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Compound Flooding and the Role of Nature-Based Solutions in Coastal and Estuarine Systems

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Abstract

Compound flooding arises from the interaction of multiple drivers such as elevated coastal water levels (tide–surge), high river discharge, and intense rainfall, and can produce hazards that differ nonlinearly from those expected under single-driver assumptions. In parallel, nature-based solutions (NbS) including floodplain reconnection, managed realignment/saltmarsh restoration, peatland restoration, and urban green infrastructure, are increasingly promoted as sustainable alternatives or complements to engineered defences. However, NbS performance under compound flooding remains weakly quantified, in part because many modelling studies focus on reconstructing a small number of historical events rather than testing interventions across a standardised range of compound severities and dominance regimes.

We present a transferable compound design-event generator that links historical observations, bivariate extreme-value modelling, and process-based hydrodynamic simulation. The framework harmonises 15-min coastal water level, rainfall, and multi-gauge river inflow series; extracts and declusters multi-day compound events and computes event features including peaks and river–coast timing; fits peaks-over-threshold (POT/GPD) marginals and a copula-based dependence model for event-scale peak coastal level (H) and peak total inflow (Q); generates return-period design peak pairs and selects representative coastal-dominant, fluvial-dominant, and balanced scenarios; and converts design peaks into SynxFlow-ready time-series.

The approach is illustrated through a pilot application to the Humber Estuary, UK, one of the country's most compound flood-prone systems. Preliminary outputs include an automated event catalogue (1993–2016), a compact baseline design suite for five return periods (5–200 years; 15 events total), and dependence diagnostics indicating very weak association between H_{peak} and Q_{peak} in the Humber record (Kendall's $\tau \approx 0$), motivating explicit regime and phasing exploration. Historical reconstructions provide additional end-to-end pipeline checks. Baseline batch simulations and subsequent NbS scenario comparisons are ongoing. The framework provides a foundation for more realistic assessment of NbS performance under compound flooding and supports evidence-based development of resilient, hybrid flood risk management strategies.

Keywords: compound flooding; nature-based solutions; hydrodynamic modelling; estuaries; flood risk

1 Introduction

Flooding is one of the most damaging natural hazards globally, with risks projected to increase due to climate change, sea-level rise, and continued urbanisation (Hallegatte et al., 2013; Paprotny et al., 2018). In coastal and estuarine environments, flooding is rarely driven by a single process. Instead, storm surge, high astronomical tides, river discharge, and intense precipitation often occur simultaneously or sequentially, producing compound flood events that amplify hazard and impact.

While recent research has improved understanding of compound flood drivers and their statistical dependence, many flood risk assessments remain single driver focused (Svensson and Jones, 2002; Hendry et al., 2019). This limits their ability to represent real-world flood dynamics and can lead to systematic underestimation of risk. At the same time, nature-based solutions (NbS), including wetlands, floodplains, and managed realignment schemes, are increasingly promoted as sustainable approaches to flood risk reduction. Although NbS have demonstrated benefits under individual hazards, their role under compound flooding remains insufficiently understood.

This paper addresses this gap by presenting a modelling framework to evaluate NbS performance under compound flood scenarios using process-based hydrodynamic models. The framework is illustrated through a pilot case study in the Humber Estuary, UK, a system characterised by strong compound flood drivers and significant NbS implementation. The key methodological contribution is a transferable design-event generator that links multivariate extremes (return periods), event sequencing (phasing) and process-based 2D modelling, enabling systematic testing of NbS performance across compound scenarios rather than single-driver events.

1.1 Compound flooding

Compound flooding refers to flood events that arise from the co-occurrence or interaction of two or more flood drivers, or from the interaction between extreme events and preconditioning factors that amplify impacts (Seneviratne et al., 2012). In coastal regions, compound floods are driven by combinations of storm surge, tide, river discharge, and rainfall (Hendry et al., 2019; Kumbier et al., 2018). These drivers are often physically linked through shared meteorological forcing, such as deep low-pressure systems that generate both storm surges and extreme precipitation. Elevated coastal water levels can also impede river drainage, producing backwater effects that exacerbate inland flooding.

The relevance of compound flooding has increased in recent decades due to observed and projected changes in climate extremes, sea-level rise, and catchment conditions (Bevacqua et al., 2018; Ward et al., 2018). Rising mean sea levels elevate baseline coastal water levels, increasing the likelihood that moderate surges coincide with high tides, while changes in precipitation intensity and antecedent soil moisture influence river and surface runoff contributions. Historical events, including Hurricane Harvey (USA, 2017), the Bristol Avon flood (UK, 2014), and flooding in Ravenna, Italy (2015), demonstrate the severe impacts that can arise from compound interactions (Hendry et al., 2019; Ganguli and Merz, 2019). Projections of increasing extreme rainfall and rising mean sea levels suggest that the frequency and severity of such events will continue to grow. As a result, compound flooding is now recognised as a key research priority for flood risk science and management.

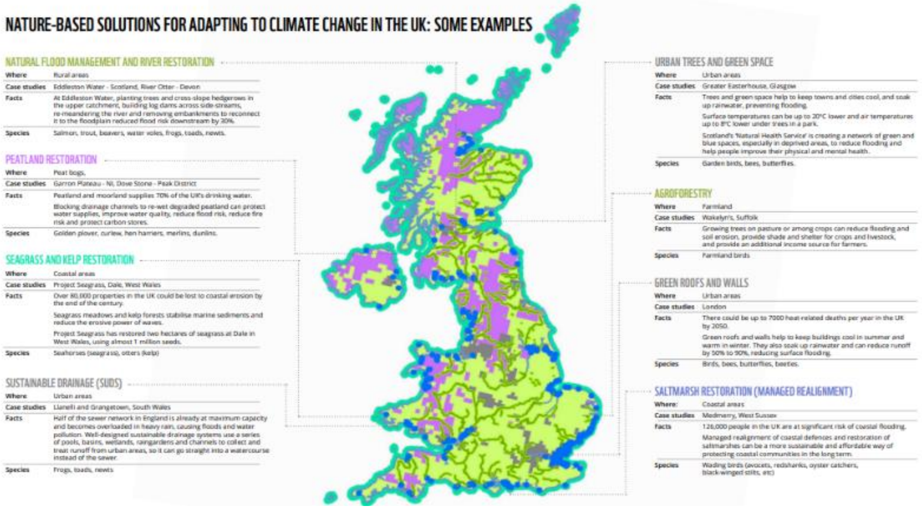
Analysis of compound flooding events has traditionally relied on statistical methods to quantify dependence between flood drivers, including copula-based techniques (Granger, 1959; Svensson and Jones, 2002; Chebana and Ouarda, 2019). While valuable for estimating joint probabilities and return periods, these approaches provide limited insight into flood dynamics, such as water depths, velocities, and inundation extents. Numerical hydrodynamic models offer a complementary approach by explicitly simulating the physical processes governing compound flooding. Two-dimensional and coupled 1D–2D models are increasingly used to represent interactions between rivers, floodplains, tides, and rainfall (Pasquier *et al.,* 2019; Xu *et al.,* 2023). When driven by compound boundary conditions or scenario-based storylines, these models can provide spatially explicit hazard information directly relevant to flood risk management.

In this study we address a practical gap in the compound-flood literature: many modelling studies use a single hydrodynamic modelling set-up to reconstruct one (or a small number of) historical compound events, rather than generating a repeatable suite of compound boundary conditions across return periods. For example, Kumbier *et al.* (2018) simulate compound flooding in the Shoalhaven Estuary using Delft3D for the June 2016 storm event, forcing model boundaries with observed water levels and discharge and validating against observations such as satellite data. Similarly, Eilander *et al.* (2023) develop an automated compound-flood modelling framework centred on a 2D hydrodynamic model (SFINCS) and test it by simulating two historical compound events (Tropical Cyclones Idai and Eloise) and comparing flood extents with satellite-derived observations. Other studies do explore severity classes, but often by tying return periods to specific historical storms: for instance, Liu *et al.* (2022) use Delft3D Flexible Mesh and treat particular historical tropical cyclones as 5–100 year events based on the storm-tide probability distribution. Similarly, Lian *et al.* (2013) used a single hydraulic modelling framework (HEC-RAS river-network model) to explore combinations of rainfall and tidal-level severities, deriving design rainfall processes and tidal hydrographs for multiple return periods; however, this approach is tailored to their case-study set-up. While these approaches are highly valuable for event understanding and validation, they typically do not provide a standardised procedure to generate a repeatable design suite of compound time-series boundary conditions across return periods. We therefore develop and demonstrate a design-event generator that produces a structured set of compound scenarios (coastal-dominant, fluvial-dominant and balanced, with explicit lag/sequence information) that can be applied consistently when evaluating NbS interventions.

1.2 Nature-based solutions and ecosystem buffering

Nature-based solutions (NbS) encompass measures that utilise or restore natural processes to reduce flood risk while delivering co-benefits for biodiversity, climate mitigation, and human well-being. In coastal and estuarine environments, NbS include tidal wetlands, saltmarshes, mangroves, dunes, and managed realignment schemes. Inland examples include floodplain reconnection, riparian woodland, peatland restoration, and soil and land management interventions (Sayers et al., 2025; Radfar et al., 2024). In the UK, NbS examples are illustrated in figure 1.

The flood risk reduction benefits of NbS arise through several mechanisms (Narayan et al., 2017; Menéndez et al., 2020; Radfar et al., 2024). These include the attenuation of wave energy


NATURE-BASED SOLUTIONS FOR ADAPTING TO CLIMATE CHANGE IN THE UK: SOME EXAMPLES

NATURAL FLOOD MANAGEMENT AND RIVER RESTORATION

Where	Rural areas
Case studies	Eddleston Water - Scotland, River Otter - Devon
Facts	At Eddleston Water, planting trees and cross-slope hedgerows in the upper catchment, building log dams across side-streams, re-meandering the river and removing embankments to reconnect it to the floodplain reduced flood risk downstream by 30%.
Species	Salmon, trout, beavers, water voles, frogs, toads, newts.

PEATLAND RESTORATION

Where	Peat bogs.
Case studies	Garron Plateau - NI, Dove Stone - Peak District
Facts	Peatland and moorland supplies 70% of the UK's drinking water. Blocking drainage channels to re-wet degraded peatland can protect water supplies, improve water quality, reduce flood risk, reduce fire risk and protect carbon stores.
Species	Golden plover, curlew, hen harriers, merlins, dunlins.

SEAGRASS AND KELP RESTORATION

Where	Coastal areas
Case studies	Project Seagrass, Dale, West Wales
Facts	Over 80,000 properties in the UK could be lost to coastal erosion by the end of the century. Seagrass meadows and kelp forests stabilise marine sediments and reduce the erosive power of waves. Project Seagrass has restored two hectares of seagrass at Dale in West Wales, using almost 1 million seeds.
Species	Seahorses (seagrass), otters (kelp)

SUSTAINABLE DRAINAGE (SUDS)

Where	Urban areas
Case studies	Llanelli and Grangetown, South Wales
Facts	Half of the sewer network in England is already at maximum capacity and becomes overloaded in heavy rain, causing floods and water pollution. Well-designed sustainable drainage systems use a series of pools, basins, wetlands, raingardens and channels to collect and treat runoff from urban areas, so it can go straight into a watercourse instead of the sewer.
Species	Frogs, toads, newts

URBAN TREES AND GREEN SPACE

Where	Urban areas
Case studies	Greater Easterhouse, Glasgow
Facts	Trees and green space help to keep towns and cities cool, and soak up rainwater, preventing flooding. Surface temperatures can be up to 20°C lower and air temperatures up to 8°C lower under trees in a park. Scotland's 'Natural Health Service' is creating a network of green and blue spaces, especially in deprived areas, to reduce flooding and help people improve their physical and mental health.
Species	Garden birds, bees, butterflies.

AGROFORESTRY

Where	Farmland
Case studies	Wakelyn's, Suffolk
Facts	Growing trees on pasture or among crops can reduce flooding and soil erosion, provide shade and shelter for crops and livestock, and provide an additional income source for farmers.
Species	Farmland birds

GREEN ROOFS AND WALLS

Where	Urban areas
Case studies	London
Facts	There could be up to 7000 heat-related deaths per year in the UK by 2050. Green roofs and walls help to keep buildings cool in summer and warm in winter. They also soak up rainwater and can reduce runoff by 50% to 90%, reducing surface flooding.
Species	Birds, bees, butterflies, beetles.

SALTMARSH RESTORATION (MANAGED REALIGNMENT)

Where:	Coastal areas
Case studies	Medmerry, West Sussex
Facts	126,000 people in the UK are at significant risk of coastal flooding. Managed realignment of coastal defences and restoration of saltmarshes can be a more sustainable and affordable way of protecting coastal communities in the long term.
Species	Wading birds (avocets, redshanks, oyster catchers, black-winged stilts, etc)

Figure 1. NbS examples in the UK. Source: Smith &

and storm surge through vegetation drag, increased hydraulic roughness that slows overland flow, enhanced storage capacity, and delayed runoff generation. For example, coastal wetlands in the United States were estimated to have avoided approximately USD 625 million in direct flood damages during Hurricane Sandy (Narayan et al., 2017). Similarly, mangroves globally are estimated to avert over USD 65 billion in flood damages annually, protecting more than 15 million people (Menéndez et al., 2020). Unlike fixed engineered structures, NbS can adapt dynamically to changing conditions, although their effectiveness may vary under extreme or prolonged loading. Quantifying NbS effects in hydraulic models remains challenging because interventions can influence multiple processes simultaneously (storage, roughness/drag, conveyance and timing) and their effectiveness may be non-linear under extreme loading. Many studies therefore rely on simplified parameter changes or single-driver forcing, which makes it difficult to identify thresholds and trade-offs under compound conditions.

1.3 NbS and compound flooding

Despite strong evidence of NbS benefits under individual flood drivers, relatively few studies explicitly examine their role under compound flood conditions. Existing modelling efforts often simplify forcing or neglect interactions between drivers, limiting understanding of how NbS perform when exposed to simultaneous surge, river, and rainfall inputs (Radfar et al., 2024; Green et al., 2024). Key uncertainties remain regarding performance thresholds, resilience under extreme events, and the conditions under which NbS should be combined with engineered defences. Addressing these gaps requires modelling frameworks that explicitly represent compound flooding and NbS strategies within the same system, enabling evaluation of both hazard reduction and potential failure modes.

Key knowledge gaps include limited understanding of NbS performance thresholds under extreme compound events, insufficient representation of non-linear interactions between drivers, and weak links between hydrodynamic benefits and risk-based metrics (Radfar et al., 2024; Green et al., 2024; Marino et al., 2025). Addressing these gaps requires integrated, process-based modelling frameworks capable of representing compound flooding and ecosystem buffering simultaneously. The framework presented here is designed to be reproducible for other estuaries where long time series of tide, river flow and rainfall are available, providing a pathway from data to a historical compound-event catalogue, return-period design peaks, and physically consistent time-series inputs for hydrodynamic models. This enables NbS testing under controlled compound scenarios and supports comparison of performance across event severity and sequencing.

2 Study site: Humber estuary, UK

The Humber Estuary is one of the UK’s most compound flood-prone systems, influenced by North Sea storm surges, high astronomical tides, river inflows from the Trent and Ouse, and heavy rainfall (Hendry et al., 2019). The estuary includes major NbS interventions, most notably the Alkborough Flats managed realignment scheme, which provides intertidal storage and surge attenuation.

The availability of high-resolution LiDAR, tide gauge records, river flow data, and monitoring reports makes the Humber a suitable pilot site. An estuary-scale model, outlined in figure 1, is used to assess NbS buffering under compound flooding, with scope for nested urban modelling in Hull to evaluate downstream impacts.

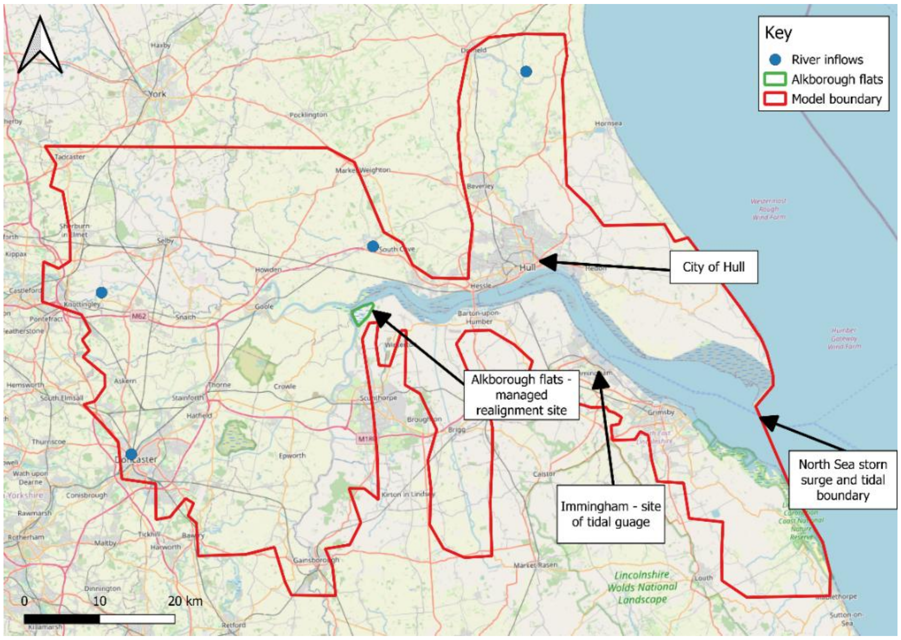


Figure 2. Location of the Humber Estuary pilot site

3 Methodology

3.1 Overview

We developed a compound design-event generator that links multi-driver observations, bivariate extreme-value modelling, and hydrodynamic simulation in SynxFlow. The generator outputs a reproducible set of return-period design events as time-series forcing (storm tide, multiple river inflows, and rainfall) suitable for batch simulation under baseline and nature-based solution (NbS) configurations. The workflow comprises: data preparation; compound event catalogue construction; bivariate peaks-over-threshold (POT) design modelling for peak coastal level (H) and peak total inflow (Q); selection of representative design peak pairs for each return period; and conversion of design peaks into SynxFlow-ready time series using historical templates.

3.2 Observational forcing data and harmonisation

We compiled 15-minute time series of coastal water level, rainfall, and discharge at four upstream gauges. All series were parsed and aligned to a strict 15-minute grid (UTC) without gap-filling to preserve extremes and event peaks. Coastal water levels were converted to ODN to ensure vertical datum consistency with the DEM. Rainfall is represented as 15-minute depth increments (mm per 15 min) and converted to rainfall rate (m s^{-1}).

3.3 Historical compound event catalogue

We identified historical compound events using a peaks-over-threshold approach anchored initially on coastal water level and applied declustering via a minimum temporal separation between retained peaks to reduce dependence between events. For each retained event time, a fixed multi-day window (centred on the anchor time) was extracted to capture tidal cycling and the river hydrograph response.

For each event window we computed peak coastal level and timing, peak discharge and timing at each gauge and for the aggregated inflow ($Q_{\text{tot}}=\sum_k Q^{(k)}$), rainfall totals and peak intensities, and a simple phasing metric defined as the lag between the peak aggregated inflow and peak coastal level. The resulting event catalogue (1993–2016) provides a sample for extreme-value modelling and dependence diagnostics and a library of historical time-series templates for constructing design events.

3.5 Bivariate design model for peak coastal and fluvial drivers

We constructed a bivariate design model for event-scale peak coastal level (H_{peak}) and peak aggregated inflow ($Q_{tot,\ peak}$). Marginal extremes were modelled using a POT framework with Generalised Pareto distributions fitted to exceedances above selected thresholds. Thresholds were chosen as quantiles of the event-peak samples and adjusted to ensure sufficient exceedance counts for stable fitting. Exceedance rates were estimated from the 1993–2016 record length and used to map return periods to annual exceedance probabilities under a Poisson exceedance assumption. Dependence between H_{peak} and $Q_{\text{tot, peak}}$ was characterised using Kendall's τ and a Gaussian copula parameterisation.

3.6 Design peak pairs and dominance regimes

For each target return period (T), candidate design peak pairs (H, Q) were generated by sampling from the fitted bivariate model and mapping samples back to physical space using the fitted marginal transforms. For each T, we retained three representative design points spanning: coastal-dominant (relatively larger coastal contribution), fluvial-dominant (relatively larger fluvial contribution), and balanced conditions. This yields a compact baseline suite of design peak pairs for time-series construction and simulation.

3.7 Converting design peaks to SynxFlow-ready time series

Each design peak pair is converted into a full set of time series by selecting a historical template event from the catalogue. The template provides realistic within-event shapes for storm tide, river hydrographs, and rainfall.

The coastal time series is adjusted using an additive shift so that the template peak matches the design peak. SynxFlow requires boundary water depth, so coastal water level (ODN) is converted to depth using a representative downstream bed elevation (z_b) derived from the DEM within the downstream boundary box. Depth is computed as:

$$h(t) = \max(0,\ H(t) - z_b)$$

River inflow hydrographs at each gauge are scaled multiplicatively using a single factor so that the peak of the aggregated inflow matches the target design (Q), while preserving within-event timing and hydrograph shape across gauges.

Rainfall depth increments are converted to rainfall rate for SynxFlow forcing:

$$R(t) = \frac{P(t)}{1000\,\Delta t}$$

where $P(t)$ is rainfall depth in mm per 15 minutes and Δt=900 s.

Each design event is written to a dedicated folder containing downstream depth forcing, four upstream inflow time series, rainfall forcing, and metadata (template ID, scaling factors, and phasing). These folders enable automated batch execution of baseline simulations across return periods and dominance regimes.

3.8 Historical event reconstructions (2007 and 2013)

To establish confidence in the domain configuration and forcing pipeline, we also simulated two historical compound events (June 2007 and December 2013) using observed 15-minute river inflows, rainfall, and coastal water levels. These reconstructions use the same DEM and boundary box definitions as the design-event simulations, with boundary time series taken directly from observations for the corresponding event periods. The historical reconstructions provide an additional check that the modelling setup can reproduce plausible inundation behaviour under real multi-driver forcing, prior to systematic testing of synthetic return-period design events and NbS scenarios.

3.9 Scenario structure, NbS parameterisation, and evaluation (planned)

Baseline simulations are first executed for the full design-event suite. NbS interventions are then represented as scenario modifications affecting one or more of: topography/connectivity (e.g., managed realignment), hydraulic resistance (e.g., saltmarsh/woodland/urban greening), and effective rainfall–runoff response (e.g., peatland restoration, green roofs). Each NbS scenario is run under identical design-event forcing to isolate intervention effects. Evaluation focuses on hazard-based metrics extracted consistently across runs, including maximum inundation depth and inundation extent above a depth threshold, with additional metrics (e.g., duration or velocity) available for extension.

3.10 Uncertainty and sensitivity analysis plan

Sensitivity analyses are planned around event declustering settings, POT threshold selection, event-window length, and phasing assumptions. Additional uncertainty arises from data quality and datum conversion of coastal water levels and from tail extrapolation in POT fitting; these are addressed through quality control of the observational record and threshold sensitivity tests. The design-event generator is structured to facilitate these tests by regenerating design suites under alternative parameter choices and rerunning identical simulation batches.

4 Results and discussion

We established an end-to-end design-event generator for compound flooding that converts multi-driver observations (15-min tide, rainfall, and four river inflows) into SynxFlow-ready design-event time series for batch simulation. After conversion and basic plausibility screening, event-scale coastal peaks fall predominantly within a physically realistic range for the site, and remaining anomalous values were treated as artefacts during extremes fitting via screening/capping.

A historical compound-event catalogue was constructed using a peaks-over-threshold identification and declustering approach, with fixed multi-day windows extracted around each event. For each event we computed peak coastal level (H), peak aggregated inflow (Q) (and per-gauge peaks), rainfall totals/intensities, and the lag between Q and H peaks. This catalogue supports both statistical design modelling (via event peaks) and time-series template selection (via event windows).

Dependence diagnostics show weak peak dependence between coastal and fluvial drivers in the Humber estuary record. Scatter plots (figure 3) of H_{peak} versus $Q_{\text{tot, peak}}$ coloured by season show a narrow band of coastal peaks (mostly ~3.6–4.3 m ODN) across which river peaks span a wide range (tens to >500 m³ s^{-1}), and Kendall's τ is close to zero. This indicates that, for this site and event definition, compound hazard is unlikely to be dominated by systematic co-occurrence of the largest coastal and fluvial peaks; instead, phasing/timing and moderately high co-occurring drivers are expected to be key controls. This motivates the design suite structure adopted here (coastal-dominant, fluvial-dominant, balanced) and supports planned extensions to explicitly test lag scenarios.

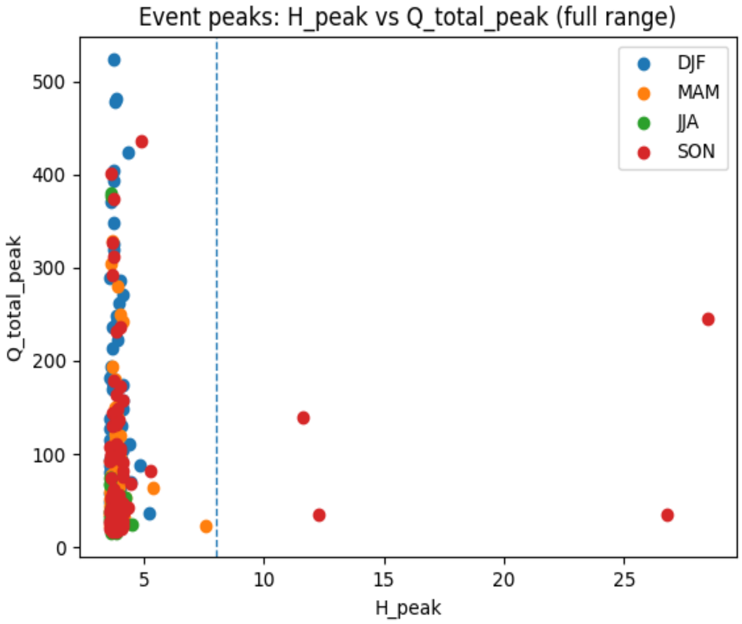


Figure 3. Dependence diagnostics: scatter of H_{peak} versus

Using POT/GPD marginals and copula sampling, we generated a compact baseline design suite of return-period peak pairs for five return periods (5, 20, 50, 100, 200 years) with three regimes per return period (coastal-dominant, fluvial-dominant, balanced; 15 events total).

Two historical multi-driver reconstructions were also simulated using observed 15-minute forcing to check the model domain configuration and end-to-end forcing pipeline prior to full NbS evaluation. Ongoing work is now focused on robust extraction and summarisation of maximum inundation depth and inundation extent outputs across all baseline design events, followed by systematic NbS scenario testing under identical forcing. The expected outcome is a set of regime- and severity-dependent NbS performance curves and maps, highlighting where NbS benefits are robust and where effectiveness diminishes under increasingly coastal-controlled compound loading.

5 Conclusions

Compound flooding represents a growing challenge for coastal and estuarine flood risk management. While nature-based solutions offer clear benefits, their performance under compound flood scenarios remains poorly quantified. As well as this, a standardised method to model compound flood scenarios across different return periods was lacking. This paper presents a process-based modelling framework to address this gap, illustrated through a pilot application to the Humber Estuary. Ongoing work will generate quantitative results to support evidence-based implementation of NbS within integrated flood risk strategies.

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