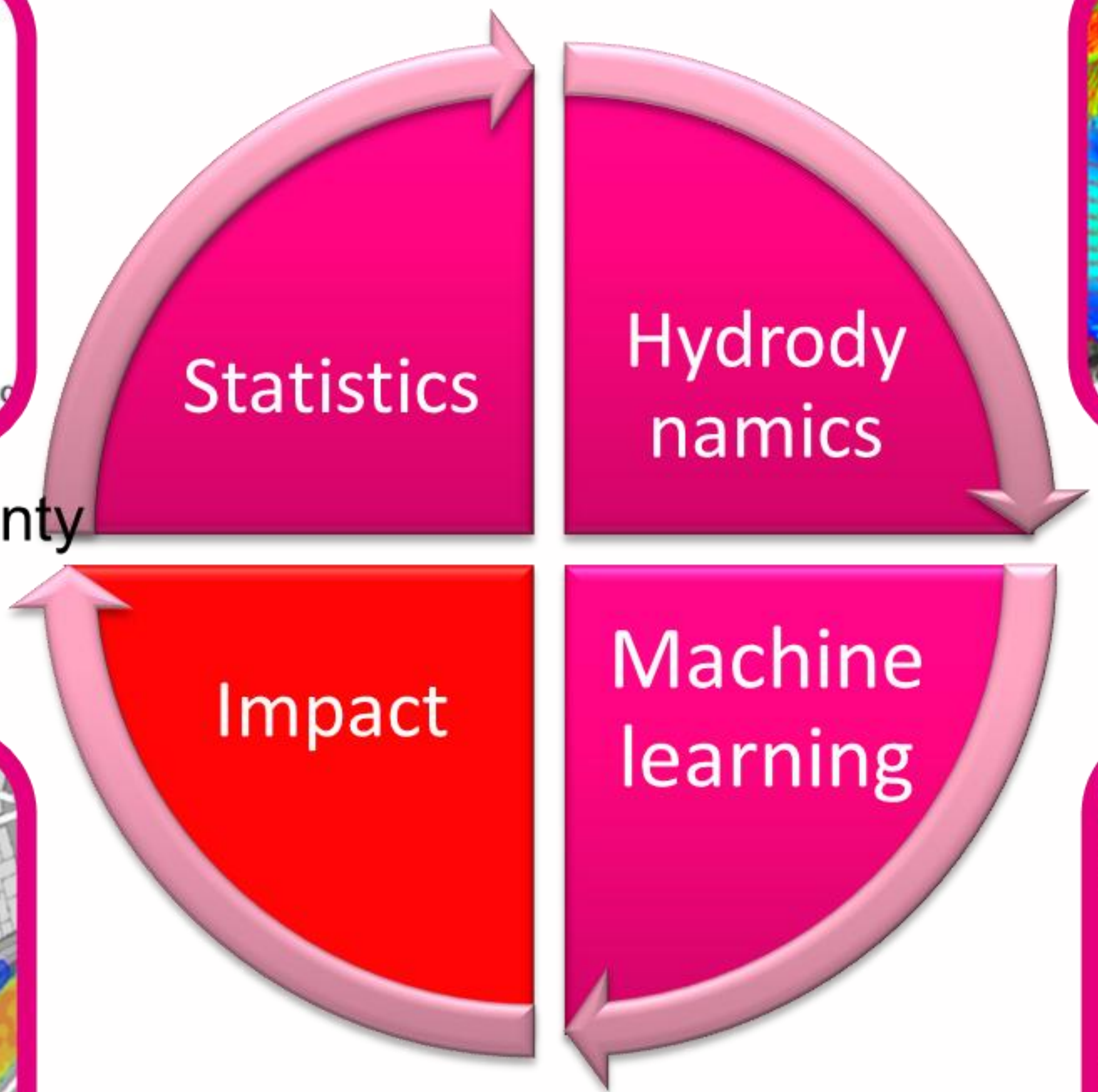
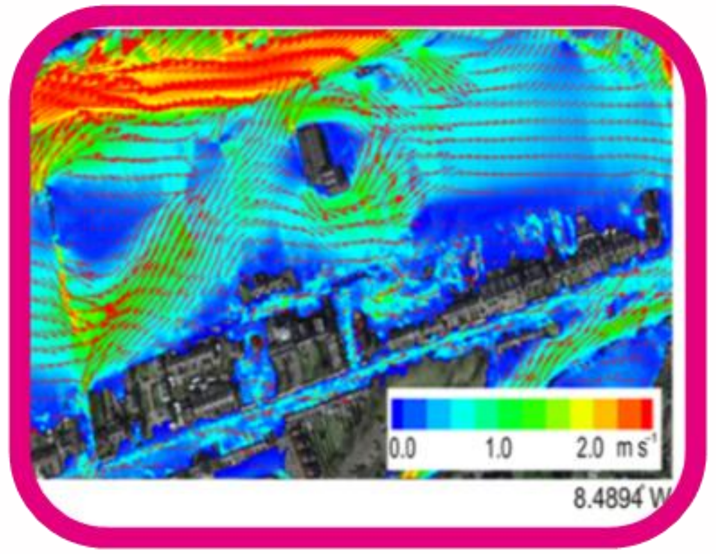
Methodology



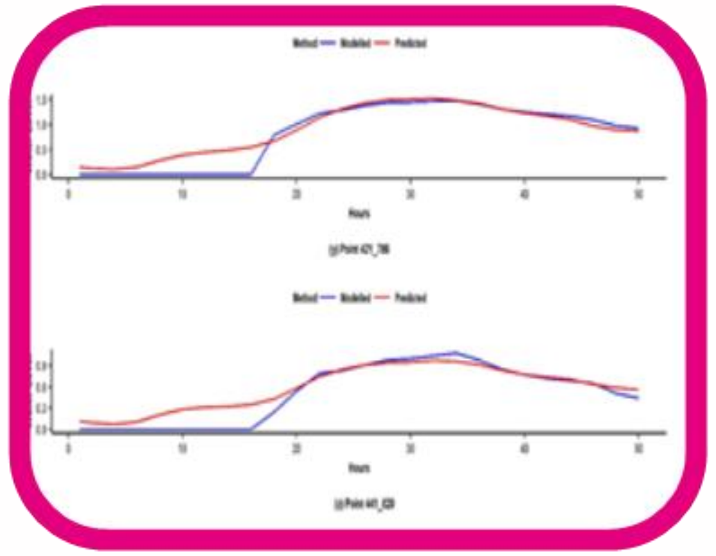
Probability + uncertainty





Flood mechanisms + inundation

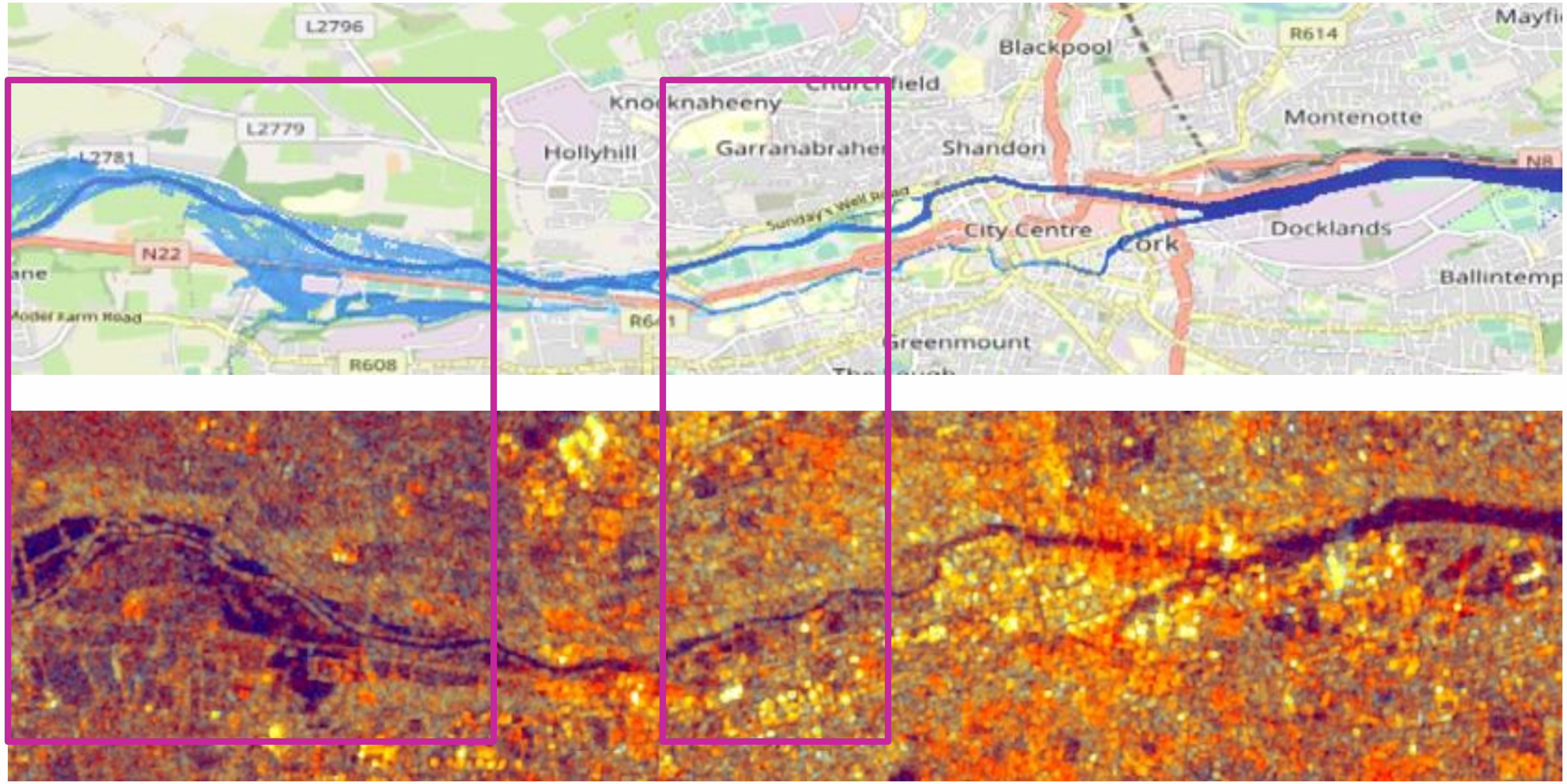
Damage assessment



Flood forecasting

Flood detection

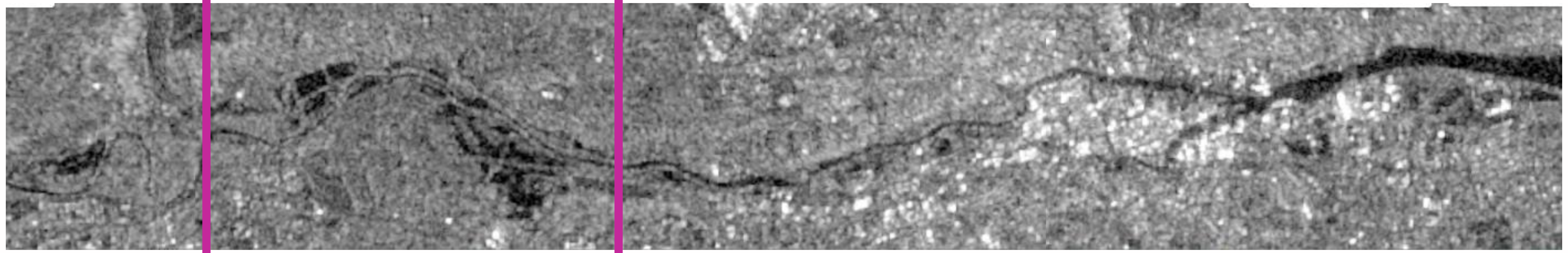
4. Earth Observation



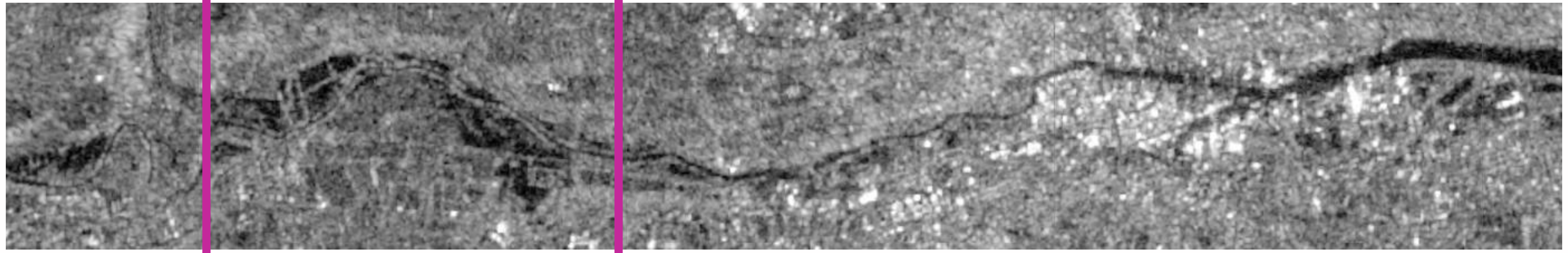
Flood detection

4. Earth Observation

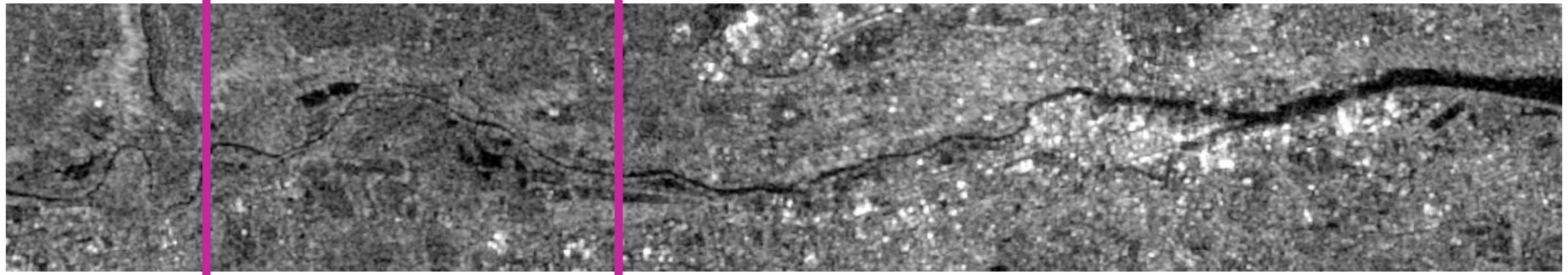
October 2023:



February 2021:

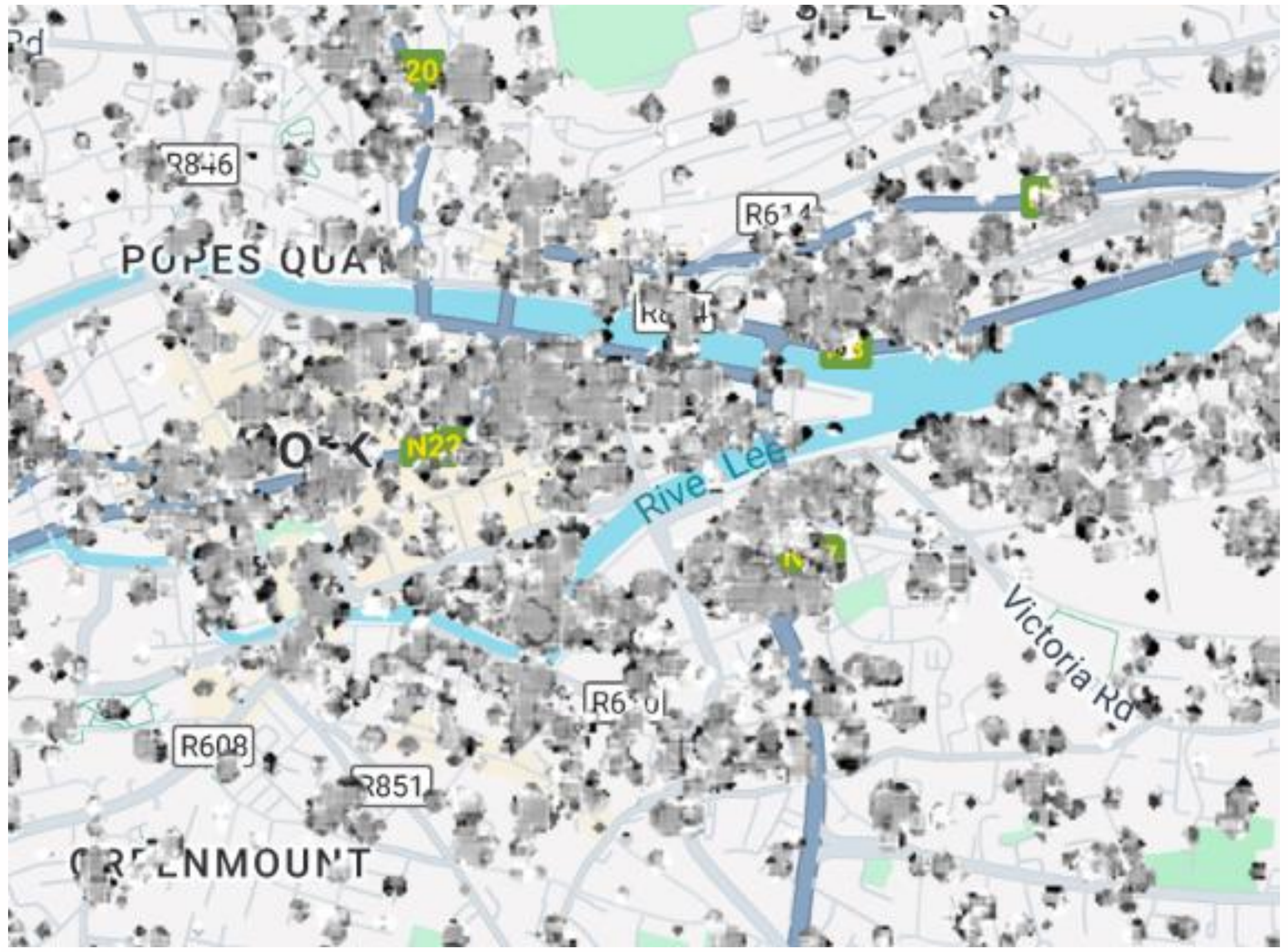


October 2016:

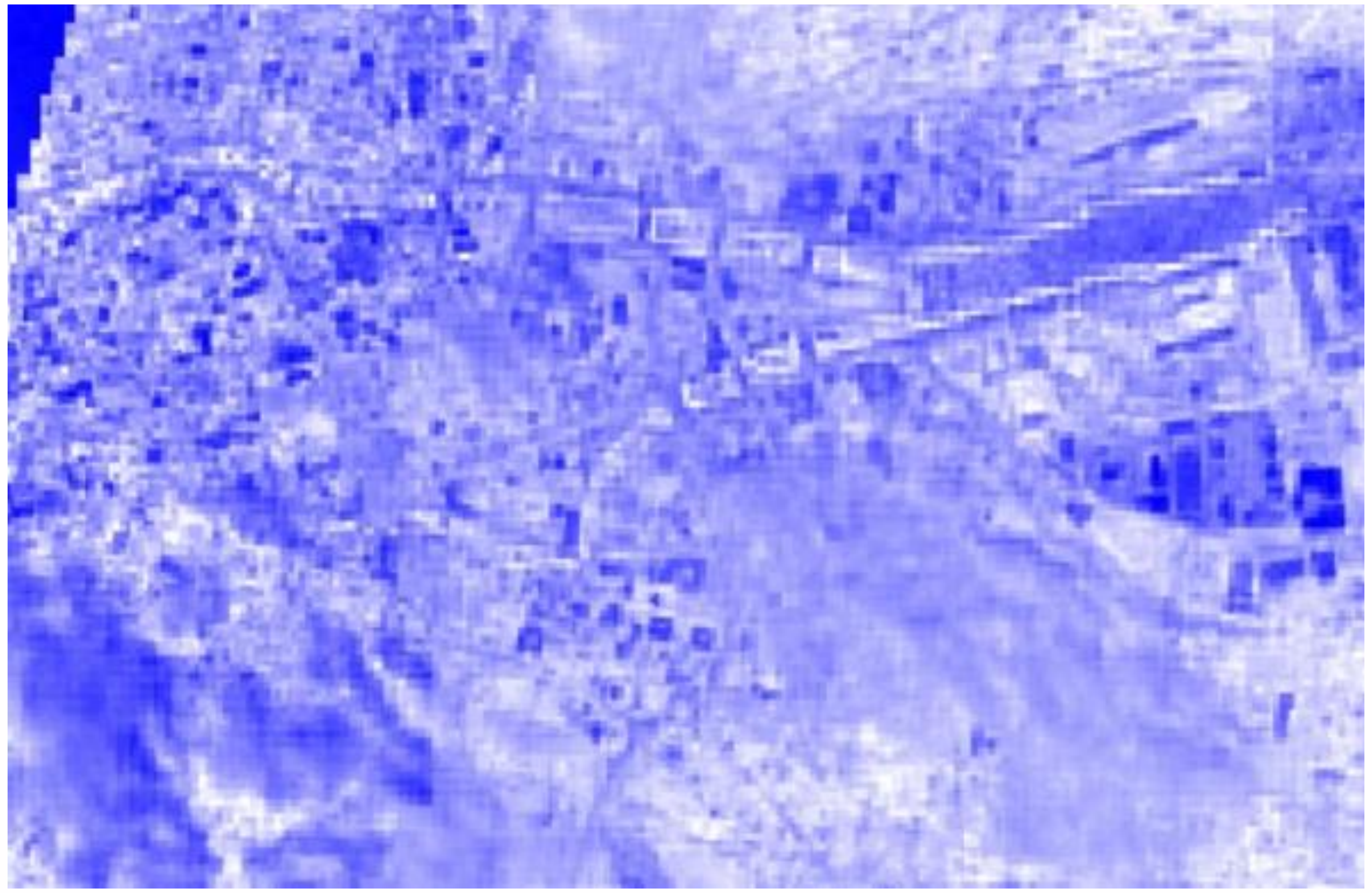


Flood detection

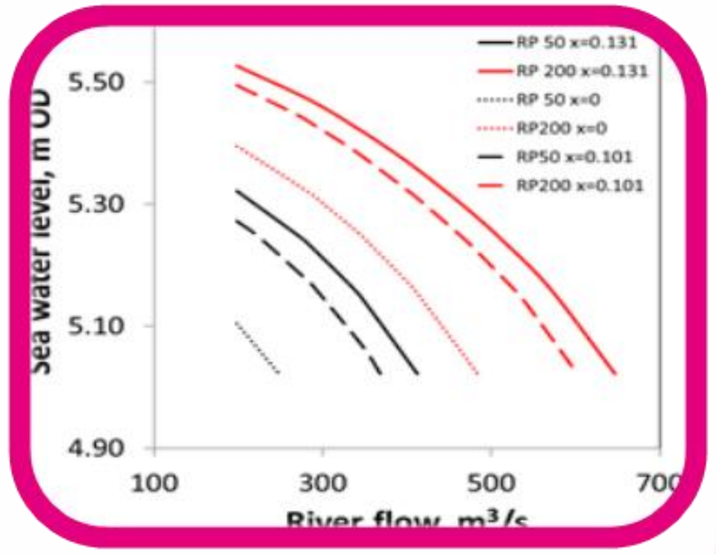
Sentinel 1



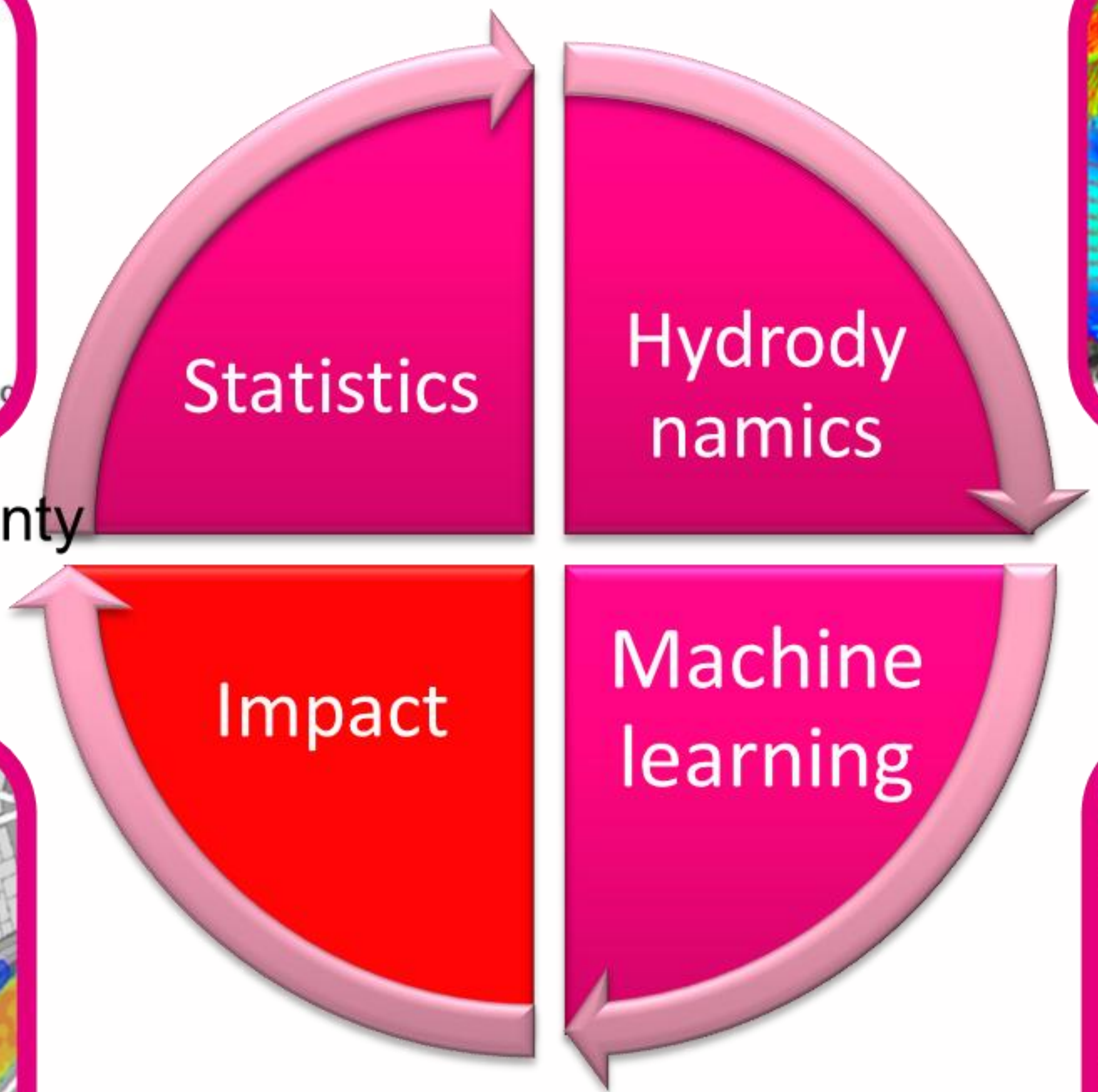
Sentinel 2

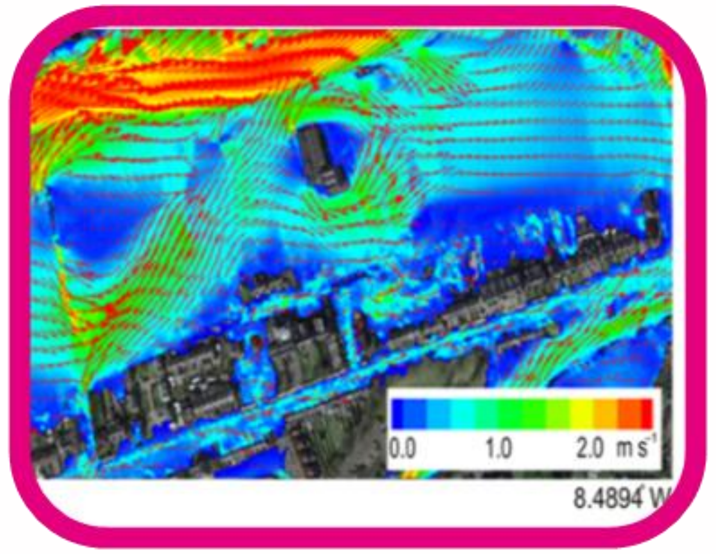


Methodology



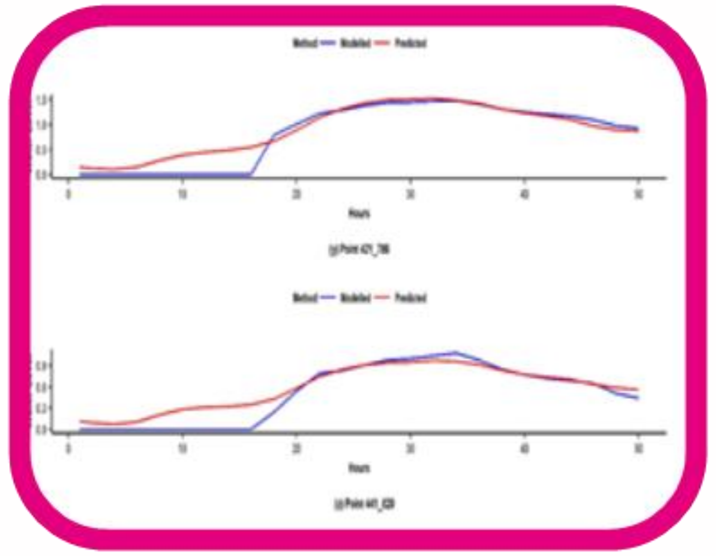
Probability + uncertainty





Flood mechanisms + inundation

Damage assessment



Flood forecasting

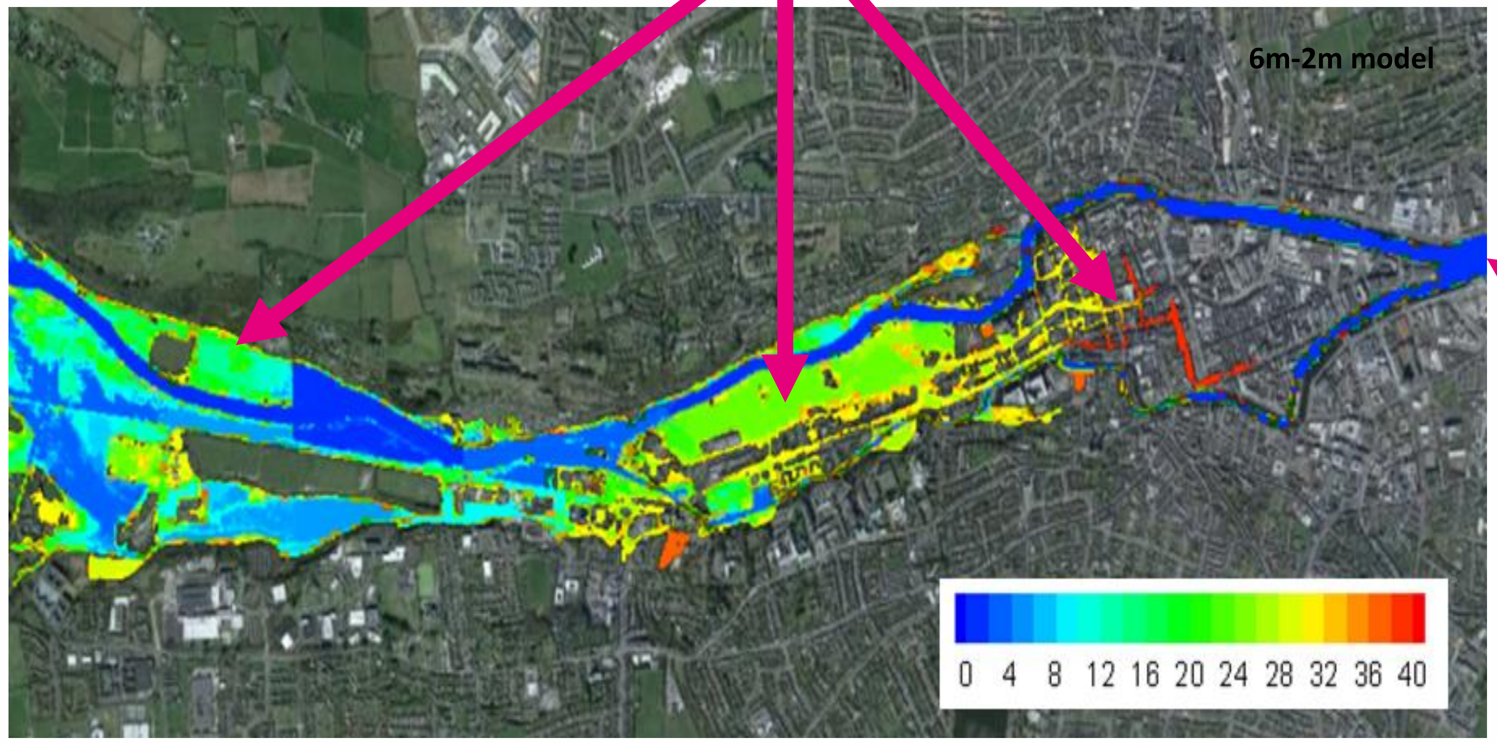
University of Galway / Ollscoil na Gaillimhe

3. Machine learning

Hydrodynamic model outputs:
- training (70%)
- validation (15%)
- testing (15%)

Output/Prediction
Water depth

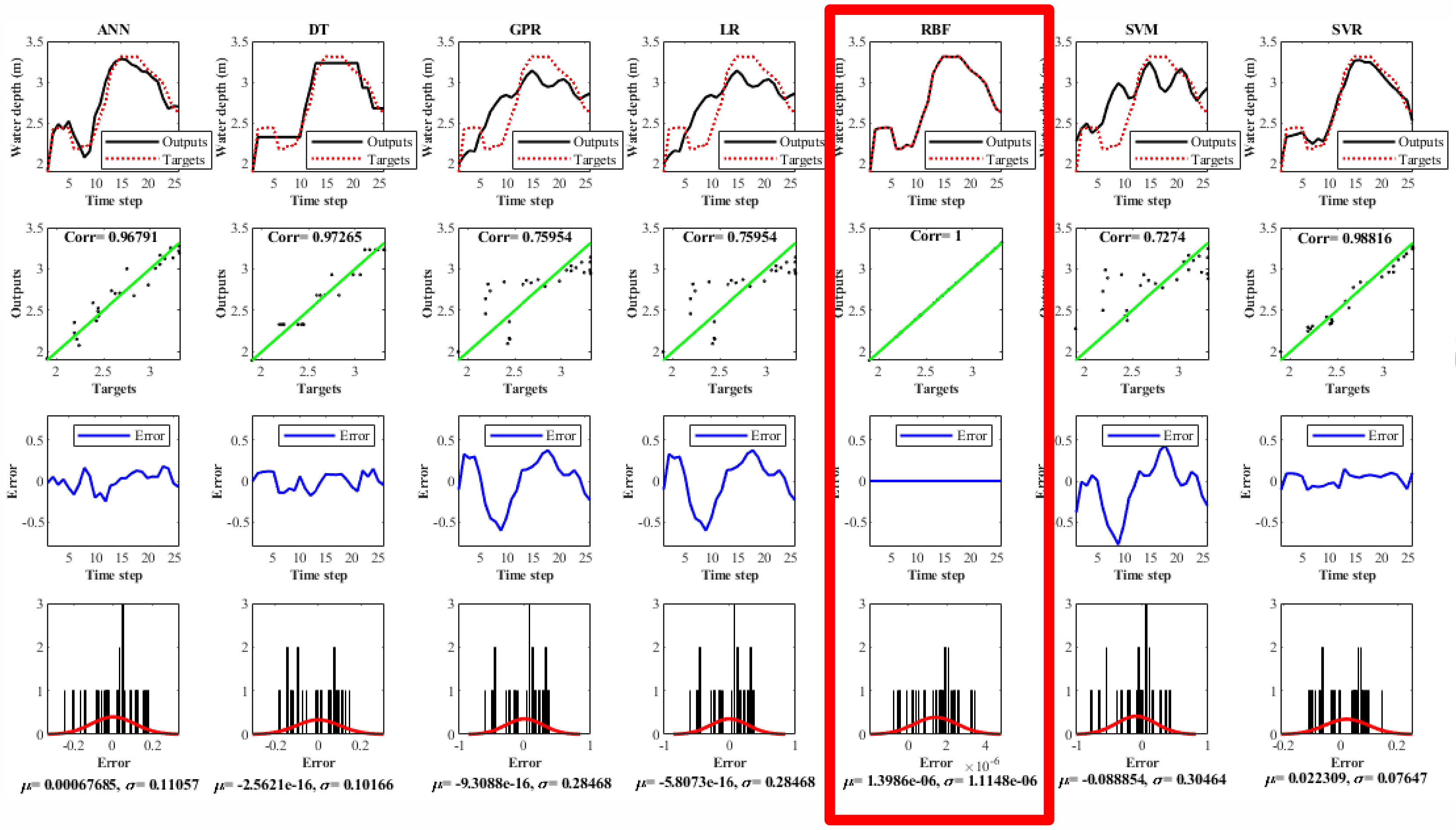
Input
Discharge

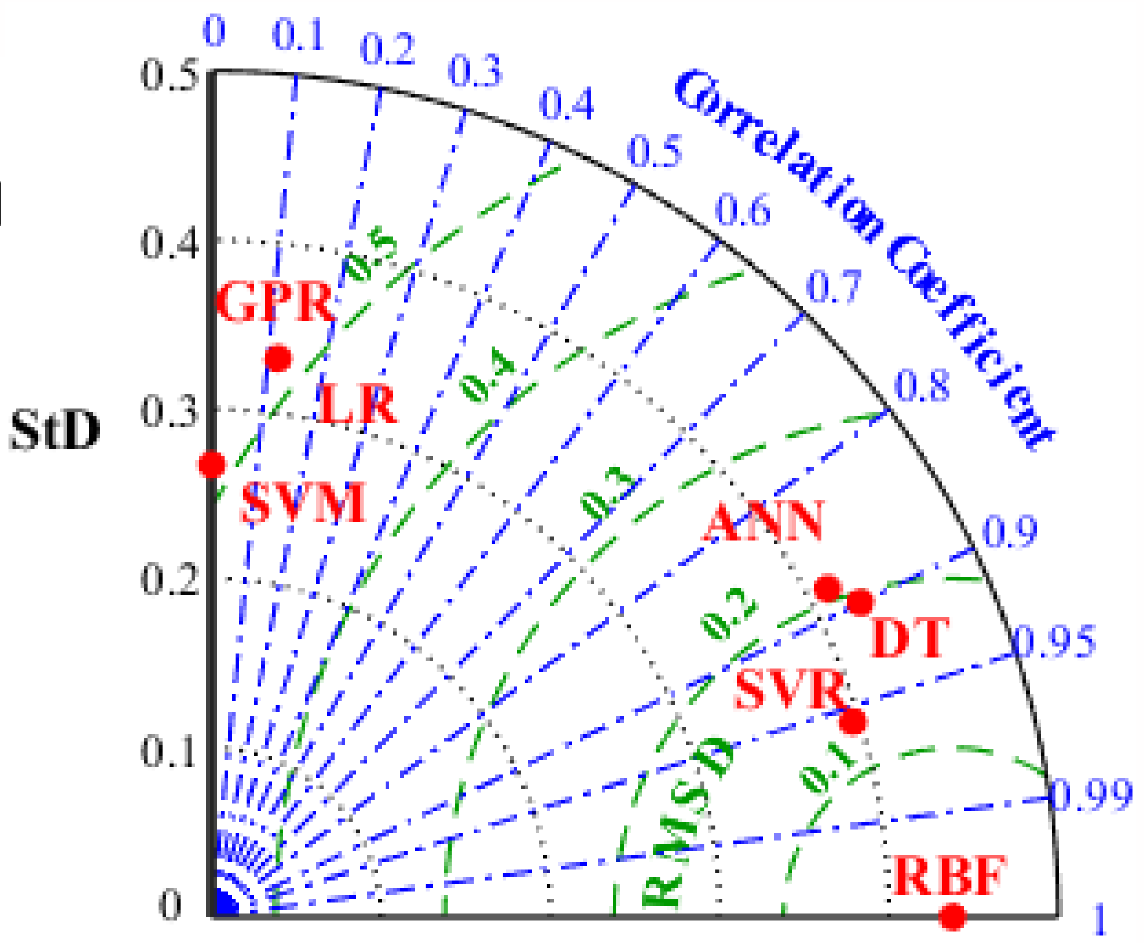


Input
SWL

Grids	ML Model	Number of runs	Flood events
i= 820 j=1650 (2-m pixels)	1 ANN 2 DT 3 GPR 4 LR 5 RBF 6 SVM 7 SVR	20 times	1 Flood event in November 2009 2 Flood with RP=20 3 Flood with RP=1000
820×1650= **{1,353,000}**	×7= **{9,471,000}**	×20= **{189,420,000}**	×3= **{568,260,000} runs**

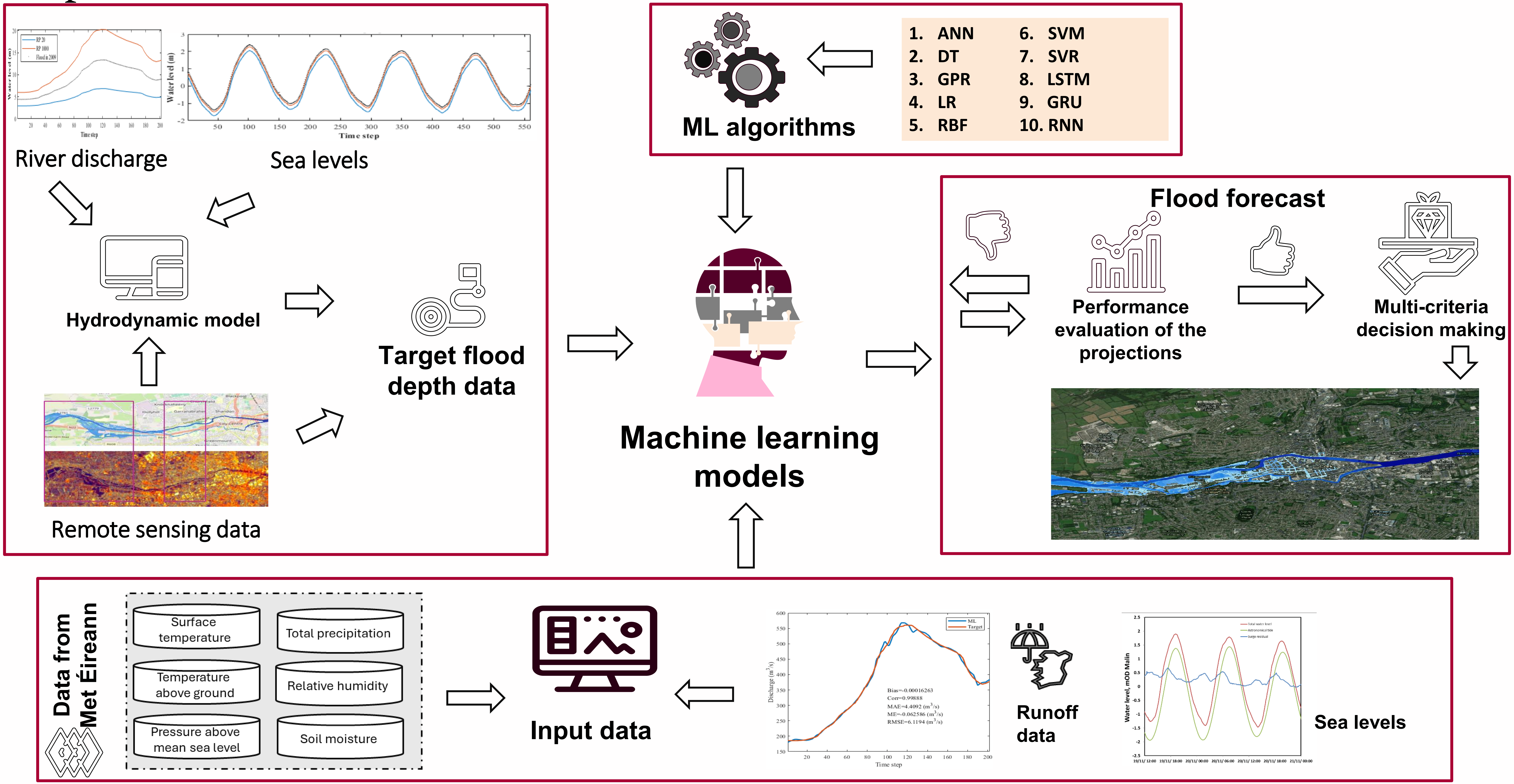
3. Machine learning



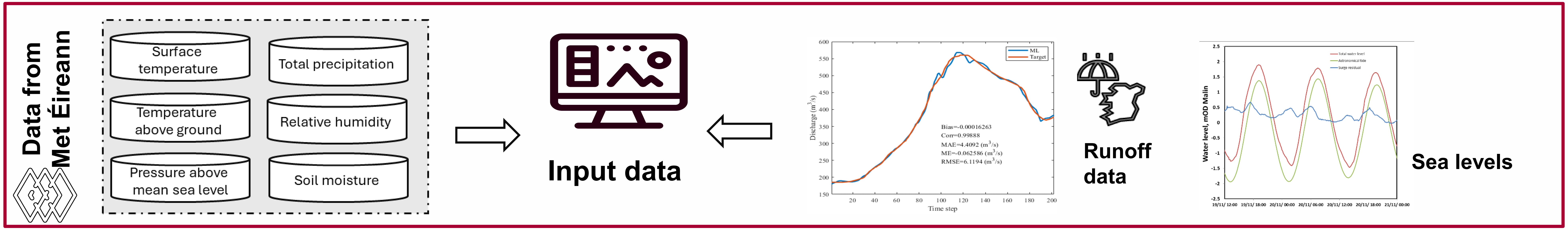


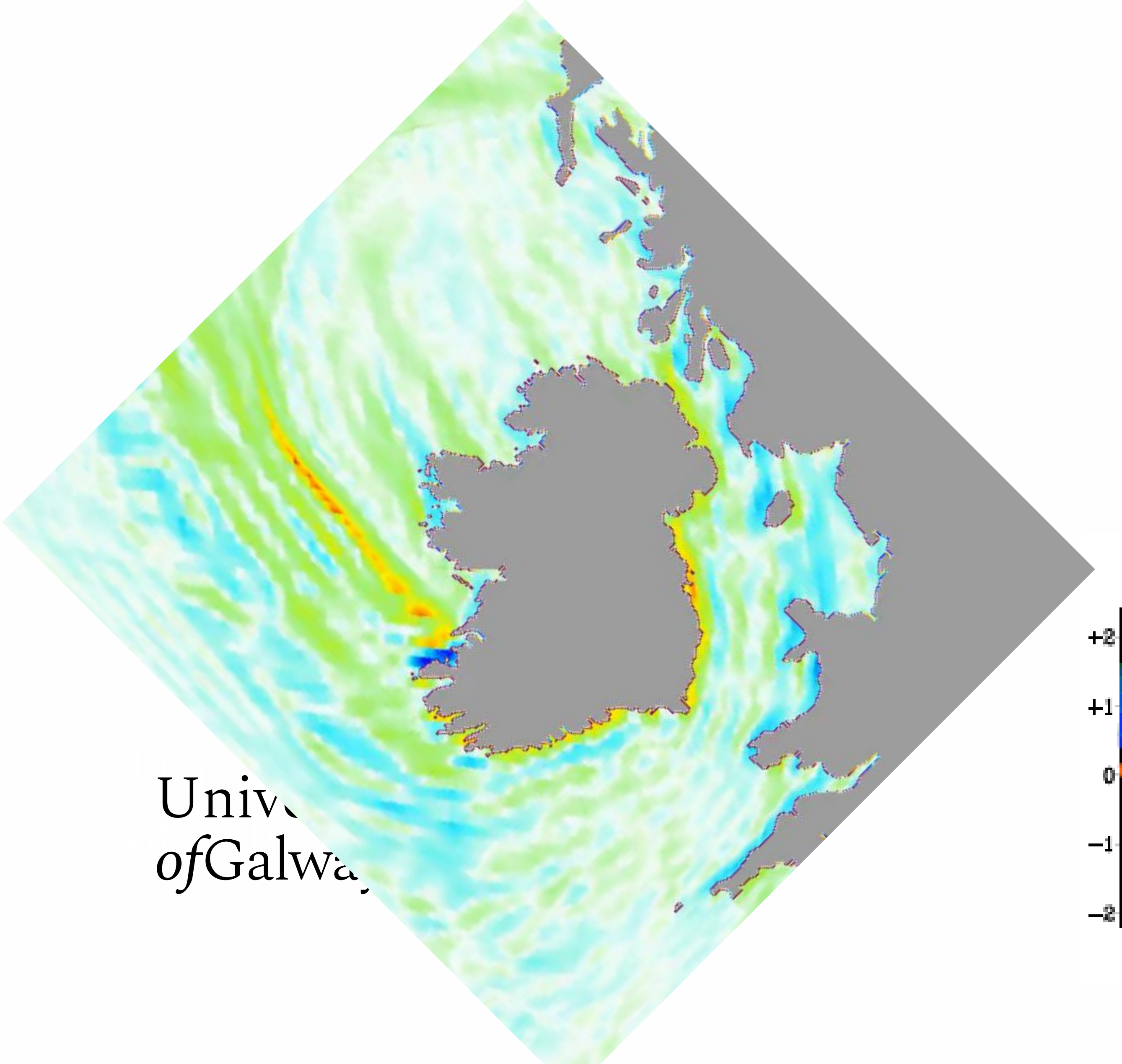
ML model	Bias	Corr	MAE	ME	RMSD	RMSE	StD	CV error	TOPSIS score	Rank
ANN	-2.4619e-4	0.9679	0.0887	-6.7685e-4	0.2076	0.1084	0.4122	0.0123	0.9488	3
DT	-2.2204e-16	0.9726	0.0885	2.5621e-16	0.1937	0.0997	0.4257	0.0103	0.9522	2
GPR	4.4409e-16	0.7595	0.2389	9.3088e-16	0.5174	0.2792	0.3324	0.0833	0.8793	4
LR	6.6612e-16	0.7595	0.2389	5.8073e-16	0.5174	0.2792	0.3324	0.0844	0.8793	4
RBF	-5.0873e-7	1.0000	1.5398e-6	-1.5398e-6	7.2236e-8	1.7751e16	0.4377	1.3755e-12	0.9989	1
SVM	0.0323	0.7274	0.2286	0.0889	0.5128	0.3114	0.2673	0.1072	0.0036	6
SVR	-0.0081	0.9882	0.0724	-0.0223	0.1296	0.0782	0.3959	0.0057	0.7486	5

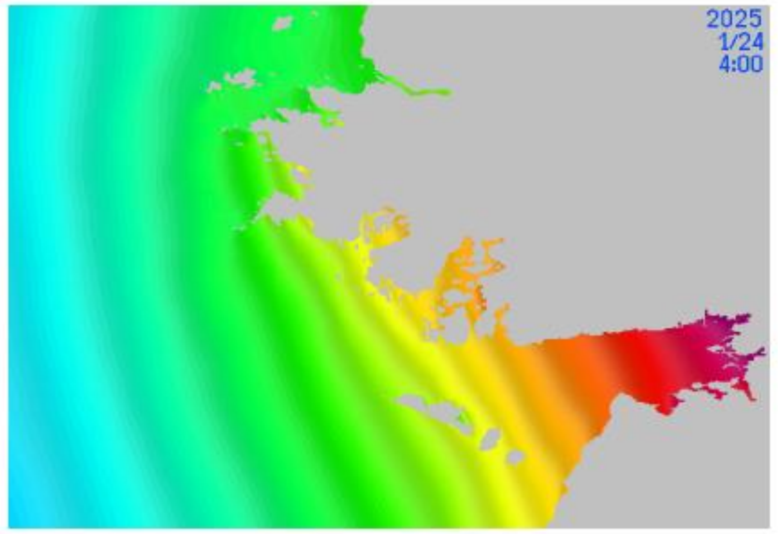
StopFloods solution: How it works

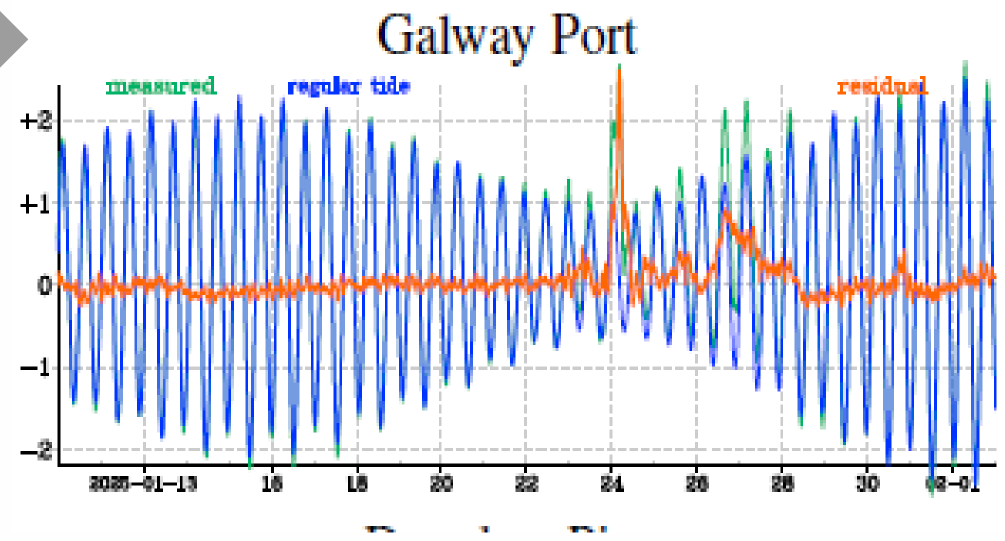


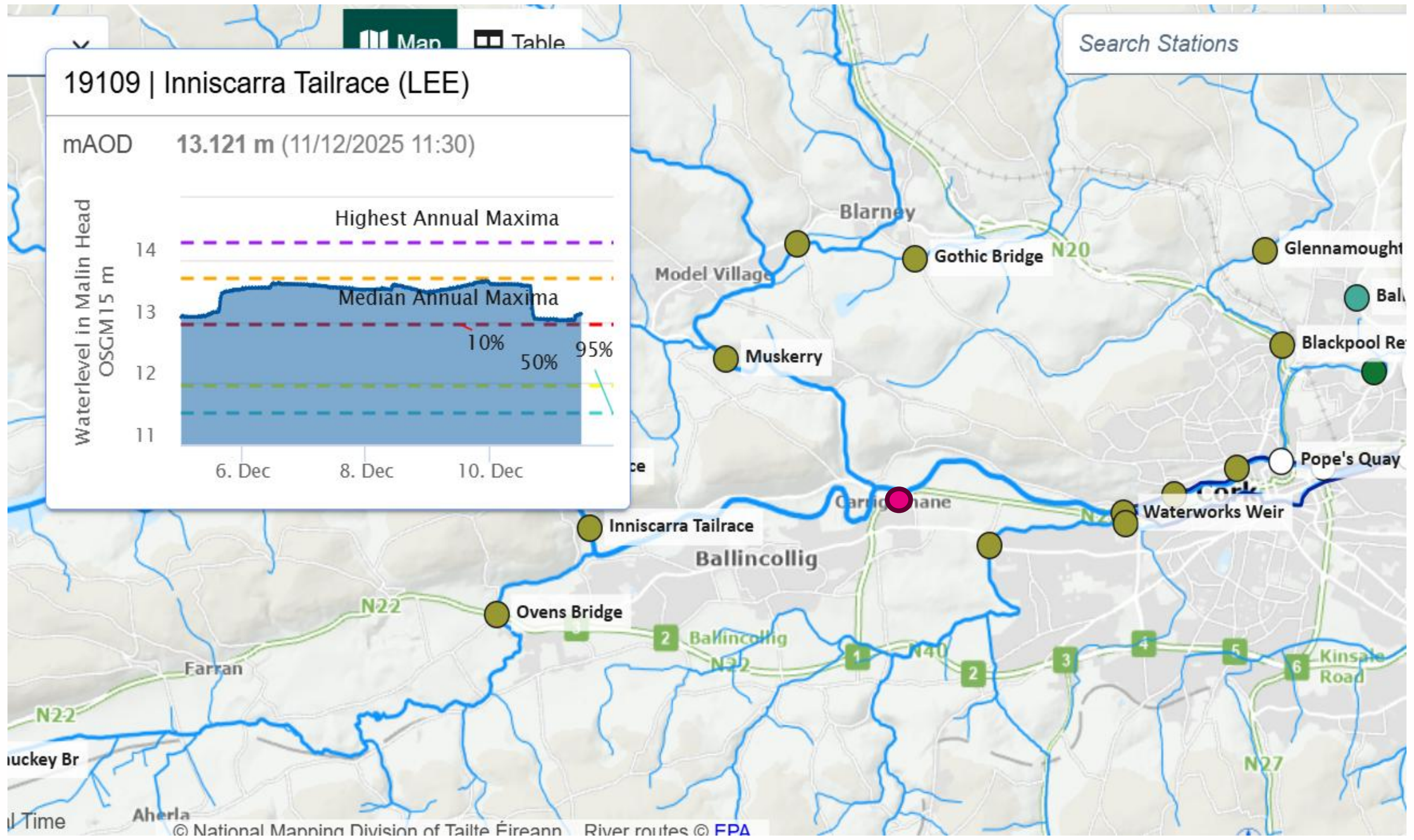
Inputs to AI model





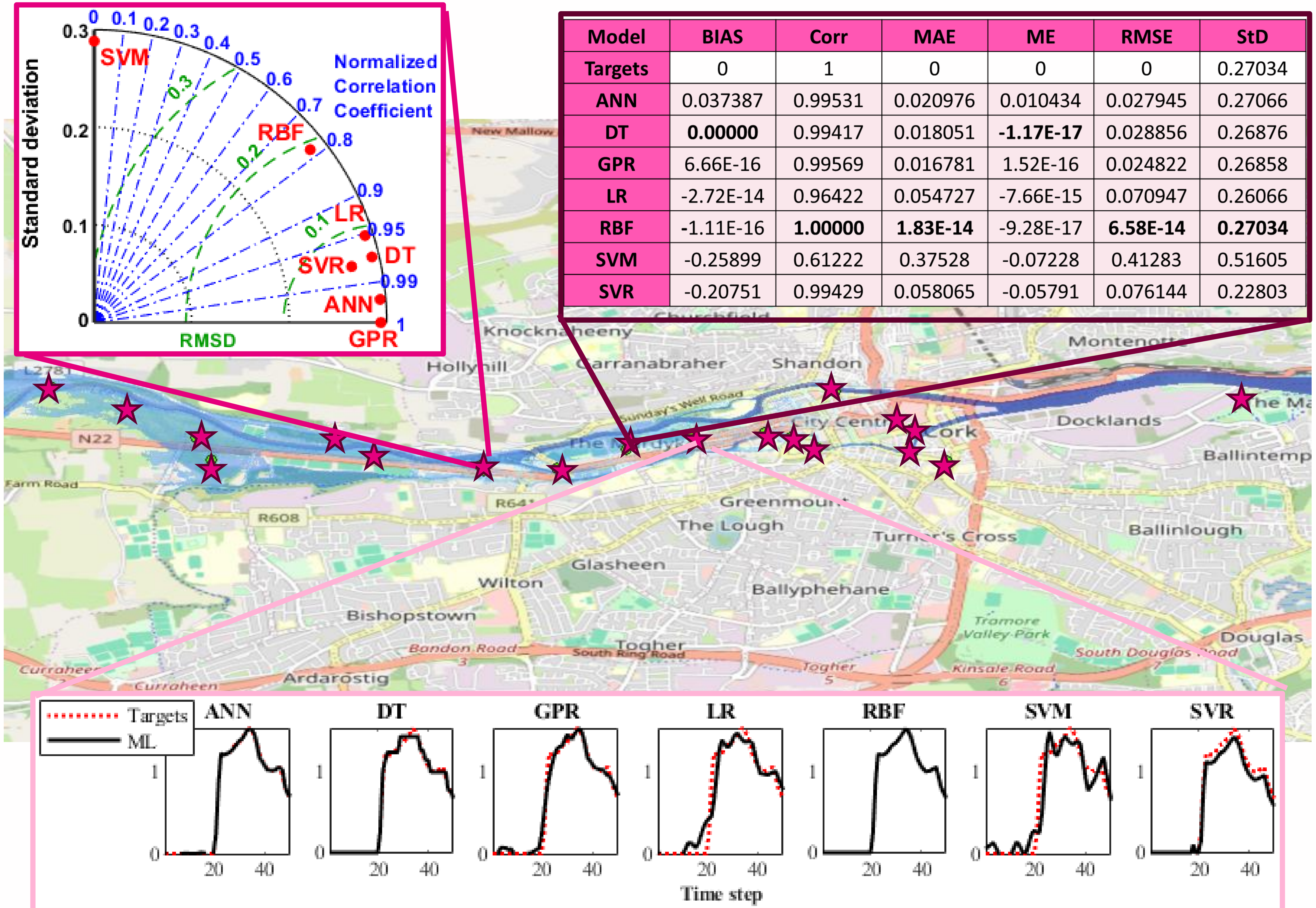






Model results and system architecture

Model	BIAS	Corr	MAE	ME	RMSE	StD
Targets	0	1	0	0	0	0.27034
ANN	0.037387	0.99531	0.020976	0.010434	0.027945	0.27066
DT	**0.00000**	0.99417	0.018051	**-1.17E-17**	0.028856	0.26876
GPR	6.66E-16	0.99569	0.016781	1.52E-16	0.024822	0.26858
LR	-2.72E-14	0.96422	0.054727	-7.66E-15	0.070947	0.26066
RBF	-1.11E-16	**1.00000**	**1.83E-14**	-9.28E-17	**6.58E-14**	**0.27034**
SVM	-0.25899	0.61222	0.37528	-0.07228	0.41283	0.51605
SVR	-0.20751	0.99429	0.058065	-0.05791	0.076144	0.22803



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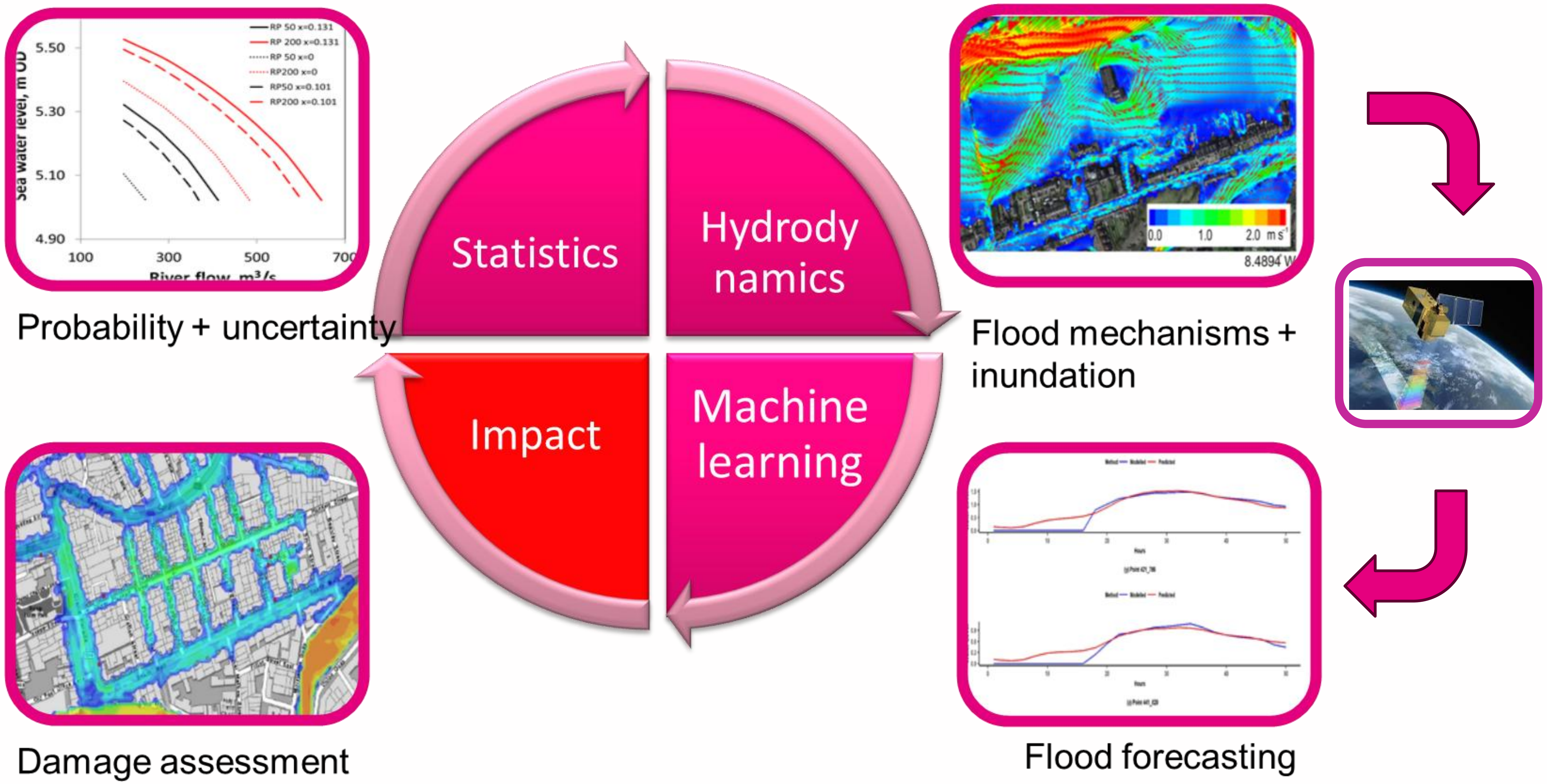
University of Galway

Methodology



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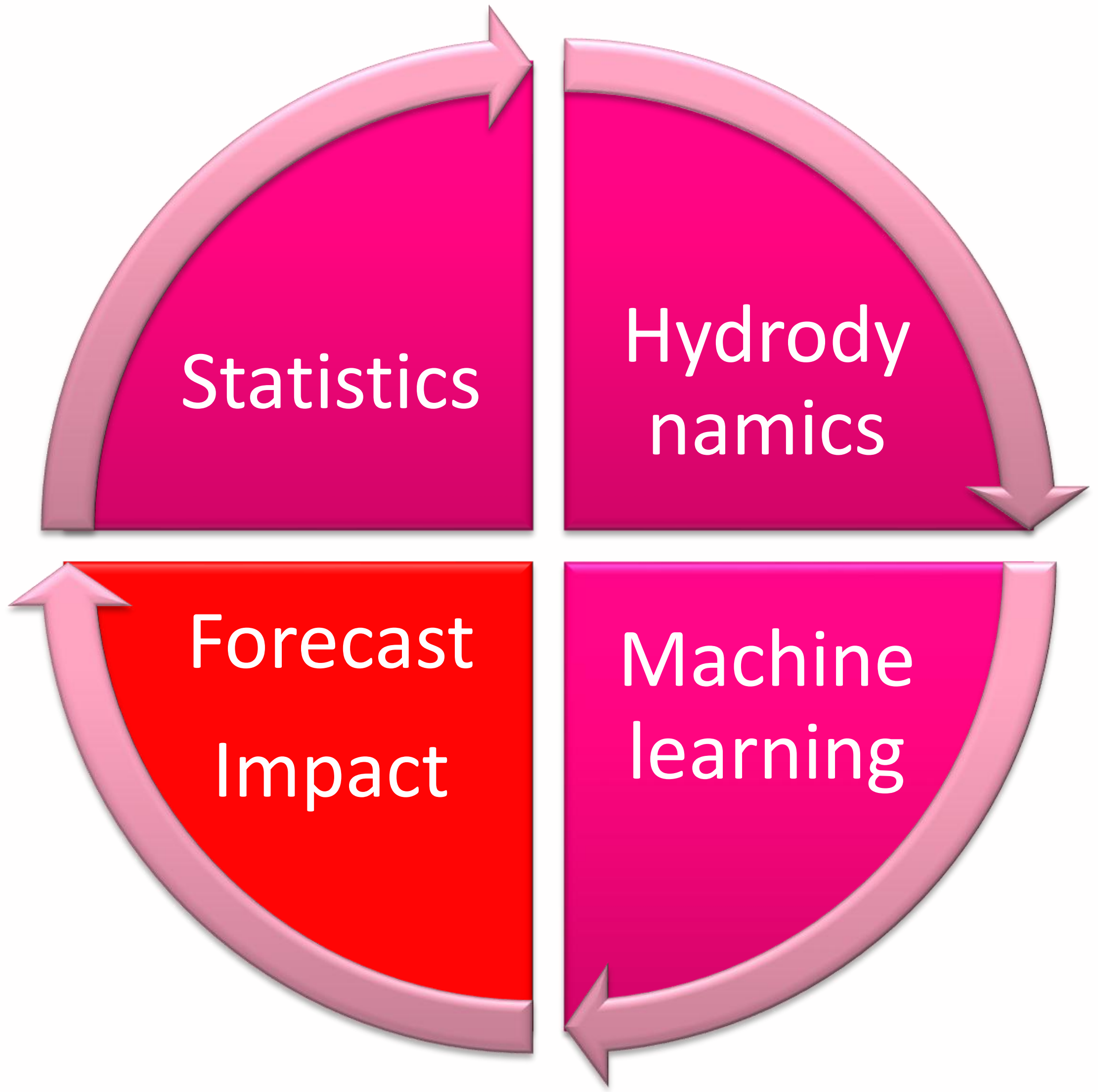
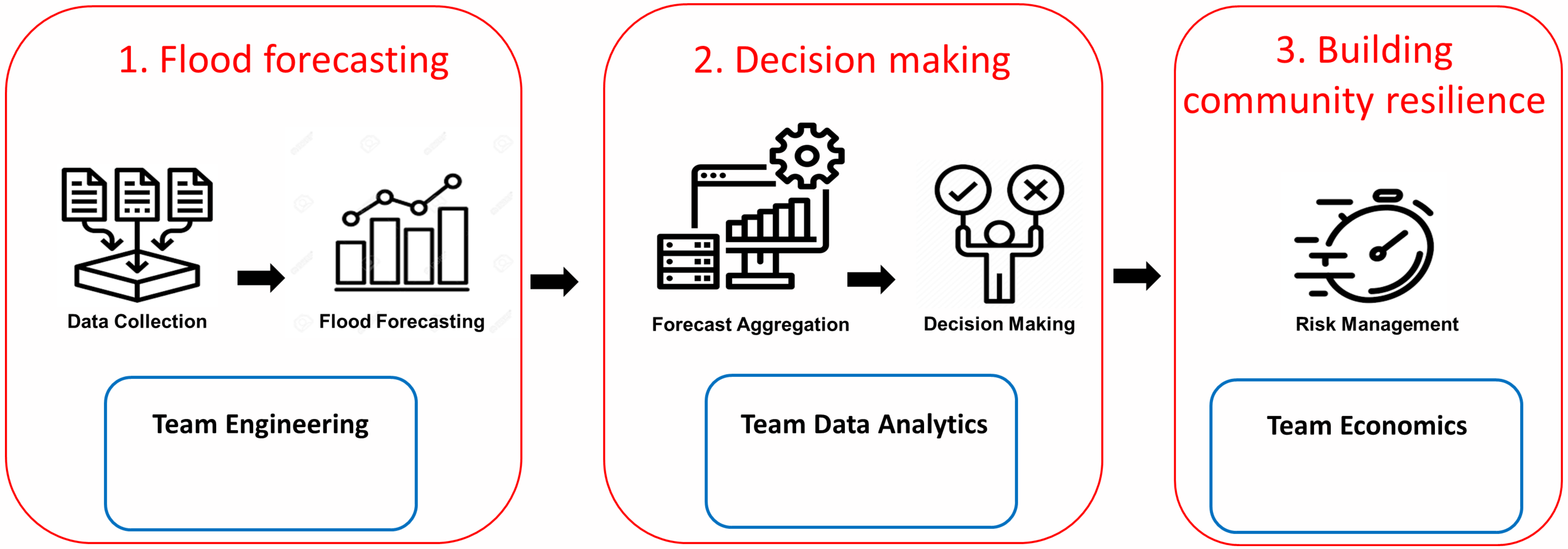
How we determine coastal flood risks?

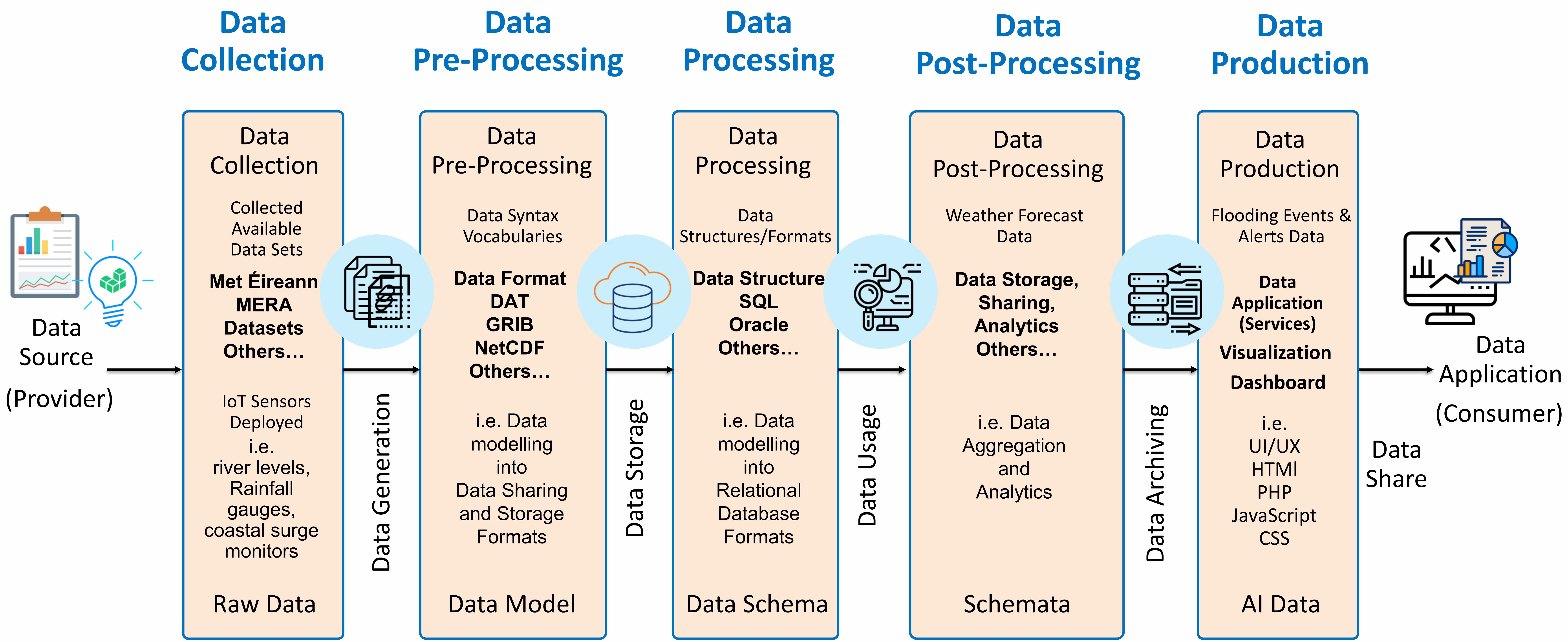
Solution

Local scale decision-support system for flood management





StopFlood4.ie Project: Data Lifecycle



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Insight
Centre for Data Analytics

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University of Galway

De

StopFloods4.ie Dashboard

The StopFloods4.ie Dashboard is a novel monitoring tool for supporting Flood Forecasting Predictions, showcasing the effective use of Machine Learning methods, AI techniques and cloud computing systems. The StopFlood4.ie project uses Coastal-fluvial Floods Data combined with Weather Forecast Data (including data from sensors) with the aim of pioneering our solution in the form of a cost-effective data analytics framework. In other words, the dashboard demonstrates how using ML and AI can support flood forecasting across Ireland conurbation.

Username

admin

Password

••••••••••••

Login

Supported By:

Rialtas na hÉireann
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University of Galway

StopFloods4.ie Monitoring

Dash | Hydro | Forecast | Logout

Selector

Select City

Cork

Select Year

2009

Choose a location:

R

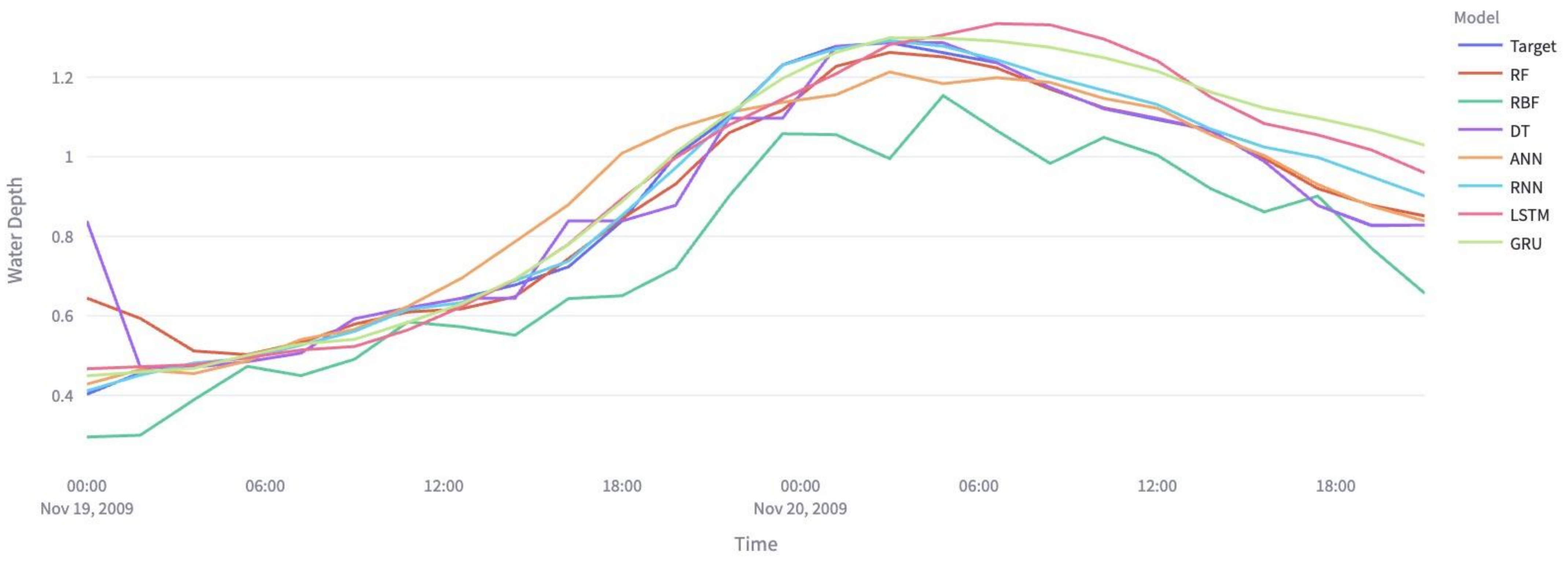
Predicted Water Depth

	ML/AI Methods	Max Depth (m)
0	Water Depth (Target)	1.2867
1	RF	1.2623
2	RBF	1.1540
3	DT	1.2867
4	ANN	1.2132
5	RNN	1.2920
6	LSTM	1.3348
7	GRU	1.2992

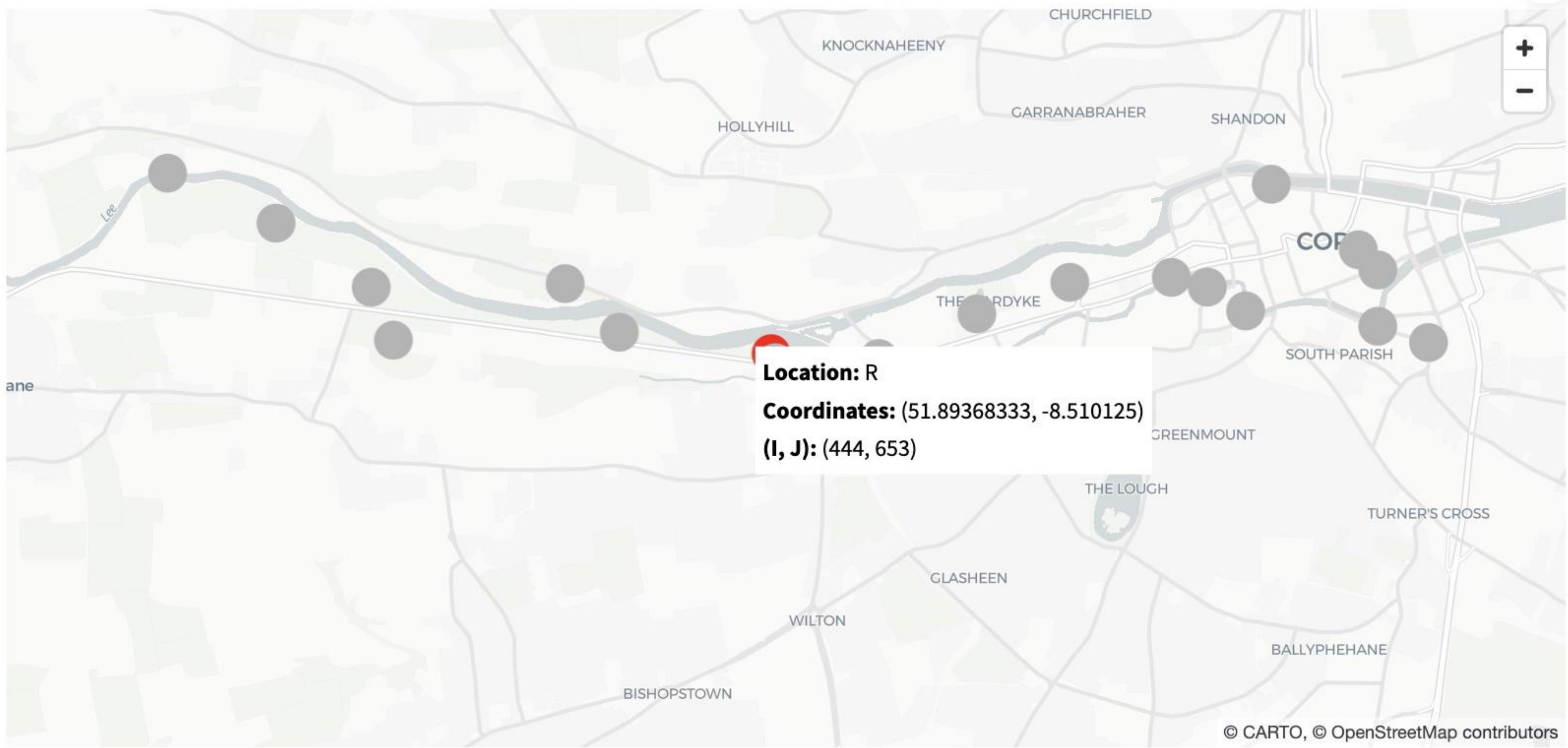
Flooding Risk Keys

Condition	Color
Water Depth < 0.5	Green
Water Depth < 0.75	Amber
Water Depth > 0.75	Red

Water Depth Predictions in Cork (Pixel R , 2009)



Location Map



Features

	Feature	Max Value	Units
0	Pressure	101,201.0000	Pa
1	Humidity	0.9433	%
2	SoilMoisture	0.2863	kg/m^3
3	Temperature	285.0935	K
4	Temperature2	286.5232	K
5	Precipitation	0.0000	kg/m^2
6	Wind	11.4399	m/s
7	RiverDischarge	13.3434	m^3/s
8	Tide	2.3100	m

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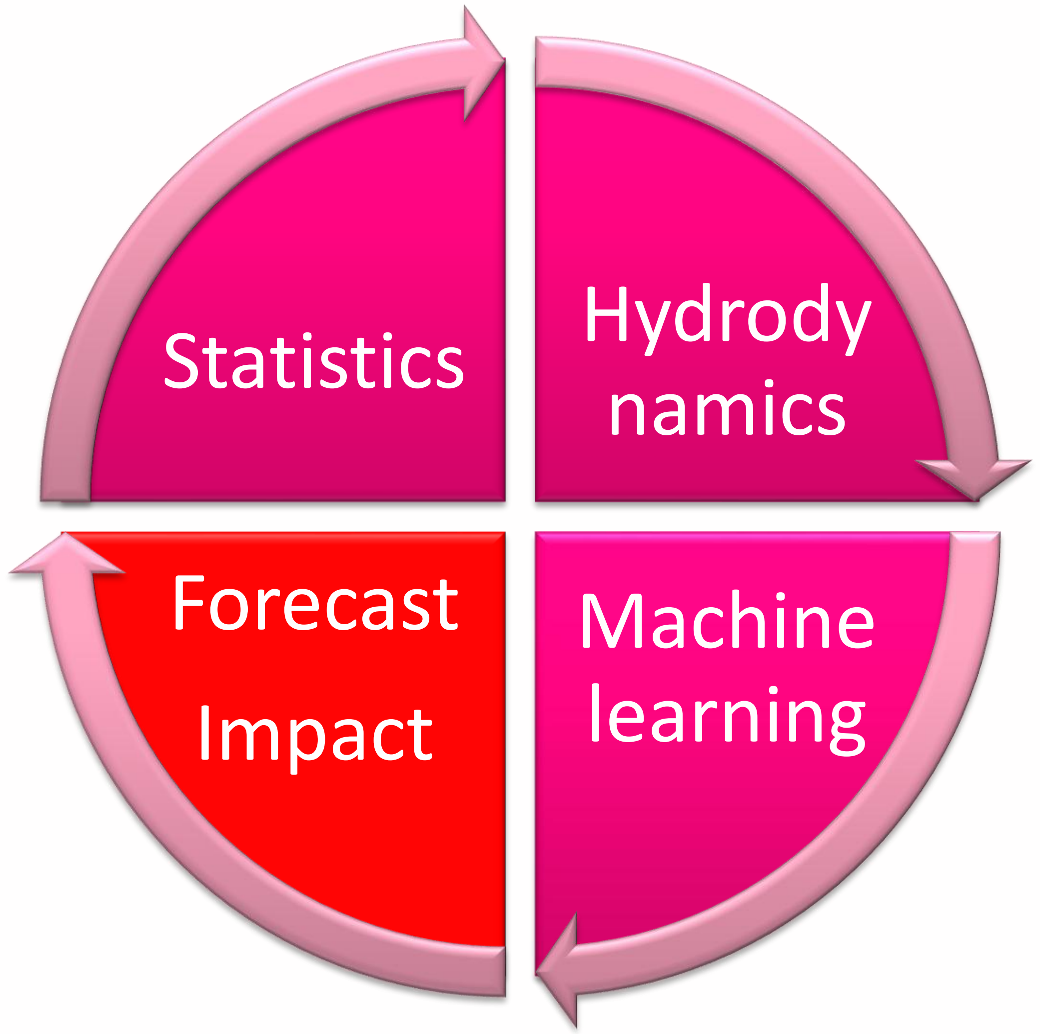
Flood forecasting



Societal Impacts

Forecasting

- Better preparedness by LAs and communities
- Increased confidence in forecast

Decision-making

- Reduction of false alarms
- Flood prevention

Management

- Better allocation of resources
- Damage reduction
- Reduction in emotional stress

Middleton, Co. Cork, Oct 2023

Three-model system can improve flood resilience and wellbeing of at-risk communities

Compound coastal-fluvial floods in urban environment

StopFloods4.ie

Indiana.Olbert@universityofgalway.ie

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Martin Serano (UG), Vinoop Sanil (UG)
Ciaran Broderick (Met Eireann)
Amir AghaKouchak (UC Irvine, CA)
Alexander Shchepetkin, Niall Madden (UG)