

Dikes, diseases, and disasters: a risk-based comparison of floods and pandemics

Cross-hazard lessons for managing low-probability, high-impact disasters

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by

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Preface

Dear reader,

Welcome to my master's thesis - Dikes, diseases, and disasters: a risk-based comparison of floods and pandemics.

Looking back on this project, I feel excited and grateful. I have greatly enjoyed working on a topic I care about; one that brings together my interests in engineering, systems thinking, health risks, and grand societal challenges. Of course there were challenges along the way, and - just like floods and pandemics - they come and go in waves and there are many lessons to learn. I reflect on a period of growth, dedication, and excitement. During my thesis, I learned as much about managing disaster risks as I learned about managing my own risks. For this I am really grateful.

I would like to thank the many people who supported me throughout this process - it really made all the difference.

To my supervisors: Pieter, thank you for your calm, thoughtful guidance and consistent support. Our weekly meetings were both grounding and insightful and I learned a lot from your risk-based perspective. Saba, thank you for your encouragement and for setting an example in how to lead with clarity and care. More than once, you complimented my resilience - one of my favorite words - and that meant a lot. Dorien, thank you for your daily support and enthusiasm. I appreciated your interest in the topic, your valuable and encouraging feedback - on both content and process - and the way we discussed and explored some of the ideas together. Bas, thank you for inviting me to write at HKV and for sharing your ideas on these topics - many of which are reflected in the red thread of this thesis.

I am also grateful to all the experts I spoke with during the thesis process - your input was incredibly helpful and helped shape both the direction and depth of the research. Many thanks as well to HKV for the warm welcome and positive working atmosphere, and to the PDPC, especially Thom and Schuyler, for their interest in my work and for inviting me to take part in meetings and discussions that added valuable perspective.

To my friends, roommates, and family: thank you for your support, positivity, and for always being there - I feel incredibly happy to have you. And Jip, thank you for getting me through the laatste loodjes - these final days in Groningen meant a lot to me.

I hope you enjoy reading this thesis, thank you.

*Nicoline Schuiling
Delft, May 2025*

Summary

Key insights

- Floods and pandemics share a common risk type: low-probability, high-impact, threat-driven disasters - posing major challenges for preparedness and governance.
- Their risk mechanisms differ: floods stem from physical and meteorological causes; pandemics from complex (and global) biological, ecological, and socio-behavioral factors.
- This greater causal complexity in pandemics results in deeper uncertainty, making prevention, prediction and early action more difficult compared to floods.
- Prevention is the most effective risk reduction strategy for both, but is less reliable for pandemics, meaning residual risk remains higher even with high effort.
- Pandemic outcomes can be significantly shaped during the response phase; for floods, this phase has limited effect on the course of the event.
- Intervention-enabling processes - such as early warning, monitoring, crisis communication, and decision-making under uncertainty - are essential across both hazards, demonstrating value for all-hazard shared efforts.
- Cross-hazard learning is valuable: flood management offers lessons on structured threshold- and scenario-based planning and preparedness, while pandemic response underscores the need for adaptability, real-time data, and societal resilience.
- Residual risk is inevitable. Neither floods nor pandemics can be fully prevented or contained. Defining acceptable risk levels - common for floods but lacking in pandemics - is key to sound governance.
- A structured risk-based analysis framework can be used to compare fundamentally different disasters and identify insights for strengthening disaster risk management.

Context and relevance

Disasters pose serious challenges to societies worldwide. In recent decades, both their frequency and severity have increased, driven by factors such as climate change, urbanization, and global interconnectedness. In response, disaster risk management has become a core priority for national governments and global institutions such as the United Nations and the World Health Organization.

Disaster risk is commonly defined by the combination of an event's probability and its potential impact. As such, it describes the expected impact of disasters over time, which - following from its definition - can be managed through probability- or impact-reducing interventions.

Floods and pandemics stand out as two of the most common and significant threats for countries globally. While the origins of these events are different - one stemming from the overflow of water, the other from the outbreak of a pandemic pathogen - their risk type is the same: both are low-probability, high-impact disasters. This is a challenge for decision-makers, as there is only limited experience in dealing with such events, but - if they occur - the consequences can be overwhelmingly large.

In addition to this low-probability, high-impact character, the risk management of both floods and pandemics has a threat-driven nature. The occurrence of these events can be forecasted, which allows for emergency action to be taken upon threat detection. This allows risk-reducing interventions for floods and pandemics to be implemented across four common phases in time: a normal phase, threat phase, disaster phase, and post-disaster phase.

In this thesis, these phases are used to structure the comparison and analysis of floods and pandemics. By analyzing how risks evolve and are managed across these phases, it becomes possible to compare the dynamics of different disaster types and identify both hazard-specific and translatable strategies. As such, this research provides an opportunity for cross-domain learning between two low-probability, high-impact, threat-driven disasters.

Gap and research question

Despite extensive literature on disaster risk and management, most studies focus on risk concepts in general or single hazards in isolation. Comparisons across hazard types remain underdeveloped, which also applies to floods and pandemics. While both are classified as low-probability, high-impact disasters, little is known about how their risk mechanisms compare, how their management evolves over time, and whether insights from one domain can meaningfully inform the other.

This also means that detailed methodologies for comparing disaster risk and risk management across disaster domains are lacking. There is no predefined method to structurally analyze and compare causes, consequences, and intervention strategies for fundamentally different hazards. As a result, there is a gap in evidence for cross-hazard learning and a lack of clarity around which risk management actions are most effective in different contexts.

This study addresses these gaps by investigating how floods and pandemics - despite their differing natures - can be compared as threat-driven, low-probability, high-impact risks. The overarching research question guiding this thesis is:

- **RQ.** What can be learned from a structured risk-based comparison of floods and pandemics (low-probability, high-impact disasters)?

Throughout the research, the concept of risk as probability times impact is central. The probability and impact dimensions are separated by the central events of interest: flood or pandemic occurrence. Essentially, the central event is a tipping point at which the disaster becomes unavoidable and triggers systemic impacts. For floods, this is defined as the point where flooding becomes uncontrollable (e.g. upon a dike breach). For pandemics, it is the moment when the spread of a pandemic pathogen within a country can no longer be prevented, and it becomes endemic. Understanding risk processes before, during, and after these central events allows for structured comparison across all phases of disaster management.

Methodological framework

To answer the research question, this study adopts a structured, comparative methodology centered on risk and risk management. The focus is on the Netherlands, analyzing the mechanisms that underlie flood and pandemic risk, and how this is understood, managed, and governed at a national level. The study applies a semi-qualitative, multi-method approach that integrates data from literature reviews, expert consultations, and case analyses.

Three sub-question - corresponding to three analytical perspectives - structure the research:

- **SQ1.** How do the causes, consequences, and interventions for floods and pandemics compare?
- **SQ2.** How do the timelines of floods and pandemics compare?
- **SQ3.** How do the effects of risk reduction strategies for floods and pandemics compare?

The research begins with a comparative system-level analysis of flood and pandemic risk using bowtie analysis to map the causal and consequential mechanisms, as well as the associated interventions aimed at reducing probability and/or impact. This is followed by a comparison of two real-world cases: the 2021 Limburg floods and the Covid-19 pandemic in the Netherlands. These cases are used to explore the temporal dynamics of risk and validate observations from the earlier systems analysis.

Finally, the study evaluates the effectiveness of selected risk reduction strategies by comparing their modeled effects on health and economic outcomes. This provides insight into the relative value of probability- and impact-reducing interventions at different phases in time for each hazard type.

By combining these three perspectives, the study aims to uncover both fundamental differences and shared characteristics in the risk governance of floods and pandemics, ultimately identifying potential opportunities for cross-hazard learning.

Findings for SQ1: comparing risk systems

The first part of this study compared the risk systems of floods and pandemics using bowtie analysis. This revealed four conceptual elements that shape disaster risk and its management: (1) risk mechanisms, which drive the probability and impact of disaster events; (2) intervention mechanisms, aimed at

reducing either probability or impact; (3) intervention-enabling processes, such as monitoring or communication, which facilitate the effectiveness of interventions; and (4) risk dynamics, capturing how risks evolve over time under uncertainty and complexity. This conceptual framework is visualized in Figure 1 and applied throughout this study.

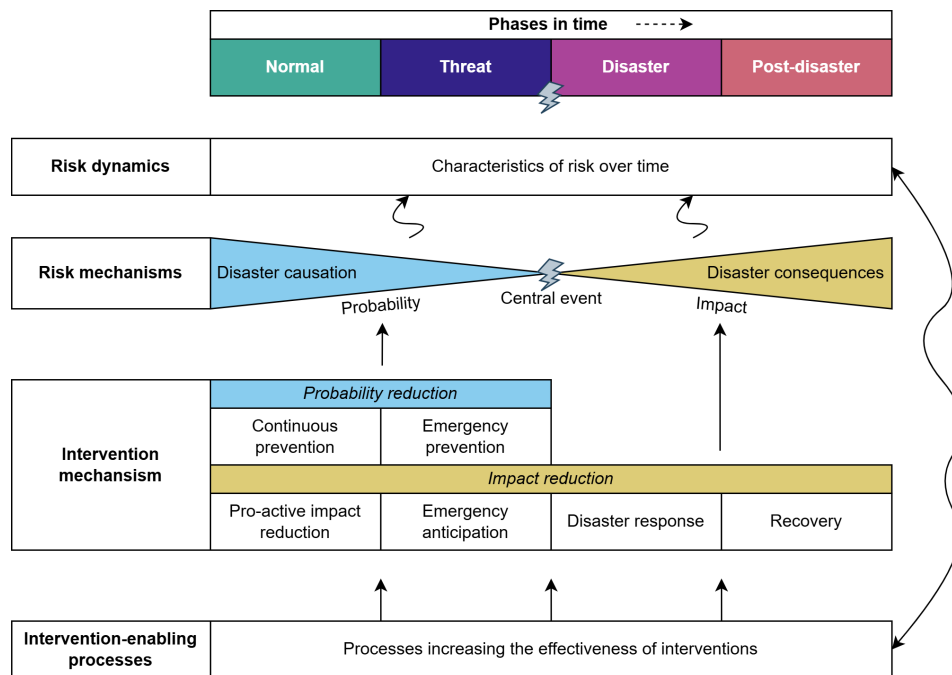


Figure 1: Conceptual framework inferred from the systems analysis. Risk (management) systems involve risk and intervention mechanisms, risk dynamics, and intervention-enabling processes.

The bowtie analysis provides insights into risk mechanisms, the associated intervention mechanisms, as well as intervention-enabling processes. The results from this analysis reveal that floods and pandemics differ in their causal mechanisms: floods are predominantly driven by physical and meteorological factors, whereas pandemics emerge from complex combinations of biological, ecological, and socio-behavioral drivers. As a result, flood prevention typically relies on technical measures (e.g. dikes), while pandemic prevention requires socio-behavioral and health system interventions, often on a global scale. Despite these differences, the consequences of both disaster types span the same types: health, economic, societal, cultural, and environmental. While the direct impacts differ (e.g. physical water damage vs. infections), the indirect effects - further away from the hazard - tend to be more similar.

Importantly, floods and pandemics also share several key intervention-enabling processes, such as monitoring, early warning, risk communication, and emergency training. However, because of their low frequency, decision-makers in both domains often lack real-world experience. This makes it crucial to strengthen institutional knowledge, scenario planning, and cross-domain learning to increase system readiness - each of which could also be seen as an intervention-enabling process.

Findings for SQ2: comparing case timelines

The second part of the study analyzed the temporal dynamics of two real-world cases: the Limburg floods of 2021 and the COVID-19 pandemic. These timelines confirmed the presence of causal and consequential mechanisms identified in SQ1 and highlighted how floods and pandemics evolve differently over time. Within the conceptual framework (Figure 1), this concerns the element of risk dynamics.

Floods are typically sudden-onset, short-duration events. The threat phase is brief and defined by relatively clear, measurable parameters (e.g. rainfall, river levels), allowing for threshold-based decision making. In contrast, pandemics are slow-onset, long-duration disasters. Their threat phase is marked by deeper uncertainty - not only about whether a pandemic will occur, but also about how it will behave. This uncertainty is driven by a higher complexity of the mechanisms underlying pandemic risk, which consist of a combination of (global, transboundary) biological, ecological, and behavioral factors - as

identified in SQ1. This unpredictability challenges timely decision-making, often resulting in delayed or inadequate early response. The complexity also seems to hinder the use of scenario planning and threshold-based decision-making in pandemics as compared to floods.

The disaster phase of floods is relatively short, with limited response options beyond search and rescue operations. In pandemics, the disaster phase can span months or years and includes highly consequential decisions about containment, vaccination campaigns, and societal restrictions. Thus, the response phase plays a much greater role in shaping pandemic outcomes. In both cases, the recovery phase is prolonged and complex, but differs in focus: physical and infrastructural restoration in floods versus societal and economic recovery in pandemics.

Findings for SQ3: comparing risk reduction strategies

The third part of the analysis used a computational risk reduction model to assess the effects of interventions on both health and economic outcomes. Results - shown in Figures 2 and 3 - demonstrate that probability-reducing interventions are the most effective for both floods and pandemics. For floods, structural measures such as dikes can reduce risk by multiple orders of magnitude. For pandemics, continuous global prevention efforts (including surveillance and international coordination) reduce risk by a factor of around four, but residual risk remains comparatively high due to the complex, transboundary nature of pandemic mechanisms.

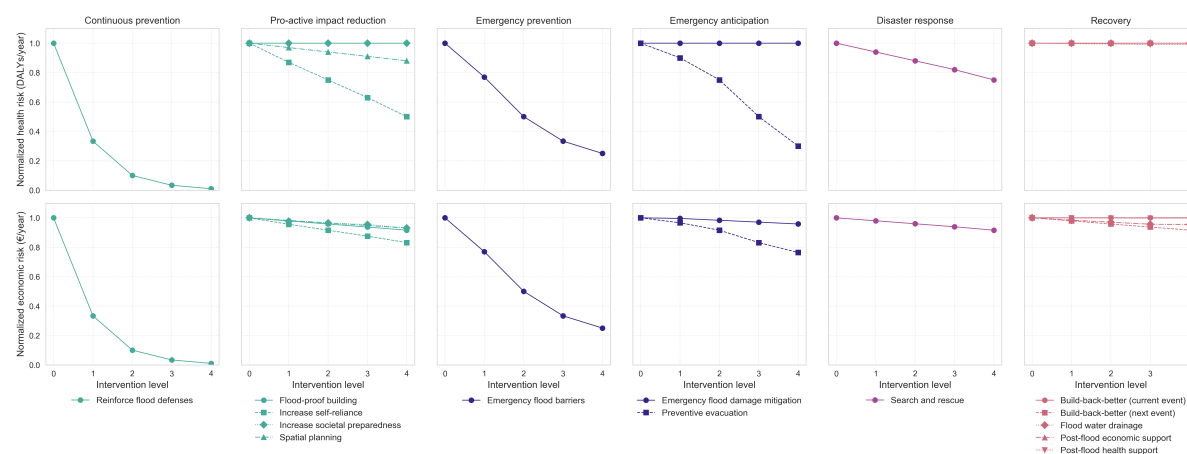


Figure 2: Flood risk (y-axis) upon the implementation of individual interventions (lines) at different levels (x-axis).

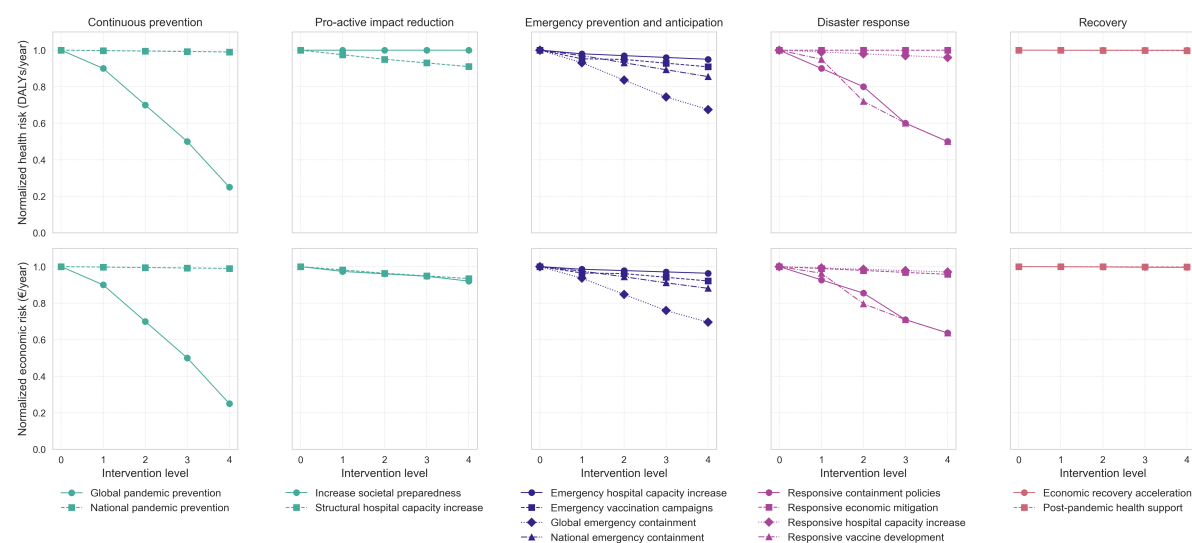


Figure 3: Pandemic risk (y-axis) upon the implementation of individual interventions (lines) at different levels (x-axis).

Emergency prevention and anticipatory measures during the threat phase offer additional benefits, especially for floods, where probability-reduction and impact-reduction measures can be clearly distinguished and sequenced. For pandemics, this distinction is blurrier - most interventions serve both functions and are heavily influenced by public behavior, timing, and adaptive decision-making under uncertainty.

Once the central event occurs, flood response options are limited. In contrast, pandemic responses can dramatically influence the trajectory of the disaster through policies such as containment, social distancing, and vaccination. While effective, these measures can also be costly and disruptive, underlining the importance of adaptive governance and timely decision-making. Finally, recovery interventions - though essential - were found to offer only limited risk reduction, as most of the damage occurs earlier in the timeline.

Overall, the findings suggest that while prevention is crucial for both hazard types, the design and timing of interventions must be tailored to the unique dynamics of each disaster. At the same time, shared intervention-enabling processes - such as early warning, communication, and scenario planning - present clear opportunities for cross-hazard learning and integrated preparedness.

Discussion

This study demonstrates the value of a structured, risk-based comparison between floods and pandemics - two disasters that, despite their fundamentally different origins, share a common risk profile as low-probability, high-impact, threat-driven events. While they differ substantially in their complexity, predictability, and response dynamics, both disasters challenge the capacity of societies to act effectively under pressure, uncertainty, and limited experience.

A key conclusion is that pandemics are characterized by greater causal complexity and deeper uncertainty than floods. This complicates early detection and delays decision-making, even though swift intervention is often critical. In contrast, floods are more predictable, often allowing for threshold-based decisions and scenario planning. While managing pandemics demands adaptive governance, structured approaches from flood management - such as predefined decision thresholds and scenario anticipation - may offer valuable, transferable practices to improve pandemic preparedness.

Both disaster types highlight a fundamental limitation of risk management: no system can eliminate all risk. Full prevention is not feasible - especially for pandemics with transboundary and evolving characteristics - and mitigation has practical and financial limits. As such, residual risk is inevitable. A key governance challenge is determining what level of risk is acceptable and under what conditions. In flood risk management, such thresholds are often formalized in planning standards, providing a basis for public communication, investment, and accountability. In contrast, pandemic governance often lacks such explicit articulation of acceptable risk levels, which can hamper decision-making and erode trust. Making acceptable risk an explicit part of the policy conversation is essential for transparent and responsible disaster governance.

Costs and trade-offs - while not quantified in this study - play a crucial role in determining the feasibility and appropriateness of different interventions. Particularly in pandemic response, many impactful measures come with significant societal and economic side effects. Understanding these trade-offs is essential for informed, balanced policy-making.

Beyond hazard-specific insights, this research underscores the importance of intervention-enabling processes such as monitoring, detection, early warning systems, crisis communication, and decision-making under uncertainty. These processes are broadly applicable across hazard types and represent key opportunities for all-hazard preparedness.

Finally, while a strict risk framework - based on quantifiable probability and impact - fits more naturally with flood management, it remains a valuable conceptual tool for pandemics as well. Even where precise risk quantification is tricky, the logic of reducing probability and impact remains a powerful way to structure preparedness and response thinking. In this sense, the risk perspective serves not only as a technical model but also as a strategic lens for approaching disaster governance in complex, uncertain contexts.

Conclusion

This thesis highlights how floods and pandemics, despite their different origins, can be meaningfully compared through a shared risk-based lens. By analyzing their mechanisms, timelines, and interventions, the study identifies both fundamental differences and actionable overlaps. Floods tend to be more predictable and technically manageable; pandemics involve higher uncertainty and demand adaptive governance. Yet, both can benefit from similar intervention-enabling processes, such as strengthened early warning, scenario planning, and institutional preparedness.

Cross-hazard learning is valuable: flood management contributes structured decision-making and planning practices, while pandemic experience emphasizes adaptability, real-time data use, and societal resilience - lessons that can strengthen responses to both hazard types. Finally, recognizing that residual risk is inevitable, this thesis argues for clearer definitions of acceptable risk - an established principle in flood governance but often missing in pandemic contexts - as a critical component of transparent and effective disaster risk management.

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Part I

Research context and framework

Introduction

1.1. Research relevance

Societies worldwide are faced with an ever-present risk of disasters. These disasters arise from both natural events - such as floods, earthquakes, wildfires, and pandemics - as well as from human-caused events like nuclear incidents, cyber-attacks, and armed conflicts. Over recent decades, the frequency and severity of these events have significantly increased, driven by factors such as climate change, rapid urbanization, and geopolitical conflicts (WHO, 2019). According to the World Disasters Report 2022 from the International Federation of Red Cross and Red Crescent Societies (IFRC), the number of disasters triggered by natural hazards has been steadily increasing since the 1970s (IFRC, 2022). These developments place an unprecedented burden on countries worldwide, disrupting economies, straining health systems, and endangering human lives.

Recognizing the pressing risks of disasters, governments and international organizations have emphasized the need for enhanced disaster risk management. Disaster risk management is about reducing the risk of disasters. At its core, *disaster risk* is about the combined effect of how likely a disastrous event is to occur (probability) and how severe its consequences might be (impact). It describes the expected impact of disasters over time, which - following from its definition - can be managed through probability- or impact-reducing interventions. Global intentions for improved disaster management are reflected in frameworks such as the Sustainable Development Goals (SDGs) (United Nations, 2015b), the Sendai Framework for Disaster Risk Reduction (UNDRR, 2015), the International Health Regulations (IHR) (WHO, 2024b), and the Paris Agreement (United Nations, 2015a). These frameworks call for investments in resilient infrastructure, early warning systems, and emergency planning, all aimed at building societal systems capable of withstanding, adapting to, and recovering from complex hazards (Harris & Charnley, 2022).

Among the various disaster risks, *floods* (CRED, 2024) and *pandemics* (WHO, 2024a) stand out as two of the most common and significant threats for countries globally. This is consistently reflected in national risk assessments, including those conducted in the Netherlands (ANV, 2022a). Floods cause immediate, large-scale physical damage, threatening lives, infrastructure, and essential services. Pandemics, on the other hand, place prolonged strain on health systems, disrupt societal functioning, and lead to widespread morbidity and mortality. While the nature of these events is different - one stemming from the overflow of water, the other from the outbreak of a pandemic pathogen - their risks share similar characteristics. Most importantly, (severe) floods and pandemics are both classified as *low-probability, high-impact* events (ANV, 2022a). This means that there is a substantial risk of such events, but only minimal experience in dealing with them.

The low-probability, high-impact character of floods and pandemics poses a significant challenge for decision-makers in these domains. Considering a limited amount of resources available, difficult trade-offs must be made between different risk reduction strategies. For example, should the focus be on the prevention of disasters (probability-reduction) or on the effective management of their consequences once they occur (impact-reduction)? Such decisions are complicated by high degrees of uncertainty:

it is rarely clear when, where, or how a disaster might strike, what its impacts will be, and what this means for the reliability of interventions. Additionally, interventions must not only be evaluated for their ability to reduce risk but also for their cost-effectiveness, feasibility, and practicality. Over time, different disaster domains - such as those of floods and pandemics - have developed their own risk management approaches to deal with such decisions.

The current study explores the risk management of low-probability, high-impact disasters, through investigating and comparing floods and pandemics. Besides sharing a low-probability, high-impact character, the risk management of both floods and pandemics has a threat-driven nature (B. Kolen, 2013). Since the occurrence of these events can be forecasted, response actions can be taken in anticipation. This can be contrasted with event-driven responses to hazards that occur unexpectedly. Sharing this threat-driven nature, floods and pandemics have similar phases in their risk management: a normal (base) phase, threat phase, disaster phase, and post-disaster phase.

During the normal and threat phases, both the probability and impact of future disasters can be reduced. Once the disaster occurs, the focus shifts to reducing its impact during the disaster and post-disaster phases. By analyzing these phases for both floods and pandemics, valuable insights can be gained into risk management decisions and intervention impacts over time. This analysis also provides an opportunity to reflect on risk thinking and decision-making within the flood and pandemic domains, as well as for low-probability, high-impact disasters more generally. Given the limited "real-life" experience with such events in either domain, there are significant opportunities for cross-learning. Ultimately, comparing these disasters can support better-informed decisions about how to invest in risk reduction.

The comparison of floods and pandemics in this study is also relevant within the context of the all-hazard approach to disaster risk management. This approach advocates for broad-spectrum preparedness rather than isolated, hazard-specific strategies (WHO, 2019). By recognizing that many hazards, despite their differences, can have similar impacts on societies and public health, the all-hazard approach enhances the efficiency and cost-effectiveness of risk management efforts. By comparing floods and pandemics, this study highlights both their differences and similarities, providing valuable insights into the potential for generic interventions.

Ultimately, this study contributes to the understanding of how societies can enhance their risk management strategies for low-probability, high-impact disasters, specifically through the lens of floods and pandemics. By identifying both the differences and similarities between these events, the findings are expected to offer valuable insights that can improve disaster risk management across these domains.

1.2. Research gap

The nature of flood and pandemic risks challenges their risk management. Generally, strong disaster risk strategies require a comprehensive understanding of the risks faced and the means of addressing them. This is emphasized in the first priority of the Sendai Framework: "Policies and practices for disaster risk management should be based on an understanding of disaster risk" (UNDRR, 2015).

From an exploration of academic and gray literature on disaster risk and risk management, it becomes clear that a substantial body of research has been developed over the years to support this understanding (Wolbers et al., 2021). However, much of this work is focused on isolated disasters - such as hurricanes, earthquakes, or floods - analyzing each hazard separately using distinct methodologies within different institutional frameworks (Mahmoud et al., 2023; Wolbers et al., 2021). As a result, there is limited cross-hazard understanding, especially between public health threats like pandemics and natural hazards like floods.

First, *there is a lack in insights into the overlapping and distinct risk management challenges posed by floods versus pandemics*. As acknowledged by approaches like all-hazard preparedness (WHO, 2022b), many disasters share common preparedness needs, such as early warning and emergency logistics. However, each hazard also presents distinct challenges. Almost no studies were found which explicitly compare hazards to characterize their similarities and differences. A structured comparison can highlight where generic efforts are useful, versus where hazard-specific strategies are necessary.

Second, *insufficient attention has been given to how lessons from one disaster domain can inform another*. There is considerable variation between risk management strategies across hazards. This

includes differences in maturation of risk management frameworks across hazard domains, as well as differences in prioritization or implementation of risk reduction strategies. For example, preventive measures may be prioritized for one hazard, while response measures are prioritized for another. Comparative analysis can help identify such differences, providing insights into the relative strengths and weaknesses of each domain. This could then be leveraged to translate insights from one hazard to the other. This can also contribute to a general understanding of how disaster risk management can be compared and adapted between hazard contexts, offering valuable contributions for enhancing disaster risk management more broadly.

Third, *there is a lack of methodological approaches to compare risk management actions both within and between hazard domains, and therefore no clear consensus on which actions to prioritize*. Different categories of interventions serve different purposes, such as probability- or impact-reduction, at different phases in time. While much research is dedicated to studying the impact of individual interventions, it is not straightforward to systematically compare interventions across phases or between disaster domains. This means there is no detailed predefined method to structurally analyze and compare causes, consequences, and intervention strategies for fundamentally different hazards. As a result, there is a gap in evidence for cross-hazard learning and a lack of clarity around which risk management actions are most effective in different contexts.

Thus, despite a large body of research studying disasters in isolation, *a comparison between different hazards and their risk management is missing*. This leaves valuable opportunities to learn from hazard parallels and differences unused, which will be addressed in this study of floods and pandemics.

1.3. Research objective

The aim of this study is to explore how two fundamentally different disasters - floods and pandemics - can be meaningfully compared as low-probability, high-impact, threat-driven events, and what insights such a comparison can provide for disaster risk governance. Insights derived from a structured, risk-based analysis can reveal both hazard-specific and hazard-generic disaster risk management challenges, including overlaps, differences, and parallels between the two types of events.

RQ. What can be learned from a structured risk-based comparison of floods and pandemics (low-probability, high-impact disasters)?

Floods and pandemics were selected as disasters of interest because they are globally relevant and share the property of being low-probability, high-impact risks. This nature makes them especially suitable for comparison using a risk-based approach, recognizing that disaster risk is shaped by both probability and impact, and that interventions can target either or both dimensions. The threat-driven character also makes it possible to analyze their risk management across common phases in time.

Based on concepts and ideas of 'risk', three comparative perspectives will be applied: a risk systems comparison, a case-based timeline comparison, and a risk reduction comparison. These perspectives provide a structured framework for conducting hazard-specific analyses of floods and pandemics, which can then be compared. Using a risk-based approach, this study supports the exploration of hazard-generic versus hazard-specific disaster management insights, and enables reasoning about the impact of different processes and interventions within and between disaster domains.

Ultimately, this analysis aims to support decision-makers in identifying which types of interventions are most effective across various phases and disaster domains, and how risk management could be improved through shared processes or cross-hazard learning. As such, the study contributes to more informed disaster risk management of low-probability, high-impact disasters.

1.4. Engineering and Policy Analysis thesis

This research is conducted as thesis for the master program Engineering and Policy Analysis (EPA) at the Delft University of Technology (TU Delft). The thesis focuses on building an understanding of how the risks and risk management of floods and pandemics compare and what can be learned from this. This aligns with multiple core aspects of the EPA program.

Firstly, a grand societal challenge is addressed: managing the risk of flood and pandemic disasters. Both floods and pandemics represent complex systems, full of uncertainties. Their management is a challenge which is impossible to fully solve - no system can fully deal with such events - which also makes it a wicked problem. Secondly, the thesis builds on the idea of a structured policy analysis to inform policy making - in this case disaster risk management. The focus is on the risk-based comparative analysis of the two hazards, including through a systems perspective, case studies, and modeling. In doing so, the thesis aims to provide policy analysts with a framework for comparing disaster risks, and provide policymakers with actionable insights into the parallels and differences between floods and pandemics, as well as cross-hazard lessons. All in all, this EPA thesis strives to contribute to a better understanding of disaster risk management of low-probability, high-impact disasters like floods and pandemics, supporting both researchers and decision-makers in these domains.

1.5. Thesis outline

This thesis is structured into five parts, each with multiple chapters. This first part (Part I) introduces the context of the study, Parts II-IV discuss the three comparative analyses (focused on risk systems, timelines, and risk reduction strategies), and Part V synthesizes these findings in a discussion and conclusions. Details on the chapters per part are shown in Table 1.1.

Table 1.1: Overview of the structure of this thesis. The main contribution is described for each chapter. Details on the chapters in the final part – references and appendices – are excluded.

Chapter	Description
<i>Part I: Research context and framework</i>	
1. Introduction	Research background, gap, and objectives.
2. Theoretical framework	Core concepts and frameworks in disaster risk management.
3. Methodological framework	Methodological basis and structure of the study.
<i>Part II: Systems of flood and pandemic risk</i>	
4. Bowtie analysis	Method for risk systems analysis (SQ1).
5. Flood risk and risk management	Systems-level insights into flood risk and its management.
6. Pandemic risk and risk management	Systems-level insights into pandemic risk and its management.
7. Comparative insights risk systems	Comparison of flood and pandemic risk systems.
<i>Part III: Timelines of flood and pandemic cases</i>	
8. Case-based analysis	Method for timeline analysis (SQ2).
9. Flood case: Limburg-21	Timeline and dynamics of the Limburg-21 flood.
10. Pandemic case: Covid-19	Timeline and dynamics of the Covid-19 pandemic.
11. Comparative insights timelines	Comparison of flood and pandemic risk evolution.
<i>Part IV: Risk reduction strategies for floods and pandemics</i>	
12. Model-based analysis	Method for risk reduction analysis (SQ3).
13. Flood risk reduction	Impact of interventions on flood risk.
14. Pandemic risk reduction	Impact of interventions on pandemic risk.
15. Comparative insights risk reduction	Comparison of intervention effectiveness.
<i>Part V: Discussion and conclusion</i>	
16. Discussion	Reflections on results, implications, and limitations.
17. Conclusions and recommendations	Answers to research questions and policy suggestions.
<i>Part VI: References and appendix</i>	

2

Theoretical framework

This chapter introduces the theoretical framework on which this study has been built. Sections 2.1 and 2.2 explain key definitions and related frameworks from the literature. Sections 2.3 and 2.4 reveal some first comparative insights between floods and pandemics.

2.1. Defining core concepts

The concepts of floods, pandemics, disasters, risk, risk management, and risk reduction form the foundation of this study. A wide range of definitions exist for these terms within the field of disaster risk science (Kelman, 2018). Therefore, it is important to clarify how they are used in this research. Their implementation in the methodological framework of this study is discussed further in Chapter 3.

2.1.1. Floods and pandemics as types of disasters

In this study, floods and pandemics are analyzed as two types of disasters. Both events can result in large-scale disruptions to society, loss of life, and economic damage.

A **flood** is defined as the temporary inundation of normally dry land, caused by natural or man-made processes such as extreme rainfall, river overflow, storm surges, or dike failures. In the Netherlands, the risk of flooding is particularly relevant due to the country's geography, being partly below sea level. Approximately two-thirds of the Netherlands is at risk of flooding from the sea, major rivers, or lakes (ENW, 2017). Floods can have severe consequences, including fatalities, long-term health impacts, displacement, and widespread infrastructure damage (Ferguson et al., 2023).

A **pandemic** is defined as the worldwide or transnational spread of an infectious disease, leading to widespread illness and social disruption. Unlike localized disease outbreaks (e.g. epidemics), pandemics affect large populations across multiple regions or countries. They can overwhelm healthcare systems, strain public services, and significantly impact economies and individual well-being (GPMB, 2024). The Covid-19 pandemic serves as a primary example of such an event in this study.

A **disaster** is a "serious disruption of the functioning of a community or a society at any scale due to hazardous events interacting with conditions of exposure, vulnerability and capacity, leading to one or more of the following: human, material, economic and environmental losses and impacts" (UNDRR, 2016, p. 13). In the Netherlands, a disaster is legally defined in the Safety Regions Act ('Wet veiligheidsregio's') as a severe incident or event that seriously threatens or harms the health of many people, the environment, or substantial material interests, and that requires a coordinated response by multiple emergency services or organizations ("Wet veiligheidsregio's", 2025, Artikel 1).

Based on these definitions, this study will focus only on flood and pandemic events with (potentially) large-scale health losses and/or societal damages. The consulted disaster definitions do not specify exact thresholds for determining what is or is not a disaster. However, historical disasters in the Netherlands have resulted in dozens to hundreds of fatalities, thousands of injuries, and billions of euros in damages. Among those disasters were the 1953 floods, known as the 'Watersnoodramp' in Dutch, and

the Covid-19 pandemic. This study focuses on flood and pandemic disasters with impacts of similar magnitude (i.e. dozens fatalities, thousands affected, billions of damages).

2.1.2. Viewing future floods and pandemics through a risk perspective

The aim of this study is to support the management of future floods and pandemics. This focus on 'potential' future disasters is supported by applying a risk-based perspective, acknowledging the uncertainty of the future as well as the ability to influence what will happen.

This study builds on one of the simplest and most commonly used definitions of **risk**, defining it as 'probability times impact'. More specifically, risk refers to the probability of an event occurring multiplied by the severity of its impact if it were to occur (Coppola, 2015a). Risk thus consists of two dimensions: a probability dimension and an impact dimension. This conceptualization is particularly relevant for the analysis of floods and pandemics, both of which are low-probability, high-impact disasters.

Building on the definitions above, **disaster risk** is defined as the probability of a disaster occurring multiplied by the potential magnitude of its impact. It is about the "potential loss of life, injury, or destroyed or damaged assets which could occur to a system, society or a community in a specific period of time" (UNDRR, 2016, p. 14).

Throughout this study, floods and pandemics are analyzed through the lens of disaster risk for the Netherlands. The comparative analyses are based on the separation of risk into a probability and impact dimension - separated by a central event. In essence, the probability of an event is driven by its underlying causes, while the impact is shaped by its resulting consequences.

2.1.3. Central events separating probability from impact

In this study, the concept of a **central event** refers to the critical moment when a hazardous event becomes unavoidable and its consequences are triggered. As such, it marks the boundary between probability (the lead-up to an event) and impact (the outcomes that follow).

For floods, the central event is defined as the point where flooding becomes uncontrollable, typically through a dike breach or other defense failure. For pandemics, it is the point when sustained pathogen transmission within a country can no longer be prevented, and the pathogen spreads endemically.

Defining central events in this way allows for consistent comparison across hazard types and phases of disaster management - ranging from the normal phase and threat phase before the central event, to the disaster and post-disaster phases after the central event. The theoretical framework incorporating these definitions is shown in Figure 2.1.

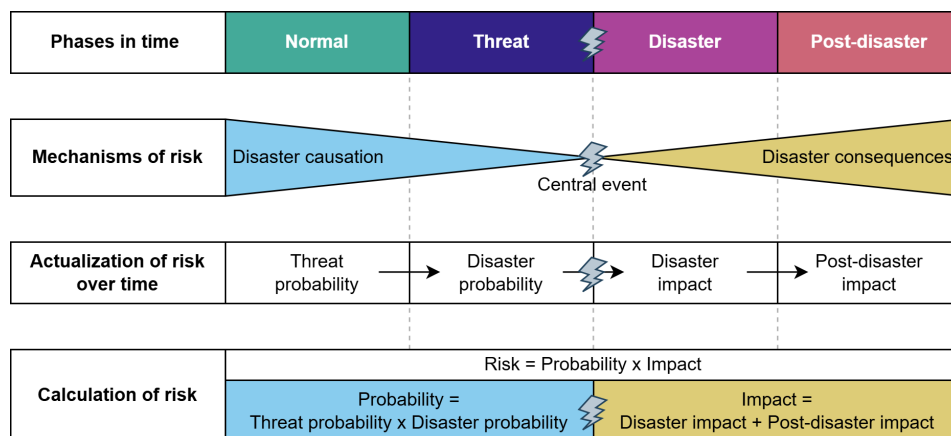


Figure 2.1: Theoretical understanding of risk on which this study was built. At the top, four phases in time are distinguished. The normal and threat phases describe the time before a central event happens and revolve around disaster causation, constituting the probability dimension of risk. The disaster and post-disaster phases describe the time after a central event happens and revolve around disaster consequences, constituting the impact dimension of risk.

2.1.4. Disaster risk management and reduction

In this study, the existence of a baseline disaster risk is considered a given: a disastrous flood or pandemic can happen. However, the size of the risk is not fixed. One of the core assumptions of this study is that risk can be influenced and reduced through targeted interventions. This relates to the concepts of disaster risk reduction and disaster risk management.

Disaster risk management is "the application of disaster risk reduction policies and strategies to prevent new disaster risk, reduce existing disaster risk and manage residual risk" (UNDRR, 2016, p. 15).

Disaster risk reduction describes the efforts "aimed at preventing new and reducing existing disaster risk and managing residual risk, all of which contribute to strengthening resilience and therefore to the achievement of sustainable development. [...] Disaster risk reduction is the policy objective of disaster risk management" (UNDRR, 2016, p. 16).

Following the definition of risk as probability times impact, risk can be reduced by lowering either the probability of the event occurring or the impact it would have if it did occur. In line with this, interventions can typically be categorized as probability-reducing (e.g. levee construction, biosecurity regulations) or impact-reducing (e.g. evacuation planning, hospital surge capacity).

In this study, the terms risk management and risk reduction are closely linked and sometimes used interchangeably. The nuanced distinction is that risk management refers more to the overarching strategic process of assessing, prioritizing, and coordinating actions, whereas risk reduction refers more to the implementation of specific interventions that address the probability or impact of disasters.

2.2. Disaster risk management frameworks

For the purpose of this study, it is valuable to understand the common frameworks used in disaster risk management, including in the management of floods and pandemics. Such frameworks are used to define and structure different types of actions that can be taken to reduce the risk of disasters. Many different ways exist for the structuring such efforts (Coppola, 2015b). For example, efforts can be structured by phases in time, by the geographical level at which action is taken, by the type of interventions that are implemented, or by the type of consequences that are averted. Moreover, risk management frameworks exist not only for general - or public - disaster risk management, but also for risk management at the level of individuals, organizations, and industries. Additionally, different risk management structures may be applied to different types of disasters, such as floods and pandemics. Some of these frameworks will be introduced in this section, chosen based on discussions with domain experts and exploratory searches online and in academic databases.

2.2.1. The disaster cycle and safety chain

Modern disaster risk management is often described in terms of a disaster management cycle (Coetzee & Van Niekerk, 2012; Coppola, 2015b). Such a cycle divides the management of disasters into multiple phases to explain and manage the development of disasters over time. Many variations of these cycles exist, but generally a disaster management cycle includes pre-event phases and post-event phases. This approach has its origins in research as early as 1920, but only appeared in its cyclic format in the 1970s (Coetzee & Van Niekerk, 2012).

Nowadays, one of the most commonly used cycles is one with four components: mitigation, preparedness, response, and recovery (Coppola, 2015b). In this conceptualization, each phase contributes to disaster management as follows (Coppola, 2015b):

1. Mitigation focuses on reducing or eliminating the probability and/or consequences of disasters. This includes efforts aimed at lessening the hazard itself or minimizing its potential societal impact.
2. Preparedness involves ensuring that individuals, communities, and institutions are able to cope with a disaster. This includes training, planning, and stockpiling resources to improve survival rates and reduce financial and social losses.
3. Response refers to immediate actions taken during or just after a disaster to protect lives and limit losses. In international contexts, this is often described as "relief."

4. Recovery aims to restore normalcy in affected communities. It begins after the acute response phase and can continue for an extended period, depending on the severity of the disaster.

Here, mitigation and preparedness concern the pre-event phase, while response and recovery concern the post-event phase. An example visual representation of this cycle is shown in Figure 2.2.

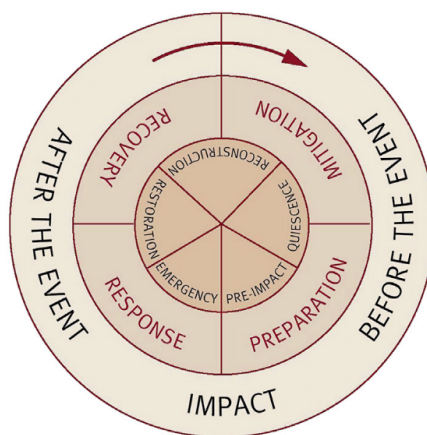


Figure 2.2: Disaster management cycle. Adapted from Coppola, 2015b

An alternative, but similar framework is referred to as the safety chain. This chain links the various stages of risk management (Jongejan et al., 2012) and has five instead of four components: pro-action, prevention, preparation, repression, and recovery. Following their definitions (Jongejan et al., 2012), pro-action refers to measures that eliminate risks by avoiding hazardous situations altogether. Prevention focuses on reducing risks through designing systems and environments to ensure safe functioning. Preparation includes all pre-incident activities that enhance emergency readiness. Repression is the actual response to a crisis, and recovery includes all post-event activities aimed at restoring normal conditions. Like the disaster cycle, the safety chain emphasizes the importance of continuous efforts before, during, and after disasters.

From these linear and circular conceptualizations of disaster risk management, it appears as if a clear distinction can be made between efforts over time. In reality, the distinction between these components is blurred. Coppola (2015b) describe that the disaster cycle components are interconnected and frequently overlap. For example, preparedness and response are very intertwined. As such, different efforts related to evacuation (e.g. training for it versus execution) belong to different components. Moreover, some response activities may begin before the disaster strikes instead of after. Similarly, recovery from one disaster may lead directly into the preparation for the next.

Reflecting on the safety chain, Jongejan et al. (2011) argue that the phases of the chain should be seen as semi-parallel layers, rather than sequential steps. This means that weakness in one layer does not mean that the cycle is broken: "the safety chain is not as weak as its weakest link" (Jongejan et al., 2012, p. 1299). Instead they argue for the use of the term 'layers of protection', in which one strong component could compensate for the weakness of other components (Jongejan et al., 2012). The idea of layers of protection is already applied in Dutch flood risk management as well (discussed below).

2.2.2. Zooming in on flood risk management

In the Netherlands, flood risk management is commonly described using the concept of multi-layer safety (ENW, 2017). Traditionally, this encompasses three layers: prevention, spatial design, and crisis management. The first layer is aimed at preventing floods from happening, for example through the building of dikes. The second layer, spatial design, is aimed at the mitigation of flood consequences by building society in ways that limit the impacts. The third layer, crisis management, aims to limit the consequences of a flood once it happens. Recently a zeroth and fifth layer have been added to expand the framework: flood awareness and recovery (Beleidstafel wateroverlast en hoogwater, 2022; de Vries et al., 2024). Flood or water awareness is aimed at ensuring that people realize that not all risk of floods can be prevented. The recovery layer is about limiting the impact of floods by ensuring a rapid recovery.

Flood risk management in the Netherlands is strictly controlled by institutions and regulations, making it stand out from other countries (ENW, 2017).

The concept of multi-layer safety is similar to that of the disaster management cycle, but uses a slightly different structuring of phases. Its layers can be understood in the context of the disaster cycle or safety chain components, as also done by Beleidstafel wateroverlast en hoogwater (2022). A visual representation is shown in Figure 2.3. Other studies have more explicitly used the disaster cycle (Rana et al., 2021) or safety chain (Ten Brinke et al., 2008) to study flood risk management.

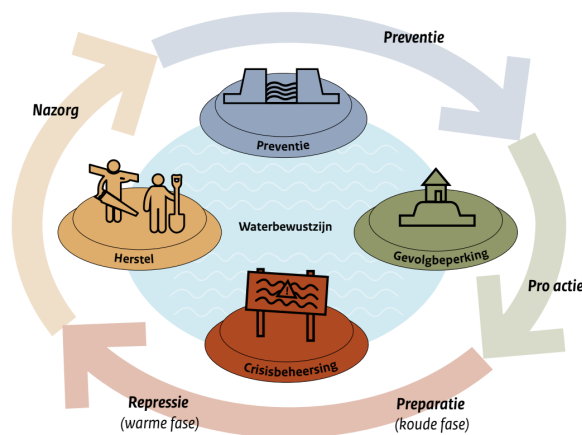


Figure 2.3: Multi-layer safety in the context of the safety chain. The concept of multi-layer safety for floods is shown in the middle, surrounded by the corresponding elements of the the safety chain. Figure copied from Beleidstafel wateroverlast en hoogwater (2022)

2.2.3. Zooming in on pandemic risk management

Essentially, pandemics are an escalated infectious disease outbreak. Therefore, pandemic risk management is best understood in the context of infectious disease outbreak risk management. Risk management of infectious disease outbreaks is commonly referred to as Infection Prevention and Control (abbreviated as IPC). The WHO developed a framework for IPC in which they distinguish the stages preparedness, readiness, and response (WHO, 2022a). Here, preparedness is more about the ability to deal with any future threat, while readiness is about preparing for a single defined threat. Compared to the disaster cycle and safety chain, this IPC framework misses a phase of prevention and recovery phase. Other infectious disease risk management frameworks distinguish efforts of prevention versus treatment. During the Covid-19 pandemic, Zhao et al., 2021 proposed a three-layer system for health security, which includes the stages prevent, detect, and contain. This framework is shown in Figure 2.4. The framework was detailed further after the pandemic, with an additional publication in a World Bank report in 2024 (Zhao et al., 2024).

2.3. Previous studies comparing disasters

In this study, the risk and risk management of floods and pandemics is compared. This addresses a societal and academic knowledge gap concerning the comparative understanding of these different low-probability, high-impact disasters. To better understand the extent of this gap and what comparative understanding already exists, a search for academic literature on relevant topics was performed. The objective of this search was to find articles which discuss disaster risk management, while comparing different types of hazards or disaster events. The search was performed in the academic database Scopus. The following search string was used:

TITLE-ABS-KEY (((disaster OR cris?s) W/5 (manag* OR cycle*)) AND ((compari* OR comparat* OR versus*) W/15 ((hazard* OR event* OR type*) OR (("natural?disaster" OR flood*) W/15 ("public?health" OR "population?health" OR infect* OR epidemic* OR pandemic*)))))*

The first part of the search string captures articles which address disaster risk management: ((disaster* OR cris?s) W/5 (manag* OR cycle*)). The second part of the string captures articles which perform

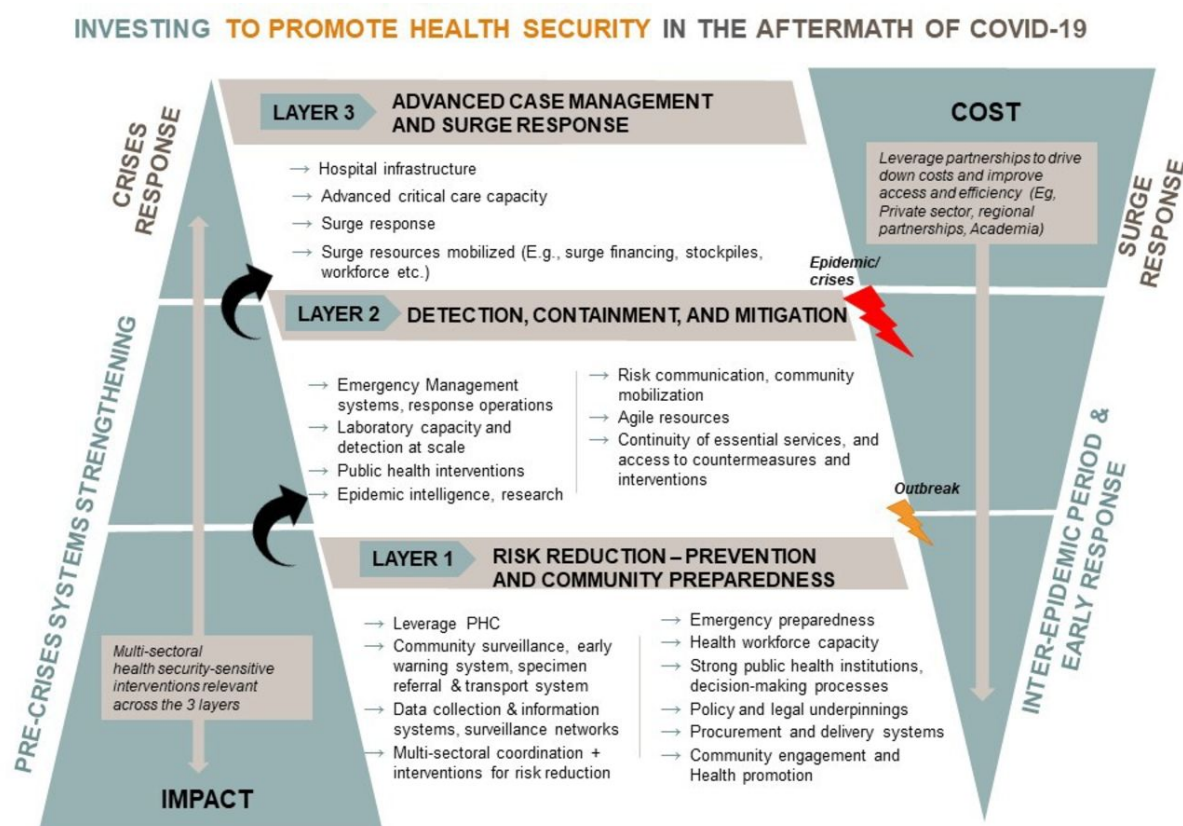


Figure 2.4: Three-layer framework for health security developed by Zhao et al. (2021). The framework separates layers of (1) pre-outbreak prevention and preparedness; (2) pre-epidemic/crisis detection, containment, and mitigation; and (3) crisis response. Figure copied from Zhao et al. (2021).

a comparative analysis: (compari* OR comparat* OR versus*). The final part makes sure that this comparative analysis is focused on the comparison of disaster types. It captures both general comparisons (hazard* OR event* OR type*), as well as specific comparisons of natural disasters or floods with public health threats like infectious disease outbreaks (("natural?disaster" OR flood*) W/15 ("public?health" OR "population?health" OR infect* OR epidemic* OR pandemic*)).

The results revealed that only a limited number of studies explicitly discuss a comparative analysis between disaster types. Y. V. Wang and Sebastian (2022) performed a study to support the quantitative comparison of disaster impacts across different types of hazards. Specifically, they developed an equivalent hazard magnitude scale, based on measures of adverse impact, population exposure, and vulnerability values. Applying expected values, regression models, and linear transformations, they show that hazard magnitudes can be analyzed and compared across disaster types, applying it to 12 different natural hazard types in their study. While this offers insights into the comparison of disaster impacts, they do not discuss disaster risk management measures.

Penta et al. (2017) performed a comparative analysis of disasters in the context of the all-hazards approach. Driven by discussions regarding the appropriateness of including public health emergencies - like disease outbreaks - under the all-hazard approach, they analyzed whether there are sufficient similarities with other hazards for generic measures to be relevant. They identify key areas of convergence between traditional disasters and public health crises: the convergence of people and resources, crisis risk communication, and medical service provision. They argue that while hazard-specific differences exist, these three core areas show enough overlap to justify the use of the all-hazards approach, although they recommend further research into differences in mitigation and recovery phases.

Building on this, Penta et al. (2021) reaffirm the applicability of the all-hazards framework during the COVID-19 pandemic. They compare the needs arising during COVID-19 with those from other disaster

types and conclude that the approach remains valid, highlighting the versatility of emergency planning principles across hazard categories.

Montz (2020) reflects on parallels between floods and pandemics in terms of risk perception, vulnerability, and behavior. He argues that both disasters reveal disproportionate vulnerabilities among socioeconomically disadvantaged groups, especially the elderly and the poor. He also notes the influence of risk perception on behavior and the persistence of gaps in preparedness - despite extensive experience with floods and growing understanding of pandemics.

Simonovic et al. (2021) examines the overlapping occurrence of floods and COVID-19, revealing the unique challenges of managing intersecting - or 'double hazard' - disasters. He highlights the difficulty of enforcing health measures like social distancing during flood evacuations, and the trade-offs emergency managers must make when two disasters demand simultaneous response. This is a relevant reflection on concurrent hazards, but not the focus of this study - which is on the comparison rather than intersection.

In summary, although comparative studies of disaster types are still relatively rare, the existing literature does suggest overlaps in risk communication, vulnerability, and institutional challenges. At the same time, authors highlight the fundamental (physical) differences between hazards. These insights provide an interesting basis for a structured, risk-based comparison of floods and pandemics, generating deeper insights into cross-hazard lessons from these disasters.

2.4. Flood versus pandemics at first glance

To lay a basis for this study, it is valuable to understand how floods and pandemics compare as they appear in existing national risk assessments. As noted earlier, both disasters are considered low-probability, high-impact threats in the Netherlands. This is reflected in the Dutch National Risk Assessment 2022, which outlines key scenarios for various hazards, including floods and pandemics. These scenarios provide a useful first glance at how these disasters are perceived and prioritized.

2.4.1. Dutch National Risk Assessment 2022

In the Netherlands, national risk assessments are performed regularly to inform the country's safety and security policies. The most recent assessment was performed in 2022 by the National Network of Safety and Security Analysts (ANV) (ANV, 2022a). The assessment used an all-hazard approach, identifying nine overarching themes of threats. Among these themes were climate and natural disasters, infectious diseases, economic threats, cyber threats, and major accidents. The current study only uses insights related to the first two threat themes, as they include floods and pandemics.

The Dutch National Risk Assessment 2022 used scenarios to zoom in on the different threats and illustrate how they may affect the Netherlands. Each scenario was assessed using the national security methodology developed by the ANV, which is based on six national security interests: territorial security, physical safety, economic security, ecological security, social and political stability, international legal order and stability. Each interest is described by a multitude of measurable impact criteria, which help define the potential consequences of a threat. For example, physical safety is measured through fatalities, injured/ill people, and a lack of basic needs. Impact sizes for each criteria are rated from "limited impact" to "catastrophic impact". In addition to impact estimations, the report includes threat likelihood estimations based on expert judgment. Likelihoods were estimated for each threat, considering a five year time period (from 2022) and a five-point scale from "very unlikely" to "very likely".

Altogether, the Dutch National Risk Assessment 2022 includes both qualitative and quantitative threat evaluations, providing a valuable basis for understanding the risk of floods and pandemics in the Netherlands. It must be noted that, as reflected in the six interests measured, the national assessment focuses on high-level, general safety and security in the Netherlands. While most of these impacts could be connected to public health, only a limited number of health consequences are considered.

2.4.2. Comparison of scenarios

As part of the Dutch National Risk Assessment 2022, ANV (2022a) published reports on infectious diseases ANV (2022b) and on climate and natural disaster risks (ANV, 2022c). These reports offer insights into the risk of floods and pandemics as perceived from a national safety and security perspec-

tive. Each report includes two scenarios of relevance for this study, namely two flood scenarios and two pandemic scenarios. The information of these scenarios is shown in Table 2.1.

Table 2.1: Comparing the risk of four hypothetical flood and pandemic scenarios from the Dutch National Risk Assessment 2022. The two flooding scenarios are from ANV (2022c). The two pandemic scenarios are from ANV (2022b).

	River flood	Sea flood	Influenza pandemic	New pandemic
Event probability	Somewhat likely (1:100 years)	Unlikely (1:10,000 years)	Somewhat likely (<1:100 years)	Somewhat likely (1:50-100 years)
Area affected	50-500 km ²	500-5000 km ²	Whole country	Whole country
People affected	100.000 - 1.000.000	>500.000	1-5 million infected	5-10 or >10 million infected
Onset duration	<7 days	<1 day to >7 days	-	-
Total duration	>7 days	Multiple week to 6 months	Weeks to months	Months to years
Economic damage	11 billion euros	45 billion euros	1-5 billion euros	>80 billion euros
Fatalities	1,428	2,470	14,000	Tens of thousands
Health care	Several injured	Several injured	40,00 to 50,000 hospitalizations	>100,000 hospitalizations, severe strain
Daily life disruptions	People can temporarily not go to work, school, etc.	People can temporarily not go to work, school, etc.	Large groups of people can temporarily not go to work, school, etc.	Long-term constraints on work, school, social, and other activities
Other significant effects	Lack of basic needs (clean drinking water) in and around affected area; panic, fear, and anger in society; long-term damage to a Natura-2000 area; part of flooded area is inaccessible for months	Lack of basic needs (clean drinking water) in and around affected area; 100,000 jobs lost; panic, fear, and anger in society; long-term damage to a Natura-2000 area; part of flooded area is inaccessible for months	-	Long-term loss of personnel disrupts vital processes; increase in unemployment; social unrest

A quick comparison reveals notable differences. River floods and pandemics are estimated to occur roughly once every 100 years, while sea floods are even less likely. Floods impact specific regions, affecting hundreds of thousands to over a million people through displacement and infrastructure damage. Pandemics, by contrast, spread nationwide, with severe scenarios involving over 10 million infections. Floods develop rapidly, whereas pandemics extend over months or years. Economic damage also differs: a major sea flood could cost €45 billion, while a severe pandemic may exceed €80 billion due to prolonged healthcare and workforce disruptions.

Floods may cause thousands of deaths, while pandemics can result in tens of thousands of fatalities and place extreme pressure on healthcare systems. Both disasters can trigger panic, fear, and long-term social and economic effects. Floods disrupt daily life in affected areas, but pandemics restrict work, school, and social activities nationwide for extended periods.

This study delves deeper into the risk of floods and pandemics. Beyond these high-level differences, what can we learn from a structured, in-depth, risk-based comparison?

Methodological framework

This chapter describes the methodological framework used in this study. Building on the main research objective and theoretical framework, three sub-questions are proposed. Each sub-question corresponds to a different risk-based perspective, analyzed in separate stages of this study. Altogether, these provide the information for answering the main research question. The current chapter explains the methodological framework, and detailed methods per stage are explained in later chapters.

3.1. Research sub-questions

This study involves a structured, risk-based comparison of floods and pandemics. The risk-based approach centers around the definition of risk as probability times impact. Both the probability and the impact of a disaster can change over time and under the influence of risk management interventions. This already highlights different aspects that are of interest for a risk-based comparison of these disasters: their causation and consequences, their development over time, and the role of interventions or circumstances in shaping outcomes.

From this perspective, the following sub-questions are proposed:

RQ. What can be learned from a structured risk-based comparison of floods and pandemics (low-probability, high-impact disasters)?

- **SQ1.** How do the causes, consequences, and interventions for floods and pandemics compare?
- **SQ2.** How do the timelines of floods and pandemics compare?
- **SQ3.** How do the effects of risk reduction strategies for floods and pandemics compare?

These research sub-questions help in structuring this research. The questions build on each other and together contribute to a comprehensive understanding of the parallels and differences between floods and pandemics. The focus will be on risks and risk management in the Netherlands.

3.2. Research approach

As reflected in the research questions, the focus of this study is on building a *conceptual understanding* of how the risks and risk management of floods and pandemics compare, and what can be learned from this. Eventually, this can contribute to enhancing disaster risk management for these hazards. For this purpose, the study adopts a *mixed-methods approach*, combining qualitative methods with a limited use of quantitative modeling.

Data will be collected with a combination of qualitative research methods, including literature analysis, case study analysis, and expert consultations. This will contribute to building a comprehensive understanding of the risk profiles and risk management of floods and pandemics separately. This provides a basis for a comparative analysis, identifying conceptual parallels and differences between the event

types and their disaster risk management. This conceptual understanding provides a basis for learning from one event for the other, and vice versa.

The study involves three stages - corresponding to the three research sub-questions: (1) a systems-level comparison using bowtie analysis, (2) a temporal comparison based on real-world case studies, and (3) an assessment of risk reduction strategies and their modeled impacts. Together, these stages support a structured comparison of floods and pandemics, enabling insights into cross-hazard lessons for disaster risk management. The different comparative perspectives are supported by the risk-based analysis framework introduced below.

3.3. Risk-based analysis framework

To support the structured comparison of floods and pandemics and address the research sub-questions, this study introduces a risk-based analytical framework (Figure 3.1). The framework builds on the definition of risk as the product of probability and impact, and on the disaster risk management frameworks introduced in Chapter 2.

Given the analysis purpose and risk definition, both the probability and the impact dimension of floods and pandemics must be understood. The probability of a flood or pandemic is driven by causal interactions leading up to such an event. The impact is composed of the consequences that follow it. In this study, such causal and consequential components are considered a part of a 'system' of risk.

Based on the disaster risk management frameworks discussed in Chapter 2, this study introduces its own categorization of risk management interventions. These categories are used to consistently analyze interventions for both flood and pandemic disasters throughout the study.

The categorization builds on two key dimensions:

- **Risk dimension:** Interventions will be separated based on whether they reduce the *probability* of a disaster occurring, or the *impact* it would have if it did occur.
- **Timing:** Interventions will be further categorized based on the phase in time in which the intervention is implemented or most actively applied. The phases have been introduced in the previous chapters: the *normal phase*, *threat phase*, *disaster phase*, and *post-disaster phase*.

Combining these two dimensions results in a matrix of intervention categories, each defined by its purpose and its primary phase of implementation (Figure 3.1). This categorization provides a consistent risk-based lens through which the risk systems, timelines, and strategies between the two disaster domains can be compared, as developed further in the next section.

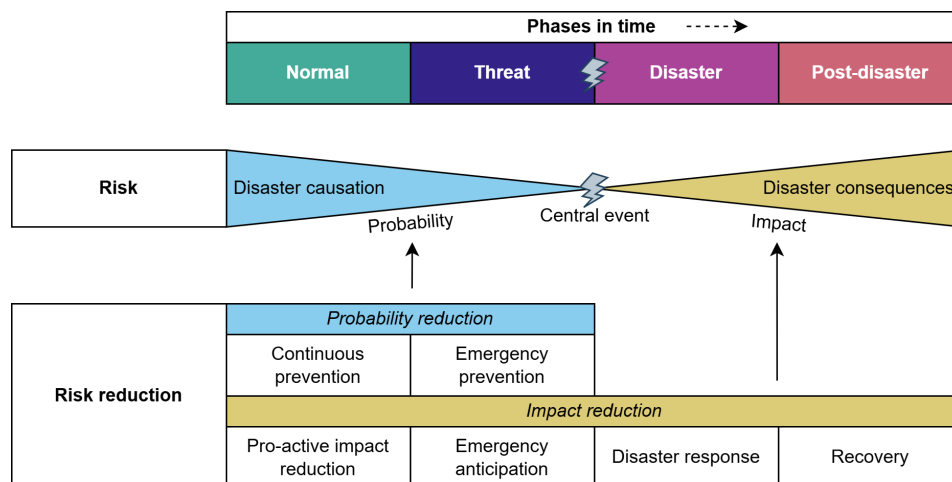


Figure 3.1: Risk-based analysis framework.

3.4. Three-stage comparative analysis

This study distinguishes three analytical stages, corresponding to the three research sub-questions and building on the risk-based analysis framework. Sub-question 1 (SQ1) will be addressed in Part II of this study, sub-question 2 (SQ2) in Part III, and sub-question 3 (SQ3) in Part IV. A detailed explanation of the methods used per analysis can be found in the first chapter of each part in this report. A quick overview of the structure is provided here.

3.4.1. Risk systems comparison (SQ1)

The first part of this study compares floods and pandemics as systems of risk, developing a systems-level understanding of their causes, consequences, and interventions. This serves as the foundation for the comparative analysis in later parts.

To structure this analysis, visual (bowtie) diagrams are used to map out the risk components of floods and pandemics. This method provides a clear and visual way to represent disaster risk by identifying: causal factors that influence the probability of an event occurring, consequences that determine the severity of its impact, and interventions that can mitigate either probability or impact.

The analysis is based on document analysis and expert consultations, and the findings from this part answer the first sub-question (SQ1): *How do the causes, consequences, and interventions for floods and pandemics compare?* This part provides a structured overview of the operational aspects of both disaster types, forming the basis for the subsequent analyses on event timelines and risk reduction strategies.

3.4.2. Case comparison (SQ2)

To build on the systems-level comparison of floods and pandemics, this part of the study examines real-world cases to analyze how risk unfolds over time. The goal is to understand the dynamics of disaster response by analyzing real-world event timelines. The cases studied are the 2021 Limburg floods and the COVID-19 pandemic in the Netherlands. These cases are examined to assess how risk management measures were implemented, how responses evolved over time, and the role of decision-making processes. The analysis focuses on identifying similarities and differences in the event progression and response strategies for both disasters.

The analysis is mostly based on document analysis, and the findings from this part answer the second sub-question (SQ2): *How do the timelines of floods and pandemics compare?* This case-based approach helps contextualize the findings from SQ1, grounding the theoretical risk analysis in practical examples.

3.4.3. Strategic comparison (SQ3)

The final part of this study builds on the previous analyses to compare risk reduction strategies for floods and pandemics. While SQ1 established a systems-level understanding of risk and SQ2 examined how disasters unfold in practice, this part focuses on risk reduction measures and their effectiveness.

This part involves the development of a risk reduction model. The model is conceptualized and formulated based on insights from SQ1 and SQ2 as well as additional documents and data. The model uses simple equations to calculate the impact of certain disaster scenarios. The parameters in the model can be changed by the implementation of risk reduction interventions. This helps in understanding the pathways through which different interventions reduce disaster risk. The model enables a comparative assessment of strategies within a hazard (flood or pandemic) or between the two.

The findings from this part answer the third sub-question (SQ3): *How do the effects of risk reduction strategies for floods and pandemics compare?* By formalizing risk reduction strategies in a structured model, this analysis supports the identification of transferable insights across disaster domains.

3.5. Supportive methods used throughout the analyses

In addition to the core analytical structure, the study relies on supportive methods that provide the necessary data and insight to implement the risk-based comparison described above. These include document analysis and expert consultations, which are outlined briefly below.

3.5.1. Document analysis

Document analysis serves as a core methodology for collecting insights throughout the different parts of this study. It is used to build a comprehensive understanding of the elements involved in the management of floods and pandemics, by building on established knowledge. Throughout the study, a combination of academic literature, international reports, book chapters, and disaster evaluations or risk assessments are used to inform the different analyses. These different types of literature offer a broad perspective on key concepts, frameworks, and strategies relevant for the comparison between floods and pandemics. Most of this literature will be about floods or pandemics separately, considering the lack of studies that addresses them together. In line with this, most of the analyses will be performed for floods and pandemics separately, followed by a comparison.

Throughout this study, the focus will be on the inclusion of academic literature or gray, but academically relevant, publications. Insights across different literature sources will be synthesized to build coherent analysis. It must be noted that the quality and completeness of the available documents may vary, which poses a limitation for this study. However, the document-based approach is complemented by expert consultations and case studies, which help to validate and enrich the insights from the literature.

3.5.2. Expert consultations

Discussions with Dutch flood and pandemic risk experts provide additional nuances to the document-based analysis. For both floods and pandemics, five experts were consulted in an interview-like meeting (ten consultations in total). Guiding questions were developed, of which examples are shown in Appendix A. Meetings were recorded (if consent was given). A data management plan and written consent form was developed. The protocol was reviewed by the HREC. Participants were contacted via leads at the university and supervisory team.

Besides these meetings, other experts have been consulted throughout this research. This includes discussions with experts at HKV lijn in water, discussions with experts from the Pandemic and Disaster Preparedness Center (PDPC), and insights gained from attending a workshop on modeling for disaster preparedness (Appendix M). Email contact with some experts provided additional insights. It must be noted that the subjectivity inherent in expert consultations could influence the findings of this study.

Table 3.1: Overview of experts consulted in meetings.

	Expert	Role	Organization
Floods	Expert F1	Flood risk advisor	National authority
	Expert F2	Flood risk advisor	National authority
	Expert F3	Flood risk professor	University
	Expert F4	Flood risk professor	University
	Expert F5	Flood risk professor	University
Pandemics	Expert P1	Public health expert	Hospital
	Expert P2	Public health expert	University
	Expert P3	Public health expert	University
	Expert P4	Infectious disease modeller	Hospital
	Expert P5	Infectious disease modeller	Hospital

Part II

Systems of flood and pandemic risk

4

Bowtie analysis

Building a systems understanding through risk mapping

This chapter describes the analysis performed for Part II of this study. A bowtie analysis is used to build a systems-level understanding of the mechanisms of flood and pandemic risk and risk management. This involves a study of causes, consequences, and interventions used for these disasters. The findings are summarized in visual bowtie maps, which capture the main causal pathways of each system. Based on this analysis, the first research sub-question, SQ1, can be answered: *How do the causes, consequences, and interventions for floods and pandemics compare?* This way, Part II provides a comprehensive overview of the operational aspects that must be dealt with in flood and pandemic management, which lays the foundation for the rest of this research.

4.1. The bowtie method

The bowtie method is an approach to systematically analyze and assess risk (de Ruijter & Guldenmund, 2015). It involves the development of a diagram which connects the relevant causes and consequences of an unwanted central event. Because all causal pathways go through this common node (the central event), the diagram has the shape of a bow-tie. Dependent on the purpose of the analysis, different types of bowties can be developed. Quantitative bowties can be used to calculate risk, while qualitative bowties are more about the communication of risk to an audience (de Ruijter & Guldenmund, 2015). In this study, qualitative bowties are used to build a systems understanding of flood and pandemic risk. The bowties combine aspects of traditional bowtie modeling and of systems mapping.

4.1.1. Traditional bowtie modeling

Traditionally, bowtie models are constructed by combining a fault tree, event tree, and barriers (see Figure 4.1). A fault tree is a diagram that visualizes the failure mechanisms of a system, leading to a single 'top event' at the end (de Ruijter & Guldenmund, 2015). The diagrams use boolean logic (and/or statements) to clarify the relation between different paths leading up to the same intermediate or top event. This structure makes it possible to quantify the diagram, as causal events can get assigned an occurrence probability, which can be used to calculate the probability of the top event occurring. Traditional bowtie models often have a fault tree as their left side. Complementing this, event trees often represent the right side of the bowtie (de Ruijter & Guldenmund, 2015). Event trees have a single initiating event, from which further possible (consequential) events or system failures are identified. The event tree thus captures the range of possibilities and outcomes from an event. Probabilities can be assigned to the tree to calculate the probability of different end outcomes. Cause Consequence Diagrams are diagrams in which a fault tree leads up to a critical event, from which an event tree describes the event's possible outcomes (de Ruijter & Guldenmund, 2015). Note that fault trees are constructed backward from an event (analyzing its causation), while event trees are constructed forward from an event (analyzing its consequences). A final element of traditional bowtie models are barriers. Barriers represent actions that can be taken to control the risk. On the left side of the bowtie (fault

tree), barriers are placed to eliminate or prevent the occurrence of the central event. On the right side of the bowtie (event tree), barriers are placed to mitigate or recover from the central event (de Ruijter & Guldenmund, 2015).

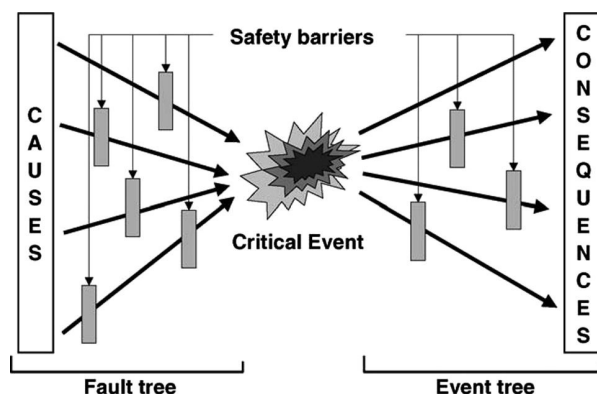


Figure 4.1: Generic example of a traditional Bowtie model. Figure copied from De Dianous and Fiévez (2006).

4.1.2. Qualitative systems mapping

Qualitative systems mapping can be used to qualitatively visualize a system, or to qualitatively and visually structure complex problems (Hanger-Kopp et al., 2024). This aligns well with the purpose of the bowtie models used in this study, namely to create a visual overview of the risk systems of floods and pandemics. As such, qualitative systems mapping offers an additional toolbox for this analysis.

Causal diagrams are a foundational form of qualitative systems mapping and are particularly relevant for this analysis. Causal diagrams visualize cause and effect relationships by connecting elements with arrows (Hanger-Kopp et al., 2024). In this study, the bowties will be built using causal diagrams instead of traditional fault and event trees. The structure of the fault and event trees will be retained, but the boolean logic and probability assignment will be omitted. The qualitative bowties (system maps) in this study thus use causal diagrams to summarize the causes and consequences of floods and pandemics. The interventions used to manage flood and pandemic risk are incorporated as barriers, blocking causal connections in the systems.

4.1.3. Strengths and limitations of the bowtie method

The use of bowtie diagrams is powerful for building a comprehensive overview of the risk systems of floods and pandemics. It helps create clarity by visually mapping the causal pathways, interventions, and consequences of floods and pandemics. These maps can integrate and connect a wide variety of information from the document analysis and expert consultations. Modifications of the bowtie would also allow them to be used for more quantitative purposes, calculating risk in the systems, based on event probability being captured on the left side of the bowtie and impact on the right side.

The bowtie method is also very flexible, which is both a strength and a limitation. Besides the basic bowtie characteristics - a central event in the middle, causation on the left, and consequences on the right - there are very little rules with regards to its design. This means that the systems can be represented with factors and pathways deemed relevant for this study and that it could be improved with additional information over the course of this study. Moreover, the bowties can be iteratively refined and restructured to support the comparison between floods and pandemics.

However, the flexibility also implies that the system can be represented in many different ways, some of which may be more suitable than others. The bowtie is just a 'model', which is merely a simplified representation of reality. Decisions have to be made with regards to which pathways to (not) include, which involves some unavoidable subjectivity. The diagrams also oversimplify the complex and dynamic nature of disaster risk systems, potentially missing nuanced interactions, feedback loops, or changes over time. Additionally, because the diagrams offer a static snapshot of risk and the analysis focuses primarily on the Dutch context, the generalizability of the results to other regions or evolving risk environments may be limited.

Risk reduction layers over time		Phases in time ----->			
		Normal	Threat	Disaster	Post-disaster
Risk	Probability	Continuous prevention	Emergency prevention	-	-
	Impact	Pro-active impact reduction	Emergency anticipation	Disaster response	Recovery

Figure 4.2: Categorization of interventions by their functionality (probability- or impact-reduction) and phase of implementation.

Acknowledging these limitations, the focus in this study is on building bowtie diagrams that are 'fit for purpose'. That means they should serve the goals of: (1) providing an overview of risk; (2) providing an overview of operational interventions as barriers; (3) supporting a risk-based comparison between floods and pandemics.

4.2. Flood and pandemic bowtie analysis

4.2.1. Central events and risk systems

A bowtie analysis is performed for floods and pandemics separately. The purpose is to capture the main causes, consequences, and barriers for flood and pandemic events in the Netherlands. The central events analyzed are floods and pandemics with disaster potential (low-probability, high-impact) in the Netherlands. These are events with the potential to cause widespread societal disruption. Since the actual outcome is dependent on the circumstances and interventions in place, such an event does not have to become a true disaster, hence the focus on disaster 'potential'. The central event for floods is the moment at which flooding is starting (unwanted inundation of normally dry land), which is for example upon the breaching of a dike. The central event for a pandemic is the moment at which the spread of a pathogen (in the Netherlands) can no longer be contained, and it thus becomes endemic. Thus, in essence, the central event is the 'moment of no return'.

The system of interest (to be captured in the bowtie) is composed of the causal pathways going through the central event, starting at root causes and ending at delayed and long-term consequences. A country-level risk management perspective is applied to focus the bowties on the most relevant causes and consequences of floods and pandemics for the Netherlands. Interventions on these causal pathways are included as barriers in the bowties.

4.2.2. Categorization of barriers

Besides causation (left side) and consequences (right side), the bowtie includes barriers to block the causal pathways. These barriers correspond to (operational) interventions which can be implemented to manage floods and pandemics. Such interventions can either influence the probability or the impact of a flood or pandemic. Based on this distinction, they should be located on the left or right side of the bowtie. Interventions (barriers) are thus placed on the causal pathways they operate on. This is separated from the moment in time in which they are implemented. For example, flood-resilient buildings must be built before a flood emerges. In time, the implementation of this intervention occurs far before the central event (a flood) happens, which corresponds to phases in time on the left side of the bowtie. However, the intervention operates on the causal pathways between flood occurrence and building damage, which is on the right side of the bowtie. The bowtie should thus not be read as a timeline, but rather as a sequence of events (left and right), which can be influenced by barriers implemented throughout time.

Overall, the barriers will be categorized based on their functionality (probability- or impact-reduction) and the phase of time during which they are (most actively) implemented: normal phase, threat phase, disaster phase, or post-disaster phase. The categories of interventions are shown in Figure 4.2. The basic structure of the bowties is shown in Figure 4.3.

4.3. Data gathering

The bowtie analysis requires data on the causes, consequences, and interventions that are relevant for floods and pandemics in the Netherlands. This data is gathered from literature and expert consul-

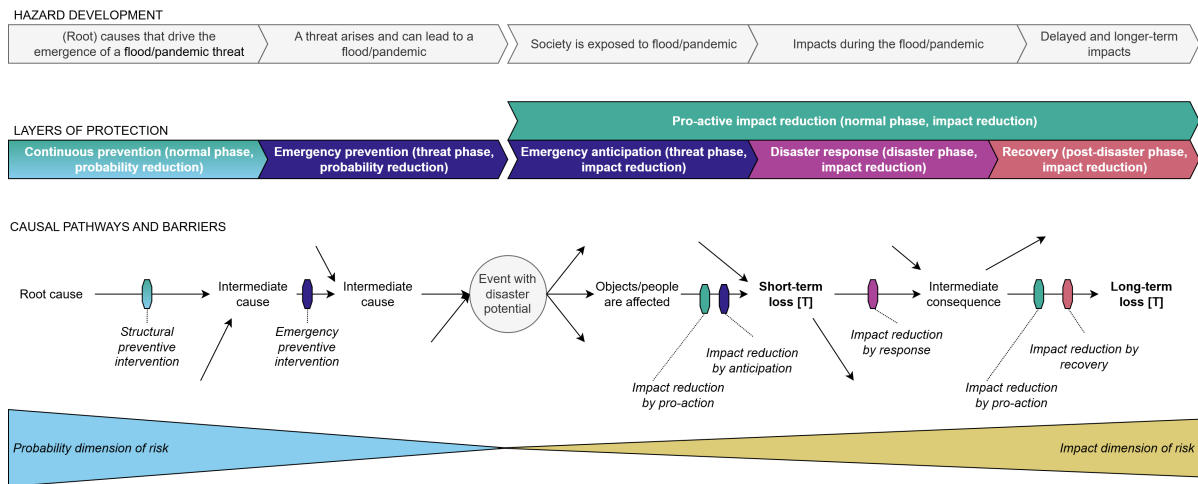


Figure 4.3: Simplified example of the Bowtie analysis. The focus is on analyzing the pathways and barriers, which will give rise to a bowtie of causes (left side) and consequences (right side) for floods and pandemics.

tations. The literature analysis is focused on core Dutch documents related to floods and pandemics, but additionally incorporates insights from broader chapters, reports or academic reviews. The expert consultations are used as an additional data source to fill gaps and to understand which system elements are more or less important to be included in the bowties. The expert consultations also contribute comparative insights of the flood versus pandemic risk systems. The general methods of document-analysis and expert consultations have been described in Section 3.5.

4.3.1. Overview of included literature

The bowtie analysis involves the study of core Dutch documents and approaches related to flood and pandemic risk and risk management. It is assumed that the core Dutch documents highlight the causes, consequences, and/or interventions that are considered important for decision-making by Dutch authorities. For example, scenarios for both floods and pandemics are considered in the Dutch National Risk Assessment 2022 (ANV, 2022a). This provides insights into key causes and consequences as perceived from a safety and security perspective. As another example, the Netherlands has a standard method that it uses to assess the impact of flood events. This method is called the Dutch standard Flood Damage and Loss Model, or the Standaardmethode Schade- en Slachtoffers 2017, which will be abbreviated as SSM2017 (Slager & Wagenaar, 2017). In its calculation of flood impact, it includes a variety of consequences, from material damages to human fatalities. As such, the method can be analyzed to infer which consequences of floods are prioritized by Dutch flood authorities.

The core Dutch documents and Dutch case studies provide the foundational understanding of flood and infectious disease outbreak risk in the Netherlands. However, both offer a relatively narrow perspective, focused on the causes and consequences of a single case or as prioritized by Dutch authorities. To widen this perspective, additional possible causes and consequences are identified in 'broader' literature. Specifically, summarizing literature such as book chapters and literature reviews into the causes and/or consequences of floods and infectious disease outbreaks are studied.

A table of key documents included can be found in Appendix B.

4.3.2. Existing flood and pandemic bowties

Existing bowties could provide a starting point for the bowtie analysis of this study. To identify publications with bowties of floods or pandemics, a quick Scopus search was performed using the search string: "TITLE-ABS-KEY ((bowtie* OR bow?tie*) AND (flood* OR pandemic*))". This search yielded 18 results (on 21 March 2025). Out of these results, only one bowtie was found which has a similar high-level systems perspective as is of interest in this study. Specifically, this is a bowtie from a 'global pandemic risk management perspective', developed by Lindhout and Reniers (2020). The bowtie is used as inspiration for the pandemic bowtie in this study. The bowtie can be found in Appendix C, which includes a reflection and comparison with the bowtie developed in this study.

5

Flood risk and risk management

Causes, consequences, and interventions for floods

This chapter analyzes flood risk as a system. The goal is to provide a foundational understanding of the risk of floods, which is determined by the probability of a flood (driven by causal factors) and its impact (dependent on its consequences). Additionally, the management of flood risk is addressed, studying the different types of interventions that can be implemented. The insights from this chapter provide the flood side of the analysis for research sub-question SQ1: *How do the causes, consequences, and interventions for floods and pandemics compare?*

5.1. Key insights

- In the Netherlands, the important possible causes of disaster-potential floods are flooding from the sea, major lakes, major rivers, and pluvial floods. Flood causation can generally be conceptualized as defense failure, with failure probability corresponding to flooding probability. Failure probability results from an interaction between (too high) load and (too little) capacity. A multitude of failure mechanisms and contributors to high load or low capacity exist.
- Floods can have consequences in each of the five considered categories: health, economic, social, environmental, and cultural impacts. Injuries and fatalities from contact with fast-flowing flood waters are the central health impact, but - dependent on the intensity of the flood event - later health consequences can result from contamination, and a lack of hygiene, food or clean water. Moreover, psychological consequences may be widespread among those affected. Large economic damages can result from the physical damage to buildings, infrastructure, and other objects; which can be followed by large indirect consequences from business downtime. Societal unrest, uncertainty, and anger may also follow the flood event and cause disruptions in society. Nature areas and cultural heritage can get damaged by the flood as well.
- In the Netherlands, most flood management interventions focus on prevention, with extensive delta plans and primary defenses. This means the probability of (disaster-potential) flooding is kept very low. Recently, there has been a shift to also focus efforts on preparedness and crisis response. Evacuation scenarios are an important aspect of this, as well as the effort to make people (and emergency workers) aware of how to respond during a flood. Evacuations and the preventive moving of valuables can save lives and economic damages. Recovery efforts involve reconstruction and compensation of damages.

5.2. Causal mechanisms driving flood probability

Causal mechanisms form the left side of the bowtie (probability dimension), shown in Figure 5.2.

5.2.1. Sources of floods

Flooding occurs when normally dry land is submerged by water. This water overflow can come from different sources. Ferguson et al. (2023) describes three common types of floods: "coastal (including tidal, storm surge, or wave overtopping); fluvial (floodwater from a watercourse); and pluvial (floodwater that cannot or hasn't yet been able to get into a watercourse)" (Ferguson et al., 2023, p. 3).

For the Netherlands, three sources of floods have long been recognized as most significant: flooding from the sea (coastal), major lakes (fluvial), or major rivers (fluvial) (ANV, 2022c; ENW, 2017; Ministerie van Infrastructuur en Waterstaat & Deltares, 2018). In the Netherlands, those water bodies are referred to as the 'main water system', 'major bodies of water' or 'outer bodies' (ENW, 2017; Ministerie van Infrastructuur en Waterstaat & Deltares, 2018). These also include transition areas where the river enters the sea, which could lead to a combination scenario (ANV, 2022c). Experts consulted in this study emphasized that the floods from the main water system are the significant ones that could lead to a disaster-type flood.

In addition to the main water system, the Netherlands has a regional water system, including canals, man-made lakes, polder waterways, and water basins (ENW, 2017). Reports from Dutch authorities, such as ENW (2017) and Ministerie van Infrastructuur en Waterstaat and Deltares (2018), recognize that flooding can also occur from the regional water system (see Figure 5.1). They estimate the consequences to be much smaller than those from flooding from the main water system. Recently, however, there has been increasing recognition for the possibility of extreme rainfall to cause (pluvial) flooding with significant damages and possibly fatalities. Triggered by the 2021 floods in Limburg, supra-regional stress tests are now being performed to better assess the risk of pluvial flooding (de Vries et al., 2024). Based on informal discussions with experts, there is already reason to believe that intense rainfall covering large areas simultaneously could lead to billions of euros of damages, as well as fatalities. Therefore, pluvial floods are included as a disaster-potential type of flood in the Netherlands as well. The current study thus considers four core sources of flooding for the Netherlands: sea, major lakes, major rivers, and intense rainfall. These causes were confirmed as important by a consulted expert.

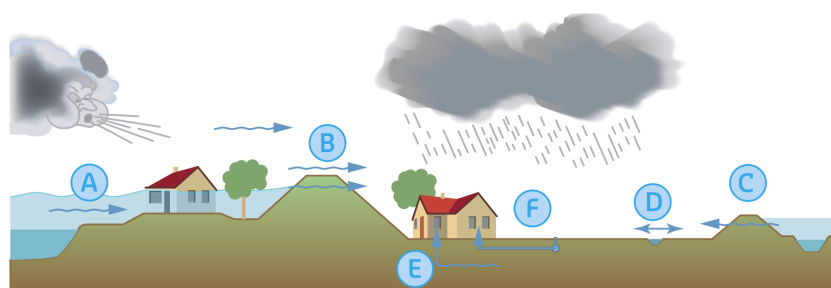


Figure 5.1: Overview of flood sources in the Netherlands. The letters indicate: (A) flooding of unprotected areas from the main water system; (B) flooding of protected areas from the main water system; (C) flooding of protected areas from the regional water system; (D) flooding of unprotected areas from the regional (surface)water system; (E) flooding from the groundwater systems; (F) flooding from intense rainfall. Figure copied from HKV et al. (2009).

5.2.2. Failure probability

Flooding from any source results from an interaction of water with some (natural) defense that normally keeps the water out. This means that flood occurrence is about defense failure. The probability of a flood is then the probability of failure in any part of a flood defense. ENW (2017) describes this probability as being driven by the load on a defense and the water retaining capacity of the defense. The load on a defense includes different types of load, including water levels, wave loads, and loads from earthquakes, traffic, or the weight of the structure itself (ENW, 2017). The load interacts with the water retaining capacity of the defense, and too high load (or too little capacity) can lead the defense to fail, with the consequence of a flood. Of course, definitions of too high/low load/capacity are interconnected, and dependent on expectations and standards for these values.

Failure mechanisms

There are different ways in which a flood defense can fail. Common mechanisms for earthen flood defense structures include: overflow, micro-instability, overtopping, macro-instability, uplift and piping, and erosion (ENW, 2017). Dunes may fail due to erosion too. Other flood defenses are hydraulic structures and special structures. These may fail due to a general loss of stability, a failure of transitional structures, or a failure to close (on time) because of human or machinery failure (ENW, 2017).

For the purpose of this research, the failure mechanisms do not have to be understood in detail. However, it is valuable to understand that each of them brings together the factors described above (load and capacity) in a different way. Eventually, failure occurs when load exceeds capacity.

Causes of increased water load

Some general causes for changes in water load can be identified. Weather is recognized as a possible natural cause of flooding, considering causation by storms, high tides, intense or long-duration rainfall, and snowmelt (ANV, 2022c). Water load can also increase by a lack of drainage capacity, a lack of rain infiltration into the ground, or blockages of water flows (Ferguson et al., 2023). An important contributor to the flood causation is the geography of the receiving area, "which could be steep, flat, or constrained and could also exhibit natural or human-induced subsidence" (Ferguson et al., 2023, p. 9).

Together, these factors give an impression of the types of causes for increased water load which could result in flooding. It is important to note that - for the current study - it is impossible and unnecessary to be comprehensive and include all causal mechanisms of floods.

5.3. Probability-reducing interventions for floods

The probability of a flood can be reduced through flood prevention. This involves interventions which block the causal pathways leading to a flood. There are two moments in time in which preventive interventions can be implemented: before a threat arises (normal phase) and once a threat arises (threat phase). The first situation describes continuous prevention, while the second situation describes emergency prevention. The barriers are shown in the bowtie in Figure 5.2.

5.3.1. Continuous prevention

Prevention is about reducing the probability of a (disaster-potential) flood. This disaster cycle phase corresponds to the preventive layer of the Dutch multi-layer safety approach. In the Netherlands, this is the phase that dominates the disaster cycle, receiving most attention, effort and investment (ENW, 2017; Ten Brinke et al., 2008). This was also emphasized by each of the consulted flood experts, rooted in the idea that prevention is the strongest contributor to risk reduction for floods. In the Netherlands, there are laws that dictate certain flood protection levels that must be maintained throughout the country. Rijkswaterstaat is the implementing authority for the main water system (the sea, major lakes, major rivers) and the water authorities are the implementing authority for the regional water systems (ENW, 2017). The practical management of these systems is divided differently.

Prevention is about reduction of flood probability and thereby about reduction of defense failure probability (Section 5.2.2). Flood defenses are *structural interventions* and can be either natural (e.g., dunes, riverbanks) or man-made (e.g., dikes, hydraulic structures). The failure of these defenses results from an interaction between the load exerted on them and their capacity to withstand that load (Section 5.2.2). Consequently, preventive interventions focus on either reducing the load or increasing the defense capacity to minimize the probability of flooding.

- **Primary defenses.** In the Netherlands, the probability of flooding from the main water system (sea, major lakes, major rivers) is reduced through the so-called primary defenses. These include dunes, levees, dams, and hydraulic structures (ENW, 2017). Examples of hydraulic structures are locks, storm surge barriers, pumping stations, and sluices. Some of the primary defenses (e.g. dunes, levees, dams) function as barriers that keep the water out. Other defenses (e.g. pumping stations and sluices) regulate water levels, reducing the water load such that it won't exceed barrier capacity.
- **Coastal protection.** Much of the coast line involves protection by naturally present beaches and dunes. Some of these are subject to structural erosion, weakening the natural defenses. This is

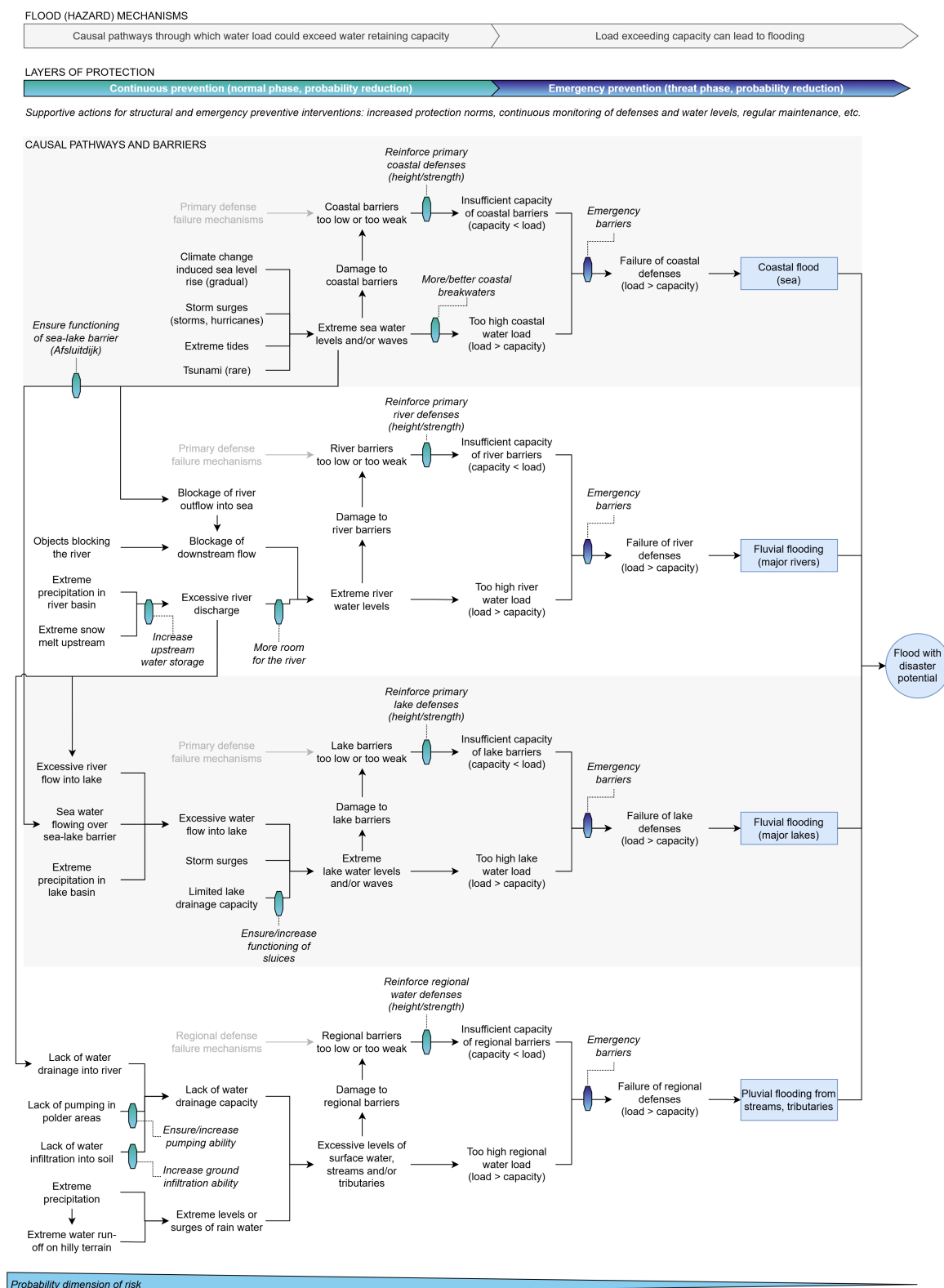


Figure 5.2: Causal mechanisms forming the probability dimension of flood risk (left bowtie). The focus is on floods with disaster-potential for the Netherlands. The gray shaded areas separate the different (main) types of disaster-potential floods for the Netherlands: coastal floods, fluvial flooding from lakes, from rivers, and pluvial flooding. The bars at the top provide a reading guide with regards to phases of hazard development (the top bar, in blue) and layers of protective interventions (the bottom bar, with colors corresponding to those of the barriers in the diagram).

counteracted by the use of groynes (interrupting water flow) and sand replenishments (ensuring that the coastline remains fixed) (ENW, 2017). Historically, the Netherlands has also shortened its coastline by building the Afsluitdijk causeway (transforming the Zuyder Zee sea into the IJsselmeer lake) and by closing off some sea inlets at Zuid-Holland and Zeeland. These structures reduce the load of water on the more in-land defenses. Another key element of coastal flood protection are storm surge barriers.

- River and lake protection. Multiple major rivers flow through the Netherlands and are subject to changing flows and peak discharges. Levees form barriers against flooding, and can be either naturally present or man-made. The prevention of river floods in the Netherlands involves efforts to strengthen the barriers on the one hand, and efforts to reduce the load on them on the other hand. Barriers are strengthened through levee reinforcements (e.g. with the past 'Delta Plan for the Major Rivers') (ENW, 2017). Load is reduced by creating more room for the river water flow, increasing the discharge capacity (e.g. with the 'Room for the Rivers' program). In the Netherlands, the water levels in large lakes are controlled using sluices and pumping stations (ENW, 2017).
- Regional defenses. An important aspect of flood risk management within regional water systems (incl. canals, man-made lakes) is the increasing of water storage and drainage capacity (Ministerie van Infrastructuur en Waterstaat & Deltares, 2018).

Overall, flood risk in the Netherlands is reduced through the integration of a variety of structural interventions. This includes a combination of direct flood barriers (e.g., dikes and embankments), controlled water retention (e.g., storage basins and room for the river), and improved drainage and infiltration (e.g., pumping stations, draining sluices, rainwater infiltration systems). The combination of such preventive measures ensures that flood defenses maintain an appropriate distribution between capacity and load. Efforts and investments are not only needed for building these structures, but also for monitoring and maintaining them.

5.3.2. Threat-driven prevention

Once a threat emerges - for example based on weather conditions or water levels - additional measures can be taken to prevent a flood from occurring. Such measures include the placement of sandbags or other temporary barriers, which strengthen the continuous preventive measures. These measures can be implemented broadly (e.g. generally increasing dike height) or at weak spots specifically.

5.4. Consequential mechanisms driving flood impact

Floods can have a wide variety of consequences. These consequences are commonly categorized as (1) direct physical consequences, caused by contact between the flood water and humans or objects, and (2) societal consequences which occur (a) within or (b) outside the flooded area (Bubeck et al., 2017; Slager & Wagenaar, 2017). Furthermore, for both physical and societal consequences, some impacts can be expressed in terms of money while other impacts cannot. For example, physical impacts on buildings are quantifiable in terms of money, while physical impacts on human health are less easily expressed in monetary terms. Similarly, monetary values can be calculated for societal losses in the production of goods, while this is less applicable to societal losses like ecosystem damage (Slager & Wagenaar, 2017). An overview of this categorization of flood consequences is shown in Table 5.1.

In this study, the consequences of floods are further analyzed based on documents from Dutch authorities and from broader reports, chapters or literature reviews. The findings are structured by the types of disaster impacts inferred from the Sendai agreement (UNDRR, 2015): health, economic, social, cultural, and environmental consequences. These impacts include both short- and long-term, and direct and indirect consequences. It must be noted, however, that this study does not aim to exhaustively identify all possible consequences of floods. Rather, it will highlight the important ones from the included literature. Before analyzing each category further, some mediators of flood consequences are discussed.

Table 5.1: Categorization of flood consequences by area and monetary valuation.
Table adapted from Bubeck et al. (2017) and Slager and Wagenaar (2017).

		Monetary (market goods)	Non-monetary (non-market goods)
Impact within flooded area	<i>Direct physical impacts from floodwaters</i>	Impact on economic assets (capital), including damage to: buildings, agricultural products, infrastructure elements, cars	Loss of life (casualties), injuries, loss of ecological goods (ecosystems, pollution), monuments, cultural heritage
	<i>Societal impacts (in floodzone)</i>	Production losses, turnover losses, income losses	Social disturbance, emotional damage, long-term health effects
Impact outside flooded area	<i>Societal impacts (outside floodzone)</i>	Traffic and infrastructure disruptions, production losses, turnover losses, income losses	Emotional damage, disturbance from infrastructure disruptions, ecosystem damage

5.4.1. Mediators of flood consequences

The consequences of a flood are scenario-dependent. At baseline, the impact is determined by the flood characteristics interacting with the people and objects in the submerged area. However, other factors can mediate the impact.

The possible physical impact of a flood depends on its characteristics. Major determinants of damages are the water depths, the rate of flow, and the rate of water rise (ENW, 2017). These factors are also included as key variables in impact calculations with the SSM2017 (the Dutch standard Flood Damage and Loss Model) (Slager & Wagenaar, 2017). Other factors that can influence flood impact are the weather conditions, the duration of the flood and its predictability (ANV, 2022c). The actual impact of a flood depends on the area that is exposed to the flood water. The affected area is dependent on the (geographical) origin of the flood and how it spreads. Within the affected area, people, objects, buildings, infrastructure, and nature can be exposed to and damaged by the flood waters (Slager & Wagenaar, 2017).

The impact can be further mediated by factors of vulnerability. For example, damage will be smaller if objects are built in flood-resistant manners. This may be the case in less protected areas already, where communities are more aware of flood risk (Slager & Wagenaar, 2017). Moreover, there are vulnerable groups in the population (such as elderly people) who may suffer more from the consequences of floods than others. The vulnerability of the affected area and population is therefore an important determinant for flood impact. Finally, vulnerability is also related to the timing of the flood and the preparedness of the population for it. When the threat of flooding is apparent in advance, people have the opportunity to reduce their vulnerability. If the lead time is short, however, the population may be surprised by the flood waters and not be able to bring themselves or their possessions to safety.

5.4.2. Health consequences of floods

Floods have a multitude of possible health effects. The total health impact of a flood could be described as a combination of direct impacts (deaths and injuries), indirect short-term impacts (other deaths and injuries, psychological effects), and long-term consequences (physical and psychological).

Direct health effects: deaths and injuries from the flood water

The direct impact of floods on human health are death and injury (Alderman et al., 2012; Bubeck et al., 2017). It has been estimated that floods caused almost 53,000 deaths globally in the 10 years between 2002-2011 (Alderman et al., 2012). Most of these deaths (ratio 23:1) occur in resource-poor countries and communities. Moreover, most deaths occur in flash and coastal floods, as a result of drowning or acute trauma. In the Netherlands, deaths from flooding have occurred in the past (e.g. in 1953), but not in recent years (Ministerie van Infrastructuur en Waterstaat & Deltares, 2018). Significant health impacts are, however, realistic in case of major floods in the future. For example, the river and sea flood scenarios in the Dutch National Risk Assessment 2022 lead to an estimated 1428 and 2470 deaths,

respectively (ANV, 2022c). Additionally, such floods could cause severe injuries and/or chronic disease from accidents and hypothermia.

During a flood, many deaths and injuries are likely to happen to people who are outdoors, trying to flee the area. This was mentioned in a consult with experts, and also discussed in the scenarios by ANV (2022c). Confrontation with the rising water (in-person or via media channels) may lead to panic and cause people to flee. Dependent on the timing, their attempts could be too late or people can get stuck in traffic. As a result, many people could drown in their cars or outside (ANV, 2022c). This can also happen as a result of (unsuccessful) evacuation attempts.

Indirect health effects: lack of healthcare, lack of basic needs, diseases, and mental health

Besides the direct impacts of the flood water on human health, there are many indirect impacts. The presence of flood waters and the damages to infrastructure play a key role. Inaccessibility of healthcare (or of patients in need of care) could lead to deaths from heart attacks/strokes, dehydration or heat stroke, "or other causes associated with a lack of sustaining medical supplies" (Alderman et al., 2012).

Moreover, basic needs - such as clean drinking water and food - may become unavailable. A lack of hygiene, lack of food, and lack of clean drinking water could lead to additional deaths and injuries (ANV, 2022c). These consequences are dependent on the duration of the flood, and/or the ability to move people from the flooded area to safer areas with those basic needs available. Importantly, if drinking water facilities are affected, this could also affect the supply for adjacent (not-flooded) areas.

Besides a lack of basic needs, there may be an increased incidence of communicable diseases, water-borne diseases, and vector-borne diseases (Alderman et al., 2012). Infrastructural damages and displacement of populations may cause contamination of drinking water, through which infections can spread. Water-borne diseases include gastrointestinal diseases, hepatitis A and E, respiratory and skin infections, and leptospirosis (Alderman et al., 2012). Vector-borne diseases are those carried by mosquitoes, who could breed in receding flood water. Potential diseases that could then spread (if already present) include malaria, dengue, yellow fever, and West Nile fever (Alderman et al., 2012). While not all of these scenarios are applicable to the Dutch context, disease spread is possible.

Finally, flooding can affect mental health in the short-term. For example, people may experience fear, anxiety, and panic during the flood event and in the period after (ANV, 2022c).

Long-term health effects

In the longer-term, flooding events can affect both physical health and mental health (Zhong et al., 2018). Again, this includes effects on mortality (death) and morbidity. Long-term mortality is difficult to attribute, but can be significantly higher among flood-exposed communities (Alderman et al., 2012). This may be caused directly by flood-increased diarrhea, or indirectly by impacts on health systems, food systems, economic systems, poverty, malnutrition, or non-communicable diseases (Alderman et al., 2012). Additionally, mental health may be affected in the long-term. People may for example fear future floods or worry about safety in their homes (ANV, 2022c). Mental health conditions associated with floods include "PTSD, depression, anxiety, psychiatric disorders, sleep disorder and suicide" (Zhong et al., 2018, p. 166). With deadly floods, the loss of loved ones may have the biggest impact on mental health (Bubeck et al., 2017).

5.4.3. Economic consequences of floods

Besides fatalities and injuries, economic damages form the core outcome of calculations with the SSM2017 (the Dutch standard Flood Damage and Loss Model) (Slager & Wagenaar, 2017). The economic consequences of floods can be serious. In the river and sea flood scenarios of the ANV (2022c), the economic damages are estimated to be 11 and 45 billion euros. These damages include the direct, physical damage to objects as well as the indirect damages from production downtime (ANV, 2022c). Other indirect damages are excluded from these estimates, but could increase the total economic damage significantly. According to consulted experts, the majority of (economic) flood loss concerns direct and indirect losses from affected homes and companies.

Direct physical damage to objects

Flood waters can cause direct, physical damage to any object in the affected area, including buildings, infrastructure, and vehicles (Bubeck et al., 2017; Ferguson et al., 2023). In calculations with the

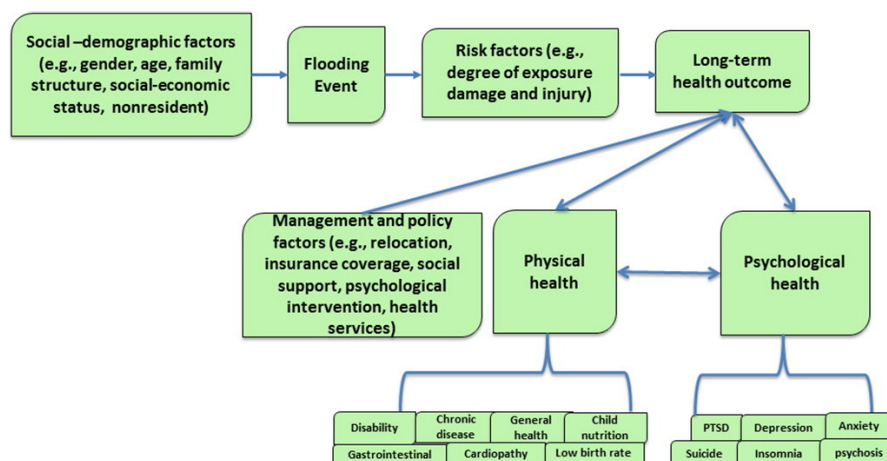


Figure 5.3: Overview of long-term physical and psychological health outcomes. Figure copied from a systematic mapping study by Zhong et al. (2018).

SSM2017 (Slager & Wagenaar, 2017), physical damages are calculated when they can be expressed in monetary terms. Such damages are then considered as economic losses.

The methodology of the SSM2017 gives an impression of the economic physical damages considered important by Dutch authorities. The SSM2017 calculations focus on multiple categories of damages, including damages to objects, capital goods and movable assets. They provide the following examples of included damages (Slager & Wagenaar, 2017, translated from Dutch): repair costs for immovable property, including owned or rented buildings and land; repair costs for production assets, such as machinery, equipment, processing installations, and transport vehicles; damage to inventories (e.g. contents and furnishings in houses and companies); loss of movable assets, such as raw materials and products, including crop losses.

In calculations with the SSM2017, economic damages are calculated for four overarching types of objects: businesses, houses (Slager & Wagenaar, 2017), infrastructure, and land use. Logically, the true physical damages depend on the specific value of each affected object. In the damage calculation method, these values are approximated by including a multitude of categories per object type. Business types include meeting locations, offices, health care, industry, education, sports, and shops. Houses include apartments at different floors (lower floors are more likely to get flooded) and single family homes. For both houses and businesses, not only the building but also its inventory can be damaged and quantified as an economic loss. Infrastructure includes roads and railways. The final category of direct damage is calculated by land use in the area, including agriculture, urban areas, recreational areas, and airports (Slager & Wagenaar, 2017).

Reflecting on the SSM2017, it must be noted that - in theory - other non-included objects may have economic worth as well. These are excluded from monetary damage calculations, but may be reflected in the other flood impact categories considered in this study.

Indirect economic damages from production downtime

Besides monetary losses from physical damages, floods may lead to significant economic losses from disruptions to business processes (Bubeck et al., 2017). Such indirect damages are directly associated with the direct damages, and depend heavily on the extent to which production can be replaced by unaffected businesses as well as the duration of the downtime (Slager & Wagenaar, 2017).

Other indirect economic damages

Economic damages are not restricted to the assets affected and the disruption of business processes. Additional damages are associated with effects on transportation networks and the business climate.

Indirect damages can result from the disruption of transportation networks (ANV, 2022c; Bubeck et al., 2017). Inability to use important railway routes, roads, or airports can cause significant damages associated with diverted passengers or freight. Interestingly, there is no consensus on the net effect

of on the economy over time. For example, reconstruction may incentivize improved productivity and other areas may compensate for the losses (Bubeck et al., 2017).

Consulted experts also mentioned the damage to the Dutch business climate. According to them, even small flooding could have tremendous impacts on the perceived safety and security of the Netherlands for companies. A flood event may lead businesses to settle in other countries, with potentially huge economic consequences.

5.4.4. Social consequences of floods

Floods can cause widespread disturbances in society, both within and outside the affected area. A large flood may significantly disrupt daily life (ANV, 2022c). For example, people may be unable to go to work, school, or supermarkets. Widespread panic and fear may capture society, and anger about the fact that the flooding happened or how it should have been handled different is possible. Flooding may also change people's perception of place and home, impair social cohesion, and destruct relationships in affected communities or families (Bubeck et al., 2017). The flood may lead to these consequences via factors such as "displacement or migration, time-consuming and exhaustive recovery processes, economic decline, (mental) health effects, and non-affected persons' lack of understanding of the flood victims' situation" (Bubeck et al., 2017, p. 18).

In addition to daily life changes at the individual level, there may be widespread unrest, mistrust, and anger in society. Severe floods may lead the public to distrust authorities and to accuse certain people or institutions for causing the severe impacts (Bubeck et al., 2017). Furthermore, the reconstruction projects after the flood can trigger public conflicts, raising questions around equity and participation and debating the economical impacts and protection of landscape and nature (Bubeck et al., 2017). With big floods in the Netherlands, response and reconstruction actions and compensation may differ per affected region, leading some people to feel worse off than others (ANV, 2022c).

5.4.5. Cultural consequences of floods

Besides health, economic, and social impacts, flooding can also impact culture. Physically, flood waters can damage cultural heritage (Bubeck et al., 2017; Ministerie van Infrastructuur en Waterstaat & Deltares, 2018), religious sites, and museums (Ferguson et al., 2023). However, while mentioned in multiple documents, the discussion and knowledge on the cultural impact of floods seems very limited.

5.4.6. Environmental consequences of floods

The final category of flood impact considered is environmental consequences. Floods can affect the environment in multiple ways. Firstly, there is the direct effect of the flood waters. Normally dry nature will be damaged when it is submerged in water for a longer period of time. Depending on the extent of the floods, it could take weeks or months for the area to dry (ANV, 2022c). Only then can the nature start recovering itself. Damages are worse from sea water, because the salt sinks into the ground.

Additional environmental consequences result from pollution of the flood waters. Pollution can occur from the sewage system or from chemicals from work places or industry (ANV, 2022c). The pollution can affect nature and vegetation affected by the flood waters, but can also affect the quality of the waters it streams into (e.g. sea, rivers, or lakes).

Damages to nature and ecology can be expressed in terms of recovery time (Ministerie van Infrastructuur en Waterstaat & Deltares, 2018). In the river and sea flood scenarios from ANV (2022c), protected nature areas (Natura-2000) are affected for over a year.

5.4.7. Summary diagram of flood consequences

Figure 5.4 shows an overview of the possible consequences of disaster-potential floods in the Netherlands. This diagram highlights the causal pathways from the flood event towards different kinds of consequences that contribute to the overall impact of the event. The diagram forms the right side of a bowtie model of flood risk, which can be connected to the left side shown in Figure 5.2.

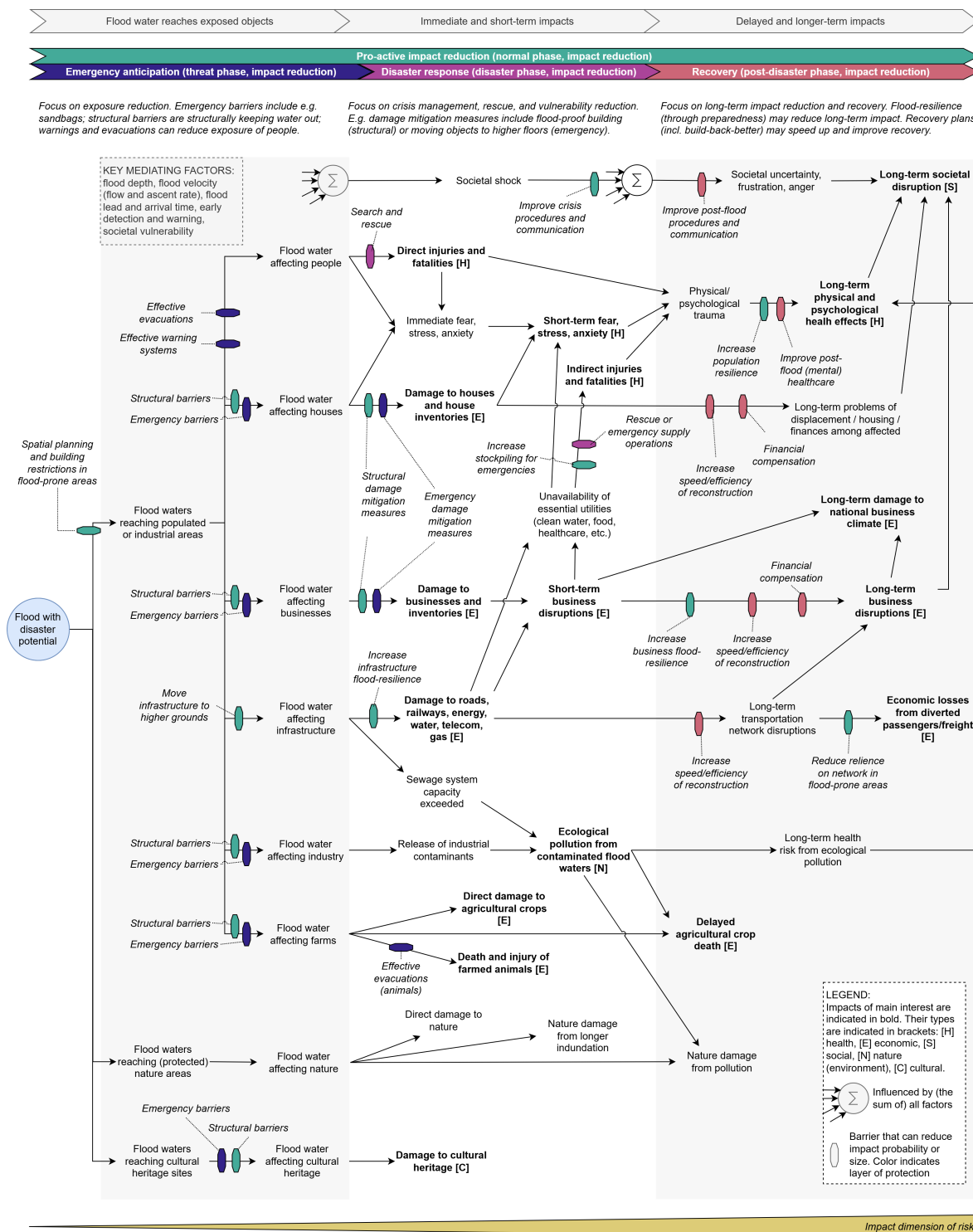


Figure 5.4: Consequential mechanisms forming the impact dimension of flood risk (right bowtie). The diagram distinguishes multiple phases relative to hazard exposure, which are separated by the gray shaded areas: exposure to the flood, immediate and short-term consequences, and delayed and longer-term consequences. These phases also correspond to the bars at the top, describing the hazard development in each phase (top bar) and the layers of interventions active in each phase (bottom bar, colors correspond to barriers in diagram). Consequences which are considered important to measure and express the 'total' impact of an event are marked in bold. Their type is indicated in square brackets, with definitions in the legend.

5.5. Impact-reducing interventions for floods

Sections 5.2 and 5.4 have provided insights into the two dimensions of flood risk: causal mechanisms driving flood probability, and consequential mechanisms constituting flood impact. The risk of floods

can be actively managed by interventions aimed at reducing the probability or the impact of flooding. An overview of each of the phases (prevention, pro-action, preparedness, response, and recovery) is provided below. The purpose is not to exhaustively list all possible interventions, but example measures will be described for each phase. Appendix D shows an overview of how the responsibility for these phases is distributed in the Netherlands.

5.5.1. Pro-active impact reduction

In the traditional safety chain, 'pro-action' is about the implementation of structural anticipatory measures that minimize the potential consequences of flooding. Unlike prevention, which aims to eliminate or reduce flooding probability, pro-action acknowledges that floods may occur and aims to limit their impact through the structural reduction of exposure. In other words, pro-action is about "separating the source of risk from the population and/or economic activities in order to avoid a disaster from happening in the first place" (Ten Brinke et al., 2008, p. 95). If there are no exposed people or societal activities in the flooded area, there is no relevant impact that would constitute a disaster. Historically, the Netherlands has done quite the opposite of pro-action, developing high population density in flood-prone areas. A cornerstone of pro-action is spatial planning. This may include land use planning and zoning, and building restrictions in flood-prone areas, such as those outside coastal dike enclosures and in river flood plains (Ten Brinke et al., 2008). Space can also explicitly be reserved to accommodate excess river discharge and to enable the reinforcement of dikes and dunes. In the Netherlands, authorities at all levels (state, province, municipal, water board) are involved in such interventions (Ten Brinke et al., 2008).

Even after the reduction of probability (prevention) and/or the reduction of structural exposure (pro-action), there is still residual risk of flooding. This means that there is always a possibility that a disaster-potential flood will at some point affect the Netherlands. To reduce the impact of potential future floods, other pro-active interventions can be implemented. This is sometimes also referred to as preparedness and is about actions that can be taken in advance to reduce flood impacts (Ten Brinke et al., 2008). In the current study, pro-active impact reduction is about general actions, before knowing when or where a specific flood will occur.

Structural pro-active measures include investment in critical infrastructure, including flood-resistant roads, bridges, and utility networks. This ensures that essential services remain functional during and after floods. Other structural interventions are the development of flood-resistant houses and buildings, which may use different materials or be placed a few meters above ground. Essentially, structural preparedness measures are about reducing the vulnerability of exposed buildings, infrastructure, and objects. This can be contrasted with pro-active spatial planning, which was about limiting exposure by not having these buildings, objects, and infrastructure in the flooded area in the first place. With structural pro-active measures, the vulnerability of built structures should thus be lowered.

5.5.2. Anticipatory impact reduction and disaster response

In many cases, there will be an early warning for a flood, allowing people some time to respond in anticipation. The lead time between the warning of the flood is dependent on the circumstances, including the type of flood and where it will occur. In some cases, there is no warning and the flood occurs unexpectedly.

Early in the response phase, immediate actions are needed to protect lives, minimize damage, and maintain critical services. Early warning may allow governments and residents to take last-minute protective measures. Residents (and businesses) can move their valuables to higher ground, which can significantly reduce economic damages. Moreover, evacuations may be initiated if deemed necessary and possible. Decisions have to be made in short periods of time, which is why preparation is important.

Different types of evacuations can be distinguished, including horizontal evacuations (preventive, leaving the area), vertical evacuations (seeking higher places), and shelter in place (ENW, 2017). The effectiveness of preventive evacuations depends on the predictability of the flood, the capacity of the infrastructure, and the conditions in which an evacuation is performed (weather, social unrest). Evacuations can also be dangerous: if there is not enough time - or the flood occurs sooner than expected - many people may be much more vulnerable (e.g. outside or in their cars) than if they would have stayed in their house or sheltered at a higher place nearby. There are therefore different scenarios of

how successful an evacuation would be, and these scenarios are also considered in risk estimations in the Netherlands (Vergouwe, 2014). The percentage of successfully evacuated people from an area is then referred to as the evacuation fraction. People that are still in the area upon flood occurrence may be able to leave via acute evacuation, escape, or rescue (B. Kolen, 2013).

5.5.3. Disaster response

The response to a flood is about dealing with it when it occurs. It is fully oriented at impact reduction. This involves search and rescue operations, often involving emergency responders, military units, and volunteers, to ensure the safety of individuals trapped by rising water levels. Damage containment measures, such as reinforcing dikes, deploying mobile flood barriers, and pumping out excess water, can help stabilize the flooded areas. Medical teams must provide urgent healthcare services, addressing injuries, waterborne diseases, and psychological trauma associated with the flood.

5.5.4. Flood recovery

Recovery is about getting over the consequences from the flood and dealing with the post-disaster impacts. While some may see this as unrelated to the idea of 'risk', it could be argued that the speed and effectiveness of recovery significantly reduce the overall, long-term impact of the flood event. Therefore, the current study views the optimization of recovery as a part of risk management, influencing the impact dimension of risk.

Early on, the recovery phase may focus on drainage of the flood waters. Thereafter, recovery focuses on restoring affected areas and strengthening resilience for future flood events (build-back-better). Damage assessments guide infrastructure reconstruction, which may include efforts to incorporate flood-resistant designs. Insurance and/or government compensation may support the recovery process of households and businesses (Endendijk, Botzen, et al., 2023). Environmental restoration efforts address flood-induced degradation of nature. Post-flood response evaluations and risk reassessments may help to improve flood risk management strategies, such that future interventions are more effective.

5.5.5. Supportive processes

Throughout all phases, supportive processes exist which strengthen the operational interventions. Many of these processes require implementation during the normal phase, ensuring preparedness for interventions during the threat, disaster, and post-disaster phases. The supportive processes include institutional planning, resource allocation, and capacity building. In the traditional disaster cycle, many of these processes are seen as part of 'preparedness'.

To prepare the population for floods, awareness of flood risk is essential. Recently, awareness has become an additional layer in the Dutch multi-layer safety approach (de Vries et al., 2024). Public awareness campaigns can educate people about flood risks, evacuation procedures, and self-protection strategies. One of the efforts to build awareness in the Netherlands is through websites such as <https://www.overstroomik.nl/>. This allows people to look up the possible water levels in their neighborhood and to learn about measures they can take before or during such events. In the normal phase, the communication of information about floods is about *risk communication*. This can be contrasted with *crisis communication* in the threat and disaster phases (ENW, 2017).

To enable a timely and effective response, early flood detection is essential. Therefore, an important part of preparedness is the development and use of flood forecasting and early warning systems. These systems allow governments and residents to be warned for a flood, giving them time to take precautionary measures before it happens. Upon this warning, governments and individuals should know what to do, which is something we can also prepare for. This involves raising awareness, developing contingency plans, training emergency services and crisis teams, or building knowledge and capacity in other ways. Often, such preparations are based on scenario analyses (ENW, 2017).

To effectively respond to floods, well-coordinated and timely interventions by crisis authorities are essential. In the Netherlands, there are no large crisis management organizations for floods. This is because - due to the small probability of floods - the development and maintenance of such organizations is considered to not be cost-effective (ENW, 2017). Preparedness in the Netherlands relies therefore mostly on the effective deployment of existing emergency services. Emergency flood response plans must be developed that outline coordination mechanisms between local, regional, and national organizations.

There must also be clear decision-support on situations in which to perform an evacuation, and how to perform it. Training drills can strengthen response capabilities of coordinators and emergency services. Preparedness may also involve the stockpiling of essential supplies (e.g. sandbags, portable flood barriers, emergency relief materials), such that they can be rapidly deployed when needed.

Throughout the flood - from the first warning till the flood is fully over - crisis communication is essential (ENW, 2017). Authorities should provide real-time updates through emergency broadcasts, mobile alerts (e.g. NL alert), and social media or other online platforms.

Finally, preparedness measures may be aimed at enabling a swift recovery after a flood event, which also limits its overall impact. Preparedness for recovery may involve the establishment of disaster relief funds and clear decisions on who pays for the damages after a flood. Insurance schemes may also provide financial protection to households and businesses against flood-related losses. Moreover, plans for reconstruction after floods may increase the efficiency of reconstruction efforts once needed. This could also involve build-back-better plans.

5.6. Bowtie overview of flood risk

The insights from this chapter have been combined in a bowtie diagram of flood risk, shown in Figure 5.5. The bowtie provides an overview of the important mechanisms of low-probability, high-impact flooding in the Netherlands. It should be noted that different representations of such a system are possible, and that it does not include all possible causes and consequences of flooding. Moreover, the focus is on the negative consequences of flooding, but in theory there may also be positive impacts.

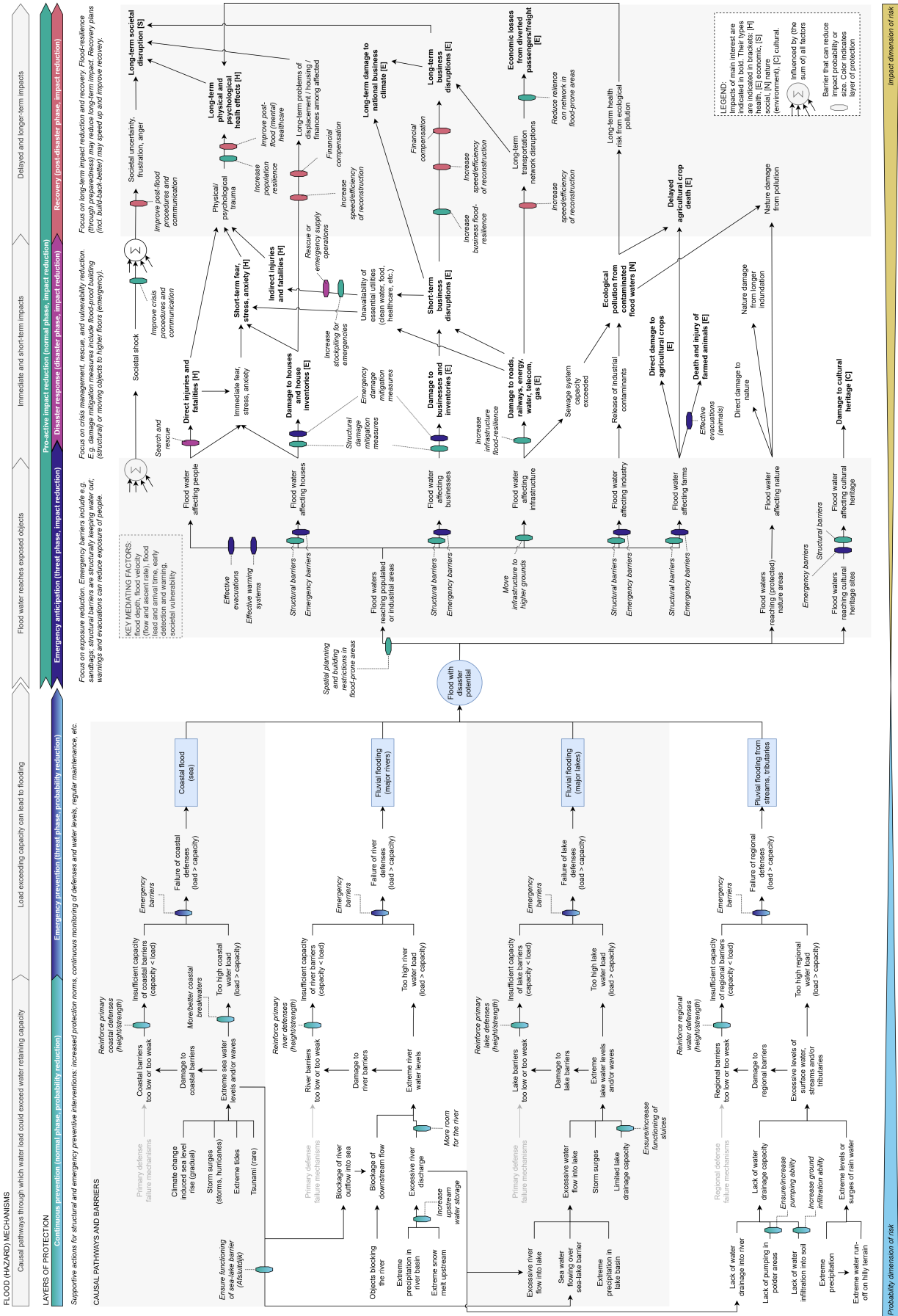


Figure 5.5: Bowtie diagram of flood risk mechanisms. The left side shows the probability dimension of risk, driven by causal mechanisms (explained in Figure 5.2). The right side shows the impact dimension of risk, driven by consequential mechanisms (explained in Figure 5.4). The bowtie includes different types of interventions which can be used to limit the probability or impact of flooding.

6

Pandemic risk and risk management

Causes, consequences, and interventions for pandemics

This chapter analyzes pandemic risk as a system. The goal is to understand the foundations of pandemic risk, as driven by its causation (probability dimension) and consequences (impact dimension). Additionally, the different types of interventions used to manage pandemic risk are addressed. The insights from this chapter provide the pandemic side of the analysis for research sub-question SQ1: *How do the causes, consequences, and interventions for floods and pandemics compare?*

6.1. Key insights

- Pandemic causation is about a combination of a pathogen spark and its spread. Pandemics are mainly caused by zoonoses from animal reservoirs, but can also emerge from human reservoirs (e.g. reemerging when vaccination degree is low) or from labs (accidental or deliberate release).
- Pandemic consequences are widespread over the whole country. Direct consequences are deaths and morbidity from the pandemic infection. High numbers of infections lead the health system to be overwhelmed, which in turn leads to healthcare disruptions and additional mortality and morbidity. Moreover, the pandemic and the interventions used against it can cause large-scale societal and economic disruptions.
- The effectiveness and feasibility of pandemic interventions is highly dependent on the nature of the pathogen. Prevention is about the reduction of spark and (initial) spread probability. Response interventions reduce spread via containment, contagiousness reduction, or susceptibility reduction. Additionally, there are interventions for health system functioning, for economic mitigation, and to employ health technologies (testing, tracing, treating).

6.2. Causal mechanisms driving pandemic probability

A pandemic involves the global spread of an infectious disease. For this to occur, two things are required: (1) a pathogen with pandemic potential must emerge, and (2) it must be able to diffuse widely in the human population. Based on this idea, Jamison et al. (2017) describes 'pandemic risk' as being driven by the combination of 'spark risk' and 'spread risk'. Spark risk relates to where a pandemic may arise, and spread risk refers to how likely it is to diffuse through populations. Applying the definition of risk as probability times impact, Jamison et al. (2017) actually seem to refer to probabilities instead of risks. Then, the probability of a pandemic emerging is a combination of spark probability and spread probability. These probabilities are determined and influenced by a variety of factors.

6.2.1. Spark probability: the emergence of a pandemic pathogen

A pandemic spark requires a pathogen with pandemic potential to enter the human population.

Pandemic potential pathogen

A pandemic potential pathogen is a microorganism (virus, bacterium, fungus, or parasite) that has the biological capability to cause a global outbreak (pandemic). The WHO maintains a "priority pathogen list" of pathogens for potential future pandemics (Ukoaka et al., 2024). The pathogens on this list have a wide variety of characteristics. The list includes pathogens that have previously caused outbreaks in humans and may 're-emerge', as well as 'emerging' pathogens that are new to appear (or spread) in humans. Additionally, it is acknowledged that a future pandemic may be caused by a still unknown pathogen, referred to as Pathogen X (Ukoaka et al., 2024).

The priority pathogen list includes pathogens with different ways in which they could infect humans. The primary modes of transmission include person-to-person transmission, vector-borne transmission (e.g. via mosquitoes), zoonotic transmission (animal-to-human), water-borne transmission, and food-borne transmission (Ukoaka et al., 2024). This highlights that pathogens with pandemic potential come with many different characteristics and may have many different origins from which they first emerge. Historically, however, most pandemic pathogens emerged from animal reservoirs (Jamison et al., 2017). Such pathogens are referred to as "zoonoses", meaning they can be transmitted from animals to humans. Before zoonotic transmission, these pathogens develop and adapt within the animal reservoirs. Environmental factors, such as animal distribution and diversity, play a role in their possible evolution to gain pandemic potential.

It becomes clear that pathogens with pandemic potential vary widely in their characteristics. However, Adalja et al. (2018) find that certain attributes do make a pathogen more likely to become a pandemic threat. These include: "efficient human-to-human transmissibility, an appreciable case fatality rate, the absence of an effective or widely available medical countermeasure, an immunologically naive population, virulence factors enabling immune system evasion, and respiratory mode of spread" (Adalja et al., 2018, p. 4). Moreover, the capacity to evolve pandemic potential traits seems greatest for viruses, particularly RNA viruses (Adalja et al., 2018).

Entering the human population

For a spark to occur, a pandemic potential pathogen must enter the human population. Most previous pandemics were caused by zoonoses which entered the human population by animal-to-human transmission. This can happen both via domesticated (e.g. farmed) animals and via wildlife (Jamison et al., 2017). Logically, a zoonotic spark (the first animal-to-human transmission) requires an interaction between animals and humans. A key interaction with domestic animals is constituted by livestock production systems (animal farming). Other sparks arise from wildlife reservoirs, including through hunting, trade, consumption, and other contact with wild species (Jamison et al., 2017). This contact may be increased through human activity in wildlife habitats, such as natural resource extraction or the extension of roads and building into such areas. Logically, the more frequent or intensive the human-animal interaction, the higher the risk of a zoonotic spark. Contact between livestock and wildlife may also bring a pathogen closer to humans (Jamison et al., 2017).

While historically the most frequent, zoonotic transmission is not the only way a pandemic spark could occur. A pandemic could also be sparked by the re-emergence or adaptation of pathogens in human reservoirs, the (accidental) release of pathogens from a lab, or from bio-terrorism events. These factors are also reflected in a report on the risk of infectious disease outbreaks for the Netherlands by the ANV (2022b). This report is part of the Dutch National Risk Assessment 2022 (ANV, 2022a), offering insights into risks as perceived from a national safety and security perspective. ANV (2022b) distinguish outbreaks from natural causes, human or technical failure, and from the intentional release of pathogens. They also clarify that outbreaks in the Netherlands can originate from pathogens already present in the country or from pathogens introduced from abroad.

6.2.2. Spread probability: the diffusion of a pandemic pathogen

For a pandemic to arise, a pandemic 'spark' must survive and spread between humans (Jamison et al., 2017). The probability of spreading is driven by the characteristics of the pathogen and the characteristics of the human population. Genetic adaptation of the pathogen and its mode of transmission

contribute to its ability to diffuse between humans. Initial localized outbreaks may provide opportunities for pathogens to adapt to human-to-human transmission, increasing their spread probability (Jamison et al., 2017). Pathogenic spread probability may be amplified by human characteristics and behavior: how susceptible is the population and how many opportunities are there for transmission?

Population susceptibility

Population susceptibility is a key determinant of spread probability. If the population is not susceptible, the pathogen will not spread. If the population is very susceptible, the pathogen can spread quickly, but only if it gets the opportunity of transmission. Population susceptibility is about population immunity. When a new pandemic pathogen emerges, humans are likely to be 'immunologically naive' to it (Adalja et al., 2018). Their immune systems have not encountered the pathogen before, allowing it to survive for a longer period of time and enabling it to multiply and spread. Conversely, when a high percentage of the population is immune (also referred to as 'herd immunity'), the pathogen cannot easily survive and diffuse through the population. Immunity for pathogens can develop naturally (e.g. as a consequence of infection) or through vaccination campaigns. However, when immunity weakens or the coverage of the population is too low, a pre-existing pathogen may re-emerge. Other factors may increase human susceptibility to infections. Particularly, vulnerable groups may be more susceptible (Jamison et al., 2017). This can be driven by social inequality and poverty, which may be associated with comorbidities, malnutrition, and caloric deficits. These factors weaken the immune system, increasing disease susceptibility. Vulnerability is often correlated with environmental factors such as lack of clean water and sanitation, which may increase morbidity and mortality in these groups (Jamison et al., 2017).

Opportunities for transmission

The spread probability of a pandemic pathogen in a susceptible population is increased by the frequency of transmission opportunities. Based on the literature, it can be assumed that the most likely pandemic potential pathogens will have (or evolve) efficient human-to-human transmissibility (Adalja et al., 2018). It then follows that the more frequent or intensive the human interaction, the higher the spread probability after a pathogenic spark in the population. Factors contributing to these interactions include human population density and human movement patterns (incl. traveling, trade, migration) (Jamison et al., 2017). This for example means that spread probability is higher in overcrowded human settlements, accelerating disease spread.

6.2.3. Pandemic probability at the national level

The current study adopts the idea that the probability of a pandemic arising is driven by a combination of spark and spread probability. The scope of this study is on the national level, focusing on the Netherlands in particular. This means that - while the interest is still in (potential global) pandemics - pandemic risk is about the probability and consequences of a pandemic affecting the Netherlands. In line with this, spark probability relates to the probability of a pandemic pathogen to arrive/emerge in the Netherlands, and spread probability relates to its probability to diffuse in the Netherlands. An overview of general pandemic phases of zoonotic pathogens is shown in Figure 6.1.

When looking at pandemic risk from a Dutch safety and security perspective, the ANV (2022b) considers two scenarios particularly probable: an influenza pandemic and a pandemic of a new human-transmissible respiratory virus. Both scenarios are assessed as "somewhat likely", meaning there are no concrete indications for them to happen, but they are conceivable. The authors also mention two external factors that may increase the likelihood of infectious disease outbreaks: globalization and climate change (ANV, 2022b).

6.2.4. Summary diagram of pandemic causation

The left of a pandemic bowtie was developed based on the findings above. The bowtie provides an overview of causal mechanisms contributing to the probability of pandemics (arriving) in the Netherlands (see Figure 6.2). The bowtie focuses on pathogens that are (or develop to be) human-to-human transmissible. The structure of the bowtie was inspired by a bowtie from Lindhout and Reniers (2020), which is reflected on in Appendix C. Consequences which can occur afterwards are discussed in the next sections, as are interventions that can block the causal pathways.

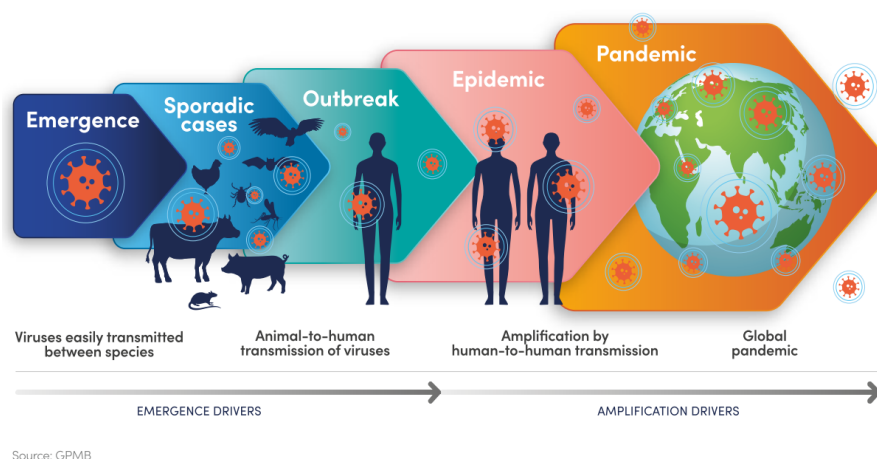


Figure 6.1: Simplified overview of zoonotic pandemic emergence. Figure copied from GPMB (2024).

6.3. Probability-reducing interventions for pandemics

6.3.1. Continuous prevention and emergency prevention

Prevention of pandemics is about reducing the probability of outbreaks of pandemic potential pathogens. This requires continuous interventions that address spark and spread risk. Jamison et al. (2017) list the following types of policies for reducing spark risk: "control animal reservoirs; monitor high-risk populations such as people working at the animal interface (for example, those involved in animal husbandry, animal slaughter, and so on); and maintain robust animal health infrastructure, biosecurity, and veterinary public health capacities" [p. 328]. If a spark occurs, early containment of infections is incredibly important to reduce their spread. Basic health infrastructure, sewage systems, hygiene, and preventive vaccinations contribute to the reduction of spread risk. Through preventive measures, public health authorities aim to intercept potential outbreaks before they escalate into widespread epidemics (RIVM, 2023).

6.4. Consequential mechanisms driving pandemic impact

Once a pandemic emerges, a wide array of direct and indirect consequences may occur. The widespread presence of a pathogen not only directly impacts the people it infects, but also affects society more broadly. For the current study, possible consequences were identified from documents from Dutch authorities and from broader reports, chapters or literature reviews. The findings are structured by the types of disaster impacts inferred from the Sendai agreement (UNDRR, 2015): health, economic, social, cultural, and environmental consequences. Both short- and long-term, and direct and indirect consequences are considered. The focus is on pandemics with human-to-human transmissible pathogens.

6.4.1. Health consequences of pandemics

Pandemics are associated with heightened mortality and morbidity. This is the result of both direct health effects from the pathogen, and indirect health effects from societal disruptions. Importantly, this not only involves physical health, but also mental health.

Direct health effects

Direct effects are experienced by those who are infected by the pandemic pathogen. A pandemic pathogen is characterized by having a significant impact on population health. Among those infected, some may be asymptomatic, but others would be mildly or severely sick. While some people may recover, others could die from the infection or develop chronic health conditions (Jamison et al., 2017). At the population level, such direct consequences of a pandemic pathogen can be expressed in terms of the number of infected people, the number of deaths from infections (mortality), and the number of people with longer-term complaints. The number of infected people is dependent on the amount of transmissions in the population. The consequences for those that are infected may be influenced by the pathogen characteristics and the availability and quality of healthcare and treatment.

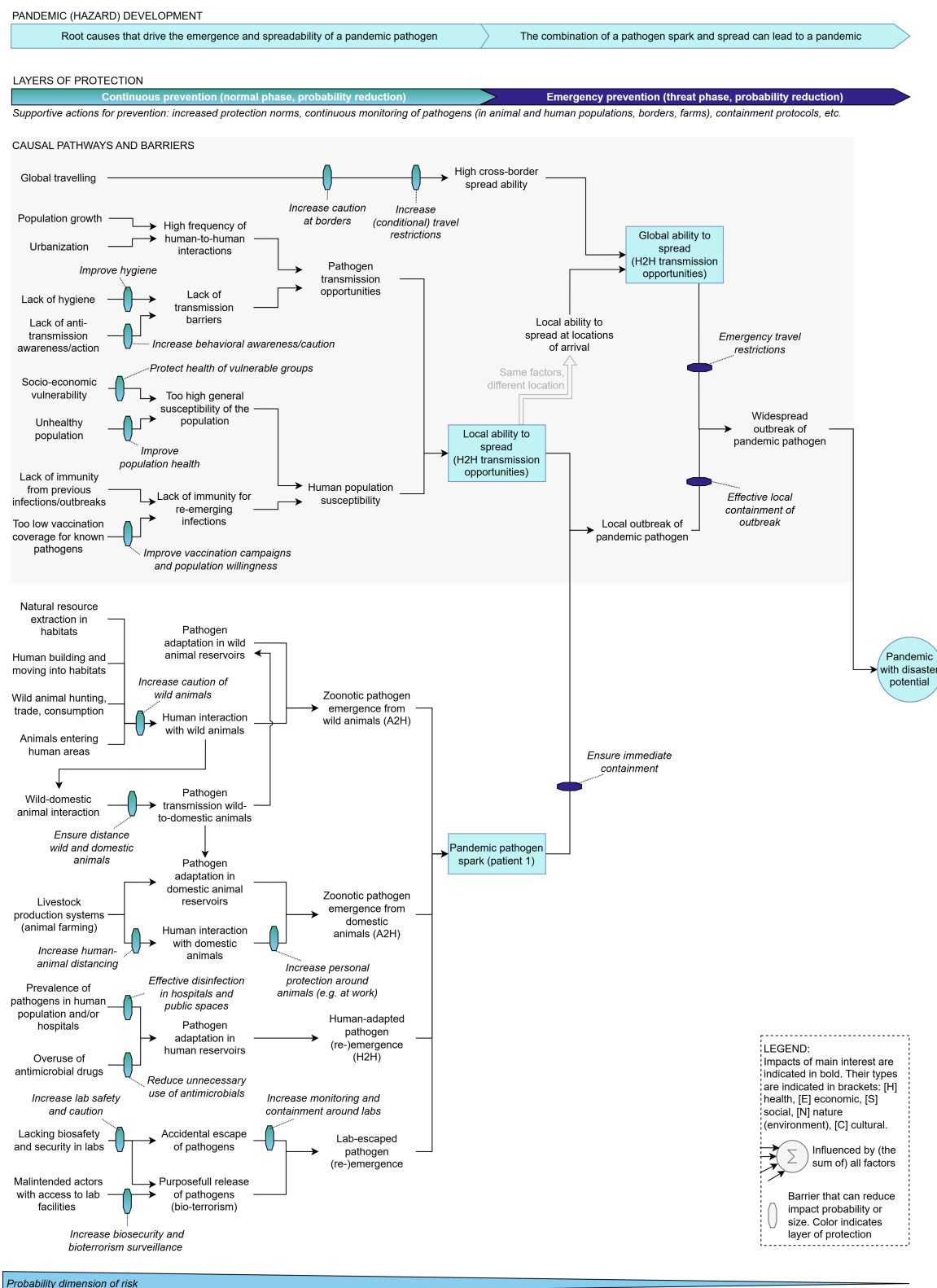


Figure 6.2: Causal mechanisms forming the probability dimension of pandemic risk (left bowtie). The focus is on pandemics with disaster-potential for the Netherlands. The gray shaded areas separate the probability of pathogen emergence (‘spark’, bottom region) from the probability of pathogen diffusion locally and internationally (‘spread’, top region). The bars at the top provide a reading guide with regards to phases of hazard development (the top bar) and layers of protective interventions (the bottom bar, with colors corresponding to those of the barriers in the diagram).

The direct health effects of present infections in the Netherlands, are published in a report by the RIVM each year (RIVM, 2024b). This offers a perspective on the consequences suffered from infectious disease in that year, from a public health perspective. The report highlights epidemiological trends and outbreaks for different kinds of infectious diseases in that year. In addition, it provides insight into the burden of disease. In this case, the burden of disease refers to the loss of health as consequence of an infectious disease. For this, they use the commonly used DALY metric, which stands for disability-adjusted life year. This includes 'years of life lost' due to death, as well as 'years lived with disability' due to illness and injury (RIVM, 2024b). This way, the direct 'epidemiological' health effects (death, illness, injury) of pandemics and other outbreaks can be quantified in a single metric.

In the scenarios analyzed in the Dutch National Risk Assessment 2022, the potential health consequences of pandemics were assessed as very severe, with many deaths; severely injured and chronically sick people (putting a large strain on hospitals and intensive care capacity) (ANV, 2022b).

Healthcare strain

Indirectly, pandemics may influence health via strains on the healthcare system. There may be a lack of routine care as a consequence of diverted or depleted resources, limited care accessibility, or the decreased availability of health care staff. This lack in accessibility may result from an inability to travel or fear, for example. Fear may also lead to an upsurge in worried individuals who seek unnecessary care and thereby burden the health care system. Health care availability may also be compromised by decreased staffing, due to illness, deaths, or fear-driven absenteeism. Moreover, healthcare workers may be unable to work because they need to care for ill family members or need to care for children because of school closures (Jamison et al., 2017). Quantifiable outcomes relating to the healthcare system include the hospitalization rate (what percentage of infected people needs hospitalization), the capacity of the intensive care, the number/shortages of medical staff.

Indirect health effects from healthcare strain

Disturbances in the availability or use of the healthcare system may lead to additional, indirect health effects on top of those caused by the pandemic infection. A lack of routine care may exacerbate the conditions of already ill individuals, or cause later diagnosis or treatment in others. This can cause increased morbidity and mortality from conditions other than the pandemic infection. The diversion of funds, medical resources, and medical personnel can also decrease routine childhood immunization, with indirect effects on mortality and morbidity from preventable diseases (Jamison et al., 2017).

Indirect health effects from societal disturbance

A pandemic can lead to large-scale societal disruptions, which can influence the behavior and (mental) well-being of people. This can have indirect effects on both physical and mental health. Importantly, the interventions used to manage the pandemic can strongly exacerbate these outcomes. Historically, most of the risk posed by pandemics came from the pathogen, but nowadays a large part - if not majority - of the impact comes from the indirect effects of the interventions (Patterson et al., 2021). Pandemics can lead to increased stress, anxiety, depression, and social isolation. Some groups are more vulnerable to this, which can amplify psychological problems. Psychological problems are not only originating from health consequences (e.g. from fear of infection), but also from societal and economic consequences (e.g. stress with an economic or societal origin).

6.4.2. Economic consequences of pandemics

Pandemics have a variety of economic impacts, including both short-term fiscal shocks and longer-term impacts on economic growth (Jamison et al., 2017). In the scenarios analyzed in the Dutch National Risk Assessment 2022, predicted consequences include very high economical costs (tens of billions of euros) and damaged economic vitality (increased unemployment, increased debt, large effects on GDP) (ANV, 2022b).

Firstly, there are costs associated with the public health efforts during a pandemic. To contain or limit an outbreak, human resource and staffing costs will increase in the beginning of a pandemic. As the outbreak grows, expenditure throughout the health care system may greatly increase, building new facilities and dealing with an increased demand for medical supplies (Jamison et al., 2017).

Pandemics have direct economic impacts, which result from reductions in the labor force caused by illness and mortality. However, the indirect consequences are much bigger. Indirectly, pandemic impact economic growth via fear-induced behavioral changes. Aversive behaviors include workplace absenteeism (reduced labor force participation), avoidance of travel, restaurants, and other public places (Jamison et al., 2017).

6.4.3. Social consequences of pandemics

In addition to health and economic consequences, pandemics may also cause social and political disruptions. The social consequences of pandemics receive increasing attention (MIT, 2024). Social consequences may include "clashes between states and citizens, eroding state capacity, driving population displacement, and heightening social tension and discrimination" (Jamison et al., 2017). Such disruptions may be driven by large mortality and demographic shocks. Existing political tensions may be amplified and unrest may be sparked. This particularly applies to already fragile states. Other factors may include suspicion from the population, riots and violent clashes with security forces, threats to health care workers, attacks on (public) health personnel and facilities. Social and political tensions may complicate the public health response, which in turn feeds back to the health consequences of the pandemic, increasing morbidity and mortality (Jamison et al., 2017).

A pandemic may also reduce state or military capacity via "increased absenteeism, decreased military capacity, and decrease readiness". This may then reduce the capacity of the state to manage social or political instabilities. Weakened security forces may amplify the risk of civil war or other violent conflict (Jamison et al., 2017). Public panic during an outbreak may lead to population migration, which can "have destabilizing effects, and migrants face elevated health risks arising from poor sanitation, poor nutrition, and other stressors". Moreover, migration can directly contribute to further spreading an outbreak (Jamison et al., 2017). Lastly, pandemics can cause stigmatization of (already) vulnerable groups. Vulnerable social groups, like ethnic minorities, may be stigmatized and blamed for the pandemic. This can lead to discrimination, causing violence, social isolation, anxiety, and economic struggles of vulnerable individuals (Jamison et al., 2017).

In the scenarios analyzed in the Dutch National Risk Assessment 2022, a multitude of societal consequences were identified (ANV, 2022b). The most significant ones are the disturbance of daily life (inability to go to work, school, societal services, etc.) and a possible lack of primary necessities or services (consequence of decreased labor participation). Other possible damages included: damages to the digital space (breach of vaccine or testing registration systems); effects on the democratic state (less freedom, effects on order and safety, demonstrations and rebellions); societal impacts (unrest and emotional responses among certain groups in response to interventions, societal unrest, avoiding certain groups, polarization; declining solidarity, tolerance, respect; demonstrations and rebellions); international relations (long-term limitations on traveling, possible international conflicts) (ANV, 2022b).

6.4.4. Cultural consequences of pandemics

Experiences from the Covid-19 pandemic reveal that the cultural sector (museums, theater, etc.) are often one of the first sectors to suffer from pandemic consequences and interventions. This makes the cultural sector particularly vulnerable for pandemics.

6.4.5. Environmental consequences of pandemics

The environment is one of the categories considered by the Dutch Societal Impact Team (MIT) in its decision framework for pandemic interventions (MIT, 2024). Pandemics may influence emissions through changes in business activity.

6.4.6. Summary diagram of pandemic consequences

The findings have been combined to build a general overview of consequences that may occur in the case of a pandemic. The causal diagram (Figure 6.3) forms the right side of a the pandemic bowtie model, with its left side in Figure 6.2.

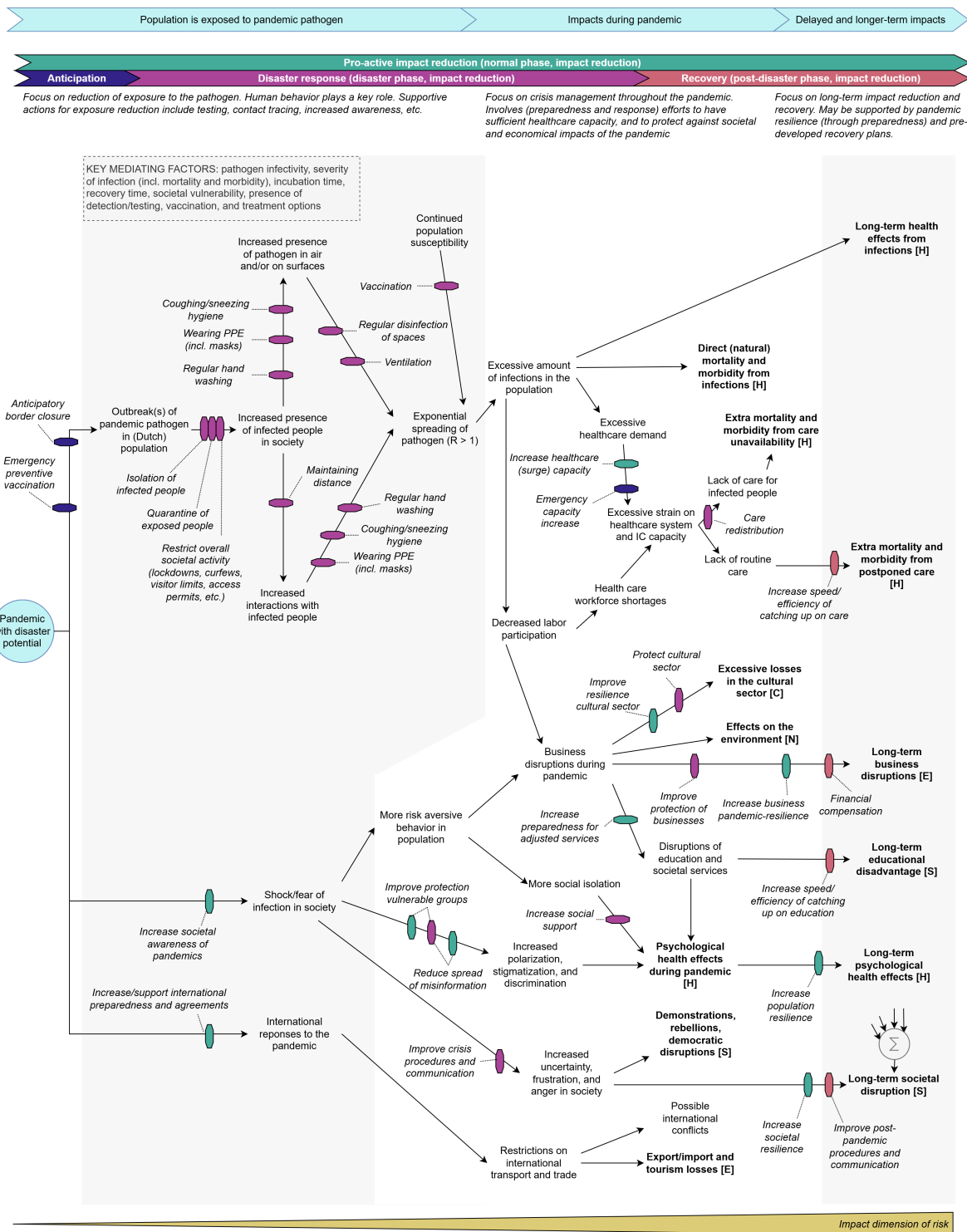


Figure 6.3: Consequential mechanisms forming the impact dimension of pandemic risk (right bowtie). The diagram distinguishes multiple phases relative to hazard exposure, which are separated by the gray shaded areas: exposure to the pandemic(/pathogen), immediate and short-term consequences, and delayed and longer-term consequences. These phases also correspond to the bars at the top, describing the hazard development in each phase (top bar) and the layers of interventions active in each phase (bottom bar, colors correspond to barriers in diagram). Consequences which are considered important to measure and express the 'total' impact of an event are marked in bold. Their type is indicated in square brackets, with definitions in the legend.

6.5. Impact-reducing interventions for pandemics

Sections 6.2 and 6.4 have provided insights into the two dimensions of pandemic risk: causal factors driving pandemic probability, and consequences constituting pandemic impact. The risk of pandemics

Examples of Pandemic Preparedness and Response Activities, by Time Period	
Prepandemic period (before a pandemic starts) • Stockpile building • Continuity planning • Public health workforce training • Simulation exercises • Risk transfer mechanism set-up • Situational awareness^a	• Contact tracing, quarantine, and isolation • Situational awareness^a
Spark period (as a pandemic starts) • Initial outbreak detection • Pathogen characterization or laboratory confirmation • Risk communication and community engagement • Animal disease control	Spread period (after a pandemic starts) • Global pandemic declaration • Risk communications • Contact tracing, quarantine, and isolation • Social distancing • Stockpile deployment • Vaccine or antiviral administration • Care and treatment • Situational awareness^a
a. Situational awareness includes passive and active animal and human disease surveillance and monitoring of public health facilities and resources.	

Figure 6.4: Examples of different interventions for pandemic management over time. Figure copied from Jamison et al. (2017).

can be actively managed by interventions aimed at reducing the probability or the impact of infectious disease outbreaks. In the Netherlands, infectious diseases with pandemic potential are categorized as 'type A infections' (RIVM, 2025b). Four phases in time are distinguished for scaling up efforts in tackling the outbreak of type A infections (RIVM, 2025a):

- Phase 0: no outbreak of Group A infection (anywhere)
- Phase 1: outbreak of Group A infection somewhere in the world, but small risk of patients or concern in the Netherlands
- Phase 2: outbreak of Group A infection somewhere in the world, with a real risk of patients or concern in the Netherlands
- Phase 3: patients with suspected or confirmed Group A infection have been admitted to hospitals in the Netherlands

Preventive and pro-active interventions can be taken during phase 0 and 1. In phase 2 and 3 the interventions shift more toward emergency prevention and anticipation, and then response. During or after phase 3, recovery interventions can be implemented to get over the pandemic impacts.

Pandemic interventions are largely non-pharmaceutical and aimed at societal and behavioral factors. This also means they can have strong societal side effects. Recently, the Dutch Maatschappelijk (Societal) Impact Team (MIT) has published a report in which they propose an assessment framework for pandemic management interventions (MIT, 2024). In addition to considering the epidemiological effectiveness of interventions, the framework emphasizes the consideration of societal (side-)effects of said interventions. The report proposes a number of societal indicators, which they based on the conceptual framework of 'broad welfare' used in the Netherlands (MIT, 2024). The indicators are categorized into eight themes: (1) subjective well-being; (2) health and care; (3) material welfare and economy; (4) labor, learning, and leisure; (5) society; (6) safety; (7) housing; (8) environment. Within each theme, both individual and systems/societal indicators are considered. The indicators are specific (measurable) factors that can be influenced by a pandemic, including the interventions applied to manage it. A full overview of the indicators is provided in Appendix F.

Examples of some pandemic interventions at different moments in time are shown in Figure 6.4. Further examples are discussed in the next sections. It must be noted, however, that it is impossible to exhaustively list all possible interventions. This is not only because there are so many, but particularly because the possible interventions are fully dependent on the characteristics of the pathogen and the population it infects. As RIVM (2023) describe it: "It is impossible to specify control measures and be exhaustive, because the behaviors and characteristics of the future pathogen are still unknown" [p. 4, translated from Dutch]. They emphasize that not only the transmission route is important, but also the chance of infection given exposure, the amount of impact on the health of infected people, the incubation period, the contagious period, and the presence of symptoms. All of these factors influence which measures will be feasible and effective in reducing the spread (RIVM, 2023).

6.5.1. Emergency anticipation and disaster response

An emergency response may be initiated once a pandemic is arising. During the response phase, interventions are implemented to contain the spread of the disease, such as enforcing social distancing, ramping up testing and contact tracing, and deploying emergency medical services (RIVM, 2023). Effective response strategies are critical for minimizing both the health and societal impacts of the outbreak, and they require adaptive decision-making and continuous monitoring of evolving conditions (MIT, 2024). This ties back to the idea of situational awareness from Jamison et al. (2017). Pandemic spread can be reduced through three types of measures:

- Limiting contact between infected and non-infected groups. For example: isolating patients, enforcing quarantine, practicing social distancing, and closing schools.
- Lowering the contagiousness of symptomatic individuals. For example: antiviral and antibiotic therapies and strict infection control measures.
- Decreasing the vulnerability of uninfected persons. For example: vaccination programs.

However, there are more types of interventions that may be implemented during a pandemic. There are many different ways to categorize such interventions, but here the CPTI framework described by Moy et al. (2023) and used by van Amerongen et al. (2024) will be used: 'Categorizing Policy and Technology Interventions (CPTI) to a viral outbreak. The framework distinguishes four types of interventions:

- Containment policies: Interventions aimed at limiting the spread of the virus, including behavioral guidance, legal restrictions, and enforcement actions. These range from voluntary recommendations to strict lockdowns.
- Prevention and care: Interventions focused on increasing the capacity of the healthcare system to manage cases. This includes expanding medical supplies, adjusting workforce allocation, integrating private resources, and prioritizing pandemic response over routine healthcare services.
- Economic mitigation: Fiscal interventions designed to counteract the economic consequences of containment efforts. These range from small-scale financial relief to extensive government intervention in markets and economic planning.
- Health technology: Innovations in testing, tracing, and treatment used to monitor and control the virus. This includes advancements in diagnostics, digital tracking methods, artificial intelligence applications, and emerging medical treatments.

The framework not only categorizes interventions by type, but also by level of effect. Each category is assessed at four levels of intervention, from minimal actions with limited impact to highly significant measures that fundamentally alter societal operations. Further examples of pandemic response interventions are shown in Table 6.1.

6.5.2. Recovery

Recovery focuses on restoring societal functions and addressing the long-term impacts following the acute phase of a pandemic. Recovery requires efforts to rehabilitate the healthcare system, rebuild economic stability, and address mental health and social welfare challenges that arise or remain in the aftermath of a pandemic.

6.5.3. Supportive processes

Pandemic interventions can be supported by what Jamison et al. (2017) refers to as 'situational awareness'. Situational awareness is about "having an accurate, up-to-date view of potential or ongoing infectious disease threats (including through traditional surveillance in humans and animals) and the resources (human, financial, informational, and institutional) available to manage those threats" [p. 327]. They describe situational awareness as critical in all stages of a pandemic, as is also reflected in Figure 6.4.

Further preparedness is about ensuring that systems and capacities are in place to respond effectively to a pandemic once it occurs. This includes developing detailed emergency response plans, conducting regular training and simulation exercises, and ensuring the availability of critical resources such as medical supplies and healthcare personnel (RIVM, 2023). A well-prepared system also establishes

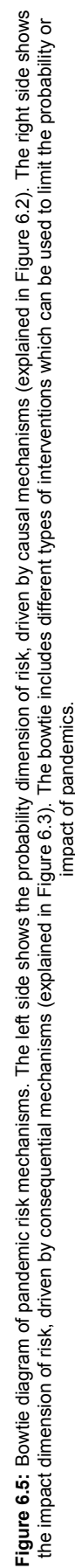
Table 6.1: Categorization of Policy and Technological Interventions. Table summarized from van Amerongen et al. (2024), who based it on the Covid-19 pandemic.

Intervention type	Minimal (1)	Medium (2)	Significant (3)	Very significant (4)
Containment policies	Recommendations (e.g., work-from-home advice, hygiene campaigns)	Legal mandates without enforcement (e.g., school closures, emergency declarations)	Enforced legal measures (e.g., border closures, mandatory quarantines)	Full lockdown (e.g., all non-essential activities suspended)
Prevention and care	Increased medical supplies (e.g., additional equipment)	Workforce adjustments (e.g., redeployment, early graduations)	Large-scale system changes (e.g., using private hospitals for public care)	Full resource shift (e.g., suspending elective surgeries, prioritizing pandemic response)
Economic mitigation	Limited aid (e.g., tax deferrals, rent freezes)	Moderate intervention (e.g., targeted industry funding, individual support)	Major stimulus (e.g., industry bailouts, wage subsidies, liquidity measures)	Full market control (e.g., temporary central economic planning)
Health technology	Basic testing, tracing, and treatment (e.g., swab tests, symptom tracking, use of PPE)	Expanded testing, tracing, and treatment (e.g., blood serology, GPS/Bluetooth-based tracing)	Advanced testing, tracing, and treatment (e.g., , AI risk analysis, mandatory telehealth)	Vaccination

robust communication networks and clear protocols for coordination among various actors, enhancing the overall resilience of the public health infrastructure.

6.6. Bowtie overview of pandemic risk

The insights from this chapter have been combined in a bowtie diagram of pandemic risk, shown in Figure 6.5. The bowtie provides an overview of the important mechanisms of low-probability, high-impact pandemics affecting the Netherlands. It should be noted that different representations of such a system are possible, and that it does not include all possible causes and consequences of a pandemic. This one is mainly focused on human-to-human transmissible pathogens, with characteristics such as those of Covid-19. Moreover, the focus is on the impacts of the pandemic itself, but this is difficult to fully separate from the impact of interventions. Appendix C includes a reflection on this bowtie model compared to a pandemic Bowtie found in literature from a study by Lindhout and Reniers (2020).



7

Comparative insights risk systems

Differences and similarities between flood and pandemic risk

This chapter describes the comparative analysis of the risk systems of floods and pandemics. Chapters 5 and 6 have described the hazard-specific bowtie analysis of floods and pandemics. The goal of this chapter is to compare the results and build an understanding of differences and parallels between the causal and consequential mechanisms of floods and pandemics. This provides practical, operational insights: are there overlaps in root causes, mediating factor, and (in)direct impacts? Are there any shared interventions between the two disaster types, and - if not - could there be? This chapter contributes to answering SQ1: *How do the causes, consequences, and interventions for floods and pandemics compare?*

7.1. Key insights

- Floods and pandemics differ substantially in their causal mechanisms - floods are driven by physical processes like rainfall and defense failure, while pandemics emerge from biological mechanisms shaped by human behavior. As a result, flood prevention is primarily technical, relying on physical defenses, whereas pandemic prevention is more socio-technical, involving behavioral and policy-based interventions.
- Despite these differences, both hazards follow a similar load-capacity logic: disasters occur when hazard loads (e.g., water levels or pathogen presence) exceed system capacity (e.g., levees or public health systems). This logic also structures their risk reduction strategies - both seek to reduce load and increase capacity, though neither can be perfectly controlled.
- On the consequences side, direct impacts differ - floods cause physical damage and trauma; pandemics cause illness and health system strain. However, indirect impacts show strong similarities: both lead to health burdens, economic disruption, social instability, and psychological distress. These parallels open up opportunities for shared strategies in preparedness, response, and recovery - especially around mitigating long-term societal consequences.
- A shared conceptual framework can be inferred from the flood and pandemic risk systems, separating four elements: risk mechanisms, intervention mechanisms, intervention-enabling processes, and risk dynamics.

7.2. Causation and probability reduction

The causation of floods and pandemics can be compared based on the left side of the bowtie diagrams and the accompanying analyses in chapters 5 and 6. Preventive interventions form the barriers on this side of the bowtie, lowering the probability flood or pandemic occurrence. Such interventions are

either structurally (continuously) present or implemented as emergency measure upon occurrence of a threat. The comparison between flood and pandemic causation reveals that causal and preventive mechanisms are very hazard-specific, but that there are parallels around the underlying processes.

7.2.1. Different causal mechanisms

When analyzing the left side of the flood and pandemic bowties, it becomes clear that there is no overlap between causal mechanisms leading up to a flood or pandemic event. The occurrence of a flood event is driven primarily by physical and meteorological processes. Phenomena like heavy rainfall and storm surges drive up water loads, while defense failure mechanisms like piping and erosion drive down the water-retaining capacity of barriers. A too high load or too low capacity can result in the physical failure of defenses, resulting in a flood event. In contrast, the occurrence of pandemics is driven by biological and ecological mechanisms in combination with societal behavior. Pandemic potential pathogens can emerge or re-emerge from animal reservoirs, human reservoirs, or labs. Their diffusion through society is driven by human behavior and interaction. This makes flood causation more of a technical challenge and pandemic causation more of a socio-technical challenge, which was also mentioned by a flood expert. In line with this, flood prevention is largely technical, relying on hydrological structures and physical barriers to prevent water from overflowing land. In contrast, pandemic prevention is much more social and behavioral, requiring safer interactions among and between animals and humans. Despite these clear differences in the causal mechanisms driving flood and pandemic occurrence, the next sections reveal notable parallels around the underlying processes.

7.2.2. Balancing load and capacity

Causation of both floods and pandemics can be understood as a load-capacity imbalance: critical events occur when the load (e.g., water levels for floods or pathogen presence for pandemics) exceeds the system's capacity to manage it. This means that the probability of such events can be lowered by either reducing the load or increasing the capacity to handle it.

For floods, load often increases due to difficult-to-tackle root causes, like weather and climate events. Loads can then be reduced by either removing this water (drainage, pumping, infiltration, etc.) or by allowing space for the increasing inflows, like done with room for the river projects. For pandemics, root causes of increasing pathogen loads are often behavioral or societal, for example relating to the ways in which we build our livestock production systems and how we interact with animals. While acknowledging the difficulty of societal change, these societal and behavioral root causes are by definition driven by humans and thus changeable by humans. In theory, it would thus be feasible to reduce many of the root causes driving pathogen emergence. This shows that root causes for increased water loads (e.g. weather) cannot be tackled, while root causes for pathogen loads (e.g. livestock) can be tackled. In turn, water loads can be reduced by removal or reserving space, while it seems less feasible to remove a pathogen or 'give it space' once it exists. Moreover, even if we do the best we can in reducing water and pathogen loads, there is always a residual load that must be dealt with, even if only for the fact that water cycles and pathogen evolution are natural and unavoidable phenomena of life on earth.

The (residual) load can be balanced out by water or pathogen retaining capacity to prevent a flood or pandemic event from happening. This retaining capacity is about preventing the water or pathogen from flowing into society. For floods, this is about the ability to keep the water out. This requires physical barriers, some of which are naturally present (e.g. dunes at the coast) and some of which are man-made (e.g. levees). For pandemics, the retaining capacity is about the ability to contain a pathogen and prevent its diffusion. This requires barriers among humans (e.g. hygiene) and between humans and animals (e.g. animal distancing).

For both floods and pandemics, a baseline retaining capacity is maintained continuously, for example by the presence of levees (floods) and sewage systems and hygiene rules (pandemics). Maintenance of these systems is required to keep up their functioning and can be guided by consistent monitoring. Additionally, water and pathogen loads can be monitored and increases in load can be responded to with increases in retaining capacity. For example, sudden increases in water levels may trigger the placement of sandbags to heighten physical barriers and keep the water out. Increases in pathogen levels may require immediate containment of cases, on top of the baseline hygiene levels and such present.

This discussion demonstrates the parallels of load-capacity dynamics between floods and pandemics. This is a useful starting point for understanding flood and pandemic probabilities, which essentially describe the probability of load exceeding capacity. Lowering the load reduces the probability of a critical event, and so does increasing the capacity. In theory, if load can always be kept below capacity, a flood or pandemic would never happen and the probability would be zero. In practice, neither load nor capacity are perfectly controllable, and load can become too high or capacity too low. Load cannot be brought down to zero and (occasional) peaks cannot be precluded, just like capacity cannot be brought up to infinity and (occasional) declines cannot be precluded. This means there is always some residual probability of a flood or pandemic event occurring. For understanding this probability, which is a prerequisite for understanding risk, it is important to have insights into the levels of load and capacities.

7.2.3. The role of monitoring and detection

From the analyses it becomes clear that the threat of water and pathogens must be balanced out by sufficient defense capacities. This can only be done reliably if both the load and retaining capacity are known: how else can we be sure that the retaining capacity is (to the best of our ability) sufficient protection against the load? This reveals a parallel process in the prevention of floods and pandemics: the role of monitoring and detection abilities.

The literature and consulted experts suggest that such capabilities are currently higher for floods than for pandemics. Efforts in this realm include systematic weather forecasts, measurements and forecasts of water levels, as well as the monitoring of defenses. The Netherlands is especially advanced in this regard, with measurements and predictions for all relevant water bodies. Tremendous advancements in water monitoring over the years have been driven by high investments, and political, societal, and scientific attention. While pathogen monitoring has also advanced, these systems are less 'watertight'. This may in part be explainable by differences in investment and attention, but it must also be acknowledged that the nature of the measurements and predictions is hazard-specific and very different: water may be better measurable than pathogens. Floodwaters are fundamentally the same substance everywhere, while pathogens exhibit vast biological diversity. Clear measurement devices exist for hydrological parameters and these can be placed in water bodies. Pathogens are less easy to measure, both in terms of their location (could be any human or animal) and in terms of their characteristics (e.g. mutation rates). Pathogens can be identified with techniques like RNA or DNA sequencing, which is for example done with infection tests at the individual level and in sewage systems at the societal level. This is mostly used to monitor known diseases, since the detection of new diseases is not yet sufficiently advanced yet. Research is ongoing to advance these efforts, with the main challenge revolving around: how do you detect something (new pathogen) you do not know you are searching for? Such pathogens are also referred to as Pathogen X. Thus, by their nature, flood threats can be predicted by clearly defined measurable parameters, while pandemic threats require the detection of unknown and highly variable factors. Such factors not only include the detection of new pathogens, but also the measurement of pathogen mutation rates, host adaptability, and other factors that influence pandemic potential. This variability makes pandemic prediction inherently more uncertain.

This highlights the important role of monitoring in both floods and pandemics, but also the clear difference in nature and challenges underlying these measurements. Advanced water monitoring and forecasting exist for flood prevention, while pandemic monitoring remains underdeveloped due to the complexity of pathogen emergence and spread. Still, both pandemics and floods require proactive monitoring - just as water bodies are continuously observed, efforts could be expanded to track potential pandemic sources. In the context of pandemic, Jamison et al. (2017) refers to such monitoring as part of 'situational awareness'.

7.2.4. Regional, global, and the presence of hotspots

Flood causation is largely regional, while pandemic causation is inherently global. The emergence of a pandemic requires both a spark (pathogen emergence) and spread (transmission within and between populations). Similarly, a flood requires both a trigger (excessive rainfall, storm surge, etc.) and flood propagation (overland flow, river overflow). In both cases, different regions exhibit varying levels of risk for emergence and spread. In floods, certain geographical areas are more susceptible due to topography and climatic conditions. For pandemics, regions with high biodiversity, intensive livestock farming, and frequent human-animal interactions are potential sources of novel pathogens. This is

relevant in the context of monitoring and detection, and the implementation of associated preventive interventions. Both event types benefit from the systematic monitoring of spark/trigger hotspots as well as spread/propagation hotspots. The monitoring of flood-prone water bodies could then be compared to the systematic monitoring of pandemic-prone animal (or human) reservoirs and relevant entry points into the country.

7.3. Consequences and impact reduction

While the probability of floods and pandemics can be reduced with preventive measures, there is always a residual probability that remains. Therefore, it is important to view the full system of risk, encompassing both the causal side and the consequences side. The consequences of floods and pandemics can be compared based on the right side of the bowtie diagrams and the accompanying analyses in chapters 5 and 6. Impact reducing interventions form the barriers on this side of the bowtie. Such interventions can be structurally (continuously) present, implemented during a crisis, or implemented afterwards to reduce long-term or delayed impacts. The comparison between flood and pandemic consequences reveals that their mechanisms are hazard-specific for direct consequences and become more generic further away from the hazard. As with the causal side, that there are notable parallels around the underlying processes.

7.3.1. The further away from the hazard, the more similar the consequences

The consequences of floods and pandemic share more overlap, especially when looking at indirect consequences. Just like the causal mechanisms, the direct consequential mechanisms of floods and pandemics are specific to the hazard's nature. Direct flood consequences result from the physical effect of water, like damages to the built environment (buildings, infrastructure, land, etc.) and injuries and deaths from drowning or trauma. Direct pandemic consequences result from the physiological effect of the pandemic pathogen, which only affects human (and possibly animal) health. This can lead to deaths and injuries, but not to physical damage to the (built) environment.

Indirect consequences, being further removed from the hazard, share more overlap between floods and pandemics. Both events have consequences in each of the five categories (inferred from Sendai agreement): health, economic, social, cultural, and environmental. The presence of direct health effects, daily life disturbance, societal shock, and short-term business disruptions in both floods and pandemics leads to parallels in delayed and longer-term consequences, especially for society, the economy, and (mental) health.

7.3.2. Shared health, economic, and social consequences

Health consequences

Floods and pandemics both lead to a mix of direct, short-term, and delayed health effects. While floods primarily cause deaths and injuries due to drowning and trauma, pandemics result in deaths due to infectious disease spread. However, total flood-related deaths are much lower than pandemic deaths - floods caused approximately 53,000 deaths globally from 2002 to 2011, whereas pandemics can kill millions at once. Beyond immediate fatalities, both disasters place strain on healthcare systems. Floods may lead to hospital overcrowding due to injuries, but the impact is often localized and temporary. Pandemics, however, can overwhelm healthcare nationwide for prolonged periods, delaying routine care and leading to excess mortality from non-pandemic causes. Both disasters also create psychological burdens, including anxiety, PTSD, and depression, which can stem from direct trauma, social isolation, or economic disruption.

Economic consequences

Floods and pandemics both disrupt economies, but through different mechanisms. Floods cause physical damage to infrastructure and property, leading to direct financial losses and costly recovery efforts. Pandemics, in contrast, do not damage physical assets but can lead to widespread economic downturns due to reduced workforce availability, supply chain disruptions, and behavioral changes (e.g., lockdowns, reduced consumer spending). Both disasters result in indirect losses from production downtime and service interruptions.

Social consequences

The social impact of both disasters is profound. Floods may displace populations temporarily or permanently, creating disruptions in education, employment, and community stability. Pandemics disrupt societies more broadly, often requiring long-term behavioral adaptations such as social distancing or remote work. Vulnerable groups - including the elderly, those with pre-existing health conditions, and low-income populations - seem disproportionately affected in both cases.

7.3.3. Mediation of severity by hazard characteristics

The direct impact of both disasters is shaped by key determinants such as hazard severity, exposure, vulnerability, and preparedness. For floods, critical factors include water depth, rate of flow, rate of water rise, weather conditions, and duration. For pandemics, the key factors are pathogen infectivity, pathogenicity, population susceptibility (immunity levels), and transmission opportunities.

7.3.4. Unintended side effects of interventions

Disaster response measures can lead to unintended negative consequences. Flood evacuations, if poorly timed or executed, can increase casualties. Pandemic restrictions, while necessary for containment, may cause social isolation, economic hardship, and mental health issues. In both cases, a balance must be struck between mitigating the immediate threat and minimizing collateral damage. In pandemic advice, the consideration of societal consequences is now actively acknowledged (MIT, 2024; RIVM, 2023). For example, RIVM (2023) describes that decision-making for interventions should include considerations of "proportionality, effectiveness (and efficiency) and subsidiarity. Furthermore, the measures to combat infectious diseases must be feasible (feasible and affordable)" [p. 5, translated from Dutch]. Feasibility and affordability are important principles for flood management as well. The consideration of societal effects seems to be growing there, but perhaps lessons could be learned from the pandemic field.

7.3.5. The role of predictability and warning

Predictability plays a significant role in shaping disaster impact. In line with the above, floods are relatively well-predicted through hydrological modeling, allowing for advanced warning and preparation. Pandemics, on the other hand, involve greater uncertainty regarding the pathogen's characteristics, transmission dynamics, and public health response effectiveness. This unpredictability complicates early intervention and risk communication.

7.3.6. The challenge of preparedness for low-probability events

Disaster-potential floods and pandemics are both low-probability events which makes them difficult to prepare for. A low probability of occurrence is the same as a high (average) return time of such events. This means that they only occur once in tens to hundreds (sometimes thousands) of years. As a consequence, there is a very limited experience in dealing with such events, the context and circumstances of a new event may be very different from that of a previous event, and the lessons we learn are only truly tested once a new event occurs. The large scale and intensity of disaster-potential floods and pandemics also implies that it is almost impossible to fully prepare a system for it and not get overwhelmed. The impact of a disaster-potential flood or pandemic cannot be brought down to zero. However, this does not mean that impact-reducing measures cannot greatly reduce the consequences of such events. The high-consequence nature of these events also means the high and multi-faceted potential for tackling consequences; some of which are more predictable (and thereby easier targets) than others. The use of scenarios can greatly help in guiding disaster preparedness and optimizing such impact-reducing interventions. Based on the analysis, it seems that scenario-based preparedness is more established for floods and less so for pandemics. In the pandemic analysis, the dominant challenge that came forward was the unpredictability of a future pandemic pathogen. While acknowledging the endless variety of possible scenarios, the consideration of scenarios may still help with thinking about and preparing for pandemics. Experts consulted have indicated that this is something that the pandemic field could potentially learn from the flood field.

7.4. Additional insights from a workshop session

During the study, a workshop about modeling for disaster preparedness was attended. This workshop brought together experts in flood and disease modeling to explore insights in disaster preparedness modeling across these disciplines. The bowtie diagrams from this study were used as basis for brainstorming about case studies for research projects on these topics. This also enabled participants to identify shared challenges and opportunities in managing flood and pandemic risks.

Key insights emerged regarding feedback loops in risk perception and decision-making. For example, the levee effect in flood management - where protective measures lead to increased development in at-risk areas- parallels risk complacency in pandemics, where successful containment efforts may reduce long-term vigilance.

A major distinction discussed was the transboundary nature of pandemics compared to the geographically confined spread of floods. While both require cross-border coordination, pandemics rely more heavily on international cooperation. Similarly, both crises highlight the need for resilient, adaptive strategies that integrate risk reduction and crisis response.

Participants emphasized the importance of balancing investments across all phases of disaster management, recognizing that unknown risks will always remain. Clear protocols, human-centric approaches, and win-win strategies - where preparedness measures offer benefits even outside of crises - were highlighted as key areas for improvement.

Lessons from each field were also exchanged. Flood risk institutions in the Netherlands provide structured, long-term risk management, which pandemic response efforts could learn from. Conversely, the rapid response mechanisms in pandemic management could inform flood crisis preparedness.

The workshop underscored the value of cross-disciplinary collaboration, reinforcing that effective disaster management requires both sector-specific expertise and integrated, systemic approaches. Appendix M show the notes that were made on the bowties.

7.5. Inference of a risk-based conceptual framework

Reflecting on the findings of this comparative analysis, four key conceptual elements could be inferred that shape the functioning and management of disaster risks:

- **Risk mechanisms:** These are the underlying physical, biological, ecological, or societal processes that influence the likelihood and impact of disasters. They encompass both the causal mechanisms that drive the occurrence of disasters and the consequential mechanisms that affect their severity.
- **Intervention mechanisms:** Concrete actions aimed at reducing the probability or impact of a disaster. Intervention mechanisms may take various forms, such as structural, behavioral, or institutional measures, depending on the type of disaster.
- **Intervention-enabling processes:** Systems and processes that support or enhance the implementation and effectiveness of interventions. While they do not directly reduce risk, they are crucial for the effective functioning of risk reduction strategies.
- **Risk dynamics:** The development and characteristics of risk over time. This captures the evolving, uncertain, and complex nature of disaster risk. It focuses on how hazards, vulnerabilities, and exposure interact through different disaster phases (normal, threat, disaster, post-disaster).

These elements form a conceptual framework, which is visualized in Figure 7.1 and used throughout this study to guide the further analysis of both flood and pandemic risk and risk management. Table 7.1 provides examples of these elements for floods and pandemics.

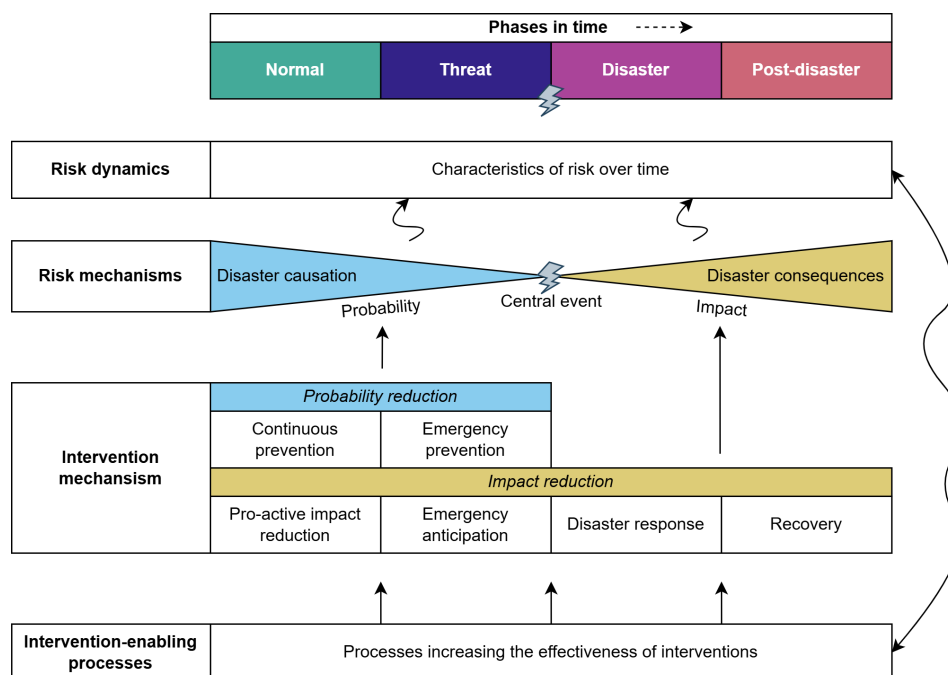


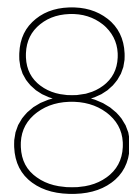
Figure 7.1: Conceptual framework inferred from the systems analysis. Risk (management) systems involve risk and intervention mechanisms, risk dynamics, and intervention-enabling processes.

Table 7.1: Conceptual elements of risk systems: illustrative examples from floods and pandemics

Element	Definition	Floods	Pandemics
Risk mechanisms	Underlying processes that influence the likelihood and severity of disasters, including both causal and consequential pathways	Rainfall, river overflow, exposure due to urbanisation	Zoonotic spillover, population density, global mobility
Intervention mechanisms	Concrete measures aimed at reducing the probability or impact of a disaster	Dikes, evacuations, spatial zoning	Animal distancing, vaccination, quarantine
Intervention-enabling processes	Supportive systems, processes, and capacities that enable interventions to function effectively	Flood forecasting, early warning, emergency training	Disease surveillance, risk communication, public trust
Risk dynamics	The evolving nature of risk over time, shaped by changing hazard, exposure, and vulnerability	Rapid onset and predictable development	Slow onset and evolving risk due to mutations and societal behavior

Part III

Timelines of flood and pandemic cases



Case-based analysis

Studying flood and pandemic timelines in practice

This chapter introduces the analysis performed for Part III of this study. Building on Part II, which focused on a mechanistic understanding of flood and pandemic risk, Part III involves the analysis of recent cases to better understand the characteristics of flood and pandemic risk over time. The cases studied are the floods in Limburg in 2021 (referred to as Limburg-21) and the Covid-19 pandemic in the Netherlands. The focus will be on the timelines of these events. The cases and their methods are shortly introduced in this chapter. The findings are discussed in Chapters 9 and 10, which will be used to answer the second research sub-question, SQ2: *How do the timelines of floods and pandemics compare?*

8.1. Case study method

A case study is a research method used to "generate an in-depth, multi-faceted understanding of a complex issue in its real-life context" (Crowe et al., 2011, p. 1). In this study, the cases of Limburg-21 and Covid-19 are used as 'instrumental' case studies, analyzing a particular case (a flood or pandemic) to gain an appreciation of floods and pandemics more broadly (Crowe et al., 2011). The purpose is mainly 'descriptive', analyzing and describing the timeline of these events (Priya, 2021).

The cases will first be analyzed separately, describing the sequence of events and inferring phases in time. The timelines will then be compared to infer differing and general patterns between the events.

The use of cases helps understand the real-life situation of a flood or pandemic in the Netherlands. However, it must be noted that neither of the events can be used to fully represent a pandemic or flood timeline. Every flood or pandemic event is different and highly dependent on the circumstances. Moreover, the cases should be compared with caution, since the Covid-19 pandemic had a much bigger impact than the floods in Limburg. For example, no fatalities occurred during the floods, while many occurred during Covid. However, there are no recent floods with fatalities in the Netherlands, and the Limburg floods are considered most relevant for this study.

8.2. The cases

The case studies of Limburg-21 and Covid-19 were chosen based on their recency and impact. Both are examples of low-probability high-consequence events.

8.2.1. Limburg-21

In July 2021, Western Europe experienced severe rainfall and flooding events, also affecting the province of Limburg in the Netherlands. Triggered by unprecedented rainfall, water levels in the rivers reached record highs, leading to flooding of villages and extensive damage. This case offers an opportunity to explore the timeline of a recent flood event in the Netherlands, including the responses from

authorities, and the recovery efforts, providing insights into Dutch flood risk management and dynamics over time.

8.2.2. Covid-19

The Covid-19 pandemic was caused by the novel SARS-CoV-2 virus and had a large global impact, including in the Netherlands. The virus was first identified in China in late 2019 and then spread rapidly around the world. This case will serve as an example of a pandemic event, exploring the timeline of events in the Netherlands. A detailed timeline of the case is included in Appendix G.

8.3. Overview of included literature

Studies into both events are still ongoing, but multiple reports have been published already. This includes gray as well as academic literature into the causes, consequences, and interventions used during these events. The studies have different focuses, including some on economic consequences, health consequences, or social consequences.

An overview of the core documents included is shown in Table 8.1 for the Limburg-21 floods and in Table 8.2 for the Covid-19 pandemic. Additional references were identified throughout the analysis, as cited in the chapters.

Table 8.1: Key documents used for the case study of the Limburg-21 floods.

Citation	Description
ENW (2021)	Describes early findings and explanations about the case, including descriptions of causes and consequences.
Kok et al. (2023)	Describes damage calculations (including application of the SSM2017).
Endendijk, Botzen, et al. (2023)	Describes the impact as experienced by households.
Endendijk, Botzen, et al. (2023)	Study on the (vulnerability to) damage of the flood for households.
De Jong et al. (2023)	Study into the health effects as perceived by health professionals after the floods in Limburg.
Pot et al. (2024)	Study into long-term lessons from the floods, as well as historical considerations.
B. Kolen et al. (2024)	Study on lessons learned with regard to evacuation and emergency measures.

Table 8.2: Key documents used for the case study of the Covid-19 pandemic.

Citation	Description
Hao et al. (2022)	Study on the (global) origins of the pandemic. Not specific to the Netherlands.
Nivel and RIVM (2022)	Systematic literature study into the effects of the pandemic on population health and well-being.
de Boer et al. (2023)	Study into the health and economical aspects of the Covid-19 crisis.
RIVM (2022a)	Study into the influence of the pandemic on the health and lifestyle of Dutch adults.
Kullberg and Vonk (2021)	Study into the (expected) societal impacts of the pandemic.

Flood case: Limburg-21

Timeline of events and interventions

This chapter describes the timeline of the Limburg-21 floods in the Netherlands. Together with Chapter 10, this analysis can be used to answer SQ2: *How do the timelines of floods and pandemics compare?* The comparative insights are discussed in Chapter 11.

9.1. Timeline of Limburg-21

The area of interest is located in the province of Limburg in the Netherlands. The focus is on two areas specifically, namely those around the river Meuse and the area around the tributary river Geul. The unfolding of events in these two rivers is discussed separately. It must be noted that there are other streams along which flooding occurred as well, but the Geul and Meuse are chosen as main areas of interest for the analysis. A map of the rivers and tributaries in the area is shown in Figure 9.1.

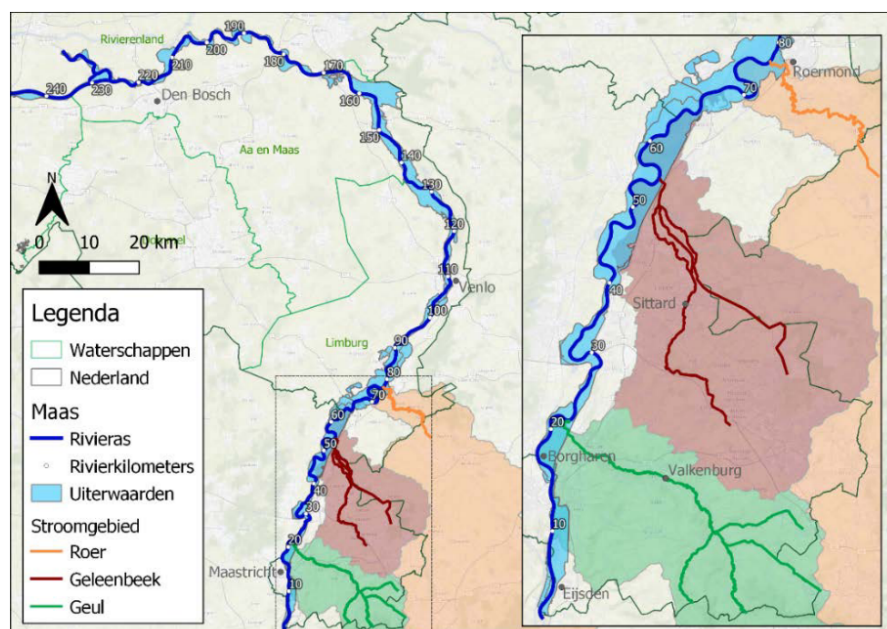


Figure 9.1: Overview of the trajectory of the Meuse river in the south-eastern area of the Netherlands. Coloured areas indicate the catchment areas of the Roer, Geleenbeek, and Geul. Figure copied from ENW (2021).

9.1.1. Normal phase: before the extreme summer rain (pre-July 2021)

Water system and flood hazard in Limburg

Meuse. Limburg's water system is primarily dominated by the Meuse river, a fast-responding, rain-fed river originating in northern France. The Meuse is classified as a primary water system, meaning its management falls under national programs and institutions, with Rijkswaterstaat overseeing its maintenance. However, flood protection levels for non-primary dikes are determined at the provincial level. The Meuse river enters the Netherlands in the south of Limburg, below Maastricht. The tributaries Geul, Geleenbeek, and Roer join the river Meuse more downstream in Limburg. The area around the Meuse consists of both unembanked areas (no levees) and small dike ring areas (protected by levees). After a flooding event in this area in 1995, measures had been taken to reinforce levees and mitigate extreme water levels on the Meuse. This included for example the Room for the River program. In 2017, new safety standards were defined for the levees, which are to be met by 2050 (B. Kolen et al., 2024).

Geul. The water system along the Geul was designed to deal with 1/25 per year flooding events (B. Kolen et al., 2024). This means that water volumes are expected to exceed the capacity of the system approximately once every 25 years. There were no levees to protect the areas around the Geul. The area of the Geul includes cities like Valkenburg and Meersem.

The foundational layers of water management in the Netherlands

The Netherlands has long prioritized flood prevention as a key element of its water management strategy, followed by spatial adaptation to minimize flood damage. However, crisis management, while essential during extreme weather events, has been a less emphasized layer in Dutch flood policies. An overview of the focus on these layers through time is shown in Figure 9.2.

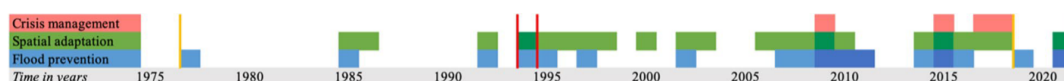


Figure 9.2: Historical overview of the presence of flood prevention (blue, bottom layer), spatial adaptation (green, middle layer), and crisis management (red, top layer) policies in the Netherlands. Extreme events, such as the floods in 1995 and 2021, brought renewed attention to crisis management strategies. The vertical lines indicate flood events (red) and extreme drought (yellow). Figure copied from (Pot et al., 2024)

Flood risk management in Limburg

Limburg's history of flooding events dates back decades, with major events in 1993 and 1995 influencing current flood risk management policies. The 1993 floods in Limburg led to the evacuation of 8,000 people and caused significant damage, estimated at 250 million guilders. In response, recommendations were made to widen the riverbed and reinforce dikes to meet a 1:250 safety standard, reflecting the need for more robust flood defenses (Pot et al., 2024).

The 1995 floods further highlighted the vulnerability of Limburg's flood defenses. In the aftermath, the Deltaplan Major Rivers was initiated to accelerate dike reinforcements and implement emergency dikes in areas where no embankments were in place. These emergency measures aimed to quickly achieve a higher safety level of 1:50, while longer-term solutions, such as riverbed widening, were pursued (Pot et al., 2024).

The Meuse Works project, launched in 1997, sought to create more room for the river while simultaneously reinforcing emergency dikes. This initiative aimed to balance flood risk reduction with ecological restoration, aligning with the Room for the River program introduced in 2006, which primarily focused on the Rhine and downstream Meuse (Pot et al., 2024).

By 2019, discussions began regarding the need for even higher flood safety standards in Limburg, specifically a 1:100 safety level. The province requested that 22 out of its 45 dike trajectories meet a 1:30 safety standard instead of the proposed 1:100, in order to minimize the landscape impact and reduce costs. However, in June 2021, the Delta Commissioner advised adherence to the 1:100 norm to ensure adequate long-term flood protection (Pot et al., 2024).

9.1.2. Threat phase: rise of a flood threat (mid-July 2021)

Note that the threat phase was different in each area: the moment of shift from threat to event is at the moment the flood happens, which differed between the Geul and the Meuse.

Extreme precipitation (13-14 July)

First signals of a water threat arose on 11 July. On this day, weather forecasts started indicating extreme precipitation events in the Limburg area (ENW, 2021). The initial forecasts underestimated the precipitation intensity, and were adjusted upward multiple times in the following days. On 12 July, the Royal Netherlands Meteorological Institute (KNMI) issued a code yellow for rain the next day (B. Kolen et al., 2024). From 13 till 16 July, rainfall occurred in large areas of Europe, including Limburg. The rainfall on 13 and 14 July was especially extreme. During these days, the KNMI adjusted their weather warnings to code orange (13 July) and code red (14 July). Record amounts of rain fell (never measured before), with estimated event probabilities between 1/100 and 1/1000 per year (ENW, 2021). These amounts of rain were especially unexpected for the summer season. It was estimated that climate change contributed between +20% and +800% to these probabilities (ENW, 2021). The widespread extreme rainfall (13-14 July) was the driver of a flood threat for the Meuse and Geul areas.

Precipitation driving up peak discharge and water levels (14-18 July)

Precipitation in the catchments of the Meuse and Geul drives up water levels and peak discharges there, which propagate through the river towards downstream areas. Water authorities therefore use precipitation forecasts to inform forecasts of peak discharges and river water levels. These forecasts in turn inform flooding predictions. On the 12th of July, the Limburg safety region started giving of warnings for expected high water levels in the Meuse and its tributaries (B. Kolen et al., 2024). Estimations of the water levels were adjusted multiple times over the following days. Peak water levels in the Meuse and tributaries in Limburg were reached between 14 and 18 July. This is further detailed below.

Peak water levels in the Geul (14-15 July) and Roer (16-17 July)

For the Geul area, the first peak discharges and water levels occurred already on 14 July. As the valley of the Geul tributary is hilly and fast-responding, peak water levels occurred in the evening of 14 July, directly following the extreme rainfall. In the Geul area, water levels were several decimeters to one meter higher than estimated (ENW, 2021). The measured water levels were estimated to have an exceedance probability of 1/100 to 1/1000 per year. Many areas along the Geul have a protection level for 1/25 per year water levels. Essentially, this means that a flood probability of 1/25 per year is accepted, and that the events in 2021 ($<1/100$ per year) were within the accepted bounds for which the water system is designed (ENW, 2021). Peak water levels in the other tributaries were reached after those in the Geul. Peak levels in the Geleenbeek tributary were reached on the early morning of 15 July, soon after those in the Geul (both hilly, fast-responding areas). Peak levels in the Roer tributary followed later (16-17 July), as this tributary stretches 165 km upstream with peak water levels propagating from Belgium and Germany to the Netherlands.

Geul response to threat (14-15 July)

On 14 July, various campsites directly around the Geul were evacuated preventively based on emergency protocols for high water levels. Some care institutions in Valkenburg and Meerssem also evacuated preventively, but did this on their own initiative. Besides the evacuation of campgrounds (regional protocol) and the health care institutions (self-initiated), no preventive evacuation notices were given. The emergency protocols and scenarios for the Geul area did not foresee large-scale evacuations for the area. During the high water, emergency measures included temporary flood defenses (mostly sand bags put down by residents) to limit the size of floods and to prevent damages to homes and businesses.

Meuse peak water levels (15-18 July)

For the Meuse area in Limburg, upstream peak discharges near St Pieter are used to estimate downstream water levels and flood probabilities (B. Kolen et al., 2024). The peak discharges near St Pieter were underestimated until just a few hours before the peak there (15 July), after most rainfall already occurred (ENW, 2021). The peak at St Pieter occurred in the night from 15 to 16 July, amounting to 3260 m³/s (B. Kolen et al., 2024).

The extreme precipitation and peak discharges then drove up water levels in the Meuse. These water levels also depend on the duration of high water and the size and timing of discharge from tributaries (ENW, 2021). For the Meuse river, water levels at the Dutch border were higher than expected. On 14 July, the forecasted water level was still 1 meter lower than the peak level measured on 15 July (NAP +45,23m at Borgharen). These peak water levels had an exceedance probability of 1/100 to 1/200 per year, and even less in summer (ENW, 2021). From 15 July, this peak water level propagated downstream through the Dutch trajectory of the Meuse, taking almost five days in total (ENW, 2021). Peak water levels downstream turned out lower than forecasted (ENW, 2021). This was due to flattening of the hydrograph along the trajectory (B. Kolen et al., 2024). The measured water levels downstream in Limburg had less extreme exceedance probabilities, such as 1/50 per year in Venlo and 1/15 per year at Gennep (ENW, 2021). Throughout Limburg, the peak levels in the Meuse were reached between 15-16 July (St Pieter), 17 July (Roermond and Venlo), and 18 July (Gennep). An overview of the water levels between 13 and 17 July at three locations in the Meuse is shown in the Figure 9.3.

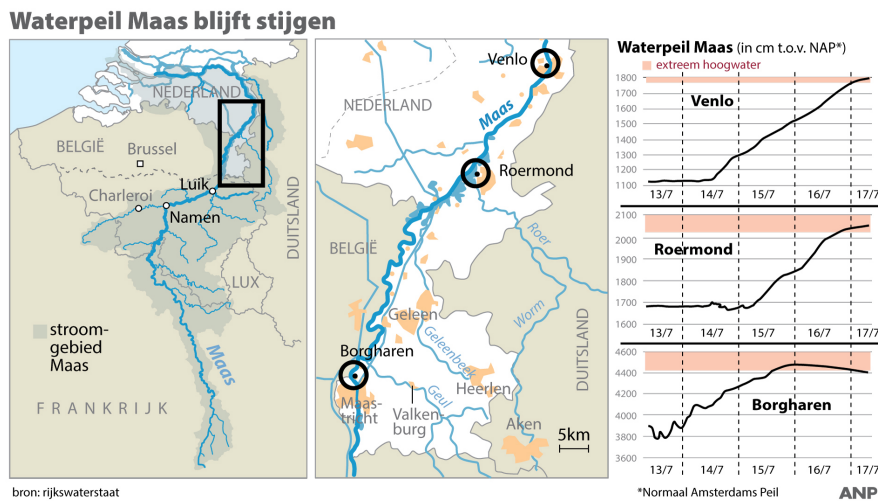


Figure 9.3: Water levels in the Meuse (between 13 and 17 July). Figure copied from <https://www.dutchnews.nl/2022/07/help-dries-up-for-people-with-limburg-flood-damage-ombudsman/>.

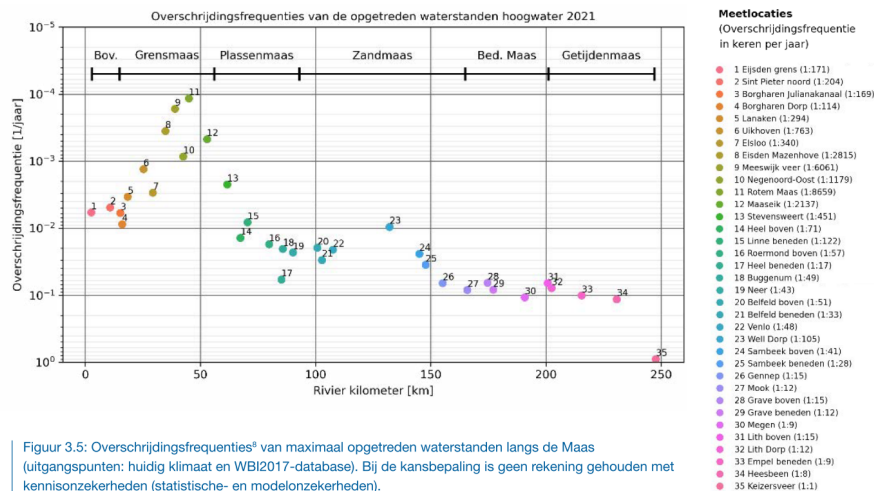


Figure 9.4: Exceedance probabilities along the Meuse river during the high waters in 2021. Copied from ENW (2021), Figure 3.5.

Meuse response to threat: determining flood probabilities (15-18 July)

In the context of the high water levels in Limburg, the Limburg water authority was responsible for carrying out an inventory of weak spots in flood defenses along the Meuse and identifying areas at risk of

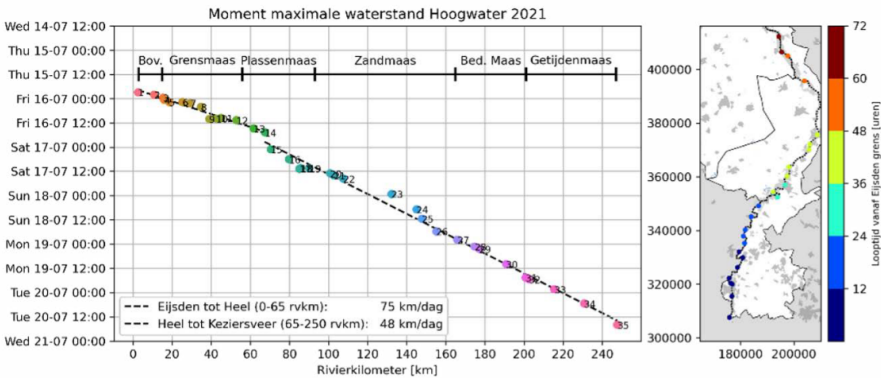


Figure 9.5: Moments of maximum water levels along the Meuse river during the high water levels in 2021. Copied from ENW (2021), Figure B1.1.2.

Dijk	15/07/2023 9:30 (H levels from RWS-H12)	17/07/2023 9:30 (H levels from RWS-H09)	16/07/2023 16:30 (H levels from RWS-H07)	16/07/2023 13:30 (H levels from Limburg water authority)	15/07/2023 (Expected discharge of 3350 m3/s - overtopping, H levels from Limburg water authority)	15/07/2023 (Expected discharge of 3700 m3/s - overtopping, H levels from Limburg water authority)
Visserweert						
Heel						
Older Veste						
Merum						
Roermond Zuid						
Hockeyvelden						
Voorstad St. Jacob						
Arndt						
Alexanderhavenroutel						
Waterzuivering Roermond						
Buggenum						
Neer						
Baarlo						
Steyl						
Venlo						
Blerick						
Velden						
Germap						
Heien						
Mock-Ottersum						

Figure 9.6: Forecasts of areas at risk of flooding between 15 (right side) and 18 (left side) July 2021. Copied from B. Kolen et al. (2024), Figure 5.

flooding (B. Kolen et al., 2024). Based on their estimations, areas were assigned code red (significant flooding probability), yellow (uncertainty), or green (safe). In turn, the safety region and waterboard could use such assessments to make decisions about emergency and evacuation measures. The Limburg water authority started their inventory before the peak discharge reached Limburg (15 July) and updated it once or twice a day after. The main input for flood probability estimations is the (forecasted) water levels. In general, the Limburg water authority is responsible for water level predictions for the tributary streams (including Geul), while the national water authority (WMCN) is responsible for predictions along the Meuse. In the case of Limburg-21, however, the Limburg water authority also carried out its own forecasts of water levels for the Meuse (B. Kolen et al., 2024). They did this because of the extreme discharges from the streams, which they thought could lead to an underestimation of water levels by the national authority. The two forecasts (Limburg authority versus national authority) were quite different, with more extreme water levels forecasted by the Limburg authority (B. Kolen et al., 2024). On 15 July and the morning of 16 July, the Limburg water authority used its own forecasts to assess weak spots in the levees and flood-prone areas. Initially many areas were assigned code red, of which most were later updated to yellow, and then green as the peak discharge passed (see Figure 9.6). On 16, 17, and 18 July, the Limburg water authority used the water level forecasts from the national authority WMCN to assess flood probabilities.

Meuse response to threat: decision for preventive evacuation (15 July)

According to protocol, the safety regions are responsible for making decisions regarding evacuations. They did this based on the inventory of weak spots and flooding probabilities as supplied by the Limburg water authority. In the case of Limburg-21, the peak discharge and water level predictions varied over time, which is something the safety regions had to deal with in their decision-making process. On 12 and 13 July, the safety region already issued warnings for high water levels (B. Kolen et al., 2024). On 14 July, they decided to issue the 'highest regional phase of alarm' (GRIP-4), which enables regional coordination of a crisis response. For their decisions regarding evacuation, they primarily used the flood predictions from the Limburg water authority of 15 July (still based on the regional water level

predictions, rather than those from the WMCN). Their highest priority was to protect people and animals. Therefore, they decided to evacuate all areas that might flood (code red and code yellow from the weak spots analysis). Areas at (even extremely small) risk of flooding or at risk of becoming cut-off (surrounded) by the water would be preventively evacuated (B. Kolen et al., 2024).

Meuse response to threat: planned temporary and removable flood defenses (14-16 July)

Certain predicted water levels trigger the implementation of planned emergency measures. These measures were laid out in roadmaps and the Limburg water authorities and municipalities along the Meuse are responsible for their execution. Planned emergency measures in Limburg consisted of temporary and removable flood defenses. On 14 July, it was decided to scale up to the highest phase of planned defense and deploy all equipment (B. Kolen et al., 2024). The used equipment included 4km of removable defenses (>200 mobile flood walls), 2-3km of temporary defenses (23 locations, approximately 2000 bigbags and 120,000 sandbags in total), 140 water pumps, and the closing of passages with valves (B. Kolen et al., 2024). Normally, these planned defenses should be constructed in 5 days, following the plan in the roadmap. However, in July 2021, it had to be done quicker. In total, the construction took 53 hours of round-the-clock work, starting on 14 July at 14.00 and finishing on 16 July at 19.00. The lowest defenses were built first and the highest last.

Meuse response to threat: execution of preventive evacuation (15-16 July)

In line with their decision, the Limburg safety region called for evacuation (15 July). Mayors were given the mandate to decide to evacuate and emergency ordinances were drawn up. Evacuations were started at different times, as the flood surge would take time to propagate from the south to the north of Limburg. Evacuation notices corresponded to a (strong) advice to evacuate, not a legal obligation, and were shared via news reports, social media, NL-alerts, civil defense sirens, and (sometimes) church bells (B. Kolen et al., 2024). In cases of acute threats, emergency services used microphones on police vans to provide information. Additionally, there was a local broadcaster which functioned as 'disaster broadcaster', assisting the safety region. Additional information was shared via informal channels, such as Whatsapp. Many people acted on the information, also resulting in citizen's initiatives and local protective measures. Overall, evacuations were carried out on the afternoon and evening of 15 July, as well as on 16 July in the North of Limburg. By that time (16 July), the flood probabilities had already reduced, but the evacuation call was not reconsidered (B. Kolen et al., 2024). For the execution of the evacuations, an order of prioritization was established: (1) flood safety of people and animals, (2) care, testing, vaccination against the coronavirus; (3) continuity of vital infrastructure; (4) production processes; (5) economic interests. The evacuation strategy focused on encouraging self-reliance of people and institutions, meaning that people evacuate themselves and organize their own assistance and shelter. People were not forced to depart, but most people did adhere to the recommendation and vacated the area in good time (B. Kolen et al., 2024). Rescue teams from all over the Netherlands traveled to Limburg to aid where necessary. It is estimated that around 50,000 people evacuated the areas in Limburg.

Meuse response to threat: emergency measures (15 July)

In addition to planned flood defenses, triggered by high water levels, additional emergency measures were realized based on assessments of the levees and initiatives of municipalities and residents. As discussed, the Limburg water authority carried out inventory of weak spots in levees, identifying vulnerable locations. This was not only used to inform evacuation decisions, but also to determine emergency measures. These decisions were mostly made on 15 July. Based on their assessment, the amount and location of anticipatory emergency measures was determined. One of the aims was to reduce the impact of potential breaches. Equipment and sand bags were deployed based on continuously updated water level predictions and the elevation of assets in each area.

Other emergency measures, carried out during the high water, were informed by reports from dike inspectors (B. Kolen et al., 2024). All primary flood defenses (levees/dikes along the Meuse) were inspected regularly (up to once every four hours). These inspections were carried out by (voluntary) dike inspectors, assisted by Red Cross workers, and at some locations also professional inspectors from the water authority. Inspection reports were communicated to a control center in Roermond, from which emergency measures were communicated to the regional coordinators of Limburg north and south. Implementation was planned from there.

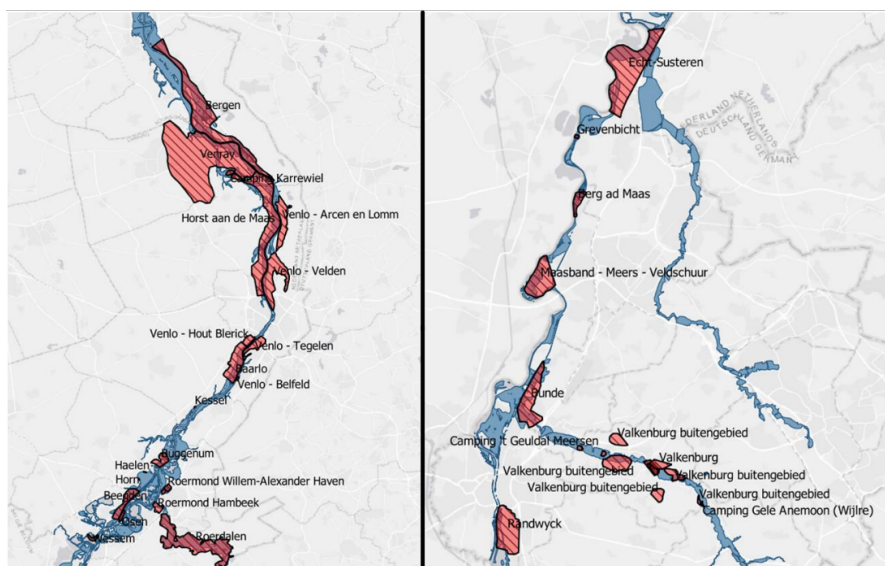


Figure 9.7: Flooded areas (blue) and areas with emergency ordinances (red) in the north (left) and south (right) of Limburg. Figure adapted from B. Kolen et al. (2024), Figure 3.

The execution of emergency measures was done by "joint efforts of the water authorities (Limburg Water Authority and the other water authorities in the Netherlands), municipalities, military, fire service and local residents" (B. Kolen et al., 2024, p. 13). Along the Meuse, these emergency measures were targeted at height deficits. This mainly involved the placement of sand bags to increase the retaining height of the dikes. These sandbags were made available by the Limburg water authority, municipalities, and local contractors. Transportation to flood sites and placement on the dikes was often done by local residents. This was possible because the water level predictions were available to the public and the retaining height of dikes was visible. The Limburg water authority supervised the execution and instructed people on the placement of the sandbags. Altogether, man power was predominantly supplied by local residents, the military, and fire services. Other water authorities assisted the Limburg water authority by providing equipment as well as inspectors and information coordinators (B. Kolen et al., 2024).

9.1.3. Disaster phase: flooding in Limburg (mid-July 2021)

Flooding of the Geul area

In the night of 14 to 15 July, the Geul area was surprised by floods, with water rising quickly (ENW, 2021). The floods particularly affected residents in Valkenburg, but also affected downstream areas including Meerssen and along the Juliana Canal. The flooding in Valkenburg started around 22:45 on 14 July, reached its peak water level around 05:30 on 15 July, and the water had resided by 22:45 that day. Around 11:00 on 15 July, during the floods, around 700 houses in Valkenburg suffered from power outages. This affected mostly flooded houses, but also not-flooded areas (ENW, 2021). Overall, the floods along the Geul were estimated to have affected 2000-2400 homes, around 4000 residents, nearly 400 companies, around 700 hectares of agricultural land, 78 vulnerable institutions (including health care and education), 60 national monuments, and 1 sewage plant. The result was a lot of physical damage, as well as damage from business disruptions. Both are discussed further in the section on consequences.

Response to flooding in Valkenburg (Geul) In Valkenburg, approximately 1000 people were exposed to the floods. These people did not leave the area until after the floods. Other people in the area did leave after the floods ('fleeing' the area), and a few were helped ('rescued') by aid workers. Following the power outages, it was decided to evacuate non-flooded districts that were affected. This was based on the assumption of possible unlivability of the area (B. Kolen et al., 2024). From 15 July, various emergency ordinances were issued in the Geul area, also to deter disaster tourism.

Category	Geul	Roer	Meuse	Total
Homes	2000 - 2400	60 – 75	300 - 400	2360 – 3000
Residents	3840 - 4160	60 – 120	500 - 600	4400 – 4880
Companies	390 - 400	10 – 15	190 - 200	590 – 615
Agriculture (ha)	700 – 725	925 – 975	9500 – 10,000	12,000 – 12,500
- pasture	73%	54%	60%	59%
- arable land	27%	46%	40%	41%
Vulnerable institutions	78	8	72	158
- care / education	12 / 5	0 / 0	2 / 0	15 / 5
Industrial emission installations	0	0	1	1
National monuments	60	8	68	136
Sewage plants	1	0	1	2

Figure 9.8: Overview of objects affected by the Limburg-21 floods, copied from Kok et al. (2023).

Flooding of the Meuse area

Flooding from the Meuse occurred spread out over the days of high water. Overall, the floods along the Meuse were estimated to have affected 300-400 homes, 500-600 residents, nearly 200 companies, nearly 10,000 hectares of agricultural land, 72 vulnerable institutions (including health care and education), 68 national monuments, and 1 sewage plant. Except for the agriculture affected, these numbers are (much) lower than those along the Geul. Figure 9.8 shows an overview of the total number of residents, objects and institutions in the flooded areas along the Geul, Roer, and Meuse.

An overall summary of the threat and event timeline is shown in Figure 9.9.

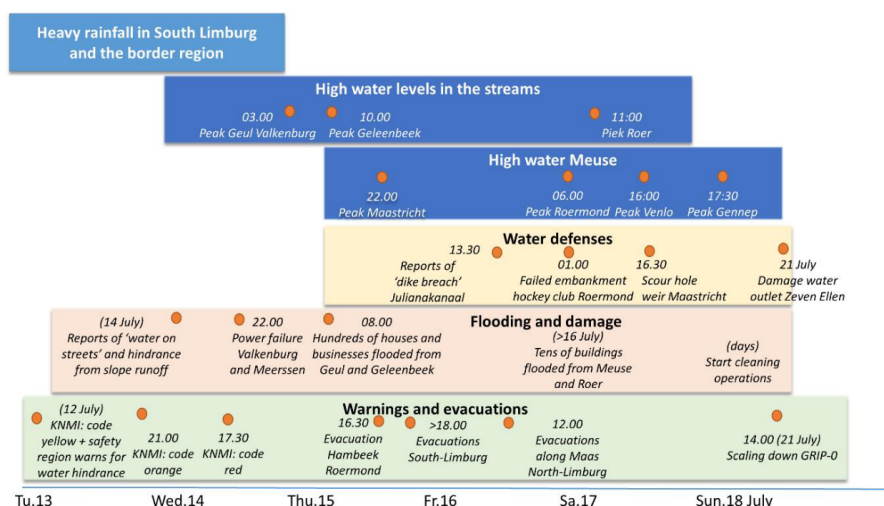


Figure 9.9: Timeline of events during Limburg 2021 floods. Copied from B. Kolen et al. (2024), who translated it from (ENW, 2021).

9.1.4. Post-disaster phase: recovering from the floods (post-July 2021)

On July 18, 2021, the safety region downgraded the alarm level to GRIP-0, marking the end of the emergency phase. In the days that followed, efforts focused on cleaning up debris and assessing the extent of the damage. Reconstruction, compensation, and longer-term recovery followed after. This also has to deal with the consequences explained in the next Section.

9.2. Overall consequences and experiences from the floods

Overall economic damages. According to first estimates in September 2021, the flood affected "more than 2,500 houses, more than 5,000 inhabitants and around 600 businesses" (ENW, 2021, p. 9). The total economic damage for the Netherlands was estimated to be between 350 and 600 million euros, with the largest of these damages happening in the smaller regional rivers in the Geul flood

plain. Moreover, the damages that were most significant were the damage to houses and businesses, the interruption of business activities, the damage to infrastructure, and the loss of crops (ENW, 2021). Later calculations updated the damages to be between 400 and 500 million euros (Kok et al., 2023). Several factors contributed to the economic damages. The main flood characteristics influencing the damages were water depth, arrival time, and flow rate. The floods only lasted one day, but buildings and inventories took a long time to dry, leading to longer recovery times. Moreover, there were not many reconstruction specialists in the area, which seems to have led to longer waiting times and associated losses (Kok et al., 2023). Cascading impacts of the flood were limited, because utilities and accessibility in the area were only disrupted briefly.

Health impacts. In a study into the health impacts of the Limburg-21 floods, De Jong et al. (2023) found that people experienced increased stress, fear and anxiety during and directly after the flood. This was related to confrontation with the flood water in their homes, the process of evacuation, and was increased among elderly and children (vulnerable groups). They also found that people experienced joint and muscle complaints as a consequence of the carrying and lifting of objects during the flood and in the cleaning up process after. Moreover, there was an increase in gastrointestinal symptoms and in respiratory infections, which may have been associated with flood-caused contamination. (De Jong et al., 2023). The researchers also found psychological complaints (including fear, stress, and depression) to be elevated one month after the flood (De Jong et al., 2023). This may have led to work or school absenteeism, just like the cleaning up and repair process did shortly after the flood. The occurrence and severity of complaints seemed related to the extent to which people were affected by the floods (De Jong et al., 2023).

Household experiences. A study into the experiences of households during the flood highlights the role of early warnings and flood risk information communication (Endendijk, Botzen, et al., 2023). They found that the perception of risk influences adaptation behavior as well as evacuation behavior. Residents who were aware of flood risks implemented significantly more flood damage mitigation measures. These mitigation measures, in turn, reduced the damages for such households significantly. A related study showed that emergency actions, such as placing sandbags as barriers and moving belongings to higher floors, had the biggest impact, reducing the damage to houses and household content by 30-40% (Endendijk, Botzen, et al., 2023). Structural flood damage mitigation measures - such as building with water-proof materials - also had a significant impact, but less than the emergency measures. Endendijk, Botzen, et al. (2023) additionally found that the majority of people who received a warning did evacuate the area. Residents who did not receive such a warning evacuated significantly less. The study also found that high levels of stress were experienced around the floods, affecting the majority of people surveyed (75%). They argue that this is likely due to the large impacts of the flood and the slow and uncertain compensation following it (Endendijk, Botzen, et al., 2023).

10

Pandemic case: Covid-19

Timeline of events and interventions

This chapter describes the timeline of the Covid-19 pandemic in the Netherlands. Together with Chapter 9, this analysis can be used to answer SQ2: *How do the timelines of floods and pandemics compare?* The comparative insights are discussed in Chapter 11.

10.1. Timeline of Covid-19

10.1.1. Normal phase: before the emergence of Covid-19 (pre-November 2019)

Before Covid-19, the world had faced several pandemics, including the Spanish Flu (1918) and more recent outbreaks like Ebola (2014) and MERS (2015). These events shaped preparedness worldwide, particularly in relation to influenza (Lindhout & Reniers, 2020). The WHO's 2018 pandemic influenza preparedness framework guided many countries, including the Netherlands, in crafting pandemic preparedness plans. The Dutch National Safety Strategy 2019 primarily focused on pandemic influenza preparedness, not on the threat of a novel, unknown virus (Lindhout & Reniers, 2020). Guidelines for dealing with infectious disease outbreaks were in place, such as the framework shown in Appendix E.

10.1.2. Threat phase: rise of the Covid-19 threat (November 2019 - February 2020)

Emergence of a pandemic pathogen in China (November 2019)

Hao et al. (2022) performed an academic analysis into the origins of the Covid-19 pandemic. First reports of the virus appeared in the city of Wuhan in China in November 2019 (Hao et al., 2022). There it emerged as a human-to-human transmissible epidemic, caused by the pathogen named 'severe acute respiratory syndrome coronavirus 2' (SARS-CoV-2). This virus has a high infectivity and pathogenicity, which was discovered early on in the pandemic. However, lacking public awareness and interventions allowed the virus to spread and mutate globally (Hao et al., 2022). Early on in the pandemic, two competing theories emerged on the origin of the SARS-CoV-2 pathogen. One theory claims that the virus escaped from a laboratory (a laboratory spillover event), while the other claims that the pathogen emerged from a zoonotic outbreak. Hao et al. (2022) argue that the latter scenario is most likely, based on considerable support for it. The Huanan Market in Wuhan was the early epicentre of the pandemic, with direct connections to many of the earliest reported cases. Additionally, other cases had had contact with other markets in the city. It must be noted that, in theory, the real first case of SARS-CoV-2 could have been located elsewhere (being unreported).

Growing global threat of Covid-19 (December 2019 - February 2020)

From China, the virus started to spread to other countries. By January 30, 2020, the WHO declared a Public Health Emergency of International Concern. Despite this, the Dutch authorities, like many others, initially underestimated the potential threat (The Independent Panel for Pandemic Preparedness & Response, 2021). At the time, the possibility of Covid-19 reaching the Netherlands seemed unlikely. By February 8, the virus has reached 24 countries according to the WHO (Lindhout & Reniers, 2020).

Introduction of the Covid-19 pathogen into the Netherlands (February 2020)

Similarly to the uncertainty of the global origin of SARS-CoV-2, the original introduction of the virus into the Netherlands is uncertain. The first case was reported in February 2020 and was someone who had recently been in Italy, where the virus was already spreading. However, later investigations found that the virus may have been present weeks earlier already (Rosman & Klaassen, 2020). Following the first case, many cases were connected to the Dutch celebrations of Carnival and to travelers coming back from skiing vacations elsewhere in Europe (Onderzoeksraad voor veiligheid, n.d.; Rijksoverheid, n.d.). While the initial responses focused on tracing and quarantining, the uncertainty around the virus's spread and severity meant that more decisive actions would be delayed.

10.1.3. Disaster phase: Covid-19 in the Netherlands (February 2020 - March 2023)

In line with van Amerongen et al. (2024), the pandemic period in the Netherlands will be divided into three sub-phases. Each of the phases lasts approximately one year. Phase I starts with the beginning of the pandemic in the Netherlands and is characterized by the absence of vaccines and the reliance on non-pharmaceutical interventions. Phase II involves the roll-out of vaccination campaigns alongside the continuation of significant non-pharmaceutical measures. Phase III is the post-vaccine phase, with boosters and minimal presence of other interventions. Each of the phases is further discussed below. A detailed timeline of interventions throughout the Covid-19 pandemic is included in Appendix G. A summary of the non-pharmaceutical interventions is shown in Figure 10.1.

Pandemic phase I (February 2020 - January 2021)

The first phase of the pandemic was marked by a steep rise in cases, pushing the government to impose an Intelligent Lockdown. This strategy relied on citizens' individual responsibility while still allowing non-essential businesses to operate under strict conditions. The Dutch healthcare system rapidly expanded its ICU capacity, doubling from 1,150 to 2,400 beds (van Amerongen et al., 2024). However, elective care was postponed, and the economic impact started to be felt, leading to significant financial support measures, including tax deferrals and aid packages for affected businesses. Testing and tracing efforts were initially slow, and a central tracing organization was established to manage the growing number of cases. Despite these efforts, the demand for testing outpaced the available capacity. There was also an implementation of economic measures during this phase. See Appendix G.

Pandemic phase II (January 2021 - January 2022)

Phase II: January 2021 - January 2022 (Vaccination Rollout and Continued NPIs) The vaccine rollout began in January 2021, with priority given to high-risk groups (van Amerongen et al., 2024). While vaccines offered a promising tool for controlling the spread of Covid-19, non-pharmaceutical interventions (NPIs) remained in place, and restrictions tightened at times due to new variants of the virus. The government continued economic support programs, extending financial aid to businesses and individuals most affected by lockdown measures. The CoronaMelder app was introduced during this phase, though it gained limited use due to privacy concerns (van Amerongen et al., 2024). The testing infrastructure was gradually expanded, and by the end of 2021, rapid antigen tests had become widely available. Economic measures were continued. More details can be found in Appendix G.

Pandemic phase III (January 2022 - March 2023)

The third phase of the pandemic saw the loosening of restrictions as vaccination rates increased and the Omicron variant prompted a shift in strategy. By March 2023, the Netherlands had lifted most Covid-19-related advisories, marking the formal end of official measures. The last official Covid-19 advices were dropped on March 10, 2023 (Rijksoverheid, 2023). The economic recovery continued, with some sectors still benefiting from targeted financial support. The government also began focusing on recovery in areas such as healthcare, where backlogs in care needed to be addressed.

Overview of interventions during the Covid-19 pandemic in the Netherlands

The Netherlands implemented a wide range of public health and social measures to manage the Covid-19 pandemic. In the beginning, the focus was especially on epidemiological containment of the pathogen. Later on, societal and economic impacts were taken more into account. A detailed timeline of interventions taken between March 2020 and March 2023, translated from the timeline published on RIVM (n.d.), is shown in Appendix G.

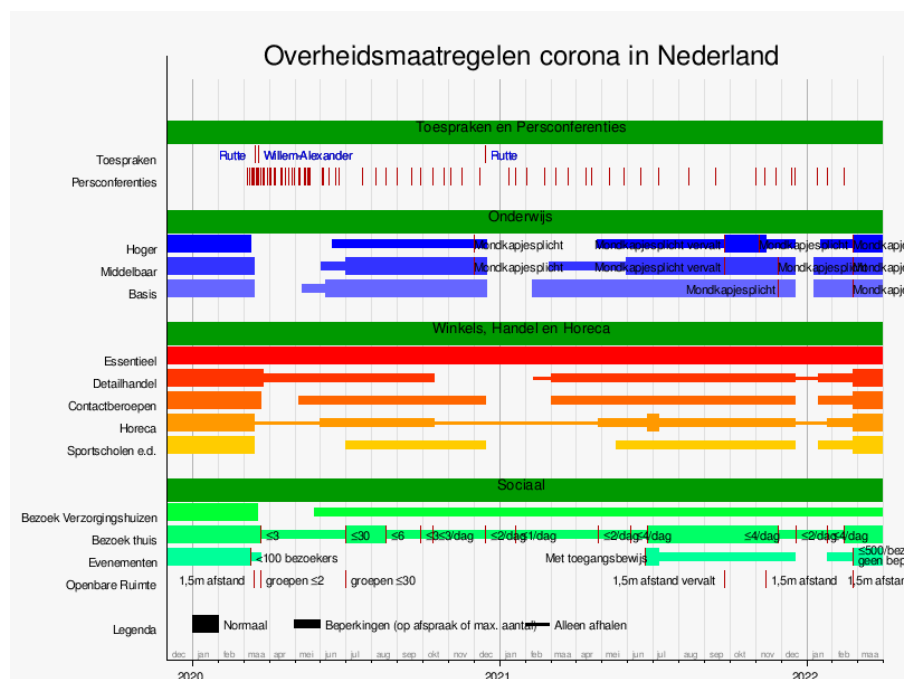


Figure 10.1: Timeline of government interventions against Covid-19 in the Netherlands between late 2019 and early 2022. The figure only includes non-pharmaceutical interventions, some of which were recommendations and others which were obligatory. Figure copied from https://nl.wikipedia.org/wiki/Maatregelen_tijdens_de_coronacrisis_in_Nederland.

10.1.4. Post-disaster phase: recovering from the pandemic

The recovery phase began during the pandemic itself, with compensation for economic losses and plans to catch up on delayed healthcare. This phase continued afterwards, addressing the long-term consequences of Covid-19, including backlogs in medical procedures, disruptions in education, and societal recovery.

10.2. Overall consequences and experiences from the pandemic

Multiple studies were performed on the impact of the Covid-19 pandemic in the Netherlands. These address population health (Nivel & RIVM, 2022), into health and economics (de Boer et al., 2023), into health and behavior (RIVM, 2022a), and into societal consequences (Kullberg & Vonk, 2021).

Covid-19 led to an estimated 550,000 Disability Adjusted Life Years (DALYs, healthy life years lost to death or injury) between 2020 and 2023 (169,400 (2020), 218,900 (2021), 93,800 (2022), 37,800 (2023)). This is based on yearly publications on the states of infectious diseases by RIVM (2022b).

Nivel and RIVM (2022) performed a systematic literature review of academic studies into the health effects of the pandemic. They highlight four frequently found consequences, relating to short-/mid-term effects of the pandemic (mostly in early 2021). Firstly, they find that a group of Covid-infected people kept long-term complaints after their infection. Many of these people were fully or partially unable to work. Secondly, they find that the mental health of young people declined as a consequence of the pandemic. This involved an increase in depression and anxiety symptoms. Mental health was especially affected during lockdowns. While recovering somewhat after relaxation of the measures, mental health remained worse in the year after the pandemic than it was before the pandemic. Thirdly, the pandemic negatively impacted social functioning. This involved less participation in social activities, feelings of social isolation, and a lower (perceived) quality of social contact. Fourthly, there was a negative impact from postponed care. Poorer health outcomes were found in people who suffered heart attacks; more or worse metastases were found in people with cancer (later diagnoses and treatment); and quality of life was found to be poorer for people with postponed operations (Nivel & RIVM, 2022). Finally, the researchers found that the negative effects of the pandemic were stronger in three vulnerable groups: young people, people with a lower socioeconomic status, and people with pre-existing health problems.

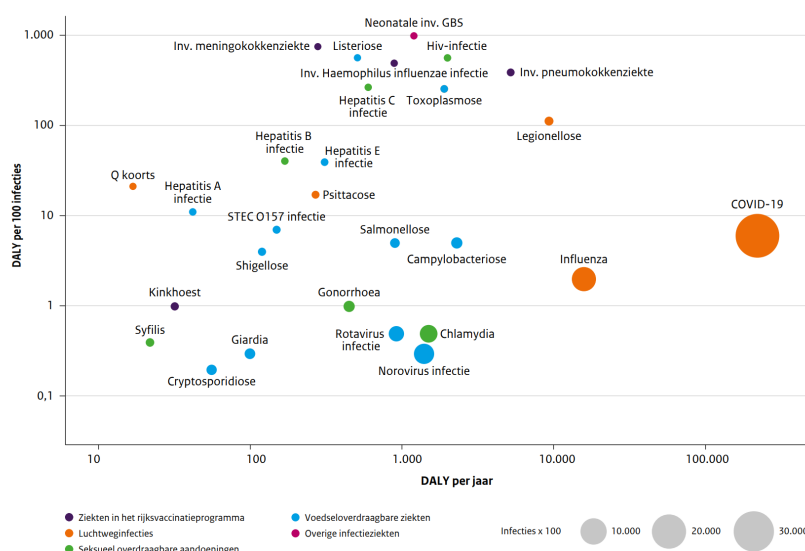


Figure 10.2: Plot showing the burden of disease of different infectious diseases in the Netherlands in 2021. It shows that Covid-19 affected over 100.000 DALYs (disability-adjusted life years) overall in that year, being the biggest burden from an infectious disease on Dutch population health during the pandemic. Figure copied from RIVM (2022b)

(Nivel & RIVM, 2022).

Working towards a social cost-benefit analysis, de Boer et al. (2023) from the RIVM mapped out consequences of the Covid-19 pandemic for Dutch society and its economy. These consequences included illness, death, postponed care, and performance in school. Importantly, they analyzed these consequences across different groups in the population and found significant differences in experiences, in line with the findings from Nivel and RIVM (2022). Specifically, differences between income groups were worsened by the pandemic. As a consequence of their generally worse health, lower income groups had the highest mortality from Covid-19, visited test lanes less often, were hospitalized more, ended up on the intensive care more, and caught up on postponed care slower than others (de Boer et al., 2023). The different income groups valued resilience. The researchers also studied the (mutual) interactions between epidemics (/pandemics) and the economy. They found that such interactions are present with and without the implementation of pandemic interventions, as people adjust their behavior to the epidemiological circumstances. Finally, the report addresses consequences such as access to care, support and trust in the government, and it finds that people value their well-being more than their health.

RIVM (2022a) studied the health and health behaviors of adults during Covid-19. In line with Nivel and RIVM (2022), they found that mental health declined during the pandemic. These effects were especially significant for young adults and women, and included increased feelings of loneliness, stress, anxiety, and depression. To differing extents, these findings were linked to the pandemic in general, experiencing an infection, or the effect of the interventions. Interestingly, the mental health of a small amount of people increased.

Lastly, Kullberg and Vonk (2021) studied the societal consequences of Covid-19. Their focus is on the changes in social contacts and social behaviors during the pandemic, which they analyze based on three behavioral drivers: the shock effect, lockdown interventions, and (expected) economic crisis. They find that the initial shock of the Covid-19 pandemic led people to feel united and be more altruistic (helpful) towards family, friends, and sometimes neighbors. The shock also caused activation of the survival instinct, leading people to hoard groceries. The shock also seemed to have made people less extroverted and more in touch with a smaller network (Kullberg & Vonk, 2021). Each of these findings are connected to the initial shock phase, and may thus fade away afterwards. Physical distancing measures were considered as a second driver of behavior during the pandemic. Finally, Kullberg and Vonk (2021) described an economical crisis and associated job losses as a possible consequence of the Covid-19 pandemic. In practice, a full-on economic crisis did not happen.

Comparative insights timelines

Differences and similarities between flood and pandemic cases

This chapter describes the comparative analysis of cases and timelines of floods and pandemics. Chapters 9 and 10 have described the cases and timelines of the Limburg-21 floods and the Covid-19 pandemic. The goal of this chapter is to derive comparative insights between these cases, which will be used to answer the second research sub-question, SQ2: *How do the timelines of floods and pandemics compare?* It complements the systems-level findings in Part II by adding a temporal perspective to the previously identified risk and intervention mechanisms. This comparison helps illustrate the element of risk dynamics as conceptualized in the framework (Figure 1).

11.1. Key insights

- Observations from the COVID-19 pandemic and the Limburg-21 floods align with the causal and consequential mechanisms identified in the bowtie diagrams from Part II.
- These cases also underscore the importance of risk dynamics - the way disasters evolve over time and under uncertainty. Floods and pandemics differ substantially in terms of onset speed, duration, uncertainty, and decision-making across the disaster phases.
- Floods (fluvial, like Limburg-21) are typically fast-onset, short-duration events with well-defined parameters. Monitoring and modeling enable relatively reliable short-term forecasts that support threshold-based decisions.
- Pandemics (like Covid-19) are slow-onset, long-duration crises marked by evolving, system-wide uncertainties. Risk unfolds more diffusely, shaped by interacting biological, social, and behavioral mechanisms. This complexity challenges timely decision-making.
- Recovery also reflects these contrasts. Flood recovery is often bounded in space and focused on physical infrastructure. Pandemic recovery spans economic, societal, and institutional domains and can begin before the disaster has ended.
- Overall, floods are more bounded in time and space, whereas pandemics unfold as prolonged, societal disruptions requiring continuous adaptation.

11.2. Validation of flood and pandemic risk mechanisms

The insights from both cases reinforce the findings from the bowtie analysis in Part II. The causal mechanisms observed during the Limburg-21 floods align closely with the pathways of fluvial flooding captured in the flood bowtie. Similarly, the COVID-19 pandemic exhibits the causal structure of a zoonotic outbreak, as depicted in the pandemic bowtie.

Additionally, nearly all consequences identified in the bowties were either observed directly or expected based on the case timelines. This overlap across the system analysis and these real-life events strengthens the internal validity of the bowtie framework and affirms its relevance for disaster risk un-

derstanding. Building on this foundation, the following sections examine how risk dynamics unfold over time in each case.

11.3. Application of the framework to floods and pandemics

To further investigate the temporal dynamics of these disaster types, the analytical framework was applied to both the Limburg-21 floods and the COVID-19 pandemic - structuring the analysis of risk dynamics across the four disaster phases: normal, threat, disaster, and post-disaster. A common disaster timeline was inferred based on the Limburg-21 and Covid-19 cases, shown in Figure 11.1. Draft versions - based on structuring by the disaster cycle - are included in Appendix H.

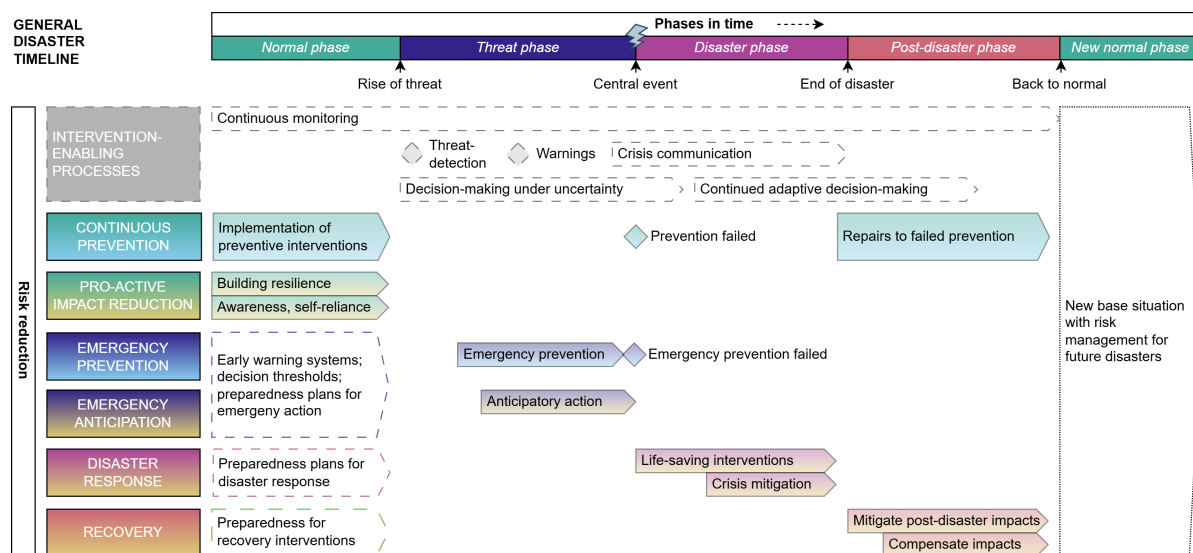


Figure 11.1: General disaster timeline inferred from the cases. The general phases and transitions are shown at the top. The development of risk reduction efforts over time is shown. The different categories of interventions - as well as intervention-enabling processes (in dashed boxes) - are included.

11.4. Analysis of flood and pandemic phases

The Limburg-21 floods and Covid-19 pandemic were analyzed as illustrative cases of floods and pandemics. This section compares the findings from their phases in time, revealing insights into the duration and unfolding characteristics of these events. The findings from the comparative analysis are summarized in Table 11.1.

11.4.1. Normal phase

The normal phase of floods last multiple decades, considering that a (low-probability, high-impact) flood is only estimated to happen once every (few) hundred years. In the Netherlands, strict protection levels have been defined to limit the risk of floods, informed by past floods and supported by a well-established safety infrastructure. There is a clearly defined acceptable risk on which policies are based. Continuous monitoring and weather predictions allow the detection of threats.

The normal phase of pandemics also last multiple decades, considering that a (low-probability, high-impact) pandemic is only estimated to happen once every fifty years. While there are risk reduction measures and guidelines in place, there is no clearly defined level of acceptable risk. Moreover, from the Covid-19 case it became clear that in the (pre-covid) normal phase, frameworks for influenza pandemics existed, but preparedness for novel pathogens (like SARS-CoV-2) was very limited.

In both floods and pandemics, the normal phase represents a prolonged period of relative stability, during which the risk of a disaster is present but not immediately pressing. However, the nature of preparedness differs markedly. Flood preparedness is grounded in physical infrastructure, quantified risk assessments, and legally defined protection standards. This leads to a more formalized and institutionalized safety regime. Pandemic preparedness, by contrast, is more fragmented, often relying on

generalized frameworks rather than concrete thresholds or enforcement mechanisms. While both hazards benefit from long-term planning and monitoring, the predictability and quantifiability of flood risk seemingly allows for clearer planning. In pandemics, the absence of a universally accepted acceptable-risk threshold and the unpredictability of biological threats create a preparedness gap - especially for novel pathogens. These differences imply that even in the absence of an imminent threat, floods are treated as a more "governable" risk, whereas pandemics require a fundamentally different mindset - one that prepares for surprise and flexibility.

11.4.2. Threat phase

The threat phase of floods lasts days to weeks. During this phase, the key uncertainty is *if, where, and when* flooding will happen. Monitoring and prediction of the weather and water levels can reduce this uncertainty by providing relatively clear estimations of what could happen. Moreover, flood scenario maps are available to detail how a flood would develop from the point where it originates. Such maps include estimations for flood depths, flow rates, and other factors of importance to its impact. Through monitoring, prediction, and scenario analysis, many of the uncertainties around floods can be addressed - to some extent. This aids decision makers in the choices for emergency preventive interventions (e.g. placing sandbags) and emergency anticipatory interventions (e.g. evacuations).

The threat phase of pandemics lasts months. During this phase, the key uncertainty is not only *if, when, and where* a pandemic will start (or arrive in the Netherlands), but more importantly: *what* its characteristics will be and *how* it would develop. These questions are inherently complex and the answers are - especially for novel pathogens - deeply uncertain. The infection dynamics of a pandemic pathogen will be influenced by a combination of (global) biological, ecological, and social processes. Important pathogen characteristics include its infectivity, pathogenicity (severity of infection), and mutation rates. Societal dynamics will influence the basic reproduction number and spread of the infection through society. These characteristics are not easily measurable or predictable. As a consequence, the threat phase is characterized by prolonged uncertainty about whether and how a pandemic will develop. This complicates decision-making on emergency prevention and anticipation. The effectiveness of interventions is highly dependent on the pathogen characteristics and the negative side effects of interventions can be severe. Uncertainty and caution may lead to delays and shortcomings in decision-making, as also shown in the Covid-19 pandemic.

The core contrast in the threat phase lies in duration and depth of uncertainty. Floods allow for high-confidence forecasting within a short window. Tools like hydrological models, satellite data, and flood maps reduce ambiguity and support timely, evidence-based decisions. In contrast, the threat phase of pandemics is defined by long-lasting, multi-layered uncertainty - not just about when or where, but about the pathogen itself and the system's capacity to respond. This complexity reduces the ability to rely on pre-defined scenarios or models. Furthermore, decision-making under uncertainty takes a different form. For floods, decision-makers act on estimated probabilities, which do have uncertainty ranges by are relatively well understood. For pandemics, probabilities and events are less predictable, often leading to precautionary delays, conflicting expert opinions, and political hesitancy. In a way, floods allow for "just-in-time" emergency actions, whereas pandemics demand more "just-in-case" thinking - early, decisive, and adaptive interventions under incomplete information.

11.4.3. Disaster phase

For flooding, once flooding starts happening, the disaster phase is entered. For floods, this phase lasts days to weeks. During this phase, the key uncertainties (*if, where, and when* flooding would occur) resolve fast. Given the relatively short duration of flood growth, the extent of the flood quickly becomes clear - and has often been predicted already. During the disaster phase, there is 'only so much' that can be done to limit the flood's impacts. The course of the floods can no longer be changed. The primary intervention that can still make a difference is aiding and rescuing people in the flooded area.

For pandemics, once the spread of the pathogen is no longer preventable (the pathogen becomes endemic), the response phase is entered. This does not mean that the uncertainty is resolved. While it may now be clear *if, where, and when* the pandemic occurs, it may still be unclear what the pathogen characteristics are and how it will further develop. The response phase for pandemics can last months to years and may involve multiple waves of infections. While the infection dynamics are highly com-

plex and may be uncertain, they are also very influential. This means that interventions during the response phase can still greatly shape the course of the pandemic, especially considering the long duration of this phase. This requires trade-offs to be made between alternatives with uncertain outcomes (including potentially negative side-effects). During this phase, societal behavior is pivotal, emphasizing the role of crisis communication and public compliance.

The disaster phase marks a divergence in how events unfold and how systems respond. Floods are acute and geographically localized; the disaster unfolds in a matter of hours or days, with limited flexibility to influence outcomes once the waters rise. A main focus becomes search and rescue, and the window for action is narrow. Pandemics, in contrast, are prolonged and systemic. Their course can still be shaped significantly during the disaster phase, particularly in the early and middle waves. This prolonged period allows for intervention adaptation, but also requires sustained public engagement and institutional adaptability. In essence, floods are fast-moving crises with fixed trajectories once triggered, while pandemics are slow-moving crises with evolving trajectories, requiring both persistence and flexibility from policymakers.

11.4.4. Post-disaster phase

Once the flood is fully developed and the water subsides, the post-disaster phase is entered. The recovery from floods may last years. The first weeks or months may require pumping and drainage efforts to fully remove the flood waters. Afterwards, the focus is on reconstruction, focused on the physical damages from the floods. However, (mental) health and economic effects may simmer too.

For pandemics, the post-disaster phase starts when declared as such by national and/or international (health) organizations or governments. This is around the time that the impact of the pathogen on society has weakened and there is no longer a threat of excessive healthcare overload. At this point, there is likely to be herd immunity and/or the pathogen has weakened or disappeared. Delayed or indirect impacts may still occur after the pandemic. Recovery can reduce such impacts, catching up on healthcare backlogs and boosting the economy.

In both hazards, recovery extends beyond the visible damage. However, the nature of recovery efforts differs fundamentally. For floods, recovery is typically infrastructure-driven and geographically bounded. It involves restoring the built environment, repairing physical damage, and restoring essential services. These processes are generally well-defined, though not without social or economic challenges. For pandemics, recovery is diffuse and multidimensional - spanning healthcare backlogs, mental health impacts, economic instability, and social cohesion. Furthermore, while flood recovery usually begins after the disaster has ended, pandemic recovery often overlaps with the event itself, requiring phased approaches and longer-term vision. Thus, while flood recovery is relatively linear - damage followed by repair - pandemic recovery is non-linear and adaptive, with phases of relapse and adaptation.

Table 11.1: Comparative characteristics of floods and pandemics across disaster phases.

Phase	Floods	Pandemics	Comparative insights
Normal	Decades-long phase with clear risk thresholds, codified safety standards, and engineered protections.	Decades-long phase with general preparedness and global health guidelines, but lacking specificity for novel pathogens.	Floods are governed risks with formal thresholds; pandemics remain abstract with preparedness gaps, especially for novel threats.
Threat	Lasts days to weeks; driven by weather events and river levels; reduced uncertainty through monitoring and flood modelling.	Lasts months; marked by deep uncertainty about pathogen behavior, spread, and system response capacity.	Flood threat phases support more confident, model-based actions; pandemic threats require anticipatory decisions under systemic uncertainty.
Disaster	Rapid onset and short duration (days to weeks); impacts unfold quickly with limited response flexibility.	Slow onset and long duration (months to years); interventions shape evolving outbreak trajectories across waves.	Floods follow fast, largely predetermined courses; pandemics unfold adaptively, requiring continuous recalibration.
Post-disaster	Begins once floodwaters recede; focused on physical reconstruction and infrastructure repair.	Overlaps with disaster phase; includes prolonged recovery in health, economy, and society.	Flood recovery is spatially bounded and infrastructure-led; pandemic recovery is diffuse, overlapping, and multi-dimensional.

Part IV

Risk reduction strategies for floods and pandemics

12

Model-based analysis

Studying risk reduction across intervention scenarios

This chapter describes the analysis performed for Part IV of this study. Building on Parts II and III, it focuses on the analysis of risk reduction strategies for floods and pandemics. This involves the development of a computational risk reduction model, which can be used to estimate the reduction of risk by flood and pandemic interventions across categories of interventions. This chapter describes the developed model, its equations, and the parameters that it uses. The application and findings for floods and pandemics are discussed in Chapters 13 and 14. This will be used to answer the third research sub-question, SQ3: *How do the effects of risk reduction strategies for floods and pandemics compare?*

The model scripts are available on Github: <https://github.com/nschuiling/dikes-diseases-disasters>.

12.1. Modeling analysis

A computational model is developed to analyze and compare the reduction of disaster risk by different intervention strategies. A model is built with a general core structure, applicable to both floods and pandemics. Secondly, it is calibrated and applied to base scenarios of a flood and pandemic. It is then used to analyze policy interventions for these scenarios. Finally, the effect of interventions can be compared within and between the disasters.

The objective of the model extends beyond the goal of 'prediction' of best policy interventions, which is often considered the one and only modeling goal (Epstein, 2008). While one of the goals is to predict and compare the performance of different policy interventions, the focus is much more on the modeling process itself. Furthermore, the focus will be on orders of magnitude rather than exact prediction. Moreover, the modeling process in itself serves important goals of system understanding, simplification, and promoting a scientific mindset. The end goal of the model is not to have one 'predicted' ideal outcome, but rather to support policy makers in (risk-based) decision-making and understanding the implications of choosing between strategies. As Epstein (2008) describes it: "by revealing tradeoffs, uncertainties, and sensitivities, models can discipline the dialogue about options and make unavoidable judgments more considered" [par. 1.7].

12.2. Model conceptualization

12.2.1. Risk as core outcome

The aim of the model is to describe the risk of flood and pandemic scenarios, both with and without the implementation of policy interventions. Comparison of the results from the base scenarios and those with the interventions then allows the inference of risk reduction. The computational model used in this study will center around the risk equation.

$$risk = probability \times impact$$

The insights from Parts II and III of this study suggest that economic and health impacts are considered the most important for decision-making. The model will calculate economic and health impacts separately, also leading to separate outcomes for health risk and economic risk, but using the same disaster probability. In theory, health impacts can also be described in economic terms, for example by taking the average statistical value of a life (Bockarjova et al., 2012). However, to enable decision makers to make decisions, premature aggregation should be avoided. Therefore, health and economic impacts will be presented separately by the model.

12.2.2. Analyzing categories of interventions

The model will be used to analyze the reduction of risk by policy interventions in the different categories of intervention. These are described in the risk-based analysis framework (Section 3.3) and are shown in Figure 12.1. Six categories of intervention are distinguished: continuous prevention, pro-active impact reduction, emergency prevention, emergency anticipation, disaster response, and recovery.

Continuous prevention and pro-active impact reduction are actively implemented in the normal phase, reducing the probability and impact of unknown future floods or pandemics. Emergency prevention and anticipation are implemented during the threat phase, while disaster response occurs in the disaster phase and recovery in the post-disaster phase. While each of these categories could be prepared for in the normal phase, the interventions become most active in the phases around and after the event. Investments in each layer can be made at any point in time, either to implement interventions or to prepare for them.

It is important to note that the interventions experimented with in the model are 'mechanistic' interventions, directly influencing the probability or impact of the disaster. This means that intervention-enabling processes such as early warning are not explicitly modeled. However, such processes do play an important role in influencing the effectiveness of the interventions. They will thus be mentioned - in that supportive way - throughout the modeling analysis.

Risk reduction layers over time		Phases in time ----->			
		Normal	Threat	Disaster	Post-disaster
Risk	Probability	Continuous prevention	Emergency prevention	-	-
	Impact	Pro-active impact reduction	Emergency anticipation	Disaster response	Recovery

Figure 12.1: Categorization of interventions by their risk-reduction dimension and phase of implementation.

12.3. Model formulation

A simplified mathematical model is defined to calculate the probability, impact, and risk of flood and pandemic scenarios - at base and with (individual) interventions. A scenario describes the circumstances of a potential disaster situation, including the severity of the hazard and factors that mediate its impact, such as the exposed area and population. For each scenario, health and economic impacts are calculated separately (Figure 12.2).

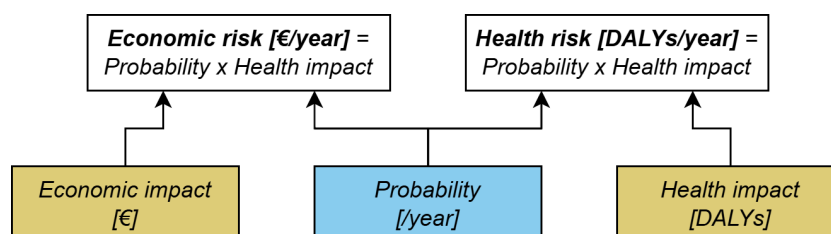


Figure 12.2: Core equations of the risk reduction model: the calculation of economic and health risk,

12.3.1. Calculation of health impact

The health impact of a scenario is calculated by summing the impact of mortality (fatalities) and morbidity (injuries). An overview of these calculations is shown in Figure 12.3.

Population physically affected by the hazard

Floods and pandemics can result in mortality and morbidity. For both events, (direct) health impacts depend on the number of people that are affected by the event and the proportion of them for which this causes death or injury. For simplicity, the model only considers 'direct' impact from floods and pandemics. Then, the affected populations are those people that are confronted with flood waters or those that are infected with the pandemic pathogen. The flood affected population depends on the number of people present in the area (not evacuated) and the proportion of them that comes in contact with the water (not sheltered). The pandemic affected population depends on the number of people exposed to the pathogen (e.g. in contact with someone who is infected) and which proportion of them gets infected.

For both events, first the population size of the exposed area is calculated:

$$exposed_area_population = size_of_exposed_area \times population_density \quad (12.1)$$

For simplicity, the model will assume one average population density, meaning that the population size of the exposed area will be linear with the size of the exposed area. Theoretically, population density could be increased or decreased to simulate urban and countryside areas, or other countries.

For floods, the affected population will then be calculated based on the evacuation fraction and the confronted (unsheltered) fraction:

$$flood_affected_population = flood_confronted_population = \\ unevacuated_population \times confronted_fraction \quad (12.2)$$

For pandemics, the affected population will then be calculated based on the infected fraction:

$$pandemic_affected_population = pandemic_infected_population = \\ exposed_population \times infected_fraction \quad (12.3)$$

In this study, a single aggregate value of 'affected population' is used per scenario, resembling the total amount of infected people over the course of a pandemic or the total amount of people confronted with flood waters over the course of a flood. In reality, the population is affected dynamically over time. More complex models could incorporate such dynamics.

Mortality from the hazard

For both events, (direct) mortality depends on the number of people that are affected by the event and the proportion of them for which this is fatal, referred to as the mortality factor. The mortality of floods and pandemics may vary over space and time. For floods, it is assumed that it is most relevant to make this distinction in space (some areas have higher mortality than others), while for pandemics this distinction is made in time (some periods have higher mortality than others). The common equation used is as follows:

$$fatalities = \sum (space_time_fraction \times \\ space_time_mortality_factor \times total_affected_population) \quad (12.4)$$

Here, the "space time fraction" describes the proportion of space (flood) or time (pandemic) in which a certain mortality factor applies. In total, the space time fractions add up to 1 and mortality is calculated over the total affected population. Interventions may influence the mortality over space and time.

Morbidity from the hazard

Besides fatalities, floods and pandemics may also cause injuries (morbidity). For simplicity, it is assumed that there is a fixed proportion between mortality and morbidity for different scenarios. Then, the number of fatalities (mortality) can be used to calculate the number of injuries. In this study, a morbidity-mortality-ratio will be used to express the number of 1-year injuries per fatality. For example: a multiplier of 5, means that for each fatality, 5 other people have a 1-year injury. However, it could also be that 1 person has a 5-year injury.

$$injuries = fatalities \times morbidity_mortality_ratio \quad (12.5)$$

Expressing health impact in DALYs

To summarize the health impacts from mortality and morbidity into a single value, the metric of Disability Adjusted Life Years (DALYs) is used. This is a measure of overall disease burden and describes the number of years lost to (early) death, ill-health, and disability.

$$DALYs = years_of_life_lost + years_lived_with_disability \quad (12.6)$$

$$years_of_life_lost = fatalities \times (life_expectancy - average_age_fatalities) \quad (12.7)$$

$$years_lived_with_disability = injuries \times average_duration_injuries \quad (12.8)$$

In this study, the number of injuries is defined as the number of (average) 1-year injuries (following the morbidity-mortality-ratio). Therefore, the average duration of injuries is 1-year. Note that the DALY captures lost years of life in full health, and does not distinguish between severities of injuries. A more complex model could use the Quality Adjusted Life Year (QUALY) metric to also incorporate the extent of disability.

Finally, it is assumed that - in addition to the health impacts happening during the disaster - a small fraction of additional DALYs occur in the longer-term (delayed) after the disaster. This may for example include mental health effects, and is assumed to be proportional to the disaster health impacts. It is therefore added based as a fraction of those impacts.

$$DALYs = disaster_DALYs + post_disaster_DALYs = \\ disaster_DALYs + (disaster_DALYs * post_disaster_DALY_fraction) \quad (12.9)$$

12.3.2. Calculation of economic impact

The economic impact of a scenario is calculated by summing the physical impact in an affected area with the impact from economic disruptions in the area and the economic impact from health losses. An overview of these calculations is shown in Figure 12.4.

$$total_economic_impact = economic_impact_physical + \\ economic_impact_disruption + economic_impact_health \quad (12.10)$$

The calculations for both physical and disruption damages involve the multiplication of maximum damages with damage factors. Those equations are a simplification of the methodology from the Dutch standard Flood Damage and Loss Model (Slager & Wagenaar, 2017).

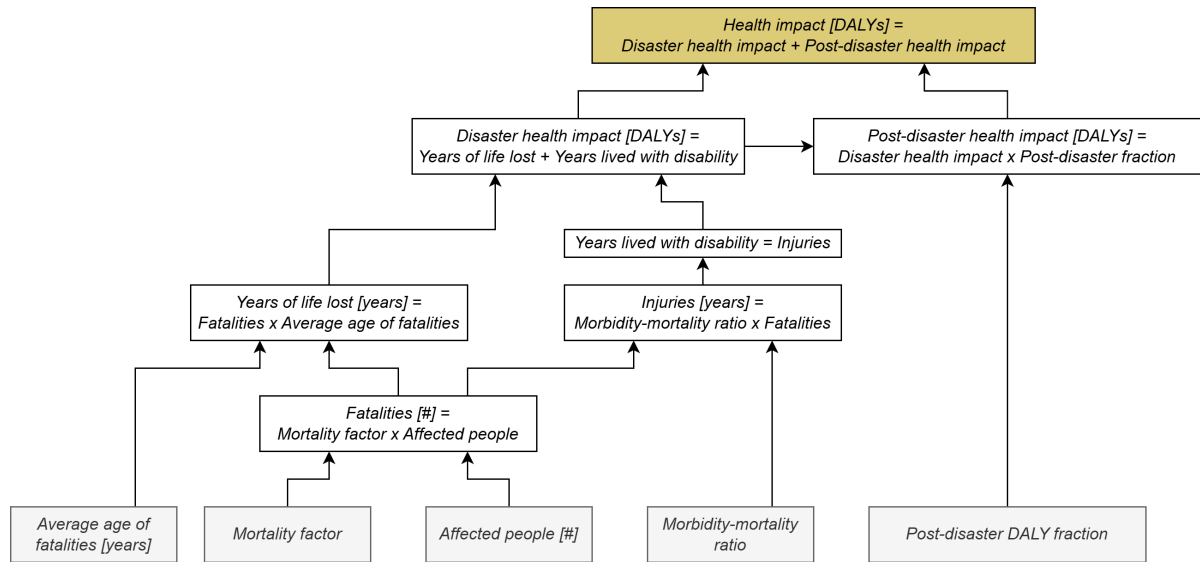


Figure 12.3: Overview of health impact calculations with the risk reduction model. Model parameters are on the bottom row, and indicated in light gray. These can differ per scenario and be influenced by interventions. The visualization is slightly simplified, as the model allows for separation of mortality factors over multiple areas or periods in time.

Physical economic impact

Physical economic impact results from the fact that physical hazards can cause physical damage to economic assets. Floods are a physical hazard, while pandemics are not. Therefore, the calculations described here are based on the damages caused by floods (generalizable to other physical hazards) and pandemics will have a physical impact of 0.

Generally, the physical intensity of a (flood) hazard varies across the affected area. This means that the physical impact is dependent on the total affected area, the size of each sub-area, the intensity of the hazard in each sub-area, and the (maximum) possible damage in each sub-area. The physical intensity of the hazard can be translated to a base physical damage factor to indicate how much of the maximum damage would be actualized without intervention. The physical damage factor has a value between 0 (low intensity, no damage) and 1 (high intensity, maximum damage). Based on this description, physical economic impact can be calculated with the following equation:

$$economic_impact_physical = \sum (area_size \times area_physical_damage_factor \times area_max_physical_damage) \quad (12.11)$$

In this study, area sizes and corresponding damage factors are defined for the base scenarios. Damage factors can be modified by interventions aimed at reducing physical damage. For the purpose of simplicity and generalizability, one general 'average' value of maximum damage per square km is used. This is because the focus is on 'average' flood impact and orders of magnitude, rather than the exact impact for specific areas. As pandemics do not cause direct physical damage, their physical damage factor is always 0.

Economic impact from disruption

Floods and pandemics can disrupt economic activity over time. Contrary to physical damage, the assumption is made that economic disruption is similar across the affected area, but different over time. The economic disruption damage then depends on the total affected area, the duration of different periods of disruption, the intensity of disruption during those periods, and the (maximum) possible disruption damage per day over the total area. Similar to the physical damage factors, a higher hazard intensity may result in a high disruption damage factor at base, without interventions. Economic impact from disruption can be calculated with the following equation:

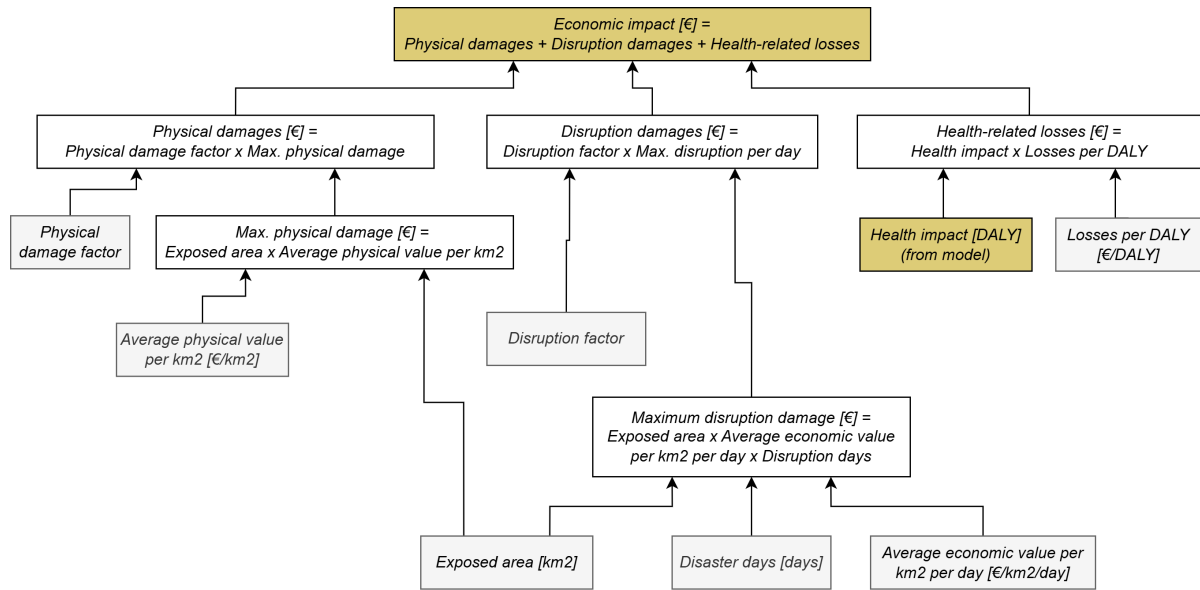


Figure 12.4: Overview of economic impact calculations with the risk reduction model. Model parameters are indicated in light gray. These can differ per scenario and be influenced by interventions. The visualization is slightly simplified: in the model, disruption damage is calculated for both the disaster phase and post-disaster phase (and the model allows further separation over sub-periods), and physical damages can be separated over different sub-areas. The figure shows the equations if aggregated and average values were used.

$$economic_impact_disruption = \sum (period_duration \times period_disruption_damage_factor \times period_max_disruption_damage) \quad (12.12)$$

The duration and indirect damage factor for each period are defined for the base scenarios and can be modified by interventions aimed at reducing delayed or indirect damage. With this equation, the assumption is made that disruption losses are limited to the affected area and that other losses are negligible. Similarly, an assumption is made that disruption can be captured by average damage factors and maximum damage values over the whole area. Like with physical impact, the study assumes a set average value of maximum damage per square km per day. Economic disruption damage may happen both during the disaster as well as in the post-disaster phase.

Economic impact from health losses

Finally, health impacts also contribute to economic losses. In this study, it is assumed that health impacts lead to lost productivity, resulting in economic losses. An economic value will be assigned to each healthy life year lost (i.e. an economic loss per DALY) (Arias et al., 2022; Dalal & Svanström, 2015; Marseille et al., 2015). It must be acknowledged that the separation of health-related and disruption-related losses is difficult. The assumption is that the disruption losses result more from business level effects, such as operations disturbed from physical damages to building and materials or from (cascading) changes in supply and demand.

$$economic_impact_health = DALYs \times economic_loss_per_DALY \quad (12.13)$$

12.4. Model parameters

Building on the equations from the risk reduction model, a number of parameters must be specified to calculate the impact of a flood or pandemic scenario. There are three types of parameters which must be specified: common parameters with shared base values, common parameters with hazard-specific base values, and hazard-specific parameters.

12.4.1. Common parameters with shared base values

The common parameters with shared base values are parameters which have the same value for the base scenarios of floods and pandemics. These parameters represent country/area-specific characteristics, which are assumed to be hazard-independent. The parameters are:

- average maximum physical damage per km² (for calculating physical damage)
- average maximum disruption damage per km² per day (for calculating disruption damage)
- average population density (for calculating the population in the exposed area)
- average life expectancy (for calculating the years of life lost to early death)
- economic losses per DALY (for calculating the economic losses from health losses)

The specification of these parameters is based on base values from the Netherland (Section 12.5).

12.4.2. Common parameters with hazard-specific base values

The common parameters with hazard-specific base values are parameters which must be specified for both floods and pandemics, but have values specific to the (base) hazard scenario. These parameters represent characteristics determining the severity and distribution of the impacts. The parameters are:

- event probability (for calculating risk)
- size of the exposed area (for calculating economic and population exposure)
- physical damage factors per sub-area (for calculating physical damage)
- disruption damage factors per sub-period (for calculating disruption damage)
- mortality rates per space-time fraction (for calculating fatalities)
- average age of fatalities (for calculating the years of life lost to early death)
- morbidity-mortality-ratio (for calculating the number of 1-year injuries)
- post-disaster DALY fraction (for calculating additional post-disaster health impacts)

These parameters will be specified for floods and pandemics separately, using hazard-specific base scenarios. Interventions across all layers could then modify these values.

12.4.3. Hazard-specific parameters

There are a few hazard-specific parameters, unique to the calculation of population exposure for floods and pandemics. These parameters are not shared by the events, but will be used to calculate a common variable ("affected population"), used by the model. The parameters are:

- pandemic infected fraction (for calculating the affected population)
- flood (non-)evacuated fraction (for calculating the affected population)
- flood confronted fraction (for calculating the affected population)

Together with the common parameters with hazard-specific base values, these parameters will be specified in the next two chapters describing the hazard-specific modeling analyses.

12.5. Specification of shared parameters (base country scenario)

The average population density in the Netherlands is set at 530 people per km². This value has been rounded up from the average population density of 526 in the Netherlands in 2022, as reported by the World Bank (n.d.). The average maximum disruption damage is set at 90,000 euro per day per km². This estimate is based on a distribution of the Dutch GDP (€1,068 billion in 2023, CBS (2024)) over the land surface of the Netherlands (34,000 km²) and one year (365 days). The average maximum physical damage is set at €50,000,000 euro per km². This value is based on an estimate by ChatGPT, using the Dutch land use division as specified by the National Bureau for Statistics (CBS, 2020) and insights from previous floods such as Limburg-21. Details of the answer by ChatGPT can be found in Appendix J. The average life expectancy is set at 81.4. This value is the average of the life expectancy for men (79.7 years) and women (83.1 years) in the Netherlands in 2020 (CBS, 2022). The economic losses for each healthy life year lost (DALY) are set equal to 50% of Dutch GDP per capita (58,000/2

= 29,000, CBS (2024)). The use of GDP per capita based values for DALYs was inspired by previous studies from Arias et al. (2022), Dalal and Svanström (2015), and Marseille et al. (2015).

An overview of the shared base parameter values is shown in Table 12.1.

Parameter	Base value
Average population density [people/km ²]	530
Average maximum disruption damage [€/day/km ²]	90,000
Average maximum physical damage [€/km ²]	50,000,000
Average life expectancy [years]	81.4
Economic losses per DALY [€/DALY]	29,000

Table 12.1: Base values set for country parameters (common parameters with shared base values).

12.6. Specification of policy interventions

The findings from Parts II and III were used as a basis for specifying policy interventions to be analyzed with the simple risk reduction model. Interventions of interest were identified for each category of intervention, for both floods and pandemics.

Floods:

- Continuous prevention: Reinforce flood defenses
- Pro-active impact reduction: Spatial planning, Flood-proof building, Increase self-reliance, Increase societal preparedness
- Emergency prevention: Emergency flood barriers
- Emergency anticipation: Preventive evacuation, Emergency flood damage mitigation
- Disaster response: Search and rescue
- Recovery: Flood water drainage, Build-back-better (next event), Build-back-better (current event), Post-flood health support, Post-flood economic support

Pandemics:

- Continuous prevention: Global pandemic prevention, Dutch pandemic prevention
- Pro-active impact reduction: Structurally increase hospital capacity
- Emergency prevention and anticipation: Global emergency containment, National emergency containment, Emergency vaccination campaigns, Emergency increase in hospital capacity (ICU beds)
- Disaster response: Responsive containment policies, Responsive increase in hospital capacity (ICU beds), Responsive vaccine development, Responsive economic mitigation
- Recovery: Post-pandemic health support, Economic recovery acceleration

The policy interventions influence parameters of the system. Each intervention has multiple levels of action. The first level of action is 'nothing' (base scenario) and the fifth level of action is 'very significant' effort. This maximum level is based on a reasonable estimate of what would be (maximally) feasible - implicitly considering effort and cost. This is based on estimates from the literature. Costs are not explicitly modeled or discussed.

The effects of each level of intervention are expressed as a multiplication factor for the parameter it influences. Note that the focus in this study is on the comparison between interventions rather than their absolute effects. The focus is more on orders of magnitude of influence than on precise influence. Additionally, the model will assume independence between categories: meaning that action in one category does not influence the impact of action in another.

The application of the model to flood and pandemic scenarios is discussed in the next chapters. This includes the specification of the base scenarios and their parameters, as well as details on the chosen interventions and the parameter-multipliers for each level of action.

13

Flood risk reduction

Modeling the impact of flood interventions

This chapter describes the application of the risk reduction model to floods. The model structure and equations are described in Chapter 12. This chapter explains the parameter values of the base flood scenario. It then describes the flood interventions that were used in the experimental analysis with the model, as well as the modeling results. Chapter 15 describes a comparison of these results with pandemics. This all contributes towards answering SQ3: *How do the effects of risk reduction strategies for floods and pandemics compare?*.

13.1. Specification of base flood scenario parameters

The base flooding scenario describes the base values of the parameters for the flood model. This scenario is used to calculate the baseline risk of flooding. The baseline is then used for the analysis of risk reduction by different intervention strategies. For the results to be useful and interpretable, the base scenario should be realistic and generalizable. This means that it should represent a situation that is possible (realistic) in multiple ways or locations (generalizable) in the Netherlands. Moreover, the base scenario should describe a situation of minimal intervention. This may differ from the true current situation in the Netherlands, where a lot of (mostly preventive) flood interventions have been implemented already. A more minimal base scenario allows for a fairer comparison of risk reduction between interventions in different layers of protection. It also enables tuning of the flood and pandemic base scenarios to be more comparable.

The focus is on flooding from primary or regional waters, particularly based on river flooding scenarios. Pluvial flooding scenarios could be very different, but are considered less relevant since their impact would likely be much lower.

13.1.1. Dike-ring 16 as inspiration

The base flooding scenario was designed based on existing scenario assessments of possible future floods in the Netherlands. Flooding of dike-ring 16 was chosen as representative foundation to build the base scenario on. Dike-ring 16 encloses the areas of Alblasserwaard en Vijfheerenlanden in the Dutch province of Utrecht. In a country-wide assessment of flood safety in the Netherlands, dike-ring 16 came forward as one of the higher risk areas of flooding (Ministerie van Infrastructuur en Waterstaat & Deltares, 2018; Vergouwe, 2014). In this area, a relatively high probability, high potential economic damage, and high potential number of fatalities come together. Building on that, flooding of dike-ring 16 was used as a representative river flooding scenario in the Dutch National Risk Assessment 2022 (ANV, 2022c). Flooding of dike-ring 16 could also be part of much worse floods than discussed by ANV (2022c), ENW (2024), and Vergouwe (2014). In their report on 'Worst Credible Flood' scenarios, B. Kolen and Wouters (2007) included the flooding of dike-ring 16 as part of a bigger Rhine-Meuse river flooding scenario. In their scenario, a breach in dike-ring 16 leads to a cascade of breaches and floods

in other dike-rings, leading to a much larger total flooded area. For the purpose of this study, flooding of just dike-ring 16 will be used as a foundation, assuming higher generalizability. Appendix I shows the flood scenario maps when a dike breach happens at km 954 of the Lek (dkr16 VY040), as retrieved from the Dutch Information System Water and Floods (LIWO).

13.1.2. Flooding characteristics

A base flood probability of 1/100 years is used, in line with previous assessments of dike-ring 16 (ANV, 2022c; Vergouwe, 2014). An exposed area of 500 km² is used. This aims to capture a slightly worse-case scenario than the floods limited to just dike-ring 16. Dike-ring 16 has an area size of nearly 400km² (392 km²), but cascading floods could become much bigger. For example, the 'Worst Credible Flood' involving dike-ring 16 had a size of 1300km² (B. Kolen & Wouters, 2007). The size of 500 km² is assumed to be realistic and generalizable to other types of floods and areas in the Netherlands. This size lies in between expected flood sizes in unprotected and protected areas in the Netherlands and could occur from both the primary and regional water system (Ministerie van Infrastructuur en Waterstaat & Deltares, 2018, Table 4.2 and 4.3).

The Dutch standard Flood Damage and Loss Model was used to infer realistic values for damage and mortality factors in sub-areas of the flood (Slager & Wagenaar, 2017). Looking at dike-ring 16 as a foundation, much of the flooded area would have flood depths above 2m, resulting in high physical damages and mortality rates. Four sub-areas of physical damages are defined for the base scenario. Of the flooded area (500 km²), 100 km² will have a damage factor of 0.9, 100 km² will have a damage factor of 0.5, 100km will have a damage factor of 0.2, and 200km will have a damage factor of 0.05. The mortality rates will also be distributed over four areas, considering that flow and ascent rate play an important role here as well. Of the flooded area, 100 km² will have a mortality rate of 0.4, 100 km² will have a mortality rate of 0.1, 100 km² will have a mortality rate of 0.05, and the rest will have a rate of 0.001. It must be noted that these values aim to represent average physical impacts, and that distributions of damages and fatalities over the flooded area can be very different.

Disruption damages can occur both during the disaster and after. For the base scenario, it will be assumed that the disaster phase lasts a week, during which there is full economic disruption (disruption factor of 1). Afterwards, the water begins to subside, but near full economic disruption lasts another week (disruption factor 0.9). Afterwards, the area remains severely disrupted for two months, with a disruption factor of 0.7. A year of slow recovery follows with high disruption in the beginning and lower disruption at the end. On average, the disruption factor for the total area for the whole year is 0.1. Still, another year with a disruption factor of 0.05 is needed to recover from the flood.

The average age of fatalities is defined as 45 years, rounded up from the average age of the Dutch population (42.4 years). This value was chosen because both children and elderly may be vulnerable groups for death from floods (Jonkman et al., 2008). This presumably keeps the average age near the middle. Estimations of injuries for floods vary widely (Doocy et al., 2013; Penning-Rowsell et al., n.d.). In this study, a morbidity-mortality ratio of 2 will be used. This means that for every fatality, there is a total 2 years of injury distributed over one or more injured people.

A base evacuation fraction of 0 is used, meaning that no one would be evacuated from the flooded area (non-evacuated fraction of 1). This is based on the idea of minimal intervention. However, it must be noted that this ignores that fact that a part of the population may vacate the area by themselves. This especially applies to sub-areas with a longer arrival time. Within the flooded area, non-evacuated people can still find shelter (for example at higher floors or locations). This relates to self-reliance. In their analysis of fleeing and rescue operations after a flood, A. B. Kolen et al. (2017) propose an upper bound of 90% and a lower bound of 60% of self-reliance during a flood. This means that 60-90% of people is able to bring themselves to safety during a flood, while the other 10-40% may be confronted with the flood waters. The base scenario assumes that 4 in 5 people find shelter, meaning that only 1 in 5 people present in the flooded area will be physically exposed to the flood water (confronted fraction of 1/5). This value also lies in between the 1/10 (urban areas) and 1/3 (countryside) used by Slager and Wagenaar (2017). Finally, it is assumed that - in addition to the health impacts incurred during the flood - 5% additional DALYs occur in the longer-term (delayed) after the flood (post-disaster DALY fraction of 0.05). This may for example include mental health effects.

Parameter	Base value floods
Event probability [/year]	1/100
Size of exposed area [km ²]	500
Physical damage factors per sub-area [km ² :damage factor]	100:0.9 100:0.5 100:0.2 200:0.05
Disruption damage factors per sub-period during disaster [duration [days]:damage factor]	7:1
Disruption damage factors per sub-period post-disaster [duration [days]:damage factor]	7:0.9 60:0.7 365:0.1 365:0.05
Mortality rates per sub-area [km ² :rate]	100:0.4 100:0.1 100:0.05 200:0.001
Average age of fatalities [years]	45
Morbidity-mortality ratio	2
Flood non-evacuated fraction	1
Flood confronted fraction	1/5
Post-disaster DALY fraction	0.05

Table 13.1: Parameters for the base flood scenario. Physical damage factors, disruption damage factors, and mortality rates may be variable over space and/or time, which is why a distribution of values is given.

13.2. Analysis of the base flood scenario

Applying the model to the base scenario results in the following outcomes:

- Population size in the exposed area: 265,000
- People present in the exposed area (non-evacuated): 265,000
- People physically confronted with the flood: 53,000
- Total physical damage: €8,500,000,000
- Disruption damage during disaster: €315,000,000
- Disruption damage post-disaster: €4,637,250,000
- Economic losses from DALYs: €6,841,688,700
- Total economic damage: €20,293,938,700
- Number of fatalities: 5,851 (2.2% of population)
- Years of injuries (spread over people): 11,702
- DALYs: 224,686

These values are deemed reasonable estimates of a large-scale flood with minimal intervention (e.g. no evacuation) in the Netherlands. The results can be compared to those in previous scenario analyses. In the scenario from the Dutch National Risk Assessment 2022, flooding of a large part of dike-ring 16 leads to 1,428 fatalities and 'several' (unspecified) injured (ANV, 2022c). The current result of 5,851 fatalities implies around 4,400 additional fatalities. This can partly be explained by the complete lack of evacuation and the bigger size of the area (>100 km² bigger). The additional difference can likely be explained by the use of a higher confrontation factor (1/5 compared to the 1/10 for urban areas in the SSM17) and a different distribution of mortality factors. Taken over the whole population of the flooded area, the mortality is 2.2%. Existing estimations of total economic damages for the flooding of dike-ring 16 vary between €11 billion (ANV, 2022c) and €9.5 billion (Vergouwe, 2014). This supports the estimation of €20.2 billion for a bigger area, minimal intervention, and including the economic damages from health losses.

In terms of risk (the impacts times a probability of 1/100 years), the base flood scenario outcomes are as follows. The health risk is 2,247 DALYs per year (corresponding to 59 fatalities and 117 one year injuries per year). The economic risk is 203 million euros in damages per year.

13.3. Specification of flood policy interventions

The findings from Parts II and III were used as a basis for specifying pandemic policy interventions. Each policy influences a parameter (lever) in the model. Each intervention has five possible levels, ranging from doing nothing (base scenario, level 0) to taking very significant action (level 4). The effectiveness of flood interventions was estimated based on the base scenario, assuming 2-4 days of flood prediction, of which 1 day would be windy, leaving 2 days for evacuation. For each intervention, the different levels are described in Table 13.2 and their effects in Table 13.3. An explanation is given in the sections below.

13.3.1. Continuous prevention (normal phase, probability reduction)

Interventions which reduce the probability of potential future (unknown) floods.

Reinforce flood defenses

Flood defenses, such as levees, are a powerful and effective way to reduce the probability of flooding from water bodies. Bak et al. (2011) performed a societal cost-benefit analysis in which they did calculations on (economically optimal) levee reinforcements throughout the Netherlands. The data and formulas in their report were used as a basis for determining different intervention levels of flood defense reinforcement. For dike-ring 16, Bak et al. (2011) found an economically optimal flood protection level of around 1/5200 or 1/6200 (using different calculations). They also report a 'decimation height' per dike section, which corresponds to the amount of heightening needed for a factor 10 reduction in flooding probability. For dike-ring 16, the decimation height is 40-60 cm. Inspired by these numbers, the levels of levee reinforcement considered will be a heightening of 0.25 m, 0.5 m (one decimation height), 0.75 m, and 1 m (two decimation heights). These correspond to flood probability reductions of approximately a factor 3, 10, 30, and 100. With a starting probability of 1/100 years, the maximum protection level that can be reached is then 1/10,000 years. This is a common protection level in the Netherlands, as reflected by the reports of Bak et al. (2011) and Ministerie van Infrastructuur en Waterstaat and Deltares (2018).

13.3.2. Pro-active impact reduction (normal phase, impact reduction)

Interventions which pro-actively reduce the impact of future (unknown) floods, if they occur.

Spatial planning

Through pro-active spatial planning, the presence of humans, buildings, and industry in flood-prone areas can be limited. In theory, if nothing of value is present in the flooded area, the damage is reduced to zero. In practice, however, space in the Netherlands is limited and much of the (more) flood-prone areas are located in regions of high economic value. Therefore, full impact reduction is impossible. Currently, there are around 8 million houses in the Netherlands (CBS, 2023). In the coming 10 years, approximately 1 million houses will be built (NL Times, 2022). This means that 1 out of a total of 9 million houses can still be strategically placed in 'flood-safe' areas. This corresponds to a maximum of 11.1% damage reduction, compared to if they were all placed in flood-prone areas. Based on this estimation, a maximum feasible damage reduction of 12% by spatial planning will be assumed.

Flood-proof building

Resilience of the built environment is about flood-proof constructions of buildings and infrastructure. This reduces the direct physical damages from the flood, which can be modeled through the direct physical damage factor. Findings from the floodings in Limburg demonstrated that damages to buildings with structural flood damage mitigation measures, wet-proofing, and/or dry-proofing were 20-30% lower than for those without such measures (Endendijk, Botzen, et al., 2023). Nofal and van de Lindt (2020) studied the implementation of such measures at the community level. Based on the findings of both studies, it is assumed that the maximum feasible risk reduction of the damage factor is 20% at the community level (i.e. on average; buildings that implement it may obtain more, but not everyone could or would). It must be noted that in reality the maximum (relative) damage reduction may be higher for less severe floods and lower for very severe floods.

Increase self-reliance

Self-reliance refers to the ability of individuals to evacuate or seek shelter without external assistance before or during a flood. Increasing self-reliance reduces the number of people directly confronted by

floodwaters, thus lowering the number of casualties and the pressure on rescue services. This intervention is modeled by reducing the “confronted fraction,” i.e. the share of people physically exposed to the flood. The base value assumes that 80% of people successfully find shelter without assistance, meaning a confronted fraction of 1/5. Interventions to improve self-reliance may range from simple awareness campaigns with general flood safety advice (level 1), to more targeted communication including practical tips and evacuation plans (level 2), to support for individuals in creating personal emergency plans (level 3), and finally to large-scale drills or practice exercises (level 4). Based on this scale, the maximum feasible self-reliance is assumed to be 90%, corresponding to a confronted fraction of 10% (50% reduction from 20%).

Increase societal preparedness

Preparedness of society is expected to improve the way that society responds to, adapts to, and recovers from floods. This may for example include preparedness of businesses through plans for continuation of operations during a flood. In the risk reduction model, this is best reflected in the indirect damage factor. The importance of societal resilience for reducing (indirect) impacts and improving recovery is emphasized by de Bruijn et al. (2022) and L. Wang et al. (2022). The importance of indirect consequences - which can thus be limited with higher preparedness - is also emphasized by Bak et al. (2011) and Koks et al. (2015). While societal resilience is expected to have a limited effect on immediate disruptions, which are typically short-lived, it can significantly mitigate longer-term impacts. Based on this, a maximum feasible reduction of 30% in post-disaster disruption is assumed.

13.3.3. Emergency prevention (threat phase, probability reduction)

Interventions which reduce the probability of an imminent flood threat becoming a flood.

Emergency flood barriers

Emergency flood barriers are temporary measures deployed when a flood threat becomes imminent. These measures include movable barriers, sandbags, and other emergency solutions aimed at reinforcing existing flood defenses or delaying water overload. They modify the flooding probability parameter. Emergency measures are only implemented once a flood threat is detected.

Lendering et al. (2016) studied the effectiveness of emergency flood prevention measures, focusing on the role of placing sandbags against dike failure by overflow or piping. They found that the probability of flooding could be reduced by a factor 4 maximum. They identify three activities which determine the reliability of the emergency defenses: detection, placement, and construction. Detection and placement are influenced by human error and the time available, while construction is more influenced by structural failure. Failure of detection and placement are most influential, meaning that human error (90% influence) and time available are the most influential factors for success (Lendering et al., 2016). Each of these factors is a relevant intervention-enabling process.

In this study, at the lowest intervention level (0), no emergency measures are taken. At level 1, reinforcing 25% of weak spots reduces the flooding probability by a factor of 1.3. This increases to a factor of 2 at level 2 (50% coverage), 3 at Level 3 (75% coverage), and reaches a maximum reduction factor of 4 at level 4, where all weak spots are reinforced. In theory, supportive interventions such as training for dike watch teams and improving early warning systems could further enhance the reliability of these emergency measures, effectively increasing the slope of the intervention effect.

13.3.4. Emergency anticipation (threat phase, impact reduction)

Interventions which reduce the impact of an imminent flood, if it occurs.

Preventive evacuation

Evacuations play an important role in the reduction of health impacts from floods. By reducing the size of the population present in the flooded area, mortality and morbidity can be lowered. A high number of evacuated people can be reflected in the evacuation fraction. The feasibility of evacuation is highly dependent on several factors, including the specific location, the timing of the flood threat, and the available infrastructure and personnel. Based on estimates in previous studies, a maximum evacuation fraction of 70% is considered feasible for this region (B. Kolen, 2013; B. Kolen et al., 2013). However, the feasibility is highly dependent on the circumstances, and may be much lower or densely populated areas and short warning times.

Emergency flood damage mitigation

Flood damage mitigation (FDM) measures implemented during a flood event, such as flood barriers around properties, temporary drainage solutions, and protection of movable objects, aim to reduce the extent of physical damage. These interventions focus primarily on safeguarding household contents and building integrity during the flooding event. Findings from previous studies, such as those by Endendijk, Botzen, et al. (2023), suggest that emergency FDM measures can significantly reduce damage to movable objects by around 40% and to building structures by approximately 30%. However, this is based on the Limburg-21 floods, which had much lower flood depths than in the current scenario. Taking into account the findings of Endendijk, Botzen, et al. (2023) for houses with high flood depths, a maximum feasible reduction of 10% will be used (average over the entire community, including those who did not implement it). The damage reduction may be lower for more severe floods, and higher for less severe floods. With high flood depths, the biggest influence will be on household contents and not so much on building structures (damage reduced).

13.3.5. Disaster response (disaster phase, impact reduction)

Interventions which reduce the impact of a flood while it happens.

Search and rescue operations

Search and rescue operations can save people from the area while the flood is ongoing. Based on the storyline analyses by A. B. Kolen et al. (2017), it is assumed that the maximum amount of people that could be rescued from dike-ring 16 is 25% over the course of a week (based on the Randstad scenario, where approximately 50,000 out of 200,000 people left behind in the area are rescued). While higher fractions are also possible, it is assumed that much of the mortality happens in the first day (before rescue), and thus that 25% is the 'effective' rescued fraction.

13.3.6. Recovery (post-disaster phase, impact reduction)

Interventions which reduce the impact of a flood once it is over.

Flood water drainage

It is assumed that it takes 3 months in the base scenario for pumping dry the area. It is assumed that with maximum effort (e.g. having more pumps and personnel), the time could be halved (to 1.5 months). It is assumed that this reduces the post-disaster disruption by a maximum of 25%, acknowledging that much of the disruption is not related to this time period, but to the damages already done.

Build-back-better

Build-back-better initiatives focus on improving the resilience of the built environment following a flood, ensuring that infrastructure and buildings are more resistant to future events. While these strategies do not reduce the immediate impacts of the current flood, they offer long-term risk reduction by making the region less vulnerable to subsequent events. This approach emphasizes flood-proofing buildings, improving land use, and integrating climate-resilient practices into recovery efforts. This does mean that the benefits of build-back-better only become real with a future flood. Therefore, the impact on damages in the current flood is 0%, but for the next flood they have the same range as "Flood-proof building", with a maximum damage reduction of 20%. This is based on the assumption that the effort for rebuilding a community to be flood-proof is (at least) as easy as 'renovating' existing and new buildings to be flood resilient.

Post-flood health support

The base scenario assumes a 5% addition of health complaints post the flood. This involves mental health complaints as well as physical health complaints. To reduce the post-flood health impact, extra care could be provided to those in the area. Of course, not all complaints are resolvable (e.g. grief induced). An assumption is made that with significant post-disaster healthcare programs, 20% of post-disaster health effects could be relieved.

Post-flood economic support

Economic compensation is a tool used to offset the financial losses incurred by individuals, businesses, and communities as a result of a flood. By redistributing losses from the affected population to government or insurance entities, compensation can alleviate some of the immediate economic impacts of

the disaster. However, compensation does not directly reduce the total economic damages; instead, it shifts the burden of those losses. Despite this, it can support the viability of affected businesses and individuals, preventing longer-term economic losses in the affected area. Based on the assumption that economic compensation can help sustain economic activity, a range of 1-20% reduction in post-disaster disruption damage factors is assumed.

Table 13.2: Overview of policy interventions modeled for floods. Each intervention influences a specific model parameter. The maximum feasible effect is distributed over five levels, where level 1 represents minimal change or baseline, and level 5 represents the maximum feasible intervention.

Intervention		Intervention level				
Layer of protection	Intervention	Nothing (0)	Minimal (1)	Medium (2)	Significant (3)	Very significant (4)
Continuous prevention	Reinforce flood defenses	No levee heightening	0.25m levee heightening	0.5m levee heightening	0.75m levee heightening	1m levee heightening
Pro-active impact reduction	Spatial planning	No building restrictions in flood prone areas	Minor building restrictions in flood prone areas	Medium building restrictions in flood prone areas	Significant restrictions in flood prone areas	Full building restrictions in flood prone areas
	Flood-proof building	No changes in building construction	Encourage the implementation of at least one measure: barriers, pumps, water-proof materials, and elevated sensitive components	Encourage and (financially) support the implementation of at least one measure (see level 1)	Mandatory implementation of at least one measure (see level 1)	Mandatory implementation of two measures (see level 1)
	Increase self-reliance	No extra efforts to increase self-reliance	Awareness campaigns	Awareness campaigns with practical advice	Major campaigns, supporting creation of individual emergency plans	Major campaigns, including practice exercises or drills
	Increase societal preparedness	No societal preparedness efforts	Awareness campaigns targeting businesses and public services	Encourage contingency planning in critical sectors (e.g., utilities, transport)	Coordinated preparedness plans across sectors, with training	Mandatory business continuity planning and flood resilience integration in public sector
Emergency prevention	Emergency flood barriers	No use of emergency barriers	Placement of sandbags at 25% of weak spots	Placement of sandbags at 50% of weak spots	Placement of sandbags at 75% of weak spots	Placement of sandbags at all weak spots
Emergency anticipation	Preventive evacuation	No evacuation	Evacuate the 10% most vulnerable people	Evacuate most vulnerable groups and locations	Major evacuation	Maximum (mass) evacuation
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Intervention		Intervention level				
Layer of protection	Intervention	Nothing (0)	Minimal (1)	Medium (2)	Significant (3)	Very significant (4)
	Emergency flood damage mitigation	No anticipatory flood damage mitigation	Minor efforts to move valuables to higher floors	Medium efforts to move valuables to higher floors and place sandbags	Significant efforts to place sandbags and move up valuables	Maximum placement of (sandbag) barriers around buildings and moving up valuables
Disaster response	Search and rescue	No search and rescue operations	Minimal rescue operation	Medium rescue operation	Significant rescue operation	Maximum deployment of personnel and materials
Recovery	Flood water drainage	Normal drainage time (3 months)	Minimal increases in drainage speed	Speed up drainage to 2.5 months	Speed up drainage to 2 months	Deployment of extra drainage materials, halving the drainage time (1.5 months)
	Build-back-better	No changes in building construction	Encourage the implementation of at least one measure: barriers, pumps, water-proof materials, and elevated sensitive components	Encourage and (financially) support the implementation of at least one measure (see level 1)	Mandatory implementation of at least one measure (see level 1)	Mandatory implementation of two measures (see level 1)
	Post-flood health support	No additional post-flood healthcare	Minimal outreach and psychological first aid to affected population	Establish temporary health support centers in the region	Structured mental and physical health programs post-flood	Comprehensive, long-term post-flood healthcare and psychological support programs
	Post-flood economic support	No economic compensation	Minimal compensation, limited to direct household losses	Partial compensation for households and small businesses	Full compensation for households, partial support to businesses	Full compensation for households and businesses

Table 13.3: Flood intervention levels: effect.

Intervention description			Multiplication factor per intervention level				
Layer of protection	Intervention	Parameter modified	Base (0)	Minimal (1)	Medium (2)	Significant (3)	Very significant (4)
Continuous prevention	Reinforce flood defenses	Probability	1	1/3	1/10	1/30	1/100
Pro-active impact reduction	Spatial planning	Affected area	1	0.97	0.94	0.91	0.88
	Flood-proof building	Physical damage factor	1	0.95	0.9	0.85	0.8
	Increase self-reliance	Confronted fraction	1	0.87	0.75	0.63	0.5
	Increase societal preparedness	Post-disaster disruption factors	1	0.9	0.85	0.8	0.7
Emergency prevention	Emergency flood barriers	Probability	1	1/1.3	1/2	1/3	1/4
Emergency anticipation	Preventive evacuation	Affected population	1	0.9	0.75	0.5	0.3
	Emergency flood damage mitigation	Physical damage factor	1	0.99	0.96	0.93	0.9
Disaster response	Search and rescue	Affected population	1	0.94	0.88	0.82	0.75
Recovery	Flood water drainage	Post-disaster disruption time	1	0.93	0.87	0.81	0.75
	Build-back-better [next event]	Physical damage factor	1	0.95	0.9	0.85	0.8
	Build-back-better [current event]	Physical damage factor	1	1	1	1	1
	Post-flood health support	Post-disaster health impact	1	0.93	0.87	0.81	0.8
	Post-flood economic support	Post-disaster disruption factors	1	0.93	0.87	0.81	0.8

13.4. Flood risk reduction analysis

The risk reduction model quantified the effects of the interventions across the six categories: continuous prevention, proactive impact reduction, emergency prevention, emergency anticipation, disaster response, and recovery. Outcomes are assessed in terms of reductions in both health risk (measured in DALYs per year) and economic risk (measured in euros per year) as intervention levels increase from 0 to 4. The results are visualized in Figure 13.1. A version with a log scale and one with absolute risk values can be found in Appendix L.

Continuous prevention, represented by reinforcement of flood defenses, leads to the most substantial reductions in both health and economic risks. As the intervention level increases, risks decline sharply - by several orders of magnitude - indicating the effectiveness of this strategy in directly reducing the probability of flooding. This steep decline reflects the predictable, controllable nature of flood hazards when structural defenses are in place.

Other interventions show more modest impacts. Of the pro-active impact reduction interventions, increased self-reliance can halve the health impact. Double the people would be able to bring themselves to safety (find shelter within the affected area), which considerably reduces the number of deaths and injuries. Flood-proof building and spatial planning have flatter curves. They show limited marginal benefit at higher intervention levels. Spatial planning influences both health and economic risk directly, since it assumes the lesser presence of both people and assets in flood-prone areas.

Emergency prevention measures - particularly the deployment of emergency flood barriers - yield a steady reduction in both risk categories, reducing flood probability by a factor 4. This leads to a higher risk reduction than most other interventions, but the impact is significantly smaller than that of permanent structural defenses. This confirms their role as a supplementary buffer when continuous prevention is either insufficient or infeasible.

Emergency anticipation shows differential effectiveness. Especially at higher levels, preventive evacuation has a considerable effect on reducing health risk, and thereby also reduces economic risk. Evacuations primarily reduce human exposure without directly mitigating physical or economic damage, but they do reduce economic damage from health losses. The role of emergency flood damage mitigation is negligible compared to the total economic impacts.

The disaster response phase - exemplified by search and rescue - provides small but consistent reductions in health risk. However, its overall contribution is limited relative to interventions that act earlier in the timeline of a flood event.

Lastly, recovery interventions, including build-back-better strategies and post-flood support measures, show negligible impact on health risk and only minimal reductions in economic risk. This reinforces the notion that post-event actions for floods do not significantly alter the primary damage outcomes, which are largely determined during the event itself.

In summary, the results highlight that flood risk is most effectively mitigated through interventions in the normal and threat phases, particularly (continuous) prevention. Evacuations and increased self-reliance can reduce human impacts, but possibilities for effective intervention narrows rapidly once flooding occurs. Recovery and response measures, though necessary for resilience, offer limited returns in terms of quantitative risk reduction.

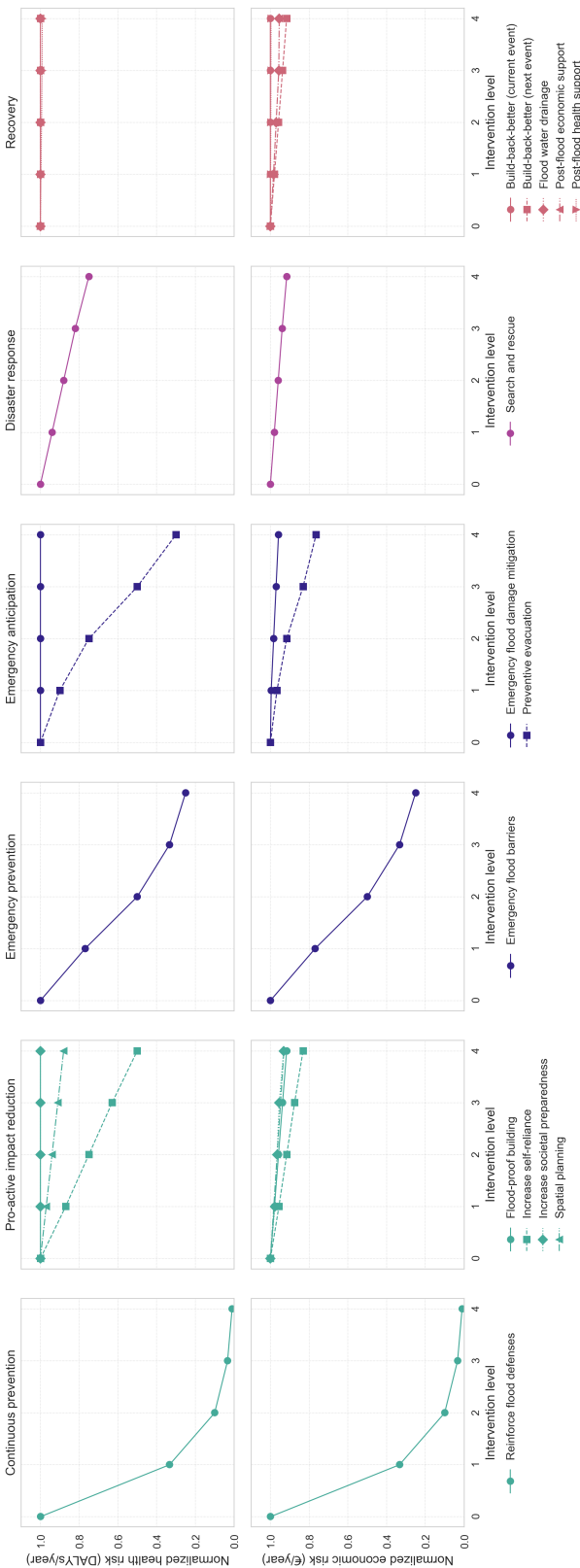


Figure 13.1: Flood risk reduction by different types of interventions. Plots for health risk reduction are shown on the top row and for economic risk reduction on the bottom row. Each intervention (line) has multiple levels of intensity, from level 0 to 4 (x-axis). The columns separate the different categories of interventions. The coloring of the lines indicates the primary phases in time during which interventions from each category are implemented. Green: normal phase, implementation of continuous prevention and pro-active impact reduction. Dark blue: threat phase, implementation of emergency prevention and anticipation. Purple: disaster response, implementation of disaster response. Pink-red: post-disaster phase, implementation of recovery.

Pandemic risk reduction

Modeling results for the impact of pandemic interventions

This chapter describes the application of the risk reduction model to pandemics. The model structure and equations are described in Chapter 12. This chapter first explains the base values used in those equations, which correspond to a base scenario that was designed for a pandemic in the Netherlands. The chapter then describes the pandemic interventions that were used in the experimental analysis with the model, as well as the modeling results. Chapter 15 describes a comparison of these results with floods. This all contributes towards answering SQ3: *How do the effects of risk reduction strategies for floods and pandemics compare?*.

14.1. Specification of base pandemic scenario parameters

The base pandemic scenario will be used to calculate the baseline risk of pandemics. Like the flood scenario, it should represent a realistic and general situation of a possible future pandemic occurring in the Netherlands. The base pandemic scenario was designed based on the 'new' pandemic scenario in the Dutch National Risk Assessment (ANV, 2022b) as well as a simple infectious disease model, which uses Covid-19 inspired values. Design of the scenario also took into account the factor of comparability to the flood scenario.

The base pandemic probability is set at 1/50 per year. This probability is modified from the estimated probability of 1/100 per year by ANV (2022b), based on (a) the assumption of minimal intervention, and (b) the fact that the experts consulted in this study already indicated expectations of more frequent pandemics (with one expert mentioning 1/20 years as a probable return time). In the pandemic scenario, the outbreak spreads over the entire area of the Netherlands (34,000 km² of land), diffusing through the entire population (around 18 million people).

14.1.1. SEIRS model as foundation for disease dynamics

To infer the parameters for the base pandemic scenario, an infectious disease model was used. This was done to account for the complex dynamics of a pandemic over time, which are more spread out than those of a flood. An infectious disease model is used to simulate pandemic spread and mortality.

Specifically, a SEIRS model was formulated, using differential equations from the methodological papers published by Bjørnstad et al. (2020) and Shea et al. (2020) (equations in Appendix K). The SEIRS model includes a susceptible population (S), an exposed population (E), an infectious population (I), and a recovered population (R). The model is an advancement on the simpler 'SIR' model, which has only three groups: susceptible (S), infectious (I) and recovered (R). With the exposed group (E), the SEIRS model accounts for the latent period between being infected and becoming infectious. The extra 'S' in the model accounts for the loss of immunity over time, which Bjørnstad et al. (2020) refer to as waning immunity. The SEIRS model also incorporates births and deaths (Bjørnstad et al., 2020) well as the possibility of vaccination for increasing immunity (Shea et al., 2020). The SEIRS

model used in this study was split over multiple phases, allowing the change of parameters over time. The model also incorporates ICU capacity and a different mortality rate for those admitted to the ICU and those who cannot be admitted (but are severely ill) because of capacity constraints.

The SEIRS disease parameters were set to describe a disease with slightly more severe characteristics than COVID-19. Inspiration from other pandemic scenarios, such as the one from ANV (2022b) and NZ Royal Commission COVID-19 Lessons Learned (2024) was used for this. The infection parameters in the SEIRS model were set as follows: a latency period of 5 days (between exposed and infectious), a recovery period of 7 days (time of infectiousness), and an immunity duration of 1 year. It is assumed that 4% of the infected people requires hospitalization. Among those 4% very severe infections, 30% die when they are hospitalized (overall mortality would be 1.2%), while this is 90% if they would not be hospitalized (e.g. no beds available; overall mortality would be 3.6%). After a bit more than a year, the mortality slightly decreases based on weakening of the virus or better treatment (10% decrease in both mortality rates).

For the spread of infections, a contact rate of 0.37 is used, which slightly decreases a few months after the first infection (e.g. because of fear) and remains at 80-90% of its original value for two years of the pandemic. Afterwards, it goes back to the original value. Thus, while assuming minimal intervention (e.g. no social distancing), the base scenario still assumes that population behavior changes throughout the pandemic. It is assumed that a vaccination campaign would start after two years, with a vaccination rate of 1% of the population per day (i.e. 100 days to full vaccination). Furthermore, The pandemic period was set to 3 years. The resulting infectious disease dynamics are shown in Figure 14.1.

14.1.2. Base health parameters

Using the results of the SEIRS model, the infected fraction is 1.54 (meaning 1.54 times the entire population). This means that every person in the population would get infected 1.54 times throughout the 3 years, which is a result from the immunity only lasting 1 year. In the first year, there is a big peak of infections (between 100-200 days from the first infection), with a maximum of around 1.5 million simultaneous infections. Each subsequent year, nearly the full population gets infected again, but than more spread out with lower peaks. Throughout the pandemic, 1.7% of those infected dies, setting the (average) mortality rate at 0.017.

It is assumed that the mortality is a bit higher among elderly and a bit lower among younger people. The average age of fatalities lies higher than with floods. In the pandemic scenario, it is assumed that elderly are more vulnerable to dying from infection than younger people. This was the case with Covid-19 and is the case with many respiratory diseases. An average age of 55 years will be used (a bit more than 10 years above the Dutch average age of 42.4).

There is a different distribution in mortality versus morbidity in pandemics. While the number of injuries in floods is often similar to the number of fatalities, the number of injuries for pandemics is much higher. In this study, the morbidity-mortality ratio is about years of injuries for each fatality. It will be assumed that for each fatality, 5 people suffer 1 year complaints from their infection. This puts the ratio at 5. Finally, it is assumed that 1% additional DALYs occur in the longer-term (delayed) after the pandemic (post-disaster DALY fraction of 0.01), for example due to mental health effects.

14.1.3. Base economic parameters

The physical damage factor for pandemics is 0 for any area; the pandemic does not physically damage any objects. The pandemic does cause disruption damage over a long period of time.

Economic disruptions were also inferred based on the pandemic peaks from the SEIRS model over time. It is assumed that, with minimal intervention, the first pandemic peak will severely disturb the Dutch economy. The peak lasts around 100 days, with peak infections of around 1.5 million people at the same time. This is assumed to severely disrupt the economy, with a disruption factor of 0.5. Afterwards, the population is mostly immune, but the immunity fades away over time. It is assumed that the big peak leaves a lasting disruption damage of 0.2 for another three months. Over the next 2 years, a lower peak occurs each year and there is a continuous presence of infections. It is assumed that the population has adapted a bit and that the disruption is a bit less, especially because the peaks are less intense. An average disruption factor of 0.005 (0.5%) for these two years will be assumed. Assuming

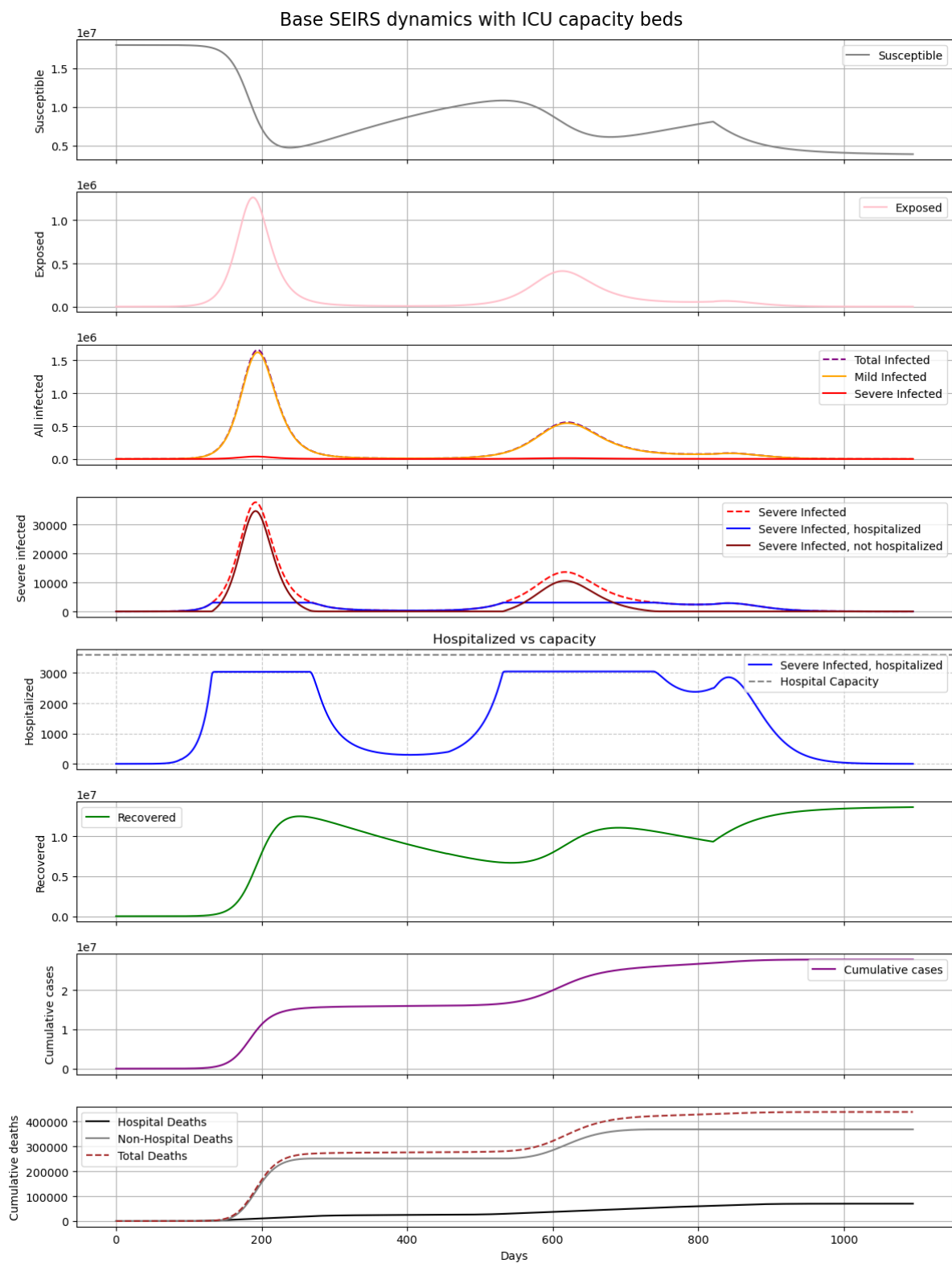


Figure 14.1: Infectious disease dynamics over a period of three years, based on the base characteristics of a pathogen (e.g. infectiousness, mortality) and population (e.g. size, immunity). Modeled with a SEIRS model.

that society will require more time to recover from the pandemics impacts, this 0.5% disruption will continue for another year in the post-disaster phase.

It must be noted that these values are averages, meaning they may have a very different distribution over the affected area and time, but are assumed to capture general total amounts over the pandemic.

Parameter	Base value pandemics
Event probability [/year]	1/50
Size of exposed area [km ²]	34,000
Physical damage factors per sub-area [area size [km ²]:damage factor]	34,000:0
Disruption damage factors per sub-period during disaster [duration [days]:damage factor]	60:0.5 90:0.2 730:0.005
Disruption damage factors per sub-period post-disaster [duration [days]:damage factor]	365:0.005
Mortality rates per spacetime fraction [fraction:rate]	1:0.017
Average age of fatalities [years]	55
Morbidity-mortality ratio	5
Pandemic infected fraction	1.54/1
Post-disaster DALY fraction	0.01

Table 14.1: Parameters for the base pandemic scenario. set for parameters with hazard-specific values. Physical damage factors, disruption damage factors, and mortality rates may be variable over space and/or time, which is why a distribution of values is given.

14.2. Analysis of the base pandemic scenario

Applying the model to the base pandemic scenario results in the following outcomes:

- Population size in the exposed area: 18,020,000 (full Dutch population)
- Infections with the pandemic pathogen: 27,750,800 (on average 1.54 times per person)
- Total physical damage: €0
- Disruption damage during disaster: €158,049,000,000
- Disruption damage post-disaster: €5,584,500,000
- Economic losses from DALYs: €433,883,812,330
- Total economic damage: €597,517,312,330
- Number of fatalities: 471,763 (2.62% of Dutch population)
- Years of injuries (spread over people): 2,358,818
- DALYs: 14,813,377

These values are high, but not unthinkable for a severe pandemic with minimal intervention in the Netherlands. For comparison, Covid-19 led to an estimated 550,000 DALYs between 2020 and 2023 (169,400 (2020), 218.900 (2021), 93.800 (2022), 37.800 (2023)). The current scenario has much worse outcomes (around 27x), which is explained by lack of intervention (unrestricted spread and late vaccination) and a higher mortality rate. Dividing the DALYs over the full population, an average of 0.82 healthy life years would be lost per person. Although the values are very high, they are not unthinkable, and also not unlikely in the situation of complete health care system overwhelmed-ness. Damages for pandemics are sometimes estimated between 50 and 80 billion (e.g. by ANV (2022b)). In this case, damages are 7.5 times as high, which is explainable especially by the huge peak (1.5 million simultaneous infections) in the first year, which severely disrupts the economy.

In terms of risk (the impacts times a probability of 1/50 years), the base pandemic scenario outcomes are as follows. The health risk is 296,267 DALYs per year (corresponding to 9,435 fatalities and 47,176 one year injuries per year). The economic risk is 12 billion euros per year. It must be noted that in this case, a severe pandemic is combined with a high return time, which gives rise to quite an extreme

scenario. Again, the purpose of this analysis is not to detail the absolute effects in risk reduction, but rather to be a reasoning tool for comparison of intervention strategies.

14.3. Specification of pandemic policy interventions

The findings from Parts II and III were used as a basis for specifying pandemic policy interventions. Each intervention has five possible levels, ranging from doing nothing (base scenario, level 0) to taking very significant action (level 4). For each intervention, the different levels are described in Table 14.2 and their effects in Table 14.3. An explanation is given in the sections below.

14.3.1. Continuous prevention (normal phase, probability reduction)

Interventions which reduce the probability of potential future (unknown) pandemics.

Global pandemic prevention

Global biosafety and biosecurity measures can reduce the overall probability of a pandemic occurring. Based on the insights from experts and the literature, it is assumed that pandemics are difficult to reliably prevent, due to their (global) complexity in spark and spread dynamics. No studies were found in which possible reductions of pandemic probability are academically quantified. However, Bernstein et al. (2022) performed an analysis on the cost-effectiveness of primary prevention of zoonotic pandemics. In their analysis, they use calculations with probability reductions by 1/3 and 1/2. It is not clear if these are upper-bounds or seemingly feasible reductions. Therefore, these numbers will be taken as feasible probability reductions for the middle intervention levels. A 10% probability reduction will be used for the minimal intervention, a 30% reduction (near 1/3) for the level 2 intervention, 50% (1/2) for a level 3 intervention, and a 75% (factor 4) for the maximum feasible intervention. It is assumed that - in theory - higher reductions may be achievable, but that this is not attainable right now, and may require further advancements in technologies and high international collaborations. Global pandemic prevention efforts must include "better surveillance of pathogen spillover and development of global databases of virus genomics and serology, better management of wildlife trade, and substantial reduction of deforestation" (Bernstein et al., 2022, p. 1).

National pandemic prevention

National-level infection prevention measures have a negligible effect on the probability of a pandemic, since outbreaks are most likely to originate abroad. However, national measures do play a crucial role in preventing local epidemics, which can also cause severe consequences. Moreover, while having very little influence at stopping pandemics alone, they remain important within a global prevention strategy. National infection outbreak prevention measures include the detection and immediate containment of pathogens. For simplicity, it will be assumed that the Netherlands contributes 1% to the global pandemic probability. It is (optimistically) assumed that - within the Netherlands - strict measures could reduce this probability by a factor 20 (95%). Then the pandemic probability overall can be reduced by a maximum of 0.95% (95% of 1%) if the Dutch put in maximum effort within their own country only.

14.3.2. Pro-active impact reduction (normal phase, impact reduction)

Interventions which pro-actively reduce the impact of future (unknown) pandemics, if they occur.

Structurally increase hospital capacity (ICU beds)

An expansion of hospital capacity allows more patients to be treated. Treatment in the hospital increases the chance of survival for patients in need of care (e.g. with severe infections), thus lowering their mortality. As long as the care demand is below the capacity, all patients can get treatment. However, once the capacity is reached, some patients cannot be cared for, which may increase overall mortality. In this study, ICU capacity (expressed in terms of 'beds') will be used as a proxy for hospital capacity. Increases in ICU capacity can decrease mortality via ensuring that as many patients as possible get the care they need. However, it must be noted that changes in hospital capacity do not influence the infection dynamics of a pandemic. Peaks in infection numbers are independent from hospital capacity, and the care demand can exceed the capacity by large (as is the case in the base scenario). It is not possible to meet such a demand, since an ICU bed is not just a bed, but requires high investments in terms of personnel, equipment, space, and more (Gandjour, 2021). This means

that additional ICU beds only delay system overload, rather than prevent it. Without infection-reducing measures in place, the capacity will still be exceeded.

The SEIRS model was used to estimate the reduction of mortality by increasing the ICU capacity. For the base pandemic scenario it was assumed that 4% of infected people get severely sick, of which 90% would die if not admitted to the ICU and 30% would die if admitted to the ICU (i.e. factor 3 reduction of mortality by ICU admission). The initial ICU capacity (base scenario) was set to 1200. As a proactive intervention, the Netherlands could structurally increase this capacity. This could be done both via adding permanent ICU beds, as well as adding staffed ICU reserve (surge capacity) (Gandjour, 2021). During the Covid-19 pandemic, the Netherlands doubled its ICU capacity. In this study, it will be assumed that if the Netherlands takes pro-active, structural measures, the ICU capacity could at most be tripled. This could involve a permanent doubling of ICU beds, with extra surge capacity to increase the number of beds up to triple during crises. Using the SEIRS model, it is found that a doubling (from 1200 to 2400 beds) in hospital capacity reduces overall mortality by 4.9%, while tripling the capacity reduces it 8.8%. In this study, additional effects of hospital capacity increases (e.g. on other patients or cascading health system consequences) are not explicitly considered.

Increase societal preparedness

Societal preparedness for pandemics involves measures such as continuity planning by businesses, remote work infrastructure, and clear public communication strategies. These efforts enhance the ability of society to maintain essential functions and recover more swiftly. In the risk model, this is best reflected in the disaster disruption factor. As with floods, a maximum feasible reduction of 30% in disruption factors is assumed.

14.3.3. Emergency prevention and anticipation (threat phase, probability and/or impact reduction)

Interventions which reduce the probability of an imminent pandemic threat becoming reality (endemic) and/or which reduce the impact of an imminent pandemic, if it occurs.

In the case of emergency action against pandemics - during the threat phase - many interventions serve both a probability-reducing and an impact-reducing role. Therefore, these are taken together here. Action within the first 30 days of cases in the Netherlands (or before then, upon signals from abroad) will be considered anticipatory, as taken during the threat phase. Many of the interventions can also be taken at a later point in time, but are by then considered to be responsive, which may influence their effects. The responsive interventions are discussed in the next section.

Global emergency containment

Global action could be taken to contain a quickly spreading outbreak before it becomes a pandemic. This differs from the intervention 'global pandemic prevention' by the phase in time. Global pandemic prevention is about structural measures taken to continuously prevent pandemics. Global emergency containment is about acting on (not-prevented) pandemic threats, such as early-stage outbreaks. It is assumed that such prevention is not as effective as global pandemic prevention can be. This is because now a pandemic-potential pathogen already exists in the population. Strong containment efforts can limit its spread, but as long as the pathogen is present in the population, it could resurge again. Containment could be strengthened if effective treatment options or population immunization (vaccination) are possible. It is assumed that strong containment measures (e.g. global travel restrictions and early lockdowns in affected populations) can reduce the probability of a threat becoming a pandemic by 25%. This is compared to the base scenario, with only minimal continuous global prevention efforts.

National emergency containment

At a national level, emergency containment efforts could reduce the chance of infections in the Netherlands becoming a widespread outbreak. However, assuming that the pandemic originates outside the Netherlands (>99% probability), prevention would be an ongoing effort throughout the entire pandemic period. Considering that other countries will be affected by pandemic outbreaks, the pathogen could spread to and within the Netherlands at any time. Containment efforts would thus have to be maintained (or frequently reintroduced) until the pandemic reduces worldwide or until vaccination or other treatments are available. Therefore, probability reduction by preventive containment policies is limited; a pandemic pathogen is likely to become endemic in the Netherlands anyways. Global efforts

are expected to have somewhat stronger effects (see above). Efforts in the Netherlands could include (incoming) travel restrictions, quarantining, and - in the most significant case - preventive lockdowns.

Regardless of the limited probability reduction, early action can still have a strong effect on the course of the pandemic in the Netherlands. Containment policies during the threat phase can have a strong influence on the infection dynamics throughout the pandemic, reducing its overall impact and mortality by flattening the curve. Thus, if national emergency containment fails in terms of probability reduction (prevention), it may still have a significant influence on pandemic impact. However, this would be very dependent on the actions taken once the disaster phase is entered. In this study, it will be assumed that strong containment efforts during the threat phase could reduce infections throughout the pandemic (if it becomes endemic in the Netherlands) by around 10%. Further reduction of infections depends on actions maintained and taken during the disaster phase itself. The interdependency between these phases is not modeled in this study.

Emergency vaccination campaigns

Early introduction of vaccines could greatly reduce the probability of a pandemic pathogen becoming endemic in the Netherlands. However, the feasibility of a vaccination campaign is highly dependent on whether a (modifiable) vaccine already exists for the pathogen, or else how fast a new vaccine is developed. This intervention is thus not a straightforward 'can do', but rather highly dependent on the circumstances. However, the Netherlands could invest in vaccine development to increase the chances of swift vaccine development. For the campaign to be preventive (rather than responsive), it must prevent the pathogen from becoming endemic in the Netherlands and hospital capacity to be exceeded. The SEIRS model was used to estimate the effect of early vaccination. It must be noted that the model assumes population coverage of 100% (i.e. everyone would take the vaccine). While full coverage is not feasible, a high coverage with sufficient herd immunity is possible. The SEIRS model also does not consider different levels of vaccination effectiveness. With vaccinations starting after two months and a 1% vaccination rate (percentage of population vaccinated per day), the disaster phase can be avoided. A low peak in infections occurs, but the amount of severe infections remains far below hospital capacity. With vaccinations starting at three months, a capacity-exceeding peak cannot be avoided. However, a more than 20-fold reduction in cumulative cases throughout the pandemic can still be obtained, since this is the only peak that would occur and further infections are prevented. Again, this shows that anticipatory measures can have a double role in terms of probability-reduction and impact-reduction. While it could be very successful, it is assumed that the chances of having a vaccine in time and executing the campaign successfully are low (5%). This probability was used to correct the impact levels.

Emergency increase in hospital capacity (ICU beds)

As discussed with the intervention 'Structurally increase hospital capacity', pro-active and structural increases in the number of ICU beds are possible. However, even if no structural changes are made, sudden increases in ICU capacity may still be realized during a crisis. Note that in this case - as opposed to pro-active increases in (surge) capacity - the increases are less structural and more improvised. The possibilities are smaller, considering the lack of personnel and equipment for spontaneously needed beds. A possibility is to redistribute beds from other hospital departments or care institutions, but that means that the supply of other care becomes smaller. Even the use of field hospitals may be an option in extreme cases. In this study, it is assumed that the maximum possible emergency increase in capacity is a doubling of the ICU beds. This is similar to the capacity obtained during the Covid-19 pandemic. Analysis with the SEIRS model reveals that the doubling of hospital capacity could reduce overall mortality throughout the pandemic by around 5%.

14.3.4. Disaster response (disaster phase, impact reduction)

Interventions which reduce the impact of a pandemic while it happens. The disaster phase is entered once the pandemic pathogen becomes endemic (it's spread is unavoidable) and the hospital capacity will be exceeded.

Responsive containment policies

As discussed with the 'emergency containment' policies, the spread of a pandemic pathogen can be reduced with containment efforts. However, once the disaster phase is entered, the role of such mea-

shifts to being 'responsive'. Containment policies (generally 'non-pharmaceutical interventions') modify the reproduction number (R), reducing transmission. The impact relates to the stringency of the measures. RIVM (2024a) estimate that, during the Covid-19 pandemic in the Netherlands, the reproduction number was reduced up to around 50% during times with highly stringent measures (see Figure 14.2). Talic et al. (2021) estimate that the relative risk of infection with implemented measures like hand washing, mask wearing, and physical distancing was around 0.5 (50% reduction). The SEIRS model confirms that lowering the contact rate can strongly reduce the number of infections throughout the pandemic. However, it must be noted that stringent measures come with highly negative economic side effects and are not maintainable for multiple years. Additionally, the true reduction in infections would be dependent on timing, behavioral compliance of people, and the maintenance or re-introduction of measures until immunity is reached. In this study, it is assumed that with significant containment policies, a reduction of infections up to 50% is feasible. This would require effective containment policies to be maintained (or strategically re-implemented before peaks) throughout the pandemic.

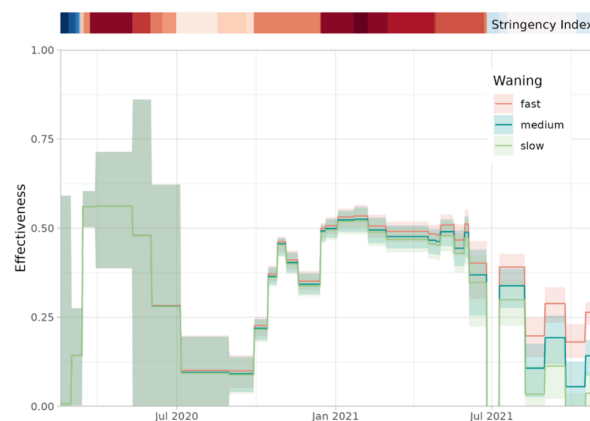


Figure 14.2: Estimated effectiveness of NPIs in terms of reduction of the effective reproduction number R throughout 2020 and 2021 of the Covid-19 pandemic in the Netherlands. The bar at the top indicates the stringency of NPIs throughout time. Figure copied from RIVM (2024a).

Responsive increase in hospital capacity (ICU beds)

If not implemented pro-actively or during the threat phase, hospital capacity may still be increased during the disaster phase. In practice, this would require similar efforts as during the threat phase; the only difference being the time of implementation. Assuming that the capacity would now be increased around the time of the first peak, the effect would be slightly delayed compared to implementing it in anticipation. A maximum mortality reduction of 4% (compared to 5% with anticipatory ICU capacity increases) will be assumed, based on doubling the ICU capacity.

Responsive vaccine development

Vaccination campaigns can be highly effective in reducing pathogen spread (Fajgenblat et al., 2024; RIVM, 2024a). As discussed in 'Emergency vaccination campaigns', vaccines can also be used as a preventive measure before a pathogen becomes endemic. However, considering the considerable possibility that a pandemic would arise from a novel pathogen, the development of a vaccine may require considerable time. During the Covid-19 pandemic, vaccination campaigns were started in the Netherlands after around a year (van Amerongen et al., 2024). This was considered to be fast and there is no guarantee that vaccines would be developed equally fast for a next pandemic. The SEIRS model was used to estimate the effect of vaccination campaigns started at different points in time. A rate of 1% (population vaccinated per day) from the start of the campaign is used. The model assumed full coverage of the population, which is not feasible. However, it is assumed that the effects approach the possible effects of herd immunity. In the base scenario, a vaccination campaign is started after 2.25 years. With this intervention, the campaign is moved forward up to as early as 6 months after the first case in the Netherlands. This would have a maximum effect of 50% infection reduction, considering that a large peak already occurs in the first month.

Responsive economic mitigation

Economic disruptions following a pandemic can extend well beyond the health crisis, particularly when businesses face long-term closures or unemployment surges. Responsive economic mitigation measures - such as direct financial support, tax relief, and liquidity injections - can help stabilize households and companies. These policies do not reduce the total impact of the pandemic but help redistribute financial burdens and prevent economic collapse. Based on assumed efficiency and international examples, a maximum feasible reduction of 16% in economic disruption is applied.

14.3.5. Recovery (post-disaster phase, impact reduction)

Interventions which reduce the (delayed) impact of a pandemic once it is over.

Post-pandemic health support

The base scenario assumes a 1% addition of health complaints post the pandemic. This involves mental health complaints as well as physical health complaints. To reduce the post-pandemic health impact, extra care could be provided to those in the area. Of course, not all complaints are resolvable (e.g. grief induced). Unlike disasters with a clear endpoint, recovery during pandemics can begin earlier, often overlapping with the final stages of the outbreak. An assumption is made that with significant post-disaster healthcare programs, 25% of post-disaster health effects could be relieved. (i.e. 25% times ca 1% of health effects).

Economic recovery acceleration

Recovery from a pandemic often includes lingering economic slowdowns, even after infections subside. In the base scenario, it is assumed that small disruptions continue for up to a year. Recovery acceleration efforts - such as stimulus packages, infrastructure projects, and employment initiatives - can speed up economic normalization. These interventions aim to reduce uncertainty and restore consumer and business confidence. A maximum feasible reduction of 50% in post-disaster disruption duration is therefore assumed.

14.4. Pandemic intervention-enabling processes

In the process of specifying pandemic interventions, several enabling processes came forward. For example, RIVM (2024a) found that the timing of interventions could make a big difference for the overall impacts of the (first wave of) the Covid-19 pandemic. This is shown in Figure 14.3 and emphasizes the role of timely action, which - as also mentioned by experts consulted for this study - is incredibly important for dealing with pandemics and could be supported by early warning systems and enhanced decision making under uncertainty.

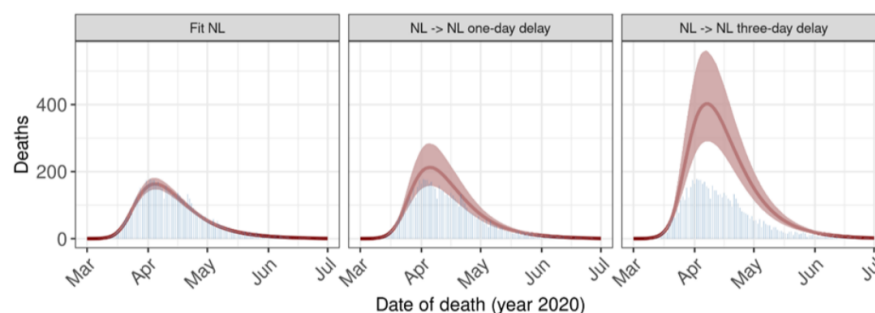


Figure 14.3: The importance of NPI timing for flattening the curve. Figure copied from RIVM (2024a).

The use of testing facilities is another example of an intervention-enabling (/supportive) process which can increase effectiveness of interventions (e.g. social distancing) during a pandemic. Enhanced testing capacity improves early detection and containment of a pandemic, reducing the fraction of infected individuals. More efficient testing allows for targeted interventions, reducing spread and enabling better healthcare responses. These examples illustrate that intervention-enabling processes can make interventions throughout the disaster phases more effective - either steering them towards level 4, or even introducing new options of effectiveness.

Table 14.2: Overview of policy interventions modeled for pandemics. Each intervention influences a specific model parameter. The maximum feasible effect is distributed over five levels, where level 1 represents minimal change or baseline, and level 5 represents the maximum feasible intervention.

Intervention		Intervention level				
Layer of protection	Intervention	Base (0)	Minimal (1)	Medium (2)	Significant (3)	Very significant (4)
Continuous prevention	Global pandemic prevention	Limited global coordination, isolated efforts	Basic global surveillance and data sharing	Moderate pandemic agreements, focus on high risk areas	Extensive regional coordination and joint prevention efforts	Global coordination with intensive monitoring and containment
	National pandemic prevention	Minimal local prevention and isolated containment	Sporadic local screening and limited early interventions	Consistent local surveillance with targeted measures	Proactive early detection combined with early actions	High-level national monitoring with comprehensive containment strategies
Pro-active impact reduction	Structurally increase hospital capacity (ICU beds)	ICU capacity remains unchanged (1200 beds)	Create surge capacity of +50% (600 beds)	Increase permanent capacity with 50% (+600 beds) and have 33% surge capacity (+600 beds)	Double the permanent ICU capacity (+1200 beds) and have 25% surge capacity (+600 beds)	Double the permanent ICU capacity (+1200 beds) and have 50% surge capacity (+1200 beds)
	Increase societal preparedness	No specific preparations in place	Basic continuity planning and communication	Remote work enabled, some continuity measures	Broad preparedness plans in sectors, strong public communication	Full continuity planning, remote work enabled nationwide, clear strategies
Emergency prevention and anticipation	Global emergency containment	Minimal global containment efforts	Global recommendations for infection prevention	Global coordination for containment in affected populations	Global border checks and quarantine requirements	Global travel restrictions and (preventive) lockdowns
	National emergency containment	Minimal public containment efforts	Recommendations against traveling, and to work from home, wear masks, wash hands, etc.	Threat-driven (fluctuating) border restrictions and quarantines	Border restrictions (incoming travel). Social distancing, mandatory quarantines	Sustained national lockdowns and (incoming) border restrictions
	Emergency vaccination campaigns	No emergency vaccinations available.	Moderately effective vaccine available within 3 months, slow campaign	Highly effective vaccine available within 3 months, fast campaign	Moderately effective vaccine available within 2 months, slow campaign	Highly effective vaccine available within 2 months, fast campaign

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Intervention		Intervention level				
Layer of protection	Intervention	Base (0)	Minimal (1)	Medium (2)	Significant (3)	Very significant (4)
	Emergency increase in hospital capacity (ICU beds)	No emergency increases	Reallocate resources to facilitate +25% ICU beds	Redistribute hospital beds to gain +50% ICU beds	Major care reallocations and redistributions to gain +75% ICU beds	Set up field hospitals to enable +100% ICU beds
Disaster response	Responsive containment policies	No restrictions.	Recommendations to work from home, wear masks, wash hands, etc.	Legal mandates without enforcement, closure of busy areas and schools.	Enforced legal measures, such as social distancing, mandatory quarantines, travel restrictions.	Strict lockdown, suspending all non-essential activities.
	Responsive increase in hospital capacity (ICU beds)	No emergency increases	Reallocate resources to facilitate +25% ICU beds	Redistribute hospital beds to gain +50% ICU beds	Major care reallocations and redistributions to gain +75% ICU beds	Set up field hospitals to enable +100% ICU beds
	Responsive vaccine development	Vaccination campaign started after 2.25 years	Vaccination campaign after 2 years	Vaccination campaign after 1.5 years	Vaccination campaign after 1 year	Vaccination campaign after 6 months
	Responsive economic mitigation	No economic support.	Limited aid	Moderate intervention	Major stimulus	Full market control
Recovery	Post-pandemic health support	No additional post-pandemic health support	Limited support (e.g. public info)	Moderate support for affected groups (e.g. mental health programs)	Widespread healthcare access for recovery, incl. mental health	Extensive post-pandemic healthcare program
	Economic recovery acceleration	No recovery acceleration	Small-scale stimulus or tax cuts	Moderate economic recovery programs	Large-scale recovery package (e.g. infrastructure, employment)	Full economic recovery initiative halving disruption duration

Table 14.3: Pandemic intervention levels: effect.

Intervention description			Multiplication factor per intervention level				
Layer of protection	Intervention	Parameter modified	Base (0)	Minimal (1)	Medium (2)	Significant (3)	Very significant (4)
Continuous prevention	Global pandemic prevention	Probability	1	0.90	0.7	0.5	0.25
	Dutch pandemic prevention	Probability	1	0.9975	0.995	0.9925	0.99
Pro-active impact reduction	Structurally increase hospital capacity	Mortality	1	0.975	0.95	0.93	0.91
Emergency prevention and anticipation	Global emergency containment	Probability	1	0.95	0.88	0.80	0.75
		Infected population	1	0.98	0.95	0.93	0.9
	National emergency containment	Probability	1	0.99	0.98	0.96	0.95
		Infected population	1	0.98	0.95	0.93	0.9
	Emergency vaccination campaigns	Physical damage factor	1	0.95	0.90	0.50	0.1
	Emergency increase in hospital capacity (ICU beds)	Infected population Mortality	1	0.1 0.98	0.08 0.97	0.05 0.96	0.03 0.95
Disaster response	Responsive containment policies	Infected population	1	0.9	0.8	0.6	0.5
	Responsive increase in hospital capacity (ICU beds)	Mortality	1	0.99	0.98	0.97	0.96
	Responsive vaccine development	Infected population	1	0.95	0.72	0.6	0.5
	Responsive economic mitigation	Infected population	1	0.96	0.92	0.88	0.84

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Layer of protection	Intervention description		Multiplication factor per intervention level				
	Intervention	Parameter modified	Base (0)	Minimal (1)	Medium (2)	Significant (3)	Very significant (4)
Recovery	Post-pandemic health support	Post-disaster DALY multiplier	1	0.95	0.88	0.80	0.75
	Economic recovery acceleration	Post-disaster disruption duration	1	0.9	0.8	0.6	0.5

14.5. Pandemic risk reduction analysis

The risk reduction model quantified the effects of pandemic interventions across the six categories of intervention. Outcomes are assessed in terms of reductions in health risk (measured in DALYs per year) and economic risk (in euros per year) as intervention levels increase from 0 to 4. The results are shown in Figure 14.4. A version with a log scale and one with absolute risk values can be found in Appendix L.

Continuous prevention, represented by global and national pandemic prevention strategies, leads to the most substantial reductions in both health and economic risk. In particular, global prevention measures - such as international biosafety regulations and cross-border pathogen surveillance - achieve the steepest reductions, lowering risk by 75% at the highest intervention level. This effect is due to a modeled reduction in pandemic probability by a factor of four. However, the high dependency on international coordination limits the direct controllability and implementation feasibility of this strategy at the national level. National prevention, while more actionable, yields only minor reductions, reflecting its limited leverage over the global nature of pandemic emergence.

Proactive impact reduction interventions, including societal preparedness campaigns and structural hospital capacity improvements, demonstrate relatively flat risk reduction curves. Even at the highest intervention levels, reductions in both health and economic risk remain modest. With higher ICU capacity, more people can be cared for during the peak infection moments - which exceed the (baseline) maximum capacity. However, they do not influence the course of the pandemic and therefore only delay capacity overload, with limited additional people saved.

Emergency prevention and anticipation measures show more pronounced but variable effects. Emergency containment - especially when coordinated globally - leads to the steepest reductions in health risk within this category, with corresponding benefits to economic outcomes. National-level interventions show smaller reductions. Emergency hospital capacity increases offer very minimal reductions in health risk, reflecting improved capacity to manage case surges - but not changing the course of the pandemic.

Disaster response interventions contribute significantly to risk reduction. Responsive containment policies (e.g., NPIs, lockdowns) show strong reductions in both health and economic risks. These effects grow sharply with higher intervention levels, underscoring the importance of maintaining intervention stringency over time. Faster vaccine development has a similar effect - and likely less negative societal side effects. Responsive hospital capacity increases and economic mitigation efforts only have a very small effect.

Recovery interventions, such as post-pandemic health support and economic recovery acceleration, have negligible effects on health risk and economic risk. This is because they influence delayed health and economic impacts, which form only a fraction of the disaster phase impacts.

In summary, while continuous prevention is the most impactful category overall, the results highlight that pandemic risk management can benefit from a distributed effort across all phases of the timeline. Pandemic prevention leaves considerable residual risk due to the complexity of the threat. As such, downstream interventions, particularly during the response phase, remain essential for reducing both health and economic consequences once a pandemic is underway. Recovery measures may be necessary to go 'back to normal', but contribute little to risk reduction as most damage has been done already.

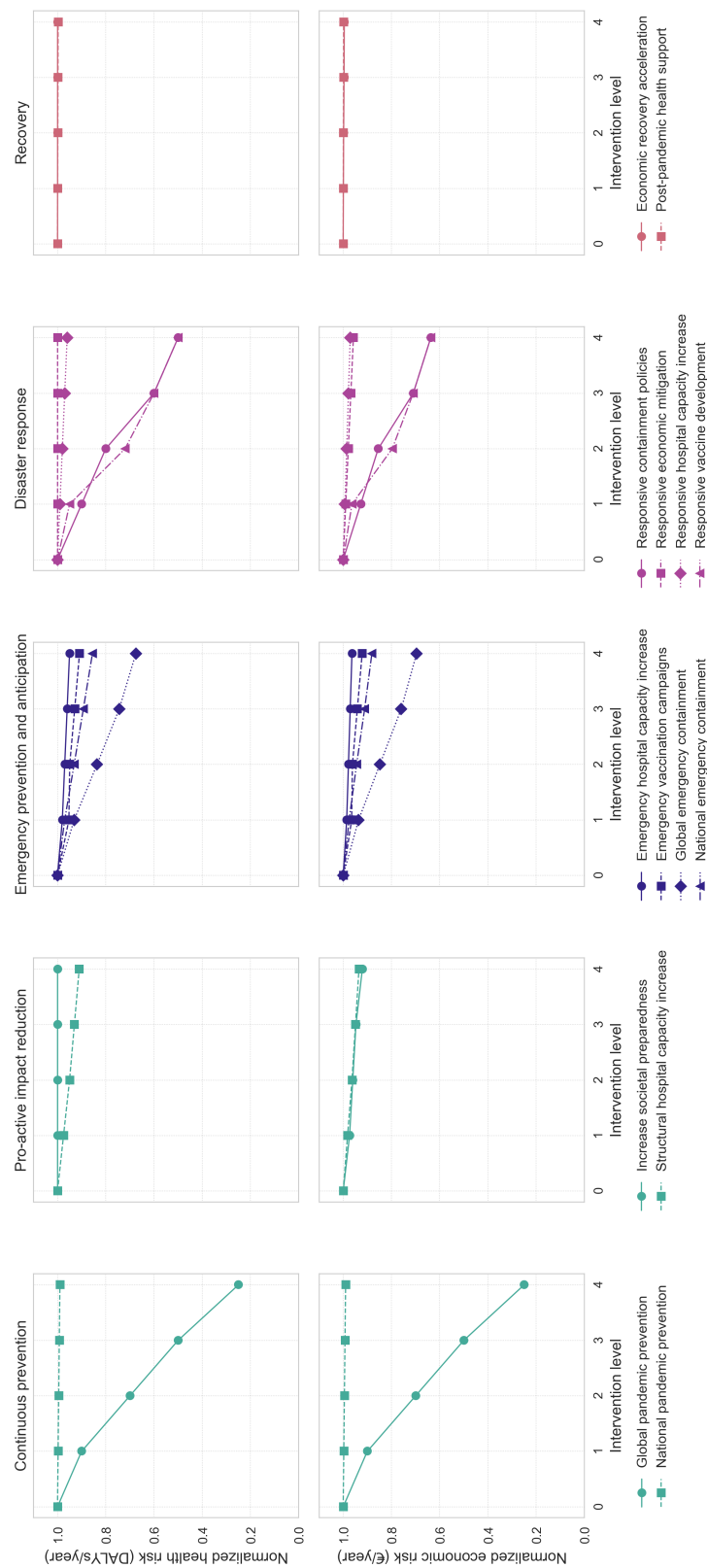


Figure 14.4: Pandemic risk reduction by different types of interventions. Plots for health risk reduction are shown on the top row and for economic risk reduction on the bottom row. Each intervention (line) has multiple levels of intensity, from level 0 to 4 (x-axis). The columns separate the different categories of interventions. The coloring of the lines indicates the primary phases in time during which interventions from each category are implemented. Green: normal phase, implementation of continuous prevention and pro-active impact reduction. Dark blue: threat phase, implementation of emergency prevention and anticipation. Pink-red: disaster response, implementation of disaster response. Post-disaster phase, implementation of recovery.

15

Comparative insights risk reduction

Flood versus pandemic intervention strategies

This chapter describes the comparative analysis of risk reduction interventions for floods and pandemics. Chapters 12, 13, and 14 have described a computational risk reduction model and its application to floods and pandemics. This chapter discusses the comparative analysis of the results for floods and pandemics. This will be used to answer the third research sub-question, SQ3: *How do the effects of risk reduction strategies for floods and pandemics compare?*

15.1. Key insights

- For both floods and pandemics, probability-reducing interventions are the most effective. However, flood prevention (e.g., structural measures) can reduce risk by multiple orders of magnitude, while pandemic prevention is less effective due to its complex and trans-boundary mechanisms.
- Residual risk after prevention is significantly higher for pandemics - in both relative and absolute terms. The effectiveness of response interventions becomes more critical.
- Flood response options are limited once the event begins, while pandemics offer significant opportunity for adaptive response throughout the outbreak.
- The effectiveness of both flood and pandemic interventions relies on similar intervention-enabling processes (e.g., early warning, risk communication, decision-making under uncertainty), which provides opportunities for cross-hazard learning.

15.2. Comparing baseline risks

The base probabilities, impacts, and risks of floods and pandemics serve as a reference for evaluating intervention effectiveness (see Table 15.1). The base flood and pandemic scenarios highlight key differences in their scope, impact, and damage pathways. The flood scenario represents a large-scale fluvial flood in the Netherlands, affecting a population of 265,000 with no major interventions in place (e.g., no evacuation). It results in 5,851 fatalities, 11,702 injury-years, and €20.29 billion in total economic damage. Most of this damage results from direct physical destruction, followed by losses related to health impacts, and then disruption-related costs. With a return period of 1/100 years, this scenario results in 2,247 DALYs/year and €203 million in annualized economic risk.

The pandemic scenario, in contrast, affects the entire Dutch population (18 million) with minimal mitigation, assuming unrestricted spread, delayed vaccination, and overwhelmed healthcare systems. This scenario leads to 471,763 fatalities, 2.36 million years of illness (1.5 months per Dutch person), and 14.8 million DALYs in total (0.8 DALYs per person). The economic cost is €597.5 billion, driven almost entirely by large-scale health losses. Assuming a return period of 1/50 years, the pandemic risk corresponds to 296,267 DALYs/year and €12 billion in annual economic losses.

Table 15.1: Comparison of baseline risk outcomes for the flood and pandemic scenarios.

Metric	Flood	Pandemic
<i>Hazard probability</i>		
Return time	1/100 years	1/50 years
<i>Health impact</i>		
Exposed population	265,000	18,020,000
Injured (years of injury)	11,702	2,358,818
Fatalities	5,851	471,763
DALYs	224,686	14,813,377
<i>Economic impact</i>		
Physical damage	€8.5 billion	€0
Disruption damage (during)	€315 million	€158.0 billion
Disruption damage (post)	€4.6 billion	€5.6 billion
Economic losses from DALYs	€6.84 billion	€433.9 billion
Total economic damage	€20.29 billion	€597.5 billion
<i>Annualized risk</i>		
Health risk (DALYs/year)	2,247	296,267
Economic risk (€/year)	€203 million	€12 billion

These figures highlight that while floods pose substantial localized risks, pandemics - especially extreme scenarios - can be far more devastating in both human and financial terms. The spatial and temporal dynamics also differ. Floods are acute, localized events causing immediate damage, while pandemics unfold gradually over months or years, disrupting health systems, economies, and society. The particularly high pandemic burden stems from a first peak of up to 1.5 million simultaneous infections, leading to systemic economic disruptions and high health losses.

The results suggest that for pandemics, the health and economic impacts are more closely linked. Interventions that reduce infections also reduce economic impact. For floods, the two types of impact are more independent, since most economic losses result from physical destruction, which occurs regardless of the health impacts. It must be noted that economic costs or side-effects resulting from policy choices were not modeled.

While these scenarios are stylized, they illustrate the relative scale of risk. Differences in frequency (1/100 vs. 1/50 years) do not alter the central conclusion: pandemics pose a much greater systemic threat in both absolute health and economic terms. However the focus in this comparison is on fluvial floods and a Covid-like pandemic, and are not necessarily generalizable to other types of pandemics or more extreme floods (e.g. coastal or cascading flood scenarios).

15.3. Comparing intervention effectiveness across categories

15.3.1. The dominance of prevention

For both floods and pandemics, the most significant risk reductions are achieved through probability-reducing interventions, especially in the normal phase (continuous prevention).

In the case of floods, physical prevention - such as dikes and levees - can reduce probabilities by multiple orders of magnitude. This is possible because of the relative predictability and physical nature of flood threats, allowing for highly effective structural protection. Flood prevention, therefore, often achieves near-complete elimination of risk.

Pandemic prevention, while still the most impactful category within pandemics, is inherently more limited. Reducing the probability of pandemics depends on global systems of surveillance, containment, and preparedness, which are complex and require continuous international coordination. As such, high efforts for (global) pandemic prevention are estimated to result in risk reductions by a factor 4 at best. Unlike for floods, complete elimination of pandemic risk through prevention alone is not feasible.

For floods, even emergency preventive measures can still obtain a factor 4 reduction in flood risk, stopping a flood from happening at the last minute. For pandemics, emergency preventive interventions focus mainly on containment, but - again - these are less reliable than those for floods.

15.3.2. Residual risk after prevention

This disparity in prevention effectiveness means that the residual risk - the risk that remains after prevention - is much higher for pandemics than for floods. While floods can be nearly eliminated (>99%) with effective and layered (continuous, emergency) prevention strategies, pandemics retain substantial risk due to the many uncertainties and transboundary factors involved. This highlights a major contrast: for pandemics, we must rely on other intervention categories to manage the remaining risk, while for floods, strong prevention can already achieve (most of) the reduction towards acceptable risk levels.

15.3.3. The higher role of response for pandemics

Floods offer a narrow window for effective response once the event unfolds. Emergency evacuation and rescue operations are vital but limited in their ability to prevent damage. In contrast, pandemic responses play a central role throughout the course of an outbreak.

Pandemics unfold over longer timescales and provide opportunities for adaptive responses. Non-pharmaceutical interventions (NPIs), vaccination campaigns, and public health guidance can dynamically reduce both health impacts and economic disruptions. These dual effects are important: health-driven risk reductions during pandemics also reduce economic losses, since the health and economic effects are connected.

Altogether, response plays a far greater role in pandemic risk management than in flood risk management. It also reflects the ongoing nature of pandemic threats, which can evolve over months or years, requiring sustained and adaptive policy action.

15.3.4. The role of other categories of interventions

Beyond prevention and response, both hazards benefit from interventions in other categories:

- Pro-active impact-reduction: For floods, increased self-reliance can limit health losses by increasing people's ability to save themselves. Spatial planning and resilient building limit damage exposure, but modestly. For pandemics, societal and healthcare preparedness enhance overall system resilience but have little influence on the course and overall impact of the pandemic.
- Threat-phase interventions: For floods, this concerns emergency preventive measures (significantly reducing risk) and evacuation (strong potential for limiting health losses). For pandemics, this phase is blurrier; early measures often affect both probability and impact (if prevention fails). This means there is high potential for changing the course of the pandemic in this phase. However - if a pandemic occurs - sustained action in the response phase becomes more important: if threat-implemented interventions are released, their impact reductions can be undone by quick pathogen spread.
- Recovery is necessary in both cases but contributes little to actual risk reduction, since most damage is already realized. For floods, this means rebuilding; for pandemics, it may involve restoring the economy, but without much effect on core health or economic outcomes in the model.

15.4. Reflecting on layered protection

Risk reduction strategies can be substantially enhanced by combining interventions across different layers of protection. In this study, the assumption is that interventions act independently, meaning their combined effects can be approximated by multiplying their individual risk reduction factors.

For example, if one intervention reduces risk by a factor of 2 and another by a factor of 4, the combined package reduces risk by a factor of 8. While this has not been implemented computationally in this study, the principle illustrates a clear strategy: layering high-impact interventions across the timeline of a disaster provides much stronger protection than relying on a single measure.

This is especially true for pandemics, where prevention alone leaves too much residual risk. To achieve similar reductions as flood prevention provides, pandemics require combinations - preventive, anticipa-

tory, and responsive measures all working together.

While flood protection can sometimes rely on a dominant intervention like dike infrastructure, pandemic risk reduction inherently depends on diversity and adaptability across layers, due to uncertainty in timing, location, and severity.

15.5. Relative versus absolute risk reduction

A key insight from this analysis is the difference between relative and absolute risk reductions across the two hazard types.

For floods, top-performing interventions reduce risk by nearly 100%, which in annualized terms amounts to a reduction of nearly all 2,247 DALYs/year. This is highly effective relative to the base risk.

For pandemics, the relative reductions are smaller, but the absolute numbers are far larger. A 25% reduction of pandemic risk already amounts to nearly 75,000 DALYs/year - orders of magnitude beyond the flood reductions. Thus, even less impactful pandemic interventions often surpass flood measures in absolute DALYs or economic loss reduction.

This difference has critical implications for policy. The concept of “acceptable risk” plays a central role in Dutch flood management, where it informs explicit thresholds for protection and public investment (Ale, 2005; ENW, 2017). In contrast, no such formalized threshold seems to exist for pandemic risk, even though the baseline threat is substantially higher in terms of expected health and economic losses. This asymmetry raises the question of why societies are willing to accept vastly higher pandemic risks without comparable levels of planning or investment. It also challenges us to consider what is a tolerable level of pandemic risk, and whether current approaches reflect an implicit (and perhaps flawed) notion of acceptability.

This also highlights a broader tension: while relative changes help us understand how efficient an intervention is, absolute changes determine the real-world value and impact.

15.6. The role of intervention-enabling processes

Beyond direct interventions, intervention-enabling processes are essential in reducing risk - especially under conditions of uncertainty.

For floods, early warning systems, threshold-based decisions, water awareness, and institutional readiness enhance the effectiveness of core interventions. These tools improve public compliance with evacuation orders, accelerate response, and can reduce both physical and human impacts.

Pandemics also benefit enormously from intervention-enabling factors. Public communication, trust-building, early detection, and adaptive governance all improve the effectiveness of NPIs, increase vaccination uptake, and ensure that response measures are timely and well-targeted.

These enabling processes are remarkably similar across the two hazards. Both rely on monitoring, early detection, clear communication, public trust, and the ability to make informed decisions under uncertainty. This opens up opportunities for cross-hazard learning - for example, applying lessons from flood preparedness and early warning to improve pandemic risk management, or vice versa.

In both cases, enabling processes do not reduce risk directly, but they strengthen the effect of interventions that do.

15.7. Limitations

Several important limitations apply to this comparative analysis:

- **Assumptions on effectiveness:** The estimated impacts of interventions rely on literature, expert-supported estimates, and assumptions. In reality, effectiveness may differ under actual conditions, different contexts, different types of flood or pandemic scenarios, and at different points in time.
- **Intervention independence:** The model assumes no significant interactions between interventions. This could overlook important relations - for example, how one intervention might enhance or reduce the impact of another.

- No sensitivity analysis: A formal sensitivity analysis has not been conducted. This limits the robustness of conclusions, particularly given the many assumptions in the model. Varying baseline parameters and intervention effectiveness could help clarify which findings are most stable.
- Relative vs. absolute comparisons: Comparing relative and absolute reductions is inherently difficult, especially across hazards with very different base risks. While absolute reductions offer more tangible insights, they don't account for feasibility, costs, or social preferences. Relative reductions, on the other hand, may overstate the usefulness of interventions for low-risk scenarios.
- Lack of explicit cost and acceptability thresholds: This study evaluates effectiveness based on health and economic impact reduction, but does not integrate intervention costs or societal willingness to pay. As a result, the analysis does not address cost-effectiveness or the notion of acceptable residual risk. This limits the ability to make policy recommendations or rank interventions based on value-for-money.
- Lack of consideration of intervention-enabling processes. Such processes (e.g. more lead time because of early warning) can influence the possible levels of effect of the interventions. An additional layer could be incorporated into the risk reduction model to explicitly consider the effect of intervention-enabling processes (e.g. add a dimension of time, which influences effect sizes).

Future research should aim to address these limitations, especially by incorporating interaction effects, testing sensitivity across key parameters, and evaluating cost-effectiveness. This would allow for more nuanced, actionable insights.

Part V

Discussion and conclusion

16

Discussion

This chapter reflects on the findings and limitations of this study. Detailed analyses for each research sub-question have been presented in the comparative chapters (Chapters 7, 11, and 15). This chapter discusses the value of risk-based disaster comparisons, reflects on themes that emerged throughout the analysis, and explores the potential for cross-hazard learning and the all-hazard approach. It also offers a critical reflection on the limits of risk-based reasoning and on this study's methodological constraints. This sets the stage for conclusions and recommendations provided in Chapter 17.

16.1. The value of a structured, risk-based comparison

This study demonstrates the value of a structured, risk-based comparison between floods and pandemics. While these two disasters have fundamental differences, they share a common risk profile as low-probability, high-impact, threat-driven events. By developing a common analytical framework - separating risk into a probability and impact dimension, and considering different phases in time - this study highlights their parallels and differences, and enables meaningful cross-hazard learning.

While a few studies have touched upon comparisons between different hazards (e.g. Montz, 2020; Penta et al., 2017, 2021), this is - to my knowledge - the first in-depth, risk-structured comparison of such fundamentally different hazards. By integrating three analytical perspectives - focused on risk systems, timelines, and risk reduction strategies - it provides a structured way to analyze risk and risk management characteristics across hazards.

The developed conceptual framework of disaster risk systems - centering on risk mechanisms, intervention mechanisms, intervention-enabling processes, and risk dynamics - proves effective in revealing both differences and parallels across disaster domains. Differences are prominent in hazard mechanisms, intervention mechanisms (as well as feasibility and effectiveness), and the nature of risk dynamics (including temporality and uncertainty). Similarities emerge most clearly in intervention-enabling processes such as monitoring, early warning, decision-making under uncertainty, and risk communication.

The findings from this study underscore the value of comparative disaster analysis, demonstrating its ability to identify both generic/transferable principles and differences which limit generalization between disaster domains. As such, the approach reveals opportunities for cross-hazard learning. Moreover, the study contributes to the growing literature on multi-hazard and all-hazard disaster risk reduction.

16.2. Themes identified across the comparison

The comparison reveals several key themes that shape the way flood and pandemic risks emerge and are managed. These themes help to identify shared challenges and learning opportunities across hazard types.

16.2.1. Complexity and uncertainty

A first key theme is the difference in complexity and uncertainty. Pandemics were shown to exhibit higher causal complexity and deeper uncertainty than floods. While flood risk - in the Netherlands - can be described relatively well through deterministic and probabilistic models, pandemic risk involves a much higher degree of uncertainty. In particular, key characteristics of the pathogen (such as transmissibility or severity) are initially unknown and may change over time. Moreover, the pathways through which infections spread are shaped by unpredictable human behavior and global mobility. Uncertainty remains an issue in floods as well (Knotters et al., 2024), but appears less complex.

This has implications for disaster management. While floods can often be responded to with predefined thresholds and protocols, pandemic response requires more dynamic and adaptive decision-making under uncertainty. This aligns with the argument of Hadjisotiriou et al. (2023) that "Deep uncertainty requires policies that are not based on 'predict and act' but on 'prepare, monitor, and adapt', enabling policy adaptations over time as events occur and knowledge is gained." (p. 1).

16.2.2. Residual risk and acceptable risk

Both disaster types confirm a central truth of disaster risk reduction: residual risk is inevitable as no system can eliminate all risk. For floods, preventive efforts can reduce residual risk to very low levels - though not mitigate it entirely. For pandemics, even high-effort prevention and response efforts leave substantial residual risk due to global interconnectivity, pathogen evolution, and behavioral unpredictability.

This raises questions about the concept of acceptable risk (UNDP, 2010); how much residual risk is society prepared to accept? Essentially, decisions on risk are "political in nature and are driven by legal and cultural histories" (Ale, 2005, p. 240). Societal approaches to defining and managing acceptable risk vary. In flood management, safety standards are often explicit and quantified (e.g., 1-in-10,000-year protection levels), balancing economic feasibility with risk reduction goals. These thresholds guide public investment and shape public expectations. In contrast, pandemic risk management involves less defined thresholds.

This highlights the potential for a more explicit investigation of acceptable risk levels across different hazards. The concept of risk acceptability, well established in flood risk management, could be further developed in public health contexts to guide pandemic preparedness planning. Ulrich (2022) already explored this idea of acceptable risk in the context of pandemics, highlighting its value while also emphasizing the challenges of uncertainty, complexity, and value-based judgments. Still, if standards can be set for floods, it is worth exploring whether they can also be set for pandemics.

This is also interesting considering the higher absolute risk of pandemics than of floods for the Netherlands. Do we (have to) accept higher levels of residual pandemic risk compared to floods? This comparison of acceptable risk - and why it may be higher for pandemics than floods - is worth exploring further. For example, it would be interesting to look at the controllability of floods versus pandemics as a possible explanation, since Philley (1992) argued that "Controllable and voluntary risk are more readily accepted than risks involuntarily imposed by some outside group." (p. 223). From this study it indeed appears as if floods are more controllable than pandemics, especially when looking at prevention.

The lesser controllability of pandemics may also suggest the need for integrating other approaches to defining risk reduction objectives, for example using As Low As Reasonably Practicable (ALARP) risk levels. Ale et al. (2015) reflected on the usefulness and limitations of this concept, and concluded that acceptable risk, ALARP, and cost-benefit analyses (also a value-based approach to dealing with risk) could be part of a broader decision-making framework.

Greater transparency around what level of risk is considered tolerable, and under what conditions, could support more consistent and equitable risk reduction strategies (UNDP, 2010). It could also help deal with - or understand - backlash and societal distrust during future crises, when actions are judged against expectations.

16.2.3. Intervention-enabling processes

While most interventions for floods and pandemics differ in terms of their mechanism, the intervention-enabling processes that influence their effectiveness are similar. These processes include monitoring,

detection, early warning systems, crisis communication, and decision-making under uncertainty.

Previous studies have also highlighted the importance of supportive processes for disaster risk management. For example, Lindhout and Reniers (2020) refers to them as support systems - which they included in their analysis on pandemic risk management. Li (2019) discusses them as delivery systems for barriers in safety systems, mentioning 'competence of personnel' as a key example.

Essentially, these processes form the "supportive infrastructure" of disaster risk management and are largely hazard-generic. Strengthening them could yield cross-hazard benefits, suggesting it would be a relevant - if not the most relevant - element of all-hazard preparedness.

16.2.4. Prevention as the core of layered risk reduction

This research supports a layered protection logic for both floods and pandemics. Rather than seeking single, definitive solutions, disaster risk reduction strategies should combine complementary interventions, each reducing risk partially. Investments in both direct interventions and enabling processes - like early warning and governance capacities - can yield further cumulative gains.

The study underscores that disaster risk reduction strategies must be tailored to the characteristics of each hazard, but also benefit from shared principles. While more pronounced for floods than pandemics, probability-reduction is generally the most effective approach to risk reduction - especially through continuous preventive efforts. This is in line with the current focus of (Dutch) flood risk management (ENW, 2017; Ten Brinke et al., 2008), and also with international calls for pandemic prevention (GPMB, 2024).

However, residual risk always remains after prevention - especially for pandemics - which does leave value for impact-reducing interventions. The higher the residual risk, the higher the potential risk reduction by impact-reducing strategies. In pandemics, response measures can greatly shape the impact, which highlights their need to be a part of a layered strategy. The idea of layered and parallel protection echoes research on layered protection and safety chains (Jongejan et al., 2012; Ten Brinke et al., 2008), extending those concepts from the flood domain into public health.

The relative effectiveness of prevention makes sense when considering the definition of risk as probability times impact - and the vastly overwhelming impact of a low-probability, high-impact event. Firstly, there are many different types of consequences which contribute to the overall impact, and - with many interventions focused on only one sub-type of impact - it becomes challenging to strongly reduce overall impact with single intervention. Conversely, prevention - e.g. the building of dikes - has the potential to directly reduce probability and thus risk by multiple orders of magnitude. A combination of many different impact-reducing interventions would be necessary to obtain similar risk reductions - if even possible. Secondly, considering the infrequent nature of such events, it is impossible to design a system to really be able to manage the massive consequences. For example, if large-scale evacuations are only needed once every few decades, it becomes very ineffective to have a large emergency workforce, just for such events. Therefore, we mostly rely on existing emergency personnel (B. Kolen, 2013), which is not necessarily enough people (in amount) or in skill (no experience with these rare events) to make a large-scale evacuation happen optimally.

16.3. Reflection on risk thinking and its limits

A central contribution of this study lies in applying risk-based reasoning as a comparative tool. Framing disaster risk as the product of probability and impact - which can be reduced across different phases in time - provides a useful framework for cross-hazard analysis.

16.3.1. Strengths and limits of risk-based reasoning

Risk-based models enable structured thinking about trade-offs, priorities, and interventions. They work well in domains where probability and consequences can be reasonably quantified - such as flood management. However, this predictability and quantifiability does not hold for all hazards. The risk of pandemics is characterized by higher causal complexity and deeper uncertainty. In these contexts, rigid probabilistic models may provide a false sense of control.

16.3.2. Decision-making under deep uncertainty

Recognition of deep uncertainty calls for the incorporation of alternative frameworks such as Decision Making under Deep Uncertainty (DMDU) (Marchau et al., 2019). Hadjisotiriou et al. (2023) already proposed its use for pandemic planning under deep uncertainty. DMDU approaches - including adaptive policy pathways and exploratory modeling analysis - offer promising tools for managing deeper uncertainties, moving away from the assumption of clearly definable risks. These approaches prioritize robustness, flexibility, and adaptive capacity over optimization (Marchau et al., 2019). DMDU methods may also enhance flood governance under (e.g. climate-induced) uncertainty.

16.3.3. Resilience thinking

Risk-based perspectives are sometimes contrasted with resilience-based perspectives (Linkov & Trump, 2019). Resilience thinking shifts the focus from predicting and controlling risks to enhancing a system's capacity to absorb shocks, adapt, and transform in the face of disruption. This approach may be more appropriate for complex and uncertain hazards like pandemics, where the pathways of risk are difficult to map and outcomes are highly unpredictable. Rather than attempting to optimize responses based on uncertain probabilities, resilience thinking emphasizes flexibility, learning, and systemic strength.

The limitations of risk thinking raise questions about whether resilience thinking may be more applicable in this context of complex disaster risk management, especially for pandemics. Both floods and pandemics are frequently studied in the context of resilience (de Bruijn et al., 2022; Sakurai & Chughtai, 2020; L. Wang et al., 2022). A resilience-based comparison could provide an interesting direction for future investigation.

16.3.4. Risk as useful logic

Finally, while a strict risk framework - based on the idea of quantifiable probability and impact - fits more naturally with flood management, it remains a valuable conceptual tool for pandemics as well. Whether or not you can quantify risk, it still exists and has these two dimensions. Even where precise risk quantification is tricky, the logic of reducing probability and impact remains a strong way to structure preparedness and response thinking. In this sense, the risk perspective serves as a valuable strategic lens for approaching disaster management in complex, uncertain contexts.

16.4. Methodological limitations

While this study provides a structured comparison of flood and pandemic risks and proposes a transferable analytical framework, several methodological limitations should be acknowledged. These relate to the scope and generalizability, analytical methods, data constraints, and assumptions made throughout the study.

16.4.1. Context, cases, and generalizability

The study focuses on flood and pandemic risk from a Dutch perspective. Moreover, it focuses mainly on river floods and Covid-like pandemics. This geographic and hazard-specific focus offers a well-documented and policy-relevant lens, but limits generalizability. Different countries or different flood or pandemic scenarios may reveal different outcomes. These are important limitations that should be considered when interpreting the results. The broad value of the comparative framework remains applicable, but the resulting insights may change in different contexts. Expanding the framework to other hazard types, such as wildfires or heatwaves, could further validate its applicability within an all-hazard context.

16.4.2. Linearity and static analyses

This study builds on a relatively linear understanding of disaster risk. By using the bowtie method for the risk systems analysis, the focus is on linear causal pathways. While this allows for a structured representation of causal pathways and interventions, it does not capture dynamic feedbacks or changes and adaptations over time. Learning processes, political dynamics, and cascading effects are also absent. This linearity is also the case for the risk reduction model, which only uses simple equations for risk calculations at a single point/scenario in time. Future research could use simulation models to build a more dynamic understanding of the risk systems and potential for risk reduction.

16.4.3. Modeling simplifications and parameter assumptions

The comparative risk-reduction model used in this study is an exploratory reasoning tool. It involves substantial simplifications and numerous assumptions - particularly regarding parameter values, intervention effectiveness, and equation structure. No sensitivity analysis was performed, meaning that the influence of assumptions on the modeling results is not clear. While the orders of magnitude in the model output are expected to be reasonable, the model serves primarily as a reasoning tool rather than a reliable prediction method. This also highlights the need for further validation by experts. Further research is needed to provide conclusive answers.

16.4.4. Limited consideration of cost-effectiveness and other trade-offs

While implicitly considered in the determination of intervention levels, the study does not explicitly quantify intervention costs or societal trade-offs. Interventions can be associated with highly varying costs, which must be balanced with their effectiveness. Moreover, some interventions come with high societal side-effects - which is particularly important for pandemic interventions that often entail economic and social disruption. The omission of cost analysis in this study limits the assessment of feasibility and appropriateness of different risk reduction strategies. Future work should integrate cost-effectiveness considerations to support informed policy-making.

16.4.5. Data constraints and assumptions

The analyses in this study rely on academic and gray literature, as well as insights from consulted experts. An important limitation is the subjectivity from experts as well as the selection of literature used. Given the vast amount of relevant research on both floods and pandemics, full coverage was not possible. Expert input was limited in amount and subject to interpretation. This introduces potential bias and underlines the exploratory nature of the study.

Conclusions and recommendations

In this study, a risk-based comparison of floods and pandemics was performed to develop insights into the challenges and opportunities for managing these low-probability, high-impact disasters. Through three risk-based analysis steps, the research generated important insights into differences and similarities in the mechanisms of flood and pandemic risk, their characteristics over time, and risk reduction through probability- and impact-reducing interventions. The use of a structured conceptual framework - combining risk mechanisms, intervention mechanisms, risk dynamics, and intervention-enabling processes - was central in enabling a meaningful cross-hazard comparison.

This chapter synthesizes the key findings, discussing the answers to the sub-questions to build a coherent, comparative understanding of the risk management of floods and pandemics. It then draws together these insights to address the main research question. Finally, it offers practical recommendations for policymakers and identifies directions for future research, emphasizing opportunities for cross-hazard learning.

17.1. Answering the research sub-questions

17.1.1. SQ1. How do the causes, consequences, and interventions for floods and pandemics compare?

An understanding of the mechanisms of flood and pandemic risk was developed through a bowtie-based analysis. This analysis mapped out the causal pathways (probability dimension of risk), potential consequences (impact dimension of risk), and mechanisms of intervention (risk reduction) for each hazard. In addition, it identified enabling processes that support interventions and captured how these risk systems evolve over time - together forming a broader conceptual framework that guided the comparative analysis. The results revealed that floods and pandemics differ substantially in their causal and consequential mechanisms, but do share a similar structural logic and indirect consequences.

Floods are primarily driven by physical and meteorological phenomena, such as intense rainfall, storm surges, and defense failure mechanisms. This makes their causal pathways relatively deterministic, driven by laws of physics. Pandemics, by contrast, emerge from complex biological and ecological mechanisms - involving pathogen evolution, zoonotic spillover, and human-to-human transmission. These processes are heavily influenced by global social and behavioral drivers, including human mobility, population density, interaction with animals, and cultural habits. This distinction makes flood probability reduction a primarily technical challenge, whereas pandemic probability reduction requires a more socio-technical approach. For example, flood prevention relies heavily on physical interventions like dikes and drainage systems, while pandemics require behavioral and policy-driven measures such as vaccination, social distancing, and healthcare preparedness. Moreover, floods are more regional in nature, while pandemics are inherently transboundary and global. Despite these differences, both hazards exhibit similar structural logic: disasters occur when hazard levels (e.g. water loads or pathogen presence) exceed a system's ability to cope (e.g. flood defenses or public health measures), resulting in a multitude of direct and indirect consequences.

In both cases, the effectiveness of interventions depends not only on their design but also on intervention-enabling processes - such as monitoring, early warning, communication, and institutional readiness - which help translate technical or behavioral measures into timely and effective action.

The direct consequential mechanisms of floods and pandemics differ. Driven by their physical nature, floods cause physical damage to the built environment and physical injuries and death to humans. Pandemics, on the other hand, do not cause physical damage and lead to injuries and death via the spread of infections. These direct consequences trigger indirect effects, which share more similarities between floods and pandemics. In particular, both disasters may have health, economic, social, cultural, and environmental consequences. Examples include the disruption of economies, societal shock, disturbance of daily life, strain of public services, and delayed or long-term societal and psychological effects. In line with this, impact-reducing interventions focused on direct consequences are distinct (e.g. evacuation versus social distancing), while impact-reducing interventions focused on indirect consequences can be more similar (e.g. businesses building resilience against disruptions). These similarities in indirect impacts present opportunities for shared interventions and cross-domain learning.

17.1.2. SQ2. How do the timelines of floods and pandemics compare?

An understanding of flood and pandemic characteristics over time was developed through a case-based analysis. Specifically, the cases of the Limburg-21 floods and the Covid-19 pandemic were studied. The results revealed that floods and pandemics follow distinct temporal patterns (risk dynamics), with differing durations and characteristics in their four phases: the normal, threat, disaster, and post-disaster phase.

Floods are typically acute, short-duration events with short threat and disaster phases. Their timelines unfold rapidly - within days or weeks - where the main uncertainties are limited to *if*, *where*, and *when* flooding might occur. These can often be narrowed down through high-quality monitoring and forecasting. This allows the use of clear triggers for action (threshold-based decisions) and scenario planning, enabling quick decision-making in the threat phase. Once a flood starts, there is little room left to steer the event, and efforts focus primarily on immediate safety and post-event recovery.

Pandemics, by contrast, are slow-onset, longer-duration crises. The threat phase can last for months, marked by deep uncertainty not only about timing and location, but also about the biological and social characteristics of pathogen spread. Especially for novel pathogens, critical questions around infectivity and severity can remain unresolved for a long time, complicating early action. This uncertainty stems from the more complex, evolving, and global nature of pandemic risk mechanisms. As pandemics evolve gradually and often involve multiple waves, intervention strategies must remain adaptive over time. Furthermore, unlike floods, the disaster phase in pandemics can span years, making it an influential period for impact mitigation. Finally, pandemic recovery often begins while the disaster phase is ongoing, which is less the case for floods.

Thus, while floods and pandemics share the same general phases, the timing and uncertainty within each phase differs. Floods allow for decisive, short-term action under relatively precise short-term risk assessments. Pandemics require more flexible, long-term governance that accepts and works within ongoing uncertainty. This underscores the importance of adaptive risk governance and continuous learning in pandemic management, in contrast to the more protocol-driven, technical management typical of flood response.

17.1.3. SQ3. How does the impact of risk reduction strategies for floods and pandemics compare?

To explore the relative effectiveness of interventions for floods and pandemics, a simple risk reduction model was developed. The model conceptualized risk as probability times impact, both of which could change across hazard and intervention scenarios. This modeling approach allowed for a comparison of how different interventions - at different stages - affect overall risk for each hazard type, providing a structured understanding of intervention effectiveness. The results demonstrate that while both floods and pandemics benefit most from prevention, the nature and effectiveness of prevention - and what follows when it fails - differ fundamentally between the two hazards.

Flood risk can be reduced by several orders of magnitude through structural defenses. This is feasible

due to the relatively predictable and spatially bounded nature of flood hazards, combined with clear protection levels from defenses. As a result, flood prevention is highly reliable, and once this layer is in place, there is only limited residual risk. If a threat arises despite continuous prevention, emergency prevention (e.g. placing sandbags) can still reduce the probability of a flood occurring. The role of prevention in pandemics is different. While global efforts for continuous prevention remain the most impactful intervention, its effectiveness is more limited (probability reduction by an estimated factor of 4). This is because pandemics are inherently more difficult to prevent, relating to their uncertain, cross-border, and evolving nature. Because of this, significant residual risk remains even after prevention efforts. This makes downstream interventions, especially during the response phase, much more critical for pandemics than for floods. Once a pandemic begins, response strategies can still significantly influence the overall impact. Notably, the response phase plays a marginal role in flood risk reduction due to the suddenness and irreversibility of physical damage; there is 'only so much' that can still be done. These differences underscore why flood risk reduction focuses heavily on technical prevention, while pandemic risk reduction must rely on a broader balance across prevention, anticipation, and adaptive response.

While the current model did not explicitly account for financial or societal costs, evaluating the cost-effectiveness of interventions is crucial for real-world decision-making.

17.2. Overview of comparative insights

To support the conclusion, Table 17.1 provides a structured overview of key differences and similarities between floods and pandemics identified throughout this study. It summarizes how each hazard behaves mechanistically and temporally, how risk is reduced, and what this implies for decision-making and cross-hazard learning.

Table 17.1: Comparison of risk characteristics and intervention effectiveness between floods and pandemics.

Aspect	Floods	Pandemics
Hazard mechanisms	Physical and meteorological processes; deterministic and regional	Biological, ecological, and societal processes; complex, evolving, and global
Risk temporality	Rapid onset; short threat and disaster phases; clearer recovery phase	Slow onset; prolonged threat and disaster phases; overlapping recovery
Probability-reducing interventions	Technical and infrastructure-based (e.g., dikes, drainage)	Behavioral and policy-based (e.g., surveillance, preparedness)
Impact-reducing interventions	Emergency response and recovery efforts (e.g., evacuation)	Adaptive response over time (e.g., containment, healthcare surge)
Effectiveness of prevention	High (can reduce risk by orders of magnitude); low residual risk	Moderate (e.g., factor 4); high residual risk remains
Role of response phase	Limited (due to short disaster window and irreversible damage)	Critical (long phase, sustained influence on outcomes)
Dominant uncertainties	IF/WHEN/WHERE a flood might occur	IF/WHEN/WHERE a pandemic emerges; HOW it spreads and evolves
Decision-making approach	Threshold-based; scenario planning; deterministic	Adaptive; prolonged uncertainty; evolving governance needs
Application of risk framework	Strongly supports quantified risk estimates and structured planning	Valuable as a conceptual lens; limited predictive precision
Transferable capacities	Monitoring, early warning, risk-based thresholds, scenario planning	Adaptive decision-making, communication, preparedness systems

17.3. Answering the main research question

17.3.1. RQ. What can be learned from a structured risk-based comparison of floods and pandemics (low-probability, high-impact disasters)?

A structured risk-based comparison of floods and pandemics reveals both fundamental differences and useful parallels that can inform the risk management of these low-probability, high-impact, and threat-driven disasters.

Mechanistically, floods and pandemics are fundamentally different. Floods are driven by physical and meteorological processes, while pandemics arise from complex, dynamic interactions between biological, ecological, and societal factors. In line with this, probability-reducing interventions for floods tend to be technical and infrastructure-based, while for pandemics they require behavioral and global health measures. Although driven by different root mechanisms, the impact dimensions of floods and pandemics share similarities, with both disasters having (indirect) health, economic, societal, cultural, and environmental consequences.

Temporally, floods are acute, short-term events, while pandemics have a slower onset and last longer. Combined with their mechanistic differences, this leads to substantially distinct challenges in their management. Driven by physio-meteorological mechanisms, floods exhibit relatively predictable behaviors. This supports their management with threshold-based decisions and scenario-based planning, the main uncertainty being *if* a flood will arise. The complex socio-biological dynamics of pandemics, on the other hand, introduce deeper uncertainties about where, when, and *how* a pandemic will unfold - or what could be done to fight it. Following from their temporality and uncertainty, floods require more sudden, deterministic decisions, while pandemics require sustained adaptive decision-making, as uncertainties persist throughout their threat and disaster phases.

In terms of risk reduction, prevention remains the most effective strategy for both disasters. However, prevention is far more reliable for floods - often able to reduce risk by several orders of magnitude - while pandemic prevention yields more modest risk reductions and depends highly on coordinated global action. As a result, pandemics leave behind a much higher residual risk and necessitate stronger emphasis on response strategies, which can significantly shape outcomes during long pandemic disaster phases.

Despite their differences in mechanisms, temporality, and uncertainty, floods and pandemics share a common risk logic: managing probability and impact across time. This supports the use of layered interventions that combine structured and adaptive approaches across disaster phases. Even when risk components are complex or difficult to quantify - as with pandemics - the risk-based framework remains a valuable lens for both hazard-specific insight and cross-hazard comparison. Similarities in intervention-enabling processes - such as monitoring, early warning, and decision-making under uncertainty - reveal transferable capacities that can support all-hazard preparedness. These insights highlight the value of combining tailored risk governance with shared systemic strategies to strengthen the management of low-probability, high-impact threats.

17.4. Recommendations

This study shows that structured, risk-based comparisons between floods and pandemics can provide valuable insights for both practice and theory. Below are recommendations for decision-makers and future research.

17.4.1. Practical implications for decision-makers

- **Adopt layered risk reduction strategies:** Prevention remains the most effective risk reduction approach, especially for low-probability, high-impact events. However, in contexts like pandemics, where residual risk is high even after prevention, response capacity is essential. Both domains

benefit from layered protection: combining prevention, anticipation, and response.

- **Leverage cross-hazard learning:** The most transferable lessons lie in intervention-enabling processes such as monitoring, early warning, decision-making under uncertainty, and risk communication. These generic processes offer potential for shared learning and generic disaster management strengthening. Zoomed-in cross-hazard comparisons can reveal where interventions can be standardized and where hazard-specific tailoring is required.
 - **Lessons for pandemics from the flood domain:** Pandemic management can benefit from flood practices, including formal risk thresholds, scenario-based planning, and robust monitoring systems. These approaches could help establish clearer criteria for acceptable health risks and enable earlier, more proportionate interventions. Emphasizing preparedness even amid uncertainty, as is common in flood planning, could reduce response delays in future health crises.
 - **Lessons for floods from the pandemic domain:** Flood governance can incorporate insights from pandemic response, such as real-time data integration, adaptive decision-making, and behavioral interventions. The pandemic has also highlighted the importance of trust, equity, and community engagement - factors that could improve flood preparedness and long-term recovery.
- **Invest in shared capacities for all-hazard preparedness:** Beyond mutual learning, floods and pandemics could benefit from generic capacities like early warning, public communication, and emergency logistics. These capabilities could be institutionalized to serve multiple hazard types. Investments in cross-hazard capacities could also improve coordination, avoid duplication of resources, and promote resilience in complex, multi-risk environments.
- **Clarify and communicate acceptable risk levels:** Acceptable risk is a foundational concept in flood risk management, often linked to explicit protection standards and probability thresholds. In contrast, pandemic preparedness lacks such structured frameworks. There is value in defining what constitutes acceptable health risk, even when quantification is difficult. Transparent thresholds can improve public trust and accountability in risk management.
- **Strengthen decision-making under deep uncertainty:** The prolonged uncertainty during pandemics differs from the short-term, probabilistic uncertainty common in floods. Flood management offers examples of how to make structured decisions despite forecast limitations. Conversely, pandemic response shows the need for adaptive governance that updates in real time. Combining both perspectives could improve decision support under complex and evolving risk conditions.

17.4.2. Directions for future research

- **Integrate cost-effectiveness and feasibility analyses:** Future studies should assess not only intervention effectiveness but also costs, feasibility, and trade-offs. This is especially relevant for pandemic measures like lockdowns or health system investments, which have far-reaching social and economic consequences. Realistic and balanced decision-making requires such multi-criteria evaluations.
- **Expand to other hazard types and probabilities:** The comparative framework developed here can be applied to other hazards - such as wildfires, cyber threats, or medium-probability events - to test its broader applicability. Including more frequent, less extreme hazards could allow richer empirical comparison and refine generalizable insights about risk reduction under uncertainty.
- **Explore acceptable risk across contexts:** What constitutes 'acceptable risk' varies by domain, culture, and political context. Research should explore how societal preferences and public trust shape risk acceptance in different hazard types. Insights from flood risk standards could inform how to set clearer, more defensible thresholds in pandemic preparedness.
- **Examine risk-based vs. resilience-based approaches:** Risk analysis emphasizes probability and impact, while resilience thinking focuses on adaptability, robustness, and recovery. Especially under deep uncertainty, these perspectives may be complementary. Comparative research could clarify when each framework adds value and how they can be combined in practice.

- **Develop and validate dynamic risk models:** The current model offers a simplified, static comparison tool. Future work could explore more dynamic approaches that simulate feedback loops, evolving risks, learning, and cascading impacts. Scenario-based modeling and real-time updating could improve realism and support more flexible planning.
- **Improve methodological robustness:** Comparative risk models must be built on transparent assumptions, structured expert input, and sensitivity testing. Further refinement of parameter choices and validation against empirical cases would increase model credibility and usefulness, especially when comparing fundamentally different hazard types.
- **Investigate interactions between hazards:** Climate change is increasing both the frequency and interconnectedness of hazards. For example, floods may exacerbate pandemic risks by damaging infrastructure or displacing populations. Investigating such compound events can improve multi-hazard risk assessment and avoid siloed preparedness strategies.
- **Assess the value of shared interventions in multi-hazard contexts:** Many interventions - such as public risk communication, emergency logistics, or scenario planning - serve multiple hazards. Research should evaluate how these shared measures perform across different contexts, supporting more efficient and scalable preparedness planning.

Part VI

References and appendix

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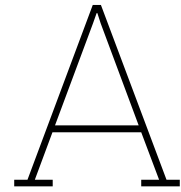
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Expert consultation questions

Throughout this study, experts were consulted for insights into flood and pandemic risk and risk management. The questions asked depend on the expertise of the consulted expert, focusing on either floods or pandemics.

A.0.1. Example questions asked in meetings or via email

Risk systems

- What are the most important causes of floods/pandemics?
- What are the most important consequences of floods/pandemics?

Risk management

- What are the most effective interventions against floods/pandemics?
- What are the strengths in flood/pandemic risk management?
- What are the biggest challenges in flood/pandemic risk management?
- In your opinion, which (types of) interventions are most relevant for reducing the probability and/or impact of a flood or pandemic?
- For floods/pandemics, how would you rank the importance of investments in each of the following phases/layers of protection: prevention, (pro-action), preparedness, threat-driven response, event-driven response, recovery? And why?
- In your opinion, what is the most important point of improvement for flood and/or pandemic management?

Risk thinking

- How are decisions made in the context of flood/pandemic management?
- To what extent is there a focus on 'probability' and 'impact' thinking?

Comparative insights

- In your perspective, which parallels or differences are there between pandemics and floods?
- Do you see any lessons that the flood field can learn from the pandemic field or vice versa?

Exploration and expansion

- Any other thoughts related to these topics?

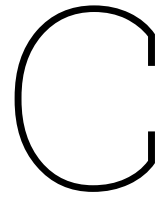
B

Bowtie analysis literature

The table includes the core Dutch documents that were used for the analysis in Part II. Additionally included literature is cited throughout the analysis.

Table B.1: Core Dutch documents used to infer causes, consequences, and interventions for floods and pandemics.

	Citation	Description	Inference of
Floods	ANV (2022c)	Thematic report on climate and natural disasters in the Netherlands. Part of the Dutch National Risk Assessment 2022.	Causes and consequences
	Slager and Wagenaar (2017)	Report on the Dutch standard Flood Damage and Loss Model (SSM2017).	Consequences
	ENW (2017)	Report on the fundamentals of flood protection in the Netherlands. Includes discussions of main causes and consequences to protect from.	Causes, consequences, interventions
	Knoop and Ligvoet (2014)	Report on the importance of considering societal consequences in flood policies.	Consequences
	Ministerie van Infrastructuur en Waterstaat and Deltares (2018)	Report of a flood risk assessment of the Netherlands.	Causes, consequences, interventions
Pandemics	ANV (2022b)	Thematic report on infectious diseases in the Netherlands. Part of the Dutch National Risk Assessment 2022.	Causes and consequences
	RIVM (2024b)	Report on the state of infectious diseases in the Netherlands in 2023. Focus on epidemiological descriptions.	Consequences
	MIT (2024)	Proposal of a framework for the consideration of societal consequences during a pandemic.	Consequences
	RIVM (2023)	Letter advising the Dutch government about interventions for pandemic potential ('type A') infections.	Interventions



Reflection on the pandemic bowtie

The pandemic bowtie developed in this study can be compared to the existing pandemic bowtie developed by Lindhout and Reniers (2020). They developed a pandemic bowtie at the beginning of the Covid-19 pandemic in 2020. They refer to their bowtie diagram as an "integrated pandemics barrier model". The bowtie designed in this study used the model from Lindhout and Reniers (2020) as an inspiration and starting point. However, critical reflection on their bowtie revealed that (1) the bowtie includes interventions in the causal pathways (instead of only as barriers), and (2) that some of the elements deemed relevant for this study were not included. Therefore, a new bowtie was developed (discussed in Chapter 6). This appendix describes a comparison of the two bowties. Figures of the bowties are included on the next two pages.

The causal side of the two bowties is very similar. Many of the root causes are shared or similar to some extent. While Lindhout and Reniers (2020) do not explicitly state it that way, they also have a separation of spark and spread events. The pandemic spark occurs at the "single case zoonosis" event in their bowtie, and the spread between humans and across borders is reflected in the subsequent events.

The consequences side the two bowties is quite different. The bowtie of Lindhout and Reniers (2020) includes many interventions in the causal pathways following from the critical event of an infection outbreak. For example, an outbreak could lead to the occurrence of quarantine, treatment, and spreading reduction. In the current study, such factors are seen as barriers rather than events inherent to the occurrence of a pandemic. Instead, the bowtie is formed based on three initial causal pathways, with a pandemic leading to: (1) the presence of infected people in society, (2) a societal shock, and (3) international responses. Each of these factors, present directly at the beginning of a pandemic, leads to further consequences. The reasoning in the bowtie is based on the scenario of minimal intervention and barriers are only added later, on top of these 'natural' pathways. Going further through the causal pathways, the three initial consequence types then lead to a combination of health, societal, economic, environmental, and cultural losses. Compared to Lindhout and Reniers (2020), the current bowtie also clearly includes and indicates consequences of (most) interest for policy making. Generally, these consequences indicate amounts that are (in theory) quantifiable, such as numbers of deaths and economic damages.

Compared to the bowtie from Lindhout and Reniers (2020), the bowtie from this study also has a bit more detailed causal pathways, which helps with placing barriers at their location of action. The integrated pandemic barrier model from Lindhout and Reniers (2020) does describe barriers at the bottom, but does not place them on the pathways. Their list of barriers is very relevant and exhaustive. They also include a list of support systems, which provides valuable information as well.

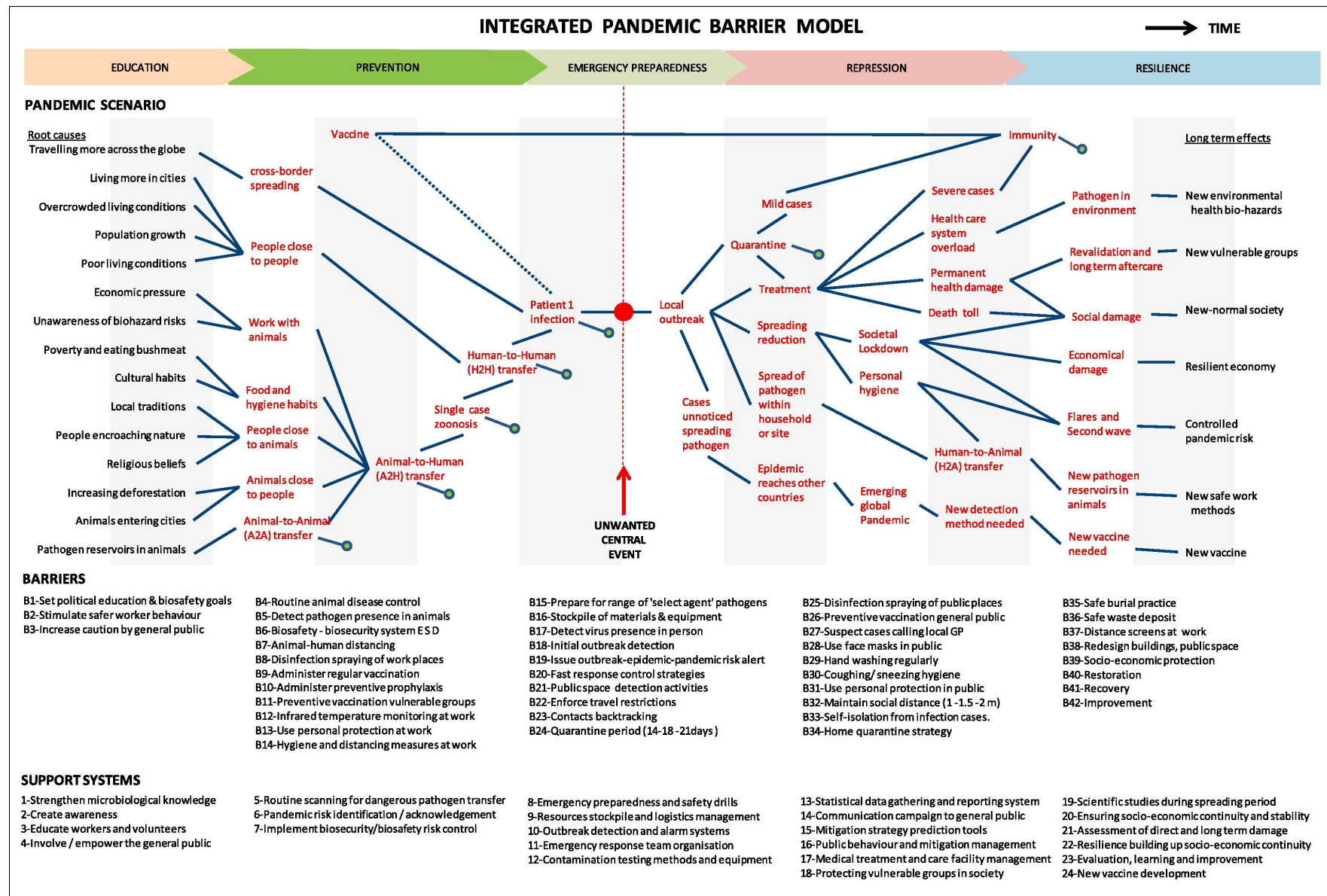


Figure C.1: Pandemic bowtie - or "integrated pandemic barrier model" - developed by Lindhout and Reniers (2020).

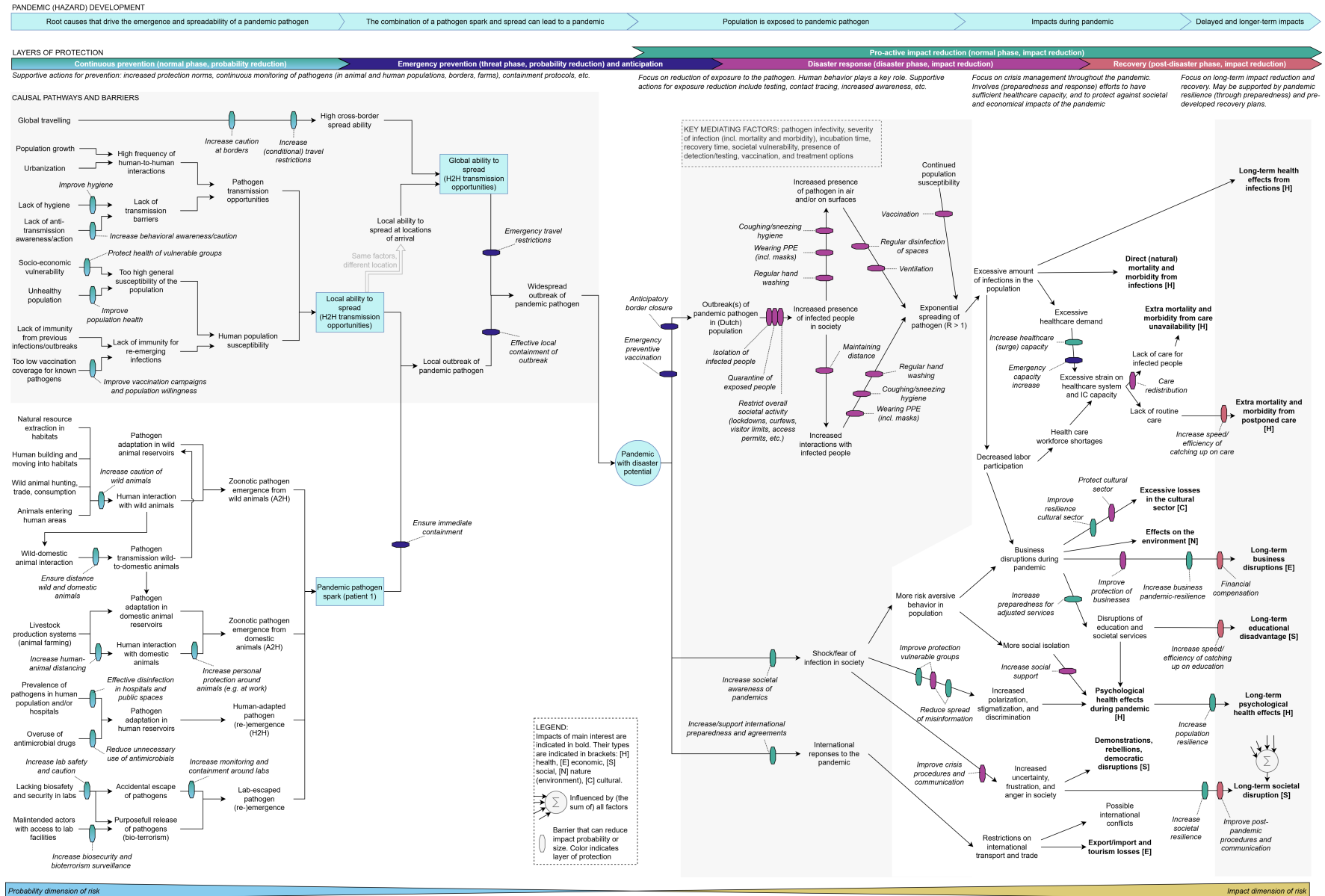


Figure C.2: Pandemic bowtie developed in this study. Details on its development are described in Chapter 6.

D

Flood management in the Netherlands

D.0.1. Overview of role division

Figure D.1 shows a division of the responsibilities of flood risk management over different actors for the different disaster cycle phases.

	Prevention	Protection	Preparation	Response	Recovery
Legislation	Spatial Planning Act (SPA)	Water Act (WA)	Safety Regions Act (SRA)		
	Provinces Act Municipalities Act	Water Boards (regional water authorities) Act	Municipalities Act "Gemeente Wet"		Disaster Compensation Act "WTS"
Administrative level	Ministry of Infrastructure and Environment		Ministry of Security and Justice		
State	National Water Plan accent on protection (WA), also zoning (SPA)				
	National Spatial Strategy (SPA)				
		National Flood protection program (WA)			
			National floods crisis plan and large-scale evacuations (SRA)		
Provinces	Provincial Water Plan (WA), zoning (urban, nature, industry, agriculture) (SPA)				
Water Boards (regional water authorities)	Water Management Plan (WA)		Flood Disaster Management Plan (WA)		
Safety regions			Crisis Coordination Plan (SRA), Disaster Management plan (SRA)		
Municipalities	Land use plan (SPA)				

Figure D.1: Overview of the disaster cycle phases and corresponding actors for flood risk management in the Netherlands.
Table copied from Slomp (2012).

D.0.2. Overview of societal considerations

Figuur 2.3

Maatschappelijke ontwrichting door overstroming

Voor overstroming	Tijdens overstroming	Na overstroming
• Maatschappelijke onrust bij dreigende overstromingen – Preventieve evacuatie duizenden mensen – Bescherming bezittingen – Huisdieren en vee – Kosten en gederfde inkomsten • Onrust rond beleidskeuzes – Discussie noodoverloop gebieden, – Herziening veiligheidsnormen, – Verdeling risico's	• Mensen die verdrinken • Chaos en paniek • Stress en mogelijk agressie • Mensen op zoek, vluchtend • Redden wat er te redden valt • Huizen en bedrijven lopen onder • Verlies waardevolle spullen • Verdrinken vee en huisdieren • Vitale functies vallen uit: – Elektriciteit – Drinkwater – Voedselvoorziening – ICT-netwerken – Transport – Ziekenhuizen • Chemische verontreiniging • Natuurgebieden lopen onder en verdrinking van dieren	• Ondergelopen gebied, chaos • Verdronken mensen • Gewonden en zieken • Duizenden evacués • Emotionele ontredde, verwerking doden, verliezen, zicht op en vertrouwen in herstel? • Ontwrichting familiebanden binnen en buiten gebied • Uitgevalen functies in gebied, met mogelijke uitstraling ver buiten gebied: – Elektriciteit – Drinkwater – Voedselvoorziening – ICT-netwerken – Transport – Ziekenhuizen • Verdronken vee • Schade aan gebouwen, huizen en bedrijven • Uitval bedrijfs-handelsketens binnen en buiten het gebied • Productieverliezen binnen en buiten het gebied • Ordeloosheid en plundering

Bron: PBL

Maatschappelijke ontwrichting door overstromingen speelt voor, tijdens en na de overstroming en omvat een groot aantal aspecten.

Figure D.2: Examples of societal impacts before, during, and after a flood. Figure in Dutch, copied from Knoop and Ligtoet (2014).

Pandemic management in the Netherlands

E.0.1. Crisis response steps for infectious disease outbreaks

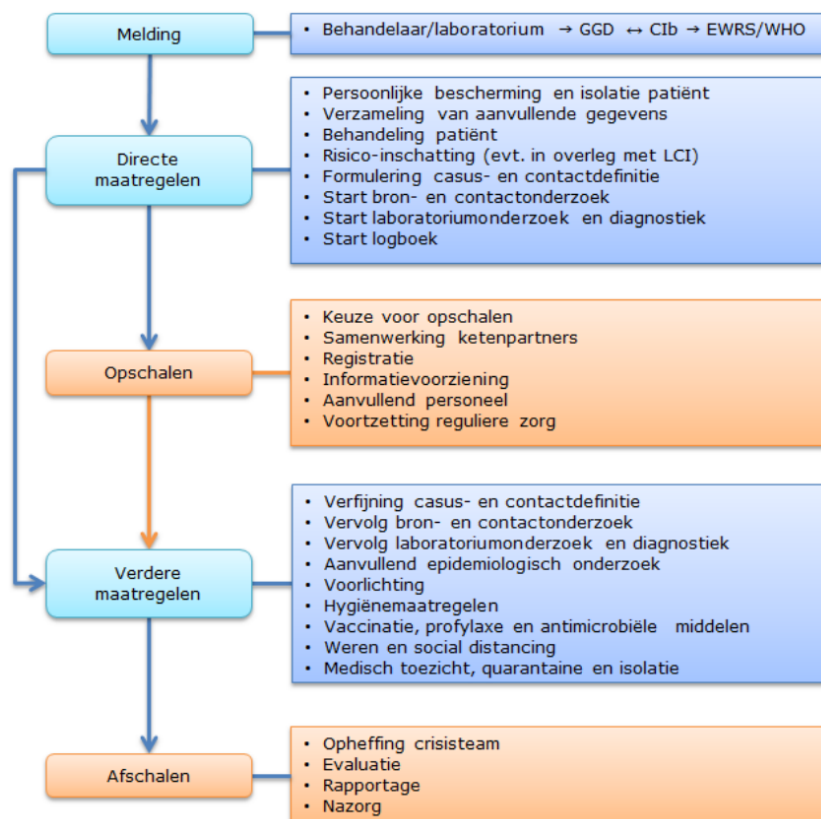
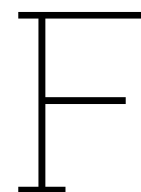


Figure E.1: Steps for crisis management of infectious disease outbreaks in the Netherlands. Figure copied from LCI and RIVM (2014).



MIT societal indicators pandemics

Table F.1 shows an overview of societal indicators proposed by the Dutch societal impact team (MIT) to include in decision-making for future pandemics.

Table F.1: Overview of indicators for societal impacts from pandemics (or their interventions). Table translated and adapted from MIT, 2024.

Theme	Individual Level - Quality of Life	Societal/System Level - Broader Welfare
Subjective wellbeing	General satisfaction with life; Experiencing control over one's life	
Health and care	Health literacy (including pandemic knowledge); Health behavior (e.g., vaccination behavior); Physical activity; Overweight Perceived health; Mental wellbeing; Loneliness	Accessibility/capacity of healthcare (including ICU capacity); Vacancy rates in healthcare and social welfare; Healthcare utilization; Mortality; Perceived accessibility of healthcare
Material prosperity and economy	Median disposable income (households); Median household wealth; Consumption expenditure (individual consumption); Consumer confidence	Savings in Dutch banks; Net labor market participation; Global trade; Added value (GDP)
Work, learning, and leisure time	Time allocation (paid work, volunteer work, informal care, education, leisure time); Working from home; Unemployment; Educational backlog; Satisfaction with work, caregiving, and leisure	Vacancy rates in education
Society	Social contacts (frequency of contact with family, friends, neighbors)	Development of norms and values; Trust in other people; Trust in institutions; Feelings of discrimination
Safety	Crime victimization; Feeling unsafe in the neighborhood	Societal dissatisfaction; Autonomy; Freedom of expression; Inviolability of the body
Living Environment	Satisfaction with housing	Urban exposure to fine dust; Environmental problems

G

Detailed timelines of the Covid-19 pandemic in the Netherlands

G.0.1. Timeline of epidemiological trends

Figure G.1 shows an overview of epidemiological trends during the pandemic in the Netherlands.

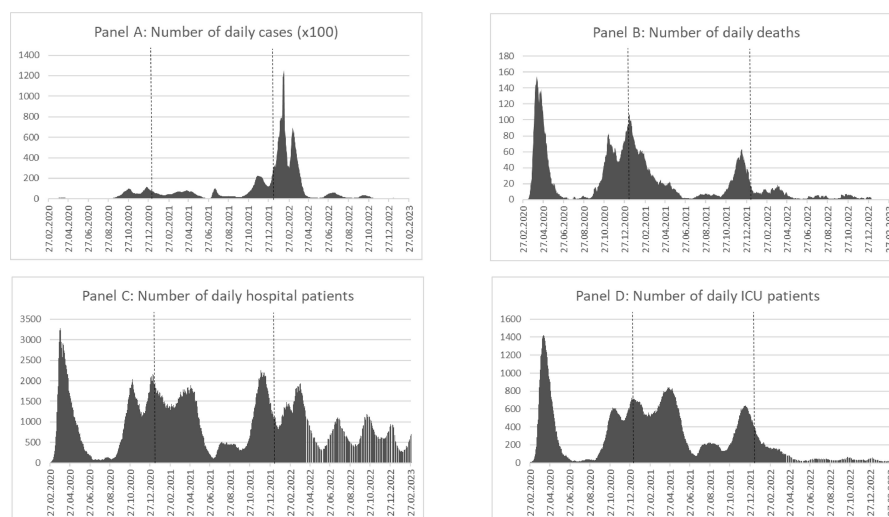


Figure G.1: Health indicators for Covid-19 in the Netherlands between February 2020 and February 2023. Figure copied from van Amerongen et al. (2024).

G.0.2. Timeline of non-pharmaceutical Covid-19 interventions

The Netherlands implemented a wide range of public health and social interventions to manage the Covid-19 pandemic. In the beginning, the focus was especially on epidemiological containment of the pathogen. Later on, societal and economic impacts were taken more into account. Below is an overview of the major interventions taken between March 2020 and March 2023, translated from the timeline published on RIVM (n.d.). Note that all of these measures are non-pharmaceutical in nature, and all are part of the threat- and/or event-driven response during the pandemic.

Early measures and initial lockdowns (March 2020)

- 12 March 2020 – Advise to limit visits to vulnerable people and to work from home as much as possible. Healthcare and essential workers have to stay home in case of symptoms.
- 15 March 2020 – Closure of the hospitality sector (restaurants, bars, etc.).

- 16 March 2020 – Closure of schools and childcare centers, with exceptions for children of essential workers. Contact professions are no longer allowed (except medical services).

Easing restrictions (May - July 2020)

- 11 May 2020 – Most contact professions allowed to resume. Primary schools and childcare centers reopen with halved class sizes.
- 1 June 2020 – Secondary schools reopen partially. Hospitality sector reopens.
- 8 June 2020 - Primary schools fully opened.
- 1 July 2020 - No limits on the number of people meeting each other (in- and outside). People must keep 1,5 meters distance. Children under 12 are exempted from these rules, and children under 18 can get closer to each other but not adults.

Reintroduction of measures (August - January 2020)

- 6 August 2020 - Introduction activities for the new school year are held online. Extra measures may be in place locally.
- 18 August 2020 - Households can receive a maximum of 6 visitors (children under 12 exempted). Distance (1.5 meters) must be kept.
- 29 September 2020 – Households can receive a maximum of 3 visitors (children under 12 exempted). Distance (1.5 meters) must be kept. Hospitality sector closes at 22:00. Contact professions must register. Sports matches must be held without audience. Sports cafeterias close.
- 14 October 2020 – Households can receive a maximum of 3 visitors (children under 12 exempted) a day. Hospitality sector fully closes again. Face masks required in secondary schools and higher education (outside lessons). Ban on events. Sports only allowed with a maximum of 4 people at 1.5 meters distance. Sports matches not allowed.
- 4 November 2020 – Advice to stay at home as much as possible. A maximum of 2 visitors or one household can be together. Public places are closed. Sports limited to 2 people at 1.5 meters distance (except children).
- 14 December 2020 – Closure of non-essential stores, gyms, schools, and childcare centers. Schools transition to remote education.
- 24-26 December 2020 - A maximum of 3 visitors can be received (except children below 12 years).
- 20 January 2021 - People can receive only 1 visitor a day, and can only visit others once.
- 23 January 2021 – Introduction of nationwide curfew (21:00 – 04:30).

Minimal re-openings (February 2020 – April 2021)

- 8 Februari 2021 - Reopening of primary schools and childcare centers. Click and collect allowed for non-essential stores.
- 1 March 2021 - Partial reopening of secondary schools and MBO schools.
- 3 March 2021 - Some contact professions (e.g. hair dressers) may resume. Stores can receive clients by appointment (max. 2 clients per floor). People up to 26 years old may do sports together outside, but only within their own team and club.
- 16 March 2021 - Sports outside are allowed with max. 4 persons, at sports associations or dedicated sports places.
- 31 March 2021 - Evening curfew starts one hour later (22.00-04.30).
- 26 April 2021 - Conditional reopening of universities and universities of applied sciences (HBO).
- 28 April 2021 - Curfew is lifted. Terraces re-open between 12.00-18.00, but max 2 people or 1 household per table. Non-essential shops open till 20.00, with max 1 client per 25 m2.

Major re-openings and short-lived relaxations (May 2021 - September 2021)

- 19 May 2021 - Outside sports, swimming pools, gyms, and cultural classes are allowed with max. 30 people per room. Libraries re-open. Outside parks and play areas re-open, but can only be visited with a reservation.
- 5 June 2021 - Households can receive max 4 visitors per day and visit others max once. Max 4 people can gather outside or do activities (e.g. museum) together. Outside sports allowed with max. 4 people, including re-opening of changing rooms, showers, and canteens. Re-opening of restaurants, cafés, terraces between 6.00 and 22.00. Re-opening of museums, cinemas, theaters, and inside areas of amusement parks and zoos.
- 26 June - No limits for group sizes at home or outside. 1.5m distance must still be kept. Masks where distance is not possible, as well as in public transportation, airports, and secondary schools. Less working from home; advice to work max. half-time at the office. Hospitality sector re-opens, 1.5m still applies. Clubs, discotheques, and some events re-open with Covid-19 entry pass. Amateur sports matches allowed, also with public (at 1.5 distance).
- 10 July 2021 - Discotheques and clubs close. Events last max. 24 hours, with restrictions and 2/3 capacity. Hospitality sector closes after 00.00. Live performances and loud music are forbidden, fixed seating required.
- 19 July 2021 - Work from home unless impossible.
- 8 August 2021 - Return from countries with yellow travel advice only possible with Covid-19 entry pass.
- 30 August 2021 - Under conditions, classes can be given at MBO, HBO, and universities, 1.5m no longer applicable there.
- 25 September 2021 - End of 1.5m distancing rule (it becomes a recommendation instead of requirement). Covid-19 entry pass mandatory for restaurants, cafes, festivals, events, sports matches, cinemas, and theaters. Advice to work at home if possible, at the office if needed. Events inside, without fixed seating, till max 00.000 and with visitor restrictions.

Reintroduction of restrictions and lockdown (November 2021 - January 2021)

- 3 November 2021 - Work at home at least half of the time.
- 6 November 2021 - Mask mandate returns for buildings without Covid-19 entry pass. Covid-19 entry pass required at more locations.
- 12 November - Keep a distance of 1.5 meters in places where no admission ticket is required. Non-essential shops are open until 18:00. Essential shops are open until 20:00. Restaurants and cafes are open until 20:00. A corona entry pass and a fixed seat are mandatory. Events last until 17:00. A corona entry pass is mandatory and a fixed seat. Maximum 1250 people in a room. No audience is allowed at sports. Not with amateurs and professional sports. A maximum of 75 people are allowed in a room on the MBO (secondary vocational education), HBO (higher professional education) and universities. Work from home, only go to work if you have to. Receive a maximum of 4 visitors per day. Children up to and including 12 years old do not count.
- 26 November 2021 - Almost everything closes at 17:00. Also events and amateur sports (training and matches). Essential shops are open until 20:00. At primary school: pupils in groups 6, 7 and 8 wear a face mask in the hallway. Pupils in groups 6, 7 and 8 regularly take a self-test. In secondary school: all students and teachers wear a face mask in the hallway. All students and teachers regularly take a self-test.
- 2 December 2021 - In case of complaints, a self-test or tests at the GCD (Municipal Health Service). In case of a positive self-test, a GGD test is always necessary.
- 14 December 2021 - Primary schools and schools for special (primary) education will close the week before the Christmas holidays. The after-school care is also closed during this week.
- 19 December 2021 - Lockdown. Stay at home as much as possible. Also during the holidays. Outside a maximum of 2 people or 1 household are together. Children up to 12 years old do not count. On 24 to 26 December a maximum of 4 people. Also during New Year's Eve. Receive a maximum of 2 people per day at home. Children up to and including 12 years old do not count. On December 24 to 26, we will receive a maximum of 4 visitors. Also during New Year's Eve. Publicly

accessible locations closed. With the exception of essential shops and services, libraries, banks and government organizations. Schools and after-school care will close. There are exceptions for vulnerable pupils and children of parents with a crucial profession.

Gradual Reopenings and Shift to Advisory-Based Measures (January – March 2022)

- 10 January 2022 – Primary schools, secondary schools and schools for special (secondary) education will reopen. This also applies to after-school care.
- 15 January 2022 – MBO (secondary vocational education), HBO (higher professional education) and universities will reopen. Drama lessons or music lessons are allowed indoors and outdoors again, but without an audience. From the age of 18, a corona entry pass is mandatory indoors and outdoors. Sports are allowed again, indoors and outdoors. Sports competitions are only allowed within their own club. Athletes from the age of 18 must have a corona pass for indoor sports. Without an audience. Shops are open until 17:00. Necessary shops until 20:00. In shops, a face mask and keeping a distance of 1.5 meters is mandatory. Shops receive a maximum of 1 visitor per 5 m². Hairdressers, nail salons and sex workers are allowed to work again until 17:00. Advice: wear a face mask if you cannot keep a distance of 1.5 meters. For example, in shopping streets. Also at work. Wear a disposable face mask. Receive a maximum of 4 people per day at home. Children up to 12 years old do not count.
- 26 January 2022 – Restaurants, theaters, and cinemas reopen (until 22:00). Restaurants, concert halls and theaters are allowed to open again between 05:00 – 22:00. This also applies to cinemas, museums, zoos and amusement parks. 1.5 meters away; Corona admission ticket required; Face mask mandatory (with the exception of seats); This applies to visitors from the age of 13; Fixed seats inside. Events such as concerts and fairs are allowed indoors and outdoors again. A maximum of 1250 people inside; Fixed seating required indoors and outdoors; Large events only outdoors; Festivals are not yet allowed. Away games are allowed indoors and outdoors again. The public is welcome again. For indoor sports from the age of 18, a corona entry pass is required. Less strict quarantine rules.
- 15 February 2022 - Visits at home are possible again. Working in the office half the time.
- 18 February 2022 - Everything is allowed to open again until 01:00 at night. For example, restaurants, cafes and cinemas. In places with a corona pass, no face mask, no fixed seat and no 1.5 meters distance required. Locations with more than 500 people, with seating and a face mask. Quarantine duration has been adjusted to 5 days and 24 hours symptom-free.
- 25 February - Normal opening hours. End of 1.5 meter distance rule. End of fixed seat. Face mask only mandatory in the OV (public transport) and at the airport. Corona entry pass (3G) expires. Testing for Access, indoors with more than 500 people without a seat.

Final Covid-19 Measures Phased Out (March 2022 – March 2023)

- 15 March 2022 – Corona rules become advice. There are no more corona rules and advice to work from home. Testing without complaints is no longer necessary. Pupils, students and teaching staff no longer have to test twice a week.
- 23 March 2022 - A face mask is no longer mandatory in and around the OV (public transport). A face mask is still mandatory at the airport after security and on the plane. No more Testing for Access (1G). No corona pass is required anywhere.
- 11 April 2022 - In case of complaints, a self-test. In case of a positive self-test, no more confirmation test at the GCD (Municipal Health Service).
- 19 April 2022 - Advice to go into quarantine after contact with someone with corona is no longer necessary.
- 20 May 2022 - Face masks no longer mandatory at Dutch airports.
- 10 March 2023 – Final Covid-19 recommendations (self-tests and isolation advice) end/lifted.

Figure G.2 shows an overview of the non-pharmaceutical interventions implemented by the government up until early 2022.

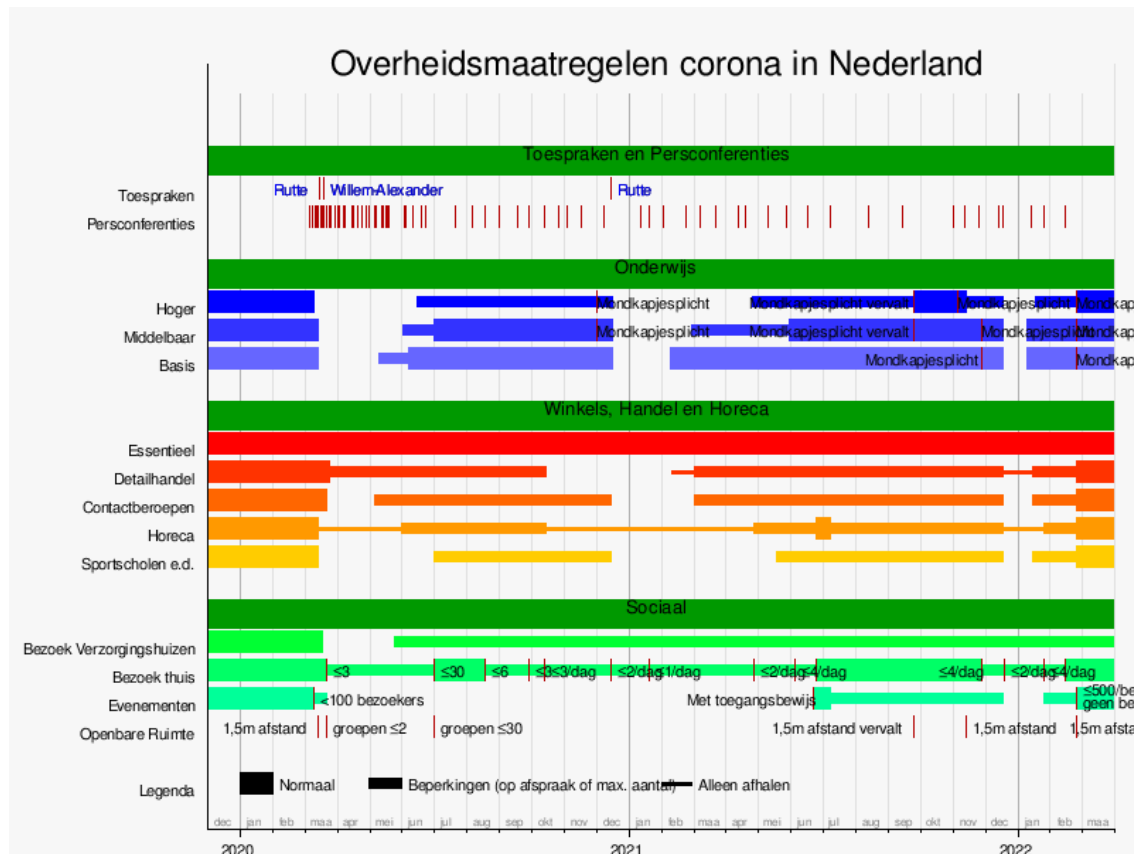


Figure G.2: Timeline of government interventions against Covid-19 in the Netherlands between late 2019 and early 2022. The figure only includes non-pharmaceutical interventions, some of which were recommendations and others which were obligatory. Figure copied from https://nl.wikipedia.org/wiki/Maatregelen_tijdens_de_coronacrisis_in_Nederland.

G.0.3. Vaccine roll-out timeline

Figure G.3 shows an overview of the roll-out of vaccines during the pandemic in the Netherlands. The first vaccination was performed on January 6, 2021.

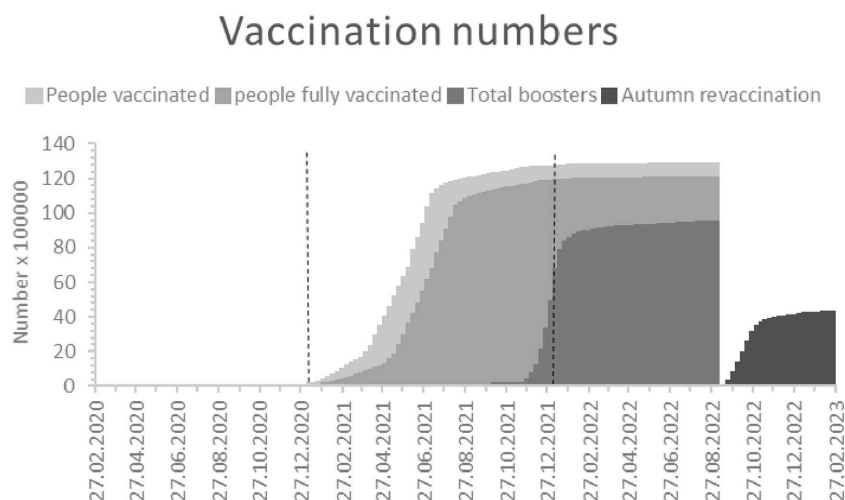


Figure G.3: Timeline of vaccine roll-out for Covid-19 in the Netherlands between February 2020 and February 2023. Figure copied from van Amerongen et al. (2024).

G.0.4. Timelines of intensity of different types of interventions

Figure G.4 shows the intensity of four categories of interventions implemented in the Netherlands throughout the Covid-19 pandemic. van Amerongen et al. (2024) categorized the intervention based on the “Categorising Policy & Technology Interventions (CPTI)” framework. This framework describes four categories of policy interventions:

- Containment measures (contain the spread of the virus)
- Prevention and care (focused on healthcare system and resources)
- Economic measures (reduce the economic impact of containment measures)
- Health technologies (focused on health monitoring and pharmaceutical treatment)

The framework also includes various criteria which can be used to assign an intensity score to the measures in each category. The intensity ranges from 1 (minimal) to 4 (very significant). The graphs in Figure G.4 give an impression of the types of interventions active throughout the pandemic.

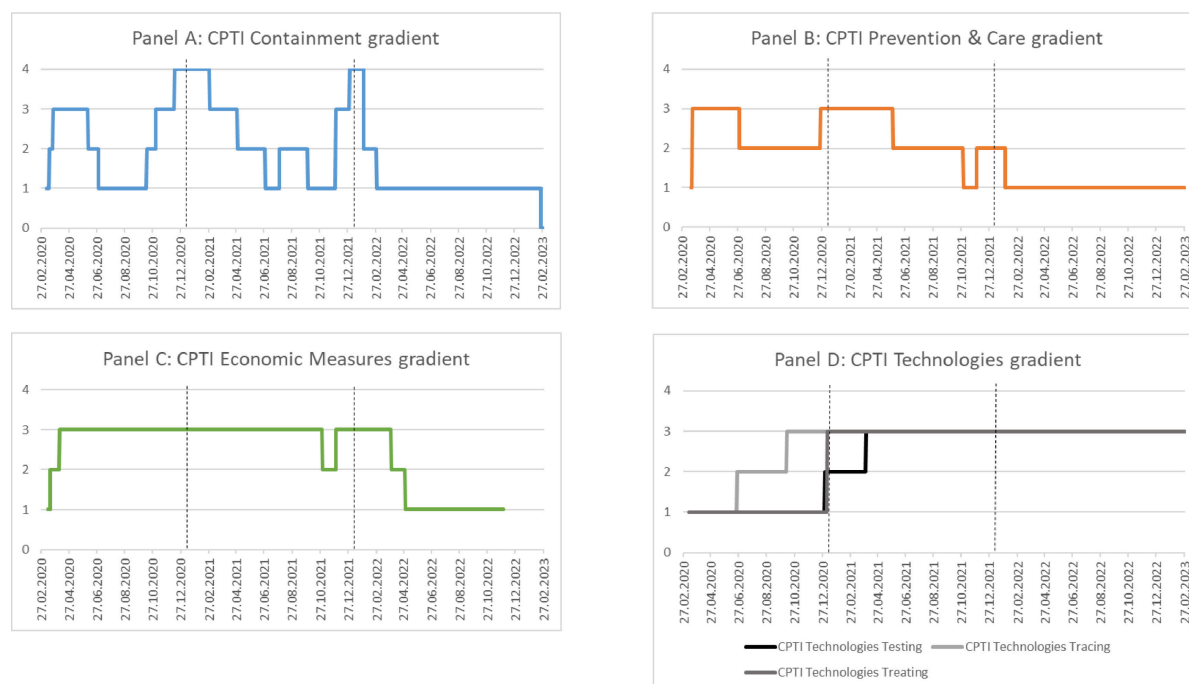


Figure G.4: Graphs with the intensity of different types of measures throughout the pandemic. The dotted vertical lines indicate a separation of three phases (one year each): a first phase with only NPIs, a second phase with NPIs and roll-out of vaccines, and a third phase with minimal NPIs and the roll-out of booster vaccines. Figure copied from van Amerongen et al. (2024).

G.0.5. Epidemiological effectiveness

The epidemiological effectiveness of measures implemented in the Netherlands was studied by RIVM (2024a). They found that the implemented measures were effective in reducing infections with the Covid-19 virus. This applied to both vaccines (proven efficiency from randomized controlled trials) and packages of measures. The more severe the package, the greater the effect. However, it must be noted that attention should also be paid to the societal consequences. For this, the MIT has established a framework of considerations (MIT, 2024), which is shown in Appendix F.

G.0.6. Other sources

A very detailed timeline of Covid-19 in the Netherlands is also maintained on <https://tijdlijn-coronavirus.nl/> (in Dutch).

H

Previous versions of case-based timelines

This appendix shows the timelines of the Limburg-21 floods, the Covid-19 pandemic, and a generic timeline - inferred using the analysis structure of the disaster cycle. Note that this study eventually used a different risk-based analysis framework, as discussed in Part I.

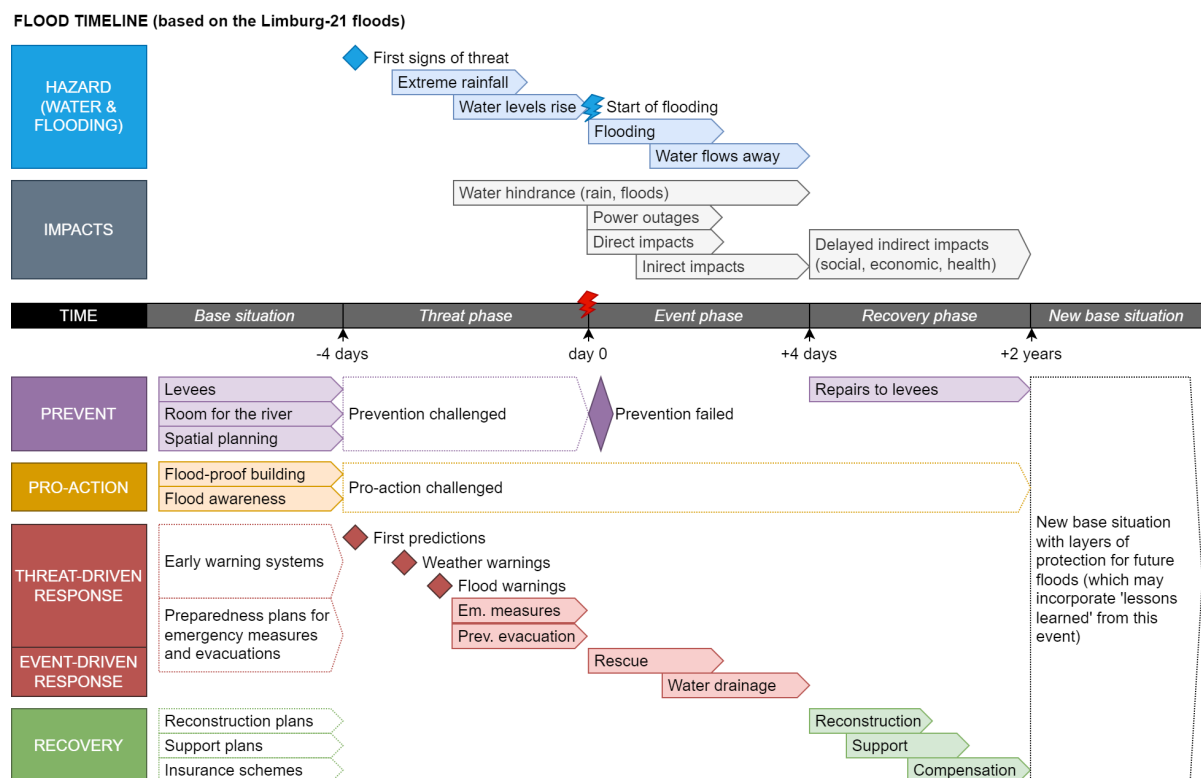


Figure H.1: Flood timeline based on the Limburg-21 floods. The figure shows threat and event phases of around 4 days each, and a recovery time of around 2 years. Layers of protection (different types of interventions) are (most) operational at different points in time.

PANDEMIC TIMELINE (based on the Covid-19 pandemic)

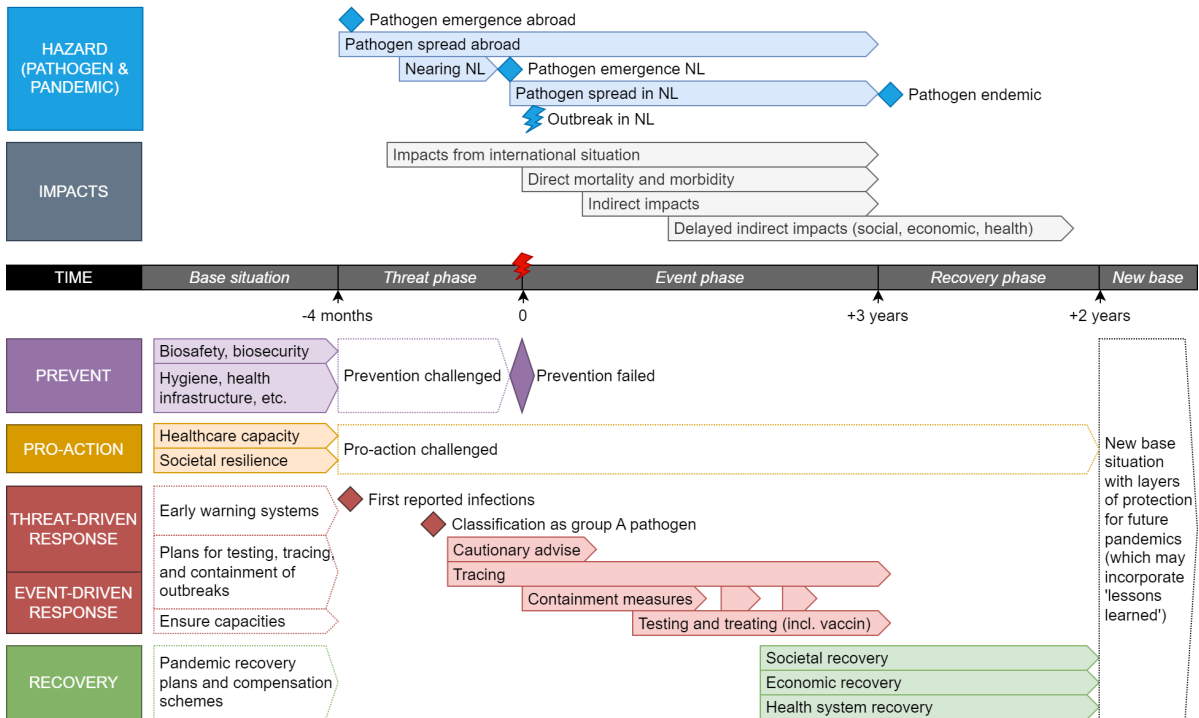


Figure H.2: Pandemic timeline based on the Covid-19 pandemic. The figure shows a threat phase of 4 months, an event phase of 3 years, and a recovery phase of around 2 years. Layers of protection (different types of interventions) are (most) operational at different points in time.

DETAILED GENERAL TIMELINE

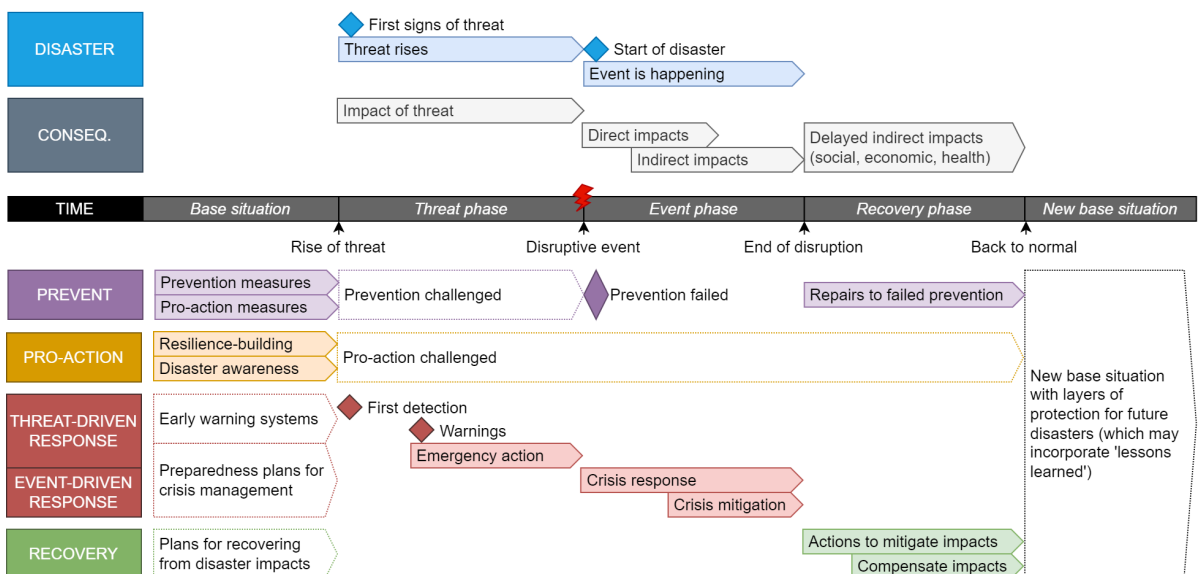


Figure H.3: Generic disaster timeline, based on Limburg-21 and Covid-19.

Dike-ring 16 flooding scenario LIWO

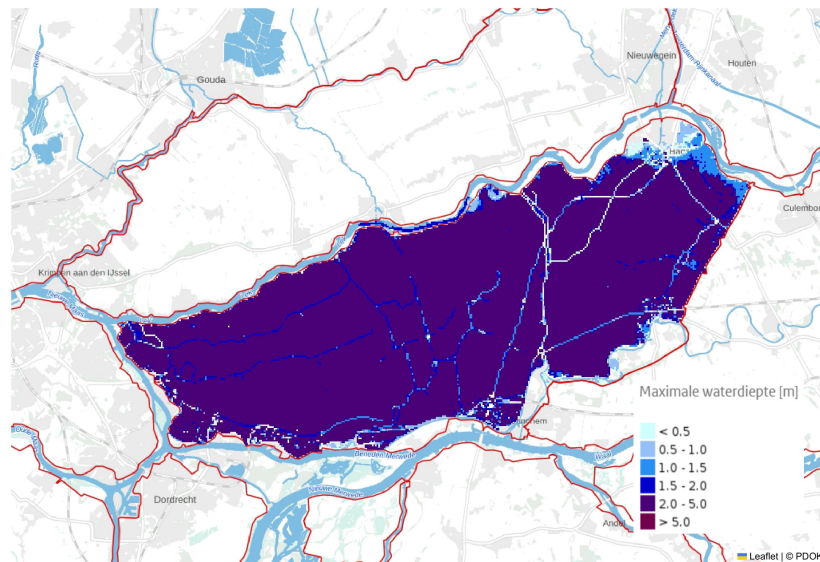


Figure I.1: Water depth.

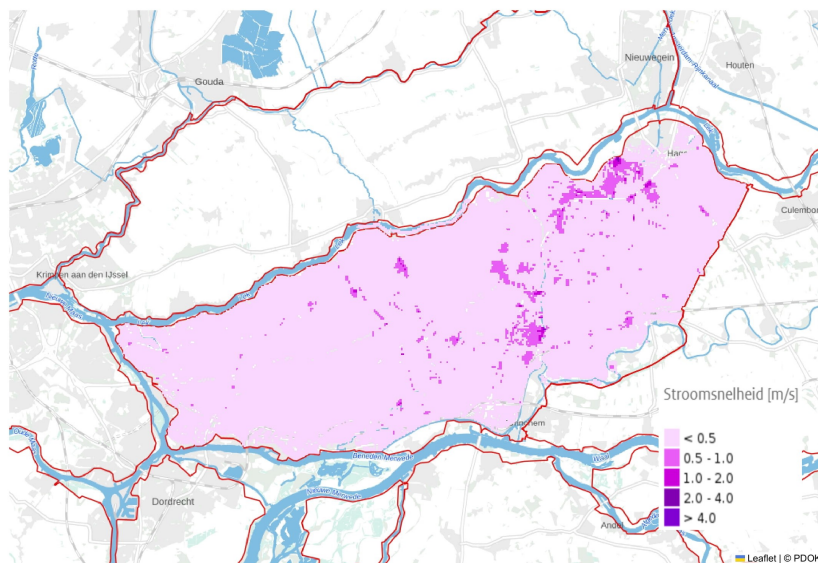


Figure I.2: Flow rate.

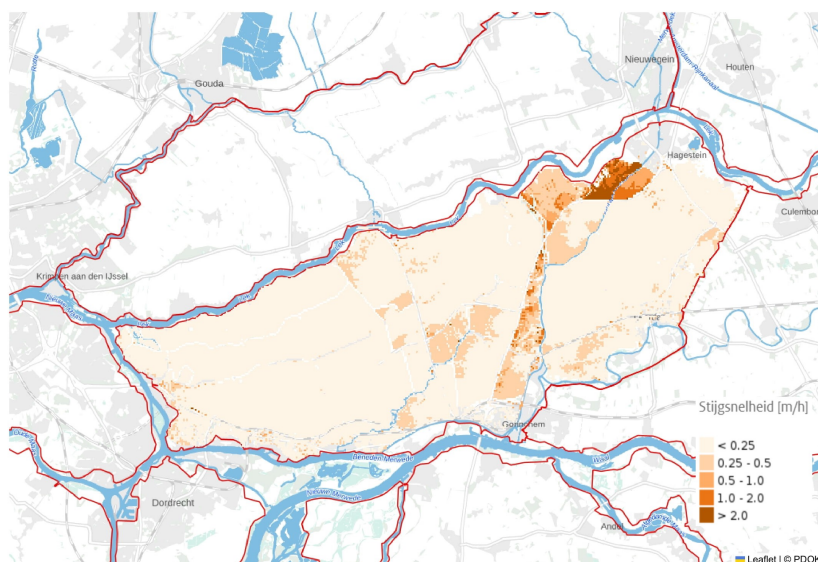


Figure I.3: Ascent rate.

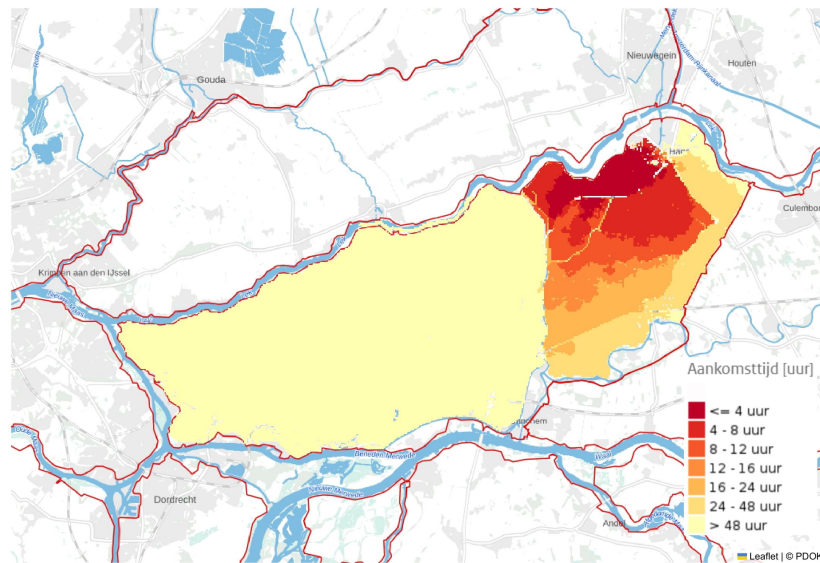


Figure I.4: Arrival time.

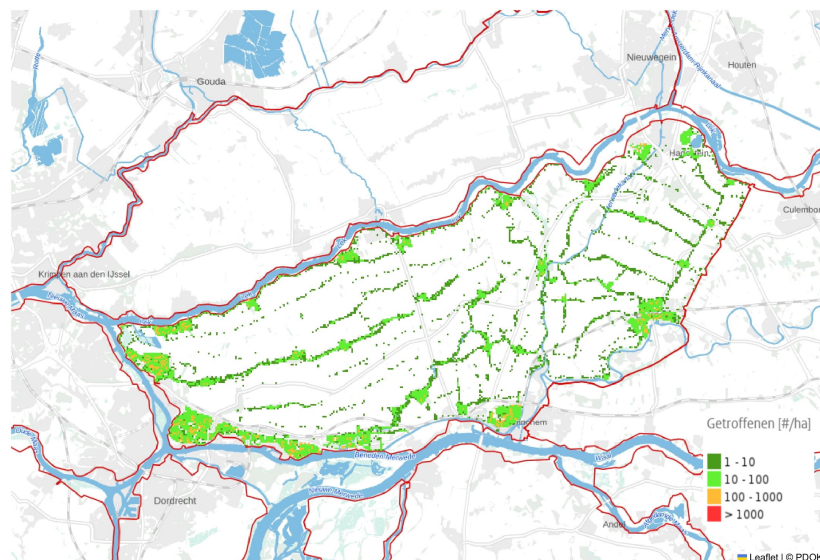


Figure I.5: Affected population.

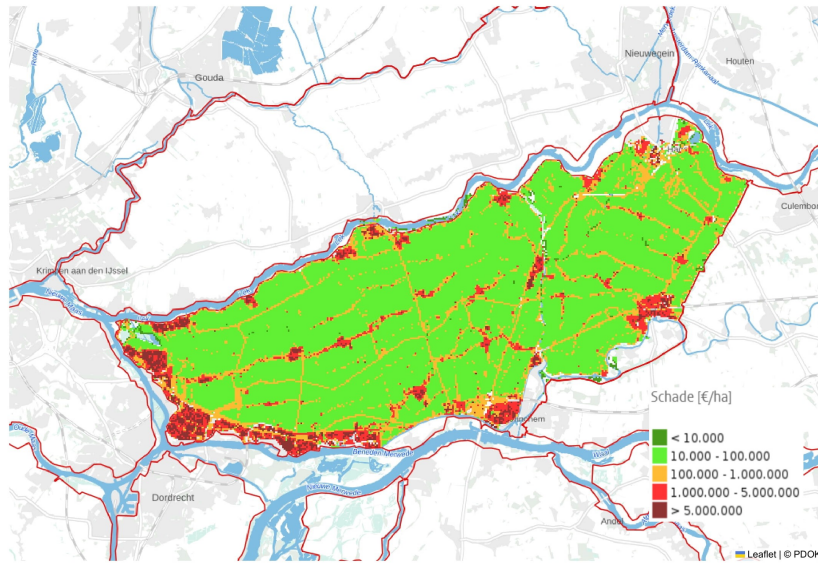


Figure I.6: Damages.

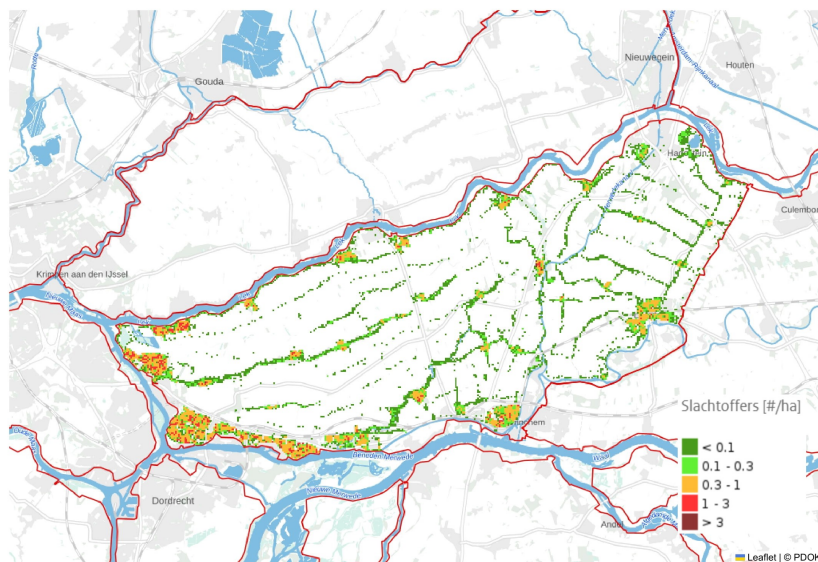
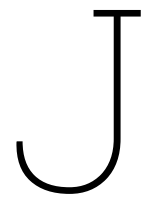


Figure I.7: Fatalities.



Estimate of damage parameter by ChatGPT

ChatGPT was used to infer an estimate for the maximum physical damage per square km in the Netherlands. The conversation is pasted below, with the headings representing the questions asked to ChatGPT.

J.0.1. How much would the maximum physical damage per km² be in the Netherlands on average?

ChatGPT said: The **maximum physical damage per km²** in the Netherlands depends on land use, but a reasonable national **average** estimate would be around **€200M to €500M per km²**, with urban areas reaching up to **€1B per km²**.

Breakdown by Land Use

Key Assumptions

- **Urban areas** have **high-value assets** (real estate, transport, commercial buildings).
- **Ports, airports, and industrial areas** have **high replacement costs** for specialized infrastructure.
- **Agricultural land** has **lower structural damage** but can suffer **high economic loss** from crop destruction.
- **The national average** is a mix of all these areas, so around **€200M - €500M per km²**.

Land Use	Estimated Max Physical Damage (€ per km ²)	Explanation
Highly Urbanized (e.g., Amsterdam, Rotterdam, The Hague)	€500M - €1B+	Dense real estate, critical infrastructure, industrial zones
Medium Urban (e.g., Utrecht, Eindhoven, Groningen)	€200M - €500M	Residential, business districts, mixed land use
Agricultural / Rural	€50M - €150M	Lower building density, damage mainly to crops and farm structures
Industrial Zones & Ports (e.g., Rotterdam Port, Schiphol Airport)	€700M - €1.5B	High-value logistics, manufacturing, storage facilities
Average Across the Netherlands	€200M - €500M	Weighted mix of urban, rural, and industrial areas

Would you like a **more detailed region-specific estimate** (e.g., Randstad vs. rural areas)?

J.0.2. How did you get to these numbers?

ChatGPT said: The estimates for **maximum physical damage per km²** in the Netherlands are based on a combination of:

1. **Dutch flood risk studies & infrastructure data**
2. **Land-use and economic density estimates**
3. **Comparisons with real-world disaster impacts**

Step-by-Step Calculation Approach

1. Urban Areas (€500M - €1B+ per km²)

- The **Randstad region** (Amsterdam, Rotterdam, The Hague, Utrecht) has some of the highest land values in Europe.
- Studies on **Dutch flood risk** (e.g., Deltares, Rijkswaterstaat) estimate that damage in highly urbanized areas can exceed **€1B per km²** in a worst-case scenario.
- Example:
 - **Office & commercial buildings**: €5,000 - €10,000 per m².
 - **Infrastructure (roads, rail, utilities, ports)**: High replacement cost.
 - **Total built-up area density**: 50-70% of land.
 - → **€500M - €1B per km² is realistic.**

2. Medium Urban Areas (€200M - €500M per km²)

- Cities like **Utrecht, Eindhoven, and Groningen** have lower, but still significant, economic density.
- Flood risk studies show lower damage potential compared to the Randstad, but still **€200M - €500M per km²** in built-up areas.

3. Industrial & Port Areas (€700M - €1.5B per km²)

- **Rotterdam Port** and **Schiphol Airport** have extremely high-value infrastructure.
- Rotterdam's **port complex value** is estimated at **€350B total**, covering ~125 km² → **€2.8B/km²** (but not all damageable).
- Schiphol Airport: Aviation-related infrastructure has a **high cost per km²**, but less flood-exposed than ports.
- → A reasonable upper-bound estimate: **€700M - €1.5B per km².**

4. Agricultural / Rural Areas (€50M - €150M per km²)

- Farmland itself has **lower structural damage**, but:
 - **Greenhouses**: €500 - €2,000 per m².
 - **Livestock & farm buildings**: €1M - €10M per km².
 - **Infrastructure (drainage, roads)**: Adds cost.
- Flooding in agricultural zones mainly causes **economic loss** rather than direct physical destruction.
- **Past flood models suggest max €50M - €150M per km².**

5. National Average (€200M - €500M per km²)

- **Weighted mix of land types:**
 - 25% **high-density urban** (€500M - €1B).
 - 25% **medium-density urban** (€200M - €500M).
 - 30% **rural/agriculture** (€50M - €150M).
 - 20% **industrial/ports/airports** (€700M - €1.5B).
- Given this distribution, the **national average** realistically falls between **€200M - €500M per km²**.

Sources & Benchmarks

- **Dutch flood risk studies** (Deltares, Rijkswaterstaat).
- **Historical flood event data** (1993 & 1995 Dutch floods, 2021 Limburg flood).
- **Land price data** from the **Kadaster (Dutch land registry)**.
- **Real estate & infrastructure cost assessments** (e.g., BouwkostenKompas, CE Delft).
- **Comparison with international disasters** (Hurricane Katrina, 2011 Thailand floods).

Would you like a **more refined estimate** for a specific region or scenario? ☐☐☐☐

J.0.3. Can you base your estimate on this site: <https://longreads.cbs.nl/nederland-in-cijfers-2-hoe-wordt-de-nederlandse-bodem-gebruikt/>. And write a section on it?

ChatGPT said: Based on data from Statistics Netherlands (CBS), the total land area of the Netherlands is approximately 4.2 million hectares (42,000 km²). This area is utilized as follows:

- **Agricultural Land:** 54% (2.2 million hectares)
- **Built-Up Areas and Infrastructure:** 13% (0.5 million hectares)
- **Nature, Water, and Recreational Areas:** 33% (1.4 million hectares)

These figures indicate that a significant portion of the Netherlands is dedicated to agriculture, while built-up areas and infrastructure occupy a smaller fraction.

To estimate the **maximum physical damage per km²** in the Netherlands, we can consider the distribution of land use:

1. **Agricultural Areas:** With 54% of the land used for agriculture, these regions are likely to have lower structural densities, leading to lower potential physical damage per km².
2. **Built-Up Areas and Infrastructure:** Comprising 13% of the land, these areas include residential, commercial, and industrial zones, which have higher structural densities and, consequently, higher potential physical damage per km².
3. **Nature, Water, and Recreational Areas:** Making up 33% of the land, these areas typically have minimal structural developments, resulting in the lowest potential physical damage per km².

Given this distribution, the **national average** for maximum physical damage per km² can be estimated by weighting the potential damages according to the proportion of each land use category. This approach aligns with previous estimates, suggesting an average of approximately **€200 million to €500 million per km²**.

It's important to note that these figures are averages; actual potential damages can vary significantly depending on specific regional characteristics and land use intensities.

J.0.4. Based on recent floods (eg limburg) i doubt whether such high values are really representative

ChatGPT said: That's a fair concern. The estimated **€200M - €500M per km²** is based on theoretical maximum damage, but **real-world flood damages** (e.g., Limburg 2021) suggest that actual losses are often much lower—especially outside dense urban areas.

Land Use Type	Estimated Damage per km ² (Revised)
Highly urbanized (Amsterdam, Rotterdam, The Hague)	€100M - €300M
Medium-density cities (Utrecht, Eindhoven, Groningen)	€30M - €100M
Industrial zones & ports (Rotterdam Port, Schiphol)	€200M - €500M (localized, extreme cases)
Rural & agricultural areas	€5M - €20M
Nature, water, and recreation areas	<€5M
National average	€30M - €100M per km²

Reassessing Maximum Physical Damage per km² Based on Real Floods

1. The 2021 Limburg Floods

- **Total reported damages:** €1.8 billion
- **Affected area:** Estimated **200-300 km²**
- **Average damage per km²:** **€6M - €9M per km²**

Even if we assume **localized higher damages**, Limburg's numbers suggest that most areas outside major urban centers experience **well below €50M per km²** in real damage.

2. 1993 & 1995 Dutch Floods (Meuse River)

- **Affected areas:** ~1,000 km²
- **Total damages:** €300M - €400M
- **Average damage per km²:** **€0.3M - €0.4M**

These floods hit **rural & small-town areas**, resulting in **very low per-km² damages**.

3. International Comparisons

- **2011 Thailand Floods (industrial zones flooded)** → **€40M/km²**
- **Hurricane Katrina (New Orleans, high-density city flooding)** → **€150M - €250M/km²**
- **Western Europe Floods (Germany, Belgium, 2021)** → **€20M - €50M/km²**

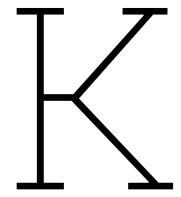
Revised Estimates for the Netherlands

Based on Limburg and international events, here's a **more realistic breakdown** for different land types:

Final Thoughts

- **€200M - €500M per km²** is only realistic in **highly built-up city centers or industrial areas**.
- The **true national average** for flood damage is **probably closer to €30M - €100M per km²**.
- Real-world events (like Limburg) suggest that **rural and small-town areas have much lower damage levels (€5M - €20M per km²)**.
- A flood affecting **high-density cities like Amsterdam or Rotterdam** could still reach **€300M+ per km²**, but those are **localized extremes**.

Would you like further refinements (e.g., impact on specific cities or risk under different scenarios)?



SEIRS infectious disease model

The figure below shows an overview of the equations used in the SEIRS model of this study. The equations were based on Bjørnstad et al. (2020), and were copied from their website: <https://shiny.bcgsc.ca/posepi3/#tab-7442-5>. Additionally, mortality was determined based on the percentage of severe infections (requiring hospitalization), and the proportion of those that could be hospitalized based on ICU capacity. Mortality among hospitalized patients (with severe infections) was lower than among those not hospitalized.

The model scripts are available on Github: <https://github.com/nschuiling/dikes-diseases-disasters>.

SEIRS system with continuous vaccination (dot indicates time derivative)

$$\begin{aligned}
 \frac{dS}{dt} = \dot{S} &= \underbrace{\mu N}_{\text{birth}} - \underbrace{\beta SI/N}_{\text{infection}} + \underbrace{\omega R}_{\text{lost immunity}} - \underbrace{\mu S}_{\text{death}} - \underbrace{pS}_{\text{vaccination}} \\
 \frac{dE}{dt} = \dot{E} &= \underbrace{\beta SI/N}_{\text{infection}} - \underbrace{\sigma E}_{\text{latency}} - \underbrace{\mu E}_{\text{death}} \\
 \frac{dI}{dt} = \dot{I} &= \underbrace{\sigma E}_{\text{latency}} - \underbrace{\gamma I}_{\text{recovery}} - \underbrace{(\mu + \alpha)I}_{\text{death}} \\
 \frac{dR}{dt} = \dot{R} &= \underbrace{\gamma I}_{\text{recovery}} - \underbrace{\omega R}_{\text{lost immunity}} - \underbrace{\mu R}_{\text{death}} + \underbrace{pS}_{\text{vaccination}} \\
 \frac{dB}{dt} = \dot{B} &= \underbrace{\beta SI/N}_{\text{infection}}
 \end{aligned}$$

SEIRS Parameters (mean values)

$$\begin{aligned}
 \text{contact rate} &= \beta \\
 \text{latency period} &= 1/\sigma \\
 \text{recovery period} &= 1/\gamma \\
 \text{immunity duration} &= 1/\omega \\
 \text{mean life expectancy} &= 1/\mu \\
 \text{infection-induced death rate} &= \alpha \\
 \text{annual vaccination rate} &= p \\
 \text{mean infectious period} &= 1/(\gamma + \mu + \alpha) \\
 \text{case fatality ratio} &= \alpha/(\sigma + \mu + \alpha)
 \end{aligned}$$

Basic reproduction number

$$R_0 = \frac{\sigma}{\sigma + \mu} \frac{\beta}{\gamma + \mu + \alpha}$$

Expected value of perfect information (EVPI) for the cumulative burden B_{ij} for model i and action j

$$\text{EVPI} = \underbrace{\text{opt}_j \sum_i p_i B_{ij}}_{\text{optimum of averages}} - \underbrace{\sum_i p_i \text{opt}_j B_{ij}}_{\text{average of optimums}}$$

Infection trajectories show a numerical solution to the SEIRS equations with 1,000 time steps and initial parameters

$$\begin{aligned}
 S(0) &= 0.999 \\
 E(0) &= R(0) = 0 \\
 I(0) &= B(0) = 0.001 \\
 S + E + I + R &= N = 1
 \end{aligned}$$

where B is the cumulative disease burden.

Figure K.1: Overview of equations used in the SEIRS infectious disease dynamics model. Figure copied from <https://shiny.bcgsc.ca/posepi3/#tab-7442-5>.

L

Additional modeling results figures

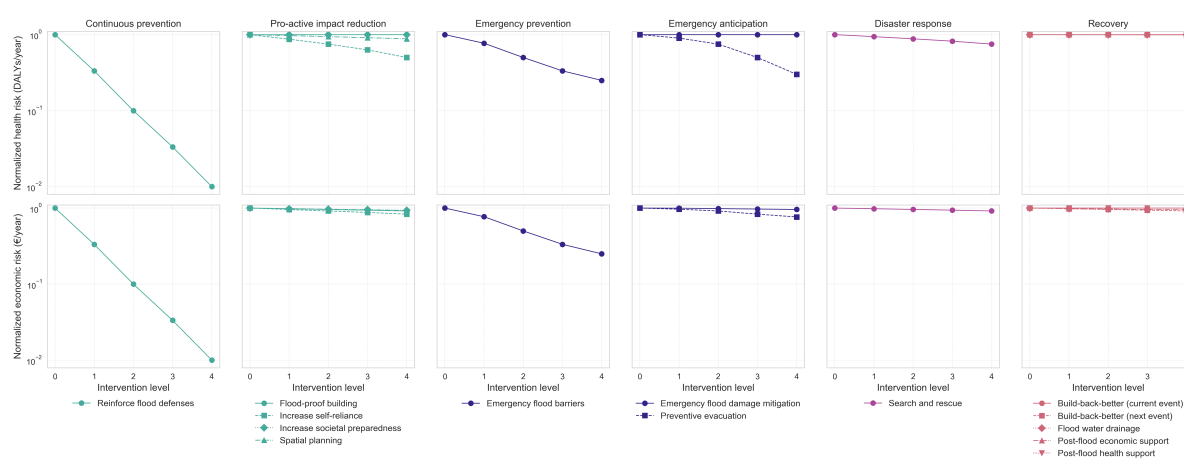


Figure L.1: Flood risk, log y-axis.

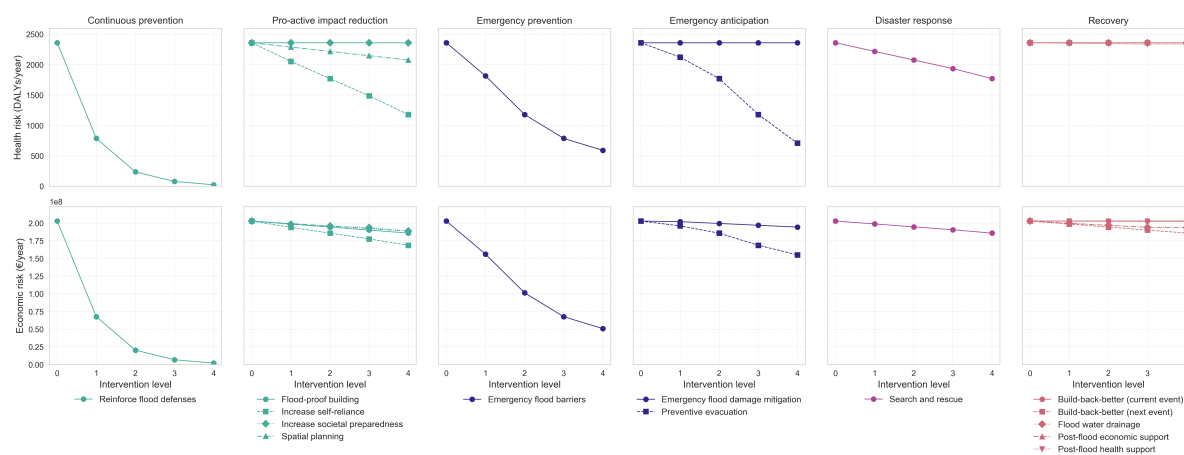


Figure L.2: Flood risk, absolute risk values on the y-axis.

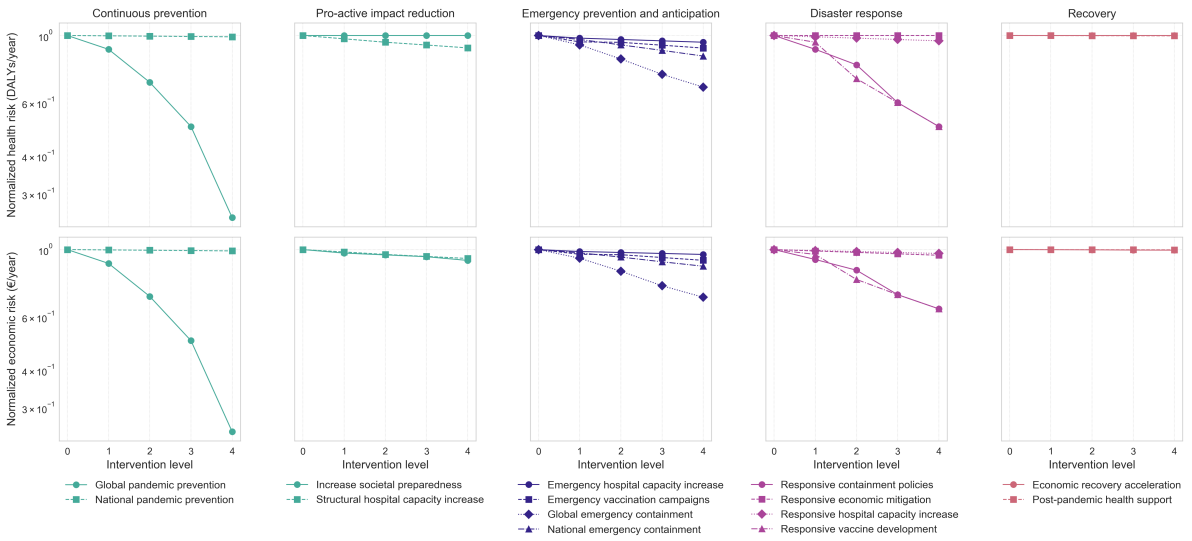


Figure L.3: Pandemic risk, log y-axis.

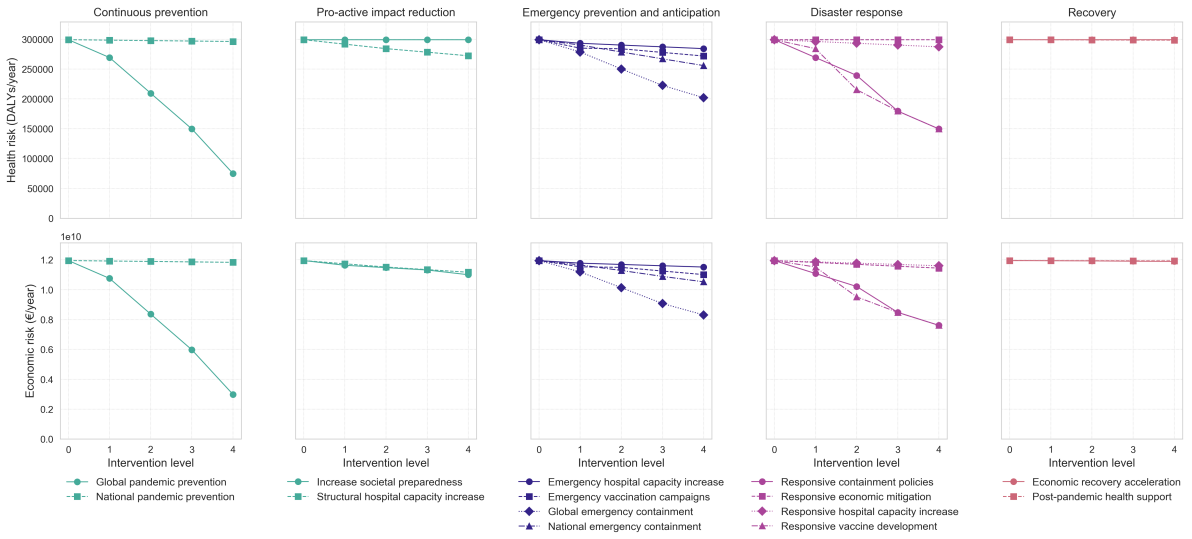
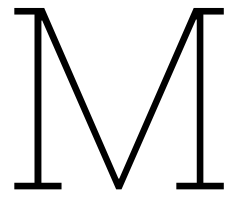


Figure L.4: Pandemic risk, absolute risk values on the y-axis.



Workshops with modeling experts

During the study, a workshop about modeling for disaster preparedness was attended. This workshop brought together experts in flood and disease modeling to explore insights in disaster preparedness modeling across these disciplines. The bowtie diagrams from this study were used as basis for brainstorming about case studies for research projects on these topics.

The next pages show the notes that were made on the bowties.



processes that drive the emergence and spreadability of a pandemic pathogen

The combination of a pathogen spark and spread can lead to a pandemic

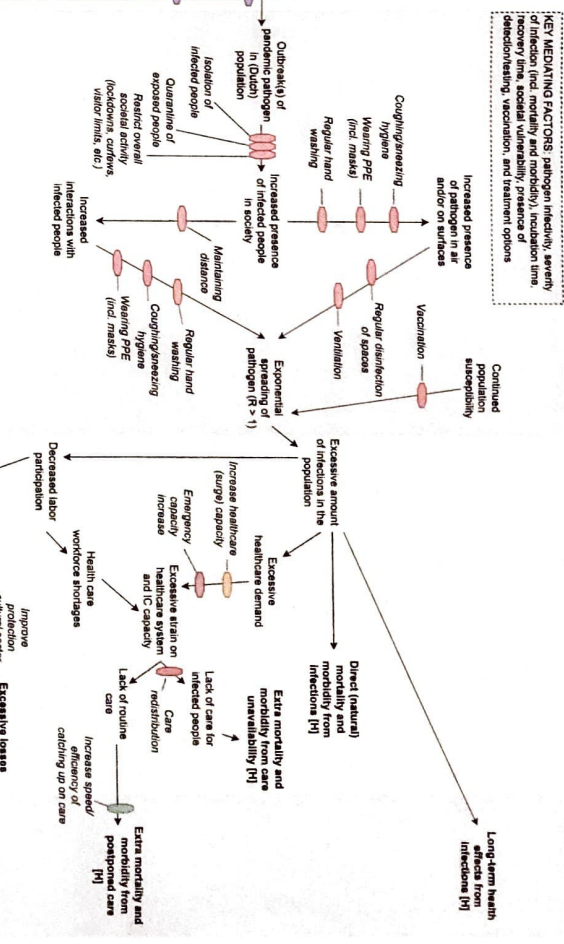
Population is exposed to pandemic pathogen

Impacts during pandemic

...to prevent pandemics from emerging (prevention)

Supporters advocate for prevention: increased protection norms, continuous monitoring of pathogens (in animal and human populations, borders, farms), containment protocols, etc.

Critical thinking



Focus on reduction of exposure to the pathogen. Human behavior plays a key role. Supportive actions for exposure reduction include testing, contact tracing, increased awareness, etc.

Focus on crisis management throughout the pandemic: involves (preparedness and response) efforts to have sufficient healthcare capacity, and to protect against societal and economical impacts of the pandemic

KEY MEDIATING FACTORS: pathogen infectivity, severity of infection (incl. mortality and morbidity), incubation time, recovery time, societal vulnerability, presence of detection/healing, vaccination, and treatment options

Continued

Long-term health

[illegible]

Natural resource extraction in habitats

Human building and moving into habitats

Wild animal hunting

Pathogen adaptation in wild animal reservoirs

Increase caution of wild animals

Zoonotic diseases

Pathogen

Resistant with disaster potential

The diagram illustrates two parallel pathways. The top pathway starts with 'Hygiene' (represented by a red pill) and 'Social activity (shopping, golfing, visiting friends, etc.)' (represented by a red pill). These lead to 'Increased interactions with infected people' (indicated by an upward arrow). The bottom pathway starts with 'Lack of routine care' (represented by a green pill). This leads to 'Extra mortality from postpaid care' (indicated by a downward arrow). A central vertical axis shows 'Increased labor participation' (upward arrow) and 'Excessive losses' (downward arrow). A box labeled 'Health care workforce shortages' is positioned between the two pathways, with arrows pointing to 'Improved' (upward) and 'Worsened' (downward) outcomes. 'Improved' points to 'Increased labor participation' and 'Worsened' points to 'Excessive losses'.

[illegible][illegible][illegible]

```

graph TD
    A[Shockwaves of infection in society] --> B[Psychological health effects during pandemic [3]]
    A --> C[Long-term disadvantage [5]]
    A --> D[Long-term public health effects [4]]
    A --> E[Long-term public health effects [4]]
    B --> D
    C --> E
    D --> E
    F[Social support] --> B
    F --> C
    F --> D
    F --> E
    G[Social isolation] --> B
    G --> C
    G --> D
    G --> E
    
```

Figure 1: Conceptual model of the impact of COVID-19 on long-term public health effects. The model shows a flow from 'Shockwaves of infection in society' to various intermediate outcomes, which then lead to 'Long-term public health effects [4]'. Key intermediate outcomes include 'Psychological health effects during pandemic [3]', 'Long-term disadvantage [5]', and 'Long-term public health effects [4]'. The model also highlights the role of 'Social support' and 'Social isolation' in mediating these effects.

[illegible]

The diagram illustrates the conceptual model of the impact of the 2009-2010 international financial crisis on the environment. The flow is as follows:

- International financial crisis to the pandemic** (yellow oval) leads to **Increased uncertainty and risk in society** (pink oval).
- Increased uncertainty and risk in society** leads to **Demonstrations, rebellions, democratic disruptions [5]** (pink oval).
- Demonstrations, rebellions, democratic disruptions [5]** leads to **Possible international conflicts** (yellow oval).
- Possible international conflicts** leads to **Long term societal disruption [5]** (yellow oval).
- Long term societal disruption [5]** leads to **Environmental impact** (yellow oval).
- Increased uncertainty and risk in society** also leads to **Long term societal disruption [5]**.
- Increased uncertainty and risk in society** leads to **improve crisis procedures and communication** (pink oval), which then leads to **restriction on** (yellow oval).
- restriction on** leads to **Long term societal disruption [5]**.
- restriction on** also leads to **Environmental impact**.
- Long term societal disruption [5]** leads to **Environmental impact**.
- Environmental impact** leads to **pollution resistance** (yellow oval).
- pollution resistance** leads to **Long term societal disruption [5]**.
- Long term societal disruption [5]** leads to **pollution resistance**.
- Long term societal disruption [5]** leads to **Long term societal disruption [5]** (self-loop).

increase biosecurity and
borderline surveillance

INTERACTIONS ?

base can indicate
type of problem

	Communication	tourism losses [E]	transport and trade
1990	100	100	100
1991	100	100	100
1992	100	100	100
1993	100	100	100
1994	100	100	100
1995	100	100	100
1996	100	100	100
1997	100	100	100
1998	100	100	100
1999	100	100	100
2000	100	100	100
2001	100	100	100
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2084	100	100	100
2085	100	100	100
2086	100	100	100
2087	100	100	100
2088	100	100	100
2089	100	100	100
2090	100	100	100
2091	100	100	100
2092	100	100	100
2093	100	100	

LEGEND:
Impacts of main interest are indicated in bold. Their types are indicated in bold. Their types are indicated in brackets: (H) health, (E) economic, (S) social, (N) nature (environment), (C) cultural.

 Influenced by (the sum of) all factors

 Barrier that can reduce impact probability or size. Color indicates level of protection

