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# Technical note: Quantifying System Limits: Flood Oriented Operational Stress Testing under Intensified Precipitation Regimes in Central Europe

Jens Reinert[1] (https://orcid.org/0009-0008-9161-6279),
Elena-Maria Klopries[1] (https://orcid.org/0000-0003-4752-6619),
Paul Hassenjürgen[1] (https://orcid.org/0009-0002-6135-4286),
Alexander Menz[1] (https://orcid.org/0009-0007-4686-9149),
Julian Hofmann[2] (https://orcid.org/0000-0002-7156-7173),
Catrina Brüll[1] (https://orcid.org/0000-0003-0079-4093),
Angela Klein[3] (https://orcid.org/0009-0007-8758-342X),
Holger Schüttrumpf[1] (https://orcid.org/0000-0002-0104-0499)

[1]Institute of Hydraulic Engineering and Water Resources Management, RWTH Aachen University, Aachen, 52074, Germany
[2]FloodWaive Predictive Intelligence GmbH, Aachen, 52070, Germany
[3]Deltares, Delft, 2600 MH, The Netherlands

*Correspondence to*: Jens Reinert (reinert@iww.rwth-aachen.de)

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**Abstract.** The rise of short-duration extreme rainfall events across Central Europe has exposed critical weaknesses in traditional flood risk management methods that depend on fixed return periods and design thresholds. In response, this paper introduces FLOOD-ST: a scenario-based operational stress testing framework designed to evaluate the functional limits and vulnerabilities of water infrastructure systems under realistic, high-impact flood scenarios.

FLOOD-ST combines synthetic rainfall archetypes, varying antecedent soil moisture conditions and infrastructure-specific scenarios to systematically evaluate system performance. By integrating elements of functional stress testing, the framework diagnoses weak points and illuminates cascading failure pathways across interconnected assets. Unlike traditional hazard mapping, FLOOD-ST does not aim to replace existing tools but complements them by offering a diagnostic view of system behaviour during extreme conditions. The framework is platform-independent, modular, and scalable, making it suitable for both urban and rural catchments, especially those characterised by high system complexity, short warning times, or critical interdependencies.

This paper describes the conceptual foundation, simulation workflow, and real-world applications of FLOOD-ST, demonstrating its potential to support adaptive planning, emergency preparedness, and climate-resilient water management.

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## 1. Motivation for Flood-Oriented Operational Stress Testing

Over the past decade, Central Europe has experienced more frequent and intense short-duration rainfall because a warmer atmosphere increases moisture availability and intensifies convective storms, while land-use change (soil sealing, drainage) increases effective runoff and peak formation (Beniston et al., 2007; Meyer et al., 2022; Hosseinzadehtalaei et al., 2020). Therefore, strategies calibrated to stationary intensity–duration–frequency (IDF) curves and single-site design flows increasingly misrepresent today's tail risk (Cheng and AghaKouchak, 2014). Consequently, conventional risk-based approaches, effective for incremental, single-hazard control, tend to under-capture compounding (e.g., soil saturation meets extreme rain), (ii) cascades across assets (e.g., bridge clogging leads to road/overtopping leads to access loss), and (iii) operational limits (e.g., warning lead time or power dependencies).(Tao et al., 2023; Nayak et al., 2024). The July 2021 floods in Germany, Belgium, and the Netherlands exemplified this, where extreme rainfall, saturated soils, clogged culverts and bridges, and delayed warnings collectively overwhelmed infrastructure designed for standardised protection levels (Lehmkuhl et al., 2022). Importantly, the most severe impacts in July 2021 were concentrated along small to medium-sized regional rivers. These local systems are characterised by short hydrological response times but often only short discharge records and a sparse gauging network. In many regional catchments, observational series are therefore insufficient to derive robust design floods or to quantify non-stationary changes in extremes, which further limits the applicability of traditional frequency-based design concepts.

These experiences have sparked climate change mitigation discussions (Truedinger et al., 2023) and a critical re-evaluation of static hazard mapping and return-period-based design frameworks. Kreibich et al.(2022) argue that recurrence-based models do not accurately reflect system behaviour when the system boundaries are surpassed, when infrastructure depends on each other, and when effects are non-linear. Linkov et al.(2022) similarly highlight the importance of scenario-based stress-testing approaches to evaluate system performance under plausible yet severe disruptions, similar to methods used in finance, health care, and infrastructure security. This paper uses stress testing methods that are well established in critical infrastructure and banking sectors. These techniques involve analysing how systems perform under challenging yet realistic conditions, and they have been adapted here to include hydrometeorological factors and infrastructure dependencies.

Flood-Oriented Operational Stress Testing (FLOOD-ST) is presented as a new approach which examines the limits of hydrological and infrastructural performance during compound flood scenarios. Instead of depending on return periods (e.g., 100 years), FLOOD-ST allows practitioners to create tailored stress test scenarios that capture catchment-specific vulnerabilities and dynamic response behaviours while providing a comparable framework. This scenario-based method supplements the European Floods Directive (Directive 2007/60/EC), which requires the identification of flood-prone areas and the development of risk management strategies, but often relies on generalised hazard metrics.

The described concept builds on emerging practices in risk-based and adaptive flood management (Kreibich et al., 2022; Linkov et al., 2022), extending conventional hazard mapping by incorporating dynamic system behaviour and failure sensitivity. Similar to multi-sectoral resilience stress tests developed for energy, health, and transportation systems (Tsionis et al., 2016), the framework emphasises the exposure of systemic limits under credible, yet non-deterministic, scenario configurations.

An important parallel can also be drawn to the financial sector, where stress tests are not only designed as sensitivity analyses of individual parameters but as structured examinations of systemic vulnerabilities under

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specific scenario logics, often evaluated through functional indicators (Obeid et al., 2023; Mustafa, 2023). The distinction between parameter sensitivity and scenario-based diagnostics is further detailed in Chapter 2.2.

Recently, within the water management sector, the concept of stress testing has been incorporated into various methodologies and emphasises, for example, the circular economy (Bouziotas et al., 2023), Water supply (Becher et al., 2023) or Water Security (Verbist et al., 2020). In response, FLOOD-ST focuses on (Flash) Flood events and expands the regulatory approach of the European Floods Directive by offering a flexible, user-defined method for assessing system fragility. This is particularly relevant for local and regional river systems, where flash floods typically occur but gauging networks are sparse and discharge records are comparatively short. In such data-limited settings, traditional return-period based design approaches reach their limits, whereas scenario-based stress testing can still be used to explore plausible stressors and functional system limits. It supports not only technical optimisation of flood protection measures but also interdisciplinary collaboration across civil protection, infrastructure management, spatial planning, and public discourse. Examples include convective rainfall on saturated soils, partial failure of retention infrastructure, or the sequential loading of connected sub-catchments. Instead of predicting specific events, the goal is to identify tipping points and hidden vulnerabilities through plausible worst-case scenarios.

A tipping point is defined as a threshold beyond which a small change in a stressor (e.g., rainfall intensity or river level) leads to a disproportionately large, often non-linear, change in system impacts (e.g., a sudden, rapid expansion of the inundated area due to levee overtopping). Similarly, weak points could be classified (e.g., hydraulic bottlenecks, structural vulnerabilities, operational logic failures).

Methodologically, FLOOD-ST follows a structured decision tree: (i) selection of representative rainfall patterns (archetypes), based on evolving European precipitation regimes (André et al., 2024; Leščešen et al., 2023; Wood, 2023); (ii) combination with antecedent moisture classes (e.g., dry, average, wet); and (iii) optional integration of system stressors such as culvert blockage, pump failure or dam breach. The resulting compound events are analysed through integrated hydrological, hydraulic, and infrastructure modelling to reveal critical weaknesses and inform adaptive strategies.

By shifting the focus from hazard to system behaviour under stress, FLOOD-ST aligns with recent efforts to operationalise resilience in climate-adaptive water management. As emphasised by the European Commission (Tsionis et al., 2016) and Linkov et al.(2022), such approaches are crucial to bridge the gap between model-based planning and real-world complexity.

This Technical Note introduces a transferable FLOOD-ST framework that can be adapted to different data conditions and organizational settings in study areas. It offers a straightforward method for identifying system thresholds, assessing resilience, and jointly developing practical, effective strategies. In doing so, it encourages cross-disciplinary discussions on complex flood risks and systemic resilience, going beyond traditional risk approaches (Zscheischler et al., 2018).

## 2. Framework and Methodology of FLOOD-ST

### 2.1 Conceptual Foundation

The suggested FLOOD-ST approach builds on emerging practices in risk-based and adaptive flood management, extending conventional hazard mapping by incorporating dynamic system behaviour and failure sensitivity. The approach is based on the following core principles:

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- System-focused diagnostics: FLOOD-ST does not evaluate compliance with design thresholds, but assesses how systems behave under stress – including the identification of failure points and cascading vulnerabilities.
- Scenario-based realism: Test cases are created using physically plausible rainfall events, based on observed extremes, analogues (e.g., July 2021 flood), or climate-adjusted storm archetypes.
- Operational relevance: Hazard Scenarios can be designed in collaboration with emergency planning, spatial prioritization, and resilience strategies, enabling dialogue between engineers, civil protection, infrastructure managers and other stakeholders.
- Interdisciplinary and transboundary orientation**:** FLOOD-ST results support broader deliberation beyond traditional hazard logic, fostering a shared understanding of functional system limits of exposed areas across sectors.

The comparison between the risk-based hazard mapping defined by the European Floods Directive and the presented FLOOD-ST approach highlights that risk-based hazard mapping relies on static, return-period-based assumptions and typically applies a top-down, regulation-driven logic, often neglecting infrastructure failures and system interactions. In practice, these assessments are frequently organised along administrative or planning units rather than functional catchment boundaries. As a result, cross-boundary dependencies and the overall behaviour of the river system can be overlooked or underestimated when local results are interpreted in isolation. In contrast, the FLOOD-ST approach embraces plausible, climate-adaptive compound scenarios, integrates infrastructure dynamics explicitly, and emphasizes system behaviour under stress through a bottom-up, interdisciplinary process at the level of the entire river system or functional subsystem. This holistic perspective enhances system understanding by making interactions between sub-catchments, infrastructure elements and jurisdictions visible. This enables FLOOD-ST to reveal systemic vulnerabilities and guide adaptive planning beyond traditional hazard mapping constraints. (**Table 1**)

**Table 1: Comparison of Risk-based Hazard Mapping defined by the European Floods Directive with the adaptive FLOOD-ST approach**

| | **Risk-based Hazard Mapping** | **Adaptive FLOOD-ST** |
|---|---|---|
| **Output** | Identify areas at risk, produce flood hazard and risk maps, and develop flood risk management plans | Identification of weak points regarding the extent of flooding, derived from scenarios, peak discharge, dam overflow, etc. |
| **Outcome** | deterministic design checks | stakeholder-specific diagnostics of system behaviour |
| **Application** | Standard planning, zoning and building regulations | Adaptive planning, worst-case planning and emergency management |
| **Direction of action/effect** | Top down - Centrally specified inputs, standardized maps | Bottom up – Sub catchment-specific and local constraints drive scenario design and decisions |

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| | | |
|---|---|---|
| **Basis** | Static, based on historical return periods, is often aggregated, neglects flood peaks and timing | Meteorologically and physically plausible trigger events, e.g., future-relevant rainfall archetypes (non-return-based), climate-adaptive, focused on extremes |
| **Hydrometeorological Assumptions** | Single event with fixed return period and rainfall amount | Combination of scenarios (stationary, convective, multi-cell) + antecedent moisture conditions |
| **Consideration of Infrastructure Failures** | Not considered or strongly simplified | Explicit integration: bridge blockage, pump failure, retention basin overflow, etc. |
| **System Behaviour** | Linear, deterministic runoff behaviour | Nonlinear, sensitive to the interaction of rainfall and infrastructure behaviour |
| **Involvement of Other Sectors** | Technically oriented, less interdisciplinary collaboration | Interdisciplinary, also on the public and decision-makers |
| **Plausibility in Climate Change Context** | Questionable: often based on past data only | Oriented towards climate adaptation, can be combined with future analogues or ensemble forecasts |

While FLOOD-ST builds on established hydrological and hydraulic modelling practices, it differs from conventional applications used in flood risk management. Current standard procedures, such as probabilistic design approaches under the EU Floods Directive, return-period-based flood hazard mapping, or event-specific simulations following national frameworks, primarily focus on regulatory compliance and deterministic design thresholds (e.g., a 100-year return period). Likewise, numerical models are generally used to reproduce observed or statistically derived flood events for planning and infrastructure design.

FLOOD-ST, in contrast, functions as a complementary diagnostic layer on top of these tools, using the same modelling environments but shifting their purpose toward scenario-based system stress testing. Instead of confirming design performance, it examines functional limits, cascading failures, and adaptive capacity across various plausible stress scenarios. This approach shifts the role of established models from predictive tools to resilience diagnostics for strategic planning and flood response capacity.

## 2.2 FLOOD-ST Structure and Simulation Logic

The framework methodically combines various design trigger events (such as severe discharge amounts or stationary/mobile convective storm events) with antecedent catchment conditions (e.g. dry, average, or wet soil states) and two levels of simulation: A functional system test and an operational infrastructure stressor input (e.g. flood wave volumes, overtopping, clogged bridges or pump failures). This results in a comprehensive set of combined simulation scenarios (S1, S2, S3, …) that capture both meteorological and hydrological variability, along with system behaviour. The goal is to transform conventional flood simulations into system-level stress tests that reveal how, where, and why a catchment reaches its functional limits. **Figure 1** illustrates this logic, comparing the usual hazard-based workflow (left) with the scenario-driven diagnostic process of FLOOD-ST (right).

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Each scenario run produces diagnostic output based on functional impact indicators, such as inundation extent, peak discharge or timing and location of critical exposure. The resulting multi-dimensional dataset forms the basis for a systematic weak-point analysis, enabling the identification of critical failure pathways and operational limits under stress. The following subsection describes each component of the framework in more detail.

FLOOD-ST significantly differs from traditional model calibration and sensitivity analysis. Calibration aims to fine-tune model parameters to fit observed data, while sensitivity analysis examines how variations in individual inputs impact model outputs. In contrast, FLOOD-ST does not focus on parameter optimization or uncertainty quantification. Instead, it aims to identify systemic weaknesses and failure modes under specific, plausible stress scenarios.

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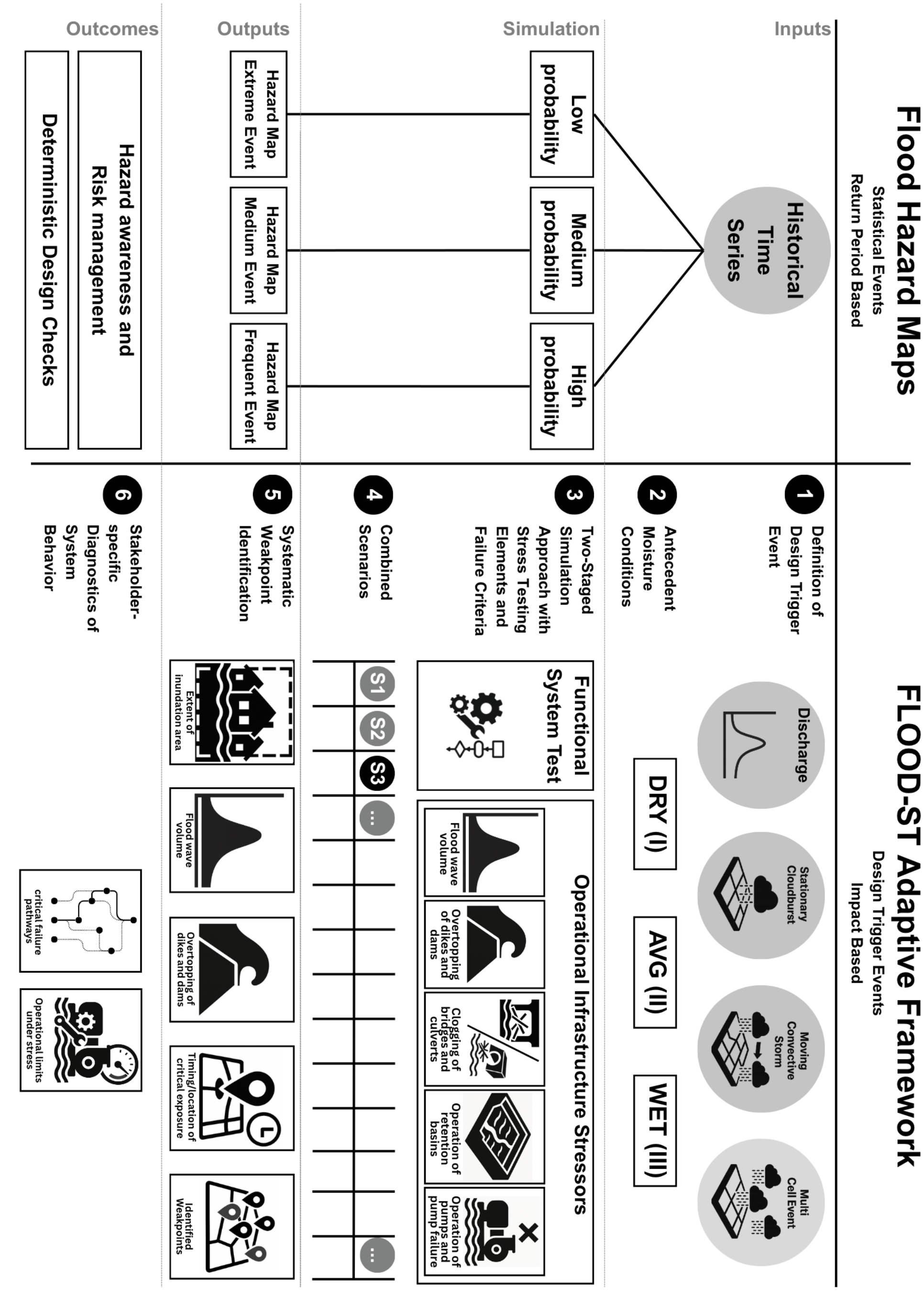


Author: D. Roschinsky (2025)

**Figure 1: Diagnostic Workflow of the FLOOD-ST Framework (right) compared to the traditional flood risk management grounded on the EU Flood Directive (left)**

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**(1) Definition of Design Trigger Event**

The classification and generation of stressor rainfall scenarios in FLOOD-ST are based on recent advances in understanding how precipitation patterns in Europe are changing under climate change. Convective storm events, whether stationary or translating, have shown disproportionately higher intensification at sub-daily timescales (Wood, 2023; Leščešen et al., 2023; André et al., 2024), which are especially important for flash flood development.

Furthermore, André et al.(2024) identified different regimes of precipitation change across Europe and the Mediterranean, emphasizing an increase in the frequency of short-duration, high-intensity rainfall, especially in convectively driven systems. Climate projections indicate that changes in short-duration extreme rainfall events will vary significantly across Europe. In particular, southern and western regions are expected to experience a stronger increase in 3-hourly precipitation extremes than in daily totals (Scoccimarro et al., 2015). Beyond intensity, recent regional climate model analyses indicate that the spatial extent of heavy precipitation events is also projected to increase, i.e. larger areas are affected simultaneously by intense rainfall (Matte et al., 2022). When larger fractions of a river network receive heavy rainfall at the same time, system behaviour shifts from isolated local hotspots to more coherent flood waves and bottlenecks at tributary confluences and downstream control structures.

These changes challenge traditional event classification and suggest the need for archetype-based rainfall definitions that better reflect future hazard patterns rather than relying on historical statistical norms. Plausible high-impact rainfall scenarios are suggested based on regional hydrometeorological features and can be automatically produced by a rainfall data generator (Welten et al., 2022). Three rainfall archetypes of rainfall intensities of e.g., 100–180 mm in 3-6 hours can be differentiated:

- Stationary cloudburst: Localised, high-intensity rainfall with spatially fixed cores.
- Translating convective storm: A moving storm cell sweeping across the catchment
- Multi-cell compound event: Overlapping or successive rain cells over the same region, often associated with storm clustering.

For comparability across archetypes, event-integrated rainfall and event duration are held constant while only the spatio-temporal organization is varied. Each stress test is conditioned on shared targets (e.g., a specified accumulated rainfall amount within an application-specific accumulation window, such as a 3–6 h window for convective flash-flood applications and a consistent hyetograph envelope), ensuring that differences in outcomes reflect pattern effects rather than amount or length. The same principle can also be applied to longer accumulation periods (e.g., 12–48 h totals for regional flooding events similar to July 2021), in which case the design trigger event represents a different type of flood rather than a flash flood. Beyond the suggested classification (stationary, translating, multi-cell), data-driven generators can sample diverse, physically plausible realisations that honour these constraints (preserving totals, duration, and optional peak-intensity limits/spatial footprints), thereby expanding the scenario space without sacrificing comparability.

**(2) Antecedent Condition Scenarios**

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Catchment response to rainfall stressors greatly depends on antecedent moisture conditions (AMC), which influence initial infiltration capacity, saturation excess runoff, and delayed contributions through interflow and baseflow processes (Ye et al., 2023; Staudinger et al., 2025). FLOOD-ST explicitly captures this by defining soil moisture scenarios, e.g., ranging from dry (low antecedent moisture) to fully saturated (high antecedent moisture) states. These scenarios can be implemented into the modelling approach using established concepts such as SCS-CN-based modelling or through soil water content thresholds in physically-based hydrological models (Godara et al., 2023).

Beyond surface runoff generation, antecedent hydrological conditions influence system behaviour through hydrological memory effects, which are the cumulative impacts of past rainfall events or groundwater recharge dynamics. These enhancing effects are especially significant in storm clustering scenarios, where a secondary event can surpass system capacity even with moderate rainfall because of carry-over saturation from an earlier storm.

Where applicable, FLOOD-ST also includes optional model initializations of reservoirs and dams, urban retention basins, and groundwater storages to represent ongoing discharge or limited buffering capacity. This allows simulation of realistic conditions where minor to moderate rainfall can cause disproportionate impacts when system capacity is already compromised (Fleischmann et al., 2019; Hanazaki et al., 2022; Shen et al., 2025).

**(3) Two-staged Simulation Approach**

To balance computational feasibility and analytical depth, FLOOD-ST follows a staged simulation logic:

**Level 1: General system analysis:** The catchment is modeled without explicit infrastructure (dams, bridges, pumps), focusing on terrain, land cover, and runoff generation to understand natural thresholds and response patterns.

**Level 2: Infrastructure Stress Testing:** Elements such as dams, bridges, sewer systems and pumping stations are explicitly modeled with operational behaviour and failure variants as a result of defined events like clogged bridges, power outages or flood protection measures (e.g. dam release, blockage of bridges, reached sewer system and pumping capacities).

**(4) Combined scenarios**

While worst-case scenarios like AMC III are crucial for emergency preparedness, the full diagnostic capability of FLOOD-ST lies in analyzing the entire spectrum of antecedent conditions, including average scenarios such as AMC II. These mid-range scenarios can reveal hidden vulnerabilities that are not apparent in either dry (AMC I) or saturated (AMC III) conditions. For instance, local backwater effects from undersized culverts or malfunctioning retention basin controls may only emerge when inflows reach hydraulic thresholds but are not high enough to cause overtopping. The logic of pump control systems may fail under partial stress, yet they remain inactive in AMC I and become overwhelmed in AMC III.

Additionally, AMC identifies further compound risks. Insufficient small discharge amounts for cooling water can threaten power supply, raising the risk of pump failure due to grid instability. Infrastructure elements such as

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embankments or infiltration zones may suffer material fatigue under extended intermediate loads specific to AMC II conditions.

This scenario diversity provides added value for various stakeholder groups. State authorities, municipalities, civil protection units, engineering offices, and policymakers can develop customized insights by identifying vulnerabilities and control logic failures to support effective planning, investment decisions and emergency protocols. FLOOD-ST thus shifts the focus from deterministic design checks to stakeholder-specific diagnostics of system resilience.

**(5) / (6) Weak point identification and systems diagnostic**

Each FLOOD-ST scenario is assessed based on hydrodynamic and functional indicators that reflect how the system responds under stress:

- Time-based indicators: Duration of critical infrastructure disruption (e.g., hours of main road inaccessibility, downtime of a key pumping station).
- Network-based indicators: Degree of fragmentation of the transport network; number of critical facilities (hospitals, schools) isolated and loss of access along predefined emergency routes.
- Cascading failure indicators: Identification of the sequence and propagation of failures (e.g., pump failure leads to substation flooding, causing a wider power outage).

Depending on data availability and the specific application, these network and cascading indicators can be implemented at different levels of complexity. In the current FLOOD-ST applications, they are derived from deterministic overlays between flood-depth rasters and simplified infrastructure graphs (e.g. road networks, locations of substations, water and wastewater assets). Thresholds for functional failure are defined together with infrastructure operators, for instance, by specifying minimum elevation and allowable water depth at critical components or by setting access criteria for key routes. This avoids the need for a full probabilistic reliability model of the networks while still revealing where redundancies may fail and which assets or areas become isolated under stress.

The Indicators furthermore include flood wave volume, peak discharge, extent and depth of inundation, as well as the timing and location of critical exposure. Special attention is given to failure triggers such as overtopping, culvert or bridge blockage, backwater effects, or pump station failure. This helps identify not only hazard levels but also tipping points where local failures could lead to broader system disruptions.

Unlike traditional approaches that focus on regulatory exceedance, FLOOD-ST takes a functional diagnostic approach that highlights how systems behave under combined loads. This aligns with recent resilience stress testing methods that view risk as a result of systemic interactions and sequential dependencies (Balakrishnan and Cassottana, 2022; Linkov et al., 2022). Scenario results are therefore evaluated by stakeholders not just for compliance but to identify vulnerabilities, assess operational limits, and determine lead times for intervention.

By emphasizing dynamic responses instead of static hazard zones, FLOOD-ST enables a more accurate assessment of vulnerability and strengthens the connection between modelling results and real-world risk management.

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**Example JCAR (Stresstest Rur)[1]**:

In the transboundary Rur catchment (Belgium–Germany–Netherlands), FLOOD-ST is applied within the Joint Cooperation for Applied scientific Research (JCAR) programme to identify systemic vulnerabilities under extreme and compound flood conditions. The scenario development follows a progression from meteorological drivers via hydraulic structures to special compound situations. At the meteorological level, both historic and synthetic extremes are considered, for instance a "2021-like" convective rainfall event with up to 200 mm precipitation in 48 hours, combined with fully saturated soils, which is translated into distributed runoff using the mesoscale Hydrological Model (mHM). Based on this input, the response of the major reservoirs in the river system, Urft, Rur, Olef, Heimbach and Obermaubach, is tested under near-exhaustion of retention capacity and emergency spillway operation. Coupling reservoir operation models (TALSIM) with hydraulic models such as Delft3D-FM and HydroAS2D enables the analysis of system behaviour both with and without active dam influence. Finally, special compound situations are incorporated, including the combination of dam exhaustion with simultaneous backwater effects at the Rur confluence, extreme discharges in tributaries beyond reservoir control such as the Wurm, or the hypothetical future use of the Indesee lignite pit as a flood retention basin. This integrated setup demonstrates how FLOOD-ST within JCAR exposes systemic tipping points, identifies failure pathways, and provides actionable insights for adaptive, cross-border flood risk management.

**Example EU FlashFloodBreaker[2]**:

In a sub catchment of the German river Emscher (North Rhine-Westphalia) in a highly urbanized area, stress tests were designed around retentions basins, critical pump stations as well as numerous culverts and bridges. A wet antecedent condition (AMC III) was combined with a multi-cell convective storm event (3 hours, 120 mm) to establish the baseline stressor. This scenario was then systematically expanded by introducing infrastructure disruptions, such as (i) failure of the pump stations, and (ii) clogging of of culverts and bridges, tested both for upstream and downstream locations.

From these combinations alone, at least four compound scenarios emerge: (1) extreme rainfall under wet conditions with full system functionality, (2) rainfall with pump failure, (3) rainfall with partial bridge blockage upstream, and (4) rainfall with partial bridge blockage downstream. Each setup highlights different failure-prone areas: loss of pumping capacity increases surcharge risk in urbanized sections, upstream clogging causes backwater buildup and local overtopping, while downstream blockage magnifies retention and raises the potential for upstream inundation. By systematically varying these stressors, FLOOD-ST not only maps inundation patterns but also explicitly diagnoses where and why systemic failure occurs offering actionable insights for infrastructure operators and emergency planners.

[1] *Joint Cooperation for Applied scientific Research to Accelerate Transboundary Regional Adaptation to Climate Extremes, 2023–2028, coordinated by Deltares, with partners from Belgium, Germany, Luxembourg and the Netherlands. More information:* https://www.jcar-atrace.eu/

[2] *Interreg North-West Europe, Project ID NWE0200167, 2024–2028, co-funded by the European Regional Development Fund, coordinated by Emschergenossenschaft/Lippeverband, Germany. More information:* https://flashfloodbreaker.nweurope.eu

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### 2.3 Tool Integration, Model Environment and Transferability

FLOOD-ST is a platform-independent and modular framework that can be implemented using a variety of hydrological and hydraulic modelling environments, depending on data availability, user objectives, and local context and the specific stress-test questions to be addressed. The standard workflow begins with rainfall-runoff modelling to characterize the hydrological response of the catchment, followed by one- or two-dimensional hydrodynamic simulations that represent flow dynamics across terrain and infrastructure systems. Depending on whether the stress test focuses on, river flooding, urban pluvial impacts or cascading infrastructure failures, different model complexities and couplings (e.g. surface–sewer interaction, explicit infrastructure modules) can be selected within the same FLOOD-ST framework.

Key infrastructure elements such as buildings, bridges, pumps, and retention basins are integrated, allowing the simulation of system behaviour under stress with operational relevance. GIS-based analyses support the spatial evaluation of exposure, land use characteristics and connectivity, enabling the identification of vulnerable or failure-prone areas (=weak points) under specific scenario configurations.

FLOOD-ST is designed to be scalable across levels of complexity. While high-resolution data improves local accuracy, strategic diagnostics can also be conducted using coarser inputs if the core diagnostic questions are clearly defined. This ensures applicability across different geographic settings and institutional environments, from local vulnerability screening to more complex infrastructure-focused stress testing.

### 2.4 Current Application and Practice-Based Implementation

The FLOOD-ST framework is currently being developed and refined through several ongoing research projects, offering practical insights into its operation across various spatial, institutional, and technical contexts. Two key examples are the EU-funded FlashFloodBreaker project and the JCAR Program.

Within the JCAR ATRACE program, FLOOD-ST is utilised to investigate system vulnerabilities in transboundary regional river basins, with the goal of developing actionable adaptation measures. The project's main objective is to enhance cooperation in flood and drought management and research, accelerating transboundary regional adaptation to climate extremes. Key objectives include helping regional governments prepare more effectively for extreme events and fostering long-term partnerships between European research institutes to enhance the shared knowledge base for transboundary river basins.

In the context of the EU FlashFloodBreaker Project, FLOOD-ST is part of a multinational effort to enhance early warning systems and response strategies for short lead-time flash floods. The framework is applied in small- to mid-sized catchments across the Netherlands, Ireland, and Germany, where convective storm scenarios with rainfall intensities are generated using both synthetic rainfall generators and observational analogues. By combining these high-intensity events with antecedent moisture states, the stress tests assess bottlenecks such as clogged bridges and non-responsive pumping stations (**Figure 2**). Importantly, stakeholder engagement is central to this effort, as civil protection units and municipalities co-develop scenario configurations to ensure operational relevance and facilitate transboundary exchange.

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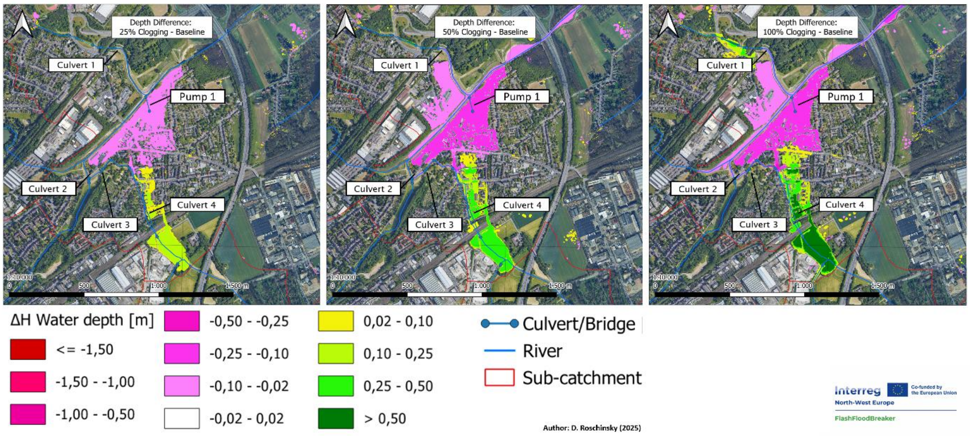


**Figure 2: Generalized Example of clogging scenarios analysed in the EU FlashFloodBreaker Project**

To ensure that the simulations accurately reflect real-world concerns, stakeholders were involved in both projects with municipalities, infrastructure operators, and disaster management authorities. These interviews helped identify concrete needs and expectations for stress test outputs, ensuring that results are directly applicable for planning, prioritisation, and crisis coordination. This stakeholder engagement operationalises the 'bottom-up' principle (**Table 1**). Instead of modellers defining stressors solely on technical criteria, the scenario portfolio is co-developed with infrastructure operators and civil protection units. This anchors the analysis in lived experience and operational reality, greatly increasing its relevance and legitimacy.

These ongoing applications demonstrate the adaptability of FLOOD-ST across various use cases. Whether improving short-term operational decision-making or supporting long-term planning, the framework provides a structured yet flexible diagnostic tool to identify weaknesses, test strategies, and inform adaptive system design in response to intensifying weather extremes. A key strength of FLOOD-ST is that these stress tests are not conducted as purely expert-driven modelling exercises, but as co-designed, joint analyses: scenarios, indicators and interpretations are developed together with authorities, infrastructure operators and emergency services, turning each application into a shared learning process across institutions.

## 3. Benefits, Limitations and Decision-Making

### 3.1 From Protection Targets to System Optimization

Rather than assessing whether specific flood protection goals are met under design events, FLOOD-ST focuses on how systems respond under plausible, compound conditions, revealing failure mechanisms and systemic gaps (Chen et al., 2023; Wang and Wang, 2024). Traditional hazard mapping usually depicts static flooding based on return periods (such as 100 years), meeting regulatory requirements, but may overlook the dynamic, interconnected nature of system behaviour during actual flood events (**Figure 1**).

FLOOD-ST adds value by enabling scenario-based diagnostics of system performance under plausible worst-case scenarios (avoiding the term *extreme*, which is often tied to return-period framing). It uncovers hidden vulnerabilities, such as blocked culverts, delayed pump activation, or cascading failures related to power outages. It promotes an optimisation mindset by enhancing functional robustness, rather than merely meeting deterministic design thresholds. Crucially, the same scenarios can be re-run with alternative structural or operational measures

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(e.g. temporary barriers, modified pump or reservoir rules, changes in emergency routing), allowing decision-makers to test and compare the effectiveness of adaptation options before implementation. In doing so, it fosters a deeper understanding of operational tipping points and response capabilities. Therefore, Flood-ST helps quantify different facets of resilience. For example:

- Absorptive Capacity: Identifying the thresholds at which the system fails to absorb the shock (e.g., dam overtopping).
- Adaptive Capacity: Testing the effectiveness of operational measures (e.g., modified reservoir release rules, revised pump-trigger levels, temporary flood barriers) under stress.
- Restorative Capacity: Using scenario outputs to estimate recovery times for critical infrastructure.

### 3.2 Participation and Risk Perception as Co-benefits

Beyond technical diagnostics, FLOOD-ST promotes interdisciplinary teamwork and participatory reflection on local flood resilience. By involving civil protection units, municipalities, infrastructure operators, and residents in scenario development, FLOOD-ST encourages shared learning and empowers stakeholders to face hydrometeorological challenges. This participatory method not only enhances planning quality but also offers psychological benefits: it increases awareness of uncertainty and systemic vulnerabilities and supports both individual and institutional preparedness (Wang et al., 2022; Rogers et al., 2020; Tate et al., 2021). By highlighting the full range of possible compound outcomes, FLOOD-ST fosters proactive behaviour and personal responsibility in flood-prone areas, bridging the gap between technical modelling and societal adaptation.

### 3.3 Current Limitations

FLOOD-ST's diagnostic value depends on input data, especially infrastructure and topography. Simplified configurations are possible, but high-resolution applications (Level 2; see 2.2 FLOOD-ST Structure and Simulation Logic) require expertise. As a consequence, the suitability of the results is strongly scale-dependent. Catchment-wide, coarse-resolution applications provide a good understanding of system-level behaviour (e.g. timing and routing of flood waves, identification of bottlenecks between sub-catchments), but they are not appropriate for deriving parcel- or building-scale damage estimates. Conversely, high-resolution urban applications can represent local inundation patterns and impacts on individual assets, but usually cover smaller domains and specific hotspot areas only. Users therefore need to interpret FLOOD-ST outputs in line with the spatial resolution and purpose of the underlying model setup.

Realism relies on rainfall archetypes and assumptions about moisture and system states, which are challenging in complex or data-limited regions. Unlike hazard maps, FLOOD-ST doesn't calculate probabilities; instead, it identifies weak points and response patterns under extreme scenarios. This is useful for planning and discussions, but less suitable for formal risk or cost-benefit analyses. It only tests predefined scenario types, system setups, and failure modes, missing unexpected behaviours, dependencies or combined effects outside the model. A comprehensive view and expert input are essential to enhance the system's understanding.

A further limitation, inherent to any scenario-based approach, is the definition of plausible archetypes. Future research should therefore explore more systematic methods for scenario discovery, such as adversarial testing, using machine learning (e.g., generative adversarial networks or reinforcement learning) to discover the most impactful yet physically plausible spatio-temporal storm patterns for a given system and stochastic exploration, i.e., systematically sampling the full parameter space of storm generators (e.g., duration, intensity, spatial extent, movement speed) rather than relying on a discrete set of archetypes, to reveal potential non-linear response thresholds.

Another limitation relates to the representation of interdependent infrastructure networks (e.g., electricity and transport). In current applications, network effects are measured using heuristic depth thresholds and graph-based connectivity metrics, rather than fully probabilistic reliability models that incorporate explicit redundancy and detailed fragility curves. More advanced approaches to infrastructure networks, therefore, require additional data and specialised modelling tools and are considered extensions of the framework rather than part of its core implementation.

### 3.4 Integration into Planning and Governance

FLOOD-ST offers multiple access points for decision-making, supporting local climate adaptation by identifying failure zones, evaluating emergency access and stress-testing infrastructure. It helps improve Flood Risk Management Plans, particularly in relation to climate change and systemic stressors. Instead of replacing traditional tools, FLOOD-ST complements them with stress diagnostics to highlight areas that require caution, redundancy or improved coordination. Because the stress tests are carried out on the full hydrological system rather than on isolated administrative units, they foster a shared understanding of overall system functioning and cross-boundary dependencies. It highlights thorough evaluations and coordinates early cross-sectoral adaptation to develop technical diagnostics. This process aids in creating a shared understanding of system weaknesses and responsibilities, potentially boosting the legitimacy and ownership of the resulting adaptation strategies.

## 4. Conclusion and Policy Implications

The escalation of hydrometeorological extremes in Central Europe and beyond underscores the urgent need to reframe flood risk management in terms of systemic vulnerability and dynamic stress exposure. As highlighted in the 2025 Global Assessment Report by UNDRR, disaster risk has become an emergent property of interconnected systems, no longer effectively captured by traditional design thresholds or hazard-return concepts (United Nations Office for Disaster Risk Reduction, 2025). FLOOD-ST addresses this challenge by providing a structured, scenario-based framework that allows decision-makers to test the operational limits of water systems and uncover hidden weaknesses before they lead to failures.

The FLOOD-ST framework is ideally suited for implementation within a Digital Twin (DT) environment. A catchment-scale DT can provide the persistent, high-fidelity model integration (hydrology, hydraulics, transport, energy) required for the analysis. In this context, FLOOD-ST functions as the 'scenario engine' or 'interrogation tool' used to systematically probe the DT for vulnerabilities, test adaptive management strategies in silico before they are implemented and provide a dynamic, rather than static, assessment of systemic resilience.

The recommended use of FLOOD-ST across various catchment types within the project environments will demonstrate its flexibility, especially where critical infrastructure, heavy rainfall, and short warning times coincide. Besides its technical advantages, FLOOD-ST can serve as a driver for organisational learning by shifting planning from mere compliance to understanding the consequences: what happens when systems are overwhelmed, how failures spread, and which points can be targeted to interrupt these failure chains.

A key pathway for future innovation involves closing the socio-operational feedback loop. Currently, FLOOD-ST is introduced as a diagnostic tool to *inform* stakeholders (Section 3.2). The next iteration of this framework should focus on modelling how stakeholders *respond* to stress test outcomes. For example, how does a shared understanding of a specific vulnerability (such as a critical bridge) influence land-use planning, investment

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choices, or emergency response procedures? These human-system adaptations can then be fed back into the model environment, fostering a dynamic, multi-stage stress test that evaluates adaptive resilience over time rather than merely assessing snapshot vulnerability.

In line with the UNDRR's recommendation for future-oriented risk governance (United Nations Office for Disaster Risk Reduction, 2025), FLOOD-ST enables resilience foresight by combining hydrological modelling with stress diagnostics and practical mitigation strategies. Its integration into strategic spatial planning, emergency response or climate adaptation policies helps stakeholders shift from passive risk anticipation to proactive system design.

To fully harness its potential, FLOOD-ST should be institutionalised not as a replacement for existing tools, but as a complementary layer of analysis, bridging the gap between probabilistic risk modelling and qualitative decision-making. Its implementation requires political commitment, cross-sector collaboration, and a willingness to engage with uncertainty as a planning asset rather than a barrier. As systemic risk becomes the new normal, FLOOD-ST offers a methodological and conceptual contribution to strengthen preparedness, adaptability, and long-term resilience in the face of deep uncertainty (Figure 3).

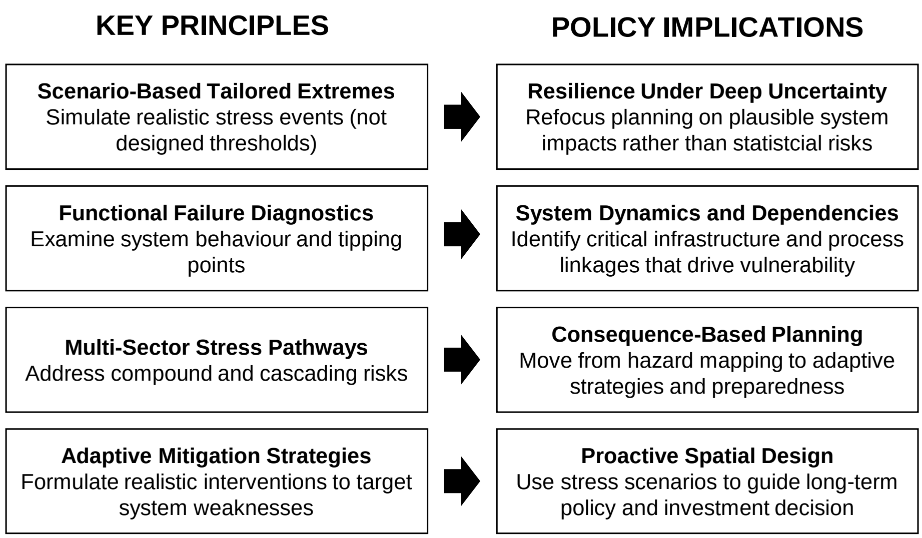


**Figure 3: Conceptual transition from conventional hazard-based planning toward scenario-driven FLOOD-ST methodology**

**Author contributions**

JR developed the overall concept of the study and the FLOOD-ST framework. JR led the methodological design, conducted the stress tests and analysed the case study within the FFB Project context, and wrote the manuscript. EMK contributed to the conceptual framework, manuscript drafting, and revisions. PH and AM contributed to the conceptual framework and analysed the case study within the JCAR Program context. All co-authors helped refine the methodology, provided contextual insights, and reviewed and edited the paper.

**Competing interests**

The authors declare that they have no conflict of interest.

**Disclaimer**

Any opinions, findings and conclusions expressed in this paper are those of the authors and do not necessarily reflect the views of the partner institutions, funding agencies, or competent authorities involved in the underlying projects.

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