Integrating Climate Emulators and Hybrid Metamodels for Estuarine Flood Risk

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[1)]Geomatics and Ocean Engineering Group, Universidad de Cantabria, Santander, Spain
[2)]University of Canterbury, Christchurch, New Zealand
[3)] University of A Coruña, A Coruña, Spain
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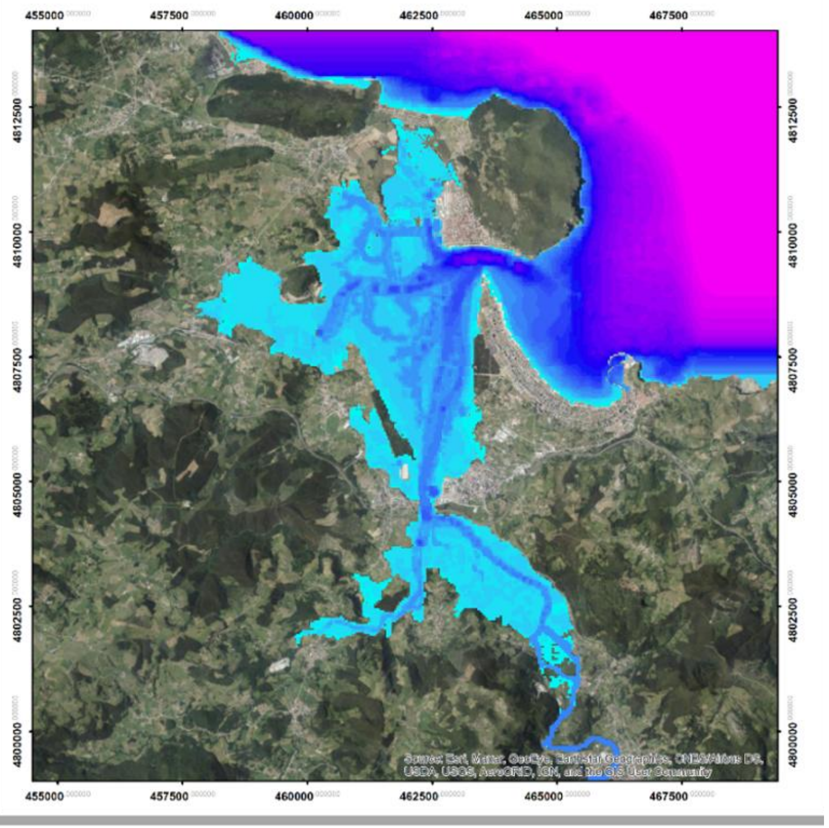
Motivation

Multiple Realizations of Flooding Events



Probabilistic Risk Assessment:

- Many different combinations of met-ocean conditions
- Flooding requires high resolution hydrodynamic modelling
- Large Computational Time Effort

Neccessity of a **Metamodel** for fast estimating thousands/millions of hydrodynamic simulations

Methodological approach

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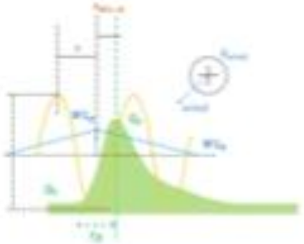
Geomatics and Ocean Engineering Group
UNIVERSIDAD DE CANTABRIA

HISTORICAL FORCING CONDITIONS

Oceanographic: Tide, Storm surge
Pluvial/Fluvial: Precipitation, River discharge
Wind magnitude and direction



METAMODEL

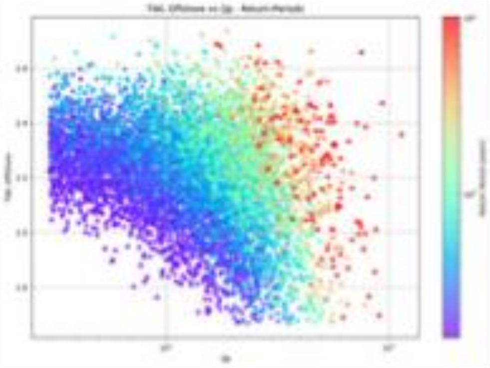
SELECTION (MDA)

SCHISM
Numerical model

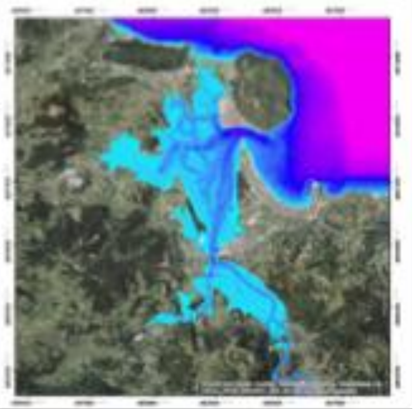
Multidimensional INTERPOLATION Function

PROBABILISTIC ASSESSMENT OF COMPOUND FLOODING HAZARD

TWV Proxy



Reconstructed flooding maps



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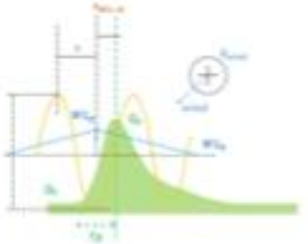

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OF COMPOUND FLOODING HAZARD**

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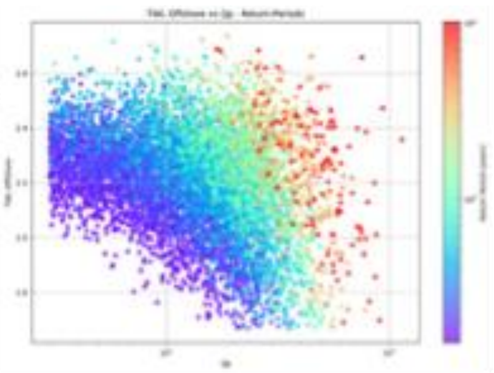

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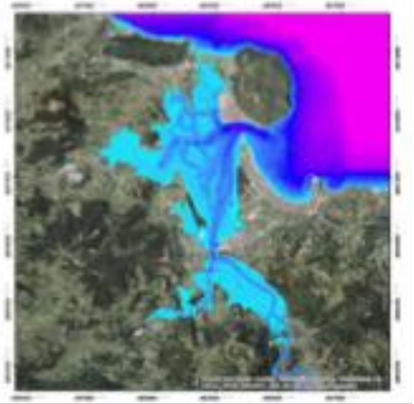
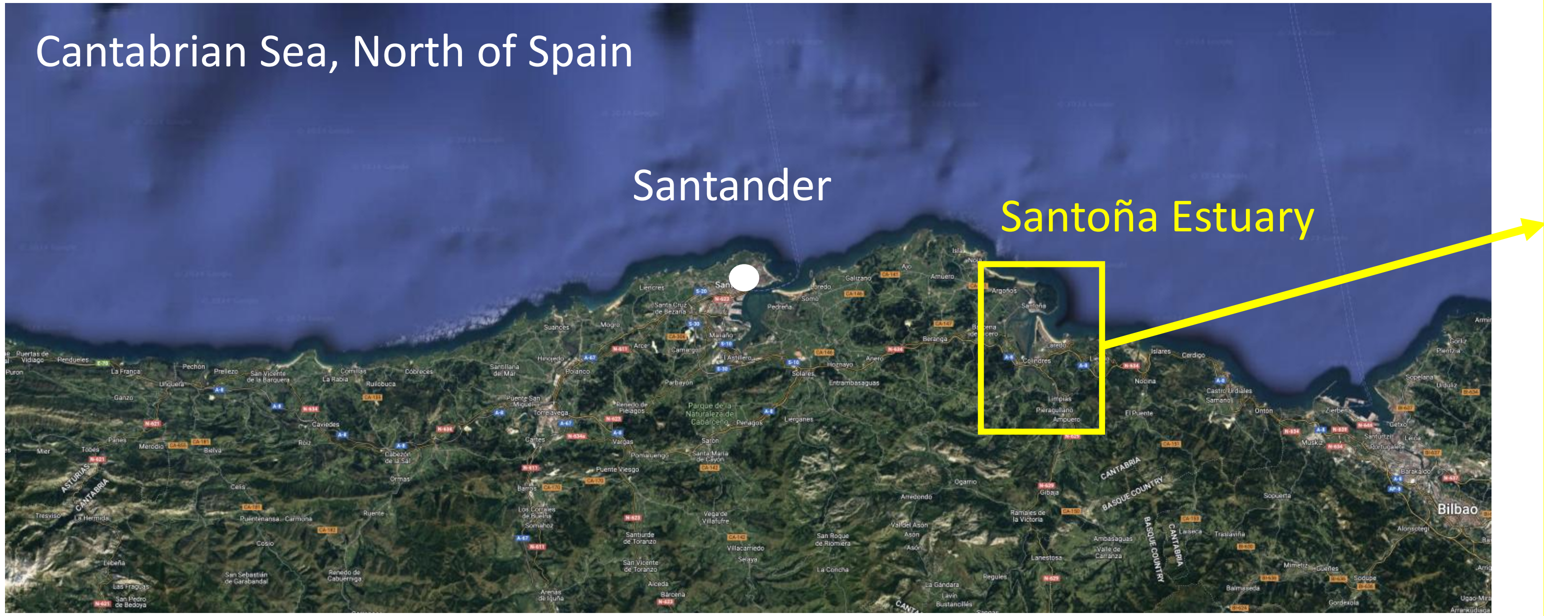


Study Site


Cantabrian Sea, North of Spain
Santander
Santoña Estuary
Bilbao

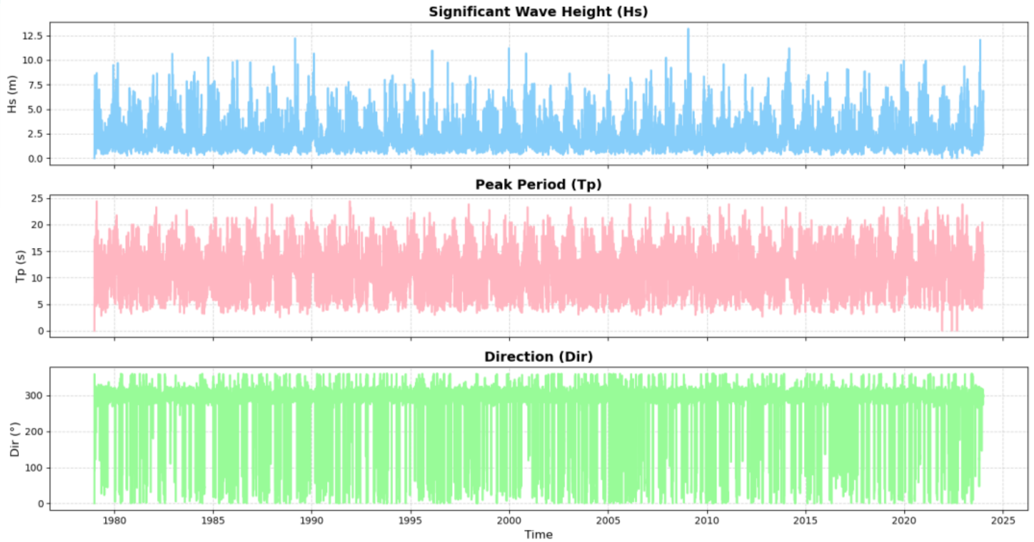

Argoños
Santoña
cena de Cicero
Laredo
Liendo
Colindres
Limpias
Pieragullano
Ampuero

Historical data

Waves

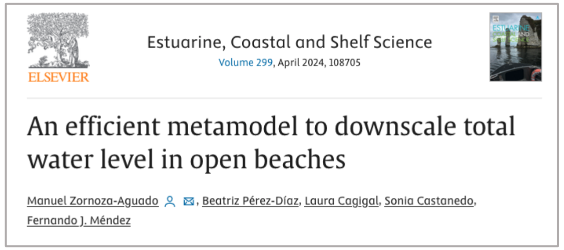
CAWCR

Variables: Hs, Tp & Dir
Location: Offshore (Study Site)
Time span: 1979 to 2023 at hourly scale



Wave set-up

Zornoza-Aguado et al., 2024


Estuarine, Coastal and Shelf Science
Volume 299, April 2024, 108705

An efficient metamodel to downscale total water level in open beaches

Manuel Zornoza-Aguado, Beatriz Pérez-Díaz, Laura Cagigal, Sonia Castanedo, Fernando J. Méndez

Storm surge

CODEC

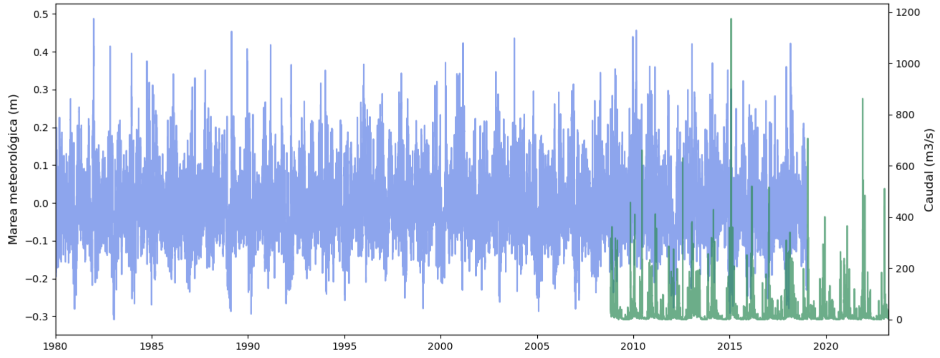
Variables: Storm Surge
Location: Station (Outside the Stuary)
Time span: 1980 to 2017 at hourly scale

River discharge

GAUGE

Variables: River discharge
Location: Station at Coterillo
Time span: 2009 to 2024 at hourly scale

CODEC (Muis et al., 2020)



GAUGE COTERILLO: 2009- 2024

Methodological approach

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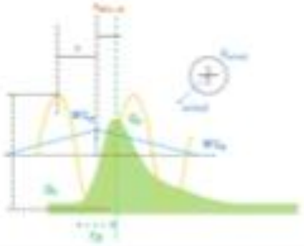

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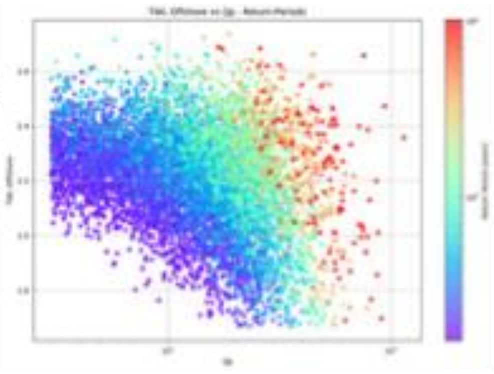
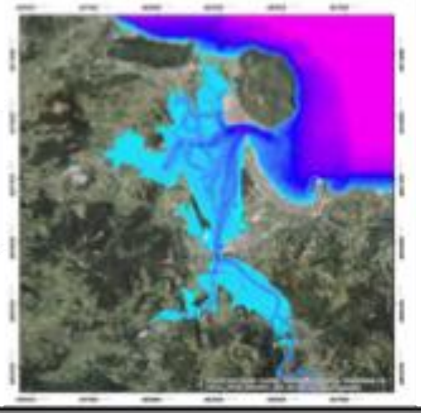
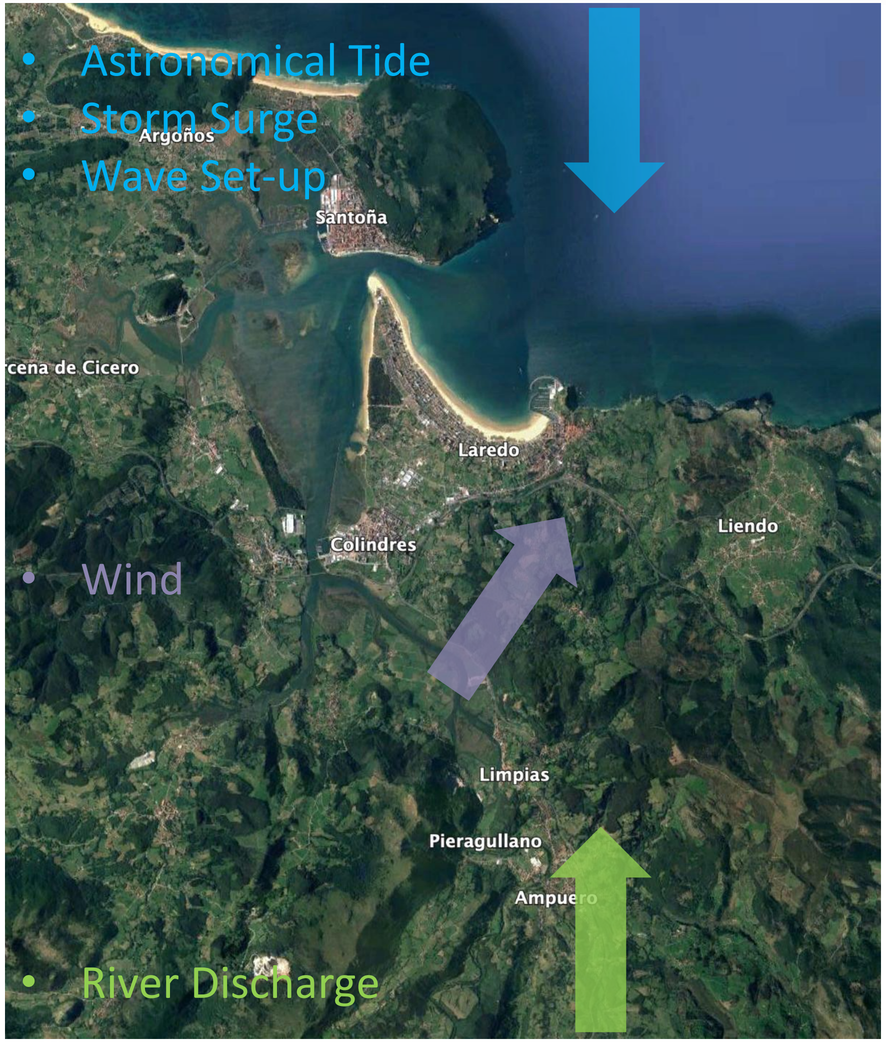


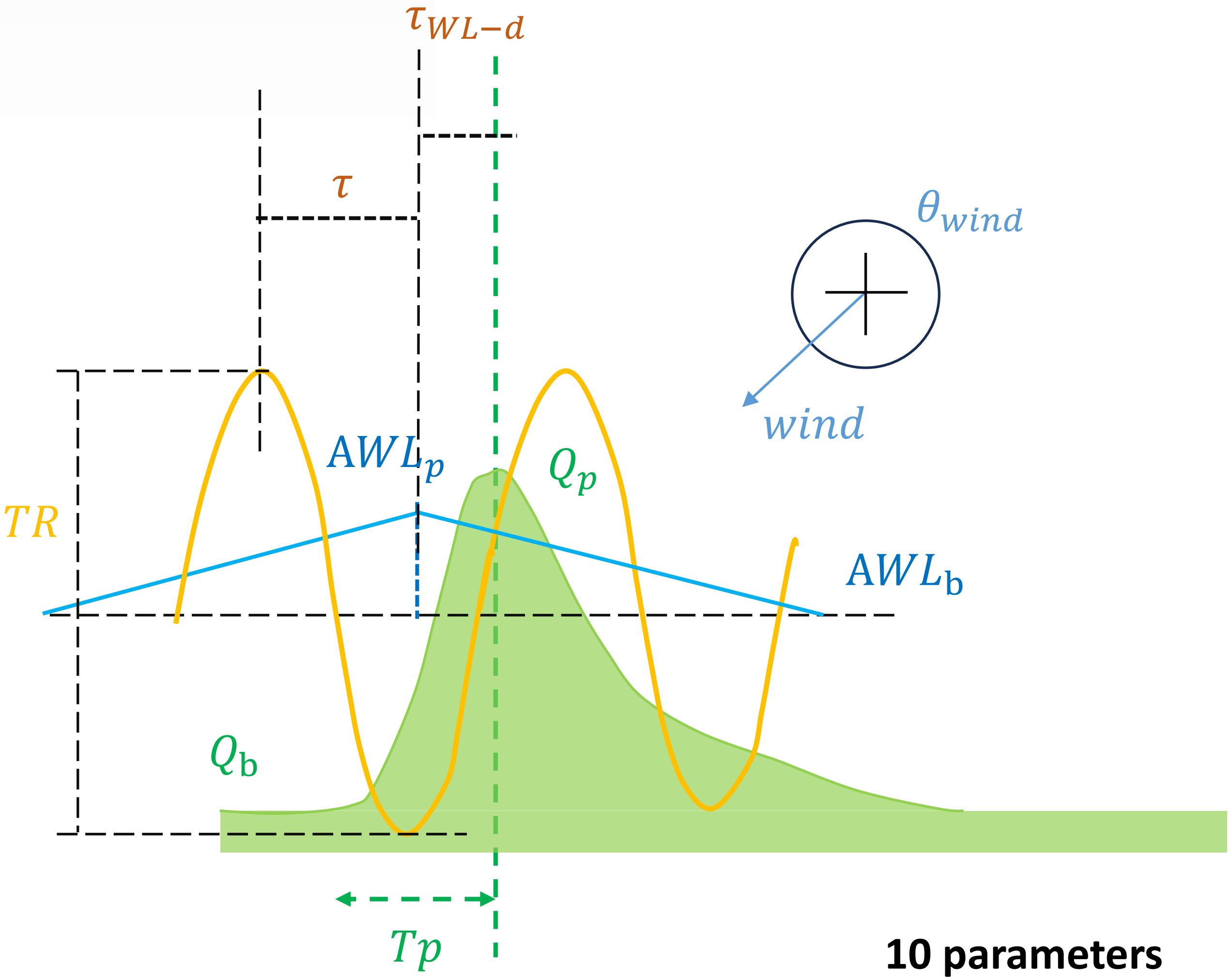
Reconstructed flooding maps



Metamodel

Forcings Parametrization





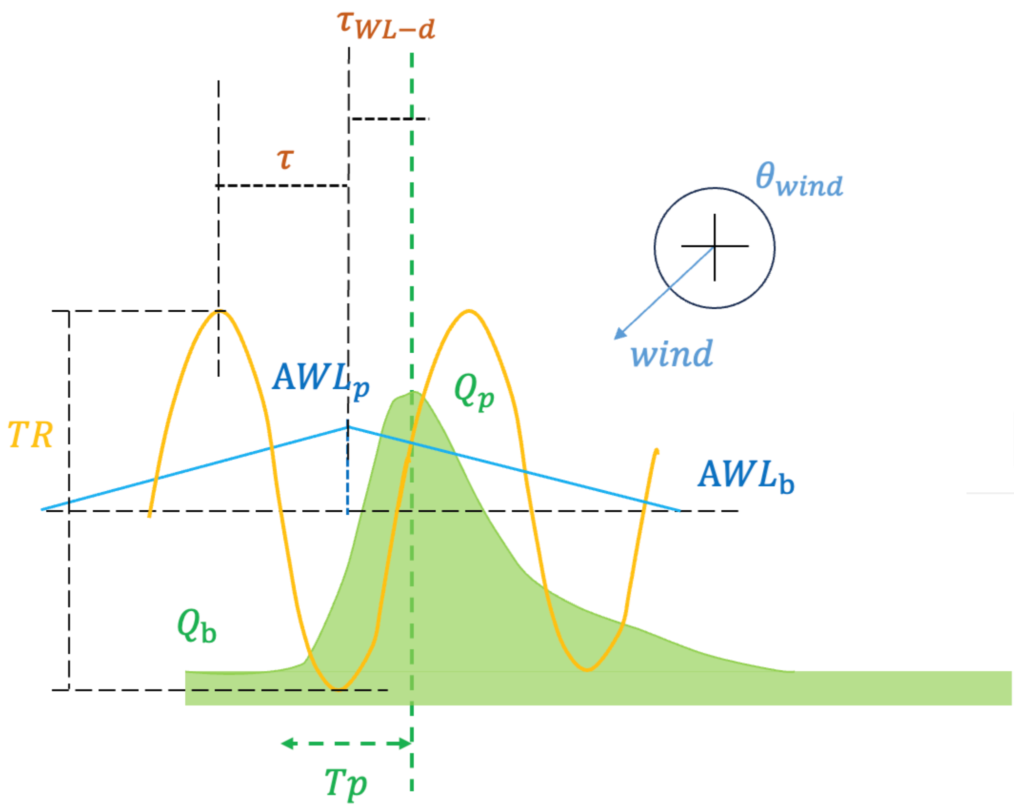
10 parameters

$$\left(Q_p, Q_b, AWL_p, AWL_b, TR, Tp, \tau, \tau_{WL-d}, wind, \theta_{wind}\right)$$

Metamodel

Parametrization

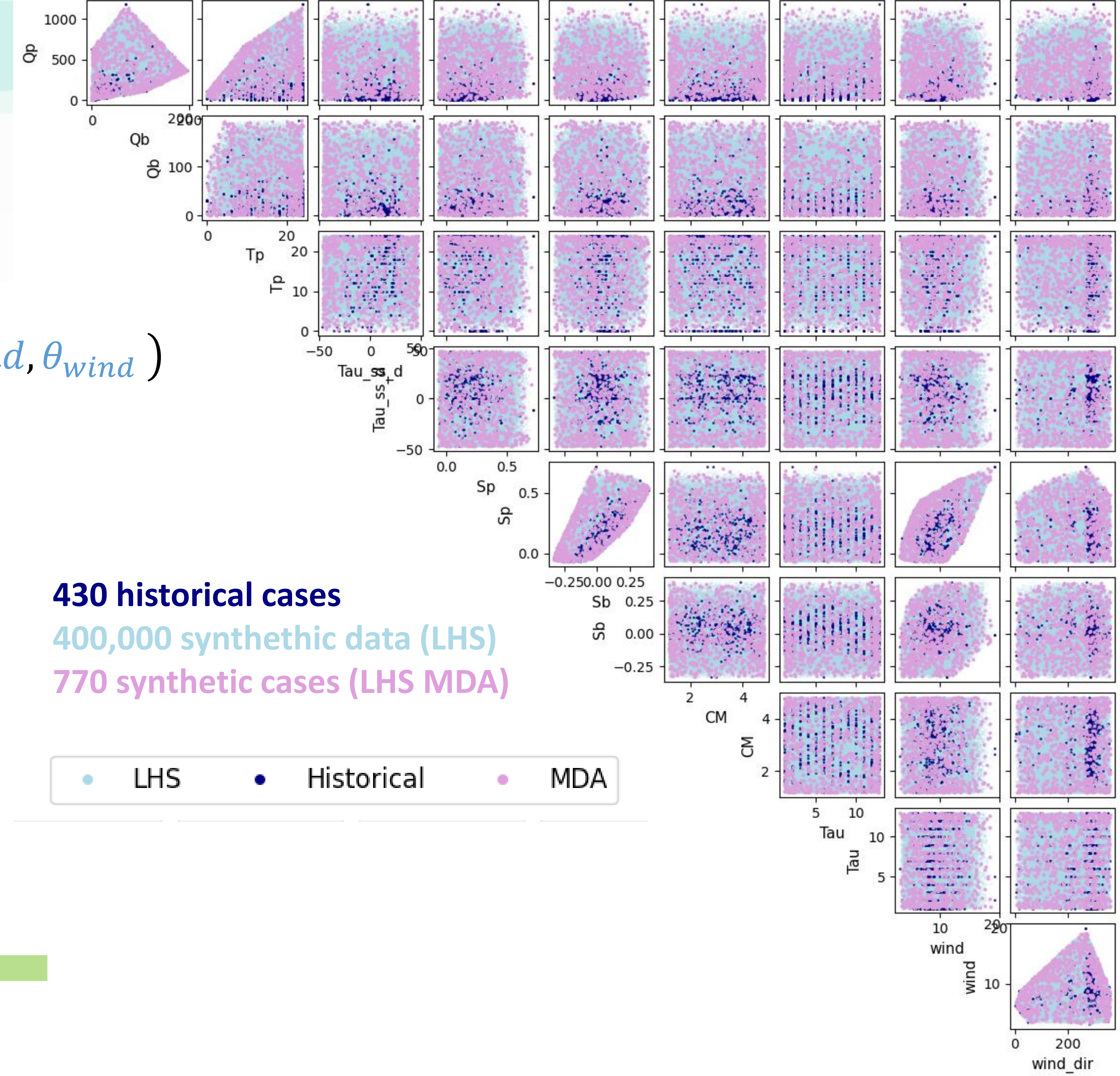
$$\left(Q_p, Q_b, AWL_p, AWL_b, TR, Tp, \tau, \tau_{AWL-d}, wind, \theta_{wind}\right)$$



430 historical cases

400,000 synthethic data (LHS)

770 synthetic cases (LHS MDA)



Metamodel

Library of cases

1200 cases =
430 historical cases +
770 synthetic cases (LHS MDA)

SCHISM

Library of simulations

First 100 cases:

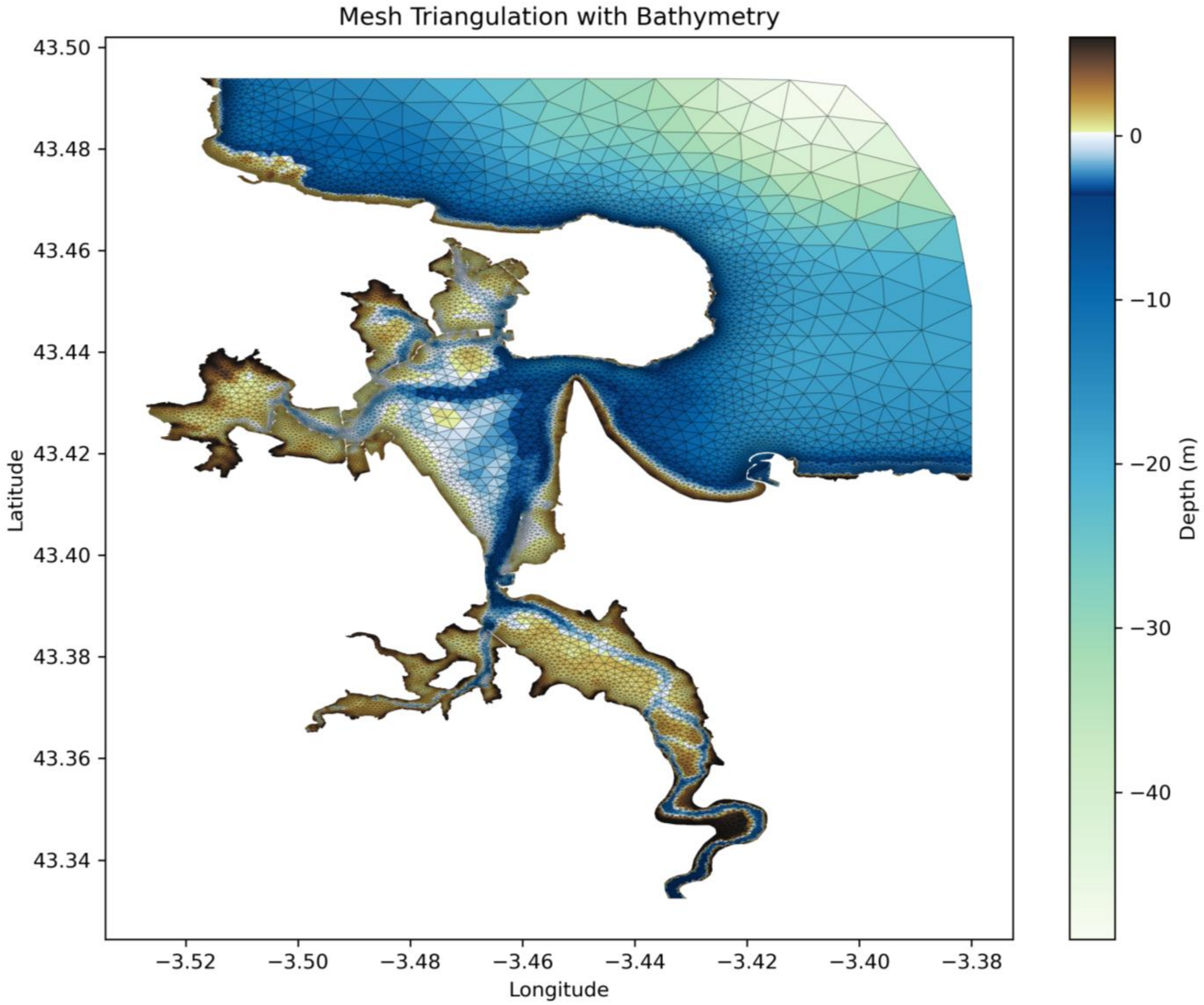
Metamodel

Hydrodinamic simulations

Unstructured mesh: > 29449 elements
Resolution: 20 m – coast
1 km - offshore

Mesher OceanMesh2D (open source)

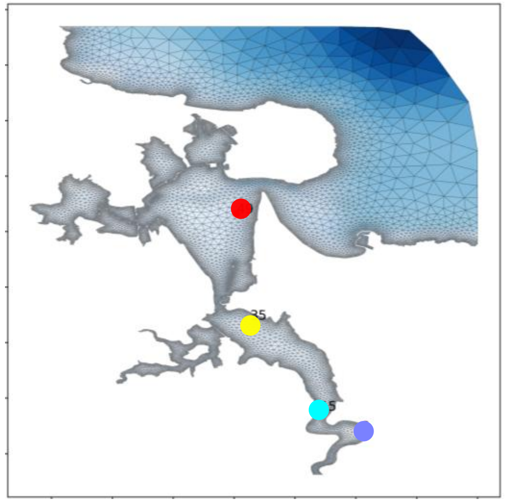
Bathymetry: LiDAR + RGB photogrammetry flights with drones (810ha flights) + nautical charts

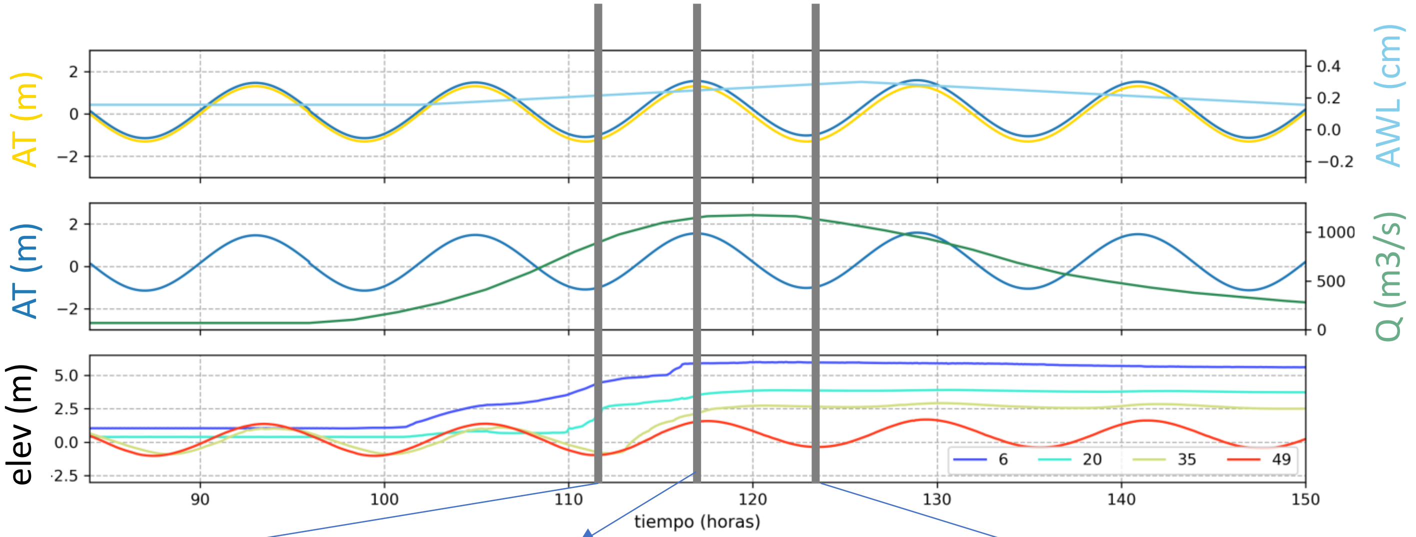


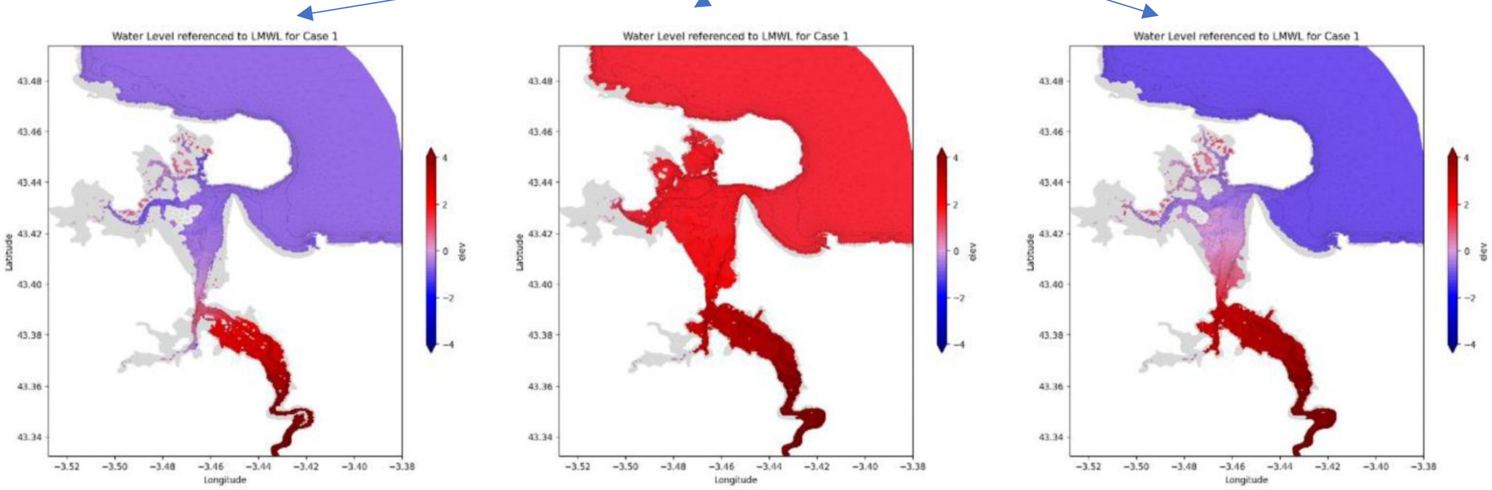
Metamodel

Library of simulations

Qp = 1100 m^3/s
Qb=100 m3/s
Tidal range = 2.5 m
Surge_base=0.15m
Surge_peak=0.3 m







Simulated Water elevation for t = 112 h - Case 1

Simulated Water elevation for t = 117 h - Case 1

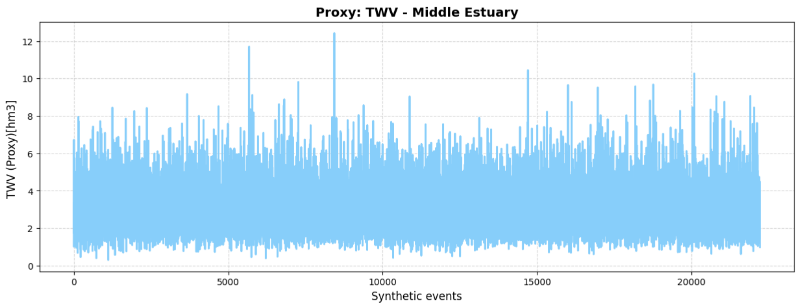
Simulated Water elevation for t = 123 h - Case 1

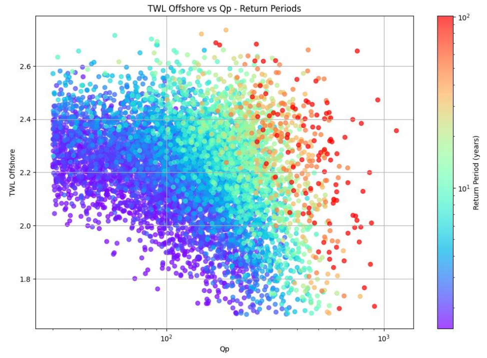
Metamodels

Total water volume proxy metamodel

RBF

RADIAL BASIS FUNCTIONS
Interpolation Algorithm





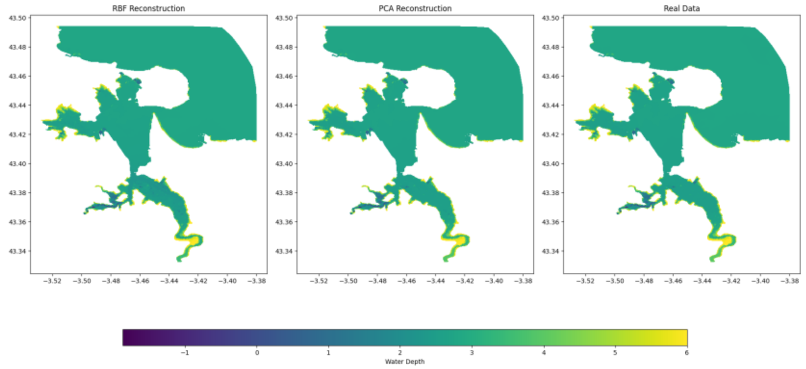
Reconstructed flood map metamodel

PCA

PRINCIPAL COMPONENT ANALYSIS
Dimensionality Reduction

RBF

RADIAL BASIS FUNCTIONS
Interpolation Algorithm



Metamodels

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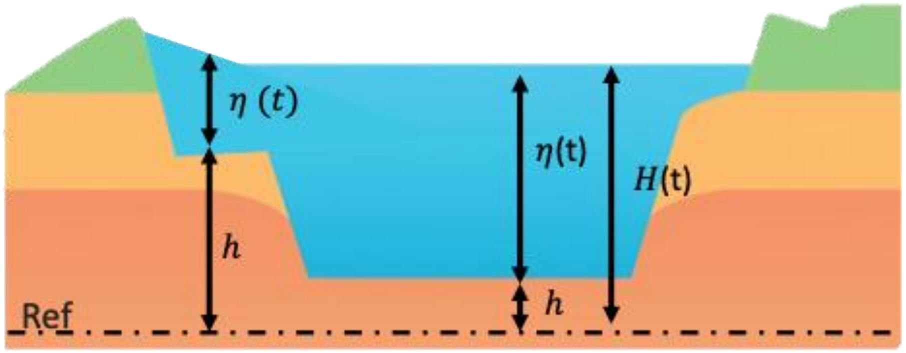


Total water volume proxy definition (hm^3)

Calculate elevation and water column at each node

$$H(t) = \eta(t) + h$$

Integrate over the whole domain to get Total Water Volume (TWV)

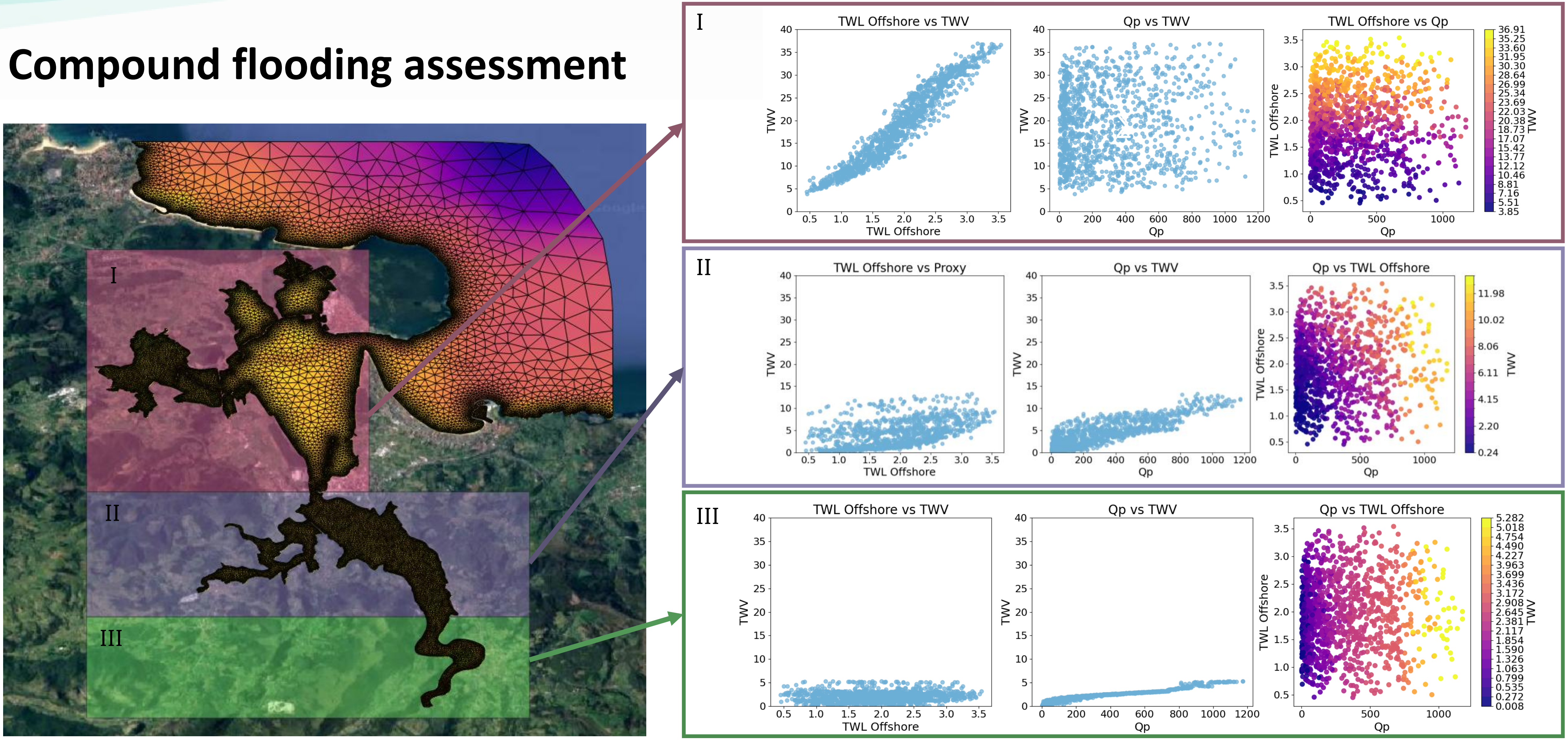
$$TWV(t) = \sum_{i=1}^{N} H_i(t) \cdot A_i$$

Extract the maximum value

$$max\_twv = \max(TWV(t))$$

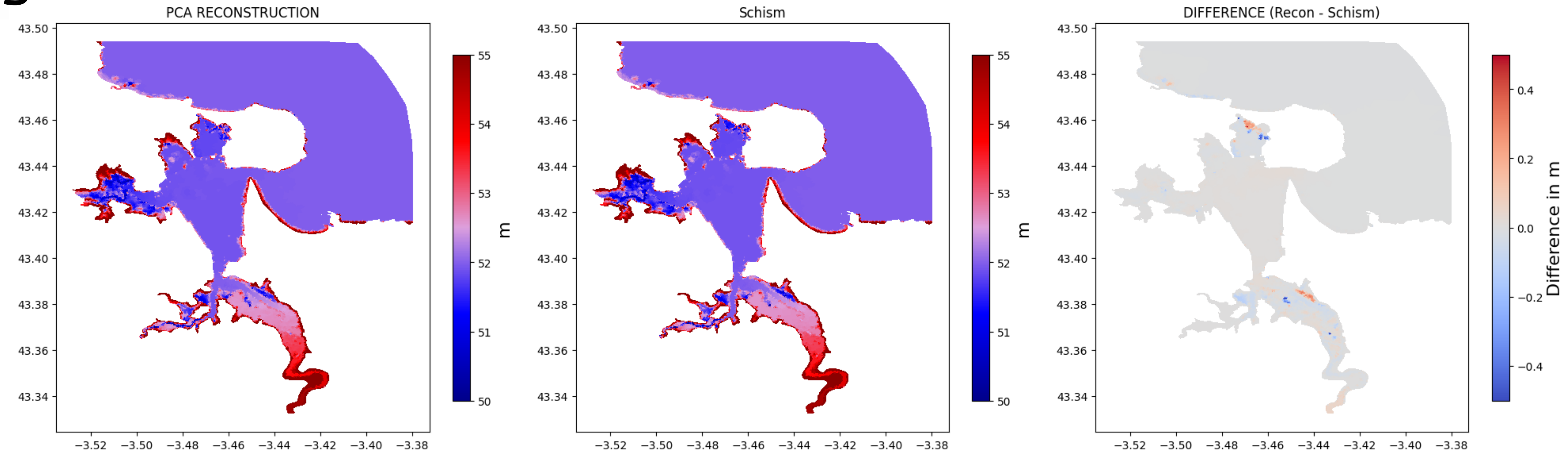
Metamodel

Compound flooding assessment



Metamodel

Metamodels



Reconstruction using 32 PCs

Reconstructed flood map metamodel

PCA
PRINCIPAL COMPONENT ANALYSIS
Dimensionality Reduction

RBF
RADIAL BASIS FUNCTIONS
Interpolation Algorithm

- Maximum flood maps – 1200 cases
- Keep the PCs that explain 95% of the variance = 32 PCs

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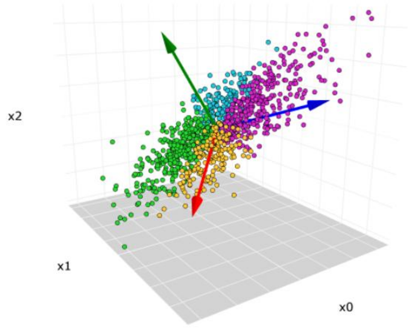
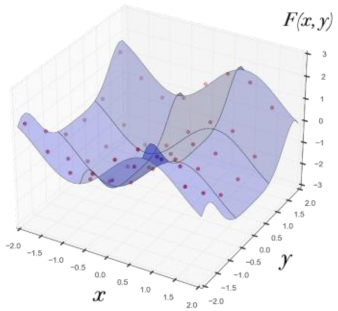
Metamodes

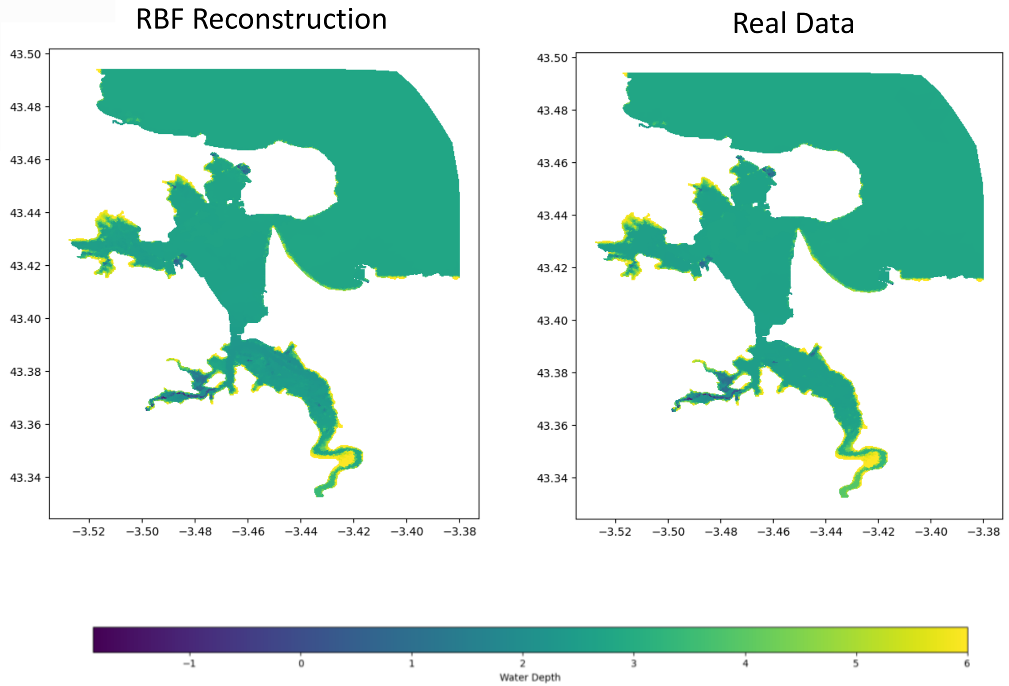
$$y(x;\ p_1, p_2, \dots, p_n) \approx \bar{y}(x) + EOF_1(x)PC_1(p_1, p_2, \dots, p_n) + \dots + EOF_C(x)PC_C(p_1, p_2, \dots, p_n)$$

Camus et al., 2011



TWV$(x; p_1, p_2, \dots, p_n)$





Reconstructed flood map metamodel

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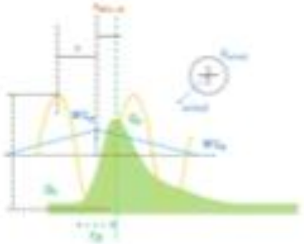

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**PROBABILISTIC ASSESSMENT
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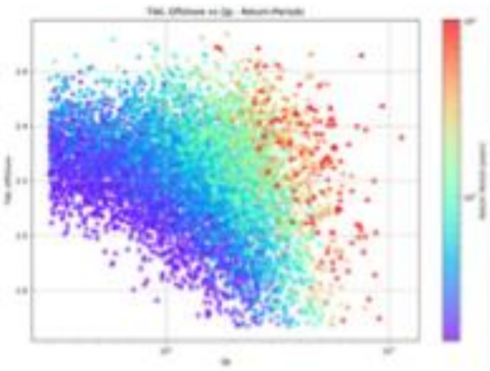
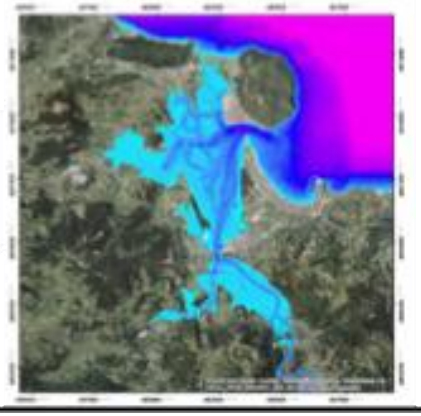


Reconstructed
flooding
maps



Methodological approach

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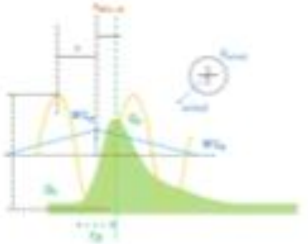

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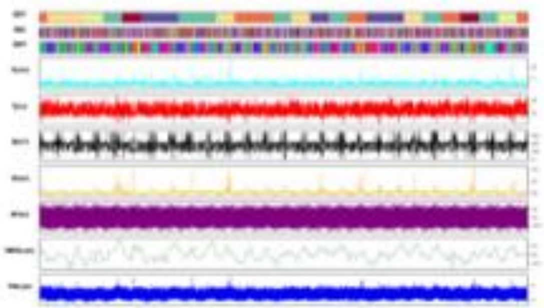
MUSCLE

SYNTHETIC FORCING CONDITIONS



PROBABILISTIC ASSESSMENT OF COMPOUND FLOODING HAZARD

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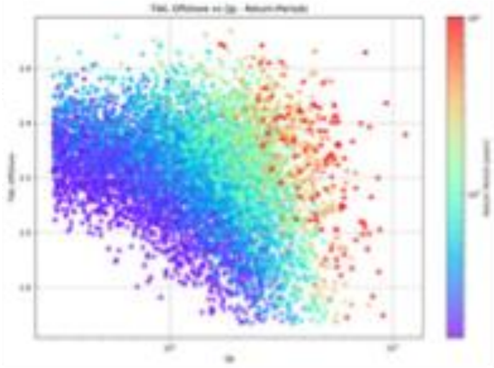
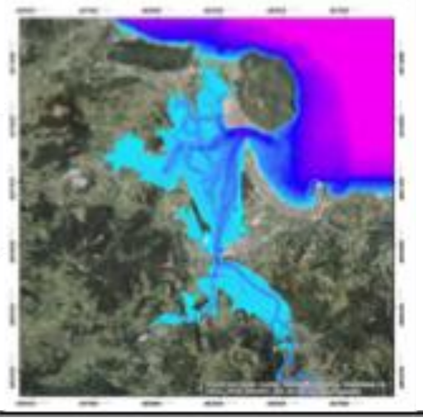
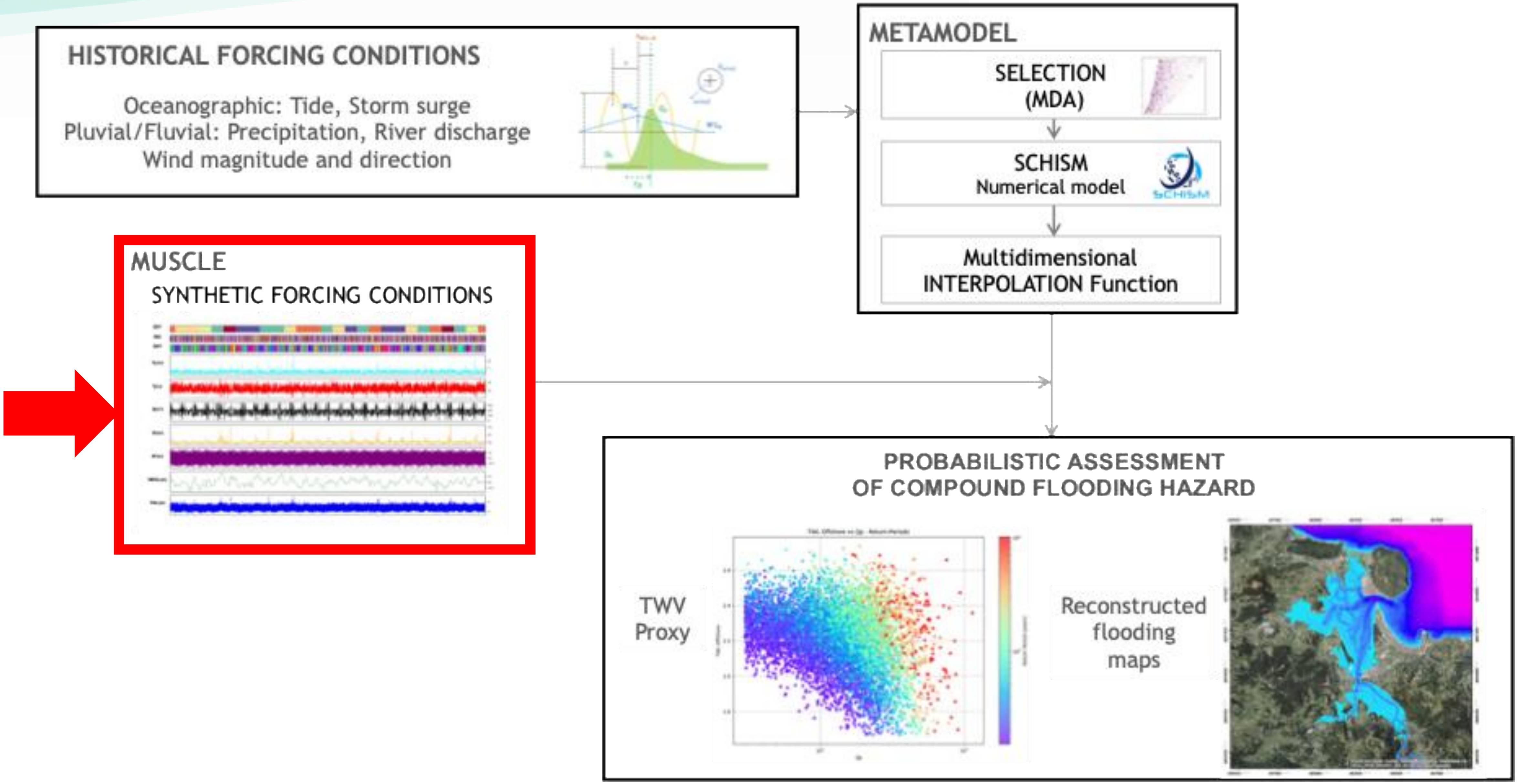


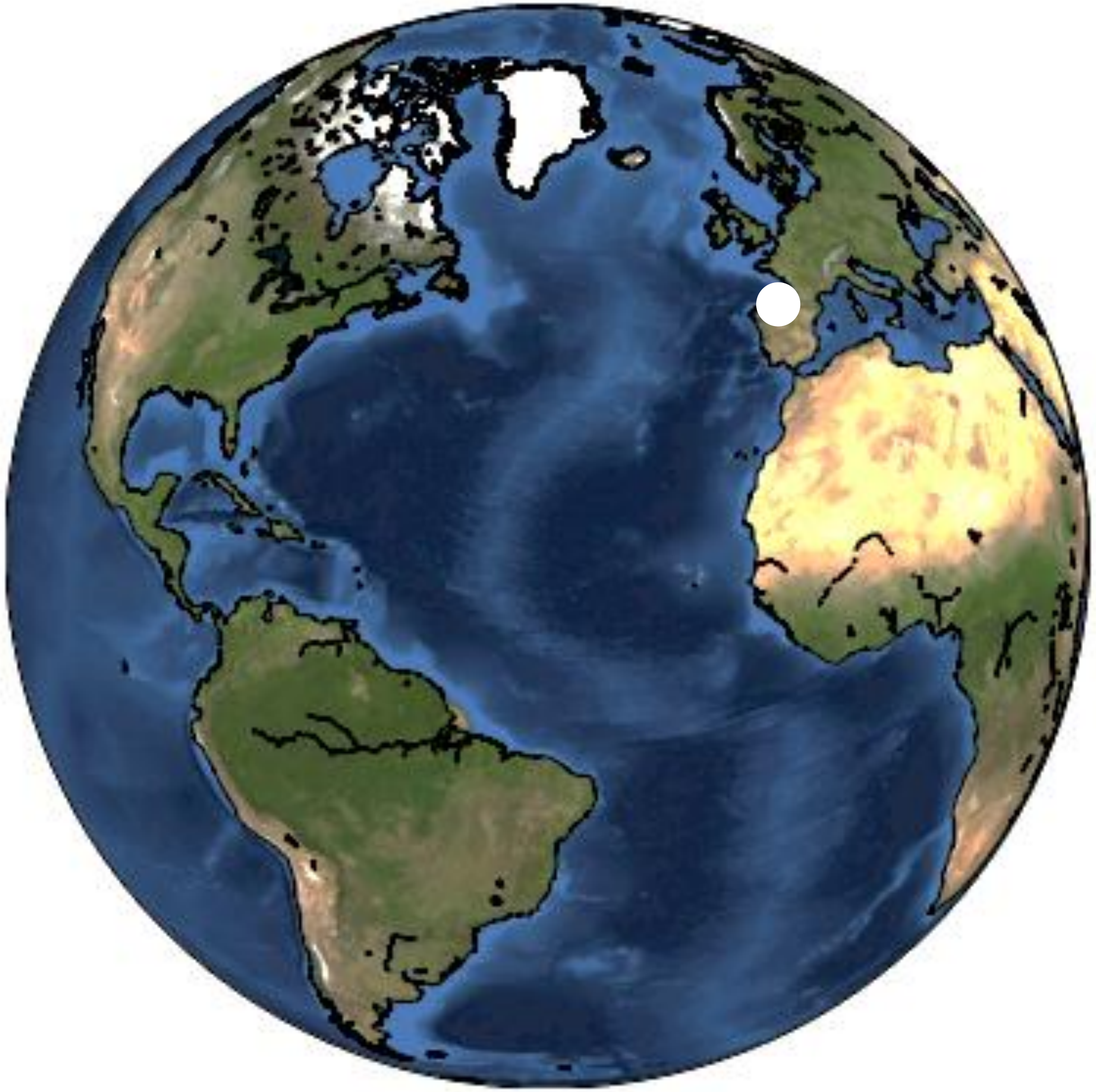
Reconstructed flooding maps



Methodological approach



MUSCLE



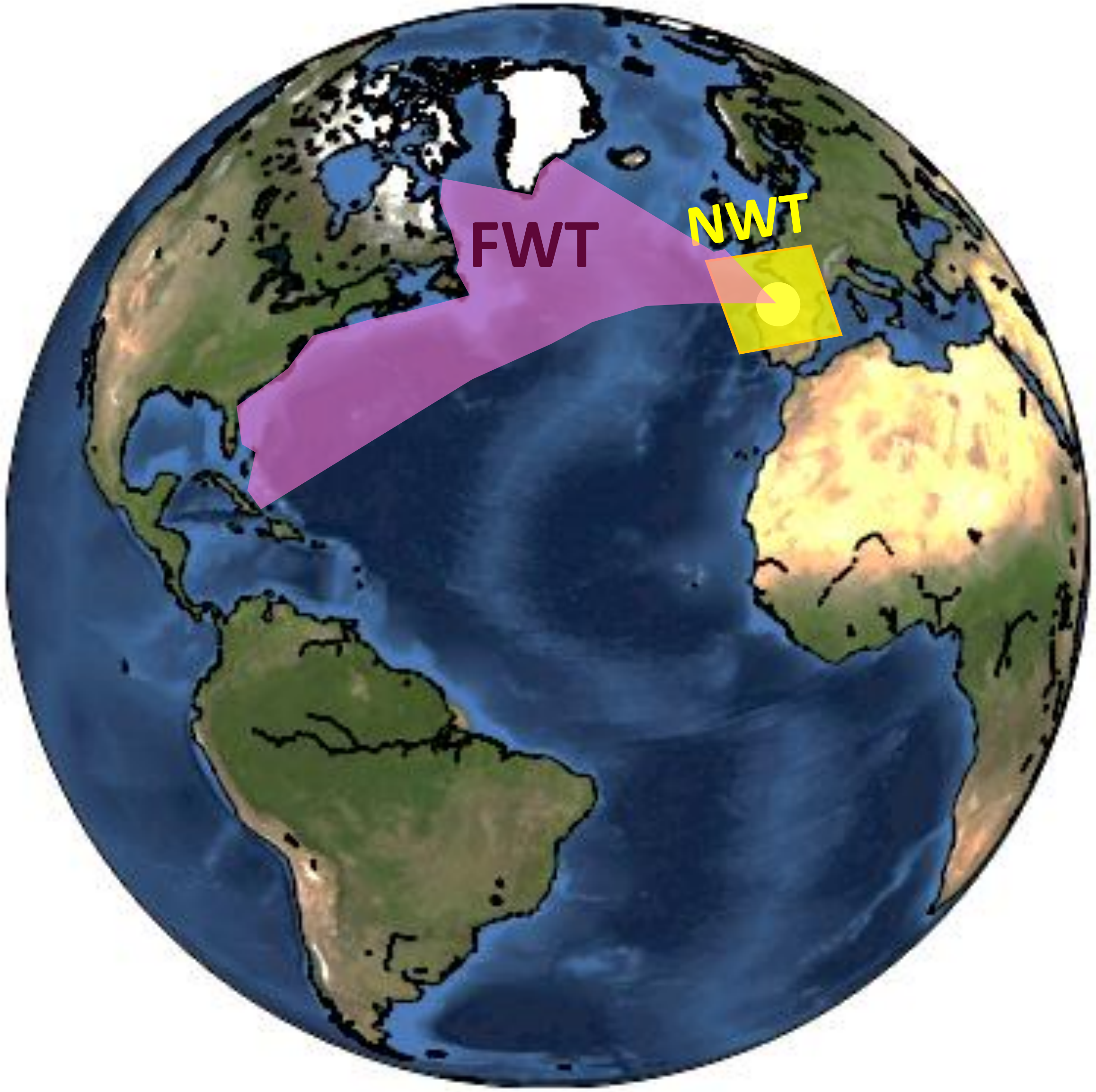
PREDICTANDS

- **Waves (Hs, Tp, Dir)**
- **SS**
- **Precipitation**
- **Wind**

PREDICTORS?

Neccessity of a **Multiscale spatial approach**

MUSCLE



Far Field Weather Types

FWT

- **Waves:**
  - **Hs**
  - **Tp**
  - **Dir**

Near Field Weather Types

NWT

- **Storm Surge**
- **Precipitation**
- **Wind**

CRONOLOGY MODEL

MONTE CARLO SIMULATIONS

NWT → f(FWT, AWT, Seasonality, MJO)

MUSCLE

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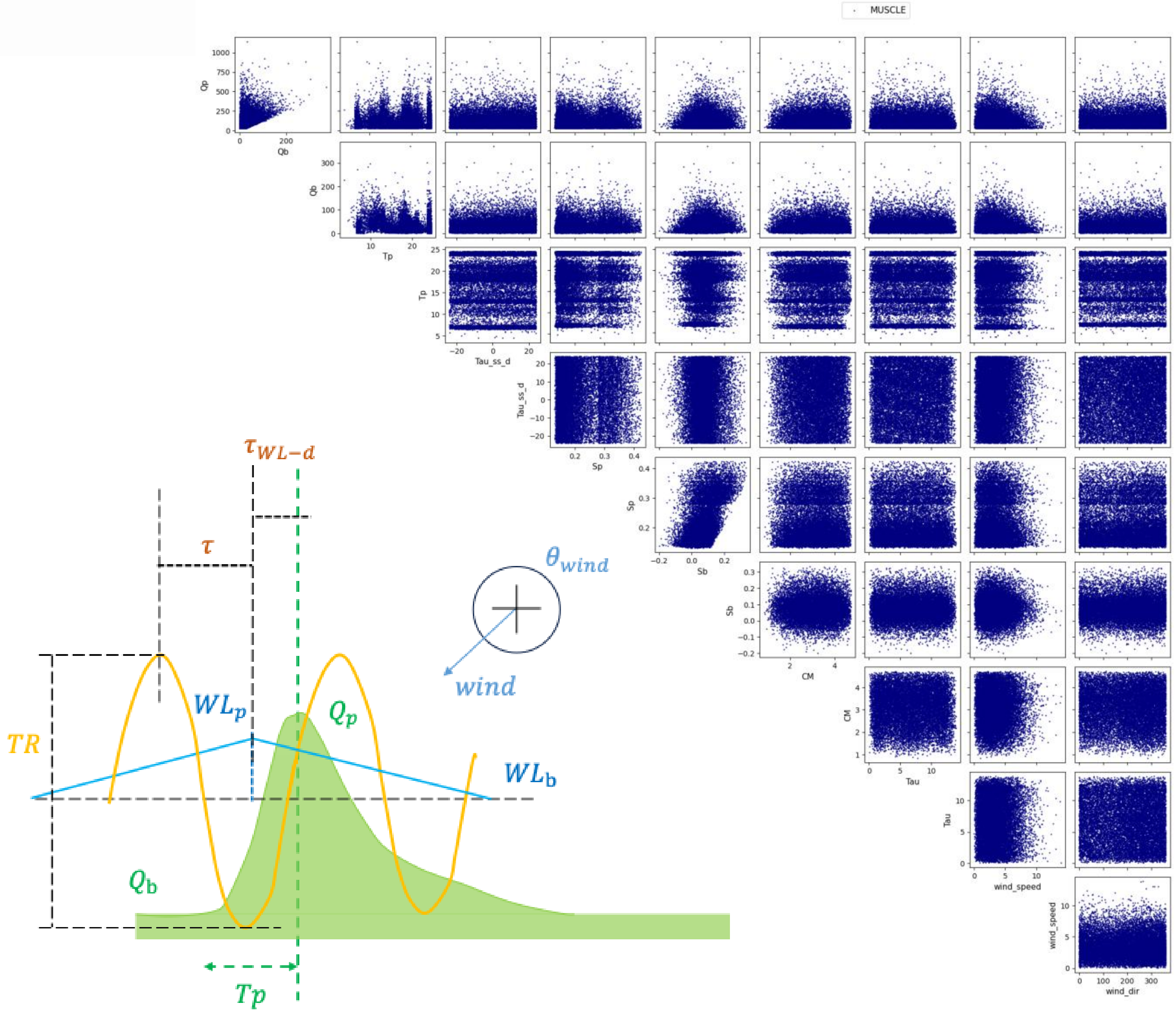
22,000 synthetic cases (MUSCLE: 100 sims x 100 years)

$$\left(Q_p, Q_b, AWL_p, AWL_b, TR, Tp, \tau, \tau_{WL-d}, wind, \theta_{wind}\right)$$

100 Simulation x 100 Years



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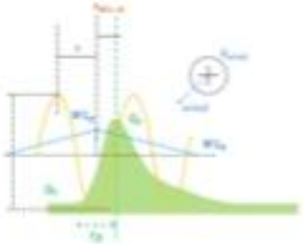

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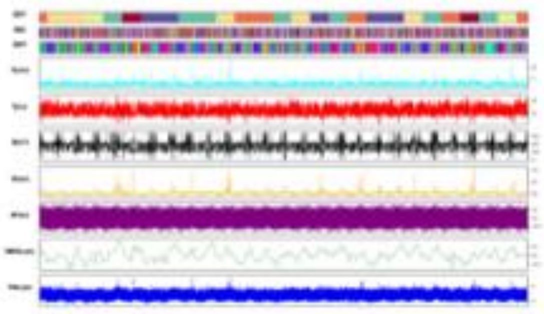
SYNTHETIC FORCING CONDITIONS



PROBABILISTIC ASSESSMENT OF COMPOUND FLOODING HAZARD

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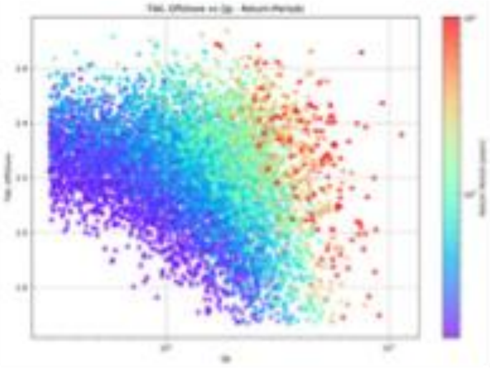
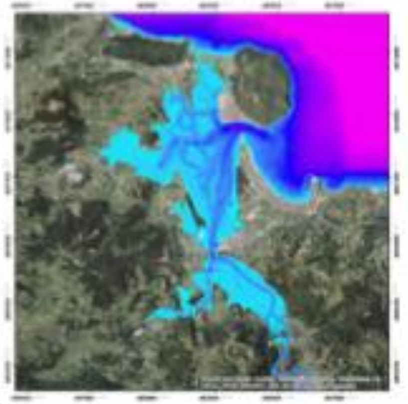
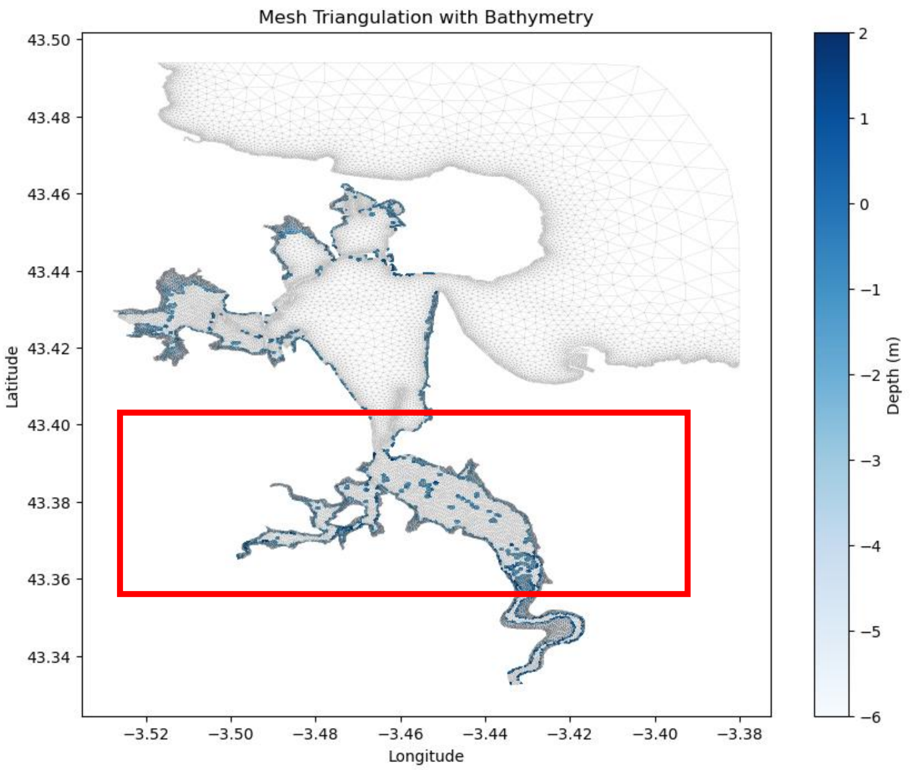


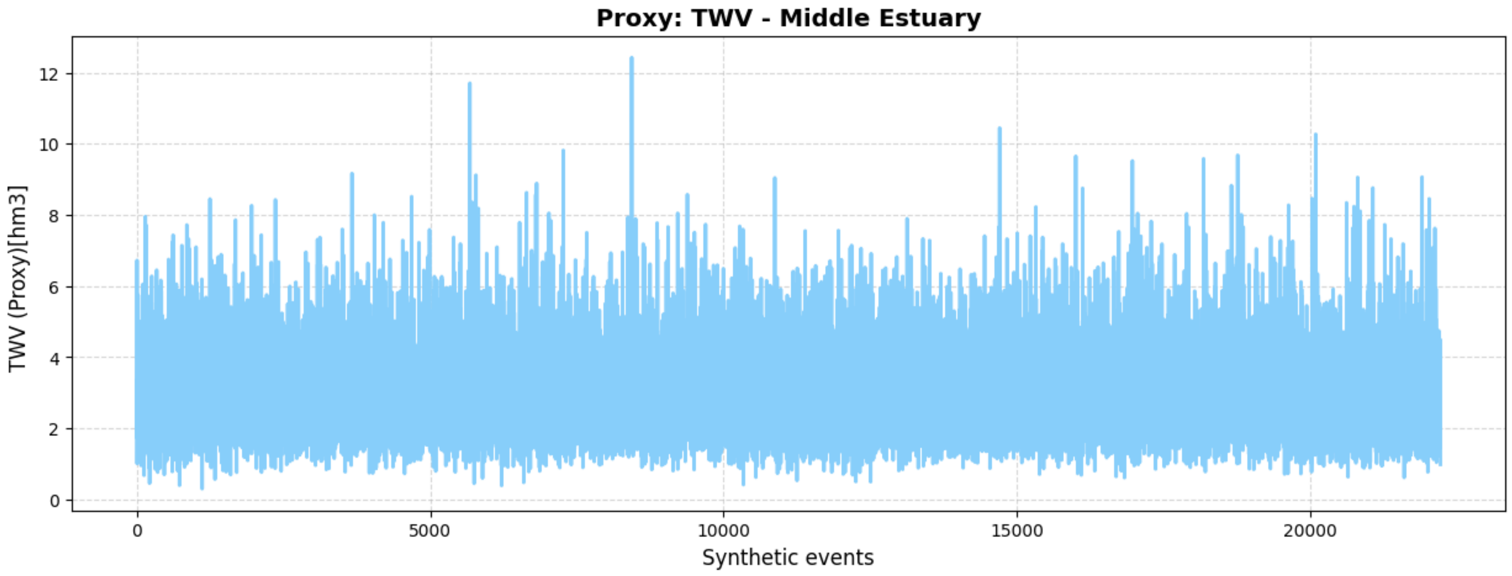
Reconstructed
flooding
maps



TWV Reconstructed Serie at Middle Estuary



Total water volume proxy metamodel

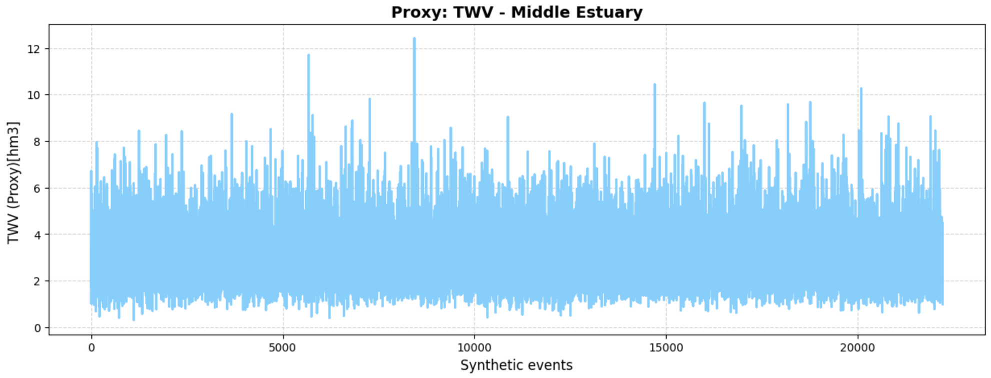


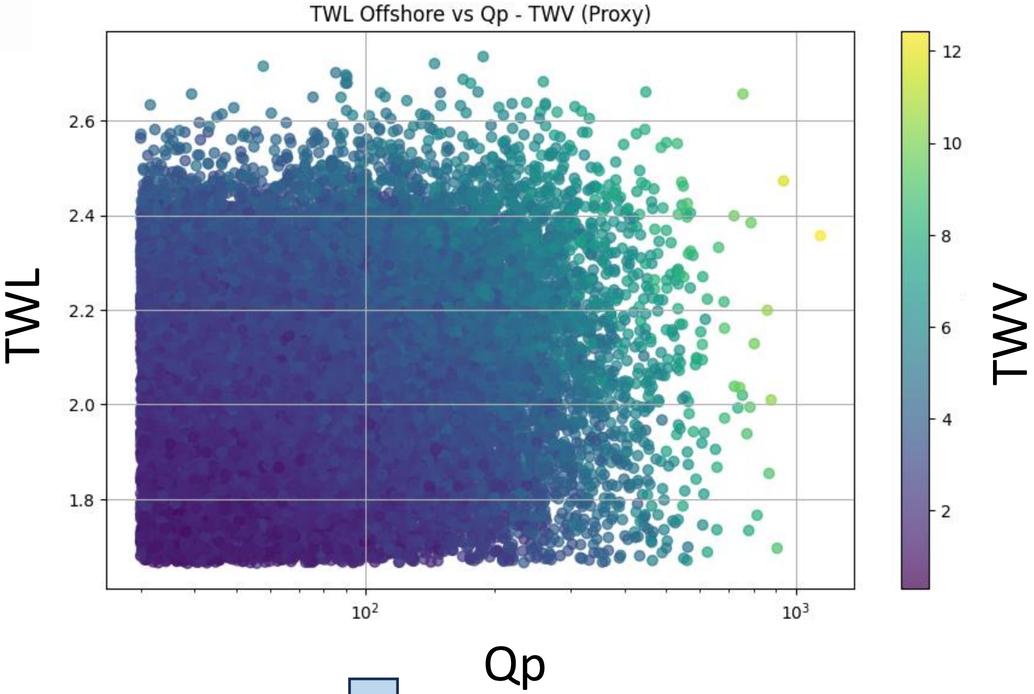
22,000 synthetic cases (MUSCLE: 100 sims x 100 years)

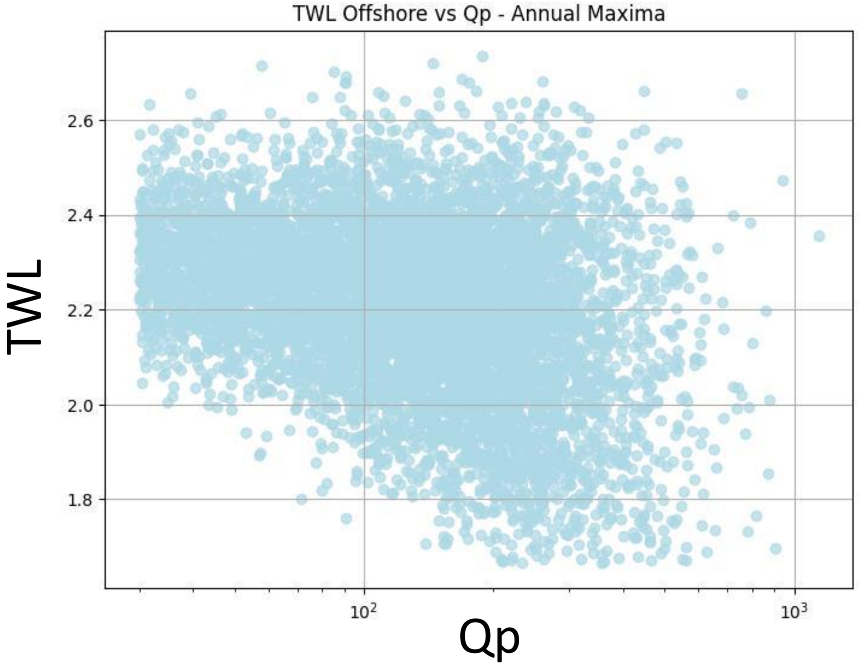
Probabilistic Assessment

22,000 synthetic cases (MUSCLE: 100 sims x 100 years)

Synthetic events (100 Simulations x 100 years)





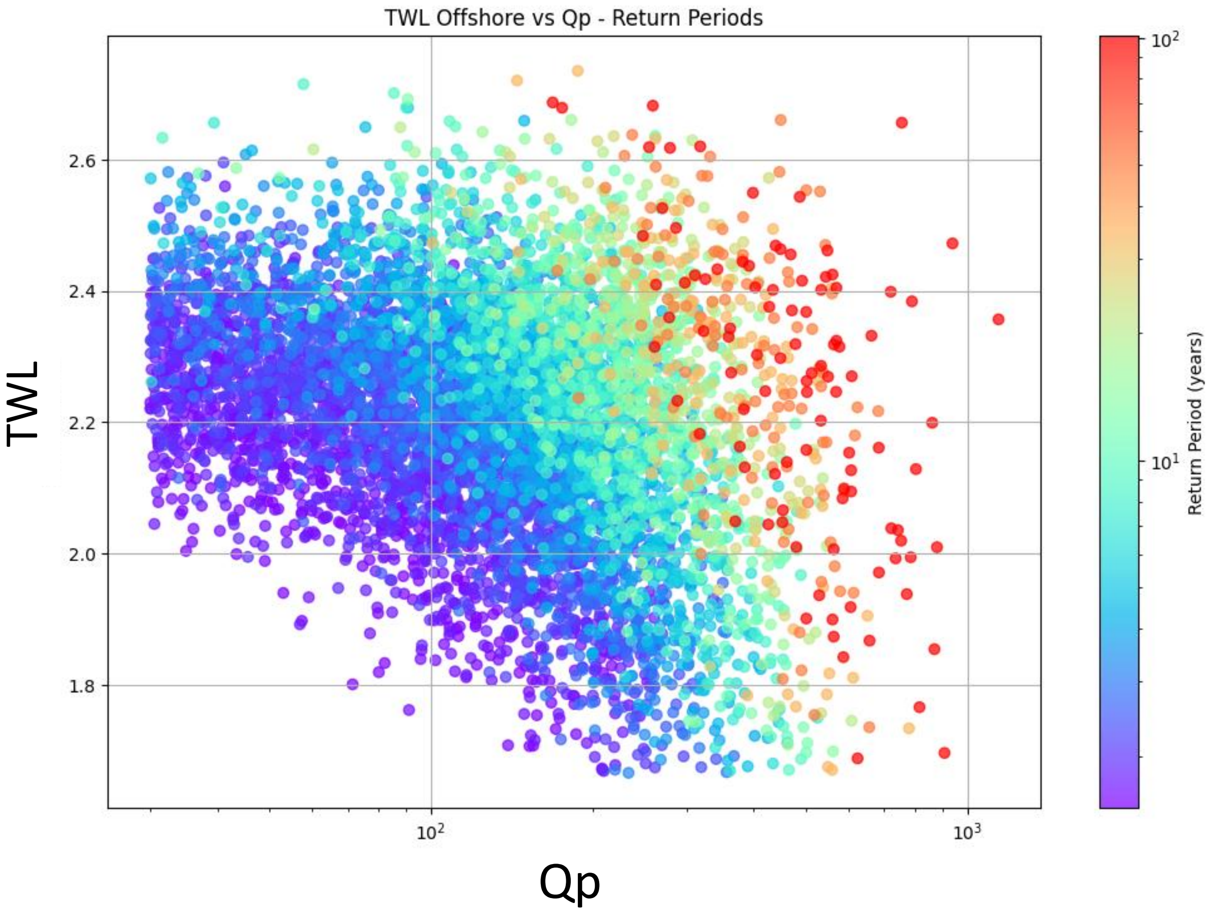


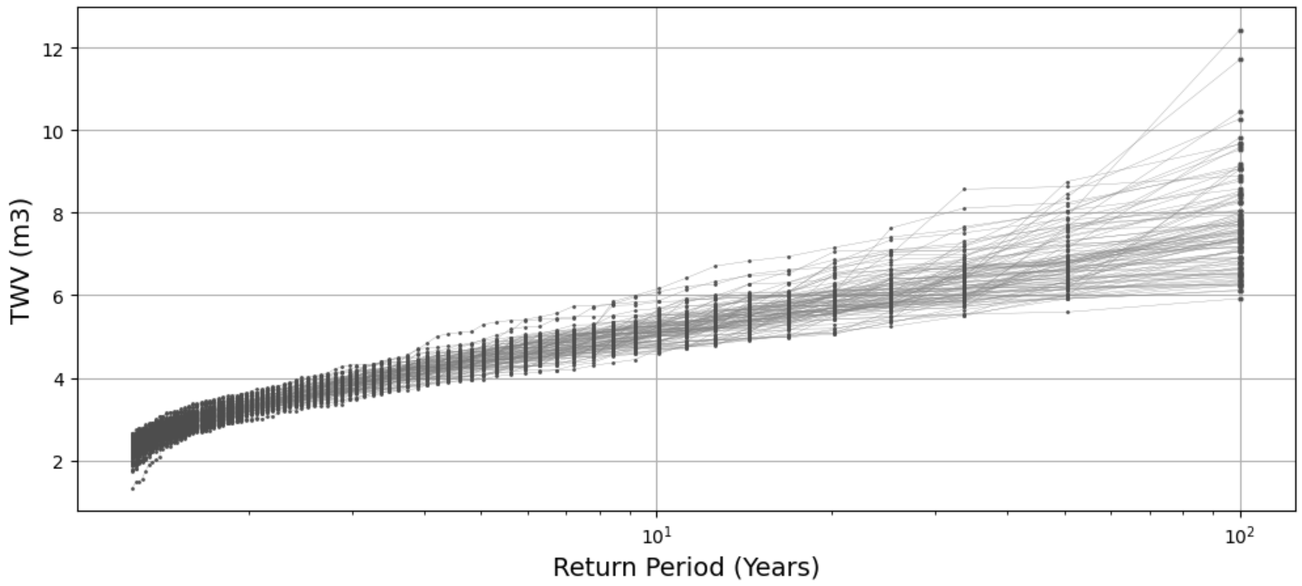
Annual maxima for all the synthehic events (100 sim x 100 years)

9:30	9:45	**Response-Based Risk Assessment of Tropical Cyclone induced coastal flooding due to Storm Surge and Waves (Presenter: Pablo Alonso Alguacil)**

Probabilistic Assessment

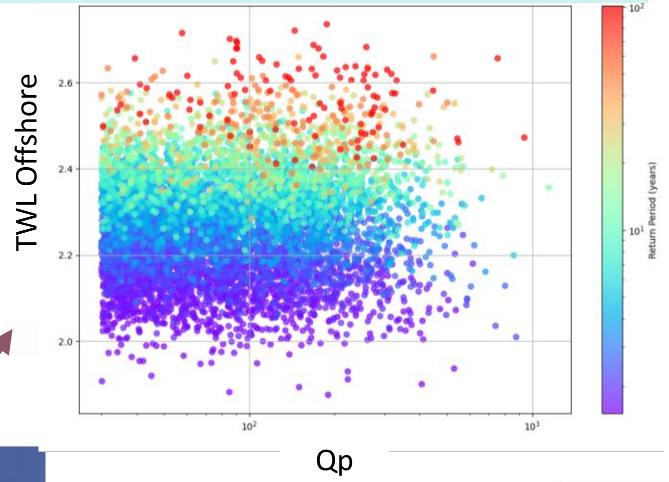
Tr calculated from the synthehic events (100 sim x 100 years)



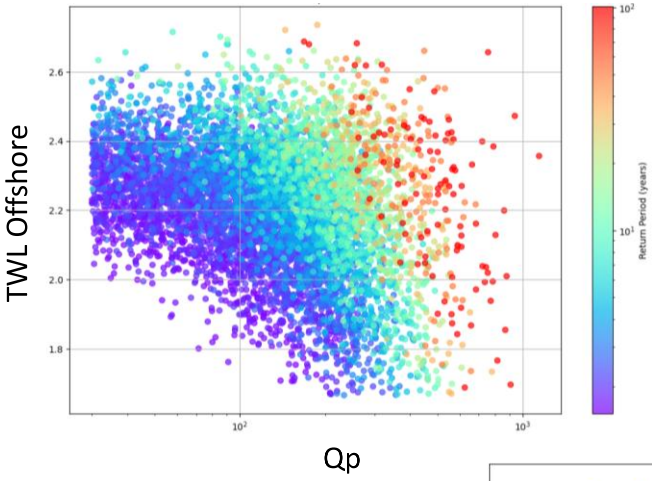


Probabilistic Assessment

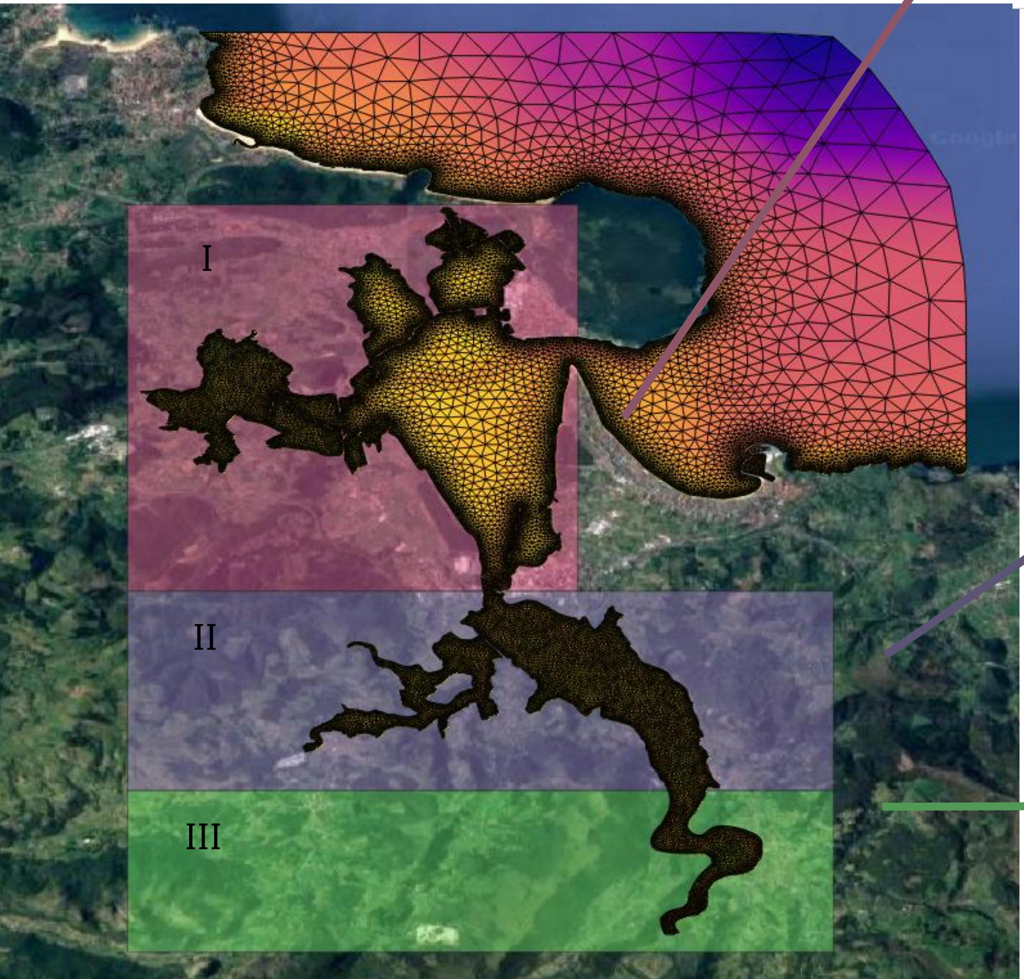
Return period = 100 years



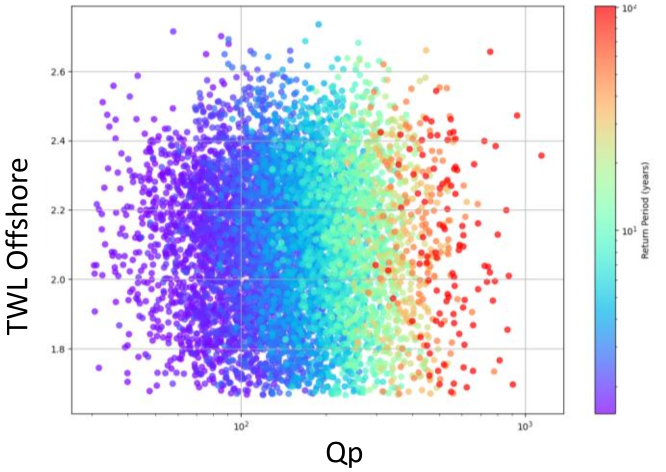
Lower Estuary



Middle Estuary

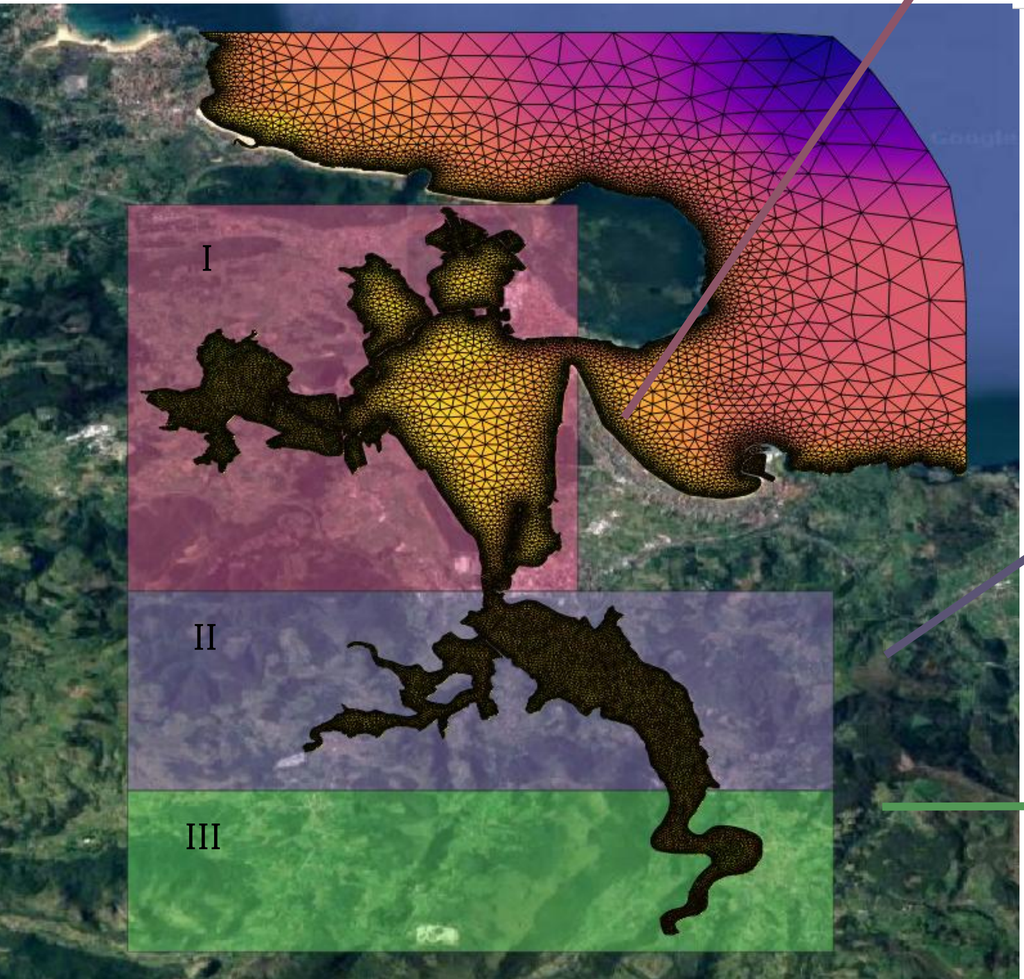


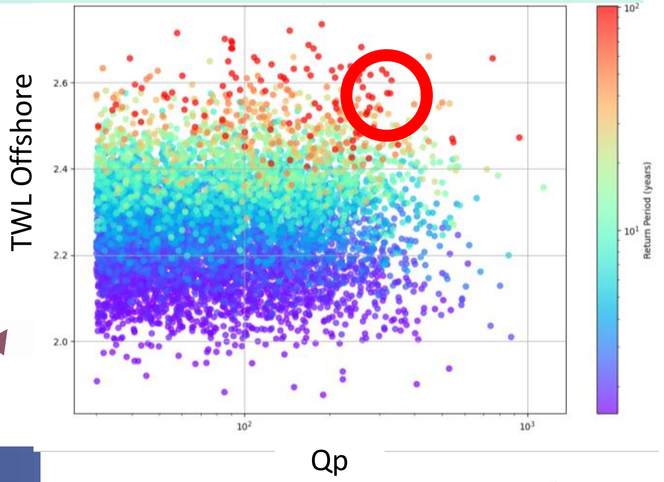
Upper Estuary



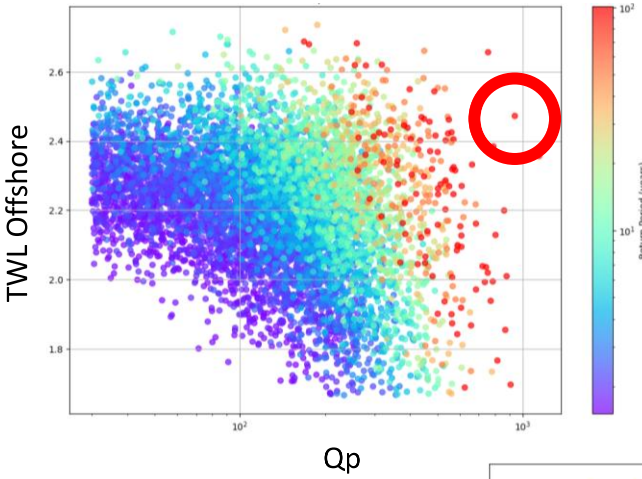
Probabilistic Assessment

Return period = 100 years



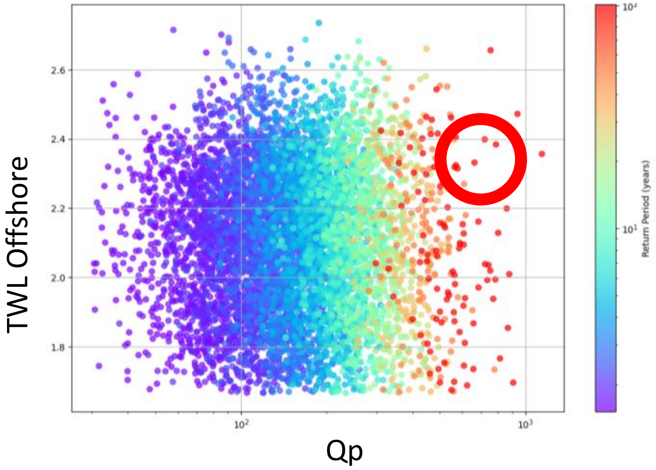


Lower Estuary



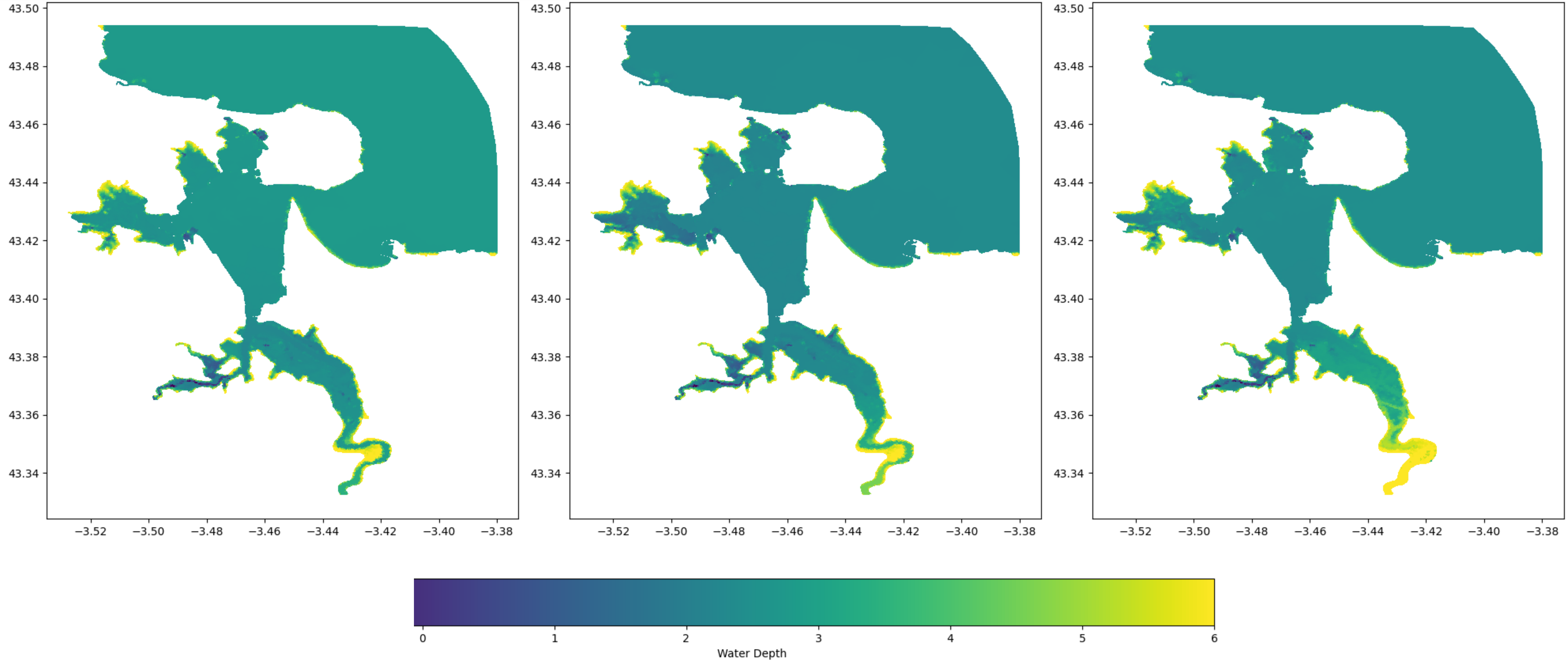
Middle Estuary

Upper Estuary



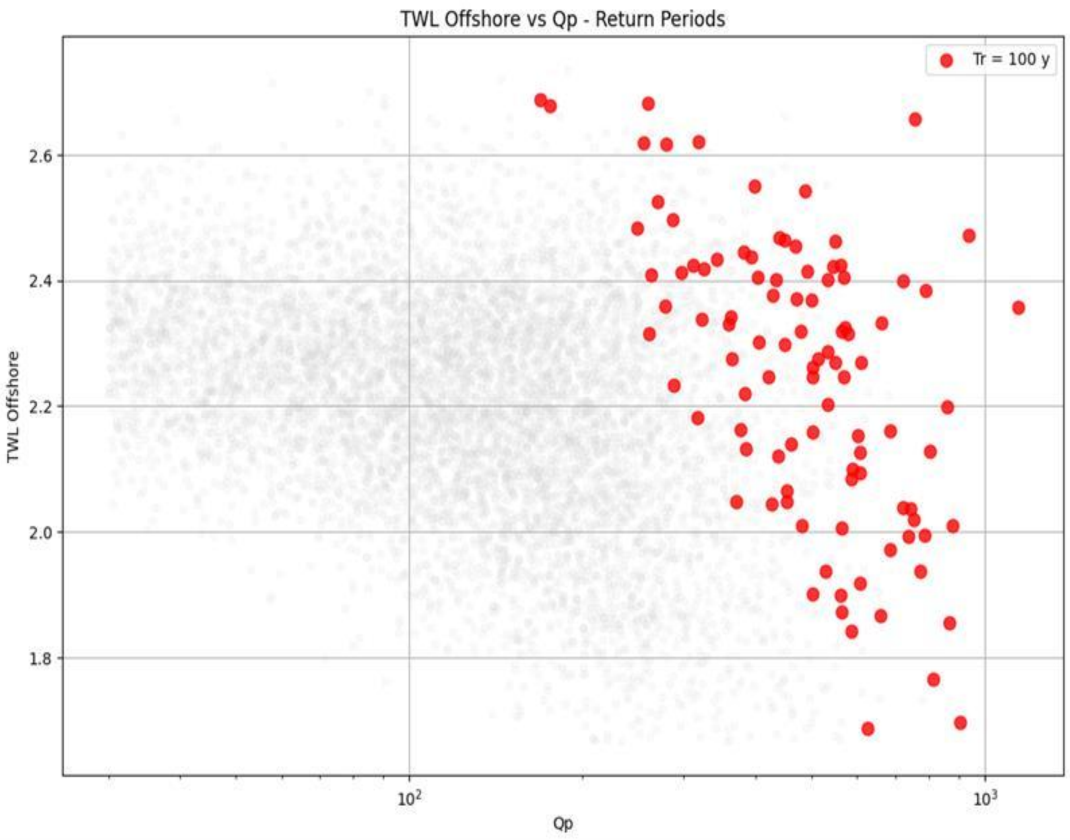
Return period = 100 years. – Flooding maps

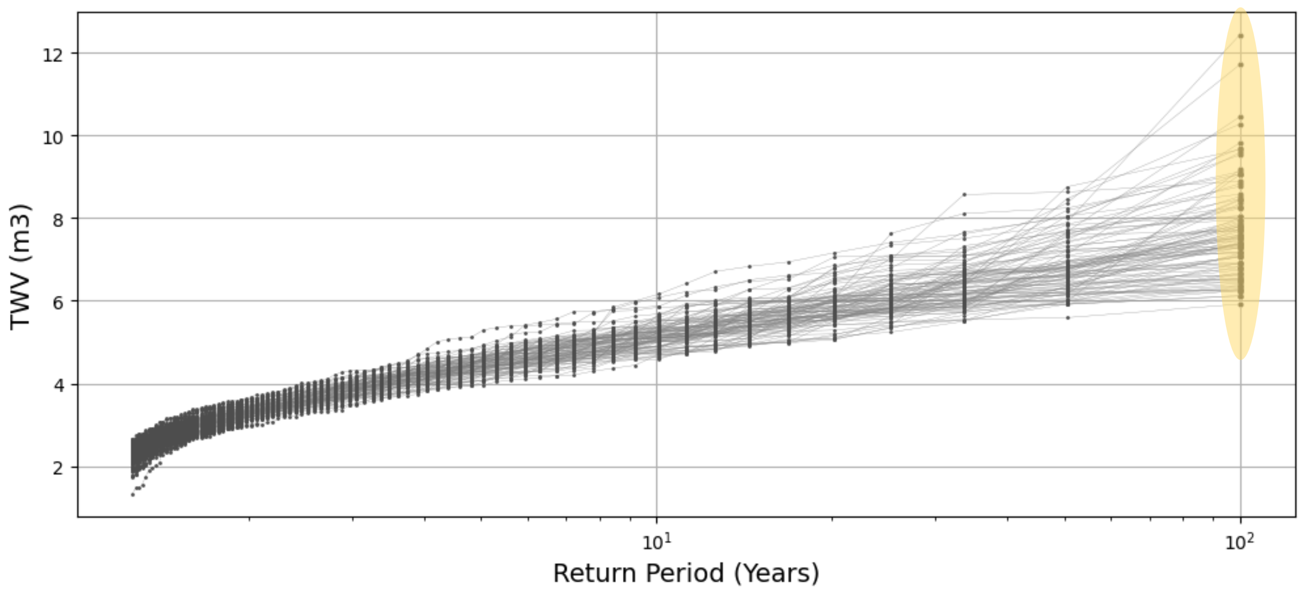
Lower Estuary Case | Middle Estuary Case | Upper Estuary Case



Probabilistic Assessment

Tr = 100 y





Probabilistic Assessment

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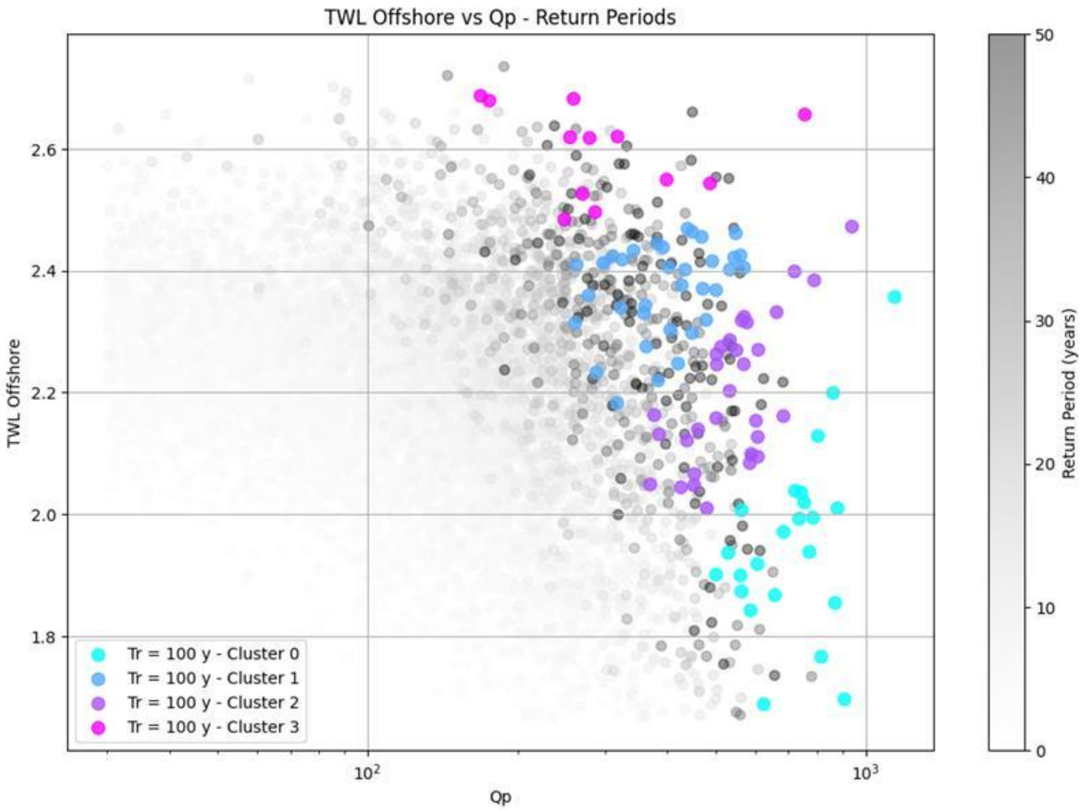
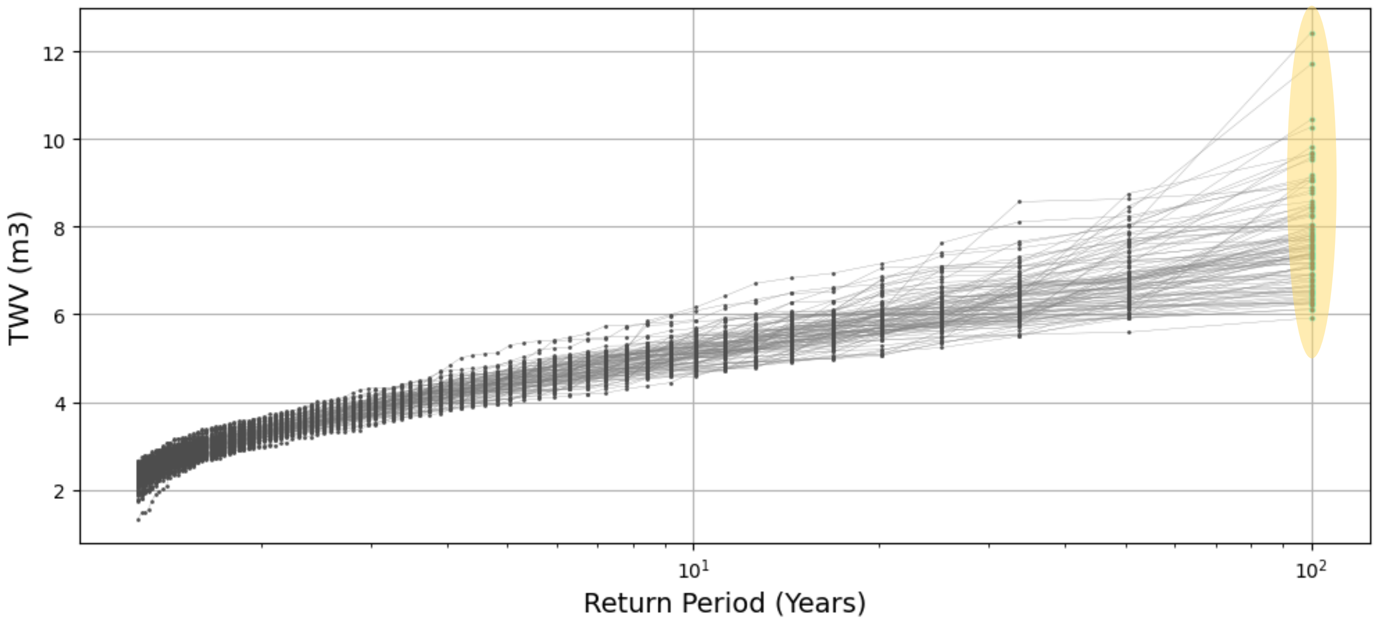
KMA

BlueMath

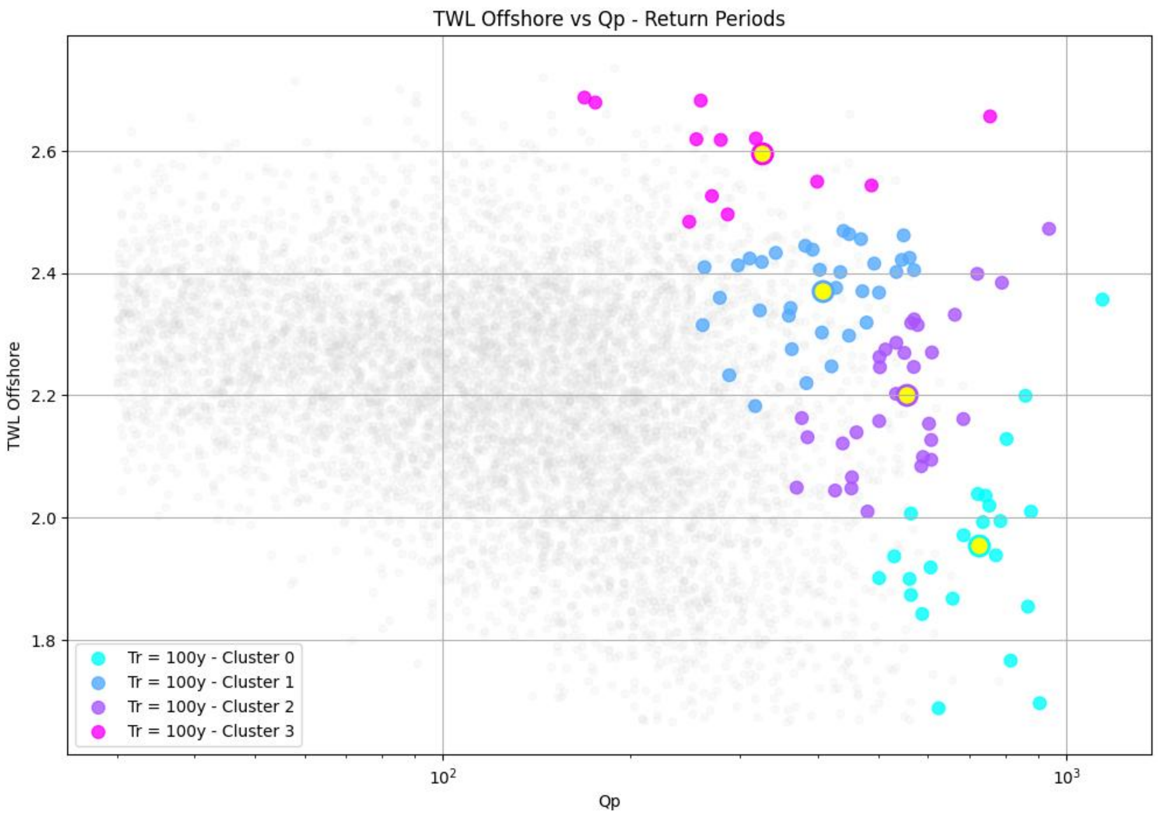
Tr = 100 y - Clusters





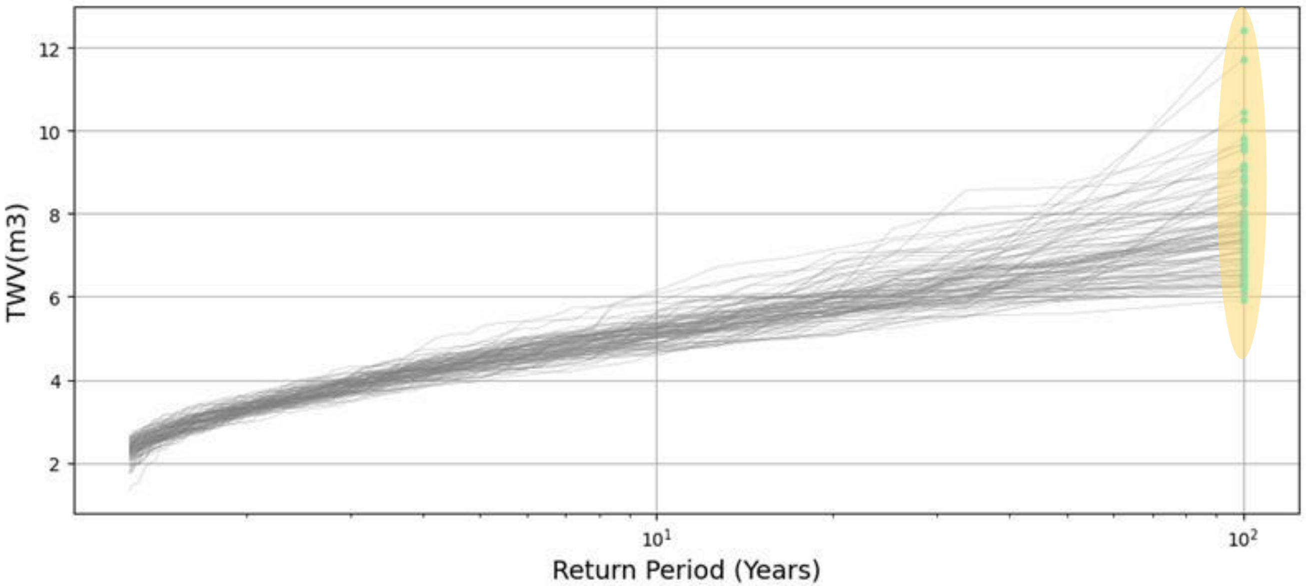
Probabilistic Assessment

Tr = 100 y – Cluster Centroids



Explore Uncertainty

100 Simulations x 100 years



Example of unique time series with different chronologies and exploration of the multivariate space

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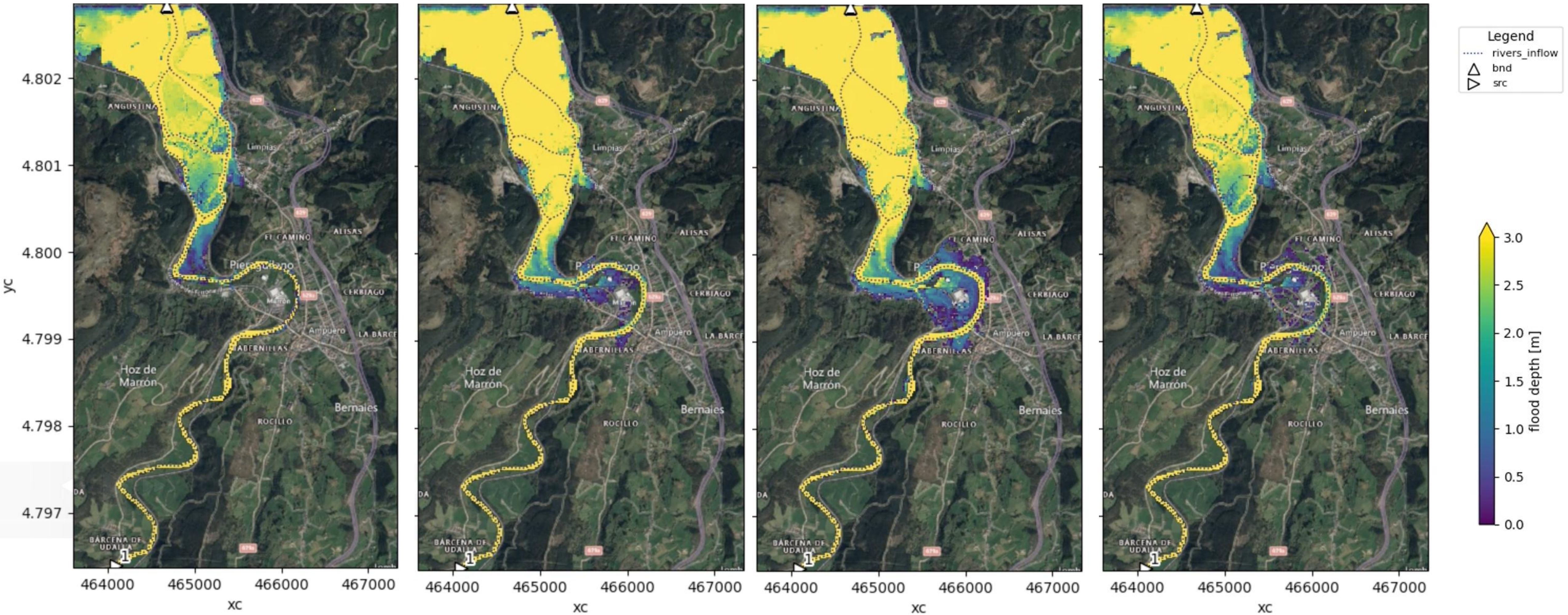
High resolution

Structured mesh: 950.176 elements
Resolution: 5 m
Mesher: SFINCS (Leijnse, et al., 2021)
Bathymetry: LiDAR + RGB photogrammetry flights with drones (810ha flights)

From the 4 Centroids

Cluster 2 (Tr 100 y)



Summary

- **Climate emulators** and **hybrid metamodels** were successfully integrated to assess **estuarine flood risk**, providing an efficient and reliable tool for flood management.

- The **Total Water Volume proxy metamodel** enables **extreme value analysis** across estuarine zones, allowing high-resolution simulation of key flood events.

- The **reconstructed flood map metamodel** can also be used as a short-term Early Warning System.

Thank you!

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https://geoocean.sci.unican.es/hyweb/

GeoOcean

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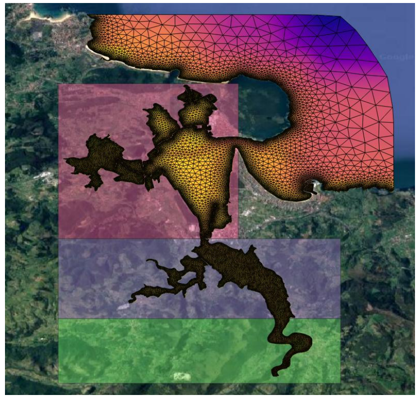
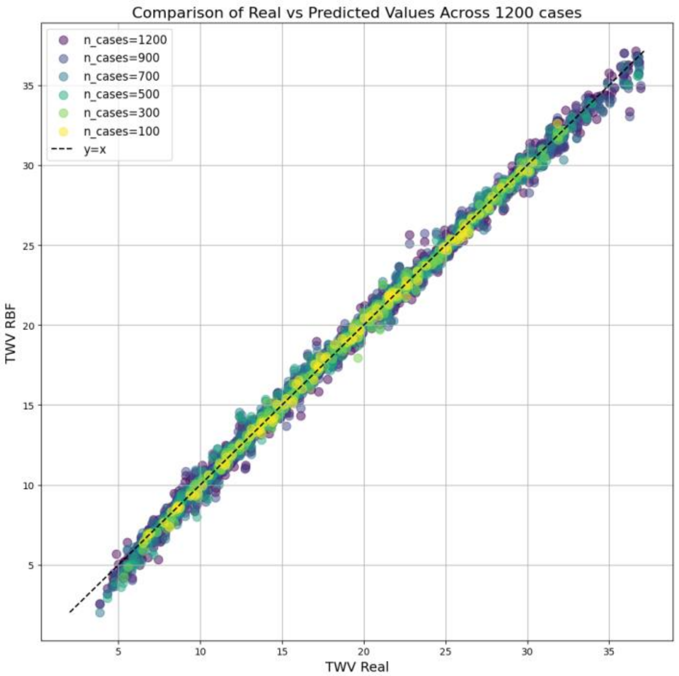
Metamodel

Cross-validation (k-fold)

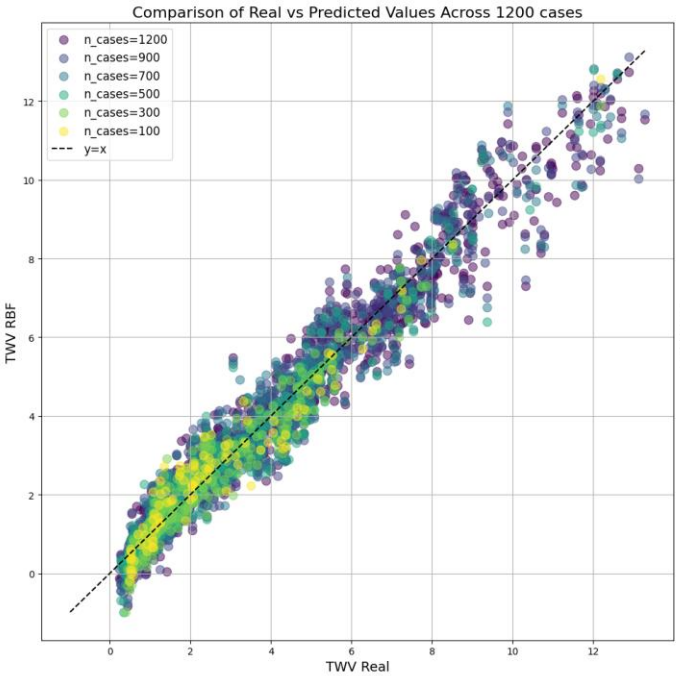
1200 selected cases



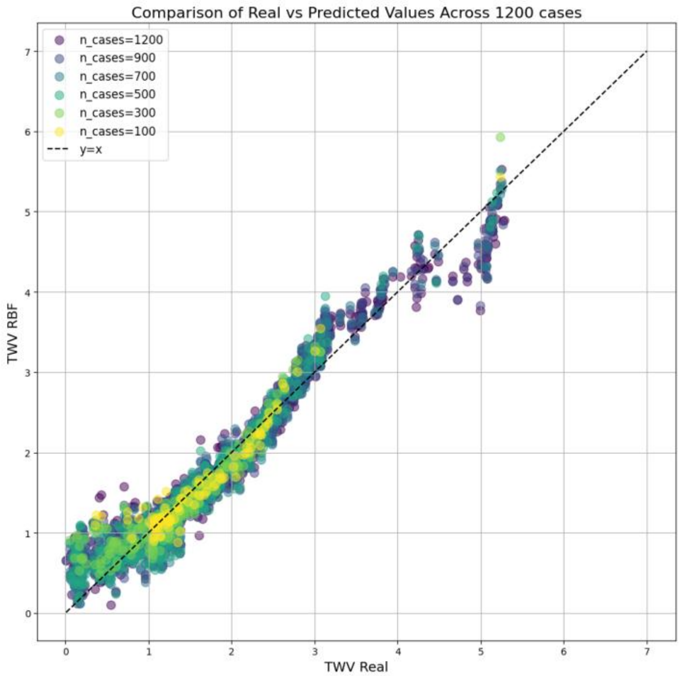
Lower Estuary



Middle Estuary



Upper Estuary



$$WV_{rbf} = f\left(Q_p, Q_b, WL_p, WL_b, TR, Tp, \tau, \tau_{WL-d}, wind, \theta_{wind}\right)$$

Metamodel

Validation