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

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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, the 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 disaster risk management (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

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balancing short-term priorities and long-term needs. This research demonstrates that DAPP-MR offers a structured approach to unravelling the 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.

1. Introduction

Past disasters have demonstrated how natural and human factors amplify disaster risks (Cutter, 2021). Multi-hazard events, defined either as the selection of multiple major hazards that a country faces or by interactions between multiple hazards due to simultaneous or sequential occurrence, can exacerbate the hazard-related impact drivers (Kappes et al., 2012; UNDRR, 2017). 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, 2024). Similarly, the Catalonia region in Spain has frequently experienced severe periods of drought and flash flood events as seen in 2024: prolonged drought conditions, combined with urbanization, 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, 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 single, isolated risks, neither accounting for multiple risks, nor interactions between them, 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 future projections are large, which means that the exact precipitation patterns cannot be predicted yet. Additionally, the expansion of the city of Barcelona, initially built 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; Sakic Trogrlic 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 address 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., 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 before being integrated 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 various stages of complexity, DAPP-MR progresses through a series of analytical stages. It begins with identifying the system boundaries, which encompass 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 framework for qualitative development and evaluation of multi-risk pathways. As an analysis framework, DAPP-MR serves as a structured set of concepts and procedures designed to guide how problems are defined, which questions are asked, and how evidence is organized for decision-making. Assessing the value of such a framework involves examining not only the insights it generates in specific applications but also its broader usefulness in achieving its purpose across various contexts, utilizing different tools and methods for its operationalization. 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?** Schlumberger et al. (2022a) identified and integrated key multi-risk elements, which could be relevant in a system, in the analytical steps of DAPP. Therefore, this question aims to analyse whether patterns are detectable regarding which multi-risk elements are generally considered and, if not, for what reasons (see Section 2.2).
2. **How helpful is DAPP-MR in navigating complexity?** Evidence from previous studies (Schlumberger et al., 2022a, 2024) indicates that a staged approach helps analyse 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 analysing multi-risk DRM options in contrast to more commonly used problem-centred approaches in risk assessment, which focus primarily on hazards and/or impacts (Schweizer, 2019). Thus, this question aims to analyse 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 the conclusions drawn regarding the above-outlined questions of interest in each case study, identifying similarities across multiple cases or unique insights specific to them (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, Fig. 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 (Sakic Trogrlic 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 selected pilot cases represent a diversity of spatial scales, ranging from subnational to multinational, which allows us to examine products and services across different levels of decision-making (Fig. 1). They also span a variety of geographical contexts and institutional settings within the European Union, covering much of Europe's biogeographical regions and reflecting their distinct vulnerabilities (EEA, 2017). The pilots also differ with regard to the combination of hazards and sectors relevant to their territory.

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 (López-Saavedra et al., 2025). For example, the 2021 La Palma volcanic eruption and the water emergency declared in 2024 highlight the region's challenges in disaster preparedness, particularly in the tourism and agricultural sectors. The pathways analysis addresses the challenge of

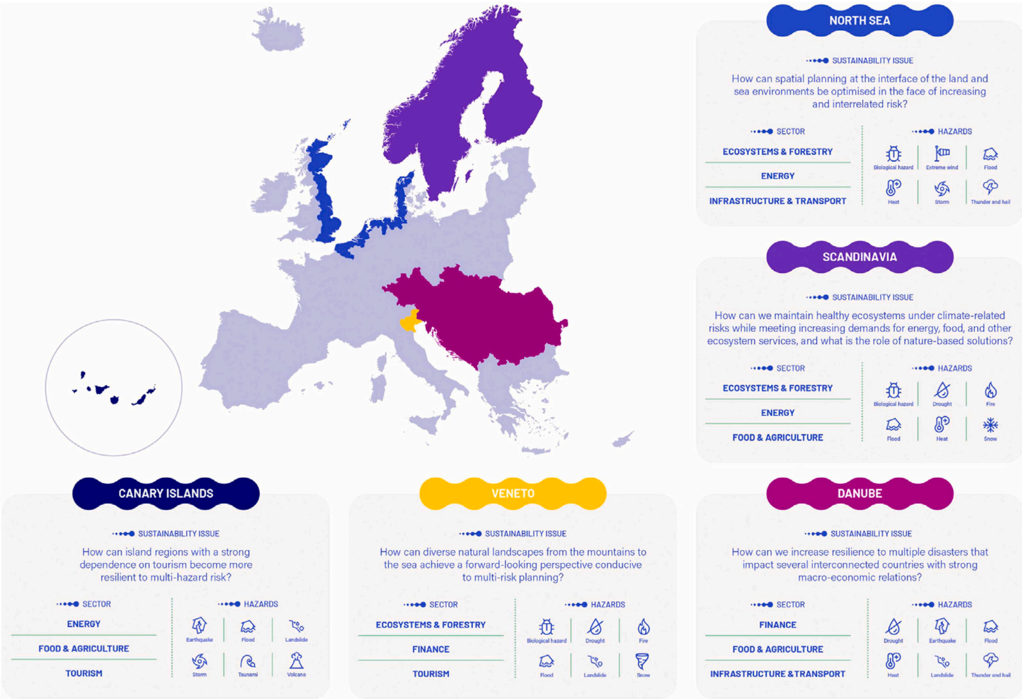

Fig. 1. MYRIAD-EU pilot regions. Overview of their considered sectors, hazards, and sustainability challenges.
Note: The Veneto pilot region is not part of this study, as it applied a different approach.
Source: Copied from Ward et al. (2022).

meeting water demand in tourism and agriculture under scenarios of increasing drought intensity and duration, while simultaneously planning the gradual recovery of tourism accommodation capacity following the 30% loss caused by the 2021 volcanic eruption. The case study evaluates alternative recovery strategies for the tourism sector, identifying which options minimize trade-offs with adaptation pathways for managing increasingly scarce freshwater resources. In addition, it examines the potential for cross-sectoral tensions under extreme heatwave conditions, particularly in relation to competing water needs between different agricultural and tourism water management strategies.

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 examines the interconnection between countries and sectors, as well as the spillover 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 utilizes generic characteristics common throughout the river basin to define the system, while acknowledging that the derived findings may require tailored contextualization for 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 pathways analysis examines how cross-sectoral maritime spatial planning can address these complex risks by leveraging synergies between different sectoral policy measures.

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 pathways analysis focuses on identifying strategies to increase renewable energy production that are least sensitive to changing climate risks. Cross-sectoral interactions are explored to identify strategies that leverage synergistic effects and minimize trade-offs across the agriculture and forestry sectors, as well as other social and environmental dimensions.

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, retaining the core analytical principles of DAPP-MR, notably the staged

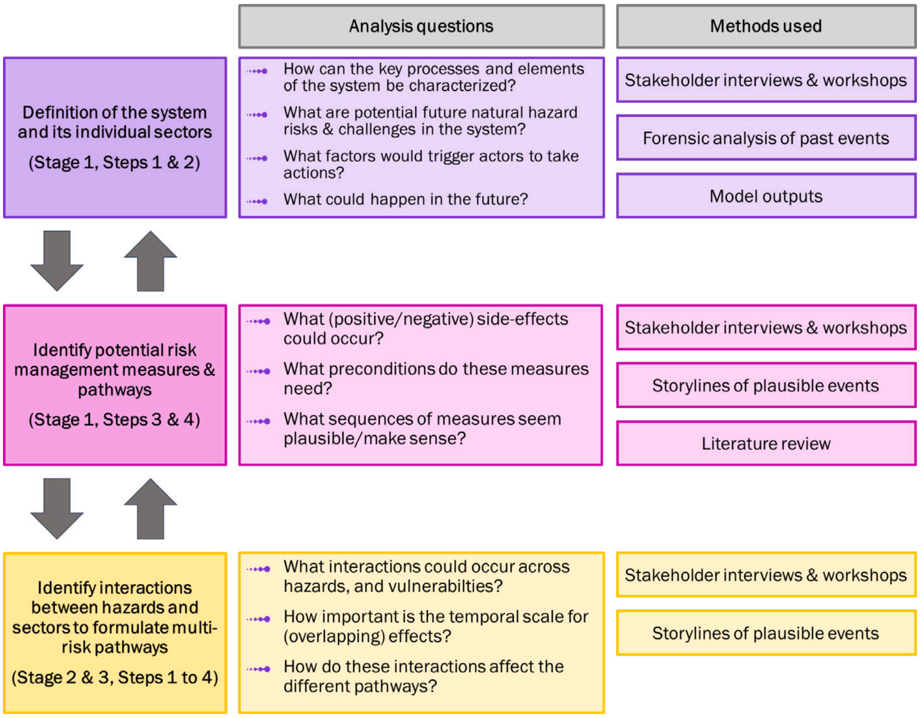

Fig. 2. Simplified analysis framework based on DAPP-MR and methods used in the case studies to develop multi-risk DRM pathways in a staged approach. The boxes on the left outline the main analysis steps and the corresponding steps and stages of DAPP-MR that were used to inform the simplified analysis framework.

approach (Fig. 2). First, we established a comprehensive understanding of the system, 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 stage-wise 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.

As such, DAPP-MR served as the framework that guided the pathways development. However, information relevant to the DRM pathway development process was collected using various tools and methods in the individual analysis steps of the framework to collect and organize the relevant data (Fig. 2). In the four case studies, the pilot leads were not obliged to choose specific tools, but were free to choose ones based on their research interests and internal expertise. 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 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 represented various sectors aligned with the case study's 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 Table A.1.

Additional information on known dynamics and connected challenges was elicited through semi-structured interviews (Schlumberger et al., 2022b; van Maanen et al., 2025). Aside from these organized data collection efforts, most case studies engaged in additional formal and informal stakeholder engagement. For example, DP conducted four key informant interviews and a follow-up group interview with key stakeholders to ensure that the development process of DAPP-MR 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.

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 facilitated the identification of DRM options, interactions, and pathways (Crummy et al., 2025). 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

To qualify the benefits of DAPP-MR, we make use of the multiple case study approach as outlined in Section 2.1.1 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 working with stakeholder groups, further supported by two DRM pathway experts. As such, we conduct a cross-case analysis (Roberts et al., 2016) using observations from the pilot leads and case study reports to identify commonalities and differences across the various cases. Confidential project deliverables, along with the final public report (Gottardo et al., 2025) that synthesizes intermediate results and stakeholder feedback regarding the pathways development process per case study, are used as the primary inputs for comparison.

To address the first question of interest, we utilize the set of key multi-risk elements and dynamics that influence the development and evaluation of DRM pathways for addressing multi-risk, as identified by Schlumberger et al. (2022a). They reviewed recent multi-hazard and multi-sector literature to identify key elements and dynamics across three interrelated themes: (1) effects of multi-hazards (i.e., both multiple hazards and interacting hazards), (2) multi-sector dynamics and interdependencies, and (3) DRM option interactions by means of trade-offs and synergies. For the development of DAPP-MR, these elements were linked to the different analytical steps as initially laid out by DAPP for the pathways development. We utilize these elements and themes to examine which aspects of multi-risk are generally well-covered and which are not. This analysis was based on the formulated system understandings and subsequent pathway analysis steps. By doing so, we investigate potential weaknesses in the applied analytical framework to identify multi-risk causes for these limitations, as well as whether other multi-risk-relevant aspects have been addressed that are not yet captured in the DAPP-MR framework.

We assess the benefits of DAPP-MR in navigating complexity and learning for DRM, using anecdotal evidence from various case studies. To investigate how the staged approach of DAPP-MR facilitated navigating complexity, we reflect on the process and the required time to complete each step for each case study. This reflection is based on the observations by the co-author team, along with the reports on the activities and discussions of the different interaction moments as presented in Appendix A. To qualitatively assess the learnings for DRM, the pilot lead co-authors were asked to compile their own observations and learnings reported by the stakeholders from applying DAPP-MR. Based on the inputs from the pilots, themes related to lessons for DRM were identified to structure the analysis.

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

DAPP-MR explicitly addresses and integrates a set of multi-risk elements in the analysis process. All case studies addressed most of these elements of multi-hazard, multi-sector dynamics and interactions across different DRM options to different degrees. None of the case studies discussed additional multi-risk elements that were not captured by DAPP-MR yet. Some elements were considered only for parts of the analysis and disregarded as the process continued (Fig. 3; Gottardo et al., 2025). Only a few elements were not considered. Reasons for partial consideration varied, including limited relevance for the analysis, involvement of stakeholders, or insufficient knowledge, data, and tools to manage the additional information. As a result, multi-sector elements are well captured in the DRM pathways, but 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, stakeholders found it difficult to envision future scenarios of multi-hazard events and comprehend 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. Instead, the exacerbating impacts of heatwaves spiking the water demand were considered as an additional stressor, resulting in major problems if the remaining water supply was not able to compensate for the sudden events. 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

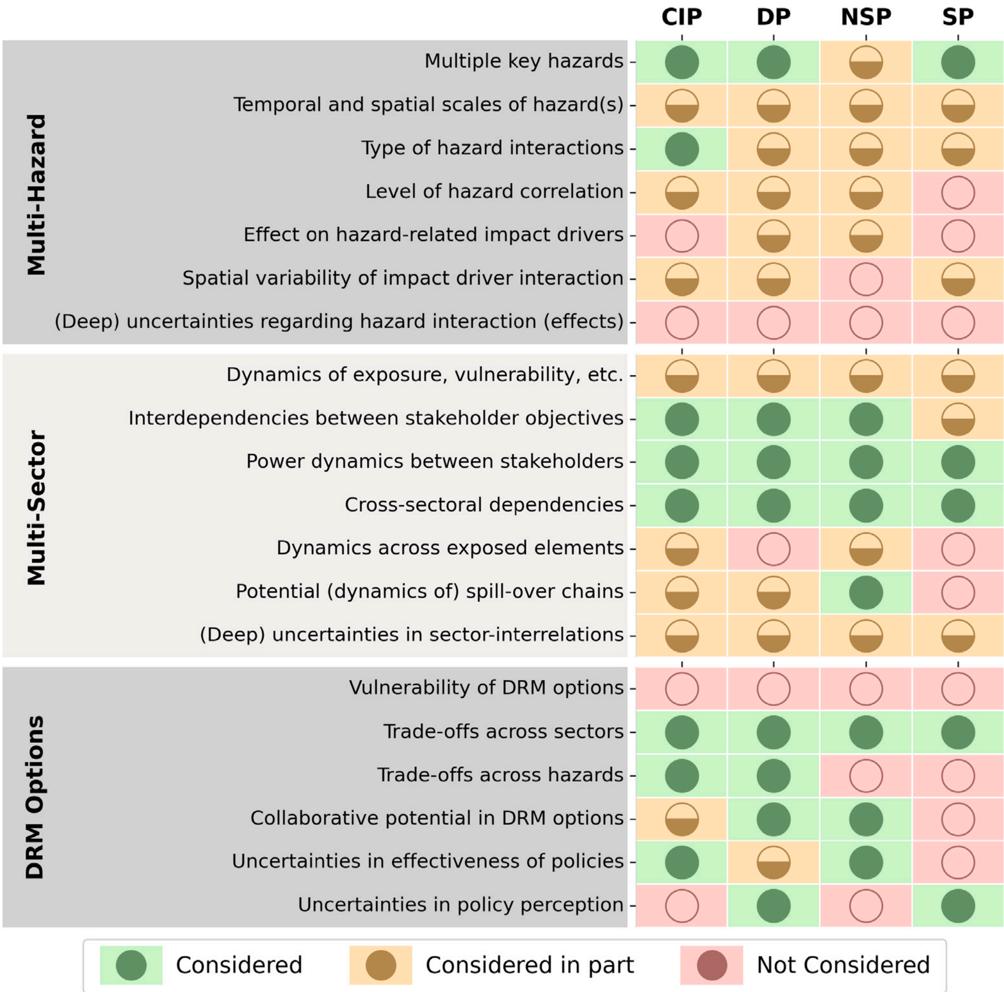

Fig. 3. Degree to which certain multi-risk elements were addressed in the different case studies to develop and evaluate multi-risk DRM pathways. CIP: Canary Island Pilot. DP: Danube Pilot. NSP: North Sea Pilot. SP: Scandinavian Pilot.

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 changes in water availability and competition across CIP sectors. Conversely, in the SP, stakeholders discussed the influence of different sectors due to current political priorities, noting that interactions are primarily determined by decisions in the energy sector, driven by energy transformation-related land-use changes that impact 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 is because tools and methods for quantifying these dynamics are still in their infancy, and only limited qualitative findings were available to the Pilots at the time of their 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 analysing 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 encompasses the impacts on the agriculture and forestry sectors, social acceptance, land use concerns, environmental impacts, social security, and resilience to climate shocks. Some case studies incorporate 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. Additionally, SP incorporates assumptions about different levels of social acceptance towards measures in the energy sector.

Patterns regarding the interaction elements in the context of DRM options are less clear across the case studies. As a result of the focus on multiple hazards without in-depth consideration of their interactions, DRM options were also not characterized in terms of their vulnerability to multi-hazard interactions in any case study. Conversely, DRM options in different sectors were either already chosen based on their vulnerability to the present hazards (e.g., NSP) or were characterized in general terms regarding 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). Through a scenario analysis, CIP also investigates how the drought DRM pathways of the tourism and agriculture sectors might lead to an increased risk from heatwaves due to co-occurring low water-supply buffers in the two sectors. Uncertainties regarding the effectiveness of DRM options are captured in some of the case studies. In NSP and CIP, some effects of measures, especially regarding interaction effects, are marked as uncertain, highlighting that the effects are unknown or context-specific. Those uncertainties are considered in the evaluation of the pathways options as an additional aspect to discuss context-specific variabilities and identify pathways with higher performance uncertainty that require additional investigation. In contrast, uncertainty regarding the perception is covered only in the SP, where the level of public acceptance was used to differentiate between 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. Fig. 4 summarizes the key development steps as implemented in the case studies. Across the four pilot studies, DAPP-MR proved helpful in navigating complexity because it staged the analysis over time rather than attempting to address everything at once. Beginning with the definition of the system and its sectors, stakeholders could first focus on the immediate challenge of reconciling divergent perspectives and scales on the sector and its relevant contexts. In CIP and DP, this early step made the interdependencies and spatial mismatches visible that would otherwise have blocked progress. At the same time, in NSP the iterative updating of the system map provided a way to cope with stakeholder turnover over time. In the second step, developing sectoral DRM pathways, the framework enabled stakeholders to shift focus from "what the system is" to "how it could evolve". This temporal sequencing helped actors unused to long-term planning (e.g., in CIP and DP) to gradually build confidence, while in SP, existing long-term strategies could be directly translated into pathways. Finally, by only after these steps turning to interactions and multi-risk pathways, the approach allowed participants to confront the most complexity by means of cross-sectoral dependencies and measure interactions once they had already developed a baseline of shared understanding and sectoral options. Tools such as interaction matrices (NSP, DP), quantitative scenario analyses (CIP), and qualitative integration (SP) provided concrete ways to expose synergies, trade-offs, and timing issues without overwhelming participants earlier in the process. 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 the majority of their project time forming and refining their understanding of the system and its sectors. This included formulating a system understanding that encompassed different sectors with distinct short-term challenges and long-term needs, based on that understanding. The initial system maps were continuously updated and refined during the pathway development process in the case studies (see Appendix B).

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 a single system understanding began very early. For example, in the Canary Islands, elements of the agricultural and tourism sectors are closely 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 time frames, as shown in Fig. 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 primarily due to the complexity of the tightly interconnected sectors being considered. Tourism is a primary driver of change in many other sectors, but also strongly depends on the services and products that other sectors deliver. Capturing this in clear, sector-specific DRM objectives 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 a suitable scale for the analysis due to the spatially divergent characteristics in the large case study area. Similar challenges regarding the scale were encountered in SP, but they 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).

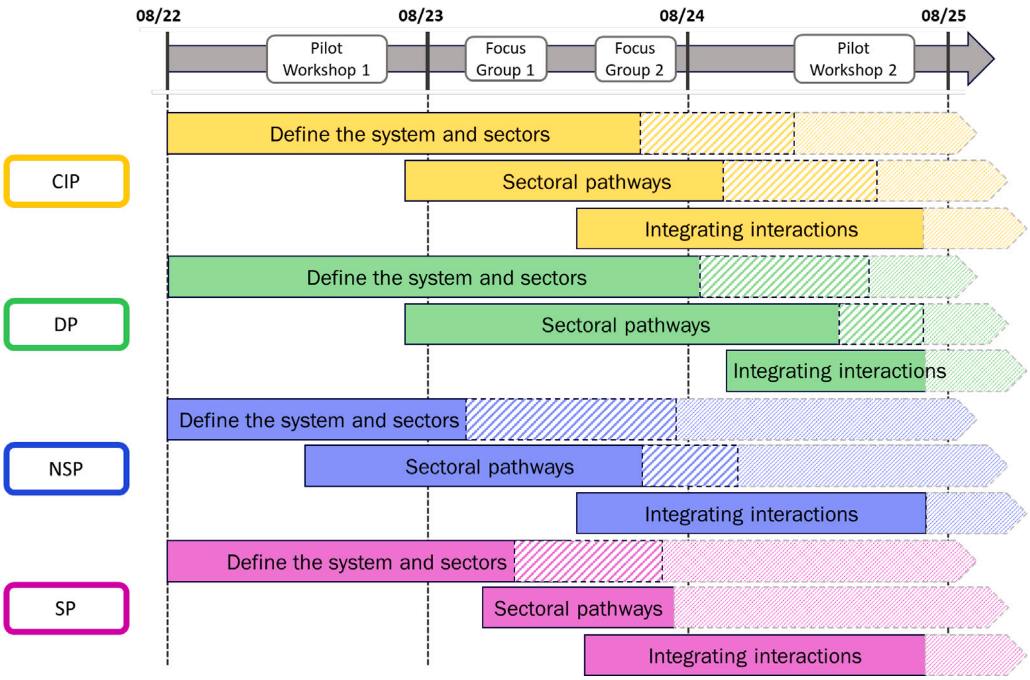

Fig. 4. Outline of the staged approach implemented in the different case studies. Hatched bars indicate that only minor revisions have been made in a given analysis step over that period. Note that the common end of the overall development process was due to the deadline for a project deliverable. Hatched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

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 also characterized in terms of other evaluation criteria relevant to the specific case studies. The case studies used scorecards to summarize the characterizations (see e.g., Fig. 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 judgement were used in SP to characterize the cross-sectoral effects of different energy measures. Synergies included integrating renewable energy projects on agricultural lands, utilizing agrarian residues for bioenergy production, and promoting agroforestry practices. Trade-offs were identified in the competition for water and land, as well as the potential negative impacts on natural ecosystems, and the economic costs associated with 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 employed narratives with different technological focuses (e.g., energy sector pathways to extend offshore wind capacity or to prioritize alternative energy sources), DP and CIP utilized perspective-driven narratives. For example, in CIP, pathways related to increasing bed capacity may 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 led to a revision of the evaluation criteria for the DRM options, uncovering criteria that stakeholders could use to characterize their feasibility or plausibility as either a short-term measure or a long-term option.

Again, some differences regarding the difficulty of this analysis step can be observed across the case studies (Fig. 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, identifying promising sectoral pathways proved to be 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 characteristics.

3.2.3. Identifying interactions and multi-risk DRM pathways

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 Fig. 6). Each combination was examined to identify pairs of measures that have positive, negative, uncertain, or no effects on each other. For example, opening

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

Fig. 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 favourable 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.

Acting measure \ Target of interaction	Shipping	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

Fig. 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.

wind farms for shipping generally increases risks for the energy sector due to the increased possibility of collisions between ships and energy infrastructure in low-manoeuvrability conditions. The increased shipping traffic may also prevent/limit specific measures related to alternative energy sources and hydrogen production due to space demand.

The matrix represented an initial step towards 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 Fig. 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 raises questions about key knowledge gaps and potential context-specific interaction possibilities.

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 Fig. 8). During Focus Group 2, expert calibration revealed challenges in gathering feedback on pre-developed pathways. Instead, stakeholders favoured co-developing sectoral pathways in parallel,

a) Single-sector pathways evaluation

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

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

Shipping	Effectiveness for reaching objectives	Cost	Impact on maritime space	Regret
Surveillance & Policy Measures (S&P M)	6	-7	-1	-7
Spatial Policy Measures (SPM)	7	-6	-3	-10
Surveillance & Windfarms (S&W)	9	-11	0	-11

b) Evaluation of effects of pathways cobinations

Combinations			Effects on			Uncertainty
			Nature	Energy	Shipping	
W&R R	OWE	S & W	2	4	1	3
NE	OWE	S & W	2	4	1	4
LNP	OWE	S & W	1	4	1	4
W&R R	WEF	S & W	2	3	1	6
NE	WEF	S & W	2	3	1	7
LNP	WEF	S & W	1	3	1	7
LNP	OWE	S&P M	2	2	1	1
W&R R	OWE	S&P M	2	2	1	2
NE	OWE	S&P M	2	2	1	2
LNP	WEF	S&P M	2	1	1	2
W&R R	**WEF**	**S&P M**	2	1	1	3
W&R R	OWE	SPM	2	1	1	3
NE	WEF	S&P M	2	1	1	3
NE	OWE	SPM	2	1	1	3
LNP	OWE	SPM	1	1	1	2
W&R R	WEF	SPM	2	0	1	4
NE	WEF	SPM	2	0	1	4
LNP	WEF	SPM	1	0	1	3
W&R R	DEM	S & W	1	2	-1	8
NE	DEM	S & W	1	2	-1	9
LNP	DEM	S & W	0	2	-1	9
LNP	DEM	S&P M	1	-1	0	4
W&R R	DEM	S&P M	1	-1	0	5
NE	DEM	S&P M	1	-1	0	5
W&R R	DEM	SPM	1	-2	0	7
NE	DEM	SPM	1	-2	0	7
LNP	DEM	SPM	0	-2	0	6

Fig. 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 favourable evaluations, while negative values indicate less desirable outcomes. The pathway combination highlighted in blue in the first column represents the best-performing sectoral pathways, excluding interactions.

drawing on a complete understanding of interactions between the shipping and agricultural sectors. Key considerations included governance, financing, and cross-sector dependencies. Parallel implementation was explored where beneficial, particularly for enabling conditions such as early warning systems and cross-border cooperation. The discussions also highlighted potential medium- to long-term land-use conflicts associated with implementing the DRM option.

In the SP, the analysis of pathway interactions did not focus on the interactions between the DRM options for energy and other sectors. Instead, it was more broadly informed by an integrated understanding of the system 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 Fig. 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 approach potentially makes it 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 2000 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 as a means to make the measures and interactions more practical, it turned out to be quite challenging to build pathways and 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 Fig. 10). This visualization helped investigate the expected lifetime of implemented DRM options, depending on whether only a climate-driven reduction in the available water budget was considered or whether this reduction was compounded with specific pathways to meet the bed capacity requirements. In this way, the impacts of different bed capacity strategies were made explicit, discussing whether pathways could meet sectoral interests with fewer adverse effects on water demand. Similarly, stakeholders discussed which water demand scenario seemed more plausible in terms of the required timing for implementing new DRM options. Finally, the visualizations 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. In addition to drought-related impacts, heatwaves were explicitly considered as an additional stressor on the water demand and supply system. The analysis employed a scenario-based approach, assuming that extreme heatwaves result in a 10% increase in annual water demand. Furthermore, it was assumed that significant disruptions occur when this additional demand exceeds the available water budget by more than 20%. This allowed for the identification of years and pathway combinations where the remaining buffer between demand and supply is too low to absorb heatwave-induced demand surges. As a result, periods of heightened risk can be identified, along with combinations of pathways for both sectors that lead to more frequent situations where both the tourism and agricultural sectors are simultaneously affected.

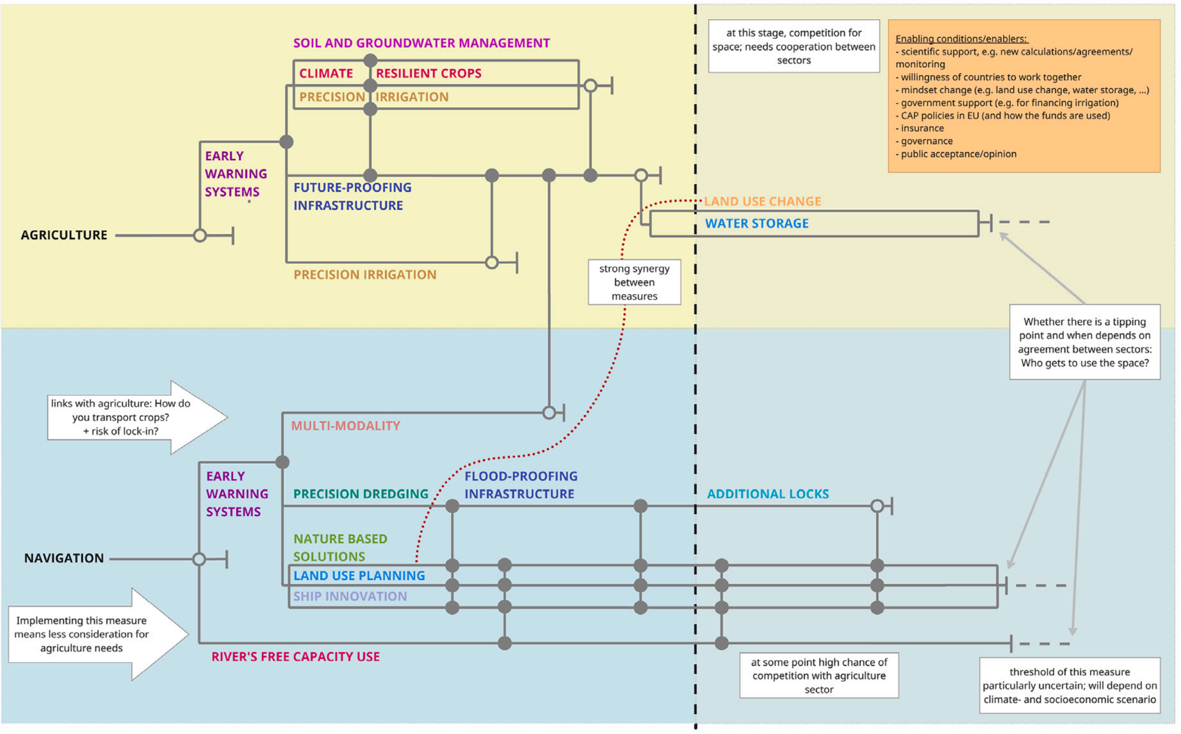

Fig. 8. Final set of multi-risk DRM pathways developed for the agriculture and shipping sector in DP.

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 (Fig. 11). 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 also 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 had not previously collaborated. 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 established in the NSP, where awareness of DRM is limited.

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 conditions of uncertainty, the pathways revealed system vulnerabilities, resource conflicts, and tipping points, enabling local authorities to align their policies more effectively, prioritize early action, and coordinate governance. Similarly, dialogue and learning occurred across sectoral boundaries and among various actors, including government authorities, non-governmental organizations, researchers, and private sector entities. Engaging this wide array of stakeholders was found to be 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

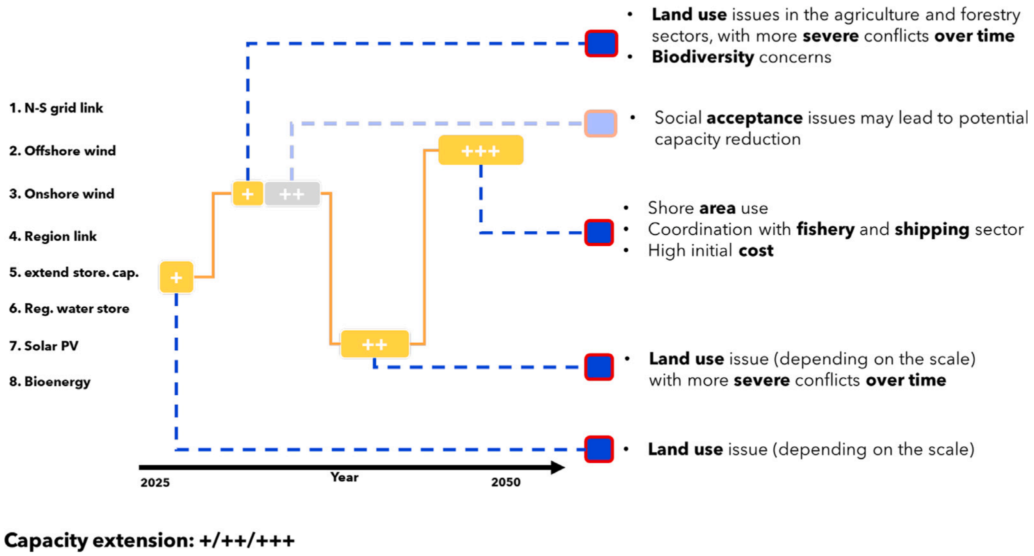

Fig. 9. Interaction analysis for measures in a specific energy pathway regarding the agriculture and forestry sectors and various other aspects.

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 of extending 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 an integrated understanding of the system, 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, in which 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; Sakic Trogrlic 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 (Fig. 11). 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.

In this study, we focused on discussing differences and similarities of the pathways development process and the final products in a set of four case studies - all using DAPP-MR for analytical guidance. It was possible to integrate (some) multi-risk complexity for the development of multi-hazard or multi-sector DRM pathways across case studies representing diverse general climatic and environmental contexts, spatial and temporal scopes, sectors and stakeholders involved, governance level, and hazards of interest. We believe this offers confidence regarding the value and benefits of DAPP-MR. It also demonstrates the framework's flexibility in making the best use of available information from various tools and sources. At the same time, the diversity in challenges and research focus also highlights that developing multi-risk DRM pathways using DAPP-MR remains highly case specific, which requires and results in tailored analysis methods and foci. However, it would be interesting to investigate the unique value that the analytical framework of DAPP-MR offers by structuring and directing the analysis in comparison to other frameworks that aim to integrate multi-risk complexity for policy analysis. Generally speaking, managing complexity can be done in different ways. While DAPP-MR offers a framework to manage complexity iteratively, other frameworks, such as the one by Hochrainer-Stigler et al. (2023), focus on a stepwise approach that emphasizes system boundaries and dependencies to reduce complexity to manageable levels. In both, the careful increase in complexity to make the framework applicable in real-world settings is a focal point.

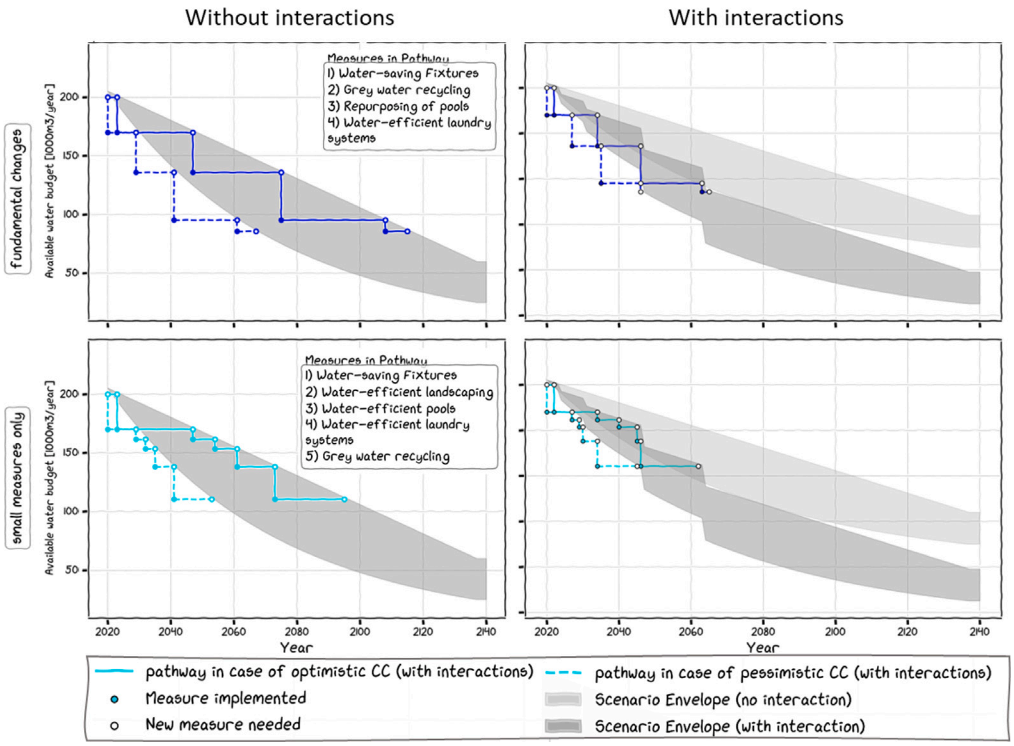

Fig. 10. Exploration of the timing of two different pathways to reduce water consumption in the tourism sector (rows) without interactions (left column) and when accounting for the effects of one specific pathway to increase bed capacity (right column). Without interactions, the timing is mainly determined 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 bed capacity combines with the climate-driven decline in water resources, resulting in sudden jumps in the scenario envelope, driving the solution space for water reduction strategies.

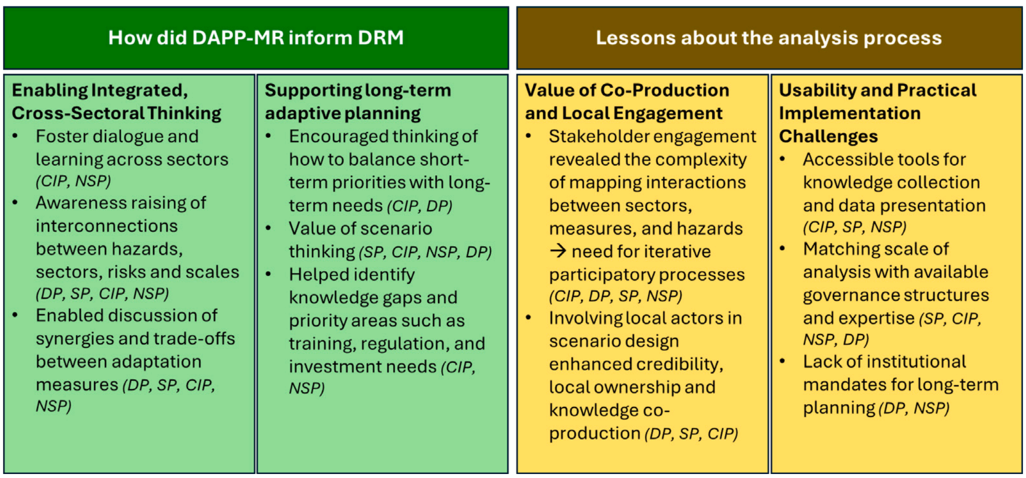

Fig. 11. Learnings for DRM and the analytical process of applying DAPP-MR.

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 (Fig. 11). 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 served as a powerful tool for cross-sectoral learning, akin to a structured brainstorming session, encouraging the shared exploration of interdependencies between hazards, sectors, and DRM options. As the outcomes of the analysis show, especially when comparing Figs. 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 to capture such diversity, given the broad range of aspects that could be analysed for 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 it receives sufficient attention and interest, what starts as a brainstorming and learning exercise can turn into full implementation 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., 2025; 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 in the analysis. While the lack of prior experience with such dynamics probably contributed to this bottleneck (van Maanen et al., 2025), 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., 2025), 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 to inform the development of pathways. 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, they are not yet tailored for qualitative application for multi-risk DRM pathways, for example, through easy-to-use visualizations or the capacity to consider future climate change uncertainty. 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 (Sparkes et al., 2024; Zebisch et al., 2021), storylines or other process-oriented methods (e.g., de Polt et al., 2023) 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 (McEvoy et al., 2025). 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 (e.g., centring one sector like in SP, developing pathways simultaneously like in DP, focusing on the shifts in timing like in CIP, or focusing primarily on the performance effects like in the NSP), 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 under-explored 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 more flexible and supportive set of tools 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 (Gottardo et al., 2025), 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 developing multi-risk DRM pathways. 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 addressing complex and uncertain risk environments 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, moving from piloting to full implementation of multi-risk pathways-thinking for 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. Additionally, future research could build on the findings developed in the case studies. These could serve as a foundation for more refined analyses, such as quantitative pathway assessments 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.

CRediT authorship contribution statement

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Declaration of competing interest

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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
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

(continued on next page)

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

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

Table A.1 (*continued*).

Case	Event	Activity	Stakeholder Profiles	#	Date
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
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
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

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The diversity of participating stakeholders reflects a broad spectrum of organizational affiliations. Public institutions played a crucial role in the case studies, including government departments at the local, regional, and national levels, which are often responsible for policymaking, planning, and delivering 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

Table A.1 (*continued*).

Case	Event	Activity	Stakeholder Profiles	#	Date
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
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

(*continued on next page*)

represented by non-governmental and community organizations, often grounded in advocacy, local development, or thematic responsibilities (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 were provided by 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 and sustainability, into the analysis process.

Table A.1 (*continued*).

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

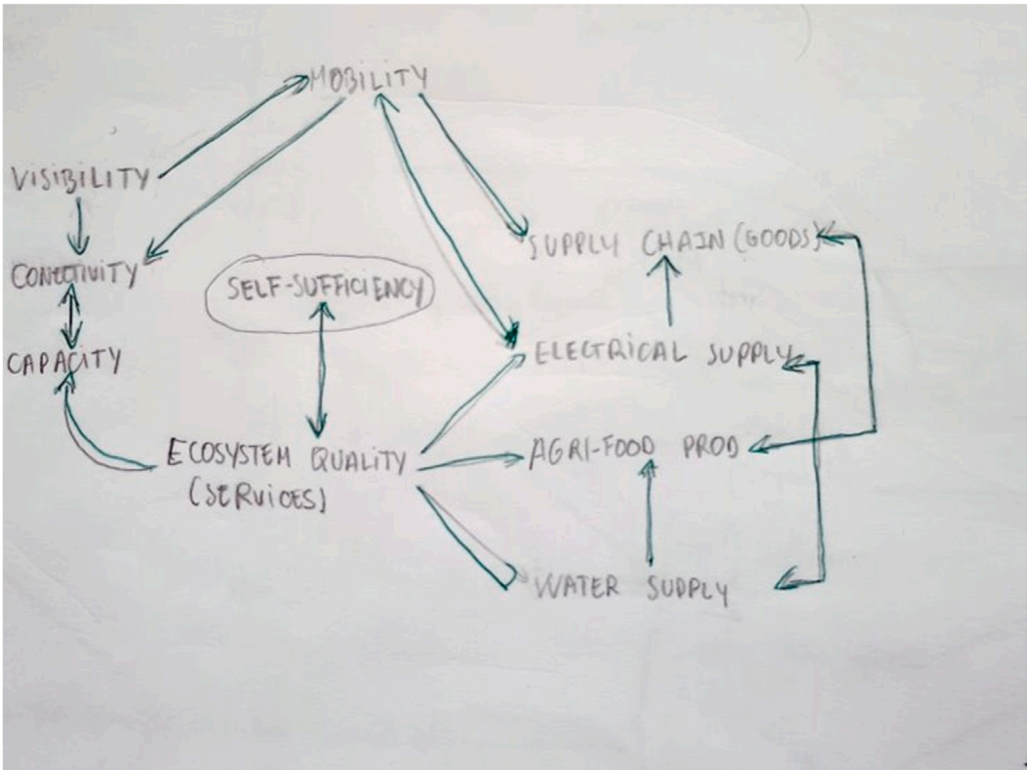

Fig. B.12. Initial system understanding in the Canary Island Pilots.

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 coordinating 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 specialized deeply in specific

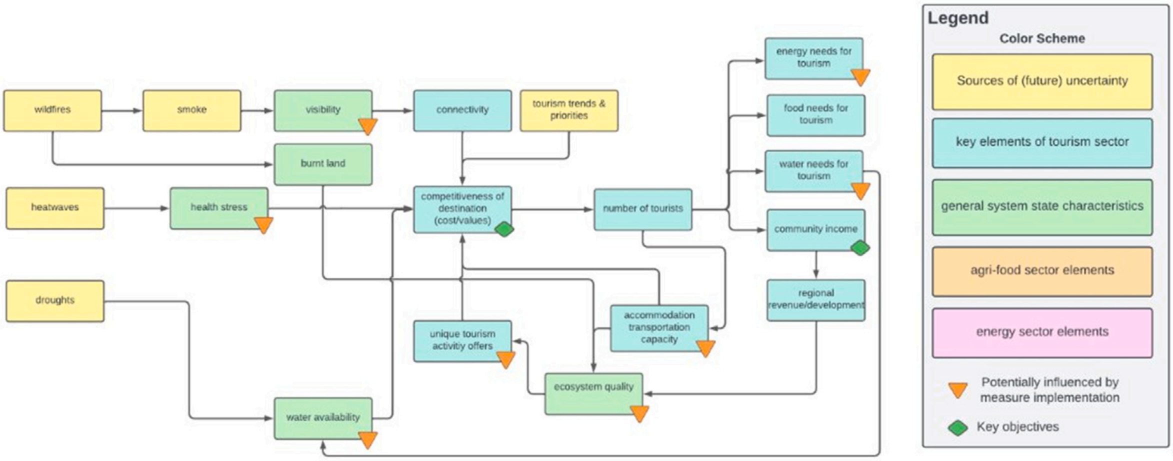

Fig. B.13. Intermediate iteration of a system map, focusing on the agricultural sector in the Canary Island Pilots.

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.

Appendix B. Examples to showcase evolving system understanding

See Figs. B.12 and B.13.

Data availability

No data was used for the research described in the article.

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