JCAR ATRACE

Stress test Rur Design choices

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Stress Test Rur

Report phase 1 – Design choices

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Summary

This document presents the analysis and screening results of the ‘Stress Test Rur’ as well as the description of the model design and experimental design planned in “Phase 2”. The aim of the stress test is to analyse the response of the Rur catchment to extreme hydrological stress and to identify potential risk mitigation measures.

The focus of the analysis is on flood events, particularly in connection with the July 2021 flood. Hydrological and hydraulic modelling will be used to simulate various extreme events and assess their impact on the water and protection system. Particular attention will be paid to the simulation of worst-case scenarios.

Results from interviews with relevant stakeholders show that floods are perceived as a central risk, while drought currently plays a subordinate role. In addition, questions regarding the optimisation of dam management, the importance of tributaries and cross-border cooperation were analysed.

Based on the findings, various risk minimisation measures are proposed. These include, for example, operational measures such as the optimisation of dams and emergency strategies, as well as structural solutions such as the construction of new flood retention basins or the renaturation of river sections. The results of this document form the basis for further modelling and decision-making processes to improve flood protection in the Rur catchment area.

Contents

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1 Introduction

Originally, a stress test is a medical test of the human heart under physical exercise. In the context of the JCAR ATRACE project we investigate how a water system reacts under extreme conditions or under which conditions the system fails. Goal of a stress test is to gain a better understanding of worst-case conditions and consequences of extreme scenarios.

The "stress test Rur" aims to gain a better understanding on how the Rur catchment reacts to worst-case conditions of extreme scenarios, learn what consequences are and to identify possible measures to mitigate unfavourable consequences. By carrying out this stress-test we will further develop the stress test approach such that the stress test Rur can become a guideline for other stress tests on the same catchment or other catchments in the cross-border area between the Netherlands and Northrhine-Westfalia.

The approach of the stress test Rur follows the method for an inter-regional stress test as outlined in Figure 1. The global method consists of three phases:

1. The starting points phase comprises scoping and system understanding.
2. The analysis is the stress test itself. Here scenarios are evaluated for system failure
3. Screening (of measures)

This document addresses parts 2 and 3 of the stress test, analysis and screening. Part 1, scoping and system understanding are described in a separate report Becker et al. 2024. In addition, the results of a thorough stakeholder survey are part of the stress test. Its results are shown in a separate report (Menz et al, 2025).

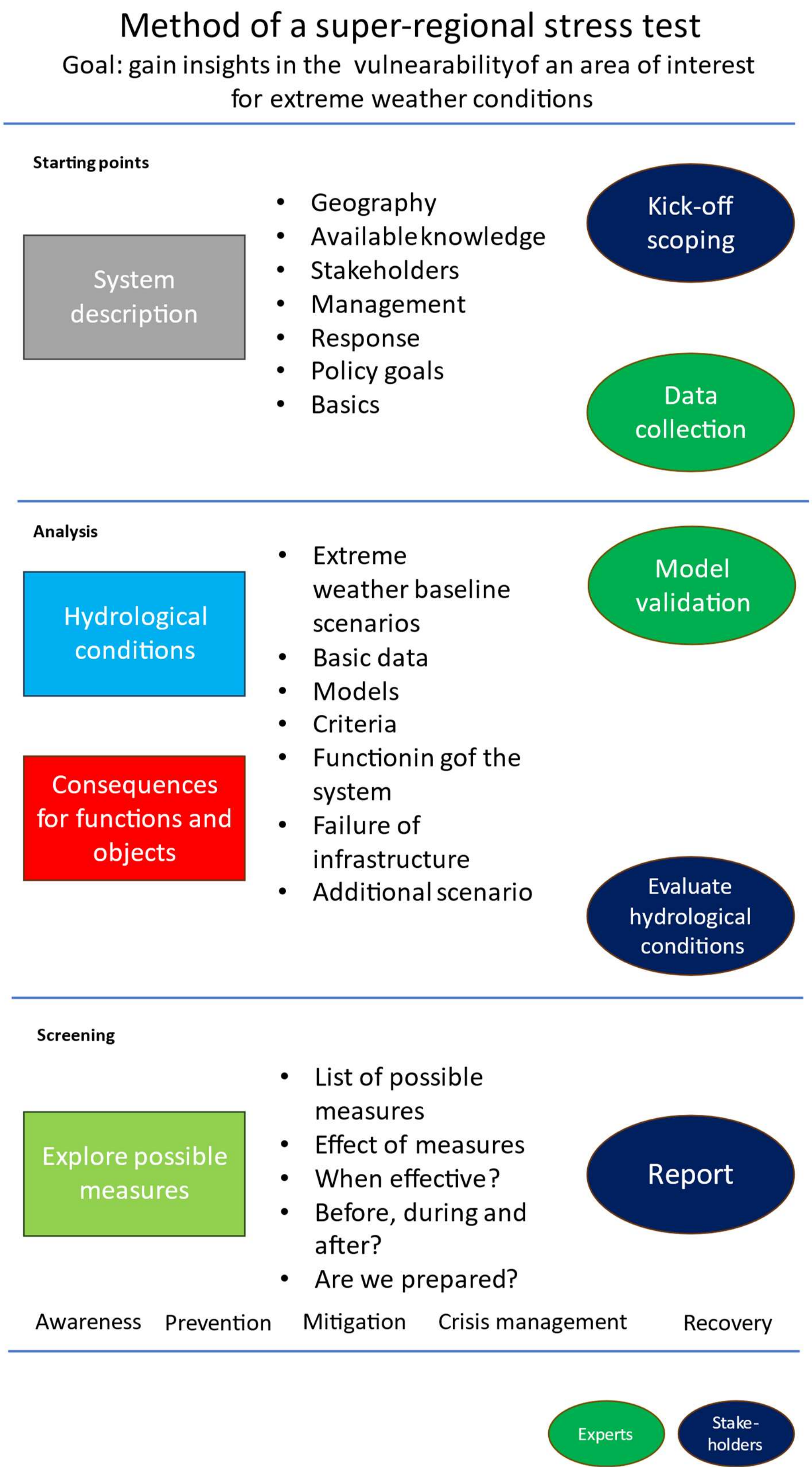

Figure 1 Approach stress test

2 Analysis: the stress test in a closer sense

2.1 Context, goal and approach

The Wasserverband Eifel-Rur (WVER) is developing a dike renewal and flood protection concept. The design discharge is the peak discharge with a return interval of once in 100 years (HQ 100). After implementing this concept, infrastructure is in place such that the system can withstand the design discharge. If the discharge is above the design level, the system probably fails.

Against this background, the stress test aims to address a situation above this design value. The primary interest are inundation areas at different locations along the Rur from its source in Belgium to the mouth in the Meuse at Roermond.

For selected locations, emergency response forces on the district level (e.g., Kreis, Katastrophenschutz) should be involved in the definition of scenarios and the selection of locations of interest.

Key element of a stress test is the stress on the water system. For floods, this is usually extreme rainfall. For droughts this is the lack of water.

We use models that represent the water system in terms of hydrological processes, hydraulic processes, shape of the land surface, hydraulic behaviour of structures and their operations. The stress is applied to this model as boundary conditions. A set of boundary conditions is called a scenario. A scenario can represent a historic event, in this case the scenario data usually is derived from observations, it can represent a synthetic event, a future event, a certain design scenario, or worst-case event. When modelling a scenario, the boundary conditions change in the model.

A measure aims to improve the situation. It is basically a change in the water system. Measures can include, but are not limited to, the installation of a structure, the modification of a structure, the change of the river bed elevation, the installation of a retention or a detention basin, construction or removal of dikes, or changes in the operational protocol for controllable hydraulic structures. When modelling a measure, the model schematization changes.

A combination of a scenario with a model schematization that represents one or more measures is called a case.

Consequences is the system response to a certain scenario. A consequence can involve system failure, and failures are in particular of interest for a stress test.

Failure basically means that the load is greater than resistance. Different failure mechanisms are thinkable:

- hydraulic failure:
    - spillway capacity exceeded
    - inundations
- hydrological failure
    - flood levels reached or exceeded
- flood damage
- geotechnical failure
    - dam breach
    - dike breach

Failure of the system is evaluated with the help of indicators. Pre-requisite for the evaluation of model results with indicators is a sound understanding of the system. It must be known beforehand where failure is expected and where critical locations are. A general analysis of stress test results usually provides a better understanding of the system and its behaviour under extreme situations (stress). Besides the evaluation with indicators, a general analysis of stress test results should be carried out.

2.2 Scenario generation – weather generator, hydrological models and reservoir outflow

2.2.1.1 Introduction

A stress-test scenario should represent a certain return interval larger than 100 years, e. g. HQ 500, HQ 1000, or HQ 10 000. Hydrological models need rainfall as the primary input. Possible approaches for generation of scenario data for rainfall are the following:

- Statistics. For the area examined, determine the relevant weather variable (mostly precipitation) over a given period of time based on the measured series and extrapolate using an extreme value function. In Germany, KOSTRA-DWD data is typically used provided by the German Weather Service (DWD, 2025).
- Based on weather generators.
    - Simple to advanced stochastic models based on weather data from one or more stations

    - Stochastic models based on historical weather maps (e. g., GRADE, Hegnauer et al. 2023; Hegnauer 2013)
- Based on analogies
    - Analogy over time, such as example years in drought studies, existing historical events for heavy rainfall
    - Analogy in space
        - relocation of historical event such as the water bomb approach (Becker et al. 2022; de Bruijn & Slager 2022)
        - the climate of the future resembles the current climate of a more southern region / location
- Based on the results of climate models
    - Use of projections and control runs of (regional) climate models
- Based on ensemble weather forecasts
    - Based on seasonal forecasts (e.g., Thompson et al)
    - Based on operational Weather forecast (new, untested)
- Demand-driven / Bottom-up approach: start with discharge
    - Choose a discharge that lets the system fail and derive the corresponding rainfall

When determining a return interval for a discharge in a river, the coincidence of rainfall events and their local distribution must be considered: the rainfall in the catchment not necessarily has the same return interval everywhere. Figure 2 shows the location of rainfall gauges and the estimated return interval of rainfall observed during the July 2021 flood event. While multiple, but not all rainfall locations in the Urft/Olef sub-catchment have a return interval higher than 1000 years, the sub-catchment of Obere Rur only received moderate rainfall with a return interval smaller than 50 years compared to KOSTRA-DWD.

The primary input for hydraulic models is a discharge hydrograph. Approaches for generating input scenarios for discharge are:

- Output from hydrological models that take rainfall scenario data as input as explained above. An example is the GRADE instrument (Hegnauer 2013, 2023)
- Synthetic flood wave simulators. Based on historic flood wave, the algorithms generate a synthetic flood wave with a defined peak discharge value that matches to the historic flood waves. Examples are the Hochwassermerkmalsimulation (Lohr 2004) or the Dutch wave generator "afvoergolven" (Becker et al. 2011; Heijnis 2004).
- Historic scenarios, including the flood of mid-July 2021.
- Modification of existing flood waves. To achieve a peak discharge, a factor can be applied to an existing data set. An example is given by Detrembleur et al. 2011.

2.2.1.2 Stress test for the Rur catchment: scenario generation

The primary stress test scenario is inspired by the July 2021 flood. Key aspects of the July 2021 flood event in the Rur catchment were (WVER, 2021A, 2021B):

- The Urft/Olef catchment received heavy rainfall (Figure 2). Consequently, the dam Oleftalsperre spilled above the design capacity of its spillway, but it did not collapse.
- The Obere Rur catchment received comparatively little rainfall only.
- Consequently, the large reservoir of Schwammenauel dam could catch most of the flood water from the upstream catchments, mainly the Urft/Olef catchment. The reservoir release did not exceed 80 m³/s. With 11 m³/s the spillway discharge was very small.
- The reservoir was filled to a level that corresponds to ca. 40 000 000 m³ below surplus level. This volume was available as flood storage volume.
- With the help of the reservoirs, the discharge in the Untere Rur could be limited such that only minor flood damage occurred.

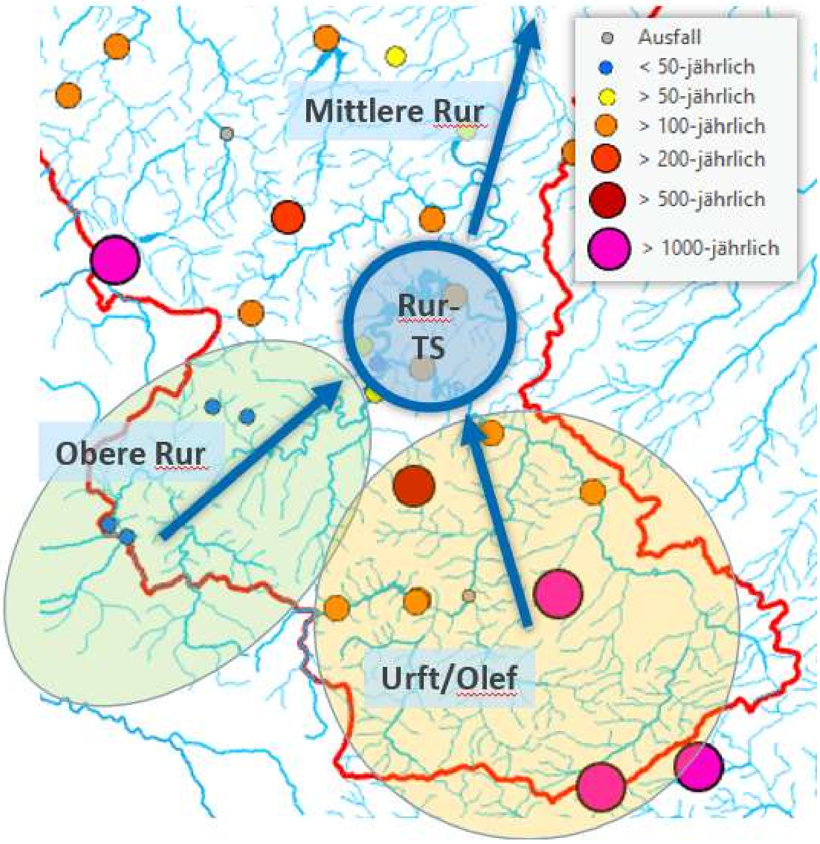

Figure 2 Location of rainfall gauges and the estimated return interval of rainfall observed during the July 2021 flood event in the sub-catchments Mittlere and Obere Rur and Urft/Olef (Reichert et al. 2024)

Assuming that the return interval for the rainfall in the Urft/Olef catchment was 10 000 years, the central question for the stress test scenario in the upper Rur area is: What would have happened if the neighboring catchment of the Obere Rur had had a rainfall event with the same intensity?

2.2.1.3 Unregulated sub-catchments

For the unregulated catchments, these are the sub-catchments of Wurm, Inde and Vicht as well as the Rur, Urft and Olef sub-catchments upstream of the reservoirs and additional small sub-catchments, we will use a weather generator and generate long-time series of climate. These are then used as input to the hydrological model, whose output is then used in turn to obtain peaks and hydrographs of certain return periods. The working steps are:

- Execute the GFZ weather generator (Becker et al. 2024; Nguyen et al, 2024; Section 2.5.1.2) and generate long time series of weather
- Feed the weather generator output to the hydrological model mHN model (Becker et al. 2024, Section 2.5.2.10)
- Select one or more events that show a similar pattern compared to the July 2021 event or that has a return period of around 10 000 years.

For the part of the catchment upstream of the Rurtalsperre Schwammenauel this approach generates discharge values to be used as boundary conditions by hydraulic models.

2.2.1.4 Untere Rur, outflow from the reservoir release

Downstream of the Rurtalsperre Schwammenauel, a part of the discharge in the Rur is driven by the outlet of the reservoir. This is not a natural hydrological process, but an outflow from a "regulated catchment". To generate reservoir outflow for the stress-test, two options are considered:

- Capacity of the spillway (450 m^3/s) plus bottom outlet capacity (120 m^3/s) = 570 m^3/s is set as peak discharge. A flood wave simulator generates a discharge curve. Note that reservoir outflow at maximum spillway and bottom outlet capacity is a regular operational mode from a reservoir perspective and not an emergency case.
- Reservoir modelling. A reservoir model (Becker et al. 2024, Section 2.5.4) produces reservoir outflow for a certain inflow scenario based on the operational protocol of the reservoir.
    - The inflow to the reservoir is the discharge modelled with hydrological models
    - The initial water volume in the reservoir is selected together with the reservoir operators. A "reasonable worst-case scenario" will be defined. The selection of initial reservoir

volume will consider typical filling levels under winter or summer conditions depending on the weather generator output.

We will coordinate with WVER about scenarios (see above) and the usage of models. A straightforward approach to make a start is to use the existing reservoir model by Johnen et al. 2021, because the modelling software is available (different to the Talsim model). The RTC-Tools model also allows us to optimize the reservoir release, which is in particular interesting for flood conditions. This is because under flood conditions the reservoir is no longer operated by solely following the volume-release plan (Lamellenplan). However, the RTC-Tools model has less detail.

2.2.1.5 Approach with spatial analogy ("water bomb experiment")

The water bomb experiment is another approach that we applied in addition to the approach described in the previous section. The rainfall pattern that hit the Uft/Olef area (Figure 2) is applied to the sub-catchment "Obere Rur", too. This made-up rainfall scenario is then fed into a hydrological model wflow (Becker et al. 2024, Section 2.5.2.3). For the reservoir outflow, the same options as for the approach with the weather generator (Section 2.2.1.3) is followed.

2.3 Hydraulic modelling

2.3.1 From hydrological model results to consequences

Extreme precipitation events generate floods. Consequently, the scenario generation addresses primarily the precipitation. For water management authorities, the parameters of primary interest are the water level and inundation extent.

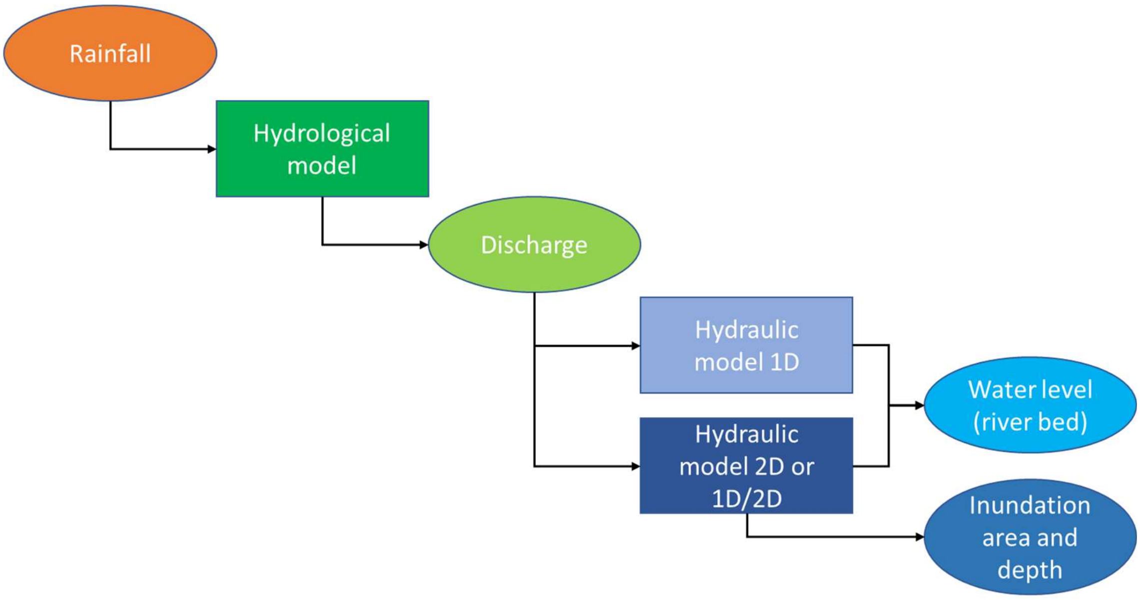

Figure 3 Model chain from hydrological model to water level, inundation area and inundation depth (modified after Becker et al. 2023)

Stakeholders have identified the inundation extent as the major parameter of interest the stress test should put out. In addition to that, flow velocities on the flood plain and within the river bed are a parameter of interest to assess the potential damage along with inundations, because high flow velocities bring potential of destruction and loss of life in addition to the wetting itself.

With rainfall (precipitation) as input, several models, each representing different physical processes, are required to generate an inundation area and an inundation depth along with the water level in the river bed. Figure 3 illustrates this model chain: rainfall data is fed as boundary condition to a hydrological model. The model result is a discharge, which is then fed to hydraulic models. 1D hydraulic models compute the water level along the river bed. Flood plains can be included in the cross-sectional profiles along the river course, this makes it possible to derive the inundation areas from a 1D hydraulic model to some extent. 2D hydraulic models have a more detailed spatial representation of river bed and flood plain, but they require much more computing time. If a run with the HydroAS 2D model for the Untere Rur takes multiple hours the 1D models typically compute within the order of minutes for a similar scenario. 1D/2D hydraulic models compute the 1D hydraulics for the river course with coupled 2D modelling for the inundation area, this allows faster computation of inundation areas than full 2D modelling. Reduced 2D models (Rim2D) compute fast, but neglect physical processes that are just relevant to flood modelling; these are processes that cause backwater effects and the dynamic wave propagation.

Although the model inventory lists many models (see Becker et al. 2024), there is not full coverage of the catchment with suitable models that can compute inundation for the stress test (Figure 4). For the part upstream of the Rurtalsperre Schwammenauel only hydrological models and an old (~2004) 1D model are available. HydroAS models are available for the Rur section between Obermaubach and the Dutch border (see Becker et al. 2024).These models are 2D hydraulic models, developed to support design studies rather than to support a stress test; as mentioned above their computational demand make them basically not suitable for a stress test.

To derive water levels and inundation extent for the stress test Rur for those areas where no hydraulic models are available, the following options have been considered:

- Usage of rating curves (Schlüsselkurven). Rating curves relate discharge to water level. With the help of rating curves, the discharge output from a hydrological model is translated to a water level. This comes with drawbacks:
    - Rating curves are derived from either observations or hydraulic modelling (discharge and corresponding water level). Consequently, the rating curves derived from observations will not comprise extreme discharge values, whereas the extreme discharge values are of particular interest for a stress test.
    - Rating curves are not available for all locations of interest.
    - Rating curves cannot be used to compare measures that change the river course or the shape of the flood plain.
- Usage of existing inundation maps. Comparing discharges from the stress test with the peak discharge that corresponds to an inundation map which is already present allows to estimate inundated areas to some extent. A problem here is that inundation maps are not generally available for the upstream parts of the area of interest, in particular if there are no hydraulic models available to generate such maps.
- Approximation methods such as the HAND method.
- Hochwassermerkmalsimulation (see Becker et al. 2024). A point of attention here is that the extreme event of July 2021 is not included in the flood wave parametrization.

- Generate new models with the reduced 2D modelling approach. Rim2D and wflow compute water level and thus inundation extent with diffusive wave approximation (see model inventory for more information, Becker et al. 2024). This approach comes with the following advantages and limitations:
    - The computation is carried out on a grid of quadratic cells. A very fine grid resolution (i. e. finer than in the corresponding hydrological model) is required to represent the river bed in the grid.
    - The grid can be based on the grid that is used for hydrological modelling. Automated processes make model generation fast.
    - The physical representation of flow processes is limited to the kinematic or diffusive wave approximation. Processes of wave dynamics and backwater effect, both relevant for extreme flood conditions, are neglected.
    - This type of models computes fast compared to full 2D models and has a complete 2D representation.
    - Implementing flood protection measures in the model is not straightforward.
    - Modelling of structures like weirs, bridges, or detention basins is basically not foreseen, and the modelling of dikes requires special attention (e. g., the adjustment of the grid cell parameters).
    - This type of models is designed for modelling pluvial flooding (water depth in the order of centimeters) rather than for open channel flow modelling (water depth in the order of meters) with fluvial flooding.
    - This type of models is usually not calibrated against water levels along the river course.
    - This type of models is fairly new, there is limited experience with such models for stress tests.
- Generate new hydraulic models, 1D or 1D/2D
    - Good representation of the physics with full flow dynamics, in particular for water level and flow velocities.
    - Comparatively fast computation with respect to full 2D modelling
    - Detailed representation of the river course with cross-sections, river bed elevation as well as hydraulic structures and dikes.
    - Although hydraulic models can be generated very quickly if the requirements in terms of accuracy are not too high, the development of a hydraulic model comes with a certain level of effort. On the other hand, there is much experience with 1D modelling.

- In particular for rapid assessment or when multiple measures are to be evaluated, 1D hydraulic modelling is considered as the standard for good modelling practice.
- Measures can easily be implemented with the help of schematization elements (a storage node for a detention basin combined with a weir node for inlet and outlet), model parameters (roughness parameter), cross sectional profiles (account for dikes and river bed elevation).

2.3.2 New hydraulic models for rapid assessment

The facts that the stress test Rur includes the evaluation of measures and that mainly fluvial flooding under extreme conditions are to be assessed, 1D hydraulic models rapid assessment are developed, if necessary with coupled 2D flood plain modelling.

1D hydraulic models for rapid assessment means that the models are basically not calibrated and generated with the available data and assumptions for data gaps. Following the rapid assessment study by Slager et al. 2022, this means:

- The river course follows the map
- River bed elevation is derived from a digital elevation model with the assumption of a channel depth
- Cross-sectional profiles have meaningful dimensions, assumed by expert judgement
- Roughness parameters are assumed based on literature
- The model is not calibrated.

Given that both SOBEK and ProMaiDes models are present in the Rur catchment, these two software packages come into consideration for the 1D hydraulic models for rapid assessment. Since SOBEK has been used for a similar purpose earlier (Slager et al. 2022) and thus tools for generating the models are available, the first choice is SOBEK.

2.4 Selection of questions, scope definition

The second phase of the Rur stress test, the modelling phase, focuses on the analysis of flood conditions and hydrological loads. The aim is to simulate various extreme events and assess their impact on the hydrological system and existing infrastructure. A key component of this phase is the 'water bomb experiment', which simulates a uniform, extreme rainfall distribution across the catchment to analyse the response of the system to a worst-case situation (Becker et al. 2022; de Bruijn & Slager 2022). This method allows a targeted analysis of the system's load limits and helps to identify critical weak points.

In addition, the modelling phase is used to answer specific scientific questions, which are listed in Table 2. These include the interactions between extreme hydrological scenarios and existing flood protection measures, the effects of changes in reservoir management and the role of tributaries in flood events. The combination of different modelling approaches is expected to provide well-founded knowledge for the further development of flood risk management strategies in the Rur catchment.

Table 1: Categorised research questions and interested institutes

No.	Interest by	Research question	Category
1	WVER	What would have happened, when extreme rainfall would have hit the whole river basin, upstream of the Rur-dam, also the 'Obere Rur' (area upstream the Rur dams)?	Hydraulics
2	WVER	Is there a possibility to regulate the (high) discharges in the Inde river?	Hydrology
3	WVER	The basis of climate change scenario study is 15 years old. Would the conclusions still be valid if they were based on the current state of knowledge on climate change?	Hydrology
4	WVER	How could the flood protection effect of the Rur dam system be maintained and even increased without compromising the minimum water discharge?	Reservoir
5	WVER	Would retention measures in the Inde/Vicht catchment area and dike relocations on the Lower Rur have an impact as far as the Netherlands?	Hydrology
6	WVER	Could emergency polders be set up that are flooded in a targeted manner in the event of extreme flooding to protect densely populated areas?	Hydraulics
7	WVER	To what extent could retention in the Urft/Olef catchment area relieve the burden on the Rur valley barrier system?	Hydrology
8	RWTH Aachen University	How to optimize Dam operation to prepare for extreme events?	Reservoir
9	RWTH Aachen University, Deltares	Stresstest - How does the Rur river basin respond to extreme events?	Hydrology
10	RWTH Aachen University, Deltares	What flood waves can be expected when dam failures happen?	Dam breach modelling
11	RWTH Aachen University	Flood retention in the Rur catchment area	Hydrology, Hydraulics
12	RWTH Aachen University	Monetary compensation for flood protection measures	
13	RWTH Aachen University	How do cross-border warning values compare?	Forecasting
14	RWTH Aachen University	Development of transboundary flood hazard maps in the event of an incident	Hydraulics
15	RWTH Aachen University	Assessment of historical flood events	Hydrology

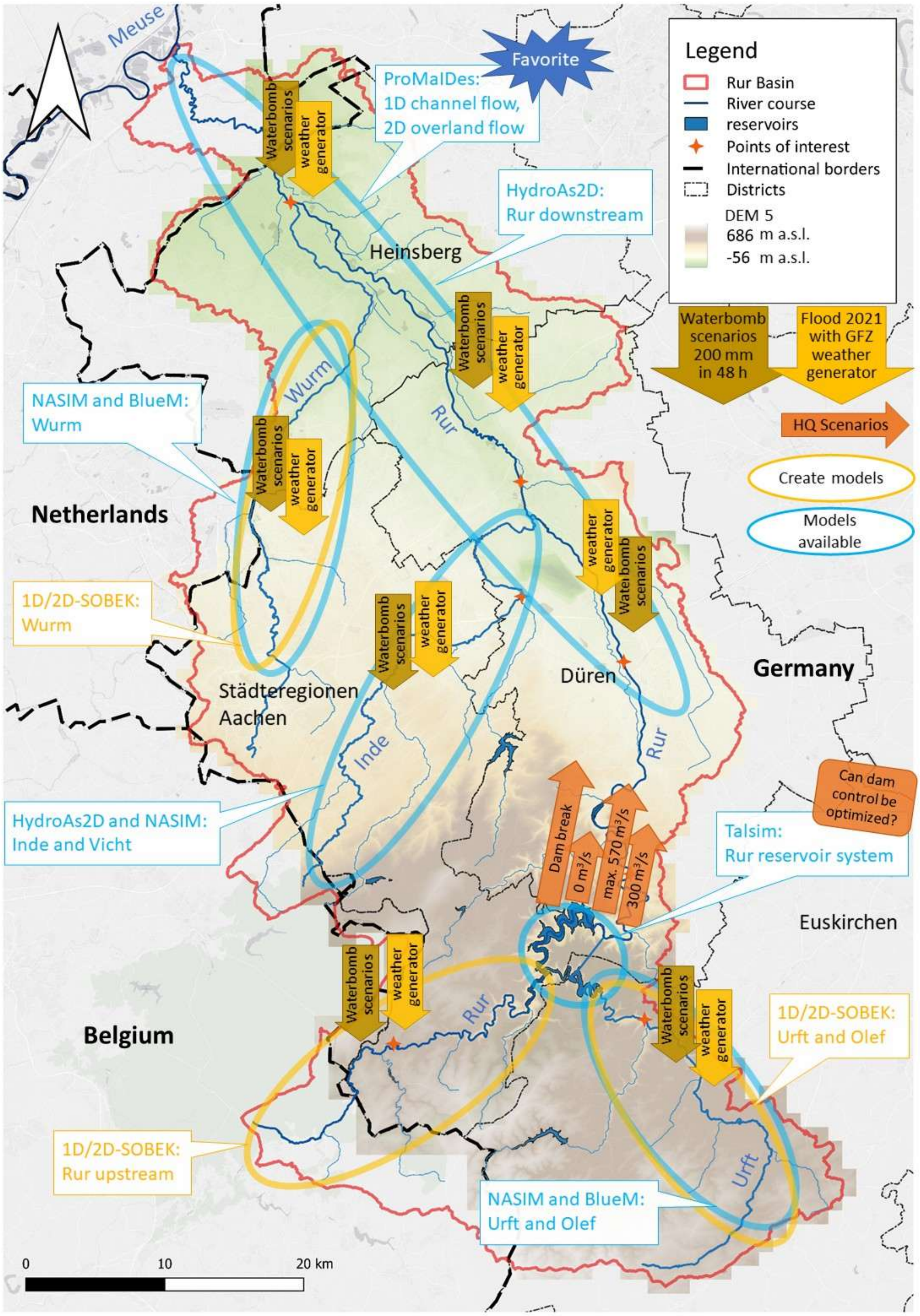

Figure 4 Study area, model coverage with hydrological models and hydraulic models (blue) and models to be developed (yellow, red) (as of beginning 2025).

Figure 4 illustrates the study area, the Rur catchment, the coverage of the existing models and the planned new modelling areas. The existing models are marked in blue, while the areas to be modelled are highlighted in yellow.

In the lower Rur, a ProMaiDes model and a HydroAs2D model already exist. For the Wurm and the Urft a NASIM and a BlueM model respectively can be used. In the catchment area of the Inde and the Vicht, a HydroAs2D and a NASIM model are available. In addition, a Talsim model exists for the reservoirs in the Rur catchment, which can simulate reservoir control and impacts. (see Becker et al. 2024)

New modelling efforts include the development of 1D/2D SOBEK models for various tributaries of the Rur. The first results of these model simulations will allow the identification of hotspots. Two types of critical discharge can be distinguished: on the one hand, there are hotspots with a critical discharge level above which damage occurs in urban areas. On the other hand, there is a positive critical discharge level, above which controlled flooding can occur in non-urban areas, allowing water retention. These regions are further analysed using detailed HydroAs2D modelling.

In addition, Figure 4 shows downward-pointing arrows indicating water bomb scenarios. These scenarios allow the simulation of different localised high runoff events. In order to investigate the effects of different weather events, the GFZ weather generator is used, in particular to simulate scenarios such as the flood event of July 2021 and to analyse its effects on the Rur catchment area. The scenarios are explained in more detail in the following chapter.

The effects of different discharge levels from the Rur reservoir will also be investigated. These discharge levels are shown in red in Figure 4. The objective is to evaluate the potential consequences of different discharge levels and to derive optimisation measures for flood risk management.

2.5 Scenarios

This chapter introduces the fundamental concepts and ideas of the scenarios. Please note that the second phase of the stress test is currently under development, which may result in adjustments and modifications being made. In addition, as part of another JCAR project (Stress Test GPRW for the Vechte, Dinkel, Berkel and Issel rivers), there is an active exchange with the project partners, which could also influence the design of the scenarios.

2.5.1 Base scenario

The baseline scenario serves as a reference for the stress test scenario results. The base case is the flood event with a return period of 100 (HQ 100). The HQ 100 is the design scenario for the Flood Protection Concept.

*Table 2: Significant gauges in the Rur catchment area with Mean Low Water (MLW), Mean Water Level (MWL) and Mean High Water (MHW) in cm in the *reference period: 2008 – 2018 (LANUV 2025)*

Name	Station number	Water bodies	MLW*	MWL*	MHW*
Altenburg_1	2823900000200	Rur	6	29	109
Dedenborn	2821790000100	Rur	7	33	147
Eschweiler	2824590000400	Inde	17	38	188
Gemuend	2822900000200	Urft	26	46	171
Herzogenrath_1	2828300000200	Wurm	54	66	207
Juelich-Stadion	2825190000200	Rur	102	124	220
Kall-Sportplatz	2822700000200	Urft	19	36	149
Kornelimuen-sterW	2824300000100	Inde	10	25	140
Linnich	2825330000100	Rur	87	109	190
Monschau	2821530000200	Rur	9	32	110
Mulartshuette	2824450000100	Vicht	19	29	117
Randerath	2828900000200	Wurm	73	90	251
Schleiden	2822870000100	Olef	89	102	191
Selhausen	2823900000100	Rur	51	78	159
Stah	2829100000100	Rur	42	78	204
Zerkall	2823500000100	Rur	45	61	136

2.5.2 July 2021 flood event

In order to analyse the hydrological impacts of extreme precipitation events in the Rur catchment, a synthetic weather event will be generated that is statistically equivalent to the flood of July 2021. This will be done using the GFZ Weather Generator, which is based on historical climate data and generates synthetic but realistic weather conditions.

To ensure the most accurate representation of the hydrological processes in the Rur catchment, the statistical models of the Weather Generator will be adapted to the specific climatic and geographical conditions of the region.

Regional precipitation patterns, temperature variations and geophysical characteristics will be taken into account to develop a robust model.

Based on these calibrated model parameters, a simulation of an equivalent extreme event will be carried out, specifically calculated for defined Points of Interest (POIs). These POIs will include critical infrastructure and flood prone areas along the Rur. The aim will be to analyse the impact of a comparable flood event at these locations under different conditions.

The synthetic weather data will then be integrated into the mHM model. This hydrological model will use the generated precipitation data as input for runoff calculations to realistically simulate the water balance of the catchment. This modelling approach will be used to determine discharge volumes, which will then be used to identify areas potentially at risk of flooding.

This methodology will allow detailed analysis of the hydrological response of the Rur catchment to extreme precipitation events and provide more accurate predictions of future flood risks.

2.5.3 Water bomb experiment

The Water Bomb Experiment is a methodological approach used to investigate the hydrological response of a catchment to extreme rainfall events. In this experiment, a simple, idealised rainfall pattern is applied to the area of interest to analyse its effect on runoff and flood extent.

A homogeneous, time-constant or impulsive rainfall event ("water bomb") is applied to the whole or a specific part of the catchment for a defined duration. Different intensities can be tested to assess the sensitivity of the system.

The synthetic rainfall distribution is fed into an mHM hydrological model to calculate the resulting runoff, water level changes and potential flood extent.

The simulation helps to determine key hydrological parameters such as peak discharge, runoff delay and water retention in the catchment. The experiment is particularly useful for evaluating POIs to assess how such an extreme event would affect critical infrastructure or highly vulnerable areas.

The results of the water bomb experiment can be compared to historical flood events, such as the July 2021 flood, to assess differences between real and idealised rainfall distributions. This comparison can help refine future modelling approaches.

The experiment aims to improve the understanding of the resilience and vulnerability of the catchment to extreme precipitation events. It will provide a targeted analysis of which areas are particularly sensitive to high rainfall and where flood protection measures should be prioritised.

2.6 Consequences for system functioning and specific objects

Below is a detailed description of the impact on system functionality and specific objects in the event of failure, e.g., when the applied load exceeds the resistance, with a clear distinction between different types of failure:

Hydraulic failure:

Hydraulic failure occurs when the capacity of a system to hold water is exceeded. This can take two forms:

- Overflow capacity exceeded: The system can no longer adequately manage the incoming volume of water, resulting in an uncontrolled overflow.
- Flooding: As a direct result of exceeding capacity, regional or local flooding occurs, which can adversely affect surrounding infrastructure and ecosystems.

Hydrological failure:

Hydrological failure occurs when water levels reach or exceed a critical flood level, compromising the safety and functionality of the system.

Flood damage:

The direct consequence of both hydraulic and hydrological failure is flood damage. This affects not only water management, but also surrounding infrastructure and residential areas.

Geotechnical failure:

Geotechnical failure refers to structural damage to structures that affect water management. Typical scenarios include

- Dam failure: A sudden failure of a dam results in a rapid, uncontrolled release of water.

- Dike failure: A breach in a levee can also result in a rapid and extensive release of water, with serious consequences for the surrounding area.

The response of the system is examined on the basis of the specific scenario (load) applied. The system model is run under the given loading conditions to determine if and to what extent a failure will occur.

For the evaluation of the modelling results (phase 2) the following indicators are crucial:

- Exceedance of thresholds: Checks whether critical parameters (such as water levels or load limits) exceed pre-defined thresholds. These indicators indicate whether the system is approaching or exceeding its limits under the specified loading conditions.
- Infrastructure failure: Another key indicator is the failure or collapse of infrastructure components, such as dam or dike breaches. This assesses the extent to which built components and systems lose their functionality under high stress.

The aim of these indicators is to develop a comprehensive understanding of how the system behaves under stress. By systematically processing the results and evaluating them against these criteria, important conclusions can be drawn about the functionality and resilience of the system. Consequently, these indicators play a critical role in the evaluation of the modelling results in Phase 2, helping to identify potential weaknesses early and address them effectively.

2.7 Explore possible measures

2.7.1 Overview

We distinguish operational measures and structural measures.

Operational measures address the operations of hydraulic structures:

- Reservoir release schedule
- Weir operations
- Opening of lateral detention basins

Structural measures are changes to the water system. These can be categorized in technical measures like

- Construction of dikes, removal of dikes
- Installation of a lateral detention basin
- Installation of a dam for a retention basin

And nature-based solutions:

- Land use change
- Extend the length of the river stretch
- Removal of ditches or installation of ditches

Technical measures can be accompanied with operational measures. A retention basin can be constructed in such a way that it can be controlled.

2.7.2 Exploring Operational and Structural Measures

The second phase of the Stress Test Rur will systematically investigate the effectiveness of these measures using hydrological and hydraulic modelling approaches. The main objective is to assess how different measures affect water levels, flow dynamics and flood risk.

Operational Measures: Timing of reservoir release and storage

- Optimise reservoir release schedules to best match hydrological outflow from unregulated catchments.
- Evaluate pre-release and storage strategies to balance flood retention and downstream flow stability.
- Use optimisation techniques to improve decision making during flood events.

Structural measures: Flood polder and retention strategies

- Investigate the potential for flood polder management at critical locations along the Rur.
- Evaluate the effectiveness of retention basins (e.g. Lamelle im Restsee Inden) in reducing peak flows.
- Evaluate dike modifications to redistribute floodwaters and minimise urban flood risks.

2.7.3 Integration of Pilot Studies

To support the identification and evaluation of measures, two current master's theses are serving as pilot studies:

- Lasse Schweim (2024) – "Dyke potential study and derivation of approaches for flood polder management using the example of the lower Rur"
- Heleen Urbach (2024) – "Optimization of Detention Basin Operation at the Lower Rur River in Germany"

The results of these studies will be incorporated into Phase 2 and enable a targeted assessment of their feasibility and impact under different hydrological scenarios. Further theses on the identification and evaluation of measures are to be tendered.

2.7.4 Identification of measures through critical discharge analysis

A key methodology in Phase 2 will be the analysis of critical discharge levels, which define thresholds at which damage occurs:

1. Damage occurs in urban or infrastructure sensitive areas.
2. Controlled flooding becomes beneficial, allowing temporary retention in designated areas.

By correlating hydrological model outputs with these thresholds, potential intervention areas can be identified. This data-driven approach will inform both structural modifications (e.g. new detention basins) and operational adaptations (e.g. early reservoir release strategies).

In summary, Phase 2 will not only validate pre-identified measures, but also discover new intervention strategies by integrating flood risk analysis with real-time hydrodynamic simulations.

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