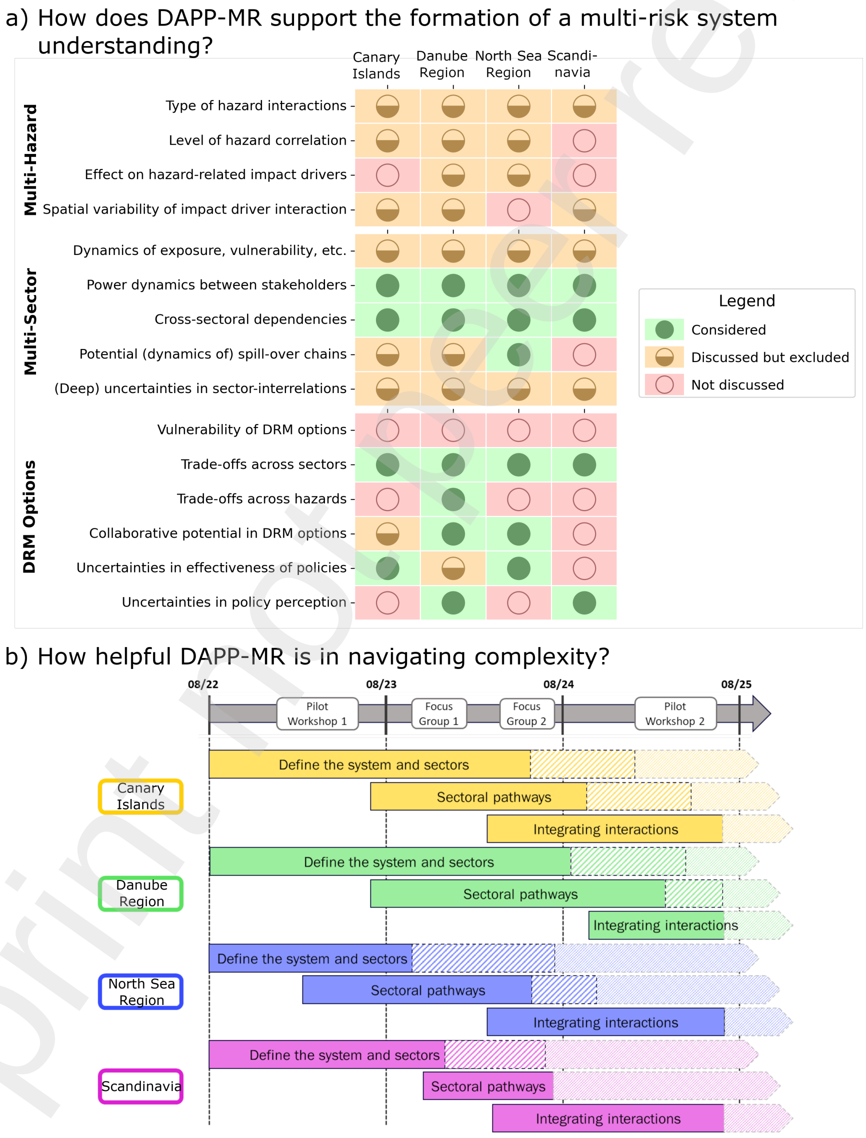
Graphical Abstract

Developing multi-risk DRM pathways – Lessons from four European case studies

Julius Schlumberger, Andrew Warren, Anne Sophie Daloz, David Geurts, Stefan Hochrainer-Stigler, Lin Ma, Noemi Padrón-Fumero, Karina Reiter, Robert Šakić Trogrlić, Sharon Tatman, Vanessa Banks, Julia Crummy, Jaime Díaz-Pacheco, Pedro Dorta Antequera, Sara García-González, Abel López-Díez, Tamara Lucía Febles Arévalo, David Romero-Manrique, Nikita Strelkovskii, Silvia Torresan, Asbjørn Torvanger, Veronica Casartelli, Roxana Ciurean, Judith N. Claassen, Stefania Gottardo, Jeroen C.J.H. Aerts, Marjolijn Haasnoot, Marleen C. de Ruiter



Highlights

Developing multi-risk DRM pathways – Lessons from four European case studies

Julius Schlumberger, Andrew Warren, Anne Sophie Daloz, David Geurts, Stefan Hochrainer-Stigler, Lin Ma, Noemi Padrón-Fumero, Karina Reiter, Robert Šakić Trogrlić, Sharon Tatman, Vanessa Banks, Julia Crummy, Jaime Díaz-Pacheco, Pedro Dorta Antequera, Sara García-González, Abel López-Díez, Tamara Lucía Febles Arévalo, David Romero-Manrique, Nikita Strelkovskii, Silvia Torresan, Asbjørn Torvanger, Veronica Casartelli, Roxana Ciurean, Judith N. Claassen, Stefania Gottardo, Jeroen C.J.H. Aerts, Marjolijn Haasnoot, Marleen C. de Ruiter

- DAPP-MR was applied qualitatively to develop multi-risk DRM pathways in four regions: the Canary Islands, the Danube, the North Sea, and Scandinavia.
- We explored DAPP-MR's potential to build multi-risk understanding, address analytical complexity, and extract lessons for multi-risk DRM.
- The staged framework helped navigate system complexity and integrate cross-sector interactions.
- Multi-hazard elements were least captured due to limited data, awareness, and analytical tools.
- Stakeholder engagement promoted cross-sectoral learning but highlighted challenges in ensuring continuity and institutional embedding of outcomes.

Developing multi-risk DRM pathways – Lessons from four European case studies

Julius Schlumberger[a,b,*], Andrew Warren[a], Anne Sophie Daloz[c], David Geurts[a], Stefan Hochrainer-Stigler[d], Lin Ma[c], Noemi Padrón-Fumero[e], Karina Reiter[d], Robert Šakić Trogrlić[d], Sharon Tatman[a], Vanessa Banks[f], Julia Crummy[f], Jaime Díaz-Pacheco[g], Pedro Dorta Antequera[g], Sara García-González[e], Abel López-Díez[g], Tamara Lucía Febles Arévalo[h], David Romero-Manrique[e], Nikita Strelkovskii[d], Silvia Torresan[i,1], Asbjørn Torvanger[c], Veronica Casartelli[j], Roxana Ciurean[f], Judith N. Claassen[b], Stefania Gottardo[i,j], Jeroen C.J.H. Aerts[b], Marjolijn Haasnoot[a,k], Marleen C. de Ruiter[b]

[a]*Deltares, Boussinesqweg 1, Delft, 2629HV, Zuid-Holland, The Netherlands*
[b]*Institute for Environmental Studies, Vrije Universiteit Amsterdam, De Boelelaan 1115, Amsterdam, 1081 HV, Zuid-Holland, The Netherlands*
[c]*CICERO Centre for International Climate Research, Gaustadalleen 21, Oslo, 0349, Oslo, Norway*
[d]*International Institute for Applied Systems Analysis, Schlossplatz 1, Laxenburg, 2361, Lower Austria, Austria*
[e]*University of La Laguna, Department of Applied Economics and Quantitative Methods, , San Cristóbal de La Laguna, 38200, Tenerife, Spain*
[f]*British Geological Survey, Keyworth, Nottingham, NG12 5GG, Nottinghamshire, United Kingdom*
[g]*University of La Laguna, Department of Geography and History, Disaster Risk Reduction and Resilient Cities Group, , San Cristóbal de La Laguna, 38200, Tenerife, Spain*
[h]*Universidad de Las Palmas de Gran Canaria, Department of Art, City and Territory, , Las Palmas de Gran Canaria, 35017, Gran Canaria, Spain*
[i]*Ca' Foscari University of Venice, Department of Environmental Sciences, Informatics and Statistics, Via Torino 155, Venice, 30170, Veneto, Italy*
[j]*CMCC Foundation - Euro-Mediterranean Center on Climate Change, Edificio Porta dell'Innovazione, 2nd floor, Via della Libertà 12, Venice, 30175, Veneto, Italy*
[k]*Utrecht University, Princetonlaan 8a, Utrecht, 3584 CB, Utrecht, The Netherlands*

Abstract

In the context of climate change and socioeconomic developments, disaster risk is intensifying, driven not only by more frequent and severe hazard events but also by complex interactions between these events and underlying vulnerabilities. These interactions can amplify impacts and trigger cascading failures across sectors. Using the Canary Islands, the Danube Region, North Sea, and Scandinavia as four case study regions, this research explores how the Dynamic Adaptive Policy Pathways for Multi-Risk (DAPP-MR) framework can support the development of integrated, adaptive DRM strategies to reduce risk while addressing these complex interactions. We examine how DAPP-MR enables a deeper understanding of multi-risk systems, facilitates stakeholder engagement, and structures the development of robust, cross-sectoral DRM pathways in these four qualitative applications. The findings indicate that DAPP-MR enables integrated, cross-sectoral thinking and encourages balancing short-term priorities and long-term needs. This research shows that DAPP-MR provides a structured approach to untangle complex dynamics between hazards and sectors, while maintaining flexibility in analytical focus. This flexibility allows context-specific priorities to guide the analysis, but it can also make comparing outcomes across different applications more challenging. This study further underscores the need for additional tools to manage and explore the information to support the development and

evaluation of multi-risk DRM pathways.

Keywords: Multi-risk, Disaster Risk Management, Adaptive Pathways, DAPP-MR, Qualitative Case Studies, Stakeholder Engagement, Multi-Hazard, Multi-Sector, Climate Adaptation

1. Introduction

Past disasters have demonstrated how natural and human factors amplify disaster risks. Multi-hazard events, defined by interactions between multiple hazards due to simultaneous or sequential occurrence, can exacerbate the hazard-related impact drivers. Similarly, vulnerability characteristics and the dynamics of exposed infrastructure, services, people, and their dependence on each other can cascade impacts across sectors, regions, and communities (Simpson et al., 2021). These phenomena with interacting hazards and vulnerability dynamics are defined as multi-risk events (Zschau, 2017). For example, storm Boris led to significant flooding in central Europe and Italy, triggering landslides that damaged railway and road networks (BBC, 19 September 2024). Similarly, the Catalonia region in Spain has frequently experienced severe periods of droughts and flash flood events as seen in 2024: prolonged drought conditions, combined with urbanisation, intensive agriculture, and flood risk protection measures, led to intensified flooding with limited relief for the drought due to the reduced infiltration and retention capacity of the soil (BBC, 17 January 2025).

Understanding and addressing these complex interactions between and across human and natural factors is essential for effective disaster risk management (DRM, Hochrainer-Stigler et al., 2023; Sillmann et al., 2022; Zschau, 2017). However, DRM often focuses on isolated risks, not accounting for these interactions, which can result in unforeseen consequences elsewhere (Nilsson, 2017; de Ruiter et al., 2021). Furthermore, deep uncertainties related to climate change, socio-economic development, and other unpredictable factors complicate DRM decision-making (Lempert, 2003; Walker et al., 2003). In the case of Catalonia, the intensity of flash flood events is expected to increase because of rising mean sea temperatures (Amiri et al., 2025). At the same time, uncertainties in current future projections are large, which means that the exact precipitation patterns cannot be predicted yet. Additionally, the expansion of the city of Barcelona, built initially next to a river, gradually took over the entire delta, replacing the natural watercourses (Del Mar Pérez Cambra et al., 2025; Wynn, 1979). Risk management cannot be static in such contexts - it requires adaptive planning dealing with (future) uncertainties. However, such multi-(hazard) risk management in Europe often remains undelivered in practice (Poljansek et al., 2021; Šakić Trogrlić et al., 2024).

Pathways-thinking has emerged as a promising approach to address challenges of uncertainties and complexities (Haasnoot et al., 2021; Ward et al., 2022). The Dynamic Adaptive Pathways Planning (DAPP) framework supports decision-making under uncertainty by identifying flexible, short-to-long-term strategies to deal with evolving risks (Haasnoot et al., 2013, 2024). By mapping out alternative sequences of measures over time, pathway-thinking helps avoid lock-ins, maintain flexibility, and facilitate adaptive changes when needed (Haasnoot et al., 2024; Lawrence et al., 2025; Thaler et al., 2023). Pathways have been developed using computational models (e.g., Jafino et al., 2021), qualitative expert knowledge (e.g., Cradock-Henry et al.,

*j.schlumberger@vu.nl

2020), or a combination of both (e.g., Colloff et al., 2016). A recent study by Haasnoot et al. (2024) shows that pathways thinking has been applied for different specific hazards and sectors, such as forest management for future wildfire risk (Colloff et al., 2016), urban water management (Carstens et al., 2019), and transport infrastructure planning for future flood risk (Hadjidemetriou et al., 2022), but is still in its infancy for multi-risk settings.

To address this gap in multi-risk pathways thinking, DAPP has been extended to multi-risk settings (DAPP-MR), which accounts for explicit interactions between multiple hazards and sectors (Schlumberger et al., 2022a). DAPP-MR follows a staged approach: pathways are developed separately for each sector-hazard combination first before integrating them to explore interactions, synergies, and trade-offs across multiple hazards and sectors. These decision stages reduce analytical complexity while ensuring that DRM pathways are robust across future conditions. To develop and evaluate pathways across the different stages of complexity, DAPP-MR iterates through a set of analytical stages. It starts with identifying the system boundaries, which include a characterization of the space and elements of the case study along with its vulnerabilities, future uncertainties, and objectives of interest. Based on this system understanding, potential DRM options are identified, characterized, and combined into different pathways (Haasnoot et al., 2021). The system understanding is updated iteratively across the stages by incorporating additional information on different dynamics and connections.

Previous applications of DAPP-MR include a synthetic quantitative, model-based case study to investigate the implications and challenges of multi-risk pathways analysis in data- and resource-rich contexts (Schlumberger et al., 2024). However, in real-life case studies, qualitative approaches are often used as an entry point to engage stakeholders in long-term planning and draw on expert input and literature for developing pathways. These approaches can inform subsequent (semi-)quantitative analyses by characterizing the scope and purpose of the analysis (Haasnoot et al., 2024; Ramm et al., 2018).

This study investigates how DAPP-MR can support the development of multi-risk pathways. We draw from the process and experience of applying DAPP-MR in four European case study areas: the Canary Islands, the Danube Region, the North Sea Region, and Scandinavia. Specifically, we evaluate how and why multi-risk elements were integrated into the analysis across the case studies. Additionally, by reflecting on the development process and feedback from stakeholder engagement activities, we investigate the means and value of breaking down complexity into analysis stages and what we can learn from applying DAPP-MR for multi-risk DRM. Finally, we discuss common challenges and opportunities and reflect on the strengths and limitations of DAPP-MR in qualitative applications.

2. Methods

In this study, we reflect on the strengths and limitations of DAPP-MR as a policy analysis framework to develop and evaluate multi-risk pathways qualitatively. We do so along the lines of a set of questions of interest that touch on the key purpose of DAPP-MR. The following subsections outline the approach and data used to answer these questions:

1. **How does DAPP-MR support forming a multi-risk system understanding?** The framework explicitly addresses a set of multi-risk elements that could be relevant in a multi-risk system and offers guidance to unravel those. Therefore, this question aims to analyze whether patterns are detectable regarding which multi-risk elements are generally considered and, if not, for what reasons.

2. **How helpful is DAPP-MR in navigating complexity?** Evidence from previous studies (Schlumberger et al., 2022a, 2024) indicates that a staged approach helps analyze complex systems without being overwhelmed by interactions. However, this approach is also subject to some limitations. Thus, this question explores the complexity captured by the case studies using the approach and whether the staged integration is helpful.
3. **What can we learn from DAPP-MR for DRM?** As a policy analysis framework, DAPP-MR facilitates the identification of relevant DRM options, synergies, and trade-offs. It offers a solution-oriented approach to identifying and analyzing multi-risk DRM options in contrast to more commonly used problem-centered approaches in risk assessment, which focus primarily on hazards and/or impacts (Schweizer and Renn, 2019). Thus, this question aims to analyze the added value regarding DRM for sectoral stakeholders and researchers by engaging in a DAPP-MR exercise.

2.1. The multiple case study approach

We use data from multiple case studies (MCS) to support our findings, offering rich evidence supporting the analysis and development of a theory (e.g., Baxter and Jack, 2015; Yin, 2009). In this study, we use MCS to investigate what conclusions are drawn regarding the above-outlined questions of interest in each case study to identify similarities across multiple cases or unique insights to specific ones (Eisenhardt, 1991; Yin, 2009). The cases considered in this study are "polar types" (Eisenhardt and Graebner, 2007, p.27), meaning they have a wide variety of characteristics in terms of general climatic and environmental context, spatial and temporal scope, sectors and stakeholders involved, governance level, and hazards of interest (see Section 2.1.1). In contrast to one case study, accounting for multiple case studies can offer more robust insights regarding the questions of interest (Eisenhardt and Graebner, 2007). Eisenhardt and Graebner (2007) highlight that MCS approaches usually take a small number of cases into account, which still significantly increases the analytic power compared to a single-case study approach. Increasing the number of cases comes at the risk of insufficient in-depth knowledge and analysis of the specific case when considered part of an MCS study (Gerring, 2004). We overcame this challenge by working in teams with in-depth knowledge of each case study, which were embedded in a broader team (see Section 2.1.2).

2.1.1. A brief overview of the case studies

The analysis presented in this work is based on four case studies from the HORIZON 2020 Multi-hazard and sYstemic framework for enhancing Risk-Informed mAnagement and Decision-making in the EU project (MYRIAD-EU,`www.myriadproject.eu`, Figure 1). MYRIAD-EU aims to provide policymakers and practitioners with practical tools to create forward-looking multi-risk DRM strategies. Central to the project are the case study teams (pilots), which test methods developed in the project (e.g., Casartelli et al., 2025; Claassen et al., 2023, 2025; Dal Barco et al., 2024, 2025; Hochrainer-Stigler et al., 2023; Stolte et al., 2024; Warren et al., 2023) by engaging in a collaborative co-development process with local stakeholders to address region-specific sustainability challenges (Šakić Trogrlić et al., 2024; Ward et al., 2022). This study focuses on methods, results, and reflections used for the pathway development process following the DAPP-MR approach. As such, we focus on four out of the five pilots of MYRIAD-EU, as the Veneto pilot followed a different approach (Casartelli et al., 2025).

The first case study focuses on the **Canary Islands Pilot (CIP)**, an archipelago highly vulnerable to multiple natural hazards, including volcanic eruptions, droughts, wildfires, and heatwaves, with increasing risks due to climate change. For example, the 2021 La Palma volcanic eruption and the water emergency declared in 2024 highlight the region's systemic weaknesses in disaster preparedness, particularly in the tourism and agricultural sectors. This case study examines the opportunities for recovering and increasing tourism capacities after the volcanic eruption in 2021 while adapting existing practices in tourism and agriculture to the increasingly limited freshwater resources.

The **Danube Pilot (DP)** focuses on the multi-hazard and multi-risk challenges in the Danube region, which comprises 14 countries. The Danube region is a socio-economically heterogeneous region exposed to numerous natural hazards (Hochrainer-Stigler et al., 2024). The Danube case study explores the interconnectedness between countries and sectors and the spill-over effects of multi-hazards in the region. The pathways analysis focuses on reducing flood and drought risks in the agricultural and river navigation sectors. Due to its large geographical scale, the Danube Pilot uses generic characteristics common along the river basin to define the system while acknowledging that the derived findings might require a tailored contextualization to the specific locations along the basin.

The third case study explores the evolving risks and challenges in the **North Sea Pilot (NSP)**. The North Sea is becoming increasingly crowded with diverse activities, such as offshore wind farms, shipping, and aquaculture. Climate change is intensifying these pressures, with more frequent storms, heatwaves, and multi-hazard events impacting sectors across the region. This case study examines how cross-sectoral maritime spatial planning can address these complex risks.

The **Scandinavian Pilot (SP)** examines the interlinked challenges of Norway's energy, forestry, and agriculture sectors within a Scandinavian context. Norway's reliance on hydropower, shifting precipitation patterns, and rising energy demands call for adaptive strategies. Agriculture faces extreme weather and land use transformations, while forestry contends with logging, land-use conflicts, and climate impacts. The study explores sustainable practices, technology, and integrated planning to achieve climate goals while maintaining economic stability.

2.1.2. The approach and methods used to develop multi-risk pathways

We used DAPP-MR as the foundation for developing DRM pathways in the case studies. While DAPP-MR is designed for comprehensive policy analysis in multi-risk settings, qualitative approaches require adaptations to accommodate varying levels of data availability, diverse stakeholder involvement, and the need for accessible, intuitive methods. We simplified DAPP-MR into a comprehensive framework that applies an iterative process that retains the core analytical principles of DAPP-MR, notably the staged approach (Fig. 2). First, we established a comprehensive system understanding, identifying key sectors, their objectives, and the interdependencies between elements, functions, and stakeholders. Then, we identified and characterized DRM measures that align with sectoral objectives and address current and future risks. Based on these sets of measures, sectoral pathways were developed. Finally, multi-sectoral and multi-hazard interactions were integrated, assessing how different measures influence each other across sectors and, ultimately, the implications for the identified sectoral pathways. By embedding increasing complexity in the final step, this simplified version of DAPP-MR keeps the stagewise analytical focus while enhancing its practical applicability in qualitative settings. The overall process remains highly iterative, allowing for continuous refinement of the system understanding, measures, sectoral pathways, and interactions as new insights emerge.

Information relevant to the DRM pathway development process was collected using various methods (Figure 2). Stakeholders were at the core of each case study. As part of the co-production process of MYRIAD-EU, each case study organized two pilot workshops and two

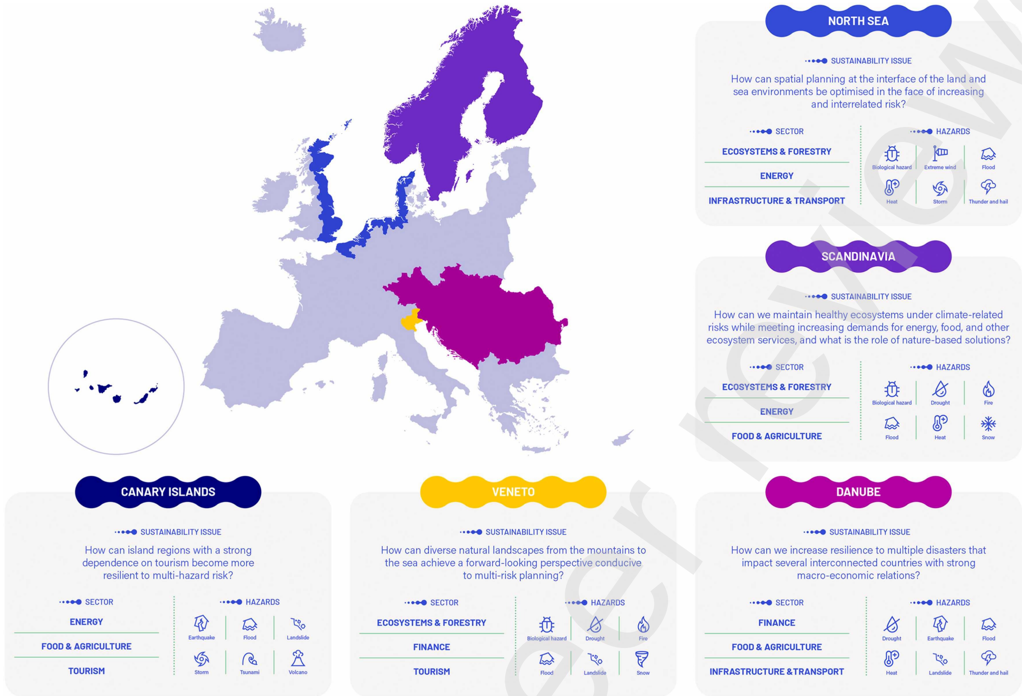


Figure 1: MYRIAD-EU pilot regions. Overview of their considered sectors, hazards, and sustainability challenges. Note: The Veneto pilot region is not part of this study, as it applied a different approach. Copied from Ward et al. (2022).

focus group meetings with stakeholders (Ciurean et al. in progress), where intermediate results of the pathways development process were presented to collect feedback and progress with the analysis. Stakeholders included local, regional, national, and transnational governmental bodies, academic institutions, private sector actors, and non-governmental or community-based organizations. Their roles ranged from policy-making and implementation to research, technical service provision, and sectoral advocacy. This functional diversity enabled the integration of strategic, operational, and experiential knowledge. Thematically, stakeholders covered many sectors aligned with the case study focus areas, including energy, tourism, agriculture, water management, civil protection, and climate adaptation. Many brought cross-cutting or interdisciplinary perspectives, particularly where systemic risk and uncertainty intersected with infrastructure, environment, and social resilience. Additional information on the contents of the key meetings and the represented stakeholder profiles is available in Appendix A.1.

Additional information on known dynamics and connected challenges was elicited through semi-structured interviews (Schlumberger et al., 2022b, ; van Maanen et al. *in progress*). Aside from these organized data collection efforts, most case studies engaged in additional formal and informal stakeholder engagement. For example, DP held four key informant interviews and a further group interview with key stakeholders to ensure that the developing process of the DAPP aligned with their field experiences. SP combined stakeholder engagement through various outreach activities, including presentations and panel discussions with relevant Norwegian industry stakeholders and policymakers.

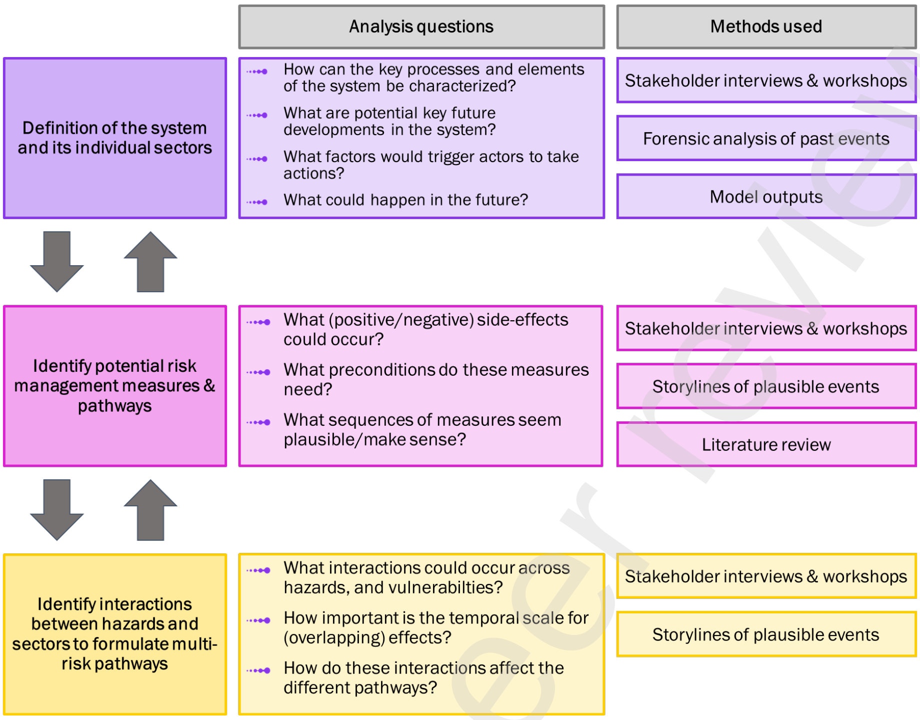


Figure 2: Simplified analysis framework based on DAPP-MR and methods used in the case studies to develop multi-risk DRM pathways in a staged approach.

Within the NSP and CP, the storyline approach was central in exploring and understanding multi-risk systems and cause-and-effect relationships between risk drivers and impacts of past and plausible future events. Storyline development aided in identifying DRM options, interactions, and pathways (Crummy et al., in preparation). A storyline constructs plausible, detailed narratives of past and potential future events to explore risk, uncertainty, and adaptation strategies (Shepherd et al., 2018; Sillmann et al., 2021). Integrating scientific data with contextual factors helps decision-makers understand how different hazards, vulnerabilities, and responses might unfold under specific conditions (e.g., Buskop et al., 2024; Goulart et al., 2021; Marciano et al., 2024). Additionally, the case studies used literature reviews to gain additional insights into the system and its dynamics.

2.2. *Qualifying the benefits of DAPP-MR*

Schlumberger et al. (2022a) reviewed recent multi-hazard and multi-sector literature to identify key elements and dynamics that influence the development and evaluation of DRM pathways for addressing multi-risk. These elements can be grouped into three interrelated themes: (1) effects of multiple interacting hazards, (2) dynamics and interdependencies of sectors, and (3) trade-offs and synergies related to the DRM options. We use these elements and themes to investigate which aspects of multi-risk are generally well covered and which are not. By doing so, we investigate potential white spots of the applied analytical framework to form a multi-risk understanding and results or data required for a comprehensive multi-risk pathway analysis.

We qualify the benefits of DAPP-MR in navigating complexity and learning for DRM based on the observations and experiences of the researchers leading the respective case studies, all of whom are part of the author team of this study. Two or three researchers were responsible for developing the DRM pathways in their case study, further supported by two DRM pathway experts. Intermediate results and stakeholder feedback regarding the pathways development process per case study were captured in confidential project deliverables, which will feed into a final public report (Gottardo et al. *in preparation*). We use these project deliverables, experiences, and discussions within the case study teams.

3. Results

In the following subsections, we will detail the observations and insights from the development process relevant to the three questions of interest on the value of DAPP-MR.

3.1. How DAPP-MR supports the formation of a multi-risk system understanding

All case studies addressed elements of multi-hazard, multi-sector dynamics and interactions across different DRM options to different degrees. Most elements were either considered in or discussed, but ultimately excluded from the analysis (Figure 3; Gottardo et al. *in preparation*). Reasons for exclusion varied, including limited relevance for the analysis or involved stakeholders, or insufficient knowledge and data. Only a few elements were not considered from the start. While multi-sector elements are well captured in the DRM pathways, multi-hazard elements have been more difficult to translate into the policy analysis process. Differences can be observed across the case studies regarding the multi-risk elements related to DRM options.

Some case studies, such as the NSP, discussed the potential of multi-hazard events and incorporated them in their initial system understanding by conceptualizing impact chains and storylines. However, they were disregarded in the further pathways analysis because of a lack of data. While individual hazards are relatively well understood, their interactions remain uncertain, particularly in their cumulative or cascading effects due to limited historical data on multi-hazard events in the North Sea. Consequently, while it was conceptually possible to consider the interactions between multiple hazards, it was difficult for stakeholders to imagine future scenarios of multi-hazard events and understand their consequences. Likewise, the NSP identified that the key driver of multi-risk stems from interactions between different sectoral development actions, while multi-hazard dynamics play a relatively minor role. Similarly, in CIP, stakeholders highlighted drought and volcanic eruptions as key risks, but discussions on their potential interactions, especially cascading or compounding effects, emerged only gradually during the post-eruption recovery process, reflecting both limited data availability and a low baseline awareness of multi-hazard dynamics. In DP, multi-hazard interactions between floods and droughts were discussed but disregarded because of limited information on the statistical relevance of interaction effects between these hazards. A combination of these reasons was identified in SP. As a result, for developing DRM multi-risk pathways, all case studies considered multiple hazards that adversely affect the sectors without accounting for interactions.

Interactions between sectors and their objectives were considered in all case studies. Explicit conflicts regarding limited resources were identified as the main drivers of sectoral interaction in CIP, NSP, and SP. For example, in CIP, allocating the limited water resources used for agriculture, tourism, and residential use is a significant challenge, as decisions in one sector affect the others. By incorporating different future scenario narratives, CIP and NSP acknowledged the dynamics between sectors for limited resources (water and space). In NSP, a set of scenarios assumed an energy-led spatial development of the North Sea, while another set assumed an ecosystem-led spatial development. Likewise, sector-specific scenarios were developed to account for water availability changes and competition across CIP sectors. Conversely, in the SP, stakeholders discussed the power of different sectors due to current political priorities: interactions are mainly determined by decisions in the energy sector, driven by energy transformation-related land use changes affecting agriculture and forestry.

Other elements addressing multi-sectoral dynamics, such as changes in exposure and vulnerability or uncertainties in the relations between sectors, were discussed but not considered in any case study. This was related to insufficient tools and data to make reasonable qualitative assumptions and manage this information throughout the analysis. Impact-related interactions were discussed in various case studies, but were not explicitly considered by most. This was primarily due to the tailored system understanding for analyzing sectoral objectives, which did not exhibit a high degree of cross-sectoral interaction. For example, SP takes the energy sector as the starting point and expands the pathways by considering the different aspects of the measures' interactions with other sectors. It includes the impacts on agriculture and forestry sectors, social acceptance, land use concerns, nature impacts, social security, and resilience to climate shocks. Some case studies add scenarios to account for general socioeconomic and climate-change-related uncertainties. For example, the DP makes assumptions about future ship traffic on the Danube and potential increases in agricultural yields, and the CIP makes assumptions about the future tourism capacity needs in La Palma. In addition, SP incorporates assumptions on different levels of social acceptance toward measures in the energy sector.

Patterns regarding the interaction elements in the context of DRM options are less clear across the case studies. In line with disregarding multi-hazard impact drivers as discussed earlier, DRM options were also not characterized concerning their vulnerability towards multi-hazard interactions in any case study. Conversely, DRM options of different sectors were either already chosen considering their vulnerability to the present hazards (e.g., NSP) or were characterized in general terms concerning the current vulnerability of cases to hydrometeorological hazards (e.g., DP, SP). In DP, synergies and trade-offs between droughts and floods were considered, particularly when identifying measures that enhance resilience to both. Early Warning Systems and Nature-Based Solutions were seen as such measures: Early Warning Systems were highlighted as a no-regret measure that supports preparedness for multiple hazards, while the potential of Nature-Based Solutions to mitigate flood risks and enhance drought resilience was recognized. Similarly, most cases consider trade-offs across sectors, primarily employing additional evaluation criteria when characterizing the methods or because of direct interactions between measures or the sectors (see Section 3.2.3). Uncertainties regarding the effectiveness of DRM options are captured in some of the case studies. In NSP, some effects of measures, especially regarding interaction effects, are marked as uncertain, highlighting that the effects are unknown or context-specific. In contrast, uncertainty regarding the perception is covered only in the SP, where the level of public acceptance was used to differentiate two different sets of scenarios (high vs. lower acceptance towards renewable energies). The effectiveness of measures or uncertainties regarding interactions was considered in the CIP and NSP, in response to a lack of knowledge or conditional performance, for example, determined by technological innovation over the coming decades.

3.2. How helpful DAPP-MR is in navigating complexity

DAPP-MR offers a structured, stage-wise approach to integrating interactions rather than directly building a complex system understanding. Figure 4 summarizes the key development

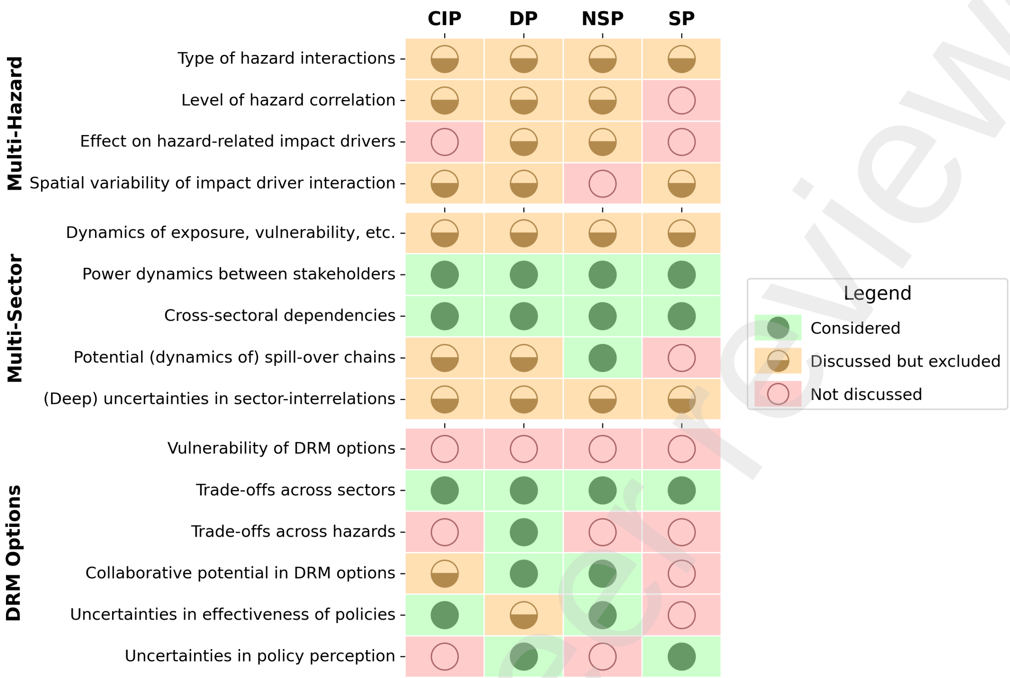


Figure 3: Degree to which certain multi-risk elements were addressed in the different case studies to develop and evaluate multi-risk DRM pathways. CIP: Canary Island Pilot. DP: Danube Pilot. NSP: North Sea Pilot. SP: Scandinavian Pilot.

steps as implemented in the case studies. In the following subsections, we will briefly touch upon the different development phases in the context of navigating complexity.

3.2.1. Defining the system and the sectors

Most case studies spent most of the project time forming and refining their understanding of the system and its sectors. This included formulating a system understanding consisting of different sectors with different short-term challenges and long-term needs based on that understanding. The initial system maps were continuously updated and refined in the case studies during the pathway development process.

The system understanding was built in all case studies, starting from the different sectoral perspectives. In some case studies (CIP, NSP), integrating different sectors into one system understanding started very early. For example, in the Canary Islands as a tourism destination, elements of the agricultural and tourism sectors are tightly intertwined. Similarly, stakeholders in the NSP identified that the primary source of disaster risk comes from the proximity of different sectoral uses of the space. In SP, the importance of the system was also discussed. However, the case study focused primarily on the energy sector because of the identified power dynamics (see Section 3.2.1). Interactions across sectors were thus integrated much later (see Section 3.2.3).

The case studies completed this step in varying timeframes, as shown in Figure 4. Especially in CIP and DP, it took much longer to develop a common understanding of the system and its sectors than for NSP and SP. In CIP, this was mainly caused by the complexity of the tightly interconnected sectors considered. Tourism is a primary driver of change in many other sectors,

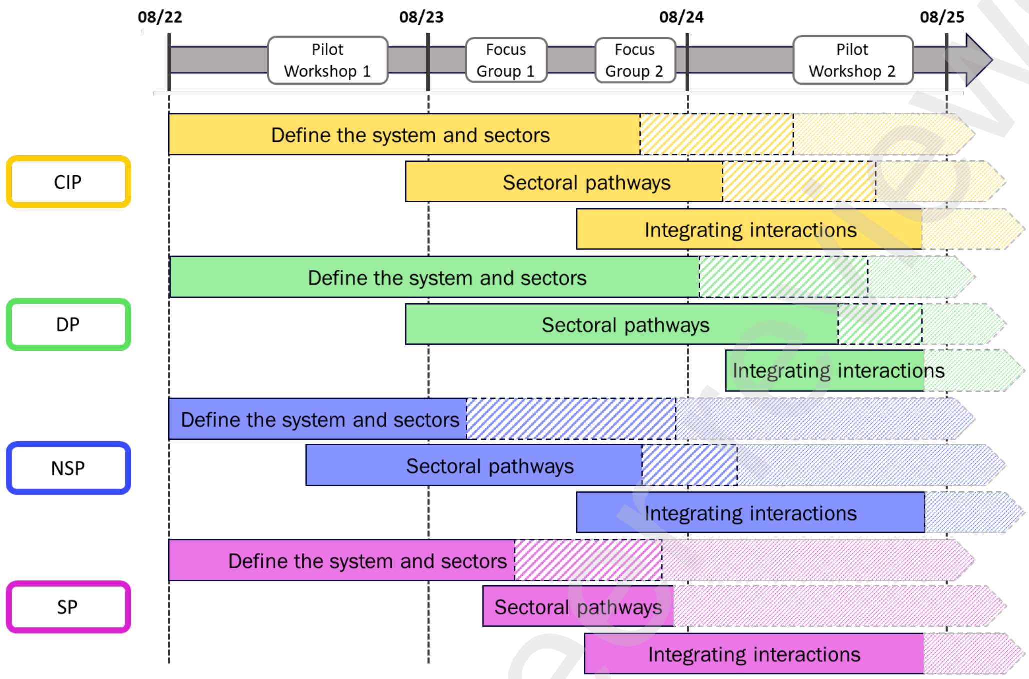


Figure 4: Outline of the staged approach implemented in the different case studies. Hatched bars indicate that only minor revisions have been done in a given analysis step over that period. Note that the common end of the overall development process was due to the deadline for a project deliverable. Hatched arrows indicate that in the future, each step could continue to be refined further.

but also strongly depends on the services and products that other sectors deliver. Capturing this in clear DRM objectives per sector was especially challenging. In DP, a general understanding of the system and sectors was found relatively early. However, there was a significant struggle to identify the scale for the analysis due to spatially diverging characteristics in the large case study area. Similar challenges regarding the scale were encountered in SP, but it could be addressed much faster due to the limited spatial extent of SP compared to DP. In NSP, the period of minor revisions was relatively long because of the significant turnover of the stakeholders involved, which required repeated revision and re-introduction (and thus feedback).

3.2.2. Developing sectoral DRM pathways

In line with DAPP-MR, all case studies identified DRM options to achieve their primary objectives (see Step 2 in Fig. 2). These DRM options were additionally characterized regarding other evaluation criteria relevant to the specific case studies. The case studies used scorecards to summarize the characterizations (see e.g., Figure 5), which were gradually populated. For most case studies (CIP, SP, DP), these evaluation criteria already include references to interactions with other sectors. For example, literature review and expert judgment were used in SP to characterize the cross-sectoral effects of different energy measures. Synergies included integrating renewable energy projects on agricultural lands, using agricultural residues for bioenergy, and promoting agroforestry practices. Trade-offs were identified in the competition for water and land, the potential negative impacts on natural ecosystems, and the economic costs of implementing adaptation measures.

In SP, most pathways were derived from existing long-term strategies of prominent energy sector actors. One additional pathway was developed based on expert knowledge regarding the plausibility/feasibility. On the other hand, NSP, CIP, and DP used narratives to form sectoral pathways - sequences of DRM options. While the NSP used narratives of different technological focus (e.g., energy sector pathways to extend offshore-wind capacity or to prioritize alternative energy sources), DP and CIP used perspective-driven narratives. For example, in CIP, pathways dealing with increasing bed capacity could have a sustainable focus (or not). In all case studies, stakeholders validated and refined the pathways regarding measures used and their sequencing. In CIP, this feedback also resulted in a revision of the evaluation criteria of the DRM options, uncovering criteria that were relevant for stakeholders to characterize their feasibility or plausibility as a short-term measure or long-term option.

Again, some differences regarding the difficulty of this analysis step can be observed across the case studies (Figure 4). In most case studies (CIP, DP, NSP), a similar process was followed to identify and characterize measures, reorganize by reducing the number of measures, and refine the criteria used for the characterization. In particular, the identification of promising sectoral pathways was challenging. Stakeholders, generally unfamiliar with long-term planning, required time to get accustomed to the concept and its implications for their sectors. This resulted in multiple iterations and adjustments of the considered sectoral pathways. A notable exception was SP, where energy companies and the government had already developed long-term strategies for the energy sector, offering relevant measures and some of their characterization.

Measure	Social Acceptance	Nature Impact	Energy Security	Climate Mitigation	Livelihood	Economic Profitability	Resilience to Shocks	Cross-sectoral
N-S Grid Link	1	-1	3	2	1	2	3	1
Offshore Wind	-1	-1	2	3	1	1	2	2
Onshore Wind	-3	-2	2	3	0	3	2	-1
Region Link	1	-1	3	2	1	3	3	1
Extend Store. Cap.	1	-2	2	3	1	2	3	2
Reg. Water Store	2	-1	2	3	1	2	2	1
Solar PV	1	-1	1	2	1	1	2	3
Bioenergy	0	-1	1	1	1	3	2	0

Legend	-3	-2	-1	0	1	2	3

Figure 5: Scorecard listing measures from the energy sector and their aggregate impacts on society, nature, and other criteria that could be considered when implementing such measures in SP. Scores reflect the relative preference for each criterion: higher positive values indicate more favorable evaluations, while negative values indicate less desirable outcomes. For example, a large negative score for costs implies high expense, whereas a negative score for effectiveness suggests poor performance.

3.2.3. *Identifying interactions and multi-risk DRM pathways*

While interactions across hazards and sectors were already iteratively considered in step 1 of the analysis, the case studies investigated the interactions between measures and sectors to develop multi-risk DRM pathways in the third step of this process. While SP used and integrated the interaction effects of the energy sector on other sectors already in their scorecard characterization of the measures (see Section 3.2.2), NSP and DP used interaction matrices to characterize interactions. The NSP case study systematically investigated how measures from one sector influence those in another (see Figure 6). Each combination was examined to identify pairs of measures that have positive, negative, uncertain, or no effects on each other. For example, opening wind farms for shipping generally increases risks for the energy sector due to the increased possibility of collisions of ships with energy infrastructure in case of low-maneuverability conditions. The increased shipping traffic might also prevent/limit specific measures related to alternative energy sources and hydrogen production because of the space demand.

The matrix represented an initial step toward developing multi-sector pathways by summarizing the general potential for interaction between sectoral measures and those of other sectors. Interactions across different pathways were identified based on specific subsets of sectoral measures. This made it possible to highlight pathways with greater synergy potential or higher risk of trade-offs, helping to identify promising combinations of sectoral pathways. As shown in Figure 7b, the selected combination of the best-performing sectoral pathways (highlighted in blue in the first column) does demonstrate some degree of synergy, but not the highest possible. This raises important questions: Should sectors choose a different sectoral pathway to maximize synergistic effects, even if it slightly compromises direct individual sector performance? Alternatively, should one sector be encouraged to modify its pathway to improve the overall synergy? As some interactions remain uncertain, it also opens the question regarding key knowledge gaps and possible context-specific interaction potential.

Target of interaction / Acting measure	Shipping	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S11	S12	Energy	E1	E2	E3	E4	E5	E6	E7	E8	E9	E10	Nature	N1	N2	N3	N4	N5	N6	N7	N8	N9	N10
S1. Sensors in windfarm														+	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
S2. Better surveillance by coastguard														+	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
S3. Training of crew														+	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
S4. Increase towing capacity														+	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
S5. Opening windfarms for shipping														-	0	0	0	0	0	0	0	-	-	0	?	?	?	0	0	0	0	0	?	?	0
S6. Marine traffic system														+	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
S7. Increase designated clearways														?	0	0	0	0	0	0	0	?	0	0	0	-	0	0	0	0	0	0	0	0	0
S8. Increase safety zones around built infrastructure														?	0	0	0	0	0	0	0	-	-	0	0	0	0	0	0	0	0	0	0	?	0
S9. Increase seperation zones between shipping lanes														-	0	0	0	0	0	0	0	-	0	0	0	0	0	0	0	0	0	0	0	0	0
S10. More manoeuvrable ships														+	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
S11. Smaller ships														+	0	0	0	0	0	0	0	0	0	0	?	0	0	0	0	0	0	0	0	0	0
S12. Bigger ships														?	0	0	0	0	0	0	0	0	0	0	?	0	0	0	0	0	0	0	0	0	0

Figure 6: Cross-sectoral Risk Management Matrix for the three North Sea sectors. Green "+": measure positively influences another. Red "-": measure adversely impacts another. Yellow "?": effects of a measure are still uncertain. "0": measure has no significant positive or negative effect on another.

A similar approach was applied in the DP, where interactions between DRM options across sectors were first identified using a matrix similar to NSP and a chord diagram. Unlike the NSP, DP did not focus on the effect on performance evaluation using a scorecard method but on the pathway timings (see Figure 8). During Focus Group 2, expert calibration revealed challenges in gathering feedback on pre-developed pathways. Instead, stakeholders favored co-developing sectoral pathways in parallel, drawing on a complete understanding of interactions between the

a) Single-sector pathways evaluation

Nature	Effectiveness for reaching objectives	Cost	Impact on maritime space	Regret
Waste & Runoff Reduction	6	-2	-1	-4
Nature Enhancement	7	-3	-1	-5
Local Nature Protection	7	-3	-2	-6

Energy	Effectiveness for reaching objectives	Cost	Impact on maritime space	Regret
Wind Energy Focus	8	-9	3	-7
Diverse Energy Mix	5	-9	2	-6
Offshore Wind Expansion	8	-11	1	-6

Shipping	Effectiveness for reaching objectives	Cost	Impact on maritime space	Regret
Surveillance & Policy Measures	6	-7	-1	-7
Spatial Policy Measures	7	-6	-3	-10
Surveillance & Windfarms	9	-11	0	-11

b) Evaluation of effects of pathways cobinations

Combinations	Effects on Nature	Effects on Energy	Effects on Shipping	Uncertainty
Waste & Runoff Reduction || Offshore Wind Expansion || Surveillance & Windfarms	2	4	1	3
Nature Enhancement || Offshore Wind Expansion || Surveillance & Windfarms	2	4	1	4
Local Nature Protection || Offshore Wind Expansion || Surveillance & Windfarms	1	4	1	4
Waste & Runoff Reduction || Wind Energy Focus || Surveillance & Windfarms	2	3	1	6
Nature Enhancement || Wind Energy Focus || Surveillance & Windfarms	2	3	1	7
Local Nature Protection || Wind Energy Focus || Surveillance & Windfarms	1	3	1	7
Local Nature Protection || Offshore Wind Expansion || Surveillance & Policy Measures	2	2	1	1
Waste & Runoff Reduction || Offshore Wind Expansion || Surveillance & Policy Measures	2	2	1	2
Nature Enhancement || Offshore Wind Expansion || Surveillance & Policy Measures	2	2	1	2
Local Nature Protection || Wind Energy Focus || Surveillance & Policy Measures	2	1	1	2
Waste & Runoff Reduction || Wind Energy Focus || Surveillance & Policy Measures	2	1	1	3
Waste & Runoff Reduction || Offshore Wind Expansion || Spatial Policy Measures	2	1	1	3
Nature Enhancement || Wind Energy Focus || Surveillance & Policy Measures	2	1	1	3
Nature Enhancement || Offshore Wind Expansion || Spatial Policy Measures	2	1	1	3
Local Nature Protection || Offshore Wind Expansion || Spatial Policy Measures	1	1	1	2
Waste & Runoff Reduction || Wind Energy Focus || Spatial Policy Measures	2	0	1	4
Nature Enhancement || Wind Energy Focus || Spatial Policy Measures	2	0	1	4
Local Nature Protection || Wind Energy Focus || Spatial Policy Measures	1	0	1	3
Waste & Runoff Reduction || Diverse Energy Mix || Surveillance & Windfarms	1	2	-1	8
Nature Enhancement || Diverse Energy Mix || Surveillance & Windfarms	1	2	-1	9
Local Nature Protection || Diverse Energy Mix || Surveillance & Windfarms	0	2	-1	9
Local Nature Protection || Diverse Energy Mix || Surveillance & Policy Measures	1	-1	0	4
Waste & Runoff Reduction || Diverse Energy Mix || Surveillance & Policy Measures	1	-1	0	5
Nature Enhancement || Diverse Energy Mix || Surveillance & Policy Measures	1	-1	0	5
Waste & Runoff Reduction || Diverse Energy Mix || Spatial Policy Measures	1	-2	0	7
Nature Enhancement || Diverse Energy Mix || Spatial Policy Measures	1	-2	0	7
Local Nature Protection || Diverse Energy Mix || Spatial Policy Measures	0	-2	0	6

Figure 7: Scorecard-based evaluation of sectoral pathways in the NSP (a) and investigating combinations of pathways with the least trade-offs regarding the three sectors and uncertain interaction effects (b). Scores reflect the relative preference for each criterion: higher positive values indicate more favorable evaluations, while negative values indicate less desirable outcomes. The pathway combination highlighted in blue in the first column represents the best-performing sectoral pathways when not accounting for interactions.

shipping and agricultural sectors. Key considerations included governance, financing, and cross-sector dependencies. Parallel implementation was explored where beneficial, particularly for enabling conditions like Early Warning Systems and cross-border cooperation. The discussions also surfaced potential medium- to long-term land-use conflicts for implementing the DRM option.

In the SP, the analysis of interactions of pathways did not focus on the interactions between the DRM options for energy and other sectors. Instead, it was more broadly informed by an integrated system understanding and the cross-sectoral interactions of DRM in Norway. As such, interactions were discussed more qualitatively and broadly per measure in a specific pathway (see Figure 9 for an example). It raises awareness that effective DRM at a national scale should be implemented in a multi-dimensional perspective. Rather than focusing on the interactions between specific measures, the SP potentially makes the approach more accessible and user-friendly for stakeholders.

In the CIP, measures regarding the effects on limited resources (water budget) relevant to multiple sectors were characterized. The effects of all measures were quantified either in absolute terms (e.g., how much water consumption a hotel with an additional 2,000 beds would contribute) or in relative terms (e.g., how much water could be saved by installing water-saving fixtures). While these numbers appealed to stakeholders to make the measures and the interactions more practical, it turned out to be quite challenging to build pathways and the interactions across pathways purely qualitatively. Instead, the case study combined the quantitative effects of the measures to determine the implementation timing under different climate scenarios with and without interactions across sectors (see Figure 10). This visualization helped investigate the expected lifetime of implemented DRM options, depending on whether only climate-driven reduction in the available water budget was considered or whether this reduction was compounded with

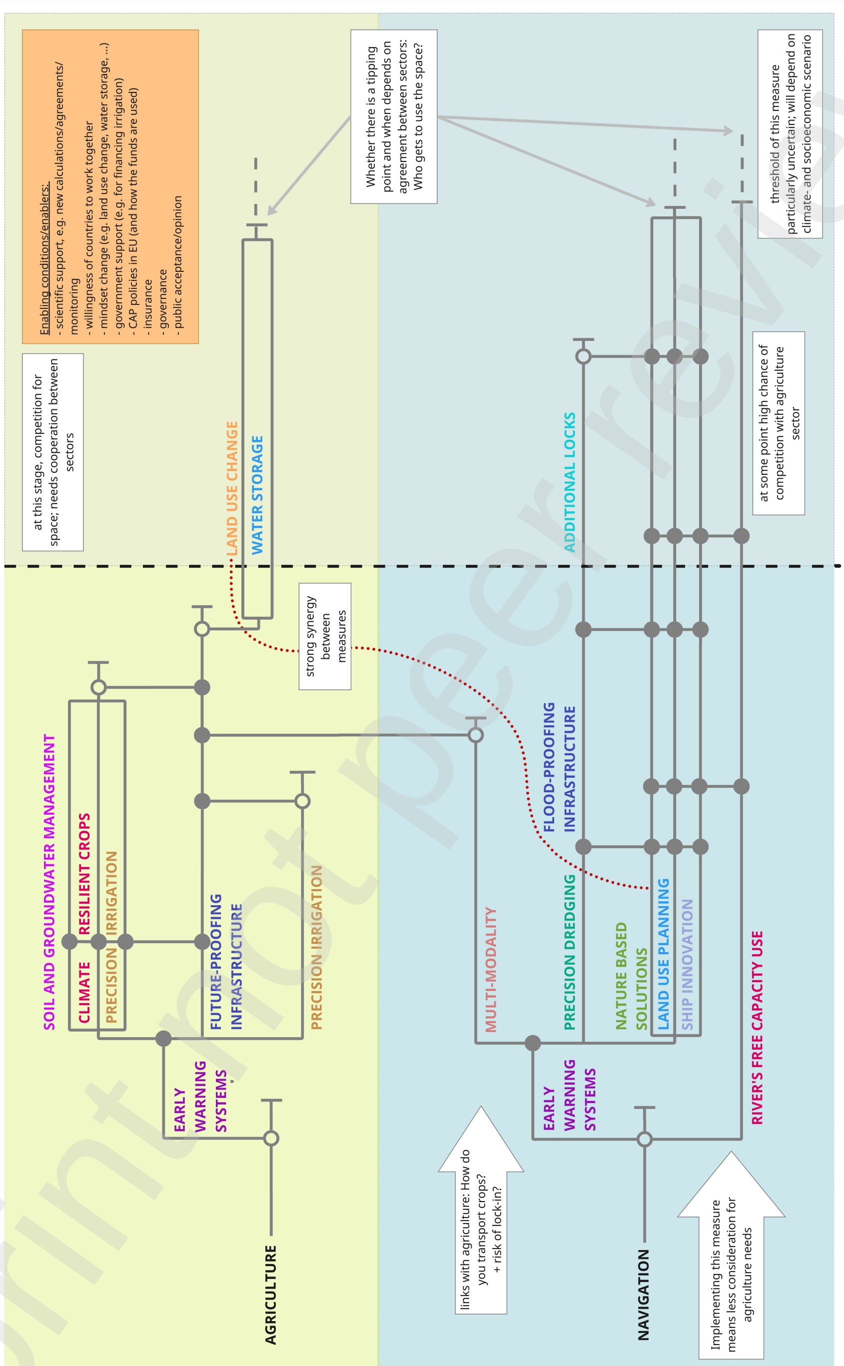


Figure 8: Final set of multi-risk DRM pathways developed for the agriculture and shipping sector in DP.

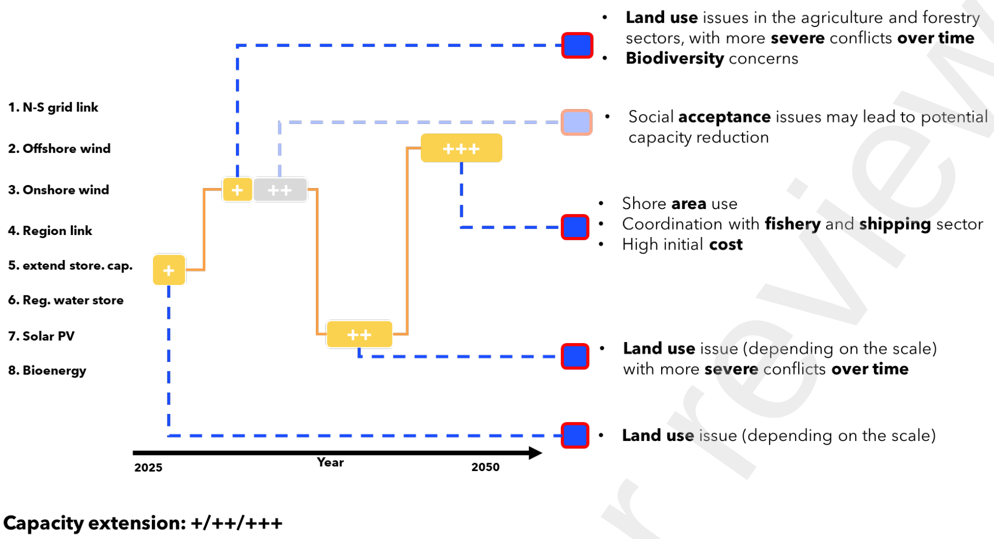


Figure 9: Interaction analysis for measures in a specific energy pathway regarding the agriculture and forestry sectors and various other aspects.

specific pathways to meet the bed capacity requirements. In that way, the impacts of different bed capacity strategies were made explicit, discussing whether pathways could meet the sectoral interests with less adverse effects regarding water demand. Similarly, stakeholders discussed which water demand seemed more plausible regarding the required timing of implementation of new DRM options. Finally, the visualisations could be used to discuss the trade-offs between tourism's consumption of local water resources and agricultural production, especially under scenarios where no additional interventions are introduced to alleviate future water scarcity.

3.3. What we can learn from applying DAPP-MR for DRM

Applying the DAPP-MR framework across the four case studies provided valuable insights into its role in strengthening DRM. Overall, the approach was recognized as a helpful tool for raising awareness and sparking dialogue around key issues: the need for long-term planning, cross-sectoral cooperation, transboundary risk management, and the synergies and trade-offs of DRM measures. It was recognized for its flexibility in working across different scales and challenges, offering inspiration and ingredients for the analysis while still allowing tailoring to the specific context.

In all case studies, DAPP-MR enabled more integrated, cross-sectoral thinking. Engaging diverse stakeholders and gathering feedback on interim results facilitated dialogue among actors who did not collaborate before. In CIP, it helped structure discussions between the tourism and agriculture sectors, revealing how sectoral pathways interact under resource scarcity and uncovering governance gaps, particularly between water planning and risk reduction. This underscored the importance of anticipating sectoral conflict before hazards emerge. In DP, the process increased awareness of interdependencies across hazards, sectors, and scales, which is crucial in the Danube's complex transboundary context. New stakeholder networks for ongoing collaboration have been formed in the NSP, where DRM awareness is limited.

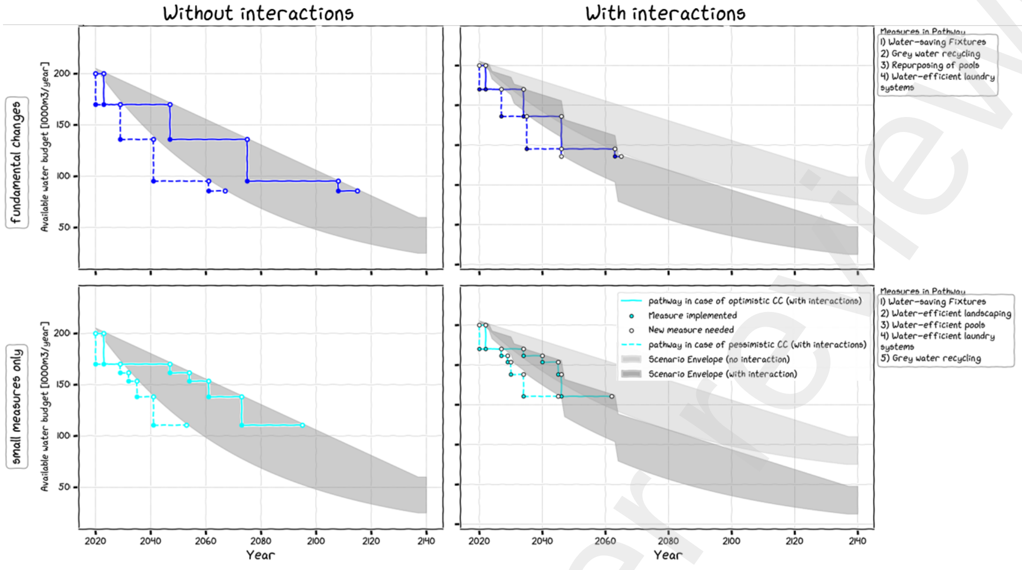


Figure 10: Exploration of the timing of two different pathways to reduce water consumption in the tourism sector (rows) without interactions (left column) and when accounting for the effects of one specific pathway to increase bed capacity (right column). Without interactions, the timing is mainly determined by the remaining available water budget driven by climate uncertainty (represented by the grey envelope in the left column). With interaction effects, the additional use of water resources linked to policies to increase the bed capacity combines with the climate-driven decline in water resources, resulting in sudden jumps in the scenario envelope, driving the solution space for the water reduction strategies.

The framework also fostered a shared understanding of multi-risk systems, emphasizing the interconnections between hazards, sectors, and DRM options. Stakeholders, especially in DP, actively discussed strategy synergies and trade-offs, ultimately co-developing sectoral pathways in parallel to balance opportunities and potential conflicts. Similar solution-oriented dialogues occurred across all case studies. CIP shifted from reactive, sector-specific approaches to integrated, anticipatory DRM. By examining tourism and agriculture under uncertainty, the pathways revealed system vulnerabilities, resource conflicts, and tipping points, enabling local authorities to align policies better, prioritize early action, and coordinate governance. Similarly, dialogue and learning occurred across sectoral boundaries and between different actors, including government authorities, non-governmental organizations, researchers, and private sector actors. Engaging this wide array of stakeholders was seen as very helpful for the analysis process.

DAPP-MR further supported long-term adaptive planning by helping stakeholders align short-term priorities with long-term goals. Most case studies translated DRM narratives (e.g., "business as usual" or "technical solutions") into two to five sector-specific DRM pathways. In SP, pathways reflected energy companies' existing strategies, complemented by an expert-informed, integrated scenario, which allowed the outcomes of the pathways analysis to be linked to ongoing discussions about energy transformation strategies. In CIP, the framework helped to put DRM in its broader context, allowing for the integration of the short-term DRM needs with long-term sustainability challenges of the tourism destination. All case studies underscored the value of scenario-based thinking for managing future uncertainty. In addition to climate-related scenarios, each case study introduced a second dimension: social perceptions (SP), spatial planning priorities (NSP, SP), external decision-making (CIP), or broader socio-economic uncertainties (DP). Across multiple case studies, the value of identifying and discussing the uncertainty in the effectiveness of different DRM measures, along with the task to extend the set of possible DRM solutions outside the typical narrow perspective, was perceived as very useful.

4. Discussion

In this study, we applied the DAPP-MR framework in four qualitative case studies to assess its value in developing multi-risk pathways. Our findings highlight the framework's capacity to foster integrated system understanding, support strategic thinking, and navigate complexity in DRM. Across all cases, DAPP-MR served as a helpful guiding structure. Multi-sector interactions were effectively captured, whereas multi-hazard dynamics remained less developed, primarily due to limited stakeholder awareness, data constraints, and insufficient analytical tools. The overall process flow where the case study teams developed intermediate results and then further updated and refined them based on feedback from stakeholders seemed adequate for the application context of multi-risk DRM pathways - a theme still emerging within the research community (Brett et al., 2025; Šakić Trogrlić et al., 2024).

The staged approach of DAPP-MR enabled the gradual refinement of analytical focus and adaptation to system complexity, resulting in diverse emphases across the cases. Focusing on DRM options helped streamline the analysis of sectoral interactions without overcomplicating the process. While the development of pathways was demanding, stakeholders found the process valuable and insightful for exploring future DRM strategies, as reported in other studies as well (Haasnoot et al., 2024; Werners et al., 2021). Similar to findings in other pathway development studies, difficulties arose in aligning scales, defining clear objectives, and selecting appropriate policy options (Bosomworth et al., 2017). Issues of scale were particularly pronounced. For example, in DP, it was challenging to generalize system elements across regions with different land-use patterns, governance structures, and planning priorities. Stakeholders emphasized that the choice of scale critically influences the identification of DRM measures and the assessment of interactions. For example, adaptation in agriculture proved highly context-specific, complicating efforts to identify general synergies or trade-offs between sectors.

4.1. The value and challenge of co-production and local stakeholder engagement for multi-risk DRM pathways development

The case studies underscored the critical role of stakeholder engagement in developing multi-risk DRM pathways. Feedback moments were essential for aligning assumptions, substantiating multi-risk knowledge, revealing oversimplifications and uncertainties, and guiding the direction of analysis. As discussed in Section 3.3, qualitative applications of DAPP-MR proved valuable for learning, capacity-building, and cross-sectoral knowledge exchange. The structured yet flexible nature of the pathway-development process functioned as a powerful tool for cross-sectoral learning, like a structured brainstorming session, encouraging shared exploration of interdependencies between hazards, sectors, and DRM options. As the outcomes of the analysis show, especially when comparing Figures 7 to 10, the directions and angles that can be used for the pathways development process are manifold. It is reassuring that DAPP-MR offered the flexibility for such diversity, given the broad field of aspects that could be captured for an analysis of multi-risk DRM. Some, like SP and NSP, framed their work around development challenges, such as expanding energy production, which were influenced by decisions in other sectors or broader socio-environmental uncertainties. Others, like CIP and DP, focused more explicitly on DRM strategies in response to climate change. This diversity suggests that DAPP-MR's ability to integrate complexity across governance levels, sectors, and types of risk may have relevance beyond DRM, particularly in the context of climate-resilient development (Schipper et al., 2022) or cross-boundary collaboration (Carter et al., 2021).

At the same time, it reflects a well-documented issue of comparability across applications due to the subjectivity in qualitative methodologies (Denzin and Lincoln, 2011). As shown in Section 3.1, each case study followed a distinct focus and set of priorities, shaped by the composition and engagement of its stakeholder group. While the process involved operational experts from key sectors, decision-makers with formal mandates for DRM or long-term planning were less frequently engaged. As a result, the involved stakeholders provided in-depth practical knowledge about the different sectors. They used the analysis process for knowledge sharing and learning. In contrast, the consideration of strategic decisions and direct impacts of the analysis outcomes on the sectoral decision-making was less central in the discussions. A key consideration for future efforts thus needs to be identifying and engaging organizations with long-term planning mandates and cross-sectoral responsibilities to embed the DAPP-MR process within the relevant sectoral and institutional contexts and set up together with representative stakeholders (Reed, 2008; Stringer et al., 2006; Stanton and Roelich, 2021). As a result, the analysis focus might shift, different forms of engagement might be needed, and different needs and potential for co-production and institutional continuity might arise (Klenk et al., 2017). However, if receiving sufficient attention and interest, what starts as a brainstorming and learning exercise can turn into real-world practice of DRM pathways, as examples from New Zealand show (Lawrence and Haasnoot, 2017; Lawrence et al., 2025).

4.2. The need for an appropriate toolbox

Qualitative applications of DAPP-MR in practice require a more extensive and integrated set of tools to support its operationalization - a common theme across policy analysis approaches for decision-making under uncertainty (Schlumberger et al. *in preparation*; Stanton and Roelich, 2021). Especially in Section 3.1, we show that some aspects of multi-risk dynamics, mainly linked to multi-hazard interactions, were only considered to a certain extent. While the lack of prior experience with such dynamics probably contributed to this bottleneck (van Maanen et al. *in preparation*), the tools and methods used to generate, collect, or structure relevant data did not yet appear fully equipped to inform multi-risk DRM. While storylines and impact chains were used to untangle the dynamics of specific events and could thus help to form a better understanding of the interaction effects (Crummy et al *in preparation*), other tools that allow for more systematic identification and mapping of multi-hazard events, such as methods developed by Claassen et al. (2023, 2025) were not applied. They are not yet tailored for qualitative application for multi-risk DRM pathways, for example, through easy-to-use visualisations or the capacity to consider future climate change uncertainty. Integrating such tools into DAPP-MR processes could help stakeholders better grasp the potential impact and risk arising from multi-hazard interactions. The latter can help judge the importance of considering multi-hazard events for long-term DRM decision-making. However, beyond identification of multi-hazard occurrence, a policy analysis framework like DAPP-MR requires tools that capture the impacts and dynamic interactions triggered by these events, particularly through shifts in vulnerability or systemic feedbacks. Here, impact chains (Zebisch et al., 2021), storylines or other process-oriented methods (e.g., de Polt et al., 2023, Buijs et al. *in preparation*) could serve as valuable starting points for more structured, yet stakeholder-accessible, tools. Similarly, tools developed for spatial analysis (e.g., van de Ven et al., 2016) offer promising leads, but their use for multi-risk challenges is still in progress (Langendijk et al. *in preparation*). Finally, while scenarios were used in this study to explore future change and uncertainty, most case studies did not implement a complete scenario-based planning process. Tools like the updated version of the Pathways Generator, which helps visualize and develop pathways under different scenarios, may offer significant value, especially in helping navigate the complexity of timing and tipping points and measuring interactions across diverse scenarios.

In addition to these identified gaps, there are opportunities to offer a collection of similar or different methods that could be used to implement each step of the DAPP-MR process. Our findings highlight the diversity in how interaction analyses were conducted, showcasing the richness of integrated system understanding and the multiple approaches available for addressing multi-risk. For example, collaborative system mapping was a key element in most case studies, yet the comparative strengths of different mapping techniques remain underexplored in the context of multi-risk. Testing different approaches, such as those reviewed by Warren et al. (2023), and reflecting on their differences regarding stakeholder engagement, focus, and system characterization, could offer a nuanced set of tools more flexible and supportive for a wide range of application contexts. Similarly, while this study's identification and prioritization of DRM options relied on narratives and expert inputs, other tools could offer additional guidance. For example, the Peer Review Assessment Framework for Disaster Risk Management tool (PRAF, Casartelli et al., 2025), applied in the Veneto pilot of MYRIAD-EU (Casartelli et al., *in preparation*), offers a structured approach for option identification and development around the DRM cycle, as well as key areas such as disaster risk governance, risk assessment, and DRM planning. It enables the identification of a coherent and comprehensive set of possible DRM options that could provide valuable insights for developing multi-risk DRM pathways.

5. Outlook

This study applied the DAPP-MR framework in four qualitative case studies to assess its value for multi-risk DRM pathways development. The findings demonstrate that DAPP-MR is a valuable addition to the existing landscape of risk assessment and decision-support approaches. Its particular strength is designing adaptive policy strategies under multi-risk and future uncertainty conditions. By emphasizing the evaluation of DRM options and their potential synergies and trade-offs, stakeholders in the different case studies recognized that DAPP-MR fills a methodological gap in how complex and uncertain risk environments can be addressed strategically. Taken together, the findings from this study suggest that DAPP-MR should not be seen as a replacement for existing approaches, but rather as a strategic complement.

Looking ahead, informing real-world DRM decisions and climate adaptation planning will require further development of tools to support the different steps of the DAPP-MR framework across diverse data and institutional contexts. In addition, future research could focus on building on the findings developed in the case studies. These could serve as a foundation for more refined analyses like quantitative pathways assessment and development, or for continued learning and co-production activities within the involved sectors. Such follow-up work could be used in future iterations of the case studies' pathways development process to refine their scope, DRM options, and evaluations of pathways. It could furthermore help assess the transferability and practical relevance of the DAPP-MR. It would also deepen the integration of multi-risk dynamics and pathway-thinking into ongoing decision-making processes.

Acknowledgement

This work was supported by the MYRIAD-EU project, which has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 101003276. MCdR was also supported by the Netherlands Organisation for Scientific Research (NWO) (VENI; grant no. VI.Veni.222.169), and JCJHA by the COASTMOVE ERC Grant (Grant No. 884442). TLFA and SGG acknowledge support from ACIISI – the Canary Islands Agency for Research. We sincerely thank all stakeholders and partner organizations, more than 100 in total, who contributed their time, insights, and expertise across the various case studies. Their engagement was essential to the work presented in this publication.

Author contribution

Julius Schlumberger: Conceptualisation, Data Curation, Formal Analysis, Investigation, Methodology, Project Administration, Visualization, Writing - Original Draft, Writing - Review & Editing. **Andrew Warren**: Formal Analysis, Investigation, Project Administration, Writing - Review & Editing. **Anne Sophie Daloz, David Geurts, Stefan Hochrainer Stigler, Lin Ma, Noemi Padrón-Fumero, Karina Reiter, Robert Šakić Trogrlić, Sharon Tatman**: Conceptualisation, Formal Analysis, Investigation, Project Administration, Visualization, Writing - Original Draft, Writing - Review & Editing. **Vanessa Banks, Julia Crummy, Jaime Díaz-Pacheco, Pedro Dorta Antequera, Sara García-González, Abel López-Díez, Tamara Lucía Febles Arévalo, David Romero-Manrique, Nikita Strelkovskii, Asbjørn Torvanger**: Investigation, Writing - Review & Editing. **Silvia Torresan, Veronica Casartelli, Roxana Ciurean**: Project Administration, Writing - Review & Editing. **Judith N. Claassen**: Conceptualisation, Writing - Review & Editing. **Jeroen C.J.H. Aerts, Marjolijn Haasnoot, Marleen C. de Ruiter**: Conceptualization, Supervision, Writing - Review & Editing.

Appendix A. Overview of key stakeholder engagement activities and stakeholder profiles

We provide comprehensive information on the various stakeholders present during the key stakeholder engagement activities. We distinguish between organizational affiliations, stakeholder types, governance levels, and thematic focus.

The diversity of participating stakeholders reflects a broad spectrum of organizational affiliations. Public institutions played an important role in the case studies, including government departments at the local, regional, and national levels, often responsible for policymaking, planning, and the delivery of public services. Academic and research institutions were also represented, providing scientific and technical expertise in various thematic areas. Private sector participation was broad, ranging from individual consulting institutions and service providers to infrastructure operators and industry associations. Civil society perspectives were brought to the table by non-governmental and community organizations, often anchored in advocacy, local development, or thematic responsibility (e.g., environmental protection or sustainable agriculture). In some cases, intergovernmental and transnational actors representing regional cooperation platforms or global institutions also participated.

Participants represented a wide range of functional roles within governance and decision-making systems. Some had formal authority to develop, coordinate, or regulate policy frameworks, while others were responsible for implementing programs, managing infrastructure, or providing technical services. Strategic insights and technical knowledge came from both consultants and academic researchers. Industry associations shared common perspectives of specific sectors or professional groups. Community organizations and interest groups brought local voices, social values, and thematic priorities such as equity or sustainability into the analysis process.

Stakeholders represented various governance levels. Local actors typically addressed place-specific needs and implementation challenges, often related to urban resilience, tourism development, or municipal services. Regional stakeholders often had responsibilities for coordination on subnational issues such as resource management or infrastructure planning. National institutions brought sectoral oversight and policy coherence to the discussion, while transnational actors, particularly in macro-regional contexts, provided insights into cross-border coordination.

The actors contributed knowledge and experience from a broad range of issues. This included sector-specific expertise in areas such as energy systems, tourism development, agriculture, marine policy, and water resource management, as well as cross-cutting issues such as climate adaptation, environmental risks, and sustainable development. Some actors brought deep specialization in specific policy areas or technical systems, while others contributed integrative or interdisciplinary perspectives. Thematic diversity reflected not only the structure of the systems involved but also the interconnectedness of the risks addressed.

Table A.1: Overview of stakeholder engagement activities contributing to the pathways development process in the different case studies, including stakeholder profiles. The number in brackets represents the number of organizational affiliations represented during the activities. Participant numbers (#) and profiles exclude pilot lead teams.

Case	Event	Activity	Stakeholder Profiles	#	Date
CIP	PW1	Understanding system (challenges and opportunities linked to multi-risk, direct, and indirect impacts)	**Governmental Agencies (7).** Policy-makers and implementers at regional and national levels, covering environmental policy and planning, civil protection and emergency management, water resource management, tourism promotion, science and innovation, and electricity infrastructure governance. **Non-governmental Organizations (3).** Implementers and community organizations at the regional level, covering rural and agricultural development, agriculture and livestock, agroecology, and ecosystem stewardship. **Private Sector Actors (6).** Industry associations, service providers, and advisors at regional and national levels, covering hospitality and tourism, regional air transport, water supply and sanitation services, energy generation and distribution, and energy transition and sustainability. **Academic and Research Institutions (2).** Researchers at the regional level, covering volcanology and geophysical research, sustainable tourism, and economic development.	22	11/22
CIP	FG1	Understanding system (sectoral causal relations and interconnections between sectors); Understanding sectors (objectives, drivers of change); Identifying and characterizing DRM options for one sector	**Governmental Agencies (5).** Policy-makers, implementers, and infrastructure operators at regional and national levels, covering water resource management, environmental planning, emergency management and civil protection, electricity transmission, and grid management. **Non-governmental Organizations (3).** Implementers, community organizations, and industry associations at the regional level, covering community energy and renewable transition, agroecology and ecosystem stewardship, and agriculture and agri-food production. **Private Sector Actors (7).** Industry associations, service providers, producer cooperatives, and advisors at regional, national, and international levels, covering water supply and sanitation, energy generation and distribution, agricultural production and marketing, hospitality and tourism, water risk assessment, and tourism risk management. **Academic and Research Institutions (1).** Researchers at the regional level, covering sustainable tourism and economic development.	20	11/23

Case	Event	Activity	Stakeholder Profiles	#	Date
CIP	FG2	Understanding system (scale, objectives); Identifying and characterizing DRM options and interactions; Developing sectoral DRM pathways; Investigating interactions between sectoral DRM pathways	**Governmental Agencies (3).** Implementers, researchers, and infrastructure operators at regional and national levels, covering environmental planning and project execution, atmospheric and climate research, electricity transmission, and grid management. **Private Sector Actors (4).** Industry associations and service providers at regional and national levels, covering hospitality and tourism, water supply and sanitation, energy generation and distribution, and agriculture and agri-food production. **Academic and Research Institutions (1).** Researchers at the regional level, covering agricultural research and food justice.	11	05/24
CIP	PW2	Developing sectoral DRM interactive pathways; Investigate pathway narratives and visualization effectiveness	**Governmental Agencies (4).** Policy-makers, implementers, and infrastructure operators at regional and national levels, covering water management and infrastructure planning, tourism promotion, and electricity transmission and grid management. **Non-governmental Organizations (2).** Implementers and community organizations at the regional level, covering rural and agricultural development, agroecology, and ecosystem stewardship. **Private Sector Actors (3).** Industry associations and service providers at the regional level, covering agriculture and agri-food production, water supply and sanitation services, and hospitality and tourism.	13	03/25
DP	PW1	Understanding system (challenges and opportunities linked to multi-risk, direct, and indirect impacts)	**Governmental Agencies (7).** Policy-makers, technical bodies, and coordinators at national, transnational, and international levels, covering road infrastructure, transport safety, environmental risk management, river basin management, civil protection, and regional policy integration. **Non-governmental Organizations (2).** Research and network organizations at transnational and international levels, covering seismology and early warning systems, and integrated water resources management. **Intergovernmental Organizations (2).** Policy-makers and facilitators at the international level, covering science and education cooperation, climate, meteorological services, and disaster risk reduction. **Academic and Research Institutions (2).** Researchers at national and transnational levels, covering disaster risk reduction, transport infrastructure, and emergency preparedness.	12	11/22

Case	Event	Activity	Stakeholder Profiles	#	Date
DP	FG1	Understanding system (interconnectedness between countries and sectors, relevance of future uncertainty); Understanding sectors (drivers of change, causal relations, sectoral objectives); Identifying and characterizing DRM options for one sector	**Governmental Agencies (2).** Policy coordination bodies at the transnational level, covering strategic planning, environmental risk management, and disaster resilience. **Non-governmental Organizations (1).** Networks at the transnational level, covering integrated water resources management.	3	11/23
DP	FG2	Understanding system (scale, objectives); Developing sectoral DRM pathways	**Governmental Agencies (3).** Policy-makers, coordination bodies, and infrastructure operators at transnational and national levels, covering regional planning, river basin management, and inland waterway transport. **Non-governmental Organizations (1).** Networks at the transnational level, covering integrated water resources management. **Academic and Research Institutions (1).** Researchers at the national level, covering environmental science, agriculture, and water management.	10	05/24
DP	PW2	Developing sectoral DRM pathways; Investigate interactions between sectoral DRM pathways	**Governmental Agencies (2).** Policy-makers and coordination bodies at the transnational level, covering strategic planning, regional integration, and river basin management. **Non-governmental Organizations (1).** Networks at the transnational level, covering integrated water resources management.	6	03/25
NSP	PW1	Understanding system (challenges and opportunities in the North Sea, multi-hazard events, impact-based storylines)	**Governmental Agencies (1).** Policy-makers and implementers at the national level, covering the marine environment, fisheries, offshore energy policy, maritime technology, and engineering. **Private Sector Actors (1).** Advisors at the international level, covering risk management, insurance, and resilience financing. **Academic and Research Institutions (1).** Researchers at the national level, covering energy systems, wind power, and climate adaptation.	3	11/22

Case	Event	Activity	Stakeholder Profiles	#	Date
NSP	FG1	Understanding sectors (main hazards per sector, impacts under future climate); Understanding system (sectoral interactions)	**Governmental Agencies (1).** Researchers at the national level, covering maritime technology and offshore engineering. **Non-governmental Organizations (2).** Advocacy and implementer organizations at national and international levels, covering marine conservation, nature protection, and wetland conservation with a focus on nature-based solutions . **Private Sector Actors (1).** Industry associations at the national level, covering offshore wind energy and renewable policy. **Academic and Research Institutions (1).** Researchers at the national level, covering energy systems, wind power, and climate adaptation.	5	12/23
NSP	FG2	Understanding sectors/the system (causal relations, hazard impact chains); Identifying and characterizing DRM options and measure interactions	**Non-governmental Organizations (1).** Advocacy and research organizations at the international level, covering wetland conservation and nature-based solutions. **Private Sector Actors (2).** Advisors and industry associations at international and national levels, covering risk management, insurance, and offshore wind policy. **Academic and Research Institutions (1).** Researchers at the national level, covering energy systems, wind power, and climate adaptation.	5	05/24
NSP	PW2	(Joint workshop with SP): Presentation of a preliminary version of the pathways; feedback from different sectors in Nordic countries.	**Stakeholders based in the North Sea context:** **Governmental Agencies (2).** Policy-makers at local and national levels, covering urban governance and coastal resilience, and agriculture, nature conservation, and marine governance in the Netherlands. **Non-governmental Organizations (2).** Advocacy and implementer organizations at the national level, covering marine conservation, sustainable seas, wetland conservation, and nature-based solutions. **Academic and Research Institutions (2).** Researchers at the national level, based in the Netherlands and Finland, covering maritime studies, energy transition, applied research, and environmental monitoring. **Stakeholders beyond the North Sea context:** **Private Sector Actors (1).** Service providers at the international level, covering energy production, transition, and climate risk. **Academic and Research Institutions (4).** Researchers based in Turkey, Nepal, Estonia, and internationally, covering development studies, urban studies, energy systems, climate risk, and environmental and social resilience.	13	02/25

Case	Event	Activity	Stakeholder Profiles	#	Date
SP	PW1	Understanding sectors (hazards and climate change)	**Governmental Agencies (1).** Policy-makers at the national level, covering civil protection and emergency management.	3	11/22
SP	FG1	Understanding sectors (known and new hazards, vulnerability characteristics, and exposure, importance of climate change)	**Governmental Agencies (2).** Implementers and policy-makers at the regional and national levels, covering civil protection, emergency management, and renewable energy policy. **Non-governmental Organizations (1).** Advocacy and association stakeholders at the national level, covering housing policy, land use, and agricultural property. **Private Sector Actors (6).** Industry associations and service providers at the national level, covering renewable energy, offshore wind development, energy efficiency, public services, electrification, and digitalization. Academic and Research Institutions (3). Researchers at the national and regional levels, based in Norway and Denmark, covering energy systems, environmental technology, climate adaptation, and innovation.	14	11/23
SP	FG2	Identifying and characterizing DRM options and interactions	**Governmental Agencies (11).** Policy-makers, regulators, implementers, and infrastructure operators at local, regional, and national levels, covering urban governance, regional planning, climate policy, energy regulation, municipal development, and transport infrastructure. **Private Sector Actors (4).** Industry associations and service providers at national and regional levels, covering agriculture, financial services, business advocacy, and geospatial data.	18	04/24

Case	Event	Activity	Stakeholder Profiles	#	Date
SP	PW2	(Joint workshop with SP): Presentation of a preliminary version of the pathways; feedback from different sectors in Nordic countries.	**Stakeholders based in the Scandinavian context:** **Governmental Agencies (1).** Policy-makers at the local level, covering urban governance, climate adaptation, and coastal resilience. **Non-governmental Organizations (2).** Advocacy and implementer organizations at national and international levels, covering marine conservation, sustainable seas, and nature-based solutions. **Private Sector Actors (1).** Service providers at the international level, covering energy transition, oil and gas, and renewables. **Academic and Research Institutions (1).** Researchers at the national level, based in Finland, covering maritime studies, energy transition, applied research, and environmental monitoring. **Stakeholders beyond the Scandinavian context:** **Governmental Agencies (2).** Policy-makers at the national level, based in the Netherlands, covering agriculture, biodiversity, marine spatial planning, and environmental monitoring. **Academic and Research Institutions (5).** Researchers based in the Netherlands, Turkey, Estonia, Nepal, and internationally, covering marine technology, urban studies, energy systems, climate resilience, development studies, and societal transitions.	13	02/25

References

Amiri, A., Gumiere, S.J., Gharabaghi, B., Bonakdari, H., 2025. From warm seas to flooded streets: The impact of sea surface temperature on cutoff low and extreme rainfall in valencia, spain. Journal of Flood Risk Management 18. doi:10.1111/jfr3.13055.

Baxter, P., Jack, S., 2015. Qualitative case study methodology: Study design and implementation for novice researchers. The Qualitative Report doi:10.46743/2160-3715/2008.1573.

BBC, 17 January 2025. After intense flooding, barcelona is still battling drought. BBC URL: https://www.bbc.com/future/article/20250116-barcelonas-urgent-search-for-water-after-floods.

BBC, 19 September 2024. Storm boris batters italy after wreaking havoc in central europe. BBC URL: https://www.bbc.com/news/articles/c30ln80z4deo.

Bosomworth, K., Leith, P., Harwood, A., Wallis, P.J., 2017. What's the problem in adaptation pathways planning? the potential of a diagnostic problem-structuring approach. Environmental Science & Policy 76, 23–28. URL: https://www.sciencedirect.com/science/article/pii/S1462901117300254, doi:10.1016/j.envsci.2017.06.007.

Brett, L., Bloomfield, H.C., Bradley, A., Calvet, T., Champion, A., de Angeli, S., de Ruiter, M.C., Guerreiro, S.B., Hillier, J., Jaroszweski, D., Kamranzad, B., Keinänen-Toivola, M.M., Kornhuber, K., Küpfer, K., Manning, C., Mattu, K., Murtagh, E., Murray, V., Bhreasail, Á.N., O'Loughlin, F., Parker, C., Pregnolato, M., Ramos, A.M., Schlumberger, J., Theochari, D., Ward, P., Wessels, A., White, C.J., 2025. Science–policy–practice insights for compound and multi–hazard risks. Meteorological Applications 32. doi:10.1002/met.70043.

Buskop, F.E., Sperna Weiland, F., van den Hurk, B., 2024. Amplifying exploration of regional climate risks: clustering future projections on regionally relevant impact drivers instead of emission scenarios. Environmental Research: Climate 3, 045030. doi:10.1088/2752-5295/ad9f8f.

Carstens, C., Sonnek, K.M., Räty, R., Wikman-Svahn, P., Carlsson-Kanyama, A., Metzger, J., 2019. Insights from testing a modified dynamic adaptive policy pathways approach for spatial planning at the municipal level. Sustainability 11, 433. URL: https://www.mdpi.com/2071-1050/11/2/433, doi:10.3390/su11020433.

Carter, T.R., Benzie, M., Campiglio, E., Carlsen, H., Fronzek, S., Hildén, M., Reyer, C.P., West, C., 2021. A conceptual framework for cross-border impacts of climate change. Global Environmental Change 69, 102307. URL: https://www.sciencedirect.com/science/article/pii/S0959378021000868, doi:10.1016/j.gloenvcha.2021.102307.

Casartelli, V., Salpina, D., Marengo, A., Vivo, G., Sørensen, J., Mysiak, J., 2025. An innovative framework to conduct peer reviews of disaster risk management capabilities under the union civil protection mechanism (ucpm). International Journal of Disaster Risk Reduction 120, 105350. doi:10.1016/j.ijdrr.2025.105350.

Claassen, J., Koks, E., Ruiter, de, Marleen, Ward, P., Jäger, W., 2025. Myriad-sim stochastic weather dataset v1. doi:10.5281/zenodo.14979281.

Claassen, J.N., Ward, P.J., Daniell, J., Koks, E.E., Tiggeloven, T., de Ruiter, M.C., 2023. A new method to compile global multi-hazard event sets. Scientific Reports 13, 13808. URL: https://www.nature.com/articles/s41598-023-40400-5, doi:10.1038/s41598-023-40400-5.

Colloff, M.J., Doherty, M.D., Lavorel, S., Dunlop, M., Wise, R.M., Prober, S.M., 2016. Adaptation services and pathways for the management of temperate montane forests under transformational climate change. Climatic Change 138, 267–282. doi:10.1007/s10584-016-1724-z.

Cradock-Henry, N.A., Blackett, P., Hall, M., Johnstone, P., Teixeira, E., Wreford, A., 2020. Climate adaptation pathways for agriculture: Insights from a participatory process. Environmental Science & Policy 107, 66–79. URL: https://www.sciencedirect.com/science/article/pii/S1462901119311578, doi:10.1016/j.envsci.2020.02.020.

Dal Barco, M.K., Maraschini, M., Ferrario, D.M., Nguyen, N.D., Torresan, S., Vascon, S., Critto, A., 2024. A machine learning approach to evaluate coastal risks related to extreme weather events in the veneto region (italy). International Journal of Disaster Risk Reduction 108, 104526. doi:10.1016/j.ijdrr.2024.104526.

Dal Barco, M.K., Maraschini, M., Nguyen, N.D., Ferrario, D.M., Rufo, O., Fonseca, H.L., Vascon, S., Torresan, S., Critto, A., 2025. Integrating ai and climate change scenarios for multi-risk assessment in the coastal municipalities of the veneto region. The Science of the total environment 965, 178586. doi:10.1016/j.scitotenv.2025.178586.

Del Mar Pérez Cambra, M., Martínez Santafé, M.D., Roca Cladera, J., 2025. Exploring the mitigation of compound events in barcelona: Urban water scarcity, flood risk and reduction of surface temperatures through water-sensitive urban design. Urban Climate 59, 102298. doi:10.1016/j.uclim.2025.102298.

Denzin, N.K., Lincoln, Y.S., 2011. The Sage handbook of qualitative research. 4th ed. ed., SAGE, Thousand Oaks.

Eisenhardt, K.M., 1991. Better stories and better constructs: The case for rigor and comparative logic. Academy of Management Review 16, 620–627. doi:10.5465/amr.1991.4279496.

Eisenhardt, K.M., Graebner, M.E., 2007. Theory building from cases: Opportunities and challenges. Academy of Management Journal 50, 25–32. doi:10.5465/amj.2007.24160888.

Gerring, J., 2004. What is a case study and what is it good for? American Political Science Review 98, 341–354. doi:10.1017/S0003055404001182.
Goulart, H.M.D., van der Wiel, K., Folberth, C., Balkovic, J., van den Hurk, B., 2021. Storylines of weather-induced crop failure events under climate change. Earth System Dynamics 12, 1503–1527. URL: https://esd.copernicus.org/articles/12/1503/2021/, doi:10.5194/esd-12-1503-2021.
Haasnoot, M., Di Fant, V., Kwakkel, J., Lawrence, J., 2024. Lessons from a decade of adaptive pathways studies for climate adaptation. Global Environmental Change 88, 102907. doi:10.1016/j.gloenvcha.2024.102907.
Haasnoot, M., Kwakkel, J.H., Walker, W.E., ter Maat, J., 2013. Dynamic adaptive policy pathways: A method for crafting robust decisions for a deeply uncertain world. Global Environmental Change 23, 485–498. URL: https://www.sciencedirect.com/science/article/pii/S095937801200146X, doi:10.1016/j.gloenvcha.2012.12.006.
Haasnoot, M., Lawrence, J., Magnan, A.K., 2021. Pathways to coastal retreat. Science (New York, N.Y.) 372, 1287–1290. doi:10.1126/science.abi6594.
Hadjidemetriou, G.M., Teal, J., Kapetas, L., Parlikad, A.K., 2022. Flexible planning for intercity multimodal transport infrastructure. Journal of Infrastructure Systems 28. doi:10.1061/(ASCE)IS.1943-555X.0000664.
Hochrainer-Stigler, S., Trogrlić Šakić, R., Reiter, K., Ward, P.J., de Ruiter, M.C., Duncan, M.J., Torresan, S., Ciurean, R., Mysiak, J., Stuparu, D., Gottardo, S., 2023. Toward a framework for systemic multi-hazard and multi-risk assessment and management. iScience 26, 106736. URL: https://www.sciencedirect.com/science/article/pii/S2589004223008131, doi:10.1016/j.isci.2023.106736.
Hochrainer-Stigler, S., Šakić Trogrlić, R., Reiter, K., 2024. Fiscal resilience over time and its management in the context of multi-risks: an application to the danube region. Natural Hazards 120, 12163–12180. doi:10.1007/s11069-024-06678-y.
Jafino, B.A., Kwakkel, J.H., Taebi, B., 2021. Enabling assessment of distributive justice through models for climate change planning: A review of recent advances and a research agenda. Wiley Interdisciplinary Reviews: Climate Change 12, e721. URL: https://wires.onlinelibrary.wiley.com/doi/full/10.1002/wcc.721, doi:10.1002/wcc.721.
Klenk, N., Fiume, A., Meehan, K., Gibbes, C., 2017. Local knowledge in climate adaptation research: moving knowledge frameworks from extraction to co–production. Wiley Interdisciplinary Reviews: Climate Change 8, e475. doi:10.1002/wcc.475.
Lawrence, J., Gallop, S.L., Marquardt, L., Bell, R., Blackett, P., Cradock-Henry, N.A., Wreford, A., 2025. Dynamic adaptive pathways planning for adaptation: lessons learned from a decade of practice in aotearoa new zealand. Journal of Integrative Environmental Sciences 22. doi:10.1080/1943815X.2025.2451424.
Lawrence, J., Haasnoot, M., 2017. What it took to catalyse uptake of dynamic adaptive pathways planning to address climate change uncertainty. Environmental Science & Policy 68, 47–57. URL: https://www.sciencedirect.com/science/article/pii/S1462901116303574, doi:10.1016/j.envsci.2016.12.003.
Lempert, R.J., 2003. Shaping the Next One Hundred Years: New Methods for Quantitative, Long-Term Policy Analysis. 1st ed. ed., RAND Corporation The, Santa Monica. URL: https://ebookcentral.proquest.com/lib/kxp/detail.action?docID=197480.
Marciano, C., Peresan, A., Pirni, A., Pittore, M., Tocchi, G., Zaccaria, A.M., 2024. A participatory foresight approach in disaster risk management: The multi-risk storylines. International Journal of Disaster Risk Reduction 114, 104972. doi:10.1016/j.ijdrr.2024.104972.
Nilsson, M., 2017. Important interactions among the sustainable development goals under review at the high-level political forum 2017. URL: https://www.jstor.org/stable/pdf/resrep02837.pdf.
Poljansek, K., Casajus Valles, A., Marin Ferrer, M., Artes-Vivancos, T., Boca, R., Bonadonna, C., Branco, A., Campanharo, W., de Jager, A., de Rigo, D., Dottori, F., Durrant Houston, T., Galbusera, L., Garcia Puerta, B., Giannopoulos, G., Girgin, S., Gowland, R., Grecchi, R., Estreguil, C., Ferrari, D., Frischknecht, C., Hernandez Ceballos, M.A., Iurlaro, G., Kambourakis, G., Karlos, V., Krausmann, E., Larcher, M., Lequarre, A.S., Liberta, G., Loughlin, S.C., Maianti, P., Mangione, D., Marin Ferrer, M., Menoni, S., Montero Prieto, M., Naumann, G., Necci, A., Oom, D., Pfieffer, H., Robuchon, M., Salamon, P., Sangiorgi, M., San-Miguel-Ayanz, J., Sousa, M.L., Theocharidou, M., Theodoridis, G., Trueba Alonso, C., Tsionis, G., Vogt, J.V., Wood, M., 2021. Recommendations for national risk assessment for disaster risk management in EU :where science and policy meet : version 1. Publications Office. doi:10.2760/43449.
de Polt, K., Ward, P.J., de Ruiter, M., Bogdanovich, E., Reichstein, M., Frank, D., Orth, R., 2023. Quantifying impact-relevant heatwave durations. Environmental Research Letters 18, 104005. doi:10.1088/1748-9326/acf05e.
Ramm, T.D., Watson, C.S., White, C.J., 2018. Strategic adaptation pathway planning to manage sea-level rise and changing coastal flood risk. Environmental Science & Policy 87, 92–101. URL: https://www.sciencedirect.com/science/article/pii/S1462901118303678, doi:10.1016/j.envsci.2018.06.001.
Reed, M.S., 2008. Stakeholder participation for environmental management: A literature review. Biological Conservation 141, 2417–2431. doi:10.1016/j.biocon.2008.07.014.

de Ruiter, M.C., de Bruijn, J.A., Englhardt, J., Daniell, J.E., de Moel, H., Ward, P.J., 2021. The asynergies of structural disaster risk reduction measures: Comparing floods and earthquakes. Earth's Future 9. doi:10.1029/2020EF001531.

Schipper, E., Revi, A., Preston, B.L., Carr, E.R., Eriksen, S.H., Fernandez-Carril, L.R., Glavovic, B., Hilmi, N.J., Ley, D., Mukerji, R., Muylaert de Araujo, M.S., 2022. Climate resilient development pathways, in: Pörtner, H.O., Roberts, D.C., Tignor, M., Poloczanska, E.S., Mintenbeck, K., Alegría, A., Craig, M., Langsdorf, S., Löschke, S., Möller, V., Okem, A., Rama, B. (Eds.), Climate Change 2022 – Impacts, Adaptation and Vulnerability. Cambridge University Press, pp. 2655–2808. doi:10.1017/9781009325844.027.

Schlumberger, J., Haasnoot, M., Aerts, J., de Ruiter, M., 2022a. Proposing dapp-mr as a disaster risk management pathways framework for complex, dynamic multi-risk. iScience 25, 105219. doi:10.1016/j.isci.2022.105219.

Schlumberger, J., Haasnoot, M., Aerts, J.C.J.H., Bril, V., van der Weide, L., de Ruiter, M., 2024. Evaluating adaptation pathways in a complex multi–risk system. Earth's Future 12. doi:10.1029/2023EF004288.

Schlumberger, J., Stuparu, D., Ciurean, R.L., Duncan, M., Mysiak, J., Khazai, B., Rimmer, J., Dochiu, C., Claassen, J., 2022b. D1.3 report on policies, policy-making processes, and governance for multi- hazard, multi-risk management. doi:10.5281/ZENODO.7096834.

Schweizer, P.J., Renn, O., 2019. Governance of systemic risks for disaster prevention and mitigation. Disaster Prevention and Management: An International Journal 28, 862–874. URL: https://www.emerald.com/insight/content/doi/10.1108/DPM-09-2019-0282/full/pdf, doi:10.1108/DPM-09-2019-0282.

Shepherd, T.G., Boyd, E., Calel, R.A., Chapman, S.C., Dessai, S., Dima-West, I.M., Fowler, H.J., James, R., Maraun, D., Martius, O., Senior, C.A., Sobel, A.H., Stainforth, D.A., Tett, S.F.B., Trenberth, K.E., van den Hurk, B.J.J.M., Watkins, N.W., Wilby, R.L., Zenghelis, D.A., 2018. Storylines: an alternative approach to representing uncertainty in physical aspects of climate change. Climatic Change 151, 555–571. URL: https://link.springer.com/article/10.1007/s10584-018-2317-9, doi:10.1007/s10584-018-2317-9.

Sillmann, J., Christensen, I., Hochrainer-Stigler, S., Huang-Lachmann, J., Juhola, S., Kornhuber, K., Mahecha, M., Mechler, R., Reichstein, M., Ruane, A.C., Schweizer, P.J., Williams, S., 2022. ISC-UNDRR-RISK KAN Briefing note on systemic risk. ISC-UNDRR-RISK KAN Briefing note on systemic risk, International Science Council, Paris, France. URL: http://pure.iiasa.ac.at/id/eprint/17848/, doi:10.24948/2022.01.

Sillmann, J., Shepherd, T.G., van den Hurk, B., Hazeleger, W., Martius, O., Slingo, J., Zscheischler, J., 2021. Event–based storylines to address climate risk. Earth's Future 9, e2020EF001783. URL: https://agupubs.onlinelibrary.wiley.com/doi/10.1029/2020EF001783, doi:10.1029/2020EF001783.

Simpson, N.P., Mach, K.J., Constable, A., Hess, J., Hogarth, R., Howden, M., Lawrence, J., Lempert, R.J., Muccione, V., Mackey, B., New, M.G., O'Neill, B., Otto, F., Pörtner, H.O., Reisinger, A., Roberts, D., Schmidt, D.N., Seneviratne, S., Strongin, S., van Aalst, M., Totin, E., Trisos, C.H., 2021. A framework for complex climate change risk assessment. One Earth 4, 489–501. URL: https://www.sciencedirect.com/science/article/pii/S2590332221001792, doi:10.1016/j.oneear.2021.03.005.

Stanton, M.C.B., Roelich, K., 2021. Decision making under deep uncertainties: A review of the applicability of methods in practice. Technological Forecasting and Social Change 171, 120939. doi:10.1016/j.techfore.2021.120939.

Stolte, T.R., Koks, E.E., de Moel, H., Reimann, L., van Vliet, J., de Ruiter, M.C., Ward, P.J., 2024. Vulneracity–drivers and dynamics of urban vulnerability based on a global systematic literature review. International Journal of Disaster Risk Reduction 108, 104535. doi:10.1016/j.ijdrr.2024.104535.

Stringer, L.C., Dougill, A.J., Fraser, E., Hubacek, K., Prell, C., Reed, M.S., 2006. Unpacking "participation" in the adaptive management of social–ecological systems: a critical review. Ecology and Society 11. URL: https://www.jstor.org/stable/26266023.

Thaler, T., Hanger-Kopp, S., Schinko, T., Nordbeck, R., 2023. Addressing path dependencies in decision-making processes for operationalizing compound climate-risk management. iScience , 107073doi:10.1016/j.isci.2023.107073.

van de Ven, F.H., Snep, R.P., Koole, S., Brolsma, R., van der Brugge, R., Spijker, J., Vergroesen, T., 2016. Adaptation planning support toolbox: Measurable performance information based tools for co-creation of resilient, ecosystem-based urban plans with urban designers, decision-makers and stakeholders. Environmental Science & Policy 66, 427–436. doi:10.1016/j.envsci.2016.06.010.

Šakić Trogrlić, R., Reiter, K., Ciurean, R.L., Gottardo, S., Torresan, S., Daloz, A.S., Ma, L., Padrón Fumero, N., Tatman, S., Hochrainer-Stigler, S., de Ruiter, M.C., Schlumberger, J., Harris, R., Garcia-Gonzalez, S., García-Vaquero, M., Arévalo, T.L.F., Hernandez-Martin, R., Mendoza-Jimenez, J., Ferrario, D.M., Geurts, D., Stuparu, D., Tiggeloven, T., Duncan, M.J., Ward, P.J., 2024. Challenges in assessing and managing multi-hazard risks: A european stakeholders perspective. Environmental Science & Policy 157, 103774. doi:10.1016/j.envsci.2024.103774.

Walker, W.E., Harremoës, P., Rotmans, J., van der Sluijs, J.P., van Asselt, M., Janssen, P., Krayer von Krauss, M.P., 2003. Defining uncertainty: A conceptual basis for uncertainty management in model-based decision support. Integrated Assessment 4, 5–17. doi:10.1076/iaij.4.1.5.16466.

Ward, P.J., Daniell, J., Duncan, M., Dunne, A., Hananel, C., Hochrainer-Stigler, S., Tijssen, A., Torresan, S., Ciurean, R., Gill, J.C., Sillmann, J., Couasnon, A., Koks, E., Padrón-Fumero, N., Tatman, S., Tronstad Lund, M., Adesiyun, A., Aerts, J.C.J.H., Alabaster, A., Bulder, B., Campillo Torres, C., Critto, A., Hernández-Martín, R., Machado, M., Mysiak, J., Orth, R., Palomino Antolín, I., Petrescu, E.C., Reichstein, M., Tiggeloven, T., van Loon, A.F., Vuong Pham, H., de Ruiter, M.C., 2022. Invited perspectives: A research agenda towards disaster risk management pathways in multi-(hazard-)risk assessment. Natural Hazards and Earth System Sciences 22, 1487–1497. doi:10.5194/nhess-22-1487-2022.

Warren, A., Stuparu, D., Schlumberger, J., Tijssen, A., Dochiu, C., Rimmer, J., 2023. Guidance document for pilots on collaborative systems analysis approaches. URL: https://doi.org/10.5281/zenodo.10082460.

Werners, S.E., Wise, R.M., Butler, J.R., Totin, E., Vincent, K., 2021. Adaptation pathways: A review of approaches and a learning framework. Environmental Science & Policy 116, 266–275. URL: https://www.sciencedirect.com/science/article/pii/S1462901120313836, doi:10.1016/j.envsci.2020.11.003.

Wynn, M., 1979. Barcelona: Planning and change 1854 - 1977. Town Planning Review 50, 185. doi:10.3828/tpr.50.2.w8q42x4125j70576.

Yin, R.K., 2009. Case study research: Design and methods. volume 5 of *Applied social research methods*. 4th ed. ed., SAGE Publications, Los Angeles Calif.

Zebisch, M., Schneiderbauer, S., Fritzsche, K., Bubeck, P., Kienberger, S., Kahlenborn, W., Schwan, S., Below, T., 2021. The vulnerability sourcebook and climate impact chains – a standardised framework for a climate vulnerability and risk assessment. International Journal of Climate Change Strategies and Management 13, 35–59. doi:10.1108/IJCCSM-07-2019-0042.

Zschau, J., 2017. Where are we with multihazards, multirisks assessment capacities?, in: Poljansek, K., Marin Ferrer, M., de Groeve, T., Clark, I. (Eds.), Science for Disaster Risk Management 2017: knowing better and loosing less. Publications Office of the European Union, Luxembourg, pp. 98–115. URL: https://gfzpublic.gfz-potsdam.de/pubman/faces/ViewItemFullPage.jsp;jsessionid=SqFhzs7_SonueO0-0V3xSVqphtV6eAm5hbcCGxGd.localhost?itemId=item_3183904_6&view=EXPORT, doi:10.2788/688605.