JOURNAL OF COASTAL AND RIVERINE FLOOD RISK

Vol. 2, 2023, 8

Storylines of the impacts in the Netherlands of alternative realizations of the Western Europe July 2021 floods

K.M. de Bruijn[1], B. Van den Hurk[2], K. Slager[3], G.W.F. Rongen[4], M. Hegnauer[5], K.J. van Heeringen[6]

[1]Karin.debruijn@deltares.nl, Deltares
[2]Bart.vandenhurk@deltares.nl, Deltares
[3]K.Slager@deltares.nl, Deltares
[4]G.W.F.Rongen@tudelft.nl, TU Delft
[5]Mark.Hegnauer@deltares.nl, Deltares
[6]Klaasjan.vanheeringen@deltares.nl, Deltares

Submitted: 7 March 2023, **Revised:** 12 September 2023, **Accepted:** 10 October 2023, **Published:** 22 December 2023.

DOI: https://doi.org/10.59490/jcrfr.2023.0008

Cite as: "de Bruijn, K., van den Hurk, B., Slager, K., Rongen, G., Hegnauer, M., & van Heeringen, K. J. Storylines of the impacts in the Netherlands of alternative realizations of the Western Europe July 2021 floods. Journal of Coastal and Riverine Flood Risk. 2, p. 8. https://doi.org/10.59490/jcrfr.2023.0008"

Abstract

The 2021 summer flooding was an extremely rare event, driven by precipitation extremes that exceed Dutch design levels for flood protection of relatively small rivers and waterways. However, similar events in neighboring locations cannot be ruled out in the near future. The implications of such extreme rainfall amounts will vary by region, subject to local topography, water systems, and societal exposure. We explore the diversity of potential flood impacts induced by a similar event by constructing impact-oriented event storylines for characteristic water management regions in the Netherlands. The plausibility of the storylines is underlined by using physical evidence, proven impact-modelling concepts, and expert judgment successfully assessing the (sometimes unexpected) outcomes. The approach supports impact assessment and risk management of extraordinary rainfall and flood events. The outcomes show the relevance for crisis management and spatial policies, and confirms the need for in depth-analysis to assess concrete adaptation options

Keywords

Flooding, flood impacts, physical climate storyline, flood risk

Dedicated to the memory of Cees van de Guchte

1 Introduction

The extraordinary precipitation between 12 and 15 July 2021 covered a large area of the Meuse and Mosel river basins in Germany, Belgium and the Netherlands. The excessive damage and number of casualties came as a true surprise for the general public and for professionals in water management and civil protection. At least 243 people died in the flash floods and multi-day flooding in a large area (Wikipedia, 2022), and direct insured damage is estimated to be the highest recorded in Europe this century, exceeding €10 bln ¹. The event triggered many public debates on societal preparedness (Fekete and Sandholz, 2021), quality of the forecasts and early warnings (Cornwall, 2021; Verkade et al., 2022) and the attribution to climate change (Kreienkamp et al., 2021; Tradowsky et al, 2023).

Particularly the widespread precipitation on 13 and 14 July was exceptional. The rainfall system covered a considerable fraction of the river basin area of the Meuse and Mosel (each comprising approximately 35,000 km^2). Forty-eight hour rainfall totals exceeded 150 mm in a contiguous domain of at least 6,000 km^2, with peak amounts exceeding 250 mm in the core of the weather system (Table 1 and Figure 1). Since the measured rainfall was unprecedented in the instrumental record for many stations in the area an accurate estimation of the event return period is not trivial. (Kreienkamp et al., 2021; Tradowsky et al, 2023) estimated this return time by pooling the maximum 2-day precipitation sums in 14 geographical regions of 130 × 130 km between the Alps and North Sea, and their most likely estimate of the probability of a similar summer event happening in this region is 1/400 year^{-1}. Ludwig et al. (2023) assessed the return times of the flooding in the Ahr region, stating that the flood 2021 levels exceeded the 1/100 year^{-1} return time significantly. The 2021 flood reached higher levels than similar rainfall events in the 19th and early 20th century possibly due to human interventions in the landscape organization and occupation.

Table 1: Surface area distribution of cumulative 48-hour precipitation recorded on 13 and 14 July 2021. Source: E-Obs data set *(Cornes et al., 2018)*.

Exceedance threshold of cumulative precipitation (mm/48 hours)	**Contiguous surface area (km^2)**
>75	70,000
>100	27,500
>120	16,750
>150	6,000
>175	1,000

Compared to the neighboring countries Germany and Belgium, the impacts in the Netherlands were relatively modest, with no deadly victims, and mainly limited to the southern half of the province of Limburg (which has a surface area of ~2,200 km^2). Although the former 1993 Meuse discharge record at the Eijsden border was broken, the main flood defense infrastructure along the Meuse provided adequate protection. However, also in the Netherlands precipitation and flooding of the regional tributaries showed considerable damages, and more than 50,000 inhabitants were evacuated, which led to considerable stress. Amongst many places, the centre of the city of Valkenburg was flooded, and compound discharge peaks of other tributaries contributed strongly to the peak wave height and duration of the Meuse river up to the city of Roermond. Downstream of the Maasplassen area available water storage capacity flattened the flood peak in this part of the river, although downstream of Roermond the discharge still exceeded usual summer levels (Task Force Fact-finding Hoogwater, 2021).

In the Netherlands flood risk management makes an explicit distinction between regimes of “major floods from the main waterways and local floods from regional waterways or local rainfall” (Kok et al., 2017). Management of major flooding addresses the protection against floods from the main rivers (Rhine, Meuse and Vecht River), the largest lakes (IJssellake) and the sea, which are generally major events that may lead to casualties and large economic damage. The management of localized flooding considers flood damage from smaller streams and canals usually induced or caused by local rainfall. Although it is acknowledged that a grey zone between these regimes exists, this distinction extends to the governance of protection infrastructure, the range of protection standards, and the geographical distribution of these standards and responsibilities. The estimated exceedance probability of the July 2021 event did exceed the protection standards of the smaller local rivers (and indeed flooding and damage occurred) but was within the protection range around the Meuse river (where protection infrastructure indeed functioned well).

In the affected countries, strategic policy evaluations are initiated in response to the event. In the Netherlands particular attention is paid to the small exceedance probability of the (summer) event, the limits to impact prevention by flood defense infrastructure, the responsibility of local governments to mitigate impacts and increase preparedness, and the plausibility of similar rainfall intensities to occur elsewhere in the country (Kernteam Beleidstafel Wateroverlast en Hoogwater, 2022). The extraordinary magnitude and spatial extent of this event, and the dramatic impact reported in neighboring countries, did raise the awareness that a similar realization of this hydrometeorological hazard occurring in a different region in the Netherlands could have caused a much larger domestic impact. In addition, debates on “acceptable risk” and public awareness, recovery capacity (including the role of commercial insurance), and preparedness of the emergency response system ask for guidance on potential implications of similar hazards, certainly against the imminent trends in exceedance frequency of extreme rainfall events in a changing climate (Botzen et al., 2010; Klijn et al., 2012; Kreibich et al., 2022).

This paper uses the hydrometeorological background of the Western European July 2021 floods to explore implications of similar extreme rainfall events at different locations in the Netherlands. It builds on the outcome of a short-duration hackathon (De Bruijn and Slager, 2021) that explored the physical plausibility of alternative event trajectories, and infers flood impacts from hydraulic modelling, damage assessments and expert judgments. The approach is designed to provide credible event storylines (Shepherd et al., 2018; Sillmann et al., 2021) to support flood risk assessment and mitigation in the Netherlands accounting for unprecedented yet plausible events (Kreibich et al., 2022). The primary goal of this study is to provide insights on consequences of such extreme large-scale rainfall events in other Dutch regions. In addition, against the background of an increasing exceedance probability of extreme rainfall and extended floods (Ranasinghe et al., 2021), its seeks to contribute to the public awareness of potential impacts and response options, to raise the level of preparedness for a changing climate and unprecedented yet plausible events.

The next section provides a description of the hydrometeorological event and the physical mechanisms that contributed to it, including an elaboration of alternative realizations of governing processes leading to different tracks of the precipitation system. Section 3 describes the approach used. Section 4 provides the results, while section 5 discusses the added value for emergency response and societal preparedness for floods in a changing climate. Conclusions are given in Section 6.

2 The precipitation event and potential alternative realizations

As described by (Kreienkamp et al., 2021) and (Task Force Fact-finding Hoogwater, 2021), the July 2021 precipitation originated from a strong and persistent “cut-off low” (named “Bernd”). This is a low-pressure system with a high altitude cold airmass promoting the sustained triggering of deep convection fueled by high-moisture air masses originating from a very large source area. The atmospheric circulation advected moisture from the Gulf of Finland (where a regional heatwave pushed sea surface temperatures to high values) particularly in lower atmospheric layers, but also from remote areas including the Mediterranean, North Sea and intercontinental transport (Insua-Costa et al., 2022). Local recycling of precipitation likely has contributed to the event, deduced from analyses of a large range of Central-European heavy precipitation situations (Krug et al., 2022). Also local topography has contributed somewhat to air mass uplift and stalling of the low pressure system (Kreienkamp et al., 2021), but the role of blocking high-pressure systems surrounding the cut-off low is considered dominant (Task Force Fact-finding Hoogwater, 2021).

Meteorological forecasts from the European Centre for Medium-range Weather Forecasts (ECMWF) and the Limited area Ensemble Prediction System COSMO-LEPS[1] did give indications for high precipitation amounts in the area a few days ahead of the event, but underestimated the observed multi-day precipitation sums throughout the forecast cycle (Verkade et al., 2022). Subsequently, hydrological forecasts operated by Rijkswaterstaat[2] estimated peak water levels that were too low up to 24 hours prior to the flood event. Discharge levels both in the main Meuse river and its tributaries were the highest ever recorded. Downstream of the flooded area Meuse water levels did not break earlier records (Task Force Fact-finding Hoogwater, 2021).

For this region the event was unprecedented in the instrumental record, but major summer flood events took place in the recent history in neighboring river catchments, including the Oder in 1997, and the Elbe in 2002 and 2013. The meteorological processes governing these flood situations were different: an exceptionally strong frontal system advecting moist and warm air from continental Eastern Europe in 1997 (Kundzewicz et al., 1999), moisture advection from the Mediterranean and subtropical source regions by an Adriatic low in 2002 (Engel, 2004), and a situation similar to the 2021 event with a cut-off low with subtropical moisture transport, but strongly enhanced by orographic uplift of the Alps in 2013 (Merz et al., 2014). Observed discharge in rivers in this North-Western European domain shows a climatological upward trend (Blöschl et al., 2019), while climate change is considered to increase the likelihood of future extreme rainfall occurrences (Seneviratne et al., 2021). (Kreienkamp et al., 2021) estimated that the historic

[1] http://www.cosmo-model.org/content/tasks/operational/leps/
[2] https://www.helpdeskwater.nl/publish/pages/132725/broch_fews_web.pdf

global warming of 1.2 °C has increased the exceedance probability of the 24-hour summer precipitation amount by a factor 1.2 to 9. While this uncertainty range is considerable, it indicates an increase in the likelihood of such events with further warming.

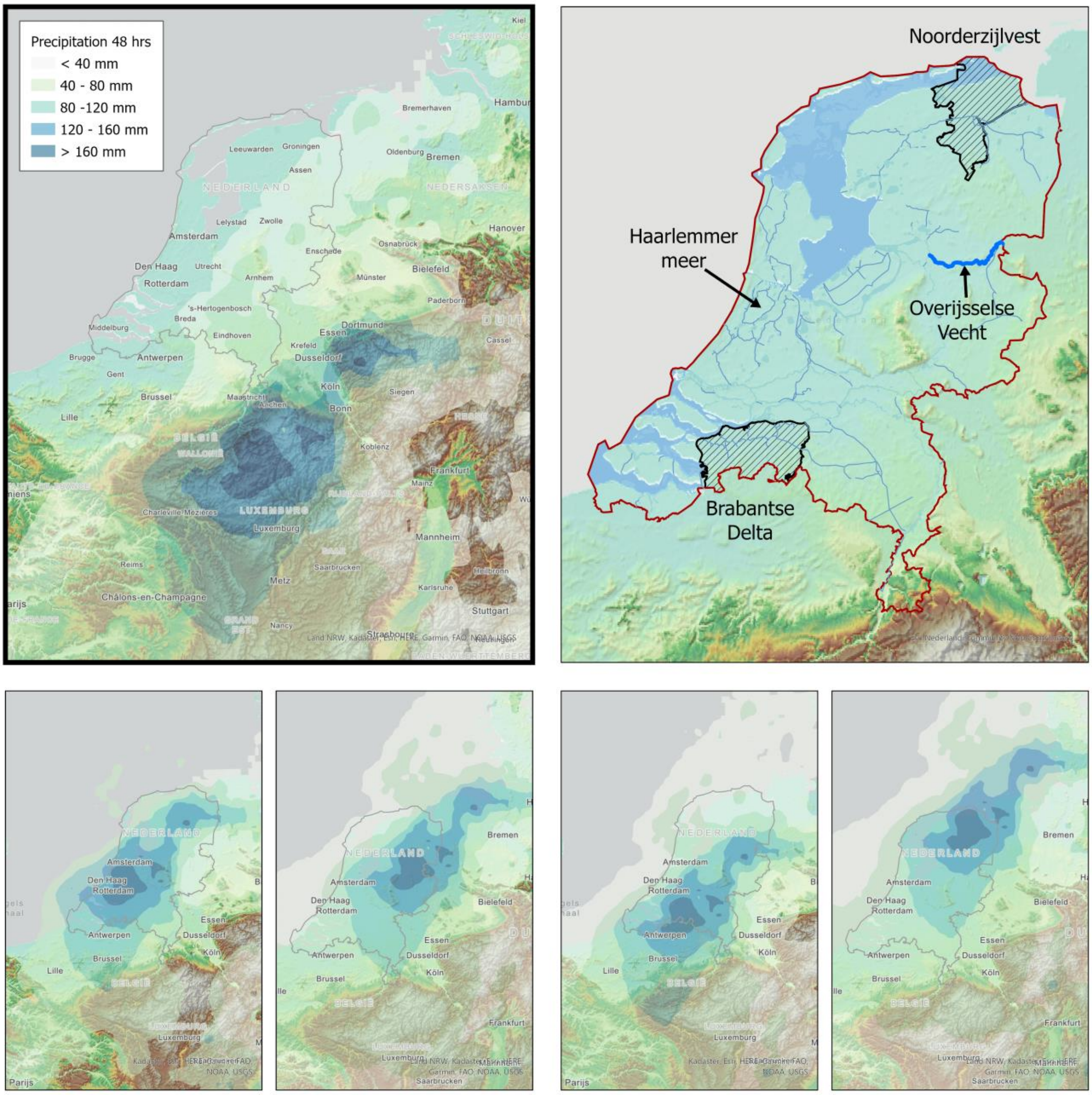

Figure 1: Upper left: Extent of July 2021 precipitation event, with 48-h total rainfall sum (Cornes et al., 2018). Upper right: geographical locations of regional study areas. Lower panels show the displacements to position the core rainfall in the domain of (from left to right) the Haarlemmermeer, Overijsselse Vecht, Brabantse Delta and Noorderzijlvest; adapted from (De Bruijn and Slager, 2021).

Although the exact scenario unfolding during the July 2021 floods is unique, it should be considered plausible that a similar event will occur again in the future. The multiple hydrometeorological mechanisms that can lead to a major flood situation in this region, and the uncertain but positive contribution of global warming to its occurrence probability justify the exploration of implications of similar events in nearby regions. Here we describe such an exploration carried out by spatial displacement of the rainfall patterns to overlap a number of water management units in the Netherlands with distinct hydrological and hydraulic features, different from the situation in the affected Meuse/Mosel domain. Different spatial displacements were carried out for different water management pilots, varying in distance between 100 and 350 km West- and Northward, respectively. An example of such a displacement is shown in Figure 1.

The horizontal displacement implies that a meteorological event could have formed at this location giving similar amounts of rainfall as were recorded during the historic event. The plausibility of this scenario can be supported by a number of physical rationales:

- Similar amounts of rainfall during summer did occur in nearby locations (see discussion above on flood events in the Elbe and Oder), despite a different combination of meteorological processes leading to the large precipitation sum;
- The orographic uplift from the Eiffel and Ardennes mountains is absent in the new target region, but additional convective uplift could have been triggered by stronger surface warming (for instance, in case of dry land surface conditions; (Vogel et al., 2017)), an even lower upper-air temperature, or the formation of strong cold-pools induced by precipitation downbursts (Kirsch et al., 2021);
- Stagnation of the low pressure system displacement supported by the local orography can also be induced by stationary positioning of high pressure systems, for instance supported by Arctic – Mid-latitude interactions (Coumou et al., 2018);
- The advection of moist air from the Baltic region is not necessarily equally effective for the new target location. On the other hand, alternate nearby moisture sources can in theory fuel a sustained rainfall event as well, including the North Sea (Lenderink et al., 2009).

Different methodologies exist to construct an alternative high precipitation scenario. Exploitation of ensemble meteorological forecast archives from for instance medium-range or seasonal forecast systems contain thousands of years of modelled weather situations consistent with present-day climate conditions (Kelder et al., 2022), and may contain high summer precipitation episodes in the region of interest. A relatively new technique is “ensemble boosting” which was applied by Fischer et al. (2023) to generate event scenarios of unprecedented heatwaves in Western Canada and United States by repeatedly perturbing atmospheric states of individual ensemble members to generate extreme conditions. Similarly, the extensive archive of global and regional climate simulations used to construct regional climate change scenarios may contain such events (Lenderink et al., 2014). Perturbation of simulations of historic events – such as the July 2021 flood – using so-called pseudo-global-warming techniques (Attema et al., 2014) or relaxation towards predefined boundary conditions (Van Garderen et al., 2021) can lead to simulated hypothetical event scenarios that can support societal impact assessments. In the current analysis and underlying hackathon, we choose to use a displaced version of the July 2021 event as a plausible realization of extreme rainfall, with the purpose to evaluate the implications of such an event for different regions. The next subsection describes this impact assessment in further detail.

3 Methods for rainfall impact assessment in other regions

3.1 Selection of regions

The impacts of a multi-day precipitation amount have been assessed for different types of regions. A supra-regional perspective is adopted as well, with the purpose to analyse issues with coordination of water management, emergency management and consistency in information exchange.

The regional systems explored are (see also Figure 1 for geographical orientation):

- **Polder systems**: a “standard polder” can be defined as a flat area enclosed by a dike system from where rainfall has to be pumped to surrounding waterways. These polder systems are found in the western and northwestern provinces in the Netherlands and many are located below sea level. In the hackathon, simple hydrological models were used to simulate the potential flood depth and duration. The displaced July 2021 rainfall is projected on the polders as a 3-day precipitation event of 200 mm in the entire polder area, distributed over time by taking 80, 80 and 40 mm/day for the three consecutive days, respectively. For illustration purposes we show the location of polder area “Haarlemmermeer” (area approximately 200 km^2) in Figure 1;

- **Systems drained by gravity**: in free-draining regions rainwater is discharged out of the area by drains and waterways flowing under gravity. During high precipitation events, water will flow in an uncontrolled way resulting in discharge peaks in the channels and river network and flooding. The Dutch area affected by the July 2021 event was a free-draining region in a hilly terrain. For the exploration in this study the region of the "Overijsselse Vecht" (catchment area ~3800 km^2) was chosen (see Figure 1), where topography shows smaller variability than in the affected region, and where exposure of urban settlements and infrastructure contributes to considerable potential flood damage. In this region several (German and Dutch) administrative agencies are jointly responsible for emergency management, civil protection and water governance.

- **Combined systems**: many systems consist of multiple polder areas which are connected through a shared water system, or of a combination of an upper system which is drained by gravity and a lower section consisting of polders; the combined discharge of the polders and upper area need to be pumped out to a main river, lake or the sea. Two examples are explored in this category: the water management units "Noorderzijlvest" (~1500 km^2) in the most northern part of the country, and "Brabantse Delta" (~1700 km^2) in the southeast (see Figure 1). The July 2021 rainfall event was displaced for each of these regions in order to situate the precipitation maximum in the center of the target water system.

3.2 Methodology and tools

A generic GIS-based water balance assessment was deployed for "standard" polder areas, allowing a time-evolving image of spatial distribution of (surface) water and flood depth governed by, amongst others, rainfall, lateral inflow/outflow and pumping. For detailed region-specific assessments, existing operational hydrological and hydrodynamic decision models were used, consisting of the SOBEK and Delft3D[3] software suites for hydrodynamic, rainfall-runoff and real-time control modelling. Parameters, boundary conditions and initialization procedures are derived from model implementations for routine water management operations.

The analysis was largely carried out during a 3-day work-session (hackathon) involving topical experts in modelling water systems, regional water management and field experience in the regions of interest. The tools and instruments used for the assessments are largely the same tools that are available and used in real-time flood management. Lessons learned from this rapid assessment include the evaluation of suitability and range of feasible operation of the available decision support systems.

4 Inventory of impacts and emergency response implications in the target regions

For each system the physical response of the displaced rainfall, the (potential) socio-economic impacts, and (potential) consequences for the emergency response are discussed.

4.1 Polder system

4.1.1 Physical response

Approximately half of the surface area of the Netherlands can be classified as (deep) polders, such as "Haarlemmermeer". Size, depth and land use vary widely across the polder systems, but they all rely on pumping to regulate water levels (Oude Essink et al., 2010). Polder areas in the Netherlands typically have a pumping capacity of 14 – 20 mm/day (Hoes and Giesen, 2015), although older infrastructure configurations with lower capacity exist. For the adopted precipitation scenario of 200 mm distributed over 3 consecutive days with 80, 80 and 40 mm/day respectively, the evolution of water fluxes and the mean water depth for a standardized polder is shown in Figure 2. In

[3] SOBEK is named after the ancient Egyptian crocodile river god; https://www.deltares.nl/en/software-solutions/sobek-and-delft3d/

this scenario we assume that the maximum pumping capacity of 20 mm/day can be maintained throughout the event and is not affected by for instance water uptake restrictions in surrounding canal systems. Effects of evaporation, infiltration and storage in soil and surface water have been accounted for but have a minor impact on the daily change of the water level once the water storage reservoirs in soil and ditches are saturated. A period of 2 days with average water depths exceeding 90 mm, and up to 7 days with 10 mm or more result from the inability of the pumping systems to match the rainfall intensity. However, as a result of elevation differences water depth may be substantially larger at specific locations within the polder. The flooding pattern of the resulting water depth in the Haarlemmermeer is shown in Figure 3. Flooding of meadows and ditches overflowing their banks lead to many locations with a small layer of standing water, while at some locations water depths may reach 30 cm.

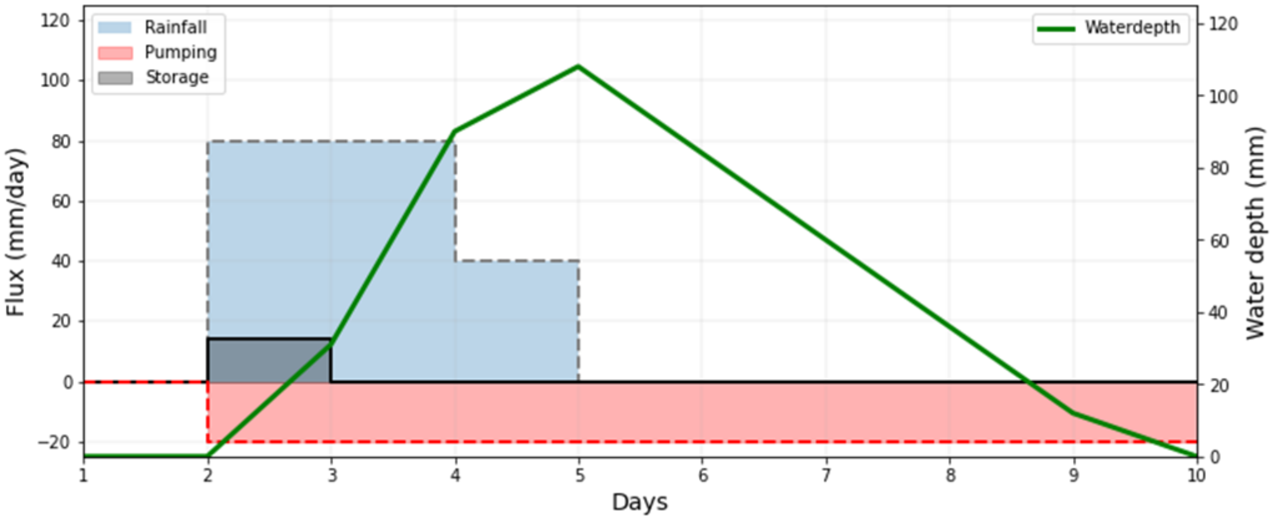

Figure 2: Time evolution of imposed rainfall (blue shading), changes in soil water storage (grey shading), and removal via pumping (red shading), all shown on left vertical axis. Resulting polder water depth (mm above ground level; green line) is shown on right vertical axis. Polder configuration parameters used are maximum water storage in soil and ditches (20 mm), infiltration to ground water (3 mm/day), maximum pumping capacity (20 mm/day), and evaporation (under dry conditions only, 3 mm/day).

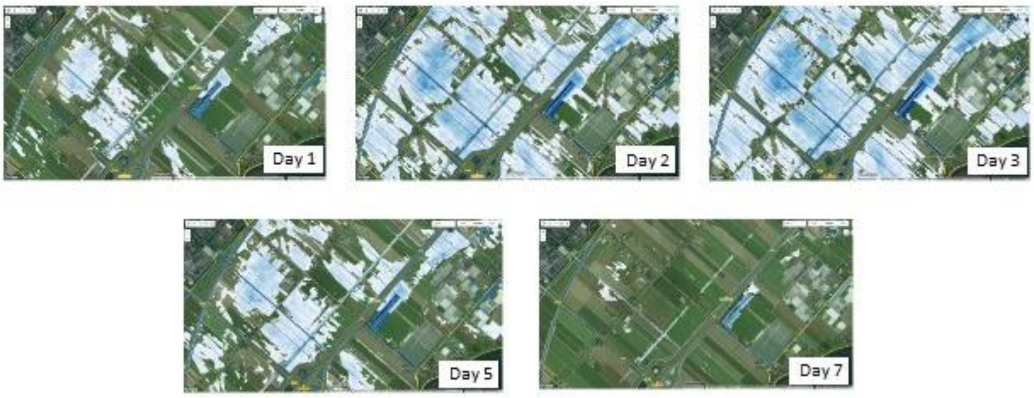

Figure 3: Time evolution of surface water in a spatial section of the “Haarlemmermeer” at day 1, day 2, day 3, day 5 and day 7 of the projected rainfall event (De Bruijn & Slager, 2021).

4.1.2 Socio-economic impacts

Expert sessions on impacts (De Bruijn and Slager, 2021) led to the assessment that, apart from economic damage to crops, the sustained pressure on water infrastructure including canals and their embankments will result in elevated risk of infrastructure failure. Functioning of main transportation infrastructure in the region becomes uncertain, and localized flooding in urban settlements may occur under these conditions. Most utility networks such as those for power and water supply and the sewer system are designed for these rain conditions and located slightly elevated, implying most will remain functioning. However, network disruptions cannot be excluded.

A detailed assessment carried out later for the province Zuid Holland (De Bruijn et al., 2022) confirms the expert session findings. Using a selection of damage models, most damage is shown in areas with greenhouse land-use, but variability across regions is large due to low water depth values. Most regional and some main transportation networks are obstructed, leading to cascading effects on health, infrastructure, environmental pollution and economic disruptions, affecting tens of thousands of households. Damage and disruptions increase with flood duration.

4.1.3 Emergency response

A detailed analysis of the potential implications of such an event in a polder system for the emergency response activities has not been made. However, activities that can be considered are early warnings to land owners in low-lying areas, precautionary measures to prevent breaches in embankments of drainage canals, traffic management, and discharge and pumping management prioritizing vulnerable areas and avoid flooding of tunnels.

4.2 Combined systems with free-flowing areas and polders: Noorderzijlvest

4.2.1 Physical response

Many water management regions in the Netherlands are configured as coupled polder/canal systems, where a network of canals allows regulation of the water levels in the polder areas. In the water management area “Noorderzijlvest” water flowing from the southern Drentse plateau is drained by gravity to waterways and canals, while the northern part consists of polders from which water is pumped into the same canals that also discharge the water from the southern free-draining area. The region drains to a coastal lake (Lauwersmeer) that is connected to the Waddensea by sluice gates that allow discharge at low tide periods.

Figure 4 illustrates the evolution of the water level at a representative location in the area (called Oude Riet) for the hypothetical situation of a July 2021 event displaced to the “Noorderzijlvest” region. The water level is projected on a historic event from January 2012, where a compounding sustained sea level surge and multiple episodes of heavy rainfall led to critical water levels in the system (Van Den Hurk et al., 2015; Santos et al., 2021). Emergency response services use multiple alert levels to trigger preparatory or emergency response actions, tailored to exceedance of local critical thresholds, such as the flooding of large areas in urban municipalities. The historic event reached the highest alert levels initiating a range of precautionary measures (including evacuation and emergency retention in the area). The July 2021 scenario would exceed this level during at least 5 days by up to 40 cm.

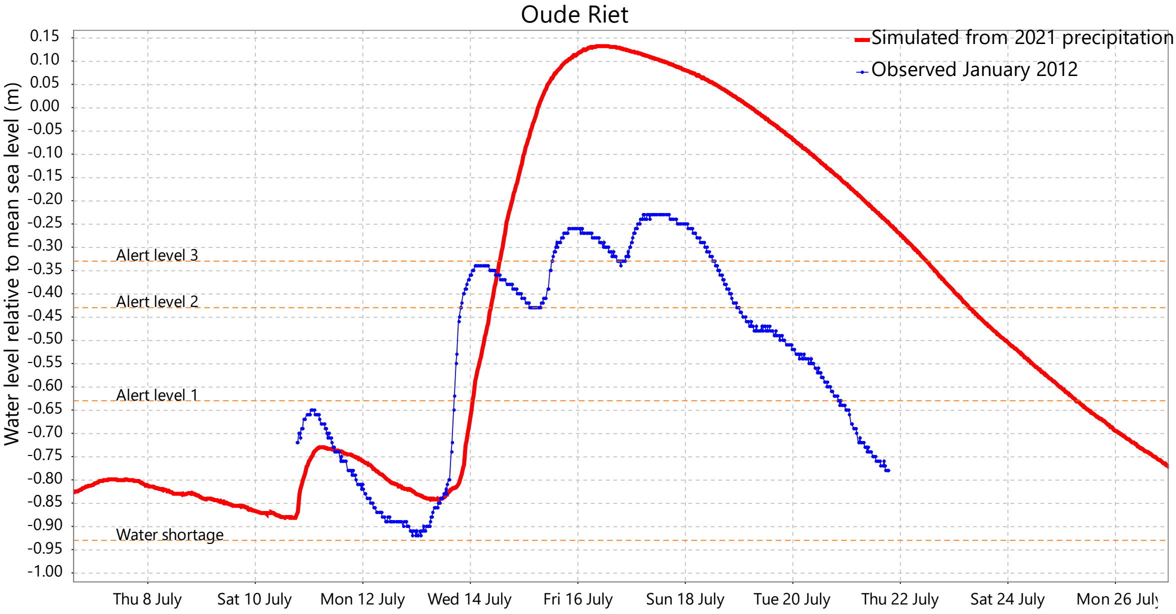

Figure 4: Simulated water level in a canal near “Oude Riet” in the Noorderzijlvest area during the 2012 heavy precipitation event (blue line), and the hypothetical evolution of this water level for the displaced July 2021 scenario (red line) projected on the historic time axis. Red lines indicate alert levels (De Bruijn & Slager, 2021).

4.2.2 Socio-economic impacts

The potential damage to the canal system and other infrastructure cannot be calculated with the available suite of modelling systems, as the projected events brings the regional water system far outside the model calibration range. The calculated water levels exceed bank levels, but in the existing model overflow is not simulated. This implies that substantial damage to infrastructure is likely, and infrastructure failure leading to dangerous flood conditions is to be expected.

4.3 Combined systems with free-flowing areas and polders: Brabantse Delta

4.3.1 Physical response

In the region of the “Brabantse Delta” the upper part of the area drains by gravity while the lower section consists of polders. In the upper part the excessive rainfall scenario causes high discharges in the brooks and regional rivers. In the lower, southern polders this event results in floods with small local water depths. The main discharge channel Mark-Dintel-Vliet (MDV) is connected to the large Volkerak-Zoommeer (VZM, a large retention area[4] connected to the network of estuaries in the province of Zeeland). For a regular water level of the VZM, the excessive rainfall in the area results in water levels in the VZM just reaching the design water levels (dimensioned at an occurrence probability of 1/100 year^{-1}). Under conditions of elevated VZM water levels such an extreme rainfall event may lead to exceedance of the design standards, with potential flooding of the surrounding areas. If the center of the rain event would have been situated above the south of the region the brooks and smaller rivers which drain by gravity would have discharged even more water, and floods near Breda would have been even more serious.

4.3.2 Socio-economic impacts

Since simulated water levels in local ditches, brooks and channels in the free-flowing areas exceed the calibration range of the operational water management models, only a rough assessment of impacts and damage is possible. This

[4] https://www.zwdelta.nl/projecten/waterberging-volkerak-zoommeer/

comprises crop losses, infrastructure damage and flooded real estate in the urban areas and amounts between several € 100 mln and € 1 bln.

4.3.3 Emergency response

Many streams and rivers originate in Belgium and flow into the Netherlands. For timely dissemination and an effective emergency management, cross-border information exchange with Belgian water management authorities is required. This can increase the lead-time for action, potentially reducing the impact of floods by for example the placement of sand bags.

4.4 Systems drained under gravity

4.4.1 Physical response

In free-draining regions water will flow in an uncontrolled way resulting in high peaks in the brooks and smaller rivers. Uncontrollable water flows can combine to high water levels and discharge in the channels and tributaries, leading to inconvenient and damaging floods at hydraulic bottlenecks like bridges, narrow gateways and syphons. These situations usually don't last very long and are strongly dependent on local conditions.

In the hackathon the "Overijsselse Vecht" was considered, a cross-border river originating in Germany, collecting water from a number of smaller rivers and discharge channels, and flowing into the IJsselmeer. This catchment is large and transboundary which complicates the management. A hydrodynamic model set up (including the WALRUS model (Brauer et al., 2014) and SOBEK) demonstrated that upon the extreme rainfall event water levels in the smaller tributaries exceed the safety design of the water system (1/300 year^{-1}) and making failure of secondary flood defenses likely. The water level in the upper part of the Dutch Vecht river exceeds embankment levels, resulting in local floods. The discharge near the city of Zwolle may exceed the design level for the primary flood defense infrastructure (550 m^3/s), implying that embankment breaches cannot be excluded.

As an example of the potential consequences of a dike breach Figure 5 shows the inundation map corresponding to design conditions and a breach in the Vecht embankment near Langenholte. The damage assessed by the Standard Dutch Damage module (De Bruijn et al., 2015) corresponding with this event is about 2 billion euros.

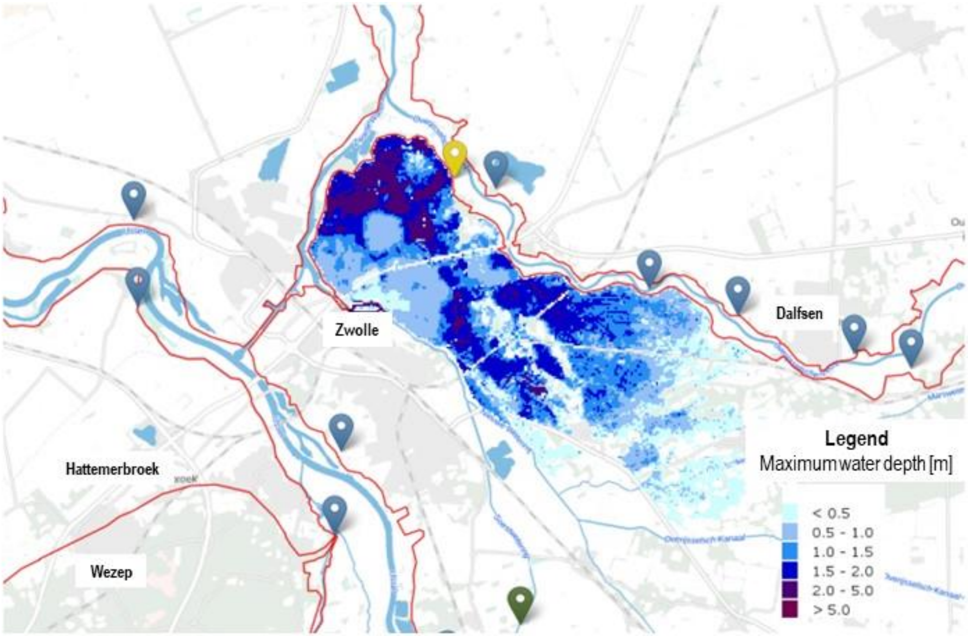

Figure 5: Simulated flood situation in the region of the "Overijsselse Vecht" following a dike breach near Langenholte assuming a 1/1250 year discharge volume on the river Vecht (shown just north of the flooded area). The city of Zwolle is located just south of the flooded area (source: Rijkswaterstaat 2022).

4.4.2 Socio-economic impacts

Despite the generally short duration of the uncontrolled water flows and high peaks these can lead to substantial damage to buildings and even to casualties (if embankments break). The emergency level warrants large scale evacuation and > € 2bln damage in the urban areas in case of breach in an embankment, as estimated from expert judgment (De Bruijn and Slager, 2021). This scenario implies an escalation from a "water damage" regime to a primary "water safety" issue.

4.4.3 Emergency response

The widespread extent of the affected region introduces a formidable coordination task of multiple national ánd international emergency response and civil protection units: at least 3 water authorities, the federal and a regional civil protection agency, a range of municipalities and a number of German response units are engaged in the immediate response and recovery process (see Figure 5). The work is complicated by limited (or incorrect) information and with protocols which were developed for either localized pluvial flood conditions or large scale floods due to dike breaches. The depicted situation requires simultaneous emergency response in 100's of settlements, including the possibility of the need for evacuation of 50,000 citizens from the city of Zwolle.

4.4.4 Summary for the regions

Table 2 summarizes the characteristics related to the response to a displaced July 2021 rainfall event for different types of regions in the Netherlands.

Table 2: Summary of findings of the scenarios with a displaced July 2021 rainfall event to different water management regions. The Dutch area affected in the historic event can be classified as "free-flowing system".

Region	Physical response / flood characteristics	Socio-economic impacts	Emergency response (examples)
Polder systems	Shallow inundation of long duration in a large area, depending on pumping capacity.	Potential disruption of road transport. Damage to agriculture and infrastructure. Long lasting societal disruption by water on the streets, impacted area can be substantial.	Early warning. Water managers response to ensure vulnerable areas are least affected. Prevent breaches in embankments. Traffic management.
Areas drained under gravity	Fast responding system. Local, short duration floods with possibly large water depths and flow velocities.	Substantial potential damage and even fatalities may occur. Area of impacts relatively small unless dike breaches occur.	Early warning. Uncontrolled floods may occur. Potential evacuation out of dangerous areas. Complex coordination and emergency management involving multiple organisations and regions. Many resources may be needed during multiple days.
Combined systems with polders and free-flowing areas	Characteristics of both. Uncontrolled discharge from the upper free-flowing part aggravates the situation in the controlled system where pumping is required.	Potentially substantial damage to infrastructure, crops and urban areas. Fatalities may occur.	Early warning. Complex coordination across multiple organisations and regions, including international agencies. Many resources may be needed during multiple days.

5 Discussion

Table 2 summarizes the main characteristics of the physical, societal and emergency response impacts of the displaced rainfall event for different types of regions. The set of alternative event storylines (also referred to as "disaster forensic" or "what-if" scenarios; Sillman et al, 2021), inspired on the historic rainfall event of July 2021, reveals several potential impacts in those regions. The results contain a number of (sometimes) unforeseen elements, such as the relatively long duration of floodings in a polder region, the interactions between regions that share common drainage canals or waterways with a limited capacity, and the escalation from a "damaging" event to a plain safety issue under uncontrolled flow regimes. By using a plausible and realistic hydrometeorological event as boundary condition, these implications are given additional credibility (e.g. (van de Ven et al., 2016; He et al., 2021)). A formal protocol for stress testing the regional water systems (Wilby, 2022) is not carried out, but nonetheless the results give an enriched impression of the potential impacts.

The justification to use a simply displaced historic rainfall event is not based on a probabilistic assessment of the exceedance probability of this event, but rather by demonstrating its plausibility given the contributing physical processes. Alternative methods using large model ensembles or perturbed weather scenarios can potentially lead to events with similar impacts. The return period of these events cannot be defined adequately given the large number of compounding governing features (size, location, transfer velocity, time evolution, seasonal timing) that jointly determine the overall impact profile. Rooting a stress-test in a historic event has the advantage that the physical plausibility of such an event and the associated societal impact has been demonstrated in the real world (Hazeleger et al., 2015; Dessai et al., 2018).

A rapid assessment via a short hackathon work-session was chosen to provide guidance on the extent to which currently available tools and data allow the quantification of the main impacts and the emergency response options during the depicted crisis situation. Additional processing, documentation and expert outreach was carried out after the hackathon, detailing the quantitative and qualitative results and the interpretation of the implications for the regional and national emergency management. A more rigorous impact assessment is possible by choosing upgraded modelling equipment, particularly instruments that are calibrated to cover the range of hydrodynamic conditions that are encountered in the tested scenario. More work can also be done on the detailed assessment of infrastructure damage, failure probability, indirect effects (such as sustained interruptions of economic activities), cascading impacts (induced by for instance failures in critical networks, emergency coordination or impact propagation over supply-demand chains) and recovery scenarios. However, the rapid assessment did serve the purpose to address the imminent question: what would happen when this event would have struck another region? The request for information on the geographical distribution of the exposure to impacts of extreme rainfall events is particularly large in the aftermath of disasters, when policy evaluations are being carried out and public awareness is high (Kousky, 2010). Policy makers and managers in different water management regions and neighboring countries showed large interest in the results of this study. Since it shows that also in other areas the impacts may be large (see e.g. De Bruijn et al., 2022), more detailed and improved analyses are planned in the near future.

Of particular interest during post-disaster evaluations is the degree to which emergency response, or more general, anticipatory risk management options could alleviate the impacts of an extreme (unprecedented) hydrometeorological event. Apart from the region-specific impact assessments, general lessons are drawn from this exercise. Also other regions in the Netherlands are not yet fully prepared for such large-scale rainfall events. They have the potential to result in significant damage and overwhelm the emergency response organizations. Concerning emergency response, the study demonstrated the need for:

- well-calibrated forecasting systems and an effective exchange of crucial observations across regions and countries;
- revisiting existing warning and emergency response protocols, including alignment of action between responsible administrative units;
- updating the inventory of critical infrastructure exposure and recovery options.

Concerning the anticipatory risk management, attention could be paid to:

- definition of "acceptable risk" and public perceptions of that risk, particularly for extreme events exceeding the (relatively low) protection and design standards in rural areas with limited urbanization. This may support the design of buildings or planning investments;
- increasing public awareness of response options for events that exceed the local protection or design standards or lead to substantial local damage due to standing water, including emergency response and financial risks of exposed property;

- evaluation of recovery scenarios, including the arrangement of insurance, coverage and payout of direct damage, and handling indirect damage. This will support recovery to reduce the impacts of events on people and society.

In many public and scientific discourses, the July 2021 rainfall event is related to climate change (Kreienkamp and et al., 2021). It happened just before the release of the Working Group 1 report of the IPCC 6th Assessment of (IPCC, 2021), which contributed to the general acceptance in the affected countries that society will continue to be exposed to extreme hazards. However, the summer of 2021 is surrounded by years in which hot and dry conditions prevailed in a large part of Europe. This challenges the preparation of water management actions aimed at increasing societal and ecological resilience against climate change: episodes with excessive rainfall and with severe water scarcity both occur, and ask for adequate adaptation. The July 2021 event, and the exploration of implications in other regions, does fuel the societal sentiment that a renewed attitude towards water management is required (Deltares et al., 2021).

In risk-based approaches a representation of all potential events, including their probabilities and consequences are considered. The use of event storylines as explored in the current study focuses on a single event drawn from the event distribution used in a probabilistic approach. This can complement risk-based decision support approaches in several ways: (a) it provides a means to reuse the existing record of extreme events at different locations, allowing a plausibility check of event scenarios contributing to flood risk, (b) it provides a tangible image of flood impacts and potential measures under different conditions to organizations and citizens, and (c) it supports the consideration of adapting designs of infrastructure and buildings improving flood-resistance, and serves to inform emergency response.

Regarding (a), the number of events that generate a large societal impact, like the Central European July 2021 flooding, is relatively small. It's estimated exceedance probability of 1/400 year^{-1} did exceed the protection standards of the smaller local rivers. The procedure to relocate the historic event does allow re-using the event and gain credible and useful information for risk-based location-specific impact assessments, provided the physical plausibility of the displaced event scenario can be demonstrated. Elaboration of such an event with water managers, crisis managers, local authorities and utility managers will support the potential impact assessment. Specific input from practitioners can generate evidence of unusual or interacting consequences which may be overlooked in rapid assessments of large ensembles of event scenarios. This evidence can benchmark data or model requirements and analysis techniques to perform comprehensive flood risk assessments involving many potential flood scenarios.

Referring to (b), generic climate datasets and scenarios generally fail to reproduce implications of complex and widely variable flood events. Multiple atmospheric, catchment and riverine mechanisms exist that can contribute to heavy tails in the statistical distributions of floods (Merz et al., 2022). In addition to climatic trends, changing patterns of land use, buildings, infrastructure and economic activities impose trends to societal flood risk tolerance. Placing historic events in different spatial contexts or climate conditions does enrich the available information without relying heavily on changing probabilistic characteristics of the events. Storylines can make these implications tangible and facilitate societal debates leading to the determination of acceptable risks, priority measures and preferred solution directions (De Bruijn et al., 2016; Shepherd, 2019).

Finally, regarding (c), extreme events like the Central European July 2021 flood receive considerable attention in media and public debates. Risk perceptions vary with types of weather events (Zhang, 2022), and with time passed since a major event. Although public risk awareness for climate change in Western Europe is not systematically affected by the degree to which individuals experience climate extremes (Gärtner and Schoen, 2021), the occurrence of extreme events does trigger societal debates that are contributing to support for environmental and civil protection policies (Lee et al., 2015). This introduces the risk of biased decision taking on risk-reduction measures, which risk management approaches aim to avoid. Risk management encompasses multiple stages and decision domains, with different use of risk information. The exploration of potential actions and interventions for low-likelihood/high impact events (De Bruijn et al., 2016) may contribute to the identification of priority locations. Stress-testing current or planned systems and measures (Wilby, 2022) may finetune these measures, or facilitate consultation of stakeholders. Evaluation of emergency response by civil protection agencies (Sillmann et al., 2021) may improve the response stages in the risk management. Decisions on investment in protection measures are usually based on cost-benefit ratios. Since storylines do not represent all potential events and usually lack a probability estimation, their use for assessing benefit/cost ratio considerations is limited. For this a full risk analysis is required.

6 Conclusion

An alternative manifestation of the July 2021 extreme rainfall event at different locations in the Netherlands reveals a strongly varying impact on the water system, potential damage and recovery potential. A rapid assessment was carried out by exposing routinely applied operational water management models to a displaced July 2021 rainfall event, and revealed a considerable damage, societal stress and potentially dangerous situations across the regions. Particularly the unprecedented spatial scale of the event would have triggered extreme challenges to the emergency response, requiring substantial coordination and alignment, a long period operating at the highest alertness level, and rapid decision taking under large uncertainty on the current and expected status of the area. In free-draining regions the water flow can become uncontrollable, leading to risk of damage to critical infrastructure, including flood defenses. In low-lying polder areas high water levels will remain present in the area and shallow floods will occur at many locations, which will result in large cumulative damage when rainfall intensity strongly exceeds pumping capacity.

The exercise has enriched the image of the consequences of a similar event occurring in other regions in the Netherlands, and contributed to the preparedness of the emergency response and climate adaptation by providing a tangible inventory of direct and long-term implications, risks and response options. It shows that also in other areas impacts can be serious, calling for in depth case studies of local impacts of large-scale rainfall events. The Dutch policy evaluation of the July 2021 event (Kernteam Beleidstafel Wateroverlast en Hoogwater, 2022) made a number of explicit recommendations, including application of “supra-regional” stress-tests to help the development of climate adaptation policies and preparation of emergency management. It is also recommended to explore standards for vital and vulnerable functions and infrastructure, and improve transboundary cooperation and knowledge base, which are all enabled by the storyline approach elaborated in this study.

Acknowledgements

Ties Rijcken provided valuable comments to earlier versions of this manuscript. This work is dedicated to the memory of our former colleague Cees van de Guchte.

Author contributions

All authors contributed substantially to conceptualisation and drafting the manuscript. Material preparation, data collection and the design of the figures was performed by KdB, KS, KJH, GR and MH. The first draft of the manuscript was written by BvdH and KdB. All authors read and approved the final manuscript.

References

Attema, J. J., Loriaux, J. M., and Lenderink, G. (2014). Extreme precipitation response to climate perturbations in an atmospheric mesoscale model. *Environ. Res. Lett.*, 14003. doi:10.1088/1748-9326/9/1/014003.

Blöschl, G., Hall, J., Viglione, A., Perdigão, R. A. P., Parajka, J., Merz, B., et al. (2019). Changing climate both increases and decreases European river floods. *Nature* 573, 108–111. doi:10.1038/s41586-019-1495-6.

Botzen, W. J. W., van den Bergh, J. C. J. M., and Bouwer, L. M. (2010). Climate change and increased risk for the insurance sector: A global perspective and an assessment for the Netherlands. *Nat. Hazards* 52, 577–598. doi:10.1007/s11069-009-9404-1.

Brauer, C. C., Teuling, A. J., F. Torfs, P. J. J., and Uijlenhoet, R. (2014). The Wageningen Lowland Runoff Simulator (WALRUS): A lumped rainfall-runoff model for catchments with shallow groundwater. *Geosci. Model Dev.* 7, 2313–2332. doi:10.5194/gmd-7-2313-2014.

Cornes, R. C., van der Schrier, G., van den Besselaar, E. J. M., and Jones, P. D. (2018). An Ensemble Version of the E-OBS Temperature and Precipitation Data Sets. *J. Geophys. Res. Atmos.* 123, 9391–9409. doi:10.1029/2017JD028200.

Cornwall, W. (2021). Europe's deadly floods leave scientists stunned despite improvements, flood forecasts sometimes failed to flag risks along smaller streams. *Science (80-.).* 373, 372–373. doi:10.1126/science.373.6553.372.

Coumou, D., Di Capua, G., Vavrus, S., Wang, L., and Wang, S. (2018). The influence of Arctic amplification on mid-latitude summer circulation. *Nat. Commun.* 9, 1–12. doi:10.1038/s41467-018-05256-8.

De Bruijn, K. M., Lips, N., Gersonius, B., and Middelkoop, H. (2016). The storyline approach: a new way to analyse and improve flood event management. *Nat. Hazards* 81, 99–121. doi:10.1007/s11069-015-2074-2.

De Bruijn, K. M., and Slager, K. (2021). Wat als de Waterbom elders in Nederland was gevallen? Available at: https://publications.deltares.nl/11206890_010_0006.pdf.

De Bruijn, K. M., Slager, K., and Juch, S. E. (2022). Case studie Zuid-Holland: "Analyse grootschalige wateroverlast." Delft, The Netherlands Available at: https://www.deltares.nl/nl/nieuws/wat-als-de-limburgbui-op-zuid-holland-valt/.

De Bruijn, K., Wagenaar, D., Slager, K., Bel, M. De, and Burzel, A. (2015). Updated and improved method for flood damage assessment: SSM2015 (version 2). Delft, The Netherlands Available at: https://www.helpdeskwater.nl/publish/pages/132789/1220043-003-hye-0012-r-updated_and_improved_method_for_flood_damage_assessment_ssm2015_version_2.pdf.

Deltares, BoschSlabbers, and SWECO (2021). Op Waterbasis - grenzen aan de maakbaarheid van ons water- en bodemsysteem. Available at: https://www.deltares.nl/app/uploads/2021/07/Op-Waterbasis.pdf.

Dessai, S., Bhave, A., Birch, C., Conway, D., Garcia-Carreras, L., Gosling, J. P., et al. (2018). Building narratives to characterise uncertainty in regional climate change through expert elicitation. *Environ. Res. Lett.* 13. doi:10.1088/1748-9326/aabcdd.

Engel, H. (2004). The flood event 2002 in the Elbe river basin causes of the flood, its course, statistical assessment and flood damages. *Houille Blanche*, 33–36. doi:10.1051/lhb:200406003.

Fekete, A., and Sandholz, S. (2021). Here Comes the Flood, but Not Failure? Lessons to Learn after the Heavy Rain and Pluvial Floods in Germany 2021. *Water* 13, 3016. doi:10.3390/w13213016.

Fischer, E. M., U. Beyerle, L. Bloin-Wibe, C. Gessner, V. Humphrey, F. Lehner, A. G. Pendergrass, S. Sippel, J. Zeder, and R. Knutti. 2023. "Storylines for Unprecedented Heatwaves Based on Ensemble Boosting." *Nature Communications* 14 (1): 4643. doi:10.1038/s41467-023-40112-4.

Gärtner, L., and Schoen, H. (2021). Experiencing climate change: revisiting the role of local weather in affecting climate change awareness and related policy preferences. *Clim. Change* 167, 1–20. doi:10.1007/s10584-021-03176-z.

Hazeleger, W., Van Den Hurk, B. J. J. M., Min, E., Van Oldenborgh, G. J., Petersen, A. C., Stainforth, D. A., et al. (2015). Tales of future weather. *Nat. Clim. Chang.* 5. doi:10.1038/nclimate2450.

He, J., Qiang, Y., Luo, H., Zhou, S., and Zhang, L. (2021). A stress test of urban system flooding upon extreme rainstorms in Hong Kong. *J. Hydrol.* 597, 125713. doi:10.1016/j.jhydrol.2020.125713.

Hoes, O., and Giesen, N. C. van de (2015). Polders (Course Lecture Notes). Delft, The Netherlands Available at: https://repository.tudelft.nl/islandora/object/uuid%3A869aad72-519c-4a75-8ca6-50a01c0f17a6?collection=research.

Insua-Costa, D., Senande-Rivera, M., Llasat, M. C., and Miguez-Macho, G. (2022). The central role of forests in the 2021 European floods. *Environ. Res. Lett.* 17, 064053. doi:10.1088/1748-9326/ac6f6b.

IPCC (2021). "Summary for Policymakers," in *Climate Change 2021: The Physical Science Basis. Contribution* *of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, eds. V. Masson-Delmotte, P. Zhai, A. Pirani, S. L. Connors, C. Péan, S. Berger, et al. (Cambridge University Press).

Kelder, T., Marjoribanks, T. I., Slater, L. J., Prudhomme, C., Wilby, R. L., Wagemann, J., et al. (2022). An open workflow to gain insights about low-likelihood high-impact weather events from initialized predictions. *Meteorol. Appl.* 29, e2065. doi:10.1002/met.2065.

Kernteam Beleidstafel Wateroverlast en Hoogwater (2022). Voorkomen kan niet, voorbereiden wel (Preventing is impossible, preparation is not). Den Haag, The Netherlands Available at: https://open.overheid.nl/repository/ronl-cddbc01e11cbe749215a9adde1803b2f346f50e0/1/pdf/bijlage-eindadvies-beleidstafel-wateroverlast-en-hoogwater.pdf.

Kirsch, B., Ament, F., and Hohenegger, C. (2021). Convective cold pools in long-term boundary layer mast observations. *Mon. Weather Rev.* 149, 811–820. doi:10.1175/MWR-D-20-0197.1.

Klijn, F., De Bruijn, K. M., Knoop, J., and Kwadijk, J. (2012). Assessment of the Netherlands' flood risk management policy under global change. *Ambio* 41, 180–192. doi:10.1007/s13280-011-0193-x.

Kok, M., Jongejan, R., Nieuwjaar, M., and Tánczos, I. (2017). *Fundamentals of flood protection*. ENW Available at: https://www.enwinfo.nl/publish/pages/183541/grondslagenen-lowresspread3-v_3.pdf.

Kousky, C. (2010). Learning from extreme events: Risk perceptions after the flood. *Land Econ.* 86, 395–422. doi:10.3368/le.86.3.395.

Kreibich, H., Van Loon, A. F., Schröter, K., Ward, P. J., Mazzoleni, M., Sairam, N., et al. (2022). The challenge of unprecedented floods and droughts in risk management. *Nature* 608, 80–86. doi:10.1038/s41586-022-04917-5.

Kreienkamp, F., Philip, S. Y., Tradowsky, J. S., Kew, S. F., Lorenz, P., Arrighi, J., et al. (2021). Rapid attribution of heavy rainfall events leading to the severe flooding in Western Europe during July 2021. Available at: https://www.worldweatherattribution.org/wp-content/uploads/Scientific-report-Western-Europe-floods-2021-attribution.pdf.

Krug, A., Aemisegger, F., Sprenger, M., and Ahrens, B. (2022). Moisture sources of heavy precipitation in Central Europe in synoptic situations with Vb-cyclones. *Clim. Dyn.* 1, 3. doi:10.1007/s00382-022-06256-7.

Kundzewicz, Z. W., Szamalek, K., and Kowalczak, P. (1999). The extreme flood in 1997 in Poland. *Hydrol. Sci. J.* 44, 855–870. doi:10.1080/02626669909492285.

Lee, T. M., Markowitz, E. M., Howe, P. D., Ko, C. Y., and Leiserowitz, A. A. (2015). Predictors of public climate change awareness and risk perception around the world. *Nat. Clim. Chang.* 5, 1014–1020. doi:10.1038/nclimate2728.

Lenderink, G., Meijgaard, E., and Selten, F. (2009). Intense coastal rainfall in the Netherlands in response to high sea surface temperatures: Analysis of the event of August 2006 from the perspective of a changing climate. *Clim. Dyn.* 32, 19–33. doi:10.1007/s00382-008-0366-x.

Lenderink, G., Van Den Hurk, B. J. J. M., Klein Tank, A. M. G., Van Oldenborgh, G. J., Van Meijgaard, E., De Vries, H., et al. (2014). Preparing local climate change scenarios for the Netherlands using resampling of climate model output. *Environ. Res. Lett.* 9. doi:10.1088/1748-9326/9/11/115008.

Ludwig, Patrick, Florian Ehmele, Mário J. Franca, Susanna Mohr, Alberto Caldas-Alvarez, James E. Daniell, Uwe Ehret, et al. 2023. "A Multi-Disciplinary Analysis of the Exceptional Flood Event of July 2021 in Central Europe - Part 2: Historical Context and Relation to Climate Change." *Natural Hazards and*

Earth System Sciences 23 (4): 1287–1311. doi10.5194/nhess-23-1287-2023.

Merz, B., Basso, S., Fischer, S., Lun, D., Blöschl, G., Merz, R., et al. (2022). Understanding Heavy Tails of Flood Peak Distributions. *Water Resour. Res.* 58, e2021WR030506. doi:10.1029/2021WR030506.

Merz, B., Elmer, F., Kunz, M., Mühr, B., Schröter, K., and Uhlemann-Elmer, S. (2014). The extreme flood in June 2013 in Germany. *Houille Blanche* 100, 5–10. doi:10.1051/lhb/2014001.

Oude Essink, G. H. P., van Baaren, E. S., and de Louw, P. G. B. (2010). Effects of climate change on coastal groundwater systems: A modeling study in the Netherlands. *Water Resour. Res.* 46, 2009WR008719. doi:10.1029/2009WR008719.

Ranasinghe, R., Ruane, A. C., Vautard, R., Arnell, N., Coppola, E., Cruz, F. A., et al. (2021). "Climate Change Information for Regional Impact and for Risk Assessment," in *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, eds. V. Masson-Delmotte, P. Zhai, A. Pirani, S. L. Connors, C. Péan, S. Berger, et al. (Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press), 1767–1926. doi:10.1017/9781009157896.014.

Rijkswaterstaat (2022). Basisinformatie Overstromingen (LIWO). Available at: https://basisinformatie-overstromingen.nl/#/scenarios/6/13061?center=52.63712,6.17950&zoom=11 [Accessed February 20, 2023].

Santos, V. M., Casas-Prat, M., Poschlod, B., Ragno, E., Van Den Hurk, B., Hao, Z., et al. (2021). Statistical modelling and climate variability of compound surge and precipitation events in a managed water system: A case study in the Netherlands. *Hydrol. Earth Syst. Sci.* 25, 3595–3615. doi:10.5194/hess-25-3595-2021.

Seneviratne, S. I., Zhang, X., Adnan, M., Badi, W., Dereczynski, C., Di Luca, A., et al. (2021). "Weather and Climate Extreme Events in a Changing Climate," in *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, eds. V. Masson-Delmotte, P. Zhai, A. Pirani, S. L. Connors, C. Péan, S. Berger, et al. (Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press), 1513–1766. doi:10.1017/9781009157896.013.

Shepherd, T. G. (2019). Storyline approach to the construction of regional climate change information. *Proc. R. Soc. A Math. Phys. Eng. Sci.* 475. doi:10.1098/rspa.2019.0013.

Shepherd, T. G., Boyd, E., Calel, R. A., Chapman, S. C., Dessai, S., Dima-West, I. M., et al. (2018). Storylines: an alternative approach to representing uncertainty in physical aspects of climate change. *Clim. Change* 151, 555–571. doi:10.1007/s10584-018-2317-9.

Sillmann, J., Shepherd, T. G., van den Hurk, B., Hazeleger, W., Martius, O., Slingo, J., et al. (2021). Event-Based Storylines to Address Climate Risk. *Earth's Futur.* 9, e2020EF001783. doi:10.1029/2020EF001783.

Task Force Fact-finding Hoogwater (2021). Hoogwater 2021 Feiten en Duiding. Available at: https://www.enwinfo.nl/publish/pages/183541/211102_enw_hoogwater_2021-dv-def.pdf.

Tradowsky, Jordis S., Sjoukje Y. Philip, Frank Kreienkamp, Sarah F. Kew, Philip Lorenz, Julie Arrighi, Thomas Bettmann, et al. 2023. "Attribution of the Heavy Rainfall Events Leading to Severe Flooding in Western Europe during July 2021." *Climatic Change* 176 (7): 90. doi:10.1007/s10584-023-03502-7.

van de Ven, F., Hoogvliet, M., and Goossen, W. J. (2016). A National Guideline for Climate Adaptation Planning the Climate Stress Test for Urban Areas. in *Proceedings of the Singapore International Water Week 2016* Available at: https://repository.tudelft.nl/islandora/object/uuid%3Afb5233a0-50fd-472b-

8b8a-c38b334745a0.

Van Den Hurk, B., Van Meijgaard, E., De Valk, P., Van Heeringen, K.-J., and Gooijer, J. (2015). Analysis of a compounding surge and precipitation event in the Netherlands. *Environ. Res. Lett.* 10. doi:10.1088/1748-9326/10/3/035001.

Van Garderen, L., Feser, F., and Shepherd, T. G. (2021). A methodology for attributing the role of climate change in extreme events: A global spectrally nudged storyline. *Nat. Hazards Earth Syst. Sci.* 21, 171–186. doi:10.5194/nhess-21-171-2021.

Verkade, J., Bouaziz, L., and van Heeringen, K.-J., Weerts, A. . (2022). QPF and QPE performance during the July 2021 flood event. in *EMS Annual Meeting 2022* (Bonn, Germany). Available at: https://doi.org/10.5194/ems2022-44.

Vogel, M. M., Orth, R., Cheruy, F., Hagemann, S., Lorenz, R., van den Hurk, B. J. J. M., et al. (2017). Regional amplification of projected changes in extreme temperatures strongly controlled by soil moisture-temperature feedbacks. *Geophys. Res. Lett.* 44. doi:10.1002/2016GL071235.

Wikipedia (2022). 2021 European floods. Available at: https://en.wikipedia.org/wiki/2021_European_floods [Accessed August 4, 2022].

Wilby, R. L. (2022). “Stress-Testing Adaptation Options,” in *Springer Climate* (Springer Science and Business Media B.V.), 41–49. doi:10.1007/978-3-030-86211-4_6.

Zhang, F. (2022). Not all extreme weather events are equal: Impacts on risk perception and adaptation in public transit agencies. *Clim. Change* 171, 1–21. doi:10.1007/s10584-022-03323-0.