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D6.4
Final Report on Collaborative Systems Analysis and DAPP-MR

Version 02
August 29, 2024

D6.4/Final Report on Collaborative Systems Analysis and DAPP-MR

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Abstract

This report presents findings on two key aspects of developing forward-looking DRM pathways: (1) the development of a flexible, generic approach to collaborative systems analysis; and (2) the development of DAPP-MR – the proposed, staged, iterative analytical process to facilitate the assessment of multiple possible pathways to adapt to current and future multi-risk challenges. Both of the developed approaches are designed to complement the MYRIAD-EU framework for systemic multi-hazard and multi-risk assessment and management.

Collaborative systems analysis approach

The generic approach for collaborative systems analysis guides decision-makers and policymakers to describe DRM decision-making contexts. This description serves as the foundation for the development of forward-looking DRM pathways.

All five pilots have adapted the approach to their particular problem contexts and applied various tools to describe these together with stakeholders. The tools most used by the pilots included the DPSIR framework, causal relationship diagrams, storyline approaches, and interaction matrices. The storyline approach in particular was enthusiastically adopted by all the pilots and has proven to be both an effective and flexible tool well-received by stakeholders. Collaborative systems analysis relies on sufficient time being allocated to both prepare and implement these activities, as well as strong and effective facilitation to lead discussions and help to synthesise system complexities for stakeholders.

DAPP-MR

Building on the existing Dynamic Adaptation Policy Pathways (DAPP) approach, DAPP-MR guides the assessment and evaluation of multiple adaptation pathways to current and future multi-risk challenges. The approach systematically considers three key themes relevant to the design of multi-risk DRM pathways: (1) the effects of multiple, interacting hazards; (2) the dynamics and interdependencies of sectors; and (3) the trade-offs and synergies of DRM policy options across different sectors and different spatial and temporal scales. It does so by staging the analysis to gradually build up problem complexity.

DAPP-MR has been applied in a synthetic multi-risk case study to assess its utility. The results highlight the complexity of assessing the effectiveness of flood and drought risk reduction measures, particularly in the context of multi-hazard interactions. However, the staged approach helps to illuminate pathways that remain valid under increasing complexity. There remains a crucial gap in visualising and communicating the relative performance and interaction effects of different pathways across scenario ensembles. Ongoing research to address this gap suggests the use of various information visualisation methods may facilitate the exploration, sensemaking, and communication of data to support decision-making processes.

DAPP-MR is presently being applied in each of the five MYRIAD-EU pilots, predominantly in a qualitative sense. Each pilot initially developed system understanding from sectoral perspectives, before developing first iterations of sectoral pathways. The pilots are presently analysing the interactions between the sectoral pathways, with their multi-risk pathways expected to be completed beginning of 2025. A forthcoming scientific publication submission will present the findings from all pilot regions, reflecting on the differences in methods used (if any) and their potential transferability to other study areas.

Dissemination level of the document

☑Public

☐Restricted to other programme participants (including the Commission Services)

☐Restricted to a group specified by the consortium (including the European Commission Services)

☐Confidential, only for members of the consortium (including the European Commission Services)

Version History

Version	Date	Authors/Reviewers	Description
V1	06/08/2024	Andrew Warren (Deltares) Julius Schlumberger (Deltares, Vrije Universiteit Amsterdam) Reviewed by Philip Ward (VUA), James Daniell (Risklayer)	Draft submitted for internal review
V2	29/08/2024	Andrew Warren (Deltares) Julius Schlumberger (Deltares, Vrije Universiteit Amsterdam)	Final version

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1 Introduction

1.1 General

Multi-risk settings are mired in complexity. How to structure, organise, prioritise and make sense of all this complexity and develop adaptive plans with which to simultaneously manage multiple risks across multiple sectors presents as one of the key challenges for policy analysts and decision-makers.

This report presents research findings on two of the key aspects of developing forward-looking disaster risk management (DRM) pathways: (1) the development of a flexible, generic approach to collaborative systems analysis (Task 6.1), and (2) the development of DAPP-MR – the proposed, staged, iterative analytical process to follow to facilitate the assessment of multiple possible pathways to adapt to current and future multi-risk challenges (Task 6.2). Both of these approaches have been developed and refined over the course of the MYRIAD-EU project and in close collaboration with the five pilot regions to test and learn from their applications. Both approaches have also been designed to complement the MYRIAD-EU framework for systemic multi-hazard and multi-risk assessment and management and have been applied in all five MYRIAD-EU pilot regions.

1.2 Existing work within MYRIAD-EU which interacts with these WP6 outputs

WP1 (Diagnosis and State-of-the-Art): WP1 provides the common set of concepts and definitions to be used by WP6 throughout MYRIAD-EU. Its comprehensive review and evaluation of policies, policy-making processes, and governance relevant to multi-hazard, multi-risk management set the foundation for the analysis of potential system interactions and interdependencies. Its typologies of inter-sector interdependence and multi-sector risk have informed the development of the WP6 approaches to improve system understanding and formulate forward-looking multi-risk pathways.

WP2 (Framework and Guidance Protocols): The development of the methodologies and frameworks in WP2 occurred in parallel to the developments in WP6 on systems analysis and pathways formulation. This has offered a rich opportunity for ongoing collaboration between the two work packages to synthesise these methods and ensure their seamless integration. Section 3 illustrates how both approaches developed in WP6 are aligned with the framework developed in WP2, which includes system definition, characterisation of direct risk, characterisation of indirect risk, evaluation of direct and indirect risk, and accounting for future system state.

WP3 (Pilot Studies and Stakeholder Engagement): The formulation and ongoing refinement of the two approaches has been directly influenced by feedback from the pilot studies and stakeholder engagement coordinated through WP3. This ensures that the two generic approaches can be tailored to real-world needs and has helped to improve our understanding of how to best implement them in practice. The developed methods have been presented to both the pilot teams and stakeholders through online webinars, while ongoing interactive support has been provided to the WP3 pilot leads during their implementation via the WP6 helpdesk (Task 6.4).

WP4 (Risk Drivers and Dynamic Feedbacks): The knowledge and methods developed in WP4 to assess the dynamic feedbacks present between multi-hazard risk drivers both directly inform and are informed by the two WP6 approaches. Our improved knowledge of feedbacks can enrich system analysis descriptions which then prioritise the interdependent risks to assess and manage, while the methods to then assess these can then be used to inform the formulation of pathways to confront and manage these risks into the (long-term) future.

WP5 (Multi-Risk Scenarios): The multi-risk scenarios developed in WP5 and associated methods for quantifying both direct and indirect risks across sectors can serve as direct inputs to the DAPP-MR approach. The scenarios are used to establish the range of uncertainty to be confronted and managed through implementation of robust and flexible adaptation pathways, while the quantitative risk assessments directly inform the specification of those pathways and help identify when any tipping points are reached and further adaptation is needed. More qualitative system analyses and pathways (e.g. via a storyline approach) to explore past and potential future multi-risk events similarly support WP5 efforts in visualising and implementing effective risk analyses and management strategies.

1.3 Document Structure

The remainder of this report is structured as follows. Section 2 presents the main scientific developments for the two developed approaches, including experiences of applying these in the five MYRIAD-EU pilot regions. Section 3 describes how the two approaches relate to the MYRIAD-EU framework for systemic multi-hazard and multi-risk assessment and management. Section 4 summarises the key challenges and opportunities presented by the two approaches. Section 5 outlines the take up of these research outputs outside of MYRIAD-EU, while Section 6 describes future research to be undertaken in these two fields of research.

2 Main scientific developments

2.1 General

This section describes the main scientific developments for the two developed approaches to support the formulation of forward-looking disaster risk management (DRM) pathways, namely collaborative systems analysis (Task 6.1) and Dynamic Adaptation Policy Pathways for Multi-Risk (DAPP-MR; Task 6.2). It presents the main research findings for the two developed approaches, including experiences of applying these in the five MYRIAD-EU pilot regions.

2.2 Collaborative systems analysis

The following section synthesises inputs on collaborative systems analysis from previous MYRIAD-EU deliverables, namely:

- *D6.2 Guidance document for Pilots on collaborative systems analysis approaches* (Warren et al., 2022)
- *D6.3 Interim report on collaborative systems and DAPP approaches to develop forward looking DRM pathways* (Warren and Schlumberger, 2023)

It commences by describing the key features and objectives of collaborative systems analysis and the generic approach developed in MYRIAD-EU, before discussing the application of these activities within each of the pilot regions in the project.

2.2.1 Developing a flexible, generic approach for collaborative systems analysis in MYRIAD-EU

A solid understanding of how systems function underpins good decision-making. In complex, 'messy', multi-sector, multi-risk problem contexts, multiple stakeholders can hold competing versions of system function and causality. It is therefore important to establish a shared, mutual understanding. Collaborative systems analysis methods are important ingredients to achieve this. Specifically, they support multi-risk decision-making to:

- avoid negative consequences when approaching problems through a sector-specific lens;
- aid in the formulation of system-wide objectives that both recognise and balance the inherent trade-offs within our systems;
- ensure a more equitable distribution of system-wide resources, costs and benefits; and
- help reduce the potential for stakeholder conflict.

The flexible, generic approach to collaborative systems analysis developed in MYRIAD-EU has been designed to support the formulation of forward-looking DRM pathways through analysis of relevant system characteristics, objectives and constraints in current and potential future situations. It reflects the findings from the WP1 analysis of typologies of inter-sector interdependence and multi-sector risk, as well as a WP6 review of promising systems analysis tools and approaches presented in literature. It seeks to incorporate knowledge on risk drivers and their dynamic feedbacks established in WP4, as well as establishes the agreed problem framing with which to assess risks and formulate pathways. The approach serves as a general roadmap for potential users to adapt to their specific needs, capabilities and resources. It reflects the three stages of the DAPP-MR approach and serves as a means by which to undertake its first step (describing the decision context, see Figure 14 later in this report). It similarly serves to support implementation of the WP2 MYRIAD-EU framework for systemic multi-hazard and multi-risk assessment and management (Hochrainer-Stigler et al., 2023, see also Section 3.2).

The approach is intended to satisfy the following (5) requirements:

- To be capable of representing the holistic, integrated system and its key functions, risks, and opportunities.
- To highlight the key interdependencies and interactions between system components, including all feedbacks, trade-offs, and synergies.
- To generate a common, shared understanding of the integrated system and its objectives among stakeholders.
- To serve to prioritise key system functions, objectives, constraints, risks, and opportunities.
- To be flexible to the needs of various users and permit the incorporation of various supporting tools and approaches with which its users are familiar and comfortable.

Collaboration (and negotiation) plays a critical role in the approach. System 'models' can only adequately and legitimately include those values, interests, and perspectives of those sectors or stakeholders that are represented in the analysis. Their priorities and interests can be promoted and negotiated while those of any which are absent can easily be neglected. Likewise, the involvement of a wide range of actors and interests can lead to the identification of novel and innovative cross-sector solutions that would otherwise not be considered in single-sector settings. It is therefore critical that any systems analysis process is founded upon sound principles of stakeholder analysis and engagement. In addition to allowing for the inclusion of a broad range of interests and perspectives, doing so reduces the potential for conflict to emerge between competing sectors by opening channels of communication, generating mutual understanding, and helping to negotiate compromise solutions. By developing and agreeing upon a common conceptual model of how a system functions, credible and effective solutions can then be identified and implemented with the support of all sectors and stakeholders. While it is not the intention of the proposed approach to include activities relating to completing risk assessments, risk evaluations, and options assessments, analogous participatory assessment methods may also be used to complement the approach through, for example, participatory modelling techniques.

The MYRIAD-EU collaborative systems analysis approach consists of the following three principal iterative steps, gradually increasing the degree of system complexity being considered in each step (Figure 1):

1. Define system boundaries and constraints
2. Undertake sector-based analyses
3. Synthesise sector-based analyses into a whole-of-system analysis

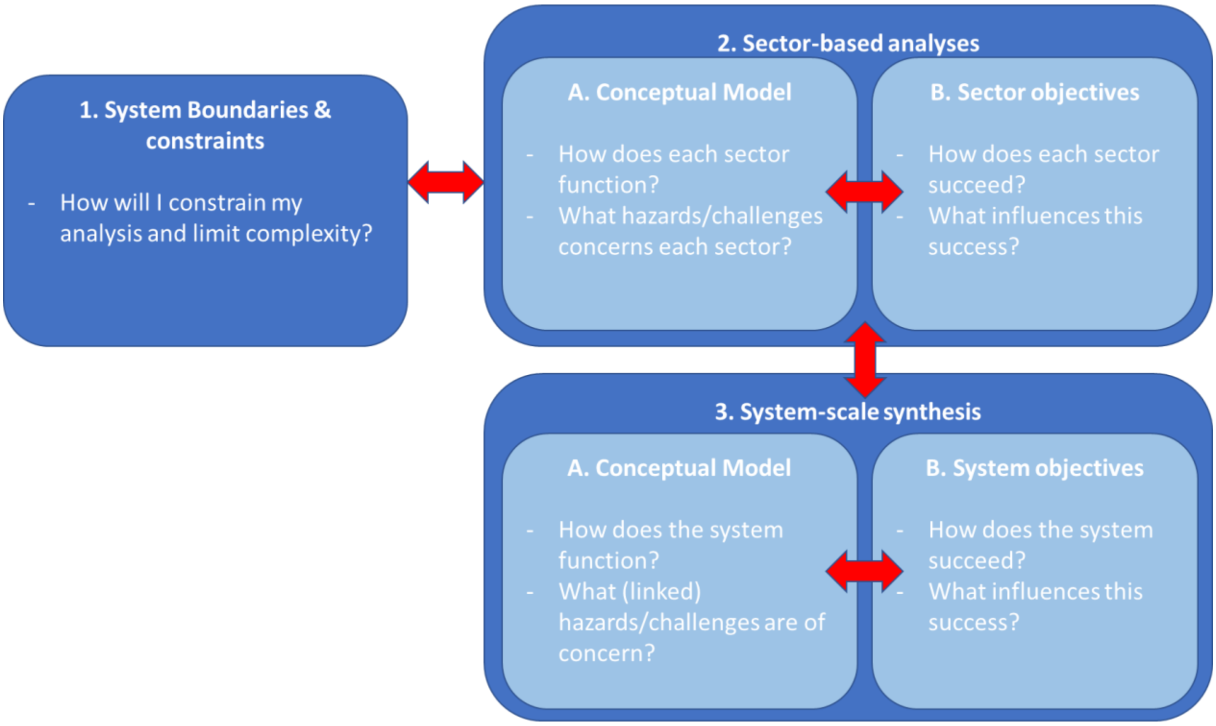
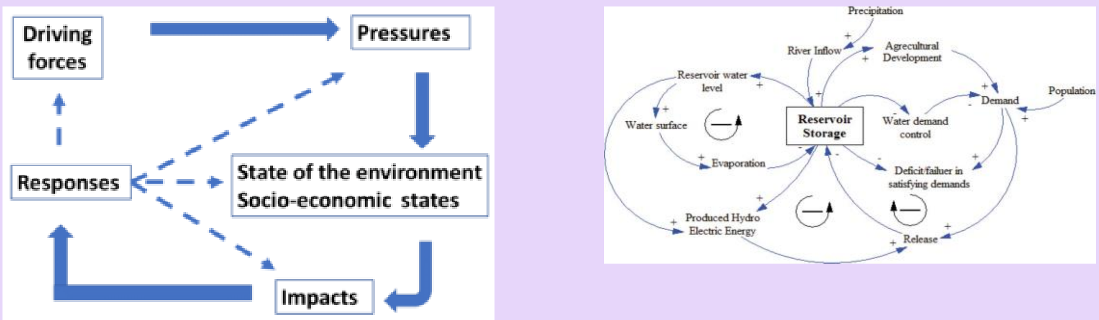


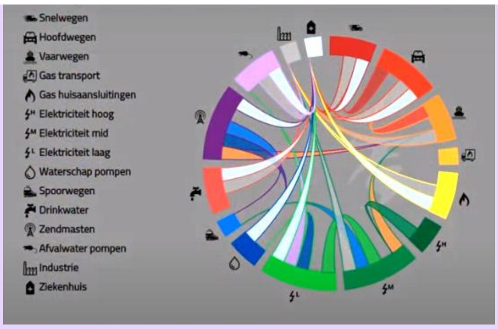
Figure 1: MYRIAD-EU Collaborative Systems Analysis approach

Although these steps are presented sequentially, the expectation is that the analytical process will be highly iterative. Appendix A presents a detailed description of the three steps presented above, along with suggested tools and question prompts to guide practitioners. Highlighted tools include the *DPSIR framework* for analysing causal relationships, *Causal Loop Diagrams* for visualising system causalities, and *CIrcle* and *Interaction Matrices* for exploring system interactions (Figure 2). Note that the generic approach should be treated as a suggestion only, from which an approach specific to each situation can be tailored according to practitioner needs, skills and preferences. That is, practitioners are invited to adapt or use the suggested (or alternative, if preferred) methods, tools, and guidance questions to yield the necessary information to define the integrated decision contexts for their multi-risk, multi-sector systems.

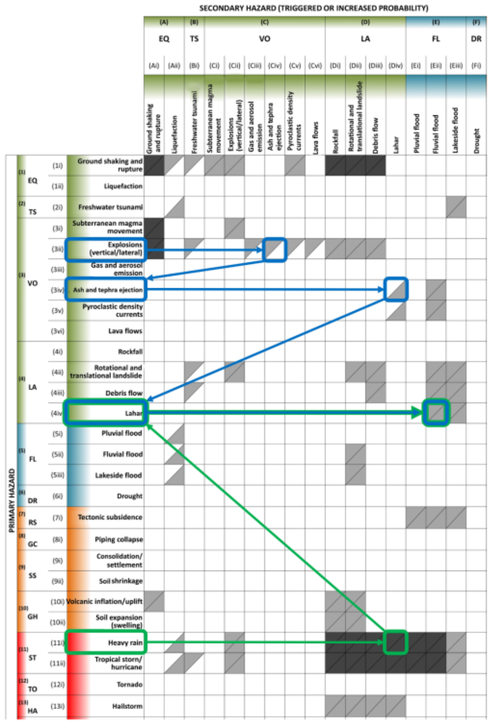


(a) DPSIR Framework of causal relationships (Source: EC, 1999)

(b) Example causal loop diagram for water management (Source: Felfelani et al., 2013)



(c) CIrcle interactions analysis (Deltares, 2022)



(d) Example of an interaction matrix for hazard cascade (Gill et al., 2020)

Figure 2: Highlighted tools within the suggested collaborative systems analysis approach

2.2.2 Undertaking collaborative systems analysis in pilot regions

(Adapted) applications of the collaborative systems analysis approach commenced in each of the pilots during the first Pilot Workshops (PW1), conducted in November 2022. This was followed by further activities during the Focus Group Discussions (FG1 & FG2) during November-December 2023 and March-June 2024. Collaborative systems analysis activities undertaken both during and in preparation of these events served to assist each pilot with:

1. Identifying the needs of each pilot's Pilot Core User and Pilot Stakeholder Groups.
2. Prioritising the research questions, challenges, and opportunities to be confronted in each pilot.
3. Supporting implementation of the MYRIAD-EU framework for multi-hazard, multi-sector, systemic risk management and the development of forward-looking multi-risk pathways.

Key outcomes of PW1, FG1 and FG2 are provided in the following MYRIAD-EU milestone reports and deliverables:

- *MS11 Pilot Workshop 1 completed and feedback to WP2, 4-6* (Ciurean et al., 2022).
- *MS13 Focus Group 1 completed and feedback to WP2, 4-6* (Ciurean et al., 2023)
- *MS14 Focus Group 2 completed and feedback to WP2, 4-6* (Ciurean et al., 2024)
- *D3.3b Interim report on implementation and testing of MYRIAD-EU methods and tools in each Pilot* (Gottardo et al., 2024)

A brief outline of the work conducted in each of the pilots relevant to this deliverable is included in the paragraphs below.

2.2.2.1 North Sea

The North Sea pilot incorporated collaborative systems analysis activities into its approach to clearly identify the elements to be included in the analysis (and those to be excluded), as well as to define current challenges, identify potential solutions and hazard/multi-hazard scenarios of interest.

In terms of tools, the pilot predominantly applied **causal relationship diagrams**, **storylines** and **interaction matrices**. During PW1 the system boundaries were identified in terms of their geography, sectors and timeframe. In addition, the first steps were taken for identifying the relevant hazards and initial causal relations for the North Sea region. These discussions continued during FG1, where stakeholders also utilised a storyline approach to identify relevant hazards for each sector. As these discussions took place in person, standard workshop tools (whiteboards, markers, flipcharts, post-its) were used to support the analysis, with these outputs later translated into digital versions using digital drawing tools. During FG2 a synthesised Causal Chain Diagram was presented to the stakeholders for validation (Figure 3), and interaction matrices were applied to analyse any interdependencies between potential risk management options across sectors to inform the formulation of pathways (Figure 4). The latter served as a first step towards the multi-risk pathways, as it assisted in identifying measures that might enhance, obstruct or limit the implementation of others across all sectors.

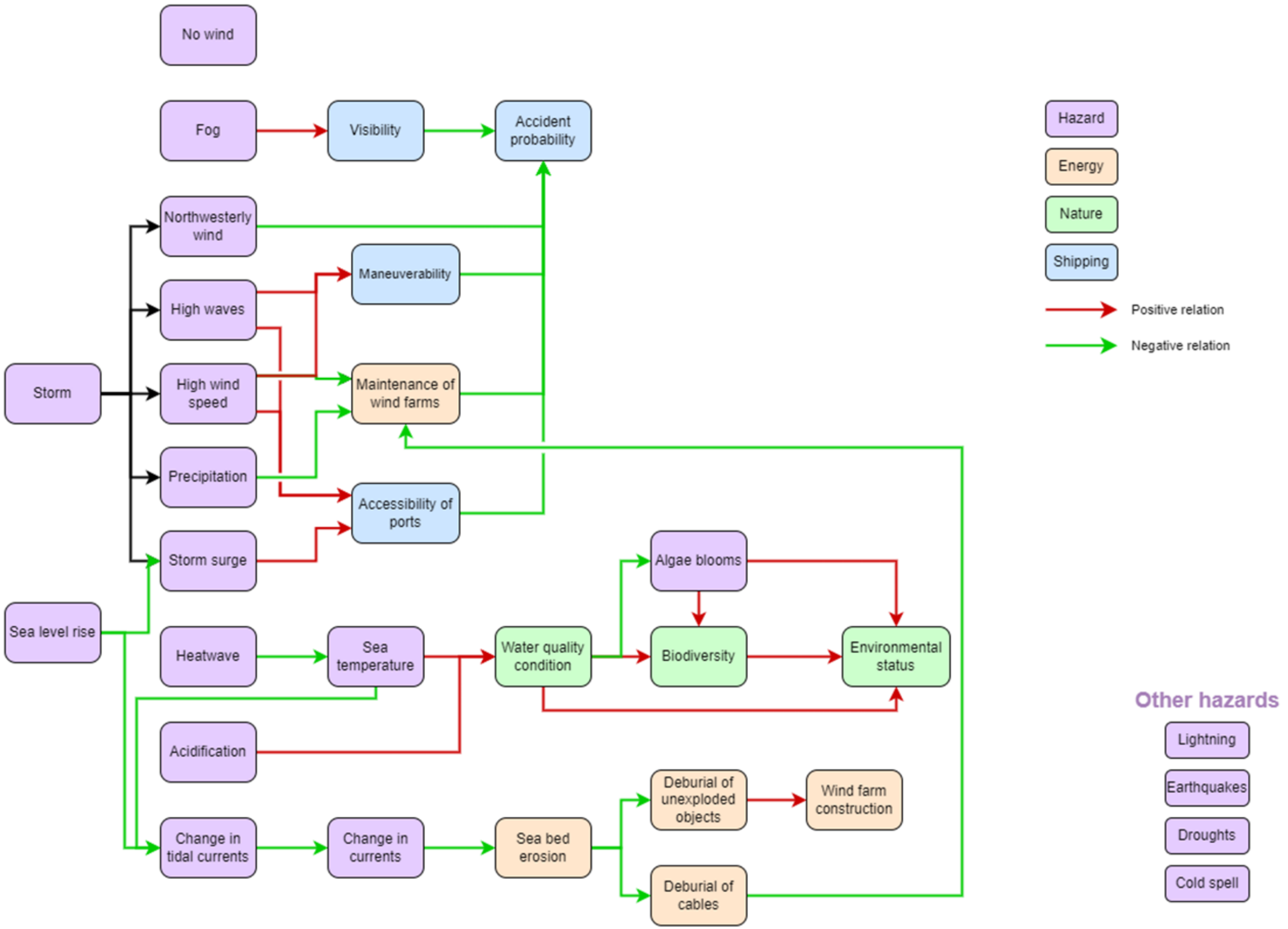


Figure 3: Causal Chain Diagram of the Collaborative Systems Analysis of the North Sea with hazards identified by stakeholders during the PW1 and FG1 workshops

	Shipping	Sensors in windfarm	Better surveillance by coastguard	Training of crew	Increase towing capacity	Opening windfarms for shipping	Marine traffic system	Increase designated clearways	Increase safety zones around built infrastructure	Increase seperation zones between shipping lanes	Widening shipping lanes	More manoeuvrable ships	Smaller ships	Bigger ships	Energy	Bigger wind turbines	Increase efficiency of wind turbines	Optimization of wind turbine positioning	Low maintenance offshore wind infrastructure	Floating wind turbines	Back-up cable	Bury cables deeper	Anti deburaial measures	Alternative sources of offshore renewable energy	Hydrogen production	Optimizing energy trade between countries	Ecosystem	Increase MPAs	Stricter regulation for MPAs	Stricter enforcement of MPAs	Ban seabed disturbing activities	Decrease runoff from land	Waste (water) management	Measures to prevent oil spills	Underwater noise reduction	Nature restoration	Combat invasive species
Shipping																																					
Sensors in windfarm															0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
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	0	0
Training of crew															0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Increase towing capacity															0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Opening windfarms for shipping															-	?	0	0	0	0	0	0	0	-	-	0	?	?	?	0	0	0	0	0	?	?	0
Marine traffic system															0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Increase designated clearways															?	0	0	0	0	0	0	0	0	?	0	0	0	-	0	0	0	0	0	0	0	0	0
Increase safety zones around built infrastructure															?	0	0	0	0	0	0	0	0	-	-	0	0	0	0	0	0	0	0	0	0	?	0
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	0
Widening shipping lanes															-	0	0	0	0	0	0	0	0	-	0	0	?	?	0	0	0	0	0	0	0	?	0
More manoeuvrable ships															0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Smaller ships															+	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Bigger ships															?	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Energy																																					
Bigger wind turbines	0	0	0	0	0	?	0	0	0	0	0	0	0	0													?	0	0	0	0	0	0	0	0	0	0
Increase efficiency of wind turbines	0	0	0	0	0	0	0	0	0	0	0	0	0	0													0	0	0	0	0	0	0	0	0	0	0
Optimization of wind turbine positioning	0	0	0	0	0	0	0	0	0	0	0	0	0	0													0	0	0	0	0	0	0	0	0	0	0
Low maintenance offshore wind infrastructure	+	0	0	0	0	?	0	0	0	0	0	0	0	0													0	0	0	0	0	0	0	0	0	0	0
Floating wind turbines	0	0	0	0	0	0	0	0	0	0	0	0	0	0													0	0	0	0	0	0	0	0	0	0	0
Back-up cable	0	0	0	0	0	0	0	0	0	0	0	0	0	0													0	0	0	0	0	0	0	0	0	0	0
Bury cables deeper	+	0	0	0	0	0	0	0	0	0	0	0	0	0													0	0	0	0	0	0	0	0	0	0	0
Anti deburaial measures	0	0	0	0	0	0	0	0	0	0	0	0	0	0													0	0	0	0	0	0	0	0	0	0	0
Alternative sources of offshore renewable energy	?	0	0	0	0	-	0	0	0	0	?	0	0	0													?	0	0	0	0	0	0	0	0	0	0
Hydrogen production	?	0	0	0	0	?	0	0	0	0	0	0	0	0													0	0	0	0	0	0	0	0	0	0	0
Optimizing energy trade between countries	0	0	0	0	0	0	0	0	0	0	0	0	0	0													0	0	0	0	0	0	0	0	0	0	0
Ecosystem																																					
Increase MPAs	0	0	0	0	0	0	0	?	?	?	?	0	0	0	-	0	0	0	0	0	0	0	0	-	0	0											
Stricter regulation for MPAs	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0											
Stricter enforcement of MPAs	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0											
Ban seabed disturbing activities	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-	?	0	0	0	0	?	?	?	?	?	0											
Decrease runoff from land	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0											
Waste (water) management	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0											
Measures to prevent oil spills	?	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0											
Underwater noise reduction	-	0	0	0	0	?	0	0	0	0	0	0	0	0	-	0	0	0	0	0	?	?	?	?	0	0											
Nature restoration	0	0	0	0	0	-	0	0	0	0	?	0	0	0	?	0	0	0	0	0	0	0	0	?	0	0											
Combat invasive species	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0											

Figure 4: Cross-sectoral Risk Management (interaction) Matrix for the three North Sea sectors, Energy, Nature and Shipping & Transport

2.2.2.2 Canary Islands

The Canary Islands was the one pilot that implemented an approach for collaborative systems analysis that most closely resembles that presented in section 2.2.1 and Appendix A. As with the North Sea pilot, **causal relationship diagrams** served as the foundation for its approach, and it developed these first for each sector before synthesising these into an overall system diagram (Figure 5, Figure 6 and Figure 7).

This pilot also extended the generic approach with additional activities to forensically explore impact chains and vulnerability factors resulting from three specific past event case studies, via a **storyline approach**. In doing so the pilot was able to refine the system boundaries and constraints, identify additional system interactions and interdependencies otherwise missing from its initial conceptual analysis, and better identify main future challenges in the face of climate change and sustainable development objectives (Figure 8).

Finally – similar to the North Sea pilot – **interaction matrices** were applied to analyse the interdependencies between potential risk management options across sectors to inform the formulation of multi-risk pathways.

System boundaries and constraints

	Biophysical dimension	Socioeconomic dimension	Institutional dimension
Functions	- Marine and terrestrial biodiversity - Hazards (storms, volcanoes, droughts…) - Water resources (7 island basins, groundwater, sea water desalination) - Natural parks and protected land - Volcanic origin - Soil properties	- Water supply - Energy supply - Food production - Health services - \Tourism services (increase scale of consumers and foreign currency) - Transport and connectivity - Recreational services - Sociocultural services	- Convergence of employment and income conditions - Design local incentives (POSEL, REA, REF, others) - Disaster risk management - Territorial planning competencies
Characteristics	- Territorial fragmentation - Insularity and remoteness - Endemism - Water and soil scarcity - Environmental degradation	- Dependence on external sources (tourism, agro-food, and energy) - Low sectoral diversification - High carbon intensity - Tourist diversification (products) - High unemployment rates	- Governance complexity (EU… municipalities) - Regulatory capture - Autonomy (competencies) - Geopolitical & strategic features (e.g., migration, Africa-America axis)
Restrictions	- Climate patterns (temperature, rainfall, wind) - Relief characteristics (slopes and coastal plains)	- Difficulty in renewable energy penetration - Low economies of scale (energy, water, and agriculture)	- Need for regulatory adaptation (and incentives) to islands - Low capacity for structural changes

Figure 5: Defining the system boundaries and constraints

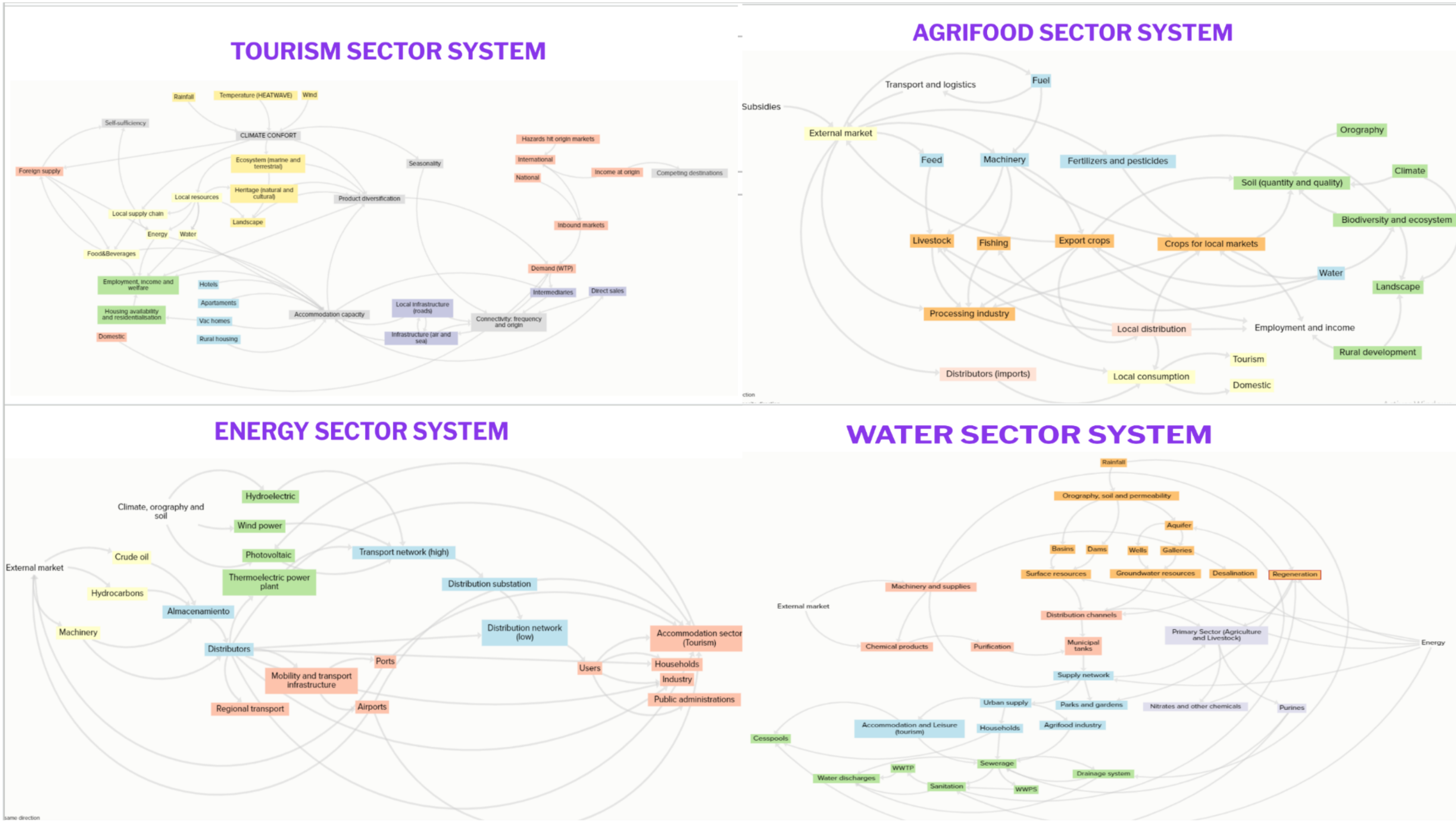


Figure 6: Sector analyses of causal relationships

SYSTEM SYNTHESIS

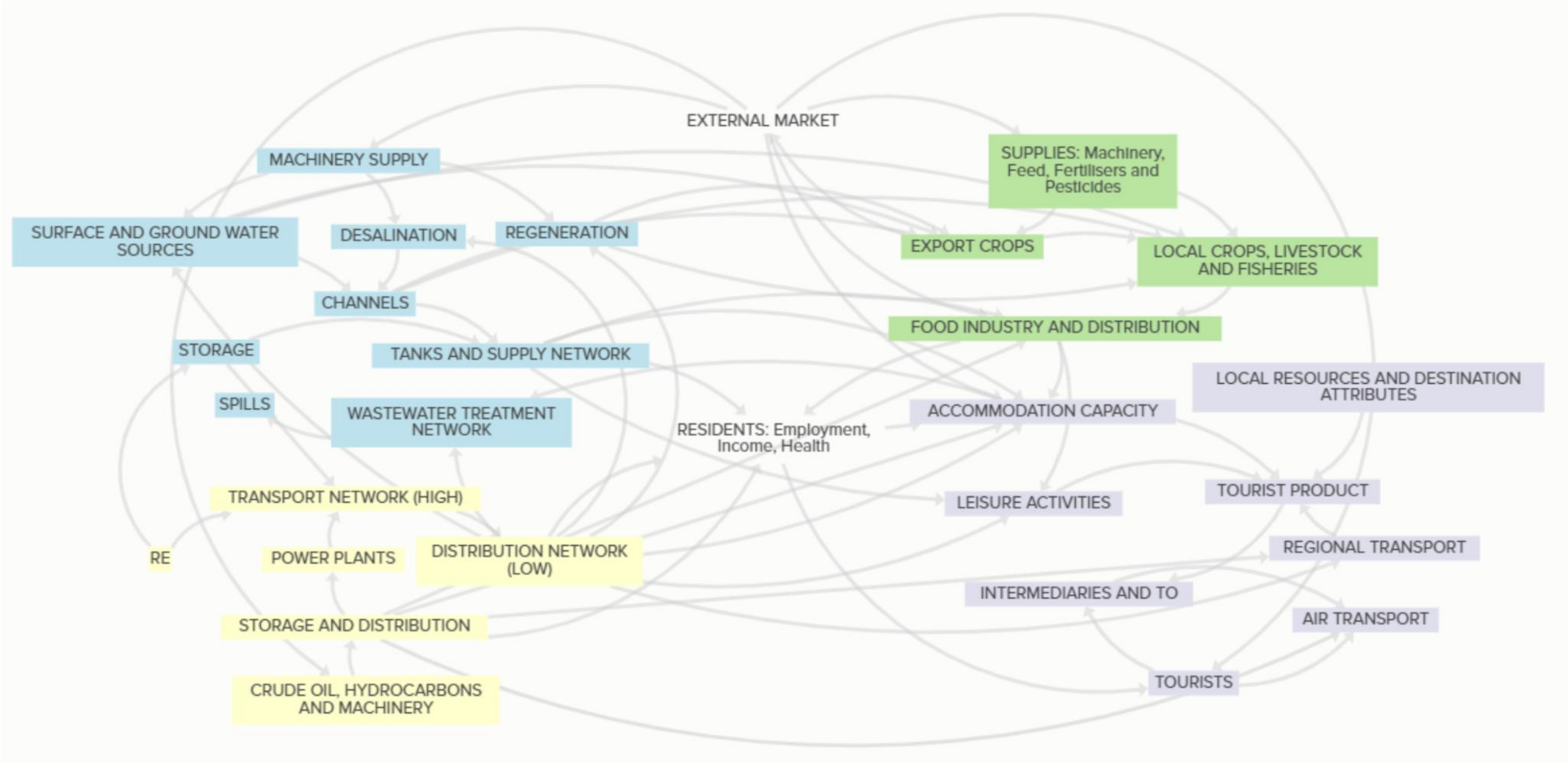


Figure 7: Synthesised system analysis of prioritised causal relationships

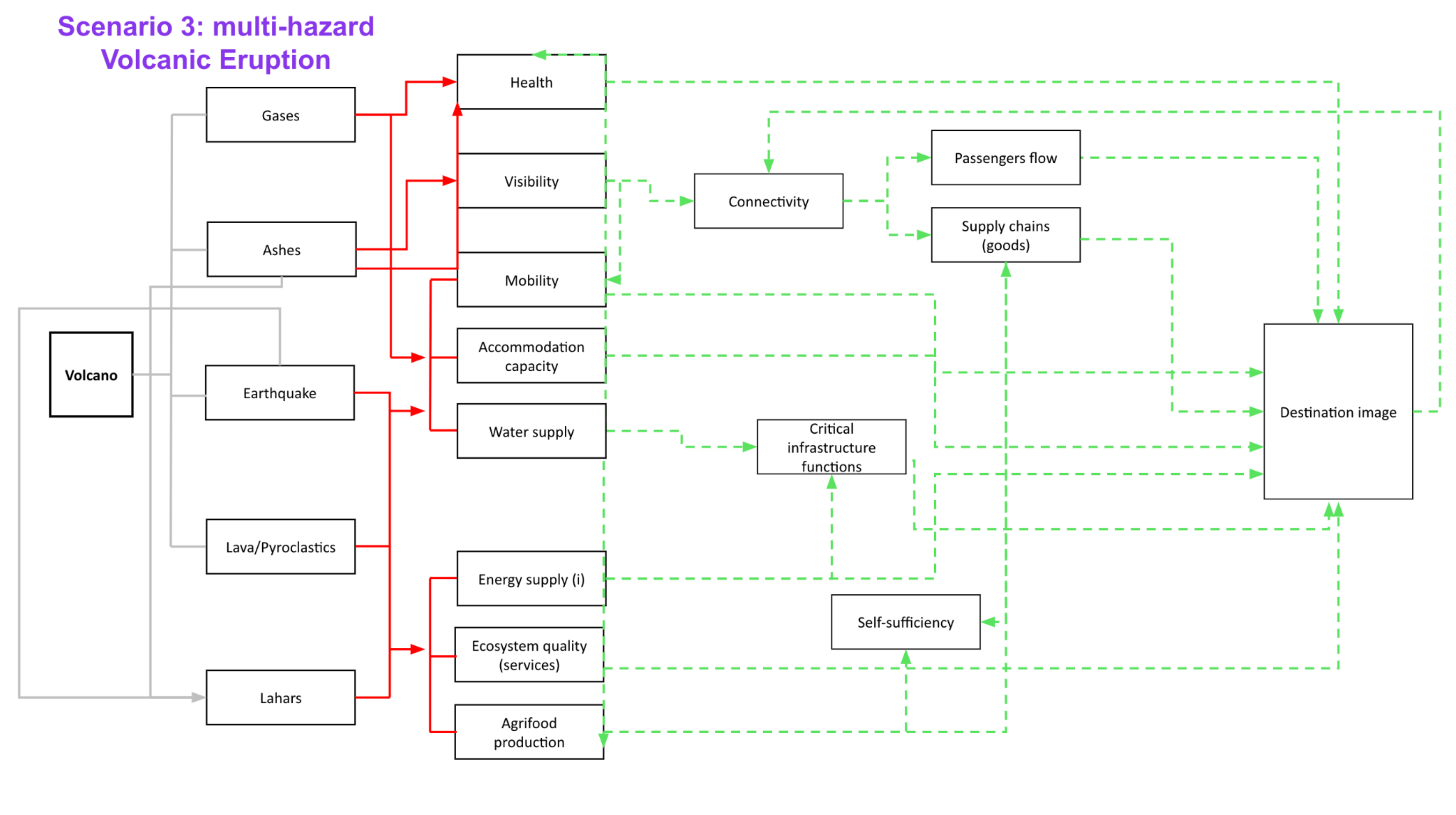


Figure 8: Example system map of vulnerability factors identified through forensic scenario exploration

2.2.2.3 Scandinavia

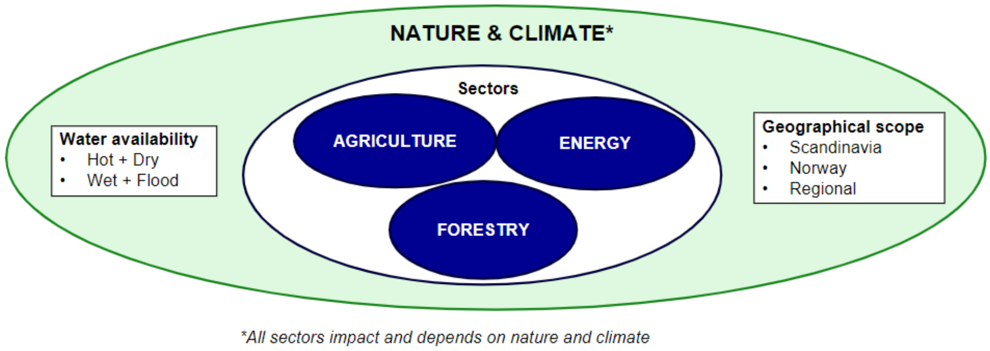
The Scandinavian pilot utilised predominantly discursive methods to explore system boundaries, sector and hazard interactions, and impacts together with stakeholders. The pilot did not develop (nor present) complex causal relationship diagrams, but rather simplified these to **schematically represent key system components, direct and indirect climate risks** (Figure 9). We understand that this is in part due to application of the GRACE model within the pilot to model risk impacts, such that many relationships were already well established. During FG1 and FG2, the pilot also employed a **storyline approach** to combine the quantitative data from the GRACE model with more qualitative information to better explore and enrich its analysis and development of multi-risk pathways. Although not yet undertaken, the pilot also proposes to make use of **interaction matrices** to explore interactions between risk management options across its three sectors, as well as **scorecards** to evaluate the capacity of these options to deliver broader sustainable development and climate change mitigation targets, as well as any barriers to their implementation.

2.2.2.4 Danube

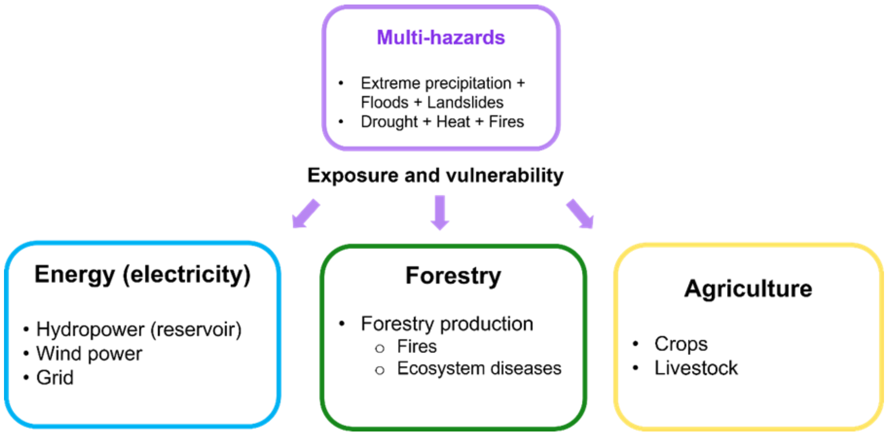
The Danube pilot undertook collaborative systems analysis activities primarily during PW1 and FG1. Causal impact chains were discussed through application of the **DPSIR framework**. This was achieved through virtual exercises conducted via the collaborative digital whiteboard software Miro. These activities were used to, variously (Figure 10 and Figure 11):

- inform sectoral system overviews for each sector, including their key drivers, causal relations, objectives and potential responses.
- establish **casual relationships** relating to the two hazards of focus, floods and droughts.
- **collect stakeholder perspectives on** the **direct impacts** of hazards on sectors.
- **prioritise risk impact metrics** to be used in the assessment.

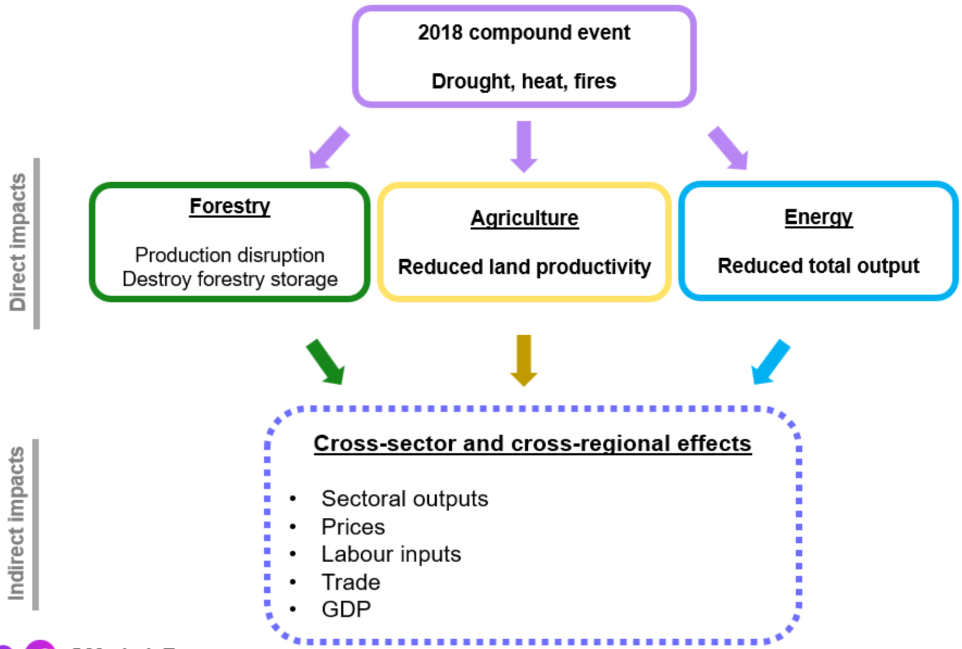
Outputs from these sessions were then used to inform the specification of quantitative scenarios and the development of the Agent-Based Model (ABM) within WP5 to quantify various indirect risks associated with flood damages in the Danube region.



(a) System components



(b) Direct climate risks



(c) Indirect climate risks

Figure 9: Schematics illustrating (a) system components), (b) direct climate risks, and (c) indirect climate risks analysed in the Scandinavian pilot

(a)

Agriculture sector						
Drivers of future change	Increased policy emphasis on the reduction of environmental and climate footprint of the food system	Overall increase in agricultural production	Increase in frequency and severity of hydrometeorological extremes, namely floods and droughts			
Causal relations	Droughts reduce yields + water availability for irrigation = in income losses + increase food prices	Floods destroy yields, equipment + infrastructure = income losses + increased food prices	new irrigation infrastructure exacerbates negative effects of consecutive droughts	excessive fertilizer use during droughts diminishes soil heath (e.g. salinization)	Flood- and drought-induced erosion as a pathway for pollution transport	excessive water use due to droughts leads to negative ecological impacts
Objectives	Minimizing crop losses	Achieving good soil conditions	Securing water availability	Reducing nutrient pollution	Minimising income losses for farmers and agricultural companies	
Responses	Crop management practices	Water management	Soil conservation and management	Risk management and financial instruments	Flood proof infrastructure	Further flood and drought management

(b)

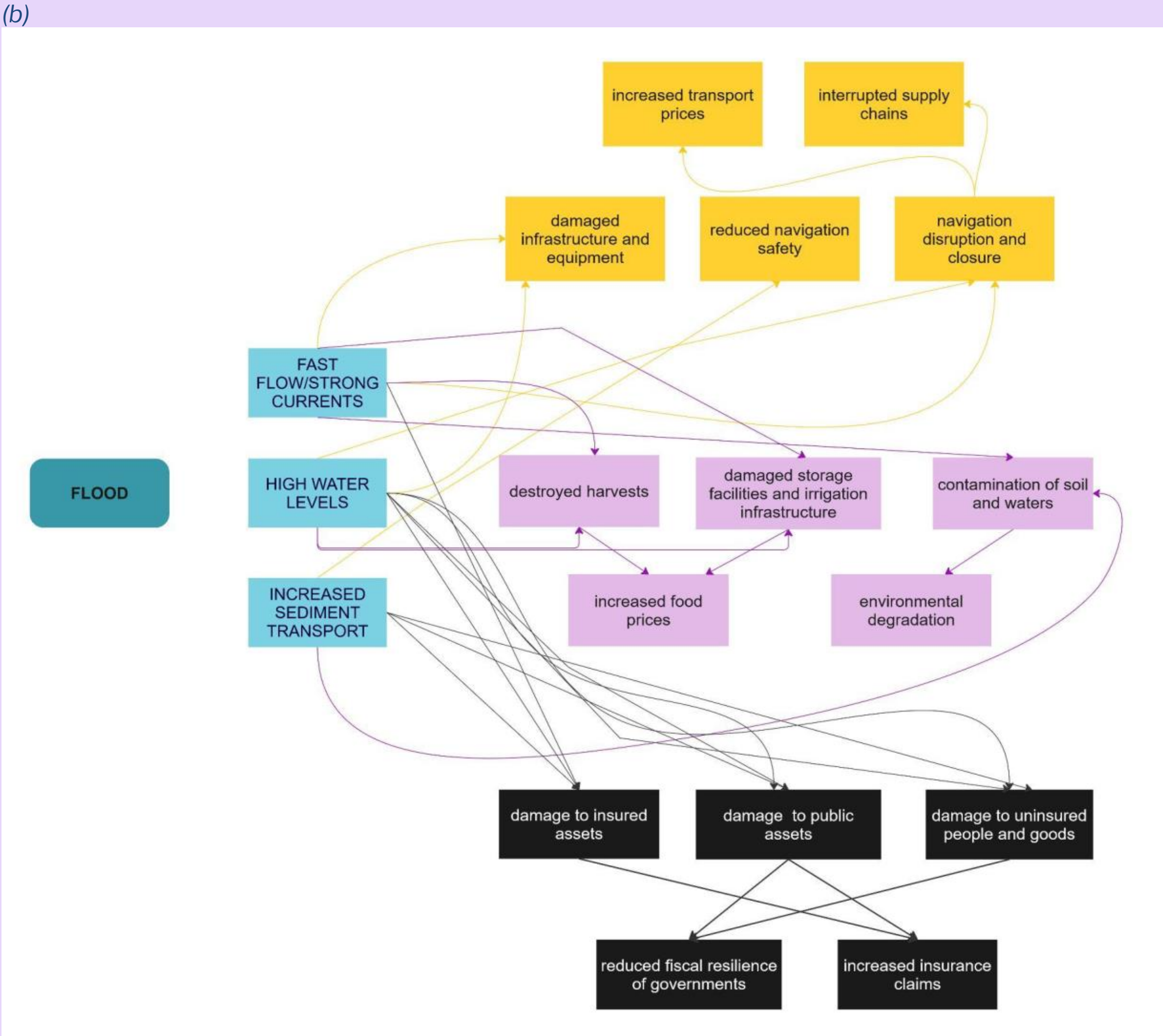


Figure 10: Example outputs from collaborative systems analysis activities in the Danube pilot. (a) Formulation of summarised sector overviews, (b) Development of hazard causal relationship diagrams

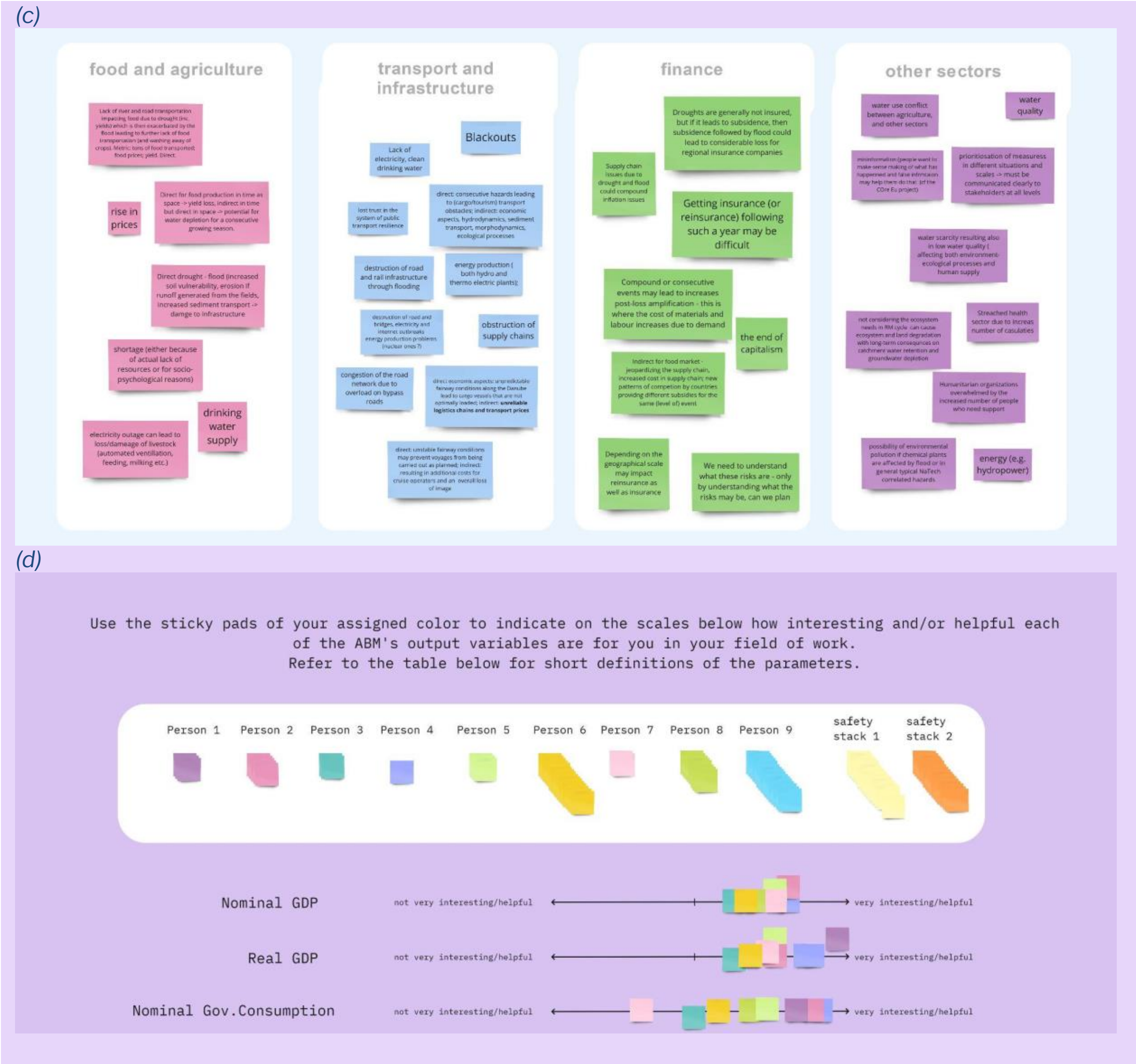


Figure 11: Example outputs from collaborative systems analysis activities in the Danube pilot., (c) Identification of direct hazard impacts, and (d) Prioritisation of risk metrics for use in the assessment.

2.2.2.5 Veneto

The Veneto pilot primarily applied collaborative systems analysis tools and methods during PW1 to help with system definition. These activities combined the **DPSIR framework** with **causal relationship diagrams** to establish the conceptual model for risk drivers in the pilot (Figure 12). As PW1 took place in-person in this pilot, small group discussions supported by flip charts, markers and post-its were used to gather initial inputs to inform development of the final conceptual model of the main hazards, their interactions, affected biophysical and socioeconomic parameters, and sector-based impact metrics in the pilot. This model could then be used to inform the development of the machine learning model to be applied for the quantitative assessment of risk impacts.

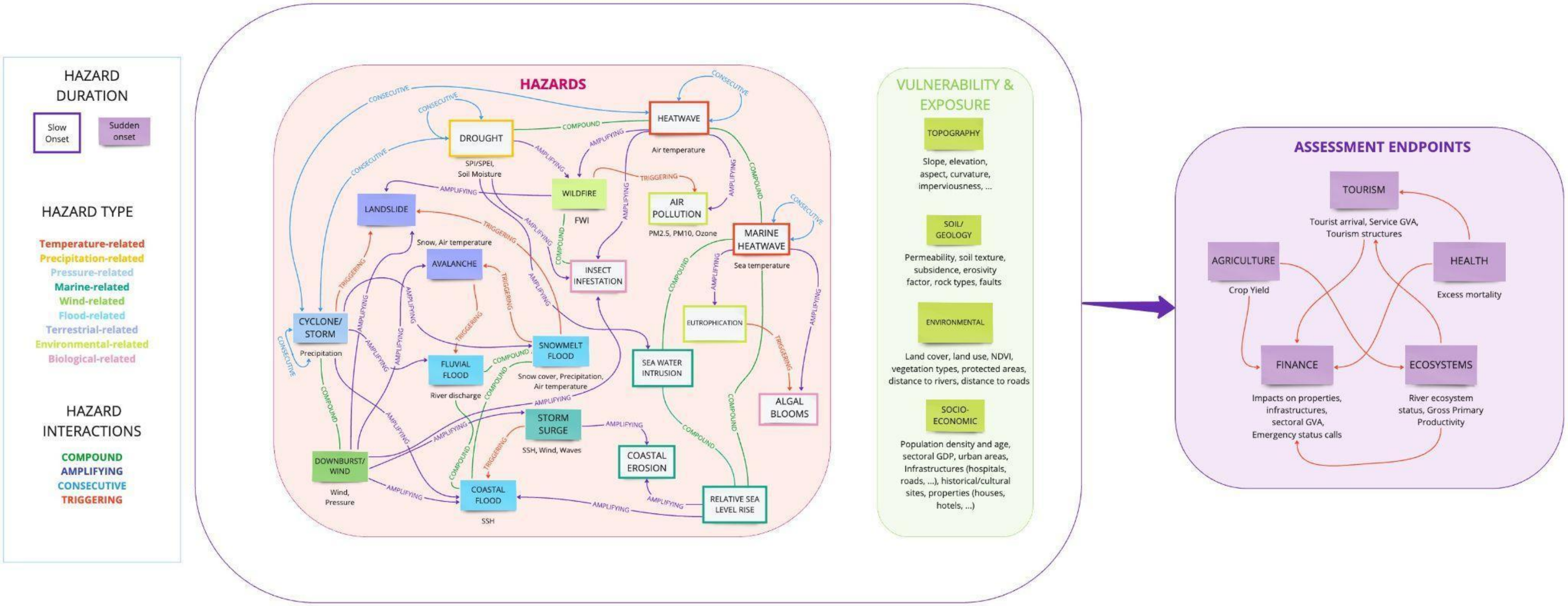


Figure 12: Conceptual risk model for the Veneto Pilot

The above analysis was enriched during FG1 and FG2 through application of a **storyline approach** to assist in the examination of specific system interactions relating to a recent historic hazard event (2018 Vaia storm). From these discussions, the pilot was able to gather additional information – in some instances not publicly available – to better characterise the event and its impacts across the region.

2.2.3 Observations following application of collaborative systems analysis in the pilots

Based on the experiences of the pilots in applying collaborative systems analysis activities together with their respective groups of stakeholders, we make the following observations:

- The tools which the pilots made the most use of included the DPSIR framework, causal relationship diagrams, storyline approaches, and interaction matrices. We note that these are tools that were either recommended as part of the generic MYRIAD-EU approach, are typically tools with which pilot leads were already familiar, or (in the case of the storyline approach) provide a new, intuitively accessible and tangible means by which to qualitatively explore system dynamics. This makes sense, and further underlines the intention of the generic approach: that practitioners should tailor the approach according to their own specific needs, skills and preferences. It matters not which specific tools are applied, but rather that the five objectives (refer to section 2.2.1) of collaborative systems analysis are achieved.
- Although a new approach for many of the pilot leads, the storyline approach was enthusiastically adopted by all the pilots to assist in the investigation of risks, impacts and actions taken in relation to past multi-hazard events, and to then use this information to explore plausible future scenarios. It has proven to be both an effective and flexible tool and was well-received by stakeholders. The North Sea pilot also emphasised its particular utility in data scarce decision contexts, and also in contexts when there is poor pre-existing stakeholder understanding of potential future threats and the need for adaptation.
- Most of the pilots reported having to revisit their systems analyses across multiple iterations as they encountered assessment challenges, or new information came to light. This seeks to emphasise that these types of processes are not linear, and that their outputs are subject to constant revision and update.
- We recognise that implementing the entire generic approach for collaborative systems analysis takes quite some time within a workshop setting. We estimate that at least a full one-day workshop would be needed to undertake a single iteration of the participatory activities suggested under the three steps. In many instances this may not be possible, such that the approach may need to be adapted to occur across multiple sessions, or alternatively streamlined to the time available. Some pilots expressed an interest in the development of a shortened version; however, the pilots also highlighted the value of discussing the issues covered by the proposed approach in full together with stakeholders to establish consensus on system boundaries, functions, and other complex characteristics.
- The pilots remarked that collaborative systems analysis activities demand strong and effective facilitation to lead discussions and help to synthesise system complexities for stakeholders. Sufficient time and resources need to be allocated to both the execution of these activities together with stakeholders, and also the preparation for these interactions. Conducting workshops and focus groups such as these demands the ability to flexibly adapt the programme to the needs and responses of the participants.

2.3 DAPP-MR

The following section is based on two published works and one ongoing work as summarised in Table 1.

Table 1: Published works relating to DAPP-MR

Authors	Title	Publication Date
Schlumberger, J., Haasnoot, M., Aerts, J., de Ruiter, M.	Proposing DAPP-MR as a disaster risk management pathways framework for complex, dynamic multi-risk	2022
Schlumberger, J., Haasnoot, M., Bril, V., van der Weide, L., Aerts, J., de Ruiter, M.	Evaluating Adaptation Pathways in a Complex Multi-Risk System	2024
Schlumberger, J., Aerts, J., Trogrlic, R., Hyun, JH, de Ruiter, M., Hochrainer-Stigler, S., Haasnoot, M.	Evaluating Multi Risk Pathways using Visualizations	ongoing
Schlumberger, J., Warren, A., Dialoz, AS., Ma, L., Tatman, S., Geurts, D., Trogrlic, RS., Reiter, K., Hochrainer-Stigler, S., Padron, N., Vaquero, MG., Gottardo, S., Torresan, S.	Lessons learned from developing quantitative multi-risk pathways in diverse European regions	ongoing

It commences by describing the development of the analytical framework to guide the formulation of multi-risk adaptation pathways (DAPP-MR), before presenting evidence on the utility of the framework gathered through a synthetic case study. It then discusses the search for improved ways for communicating the complexity represented by multiple multi-risk pathways, before discussing applications of the approach within the pilot regions in the project.

2.3.1 Developing an analytical framework

Building on the existing Dynamic Adaptation Policy Pathways (DAPP) approach, DAPP-MR is proposed to guide the assessment and evaluation of multiple adaptation pathways to current and future multi-risk challenges. The approach aims to systematically consider the three key themes relevant to the design of multi-risk DRM pathways: (1) the effects of multiple, interacting hazards; (2) the dynamics and interdependencies of sectors; and (3) the trade-offs and synergies of DRM policy options across different sectors and different spatial and temporal scales.

To account for the potential **effects of interacting hazards** while developing adaptation pathways, it is important to be able to characterise natural hazards in terms of hazard drivers, and hazard-related impact drivers (Murray et al., 2021) and their temporal and spatial scales to identify where interactions of hazards-related impact drivers can be expected (Gill and Malamud, 2014; de Angeli et al., 2022). **Interrelations of stakeholders** are mostly linked to impact interrelations, driven by connectedness and multi-vulnerability characteristics. Different types of multi-sectoral interrelations make sectoral systems differently prone to impact-driven interrelations. It is important to consider decision-making beyond risk management, as it drives changes in existing systems. It, therefore, affects the exposure and vulnerability of interdependent system elements, influencing not only the individual risk of a sector but also the cross-sectoral systemic risk. Adaptation or risk reduction measures cannot be considered in isolation because of synergies across time, space, and sectors as well as because of potential asynergies, defined as "the potential adverse effects of measures aimed to decrease the risk of one hazard on the risk of another hazard" (de Ruiter et al., 2021, p. 1). **These trade-offs and synergies of DRM options** require the balancing of needs and interests beyond risk management. Different stakeholders will have mandates and resources for different policy options and might value the benefit of adaptation differently in different contexts.

We assessed the capability of the analytical steps of DAPP to integrate these three themes. These aspects were attributed to one or more analytical steps of DAPP. It is important to note that hazard- and vulnerability-related interactions require additional information and iterations per analytical step. Furthermore, we discussed that the increased amount of information and cross-step interconnectedness may require additional, iterative considerations when developing DRM pathways for complex, dynamic multi-risk. Accordingly, we propose DAPP-MR consisting of a rearrangement of the seven steps of DAPP. In addition to the original iterative steps of DAPP, three stages of iterations are included to characterise the decision context, vulnerabilities, and opportunities, potential promising policy options and promising pathways:

- Stage 1: DAPP-MR starts with a single-sector, single-hazard perspective.
- Stage 2: Subsequently, all single-hazard considerations are integrated per sector to result in a single-sector, multi-hazard perspective.
- Stage 3: The single-sector, multi-hazard information is integrated into a multi-sector, multi-hazard perspective.

2.3.2 Providing evidence regarding the utility of the developed framework

DAPP-MR has been applied in a synthetic multi-risk case study to prove its utility. An integrated assessment meta-model was used to quantitatively stress test potential DRM adaptation measures and pathways, with these evaluated according to one or two criteria: pathway robustness across all stages of the analysis, and pathway interdependency across stages 2 and 3. The results highlighted the complexity of assessing the effectiveness of flood and drought risk reduction measures, particularly in the context of multi-hazard interactions. The interactions between different pathways, their timing, and the presence of other sector-hazard DRM measures all play significant roles in determining overall outcomes. However, the staged approach helps to illuminate pathways that remain valid under increasing complexity.

We applied DAPP-MR to develop and evaluate pathways in a synthetic multi-risk test case, which was conceptualised using the Drivers-Pressure-State-Impact-Response (DPSIR) framework (Smeets & Weterings, 1999) . As a multi-risk test case, we build on the existing "Waas" test case, based on a fictional river stretch in the Netherlands, adding interaction effects of floods and droughts as well as their impacts on different sectors. We employ a model-based approach to investigate how multi-hazard and multi-sectoral interactions affect the flexibility and robustness of DRM strategies, see **Error! Reference source not found.**.

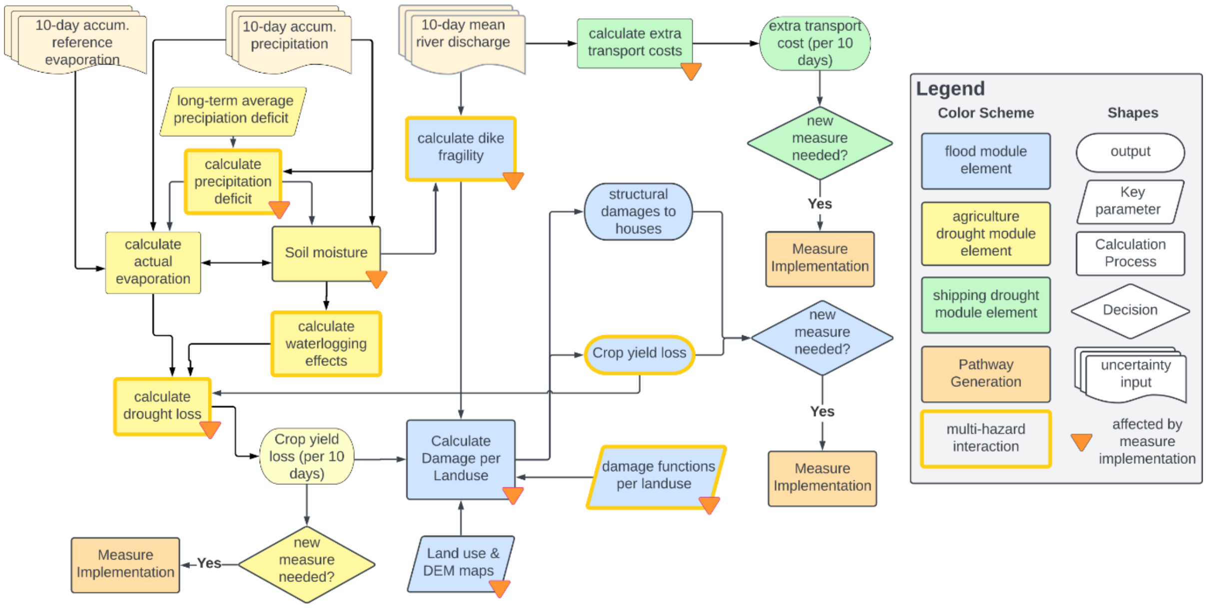


Figure 13: Simplified representation of the Waas-MR integrated assessment meta-model inputs, processes, decisions, and outputs. Processes or parameters affected by multi-hazard interactions or the implementation of Disaster Risk Management measures are highlighted. Copied from Schlumberger et al. (2024)

In the case study, we focused on step 4 of DAPP-MR (Develop & Evaluate Pathways) as shown in **Error! Reference source not found.**. Exploring the implications of interactions in complex systems for DRM decision-making, we offered insights into the benefits and limitations of the DAPP-MR approach. The results of this test case underscore the significance of the interplay between hazards, risks and measures in determining the timing and nature of measure implementations. It is clear from the analysis that multi-hazard and multi-sector interactions significantly influence pathway viability. However, when accounting for droughts, drought risk strategies and other sectors, additional viable alternatives emerge that alter best performance assessments. For example, Medium flexible pathways scalable with external climate scenarios are promising for the agricultural sector alone, however, more robust and less flexible pathways become attractive under a multi-sectoral perspective. This case-specific finding suggests the need for further investigation into the dynamics of specific measure interaction effects.

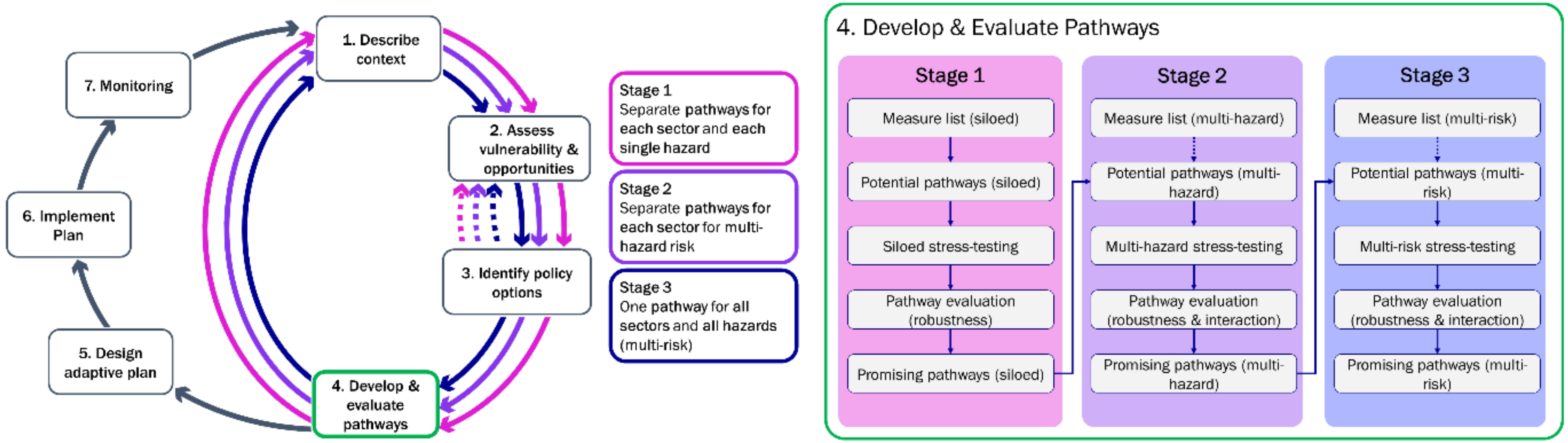


Figure 14: Left: The Dynamic Adaptive Policy Pathways for Multi-Risk (DAPP-MR) framework of steps and stages to develop pathways in multi-risk systems, as proposed by Schlumberger et al. (2022). This study focuses on the development and evaluation of pathways (step 4 highlighted green box). Right: Operationalization of step 4 of DAPP-MR to develop and evaluate Disaster Risk Management pathways, starting with single hazard pathways for each sector (stage 1), progressing to multi-hazard pathways for each sector (stage 2) and culminating in pathways designed for multi-risk systems (stage 3).

2.3.3 Finding better ways to communicate complexity

DAPP-MR has been tested in a synthetic case study, which offered evidence regarding the utility of the analysis framework (Schlumberger et al., 2024). Yet, it remains an open research question how to communicate these complex modelling results and use them for decision-making to assess the performance and interaction effects of DRM pathways alternatives.

One promising approach to address this gap is the use of information visualisation methods, which can facilitate the exploration, sensemaking, and communication of data to support decision-making processes (e.g. Salo & Hämäläinen, 2010, Hindalong et al. 2020). A key question, however, is which visualisation approaches are suitable to visualise multi-risk pathways considering uncertainties from interactions between different actors (Hadjimichael et al., 2023). Therefore, we design a set of information visualisation alternatives that are fit-for-purpose for the analysis of performance, flexibility and path-dependence of DRM pathways in multi-risk environments. We develop a set of visualisation alternatives following a systematic visualisation design process (Munzner, 2009). This systematic design process includes engagement with a targeted group of experts from the field of climate adaptation, DRM and long-term decision-support through workshops and interviews.

As a first step of the design process, we define the domain of multi-risk DRM decision-making under deep uncertainty in terms of target audience(s), and available data. In the domain of multi-risk DRM decision-making under deep uncertainty, data can be derived from model-based stress-testing approaches, where DRM pathways are tested across a set of scenarios characterised by (multiple) external sources of uncertainty (e.g. climate change, socio-economic development, climate variability, etc.) and internal sources of uncertainty (e.g. what combinations of (interacting) measures are implemented by different risk owners).

The target audience(s) for multi-risk DRM decision-making is diverse, including actors from different disciplines and administrative levels. In the European context, the domain of multi-risk DRM decision-making accounting for multi-risk interactions or the benefits of long-term planning is not yet legally formalised or applied in common practice (Schlumberger et al. 2022). This implies that the domain audience perceives engagement in the domain as a collaborative learning exercise and consists of front-runners who are interested in exploring the effects of pathway-thinking and multi-risk dynamics.

A typical target audience could thus consist of different actors as shown in Figure 15, where a central service provider (e.g. consultancy, research project) processes the data based on information and preferences indicated by different actors involved in the activity. While system actors approach the analysis from a systemic level accounting for different subsystems equally, not worrying too much about all details, sectoral actors have a priority focus on their specific sector and might be interested in more detailed information. There is obviously no clear allocation of specific audiences to these three types as it depends on the system definition and specific interests and capacities of the audience.

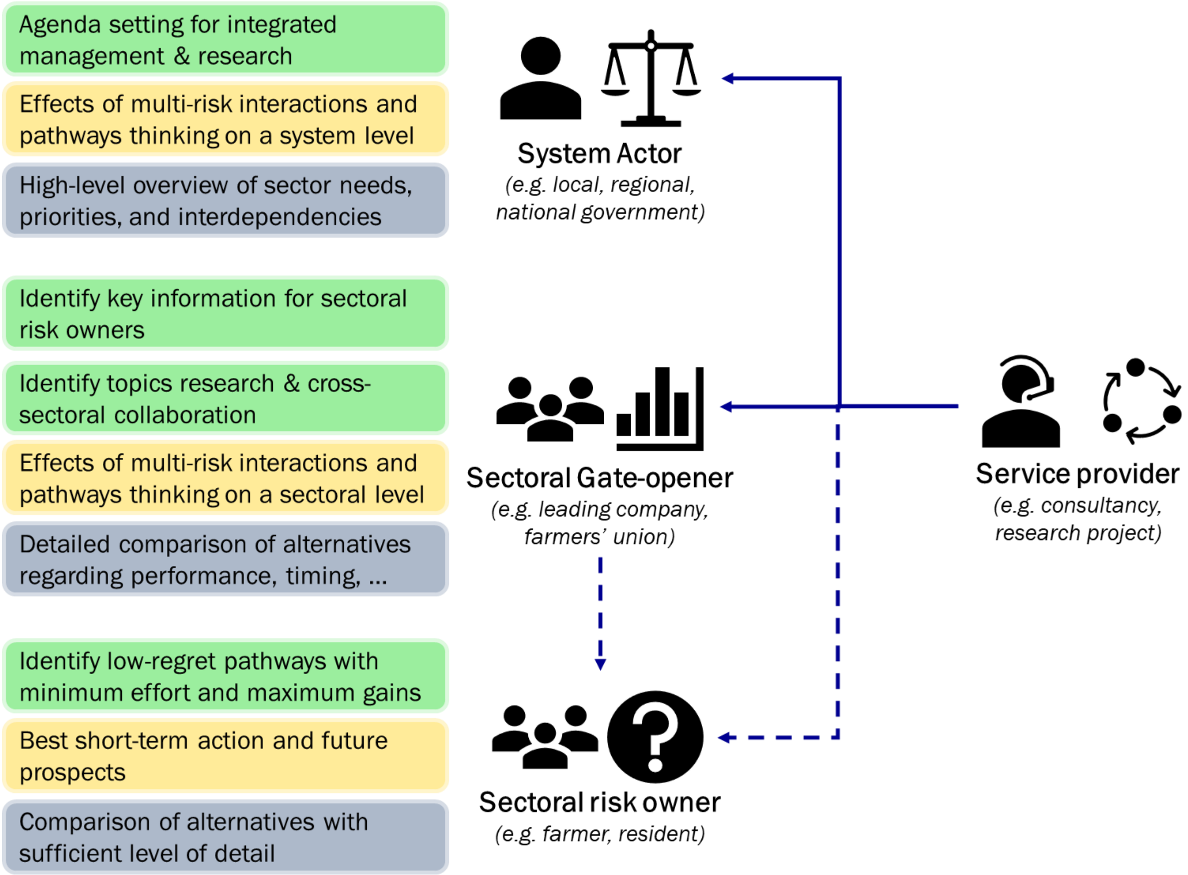


Figure 15: Domain definition for multi-risk DRM decision-making under deep uncertainty. The domain is a collaborative learning context, where actor types with different motivation (green boxes), analysis objectives (yellow boxes) and level of detail regarding the data (grey boxes) are involved. Depending on the respective sector, sectoral risk owners might be involved directly or indirectly by receiving information through a sectoral gate opener (dashed lines).

For different audiences, different (sets of) system parameters at different timescales serve as objectives to determine preferred and undesired DRM measures or pathways (Schlumberger et al. 2024). As such, data for multi-risk DRM decision-making under deep uncertainty are multi-dimensional. Generally, four types of key attributes are relevant in the data for the analysis:

1. Performance attributes capturing various objective parameters (e.g. damages, maintenance cost, side effects).
2. Time attributes capturing the timing of a certain realisation of the objective parameters within the planning horizon.
3. Uncertainty attributes regarding the considered deep uncertainties (e.g. climate change scenarios and climate variability).
4. Multi-risk attributes regarding the specific combination of multi-risk pathways (e.g. performance of risk owner pathway 1 for drought-DRM, given that another risk-owner implemented another pathway for flood-DRM).

In the context of multi-risk pathways, dimensionality reduction is one key transformation process to highlight the most relevant aspects regarding the multi-risk pathways for the analysis (Sedlmair et al., 2012). In recent years, the benefits of visual analytics to solve complex problems have been increasingly explored (Ceneda et al. 2017, Cui et al. 2019; Keim et al. 2010). Amongst others, designing interactive visualisations allows audiences to zoom, filter, reconfigure what they view and get additional details on demand

(Shneiderman et al. 1996; Few et al. 2009). As such it places the human within the analysis process and allows for an iterative manipulation, interpretation and learning process (Keim et al. 2010, Yi et al. 2007). Additionally, it offers new ways of showing large, multi-dimensional data (Saket et al. 2015).

Based on the comprehensive summary of available idioms for table data presented by Munzner (2014), we identified Stacked Bar Charts, Parallel Coordinate Plots, Heatmaps, Tree Maps and Pathways maps as promising starting points to develop the visualisation alternatives. They are currently implemented in a dashboard environment to include visual analytics elements. The current version of the dashboard can be found here: Introduction (pathways-analysis-64fdc870fca3.herokuapp.com), which is still under development and will be tested with a wide range of potential users through a survey. Our validation approach collects qualitative and quantitative evidence regarding the utility of visualisation and preferences of audiences. The survey takes roughly 15 minutes and consists of three parts: (1) collecting general information on the participants' background and visualisation expertise, (2) evaluating the objective fit of visualisations (correctness of answers) by means of a set of tasks participants should complete based on different visualisations; and (3) collecting feedback and perceptions regarding confidence and experience by the participants regarding the visualisations. As a result, different visualisation alternatives can be described with regards to their objective and subjective fit and a set of improvements/alterations can be implemented that address constructive feedback to further refine the visualisation alternatives.

We will report the findings of this work in a scientific paper that is expected to be published by the end of 2024.

2.3.4 Developing multi-risk pathways in pilot regions

Co-developing methods and frameworks for decision-support is fundamental for impactful science. One of the core outcomes of MYRIAD-EU is to co-develop approaches to enable policy-makers, decision-makers, and practitioners to be able to develop forward-looking disaster risk management pathways that assess trade-offs and synergies of various strategies across sectors, hazards, and scales. Testing of these methods in various European regions leads to refinement of the methods and lessons learned about the co-development process.

Since the beginning of the MYRIAD-EU project, WP6 Helpdesk has been involved in supporting the pilots in developing their forward-looking DRM pathways. Part of this support was to tailor the proposed DAPP-MR framework to the level of detail of analysis in the pilots. As previous activities with the pilots showed that pathways-thinking and multi-risk data are scarce in the pilots, the focus was on a first qualitative analysis as a preparatory exercise for more in-depth analysis where appropriate, see Figure 16.

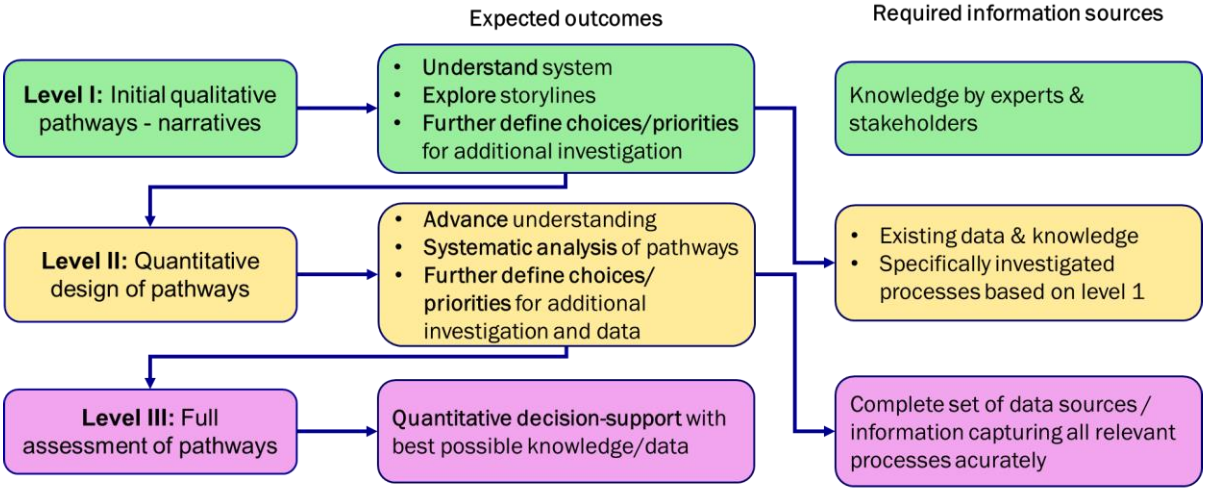


Figure 16: Overview of the levels of detail for the application of DAPP-MR, expected outcomes and required knowledge (sources).

As a result, we simplified the DAPP-MR framework in terms of language and concepts to help pilots through the analytical steps and offered approaches to conduct these steps.

In upcoming work (to be published), we will present and reflect upon five examples of applying an approach to develop systemic pathways in complex multi-sector systems. Those examples are diverse case studies ranging from the offshore strategic spatial planning managing the needs of energy, ecosystem and shipping in the North Sea, the highly interconnected and co-dependent system of the tourism destination Canary Islands to the regionally interconnected energy and water supply system and demand in Scandinavia to a multi-country region of the Danube and the highly diverse and agile region of Veneto, Italy.

We will present results of qualitative applications of DAPP-MR in a set of very heterogenous case studies, reflect on the differences in used methods (if any) and their potential transferability to other study areas. In short, each of the case studies first developed a system understanding from a sectoral perspective. Figure 17 shows an example from the Canary Islands Pilot region for the agri-forestry sector including components influenced by future uncertainty, general system characteristics, sector specific elements and tangential elements of other sectoral systems. Of all these elements some are defined to be influenced by DRM measures, and others are key objectives.

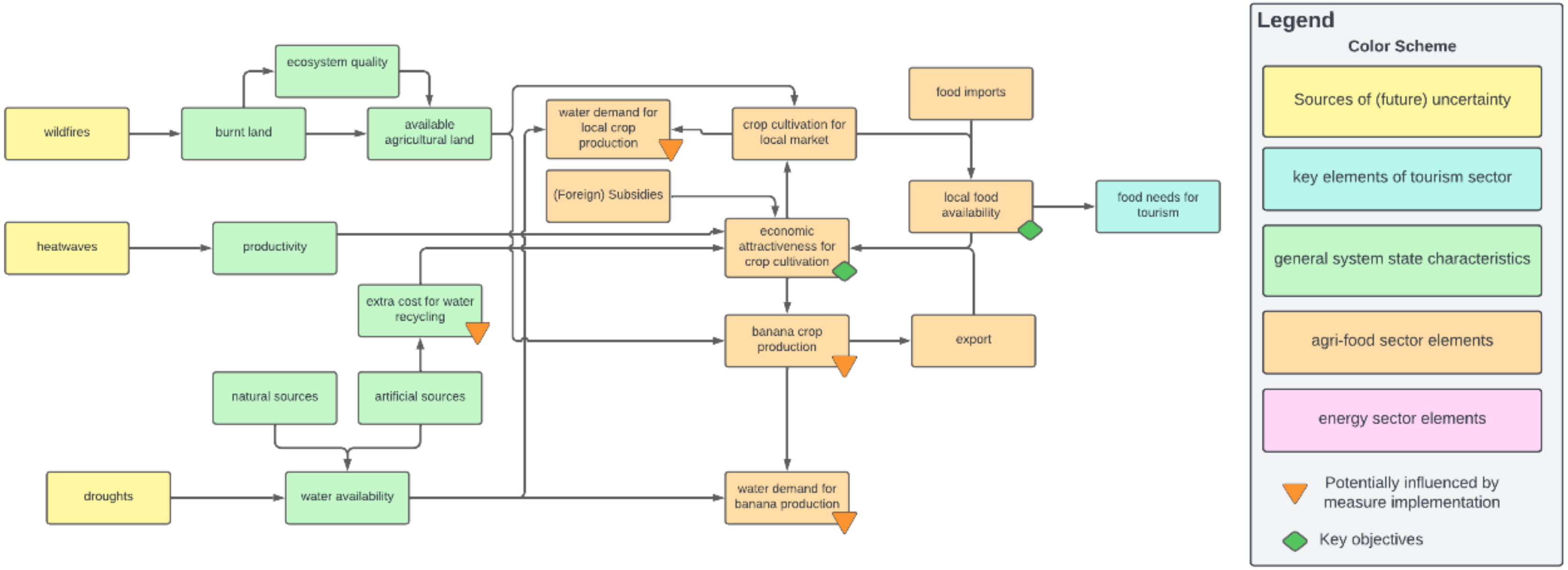


Figure 17: Intermediate system conceptualization for the agri-forestry sector in the Canary Island Pilot region.

Following from the sectoral understanding, the pilots then developed first iterations of sectoral pathways, for example, (as shown for the North Sea, Figure 18) spanning different time horizons depending on different socioeconomic-climate-scenarios and following certain narratives. Analysis into the interactions between sectoral pathways to formulate sectoral multi-risk pathways is currently ongoing and expected to be completed in the beginning of 2025. We will report the findings of all Pilot regions in a scientific paper that is expected to be submitted for publication in the first half of 2025.

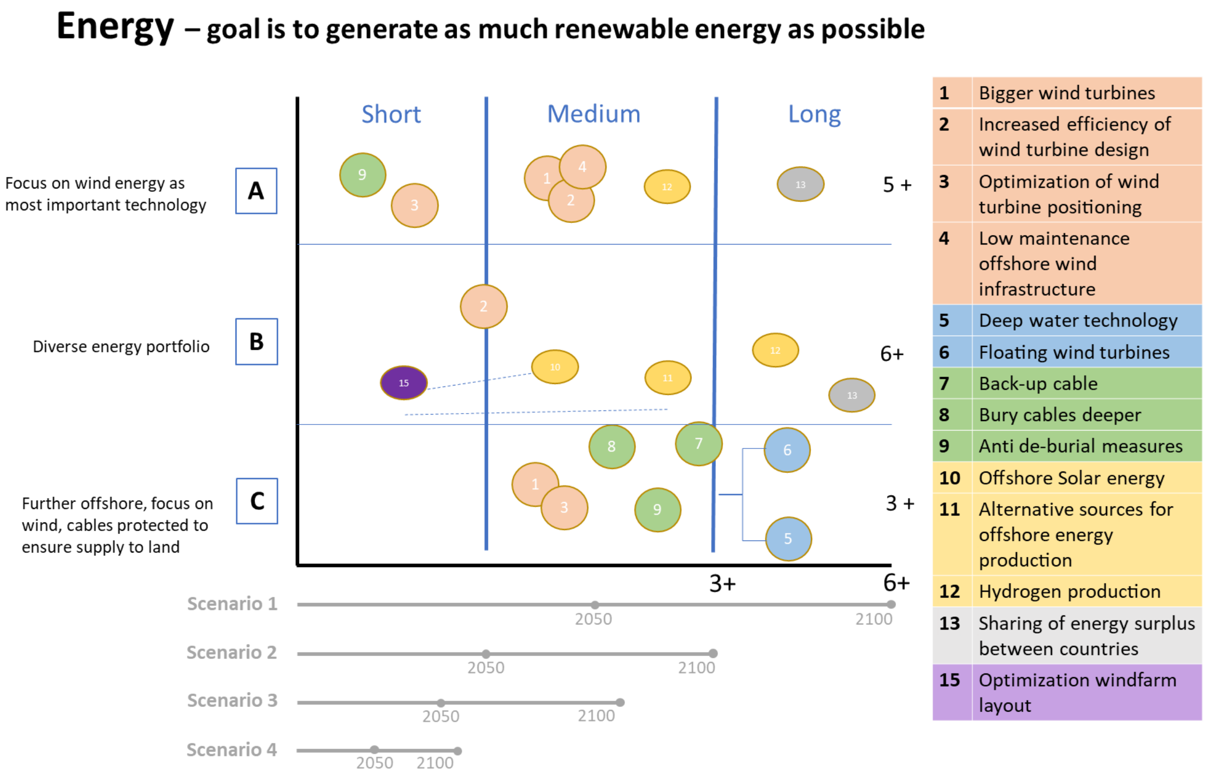


Figure 18: Intermediate pathways for the energy sector in the North Sea Pilot region.

3 How the methods relate to the Framework

3.1 General

This section describes how each of the two approaches relate to the MYRIAD-EU framework for systemic multi-hazard and multi-risk assessment and management. The framework consists of six steps (for a detailed description, see deliverable D2.3 and Hochrainer-Stigler et al. (2023):

1. Finding a system definition
2. Characterization of direct risk
3. Characterization of indirect risk
4. Evaluation of direct and indirect risk
5. Defining risk management options
6. Accounting for future system state.

3.2 Collaborative systems analysis approach

The MYRIAD-EU suggested approach to collaborative systems analysis complements the MYRIAD-EU Framework as far as it proposes a means by which to collaboratively undertake the initial framing and context setting aspects of each step in the framework together with stakeholders. The below sections summarise the aspects of the framework the proposed approach supports (and which it does not).

3.2.1 Step 1: Finding a System Definition

In Step 1, application of the suggested collaborative systems analysis approach can be used to support the following activities to define the system:

- Identifying the system at hand, its components and clear system boundaries
- Determining the hazards threatening the system and the system's exposed and vulnerable elements
- Characterising the governance landscape, sustainability challenges, desired vision and initial risk management options for the system.

3.2.2 Step 2: Characterization of Direct Risk

In Step 2, application of the suggested collaborative systems analysis approach can be used to support the following activities to characterise direct risk:

- Identifying direct risks resulting from physical contact with the single- or multi-hazard
- Defining direct risk metrics.

Note that the approach is not used to formally characterise these risks, but simply to identify them. Their characterisation occurs via, for example, assessment using WP4 and WP5 tools for qualifying and quantifying direct risks against the specified set of multi-hazard scenarios and according to the set of specified risk metrics.

3.2.3 Step 3: Characterization of Indirect Risk

In Step 3, application of the suggested collaborative systems analysis approach can be used to support the following activities to characterise indirect risk:

- Identifying indirect risks due to interdependencies in the systems
- Defining indirect risk metrics.

Note that the approach is not used to formally characterise these risks, but simply to identify them. Their characterisation occurs via, for example, assessment using WP4 and

WP5 tools for qualifying and quantifying indirect risks against the specified set of multi-hazard scenarios and according to the set of specified risk metrics.

3.2.4 Step 4: Evaluation of Direct and Indirect Risk

In Step 4, application of the suggested collaborative systems analysis approach can be used to support the following activity to evaluate risks:

- Defining direct and indirect risk evaluation criteria.

Note that the approach is not used to formally evaluate these risks and selecting those to manage, but rather serves as an input to these processes. The approach can therefore be used to specify the necessary inputs for the WP5 software capabilities that combine both semi-quantitative resilience indices with qualitative scorecards assessments.

3.2.5 Step 5: Defining Risk Management Options

Application of the suggested collaborative systems analysis approach is not intended to directly support Step 5 activities, but it does serve as a foundation from which to undertake these activities, particularly in terms of analysing potential interactions and interdependencies present between the available management options.

3.2.6 Step 6: Accounting for Future System State

In step 6, application of the suggested collaborative systems analysis approach can be used to support the following activity to account for the future system state:

- Identifying the key factors driving risk in future system states (e.g., due to processes such as climate change, economic change, land-use change, etc.).

Note that the approach is not used to specify these future system states according to the identified factors, but rather can serve to generate the inputs necessary from which to develop the scenarios. This can be achieved through more qualitative means (e.g. as storyline narratives), or through quantitative specification. In the latter case, the WP5 software can be used to generate the multi-hazard scenario events that have been subjected to future climate change forcing.

3.3 DAPP-MR

DAPP-MR is a planning process that occurs around the Framework's risk analysis procedures as conceptualised in Figure 19. The approach seeks to stage the risk analysis across the three iterations outlined in section 2.3.1. Although presented as sequential iterations, much of the informing risk analysis work for all stages can occur in parallel.

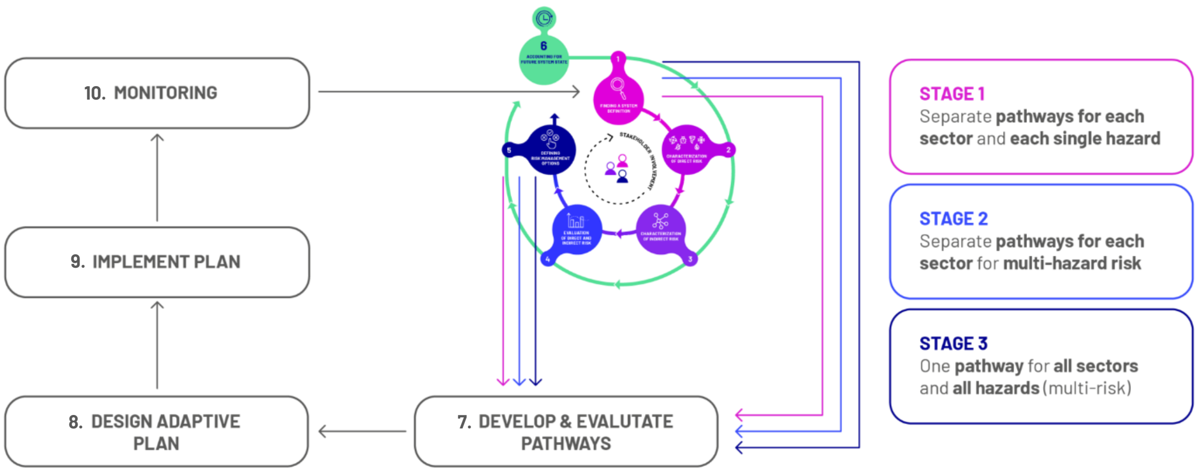


Figure 19: The DAPP-MR process to formulating multi-risk pathways, based on risk analyses conducted using the MYRIAD-EU Framework.

In each of the three stages of the pathways analysis, the approach takes the list of available risk management options defined for both the present and future system states (Framework step 5), before sequencing these to formulate alternative DRM pathways that adapt to the conditions as they continually change (step 7). These are then evaluated against their generated co-benefits and trade-offs to determine one's preferred pathways. At the end of each stage, the next stage's iteration commences, until a complete set of synthesised multi-sector, multi-risk pathways emerges. These are then elaborated through the design of the final multi-risk adaptive plan (step 8), before moving on to its implementation (step 9) and monitoring (step 10).

3.3.1 Step 1: Finding a System Definition

The specification of boundary conditions for the ensuring risk analysis and pathways formulation activities during each DAPP-MR stage. Key considerations here include:

- the geographic scale of the assessment
- the hazards, exposed sectors and vulnerable elements of concern
- the key (uncertain, exogenous) drivers of risk within the system
- the planning time horizon
- the overarching risk reduction objective(s) to be achieved for each sector and the system as a whole
- the criteria by which one will evaluate any trade-offs present between alternative pathways that achieve risk reduction objectives

3.3.2 Step 2: Characterization of Direct Risk

The definition of relevant metrics for characterising and managing direct risks account for the impacts of physical contact with the hazards during each DAPP-MR stage. In order to develop DRM pathways, it is important to ensure that these metrics: (1) are sensitive to the uncertain drivers of risk (to be specified in step 6), (2) will be impacted by the risk management options (identified in step 5); and (3) are appropriate to the scale of the system and its challenges (defined in step 1). It is typically against these "core" direct risk metrics that pathways are formulated, however this ultimately depends on the evaluation of direct and indirect risks (step 4). In this step there can be a strong interplay with both the WP6 storyline approach (for qualitative assessments) as well as the knowledge, methods and tools developed in WP4 and WP5 to quantifiably assess direct risks.

3.3.3 Step 3: Characterization of Indirect Risk

The definition of relevant metrics for characterising and managing indirect risks account for any additional risks experienced due to interdependencies present in the system during each DAPP-MR stage. As with direct risks, in order to develop DRM pathways, these metrics should also be sensitive to the uncertain drivers of risk (step 6), be impacted by (a different set of) risk management options (step 5) and be appropriate to the scale of the system and its challenges (step 1). Depending on the evaluation of direct and indirect risks (step 4), pathways may also be formulated to address indirect risks in addition to direct risks. In this step there can similarly be a strong interplay with the WP6 storyline approach (for qualitative assessments) as well as the knowledge, methods and tools developed in WP4 and WP5 to quantifiably assess indirect risks.

3.3.4 Step 4: Evaluation of Direct and Indirect Risk

The evaluation and prioritisation of risks to be managed by the risk management options and pathways during each DAPP-MR stage. These approaches are supported by the WP5 software capabilities that combine both semi-quantitative resilience indices with qualitative scorecards assessments.

3.3.5 Step 5: Defining Risk Management Options

The identification and assessment of alternative risk management options to address the prioritised risks during each DAPP-MR stage. Note that when identifying options, we distinguish between those which will measurably impact the risk reduction metrics specified in steps 2 and 3, and those that more support or enable the options available to directly reduce risks. For example, flood protection measures are supported by improved coordination and governance arrangements between multiple government agencies responsible for different elements of DRM. This second set of actions will be considered in step 8.

These options serve as the main building blocks for the DRM pathways.

3.3.6 Step 6: Accounting for Future System State

Recognising that risks will continue to change in time due to uncertain drivers (identified in step 1), this step involves the specification of a set of future scenarios for the identified sectors and risks, against which the pathways will be assessed during each DAPP-MR stage. These scenarios should encompass the plausible range of each of the prioritised uncertain risk drivers and should measurably impact each of the prioritised core risk metrics selected in step 4. The scenarios can either be qualitatively described (e.g. as storyline narratives), or quantitatively specified. In the latter case, the WP5 software can be used to generate the multi-hazard scenario events subjected to future climate change forcing.

3.3.7 Supplementary steps for formulation of DRM pathways

DAPP-MR requires four additional steps to move beyond the framework's risk analysis to the design and implementation of a future-focussed, adaptive DRM strategy. DAPP-MR therefore constitutes a complete adaptive policy analysis process.

3.3.8 Step 7: Formulate and evaluate pathways

Using the outputs from the risk analysis, pathways are formulated according to DAPP-MR's three-stage approach. In Stage 1, the available risk management options are assessed for their risk reduction effectiveness, costs, implementation constraints (e.g.

lead-time), social acceptability, and potential levels of future regret (i.e. what are the chances one will regret having implemented the action in the future?).

Pathways are formulated for each sector and risk, with priority in the short term given to those exhibiting lower regret and fewer implementation constraints. Higher regret options, or those that may take some time to implement or build the necessary social support are left open for the mid-longer term if needed to address future risks.

Alternative pathways are formulated according to competing stakeholder perspectives or values, and these are evaluated against the set of evaluation criteria (specified in step 1) to identify and compare the co-benefits and trade-offs generated. Evaluations can range from simple scorecard approaches to more extensive cost-benefit analyses, subject to data and resources availability. Preferred pathways consisting of short-term actions to be implemented and longer-term options to leave open for the future are then prioritised.

In Stages 2 & 3, the various preferred single-sector, single-risk pathways and their evaluations are updated as needed following analysis of the interdependencies or interactions present between options to manage multiple risks across multiple sectors, see Figure 20. These interactions may lead to actions within each sector-based pathway being enhanced, inhibited, advanced or delayed.

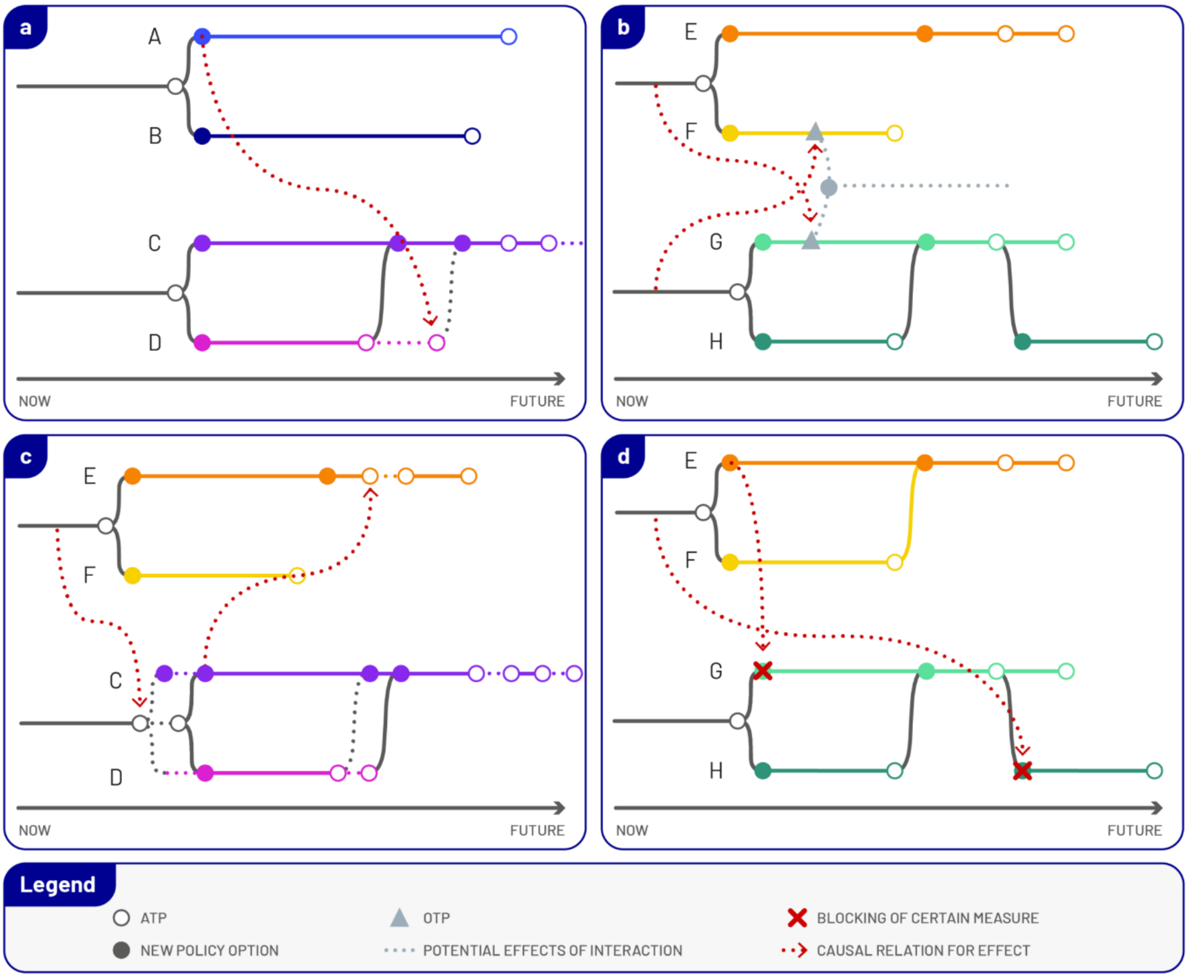


Figure 20: Potential interaction effects across multiple pathways: (a) actions selected in one pathway delaying the adaptation limit (or ATP) being reached in another, (b) two selected actions creating new opportunities (or

OTP) being established, (c) accelerating adaptation limits being reached, and (d) actions inhibiting others (Schlumberger et al, 2022).

3.3.8.1 Step 8: Design the adaptive plan

The adaptive plan is elaborated by identifying and specifying the necessary preparatory, supporting and enabling activities required for its implementation. These guarantee the viability of the plan into the future. Common activities that are included in this step include:

- Planning any further studies, additional research, planning or design needed for the interventions included in the plan
- Identifying land reservation needs for any (future) infrastructure
- Identifying any regulatory or legislative changes
- Devising clear governance mechanisms and sustainable institutions to implement, manage and monitor the plan
- Planning public outreach and capacity development activities
- Establishing compensation funds for those negatively impacted by the DRM plan

An implementation plan is also formulated, encompassing the logistics, governance mechanisms, and financing and (future) assurance arrangements necessary to enact the plan. Similarly, a monitoring plan is established that specifies the set of timely, reliable, and measurable indicators to assess conditions in the system and signal when subsequent actions in the plan are to be implemented or become feasible. Signals may include, for example, trends or events in the physical environment, human-induced trends or events, or changing societal values and perceptions of risk.

3.3.8.2 Steps 9 & 10 – Implementation and Monitoring

With the conclusion of the preceding step, the plan is ready for implementation and can proceed to the next phase of its realisation. Short-term interventions can be further detailed and designed, their financing arranged, governance relationships established, and the implementation and monitoring plans enacted. Any supporting actions are also implemented at this time, or subjected to further preparation, as required. Signalling information begins to be collected, and actions are started, altered, stopped, or expanded in response to the continued monitoring.

4 Key challenges and opportunities

4.1 Collaborative systems analysis

Establishing a sound understanding of how systems function serves as the basis for good disaster risk management planning. However, this is not always easy to achieve in multi-sector settings, given the competing knowledge, values, perspectives and priorities of the various stakeholders involved. Designing a process by which to identify and recognise these differences, before reconciling these to agree on a common, shared understanding of system functions, characteristics and constraints, along with a set of prioritised risk management objectives is no easy task. There is no 'one size fits all' approach that will suit all situations. The generic approach we have developed remains intentionally flexible and open to adaptation for this reason. Practitioners need to define and tailor the specific tools, methods and participatory processes to meet their specific needs and requirements.

This, however, can present as a challenge – which parts of the process to emphasise and focus on? Which to ignore or give less attention to? Which tools will provide risk analysts with the necessary inputs to conduct their assessments, while also allowing stakeholders to build sufficient understanding of the problem to be addressed? Tailoring these types of processes is not necessarily straightforward and relies on the individual skills and capacities of the practitioner to make the 'right' decisions in order to yield the desired outcomes. All pilots to a certain extent struggled with these challenges, particularly in the context of the limited number of moments and duration of interactions they had with stakeholders throughout MYRIAD-EU. However, the positive reactions to the storyline approach suggests that it may offer a means to effectively complement other tools and address several of these concerns.

Similarly, processes of collaborative systems analysis are often messy, as stakeholder responses can take discussions in a different direction to that which was planned. This demands flexibility and/or prior 'scenario planning' on the part of the practitioner to adapt the process to the needs of the collaborating group. For example, the North Sea pilot paid particular attention to simplifying the generic approach to a few critical activities that reduced the complexity of issues being discussed and confronted, and in order to serve its immediate and pressing need to raise awareness among its stakeholders that they were actually facing an adaptation challenge. Furthermore, when serving as a basis from which to develop adaptation pathways, one often needs to 'try on' different conceptual models and problem framings with stakeholders before finding the one that 'fits best'. This was the experience within the Canary Islands pilot, who went through several iterations of their systems analysis before settling on a final version to carry forward with its assessment.

Essentially, the core challenge of collaborative systems analysis approaches is that they rely on skilled and sensitive facilitation. This cannot be overemphasised; when dealing with messy problem contexts, practitioners may need to simultaneously play the role of the process manager, guide, technical expert, and mediator. One needs to be able to think along, and again adapt one's own preconceptions of any anticipated outputs. And, one needs to be able to balance one's own needs with those of your stakeholders, which may or may not necessarily align.

4.2 DAPP-MR

4.2.1 Regarding the analytical framework

Given the required extent of information to be collected, organised, analysed, and comprehensively presented to support good multi-risk governance (Scolobig et al., 2017), useful tools and methods to aid this process should be investigated. We discussed that complex multi-risk systems have high degrees of interactions, interdependence, and uncertainty on one hand, and showed that already very simple systems can get rather complex in an analysis on the other hand. It is therefore questionable whether DRM pathways for complex multi-risk systems can be designed in a purely qualitative, narrative-driven sense. Computational methods and tools may be necessary to account for and keep track of the different hazard-, sector- or policy-driven influences for example on the timing of reaching ATPs, or multi-temporal dimensions of system interactions. A promising starting point could be elements and tools from other approaches supporting decision-making under deep uncertainty (Kwakkel and Haasnoot, 2019). For example, model-based elements of Many-Objective Robust Decision-making (MORDM) (Kasprzyk et al., 2013) could be helpful for navigating the complexity of generating and evaluating pathways (Lawrence et al., 2019). Robust Decision-making makes use of models to simulate the implications of assumptions. In combination with approaches of scenario discovery (Groves and Lempert, 2007), it identifies relevant uncertainties (e.g., from multiple hazards) and can stress-test strategies against these scenarios to identify robust decision and contingency options. This has for example been incorporated into the Deep Uncertainty pathways framework (Trindade et al., 2019), which has been developed to discover robust pathway policies in the context of multi-actor systems.

Nevertheless, while DAPP-MR (with the right tool set) could provide support to find solutions for "difficult-to-answer" questions, complex multi-risk systems also face the challenge that they are wicked (Rittel and Webber, 1973) meaning "difficult to define problems." In our highly interconnected and interdependent society, the problem definition (i.e., what types of compounding/cascading hazards could interact in combination with growing multi-sectoral demands, or which elements do we include as exogenous forcing or within endogenous dynamics in our system definition) already introduces significant uncertainty and ambiguity (Ringsmuth et al., 2022; Srikrishnan et al., 2022). A challenge remains whether informative pathways of actions for navigating the problem can be developed in such difficult and highly uncertain systems. Hence, while methods exist to investigate the relevance of multi-hazard interactions for risk management to avoid unnecessary complex analysis (Liu et al., 2015), additional approaches might be required to help identify the upper limits of considerable complexity in light of uncertainty.

Additionally, recent research shows that successful multi-risk DRM requires an inter- and transdisciplinary approach (Schweizer and Renn, 2019). This means that knowledge from various natural, technical, social, and political science disciplines (interdisciplinarity) is combined with local knowledge and practices to enhance the integrative and adaptive capabilities of risk governance processes. If adequately initiated and managed, such processes can result in the co-production of knowledge, new relationships between involved stakeholders, changes in institutionalisation, and new practices or policies (Wyborn et al., 2019). Conversely, if representatives in such co-production processes are not diligently selected to represent a variety of perspectives (Klenk et al., 2017; Dilling and Lemos, 2011) and carefully managed to account for institutional characteristics (e.g. inequalities of power and resources; Sutherland et al., 2017) the outcomes can be suboptimal (Wyborn et al., 2019). These issues related to co-production processes should be accounted for in approaches to support multi-risk DRM together with the attribution of multi-hazard and multi-sector considerations. DAPP-MR implicitly assumes a functional and meaningful co-production process to be used for inter- and transdisciplinary collaboration across sectors and hazards to design pathways for complex multi-risk. Consequently, guidance on tailoring a co-production process to the application for DAPP-MR is still needed for an operational decision support tool for complex multi-risk DRM.

4.2.2 Regarding evidence of the utility of DAPP-MR

While our test case is grounded in literature, it does not entirely reflect real-world dynamics or offers robust insights. Previous research indicates that limiting ensemble realisations could impact the sensitivity and outcomes of the system (Kwakkel et al., 2015). Despite testing various climate scenarios, future studies should consider broader uncertainties (Srikrishnan et al., 2022) and apply a global sensitivity analysis. This would improve model confidence and highlight the significance of certain tipping point definitions (Gao et al., 2016; Pianosi et al., 2016). Particularly concerning socio-economic uncertainties, this study had a narrow focus, overlooking factors like population growth in the area or interaction effects such as the "levee effect" (Di Baldassarre et al., 2015).

Our method, assessing pathway performances using simple, quantitative criteria, requires a more comprehensive evaluation, incorporating qualitative metrics to realistically reflect current and future needs (Bosomworth et al., 2017; Siders & Pierce, 2021). The independent, impact-based adaptation tipping point rules oversimplify the integrated understanding sectors might have of their dynamics. Consequently, identified synergies and trade-offs in the model might not have real-world relevance. Current practice tends to focus more on the current needs of the farmers, while the pathways analysis and chosen performance evaluation of robustness indicators total benefits across the entire planning horizon more (Jafino et al., 2019). A bottom-up approach such as ours also overlooks top-down considerations, suggesting that future DAPP-MR applications should include government-led performance targets alongside individual sector objectives.

Despite these limitations, the study demonstrates DAPP-MR's utility for decision-makers and policy analysts. Following a systematic staged approach allows for a step-by-step analysis of cause-effect relations, identifying recurring patterns and unique multi-process influences. Interestingly, pathways that performed well in less complex dynamics tended to remain viable even under increased complexity.

From the stylised case study we can learn that the DAPP-MR approach has been instrumental in revealing how DRM strategy performance is influenced by the complex interplay of measure implementations, timing and the dynamics of a multi-risk system (Hochrainer-Stigler et al., 2023; Simpson et al., 2021). As such the approach facilitates understanding of the trade-offs and synergies of sectoral DRM pathways and highlights the conditions under which these dependencies significantly affect decision-making. Some interactions were predictable, while others like sector trade-offs prompting adaptive responses appeared counterintuitive. Increasing complexity can diminish the attractiveness of certain pathways, suggesting that eliminating less promising options early may overlook viable alternatives. Our study challenges the notion that a staged approach can reduce computational burden (Schlumberger et al., 2022). Future applications of DAPP-MR could include a pre-assessment step to limit the number of pathway combinations requiring stress-testing, focusing on those with distinct trade-off or synergistic effects.

5 Take up of research output outside of MYRIAD-EU

Results and progress reported in previous sections have been presented and discussed with scientists and practitioners at multiple conferences over the course of the first three years of the project. Amongst others, at a DAMOCLES science-policy-practice workshop in Glasgow 2022 where the next steps and future research ideas for the compound community were discussed, during Adaptation Futures 2023 in Montreal, where we hosted a session on emerging topics of the Decision-Making Under Deep Uncertainty Research community and another session on “Compound, cascading and complex climate risks and their impacts: getting from methodological advancements to practical outcomes”.

Similarly, the work has been discussed in the context of other research projects, notably Reachout, a project aiming to develop climate-resilient development pathways, and Miraca, focusing on Multi-hazard infrastructure Risk assessment for climate adaptation which might pick up DAPP-MR to develop multi-hazard pathways for transport in some case studies. Since collaborative systems analysis forms a common foundation with these and many other climate adaptation and disaster risk reduction research projects, the work that has informed the development of the generic approach in MYRIAD-EU has already been discussed and adapted with the Mission Adaptation, and particularly within the Pathways2Resilience project. Furthermore, DAPP-MR and the developed multi-risk policy analysis model is picked up by researchers at University of Utrecht to further investigate multi-sectoral/objective decision-making in the context of multi-risk management using Evolutionary Algorithms, Explanatory AI and interactive visual analytics.

Lastly, work on DAPP-MR has been taken into account when creating a PhD position at the University of Utrecht on "Rhine-Meuse Delta Adaptation to Extreme Compound Events focuses on understanding adaptation measures and pathways to uncertain compounding climate extremes such as extreme rainfall, river flow, and storm surge. " which will kick-off in September 2024.

5.1 Impacts as stated in the Description of Work

This section outlines the contribution of the work executed in WP6 towards the expected impacts as foreseen in the Call text and the project's Grant Agreement.

"...consensus in better definitions, indicators and functions to characterise multi-hazard risk through enhanced inter-disciplinary collaboration..."

WP6 has contributed to the Handbook (D.1.1) and through this to the Disaster Risk Gateway offering definitions relevant in the context of forward looking DRM pathways for multi-hazard risk. It has contributed to discussions on the functions of dynamic vulnerability and indicators adding the perspective of systems analysis and particularly the short-to-long-term perspective of pathways thinking as applied in DAPP-MR.

"...prioritisation of investments & selection of effective DRM options..." & "...enhanced risk-informed decisions ... addressing trade-offs between... options"

Good decision-making is founded on sound systems analysis. The collaborative systems analysis approach helps practitioners describe systems in all their complexity, all the while including mechanisms to prioritise and frame multi-risk challenges that are capable of delivering the greatest resilience dividends. The approach has been developed and tested together in the five pilots (see section 2.2.2). Similarly, DAPP-MR is designed to yield better-informed decisions to multi-risk challenges by identifying pathways of investment decisions that acknowledge the uncertainties surrounding future risks and can flexibly adapt to the conditions that emerge. DRM pathways therefore help avoid maladaptive outcomes such as lock-ins, all the while respecting the complex interactions and interdependencies at play in multi-hazard and multi-sector settings. We are developing forward-looking DRM pathways in five Pilots (ongoing activity, see section 2.3.4) and have tailored DAPP to multi-risk settings (completed, see section 2.3.1).

"...enhanced capacity for identification of vulnerable, threatened areas and infrastructures most at risk from multi hazards in Europe"

The intention of both the collaborative systems analysis approach and DAPP-MR is to identify and address those risk and risk factors that yield the greatest impacts on society. Central to both approaches is the identification and prioritisation of risks and potential solutions that deliver the greatest impacts and build broad resilience across integrated systems.

"...better informed forward-looking national risk assessments that take into account long-term drivers such as climate change...enhance implementation of existing legislation and streamlining of policies..."

Sound systems analysis also underpins reliable risks assessments. The collaborative systems analysis approach guides practitioners to properly frame their complex multi-risk problem contexts to inform risk assessments that include long-term drivers like climate change. This includes the identification of critical, determinant risk factors, enablers and barriers as well as associated metrics against which to measure the ability of the system to confront and manage risks. DAPP-MR explicitly demands long-term risk analyses are considered in the policy analysis process, acknowledging the uncertainties present in these and then devising the adaptive strategies capable of addressing these risks. DAPP-MR's action planning step introduces consideration of broader policy objectives and governance changes that may be necessary to implement DRM pathways.

"...enhanced understanding of relationships and interactions of multiple hazards ... driven by ... changes on different time and spatial scales"

The collaborative systems analysis approach provides practitioners with a methodology and catalogue of tools with which to explore the interactions between hazards, sectors, investment options and other system components. DAPP-MR offers similar functionality for the exploration of pathway interactions. More qualitative applications of both approaches through the Pilots have helped to unpack and enhance stakeholder understanding of such interactions in each of these complex settings. The quantitative application of DAPP-MR in the synthetic case study has underscored the challenges and complexities associated with planning the timing of investments. Multi-hazard and multi-sector interactions significantly influence pathway viability and suggests the need for further investigation into the dynamics of specific measure interaction effects.

"...better knowledge exchange through platforms such as DRMKC, and stakeholder networks on emergent risks and extreme events (e.g., Community of Users, Risk KAN)"

The findings of WP6 and the other technical WPs in the MYRIAD-EU project have been discussed, presented and exchanged with others through platforms, stakeholder events and communities of practice / conferences as described above in section 5.

5.2 Sectoral impacts

Through the pilot workshops used to collect feedback on the pathway development process, interest and awareness for the relevance of forward-looking DRM pathway thinking was sparked. As most participants represented operative arms of sectoral actors, the current planning period of interest is significantly shorter. Sectoral actors showed interest in the collaborative learning and knowledge co-production exercise which is guided by DAPP-MR and collaborative systems analysis activities.

6 Future research

Work on improving collaborative systems analysis approaches and tools to better equip these to be easily adapted and tailored to specific contexts will continue. Many systems analysis tools have been designed with specific purposes in mind; whereas the generic approach for multi-risk systems developed in MYRIAD-EU is intentionally flexible and open to be adapted as practitioners see fit. Room remains, however, to build upon this work and develop specific tools and methods to better support delivery of the approach in a variety of decision contexts, and according to varying levels of available skills and resources.

Work on DAPP-MR will continue to progress in the remaining year of the project. Apart from finalising ongoing work as reported in section 2.3, efforts will be put into disseminating the approach to apply in different case studies and gaining additional insights regarding the complexities of multi-risk pathways. For this, we are planning to develop a modelling-framework to explore realistic multi-risk pathways for the Netherlands – work that will be continued beyond the end of the project. As part of this case study, effort will be made to explore how other tools and software developed in other Work Packages of MYRIAD-EU can be used (e.g. the VINE-copula package developed in WP5 and dynamic vulnerability functions developed in WP4).

While many MYRIAD-EU tools and the WP5 software are primarily focused on systemic risk assessments for current and future states, integrating and extending the tools and software to be able to address the complexity required to develop forward-looking DRM pathways would be a logical elaboration. Such developments could include: developing an component to interactively explore the impacts of uncertainties; the option to consider transient scenarios (timelines spanning multiple decades) instead of event based/probabilistic assessments to account for path-dependencies between events and across (timing of) decisions; and the option to assess the utility of different DRM measure (combinations). With these integrations we could further improve the decision-support quality of the tools and software developed in MYRIAD-EU and take a significant step to scaling up the option to develop forward-looking DRM pathways in any context or region.

Another open question regarding DAPP-MR is the concept of integrating spatial complexity. While current work has primarily focused on interactions in time and across sectors, information about the spatial distribution of impacts, decisions and effects has often been simplified or disregarded. However, the spatial planning component of climate adaptation and forward-looking DRM may be significant when exploring cross-sectoral interaction effects and dynamic changes in vulnerability and exposure.

Similarly, further research could explore what types of interactions (across (specific) hazards or (specific) sectors) actually have relevance for developing long-term strategies. Investigating decision-rules for risk-owners and how they are influenced by the consideration of multi-hazard/multi-sectoral interactions would enhance understanding on whether climate adaptation or forward-looking DRM strategies significantly change in response to these, i.e., in terms of when certain decisions need to be taken and the options that are considered. Gaining clarity on this question would significantly contribute to the tailoring of decision-support to responsible actors and determining whether or not the consideration of interactions is relevant for their DRM focus.

7 Conclusion

How to structure, organise, prioritise and make sense of all the complexity present in multi-risk settings and develop adaptive plans with which to simultaneously manage multiple risks across multiple sectors presents as one of the key challenges for policy analysts and decision-makers. This report has presented findings on two key aspects of developing forward-looking DRM pathways: (1) the development of a flexible, generic approach to collaborative systems analysis, and (2) the development of DAPP-MR – the proposed, staged, iterative analytical process to follow to facilitate the assessment of multiple possible pathways to adapt to current and future multi-risk challenges. Both of the developed approaches have been designed to complement the MYRIAD-EU framework for systemic multi-hazard and multi-risk assessment and management.

Collaborative systems analysis approach

In Task 6.1, we developed a flexible, generic approach for collaborative systems analysis to guide decision-makers and policymakers to accurately describe their DRM decision-making contexts. This description serves as the foundation for the development of forward-looking DRM pathways. The approach satisfies the following (5) requirements:

- It is capable of representing the holistic, integrated system and its key functions, risks, and opportunities.
- It highlights the key interdependencies and interactions between system components, including all feedbacks, trade-offs, and synergies.
- It generates a common, shared understanding of the integrated system and its objectives among stakeholders.
- It serves to prioritise key system functions, objectives, constraints, risks, and opportunities.
- It is flexible to the needs of various users and permit the incorporation of various supporting tools and approaches with which its users are familiar and comfortable.

The approach reflects the three stages of the DAPP-MR approach and serves as a means by which to undertake its first step (describing the decision context, see Figure 14 in this report). It similarly serves to support implementation of the MYRIAD-EU framework for systemic multi-hazard and multi-risk assessment and management.

All five pilots adapted the approach to their particular problem contexts and applied various tools with which they were familiar and comfortable to describe these together with stakeholders. The tools which the pilots made the most use of included the DPSIR framework, causal relationship diagrams, storyline approaches, and interaction matrices. The storyline approach in particular was enthusiastically adopted by all the pilots and has proven to be both an effective and flexible tool well-received by stakeholders. The approach nevertheless relies on sufficient time being allocated to both prepare and implement its activities, as well as strong and effective facilitation to lead discussions and help to synthesise system complexities for stakeholders.

DAPP-MR

Building on the existing Dynamic Adaptation Policy Pathways (DAPP) approach, DAPP-MR is proposed to guide the assessment and evaluation of multiple adaptation pathways to current and future multi-risk challenges. The approach aims to systematically consider the three key themes relevant to the design of multi-risk DRM pathways: (1) the effects of multiple, interacting hazards; (2) the dynamics and interdependencies of sectors; and (3) the trade-offs and synergies of DRM policy options across different sectors and different spatial and temporal scales. It does so by proposing three, iterative stages of the first four steps of the DAPP policy analysis cycle to gradually build up problem complexity:

- Stage 1: DAPP-MR starts with a single-sector, single-hazard perspective.
- Stage 2: Subsequently, all single-hazard considerations are integrated per sector to result in a single-sector, multi-hazard perspective.
- Stage 3: The single-sector, multi-hazard information is integrated into a multi-sector, multi-hazard

DAPP-MR has been applied in a synthetic multi-risk case study to assess its utility. The results highlighted the complexity of assessing the effectiveness of flood and drought risk reduction measures, particularly in the context of multi-hazard interactions. The interactions between different pathways, their timing, and the presence of other sector-hazard DRM measures all play significant roles in determining overall outcomes. However, the staged approach helps to illuminate pathways which remain valid under increasing complexity.

The application also demonstrated a crucial gap in terms of how to visualise and communicate the relative performance and interaction effects of different pathways across scenario ensembles to better support decision-making. Ongoing research to address this gap has suggested the use of information visualisation methods, which can facilitate the exploration, sensemaking, and communication of data to support decision-making processes. To this end, we have identified Stacked Bar Charts, Parallel Coordinate Plots, Heatmaps, Tree Maps and Pathways maps as promising starting points to develop visualisation alternatives, and these are currently the subject of both qualitative and quantitative research to further refine these.

DAPP-MR is presently being applied in each of the five MYRIAD-EU pilots, predominantly in a qualitative sense. In short, each pilot first developed a system understanding from a sectoral perspective, before developing first iterations of sectoral pathways. The pilots are presently analysing the interactions between sectoral pathways to formulate sectoral multi-risk pathways and expected to be completed in the beginning of 2025. An upcoming scientific publication will present the findings of all pilot regions, reflecting on the differences in methods used (if any) and their potential transferability to other study areas.

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Appendix A

This appendix presents a detailed description of the MYRIAD-EU collaborative systems analysis approach (section A.1). It also lists the promising set of tools for collaborative systems analysis identified in the literature (section A.2)

A.1 Collaborative systems analysis approach detailed description

The MYRIAD-EU collaborative systems analysis approach consists of the following three principal iterative steps (Figure 21):

1. Define system boundaries and constraints
2. Undertake sector-based analyses
3. Synthesise sector-based analyses into a whole-of-system analysis

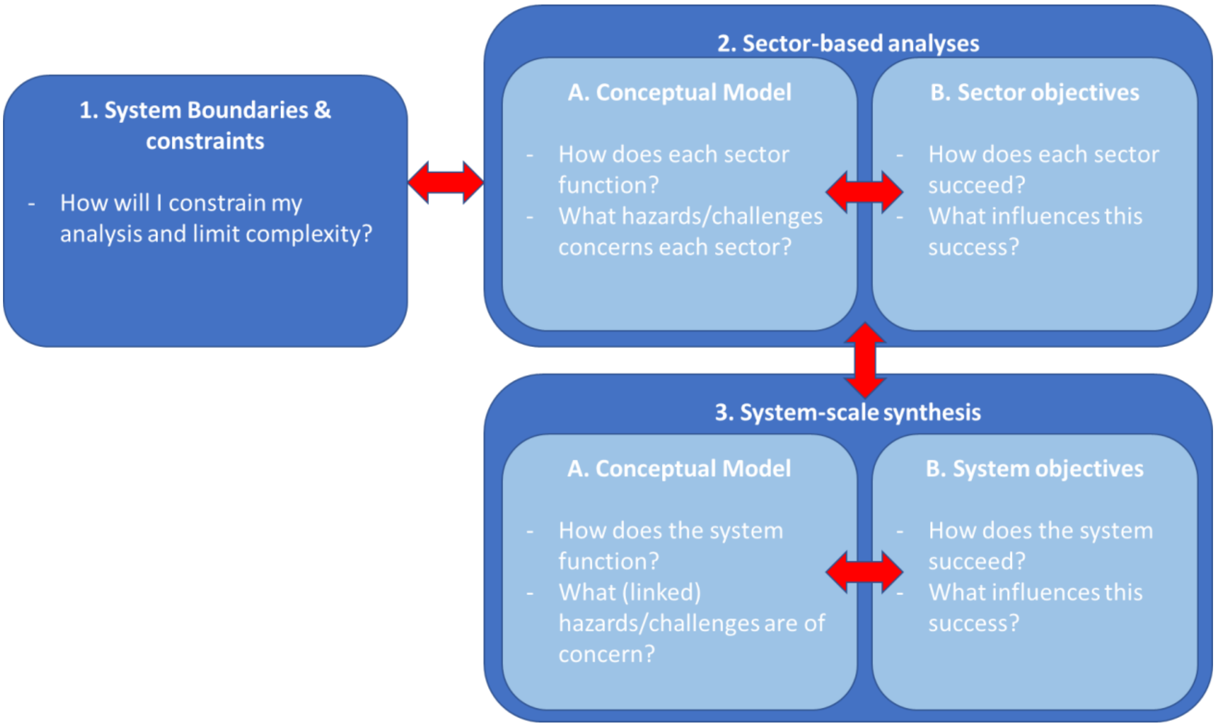

Figure 21: Proposed collaborative systems analysis approach to be applied in MYRIAD-EU

Although these steps are presented sequentially, the expectation is that the analysis process will be highly iterative. For example, performing the sector-based analyses may reveal that any earlier defined system boundaries and constraints may need to be redefined or further elaborated. Or it may be that in performing the system-scale synthesis that components present in some sector sub-systems are recognized to have been omitted from others, demanding further elaboration. This is the nature of systems analysis; the aim is to structure the process as far as possible while recognizing that building a system model can often feel messy and unstructured.

The following sections further detail the information to be gathered during each step of the process. Methods and tools are proposed to assist in this regard; however, these are to be treated as suggestions only. Practitioners are welcome to apply alternative methods and tools which they believe could assist in yielding the necessary information to describe their integrated decision contexts. The proposed tools have been drawn from literature and are detailed further below in section A.2.

We recognize that implementing the entire approach would take quite some time within a workshop setting. We estimate that at least **a full one-day workshop** would be needed to undertake the participatory activities suggested under the three steps. In many instances this may not be possible, such that the approach may need to be adapted to occur across multiple sessions, or alternatively streamlined to the time available.

Note also that the approach has been designed with large group settings in mind. That is, we have presented an approach where breakout groups of sector-specific stakeholders make sense, which results in a process whereby Steps 2 and 3 are completed as separate activities (Step 2 in breakouts, Step 3 in plenary). In smaller group settings with few stakeholders, it would equally be appropriate to combine Steps 2 & 3 in the one conceptual modelling exercise. In this case, each sector could still be dealt with in turn as the whole-of-system model is gradually built up collaboratively.

The approach is intended to be flexible and practitioners should adapt it as needed to the practical realities of each stakeholder group.

A.1.1 Step 1: System Boundaries and Constraints

The first step of the proposed systems analysis approach is to define the system boundaries and constraints. The purpose of this step is to initially specify limits to the complexity of the system to be unpacked during later steps. In defining system boundaries, key considerations should include its spatial extent, temporal extent and resolution (i.e. planning time horizons), sectors to be included, and an initial consideration of key system functions (biophysical, socioeconomic, institutional), characteristics, and constraints (example functions are available in Table 2). An initial consideration of the key hazards and risks to the system can also be carried out to ensure that all represented stakeholders agree on the (multi-)hazards to be addressed. Note that it is not the intention to map out every possible element and relationship present in the system, but rather to prioritise these according to the core issue(s) being addressed.

Table 2: Example system functions, characteristics, and constraints for biophysical, socioeconomic, and institutional sub-systems

	Bio-physical	Socio-economic	Institutional
Functions	- Rainfall, river discharge - Earthquakes - Heat regulation - Primary production - Hazards, e.g. extreme weather, flooding, pandemic	- Water supply - Flood protection - Food production - Energy production - Tourism services - Transportation - Health services - Recreational services, e.g. fishing, swimming, hiking - Financial crisis	- Governance responsibilities - Subsidies - Penalties/fines - Hazards, e.g. state capture, corruption
Characteristics	- Self-regulating - Suffering scarcity or degradation	- Social values, e.g. allowable water use, transportation preferences, dietary requirements - Economic dependencies, e.g. supply chains	- Hierarchies, between and within institutions - Institutional dependencies, e.g. transport fines that fund road improvements

Constraints	- Resource availability, e.g. water, wind, soil - Environmental requirements (e.g. e-flows, maintenance of biodiversity) - Temperature patterns - Rainfall patterns	- Demands, e.g. water, energy, food, transport - Minimum production limits	- Regulatory limits - Jurisdictional boundaries - Planning controls/zoning

Potential questions to pose during this step include:

- What are the limits to the area/topic/challenge that we are going to consider/assess?
- What is the core purpose of each of the represented sectors in terms of overall system function? For example, the energy sector provides energy to power services and produce goods, the water sector provides flood protection, etc.
- What are the key pieces of infrastructure that are related to each sector?
  - Where are these located?
- What are the key socioeconomic functions that relate to each sector? For example, the tourism sector serves to drive local economies, the shipping sector serves to deliver goods, the health sector serves to maintain a healthy society, etc.
  - Where are these key socioeconomic functions located (if possible)?
- What are the key institutional constraints relating to core system functions?
  - For example, are there any legal requirements or regulatory limits which must be adhered to?
- What are the key system challenges and hazards that we are aiming to address in MYRIAD-EU?
  - Where are the impacts from these most felt?
- What time horizons are we interested in for planning?
  - Have we sufficiently considered long-term impacts?
  - Do the time horizons match well with the anticipated timescales for the hazard impacts we aim to mitigate?

In terms of methods, several tools can be applied to support these discussions. One of the simplest tools to stimulate stakeholder discussions is a *collaborative geographical mapping exercise*. Place a map of the area in front of stakeholders and set them the task of situating key (physical) features on it. Prompt stakeholders to locate the physical aspects of core system functions and critical infrastructure on the map (e.g. energy plants and substations, water treatment plants, ports, priority industries, etc), before identifying locations where impacts from the identified hazards are primarily experienced. Both digital and hard copy maps can be used for this purpose, depending on whether the session is taking place virtually or face-to-face. If taking place virtually, paste a picture of an existing map of the area in a digital whiteboard environment (e.g. Mural, Miro, MS Whiteboard) and allow participants to actively engage and place icons, shapes, or comments directly on the map. In face-to-face settings, markers, stickers, post-its, and the like can be deployed in the same way.

For the non-physical elements of the system, an initial *'CIrcle'-type analysis* can be performed to identify the initial set of linkages assumed to exist between system sectors, functions, characteristics, and constraints. In CIrcle analyses, system components are placed around the outside of a circle, before any links are established between them (see Figure 31). Again, these types of analyses can be performed using digital or paper-based drawing and visualisation tools. In these analyses, it is the existence of the link that is important to visualise, rather than the precise nature of the link (although it should nevertheless be noted down).

It is important to keep in mind that the critical outcome of step 1 is to get stakeholders talking about their system and to develop an initial set of ideas about how its various components are related to each other. It is therefore recommended to also assign a dedicated notetaker to capture any additional (e.g. non-spatial, non-visualized) information to be gathered from the responses to the facilitated discussion points above. Table 3 summarises the information presented in the preceding paragraphs.

Table 3: Step 1: Objectives and (suggested) methods

Objective	Suggested Method(s)
Broadly define systems in terms of: - Space - Sectors to include - System functions, characteristics and constraints (physical, social, institutional) - Planning time horizon and resolution - Challenges/hazards	1. Geographical mapping exercise (initial quick scan) a) A collaborative geographical map of the pilot area is produced b) Sectors and physical location of key system functions are placed on (virtual) map c) Physical locations of identified hazards placed on map (where possible) 2. Facilitated group discussion, supported by Circle analysis to establish simple linkages between system components a) Elaborate physical system functions with initial set of social/institutional functions/characteristics/constraints b) Establish appropriate planning time horizon and resolution, given sector, function and hazard profile

A.1.2 Step 2: Sector sub-system analyses

In the second step – and in light of the system boundary conditions and constraints defined in Step 1 – the aim is to analyse each sector sub-system separately and develop the conceptual model for how it functions in isolation. The task is to elaborate the broad system outline developed in step 1 with the specific complexities of relevance to each sector sub-system, particularly in terms of its physical, socioeconomic, and institutional characteristics and constraints, its key actors and their agency, and the specific impacts of the (previously) identified system-wide hazards and risks. Additional sector-specific challenges, hazards, and risks can also be included at this stage, especially where system-level hazards cascade to other sector-specific hazards (e.g. via multi-hazard impact relations). Considering the impacts of any multi-risk scenarios to be applied can also be introduced and considered in this step (e.g. via a *storylines*). By analysing each sector sub-system in isolation, the aim is to gradually build the whole system model from the 'bottom-up', rather than trying to dive deeply into the more abstract and complex system as a whole. The expectation is that sector stakeholders hold expertise on how their sub-system functions, whereas their knowledge of the complexity of the complete system may be more limited. Note that in undertaking the sector analyses, components of relevance to other subsystems may also be included (e.g. for water supply sub-system: economic growth, climate change, energy supply, etc.), but the system as a whole is not being considered in this step. Knowledge and understanding on dynamic sectoral feedbacks can also start to be brought in to inform the analysis.

Following the development of each sector's conceptual model, sector stakeholders can then use this model to derive/refine a limited and prioritised set of sector objectives and indicators. These should be developed for each of the planning time horizons that were specified in Step 1 (e.g. short-term, mid-term, long-term). Objectives should be framed in such a way as to focus on the core outcomes that the sector is trying to achieve (e.g. supply sufficient energy to society to support economic growth, protect energy supplies from hazards, drive energy sector climate mitigation efforts, etc.). The key is to focus on trying to answer the question 'How does each sector succeed?', with the resulting objectives being those that would enjoy widespread societal support (i.e. are largely uncontroversial). Once the set of objectives has been formulated, these are then translated across to a set of SMART (specific, measurable, assignable, realistic, and time-based) indicators, even if the later assessment will be qualitative in nature (e.g. zero unmet energy demand (MW), energy substations protected from floods to (future) 1:100 flood level, supply *x* MW renewable energy by 2030).

Potential questions to pose during this step include:

- How does this sector succeed?
- How can we measure this success?
- What other factors influence sector success?
- What factors influence these factors?
- What factors are necessary to support the core sector functions?
- What factors can we identify that stress core sector functions?
- What are the key biophysical functions that relate to this sector? e.g., wave height, sea level rise, storm surge, wave dissipation
- What are the key socioeconomic functions that relate to this sector? e.g. flood protection, income generation
- What are the key institutional enablers and constraints relating to core sector functions? e.g. planning controls, DRR governance structures
- How are all the preceding considerations linked?
- Have we considered exogenous drivers of change in our sector?
- How do the identified system hazards influence sector functions?
- What additional sector-specific hazards can we identify that influence sector functions? Are these in any way linked?
- Are there any functional, spatial, financial, or societal interdependencies or multi-hazard impact relations that we need to consider (refer to the separate table of questions listed in section A.3)?

This type of analysis similarly lends itself to several tools and approaches available in the literature. While we do not recommend a specific tool/methodology, the output from this step should preferably be a visual representation of the sector sub-system conceptual model. Tools to be applied in this step could range from the more sophisticated purpose-built digital tools (e.g. Kumu, Vensim), to simpler manual (digital, physical) whiteboard representations composed with post-its and (hand-)drawn arrows. The key is to unpack how each sector functions in detail and to uncover the *causal relationships* between each of the system factors (e.g. Figure 22). Here, the first four steps of the *DPSIR* framework (see Figure 24) may be useful to unpack and identify the drivers, pressures, and sub-system states that relate to the corresponding sector impact (i.e. objective). The process applied in Group Model Building-type approaches to identify components, causes, consequences, and feedback loops may also be useful (Figure 23). Whatever method is employed, causal relationships can be constructed in the form of chains, loops, matrices, or webs as per practitioner preference. What is important is to generate a common, shared understanding of how each sector sub-system functions for the relevant stakeholders, and to a resolution and level of complexity that matches with the system-scale analysis.

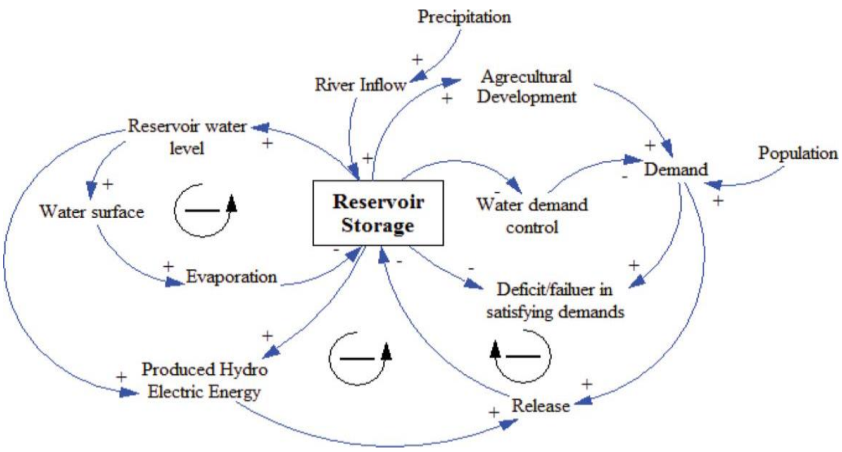

Figure 22: Example causal loop diagram for water management (Source: Felfelani et al., 2013)

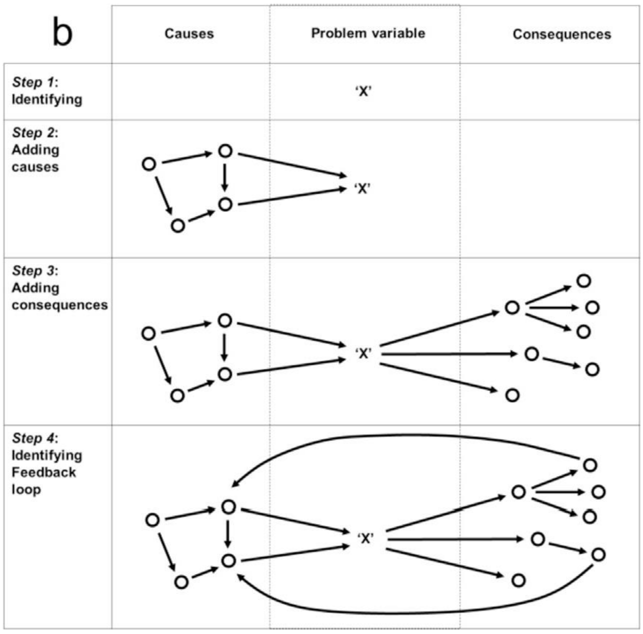

Figure 23: The process of causal loop diagram development (Source: Purwanto et al., 2019)

For the prioritisation of system objectives, a simple voting exercise can be conducted together with relevant sector stakeholders. This can either be performed through a show of hands or via an exercise where each stakeholder is given a limited number of 'tokens' (e.g. stickers) which they can allocate across the identified objectives. The aim is to rank each objective in terms of its importance relative to each other. Table 4 summarises the information presented in the preceding paragraphs.

Table 4: Step 2: Objectives and (suggested) methods

Objective	Suggested Method(s)
Given system boundary conditions and map, elaborate each sector sub-system in terms of: - Sub-system functions and characteristics (physical, social, institutional) - Key actors and agency - Impacts of challenges/hazards on sector functions, including multi-hazard impact relations	1. Conceptual modelling exercise, e.g. develop Causal Loop Diagram using (virtual) post-its, Kubu or other online tool. Each sector builds own conceptual model of its sub-system: a) Conceptually map each sub-system function. Can use DPSI to frame discussions b) How are the functions linked? What additional (linking) characteristics do we need to include? c) Conceptually map relevant challenges/hazards that impact sub-system function d) How are the challenges/hazards linked to the functions/characteristics? What additional (linking) characteristics do we need to include? e) Are there any multi-hazard impact relations that also need to be considered?
Based on the above, derive (limited, prioritised) set of sub-system objectives & indicators at different time horizons - Short term - Medium term - Long term	2. Setting objectives (facilitated group discussion) a) What is the main objective relating to each function, hazard/challenge for each of the three time horizons? • How does each function succeed? b) Prioritisation. How can the respective objectives be ranked? Each participant is given e.g. 5 votes to allocate to their priority objectives. Results are tallied to establish priority sector-based objectives • How does the sector succeed? • How do we measure this success? • What are the main influences on this success (update conceptual model if necessary)?

A.1.3 Step 3: System-scale synthesis

In the last step, all of the individual sector-based conceptual models are then analysed for any components which can be translated across to an integrated whole-of-system model. Here the aim is not to necessarily translate all sector-specific complexity across to the system model, but rather to identify those components that are central to the functioning of the complete system. The task is therefore to harmonise and synthesise the outputs developed in Step 2 and to formulate the system-wide conceptual model that includes all relevant interactions and interdependencies between the sectors, including multi-hazard impact relationships. The output from this step should preferably be a visual representation of the system-wide conceptual model. This can again incorporate relevant outputs relating to any multi-risk scenarios to be applied along with their dynamic system feedbacks.

Following the development of the system-wide model, this is used in combination with the prioritised lists of sector objectives to derive the prioritised set of system-wide objectives and indicators. Again, these should be developed for each of the planning time horizons that were specified in Step 1 (e.g. short-term, mid-term, long-term). The key is to focus on trying to answer the question ‘How does our system succeed?”, with the resulting objectives again being those that would enjoy widespread societal support (i.e. are uncontroversial). As in step 2, these objectives are then translated across to a set of SMART indicators.

Potential questions to pose during this step include:

- What sub-system components are common to multiple sectors?
- What uncommon sub-system components can be ignored at the system scale?
- What uncommon sub-system components cannot be ignored but remain central to system function?
- How are all these factors linked to each other?
- Are there any additional components that we need to include in light of these linkages?
- Does our model capture all the key biophysical functions that relate to the system?
- Does our model capture all the key socioeconomic functions that relate to the system?
- Does our model capture all the key institutional enablers and constraints that relate to the system?
- How does the system succeed?
- How can we measure this success?
- Are there any additional functional, spatial, financial, or societal interdependencies or multi-hazard impact relations that we need to consider at the system scale (refer to the separate table of questions listed in section A.3)?

The methods applied in this step are largely similar to those of the preceding steps. Ideally, the chosen method should match with that applied in Step 2, as then many of the existing relationships present in those models can be simply translated across to the whole-of-system model. But it may be that a simpler approach is needed, in which case a repeat of the CIrcle-type analysis completed in Step 1 with the harmonised/ synthesised set of system components can be used to establish an updated set of system dependencies. Table 5 summarises the information presented in the preceding paragraphs.

Table 5: Step 3: Objectives and (suggested) methods

<table>
<tr><th>Objective</th><th>Suggested Method(s)</th></tr>
<tr><td>Given core sub-system/sector <u>functions</u>, identify the synergies/interactions/dependencies between the sub-systems
• Functional
• Financial
• Societal
• Spatial

Also, identify any additional multi-hazard impact relations between the sectors</td><td>1. OPTIONS:
• Synthesised CLD from sector models to create single system-wide conceptual mode
o What are common elements (inc. hazards) to all sector models?
o What uncommon elements can be ignored (to simplify complexity) at the system scale? Which elements cannot be ignored?
o How do the various sector-specific elements link to other sector elements?
o Are there any additional multi-hazard impact relations that also need to be considered?
• Reperform CIrcle-type analysis with prioritised system components to establish linkages between stakeholders/sectors
o Detailed note-taking on discussions to establish additional complexity</td></tr>
<tr><td>Given core sub-system/sector <u>objectives</u>, what are the synergies and trade-offs between these? Derive set of prioritised system-level objectives & indicators at different time horizons
- Short term
- Medium term
- Long term</td><td>2. Setting objectives (facilitated group discussion)
a) From the set of prioritised sector objectives:
• Are there any common objectives?
b) Prioritisation. How can the respective sector objectives be ranked? Each participant is given e.g. 5 votes to allocate to their priority system objectives. Results are tallied to establish priority system objectives
• How does the system succeed?
• How do we measure this success?
• What are the main influences on this success (update conceptual model if necessary)?</td></tr>
</table>

A.2 Catalogue of tools for systems analysis from literature

A.2.1 Introduction

This section presents a catalogue of promising tools and approaches for collaborative systems analysis identified in the literature. The purpose of this catalogue was to initially inform the development of each of the tailored approaches to collaborative systems analysis applied in each of the Pilots, however, we see the catalogue as serving a similar function for multi-risk practitioners more generally. Its intention is to serve as inspiration to practitioners when devising their own approaches to collaborative systems analysis, suggesting potential tools to be applied to enhance system understanding. As reported elsewhere (see main report section 2.2.2), the Pilots made most use of the DPSIR framework (A.2.2.1), causal relationship diagrams (A.2.3), storyline approaches (A.2.2.4), and interaction matrices (A.2.4.3).

The approaches and tools listed below each involve varying degrees of systems thinking. Many of the identified approaches/tools share similarities, and our review identified five broad categories of tools/approaches:

1. those that provide a conceptual framework from which to approach systems analysis;
2. those that focus on the development of system causal relationships;
3. those the focus more exclusively on system interdependencies;
4. those that serve primarily as visualisation tools and can be combined with other approaches; and
5. other approaches that do not fit into either of the above categories and do not generate conceptual system models.

The following sections deal with each of these categories in turn. Note that this list and the brief synopsis of each approach/tool should not be considered to be exhaustive, and practitioners are encouraged to incorporate other tools with which they are familiar. Further information on these can be found in D6.2 *Guidance document for Pilots on collaborative systems analysis approaches* (Warren et al., 2022).

A.2.2 Conceptual frameworks for systems analysis

A.2.2.1 DPSIR

DPSIR (Drivers, Pressures, States, Impacts, Responses) framework (EC, 1999; Figure 24) is used for highlighting key relationships between social and environmental factors and can be used as a communication tool between researchers from different disciplines. It represents a structure of visualising a system as a simple, generic causal chain that commences with 'driving forces' (e.g. economic sectors, human activities), which generate 'pressures' (e.g. emissions, waste) that influence system 'states' (e.g. physical, chemical and biological), which lead to 'impacts' on ecosystems, human health, and functions, and eventually political 'responses' (prioritisation, target setting, indicators). The transferability to multi-risk conceptualisation stems from the complexities of socio-ecological systems and organising the elements potentially identified by the stakeholders in the predefined categories. DPSIR has been widely applied to complex natural resource management problems as a means to unpack system elements and to develop a conceptual understanding of how social-ecological systems function.

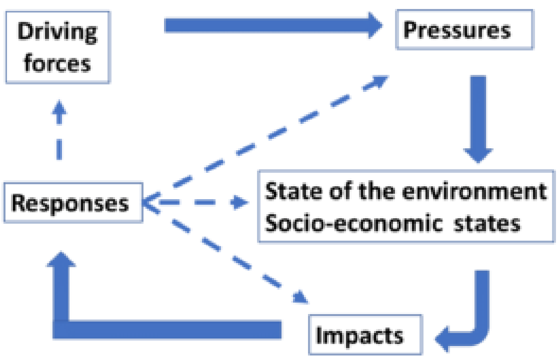

Figure 24: DPSIR framework of causal relationships

A.2.2.2 Bow-Tie

The Bow-tie framework (Delvosalle et al., 2006, Figure 25) is used to analyse risk management practices and evaluate risk responses. It is centred on a critical event (or hazard), which is conceptualised as having a series of causes (fault tree, situated on the left) and consequences (event tree, situated on the right). It is a barrier-based approach that considers risk and its possible barriers that can either mitigate the causes or consequences of the critical event. Once a bow-tie has been structured, quantitative analyses can then be performed (if desired) by assigning probabilities to the primary events of the fault tree and the safety barriers of the event tree. Originally applied in the analysis of workplace accidents, it has been successfully applied in a range of industries including chemical, mining, rail, aviation, oil, and gas. Given its focus on the critical event, the bow-tie framework is most applicable in the analysis of cascading events and impacts within specific sectors and industries. It is less useful at representing more complex multi-sector system interactions.

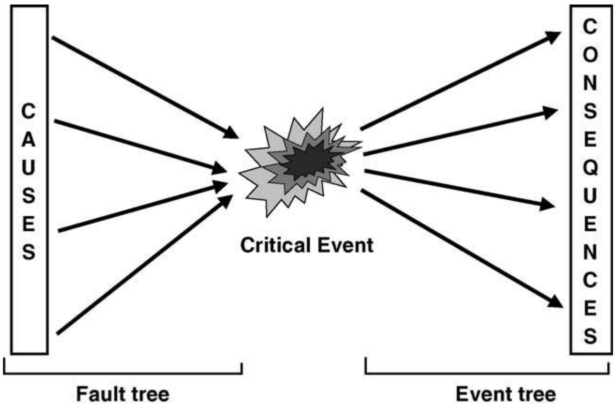

Figure 25: Generic scheme of the bow tie (Delvosalle et al., 2006)

A.2.2.3 Strategic options and development analysis (SODA)

SODA (Ackerman and Eden, 2010) is based on cognitive (or causal) mapping, which allows for views to be captured and be structured in a "means-end" format that generates chains of argument. It enables a group or an individual to construct a graphical representation of a problematic situation in the form of outcome statements (e.g. “develop and deliver strategy for protected areas”), and thus explore options and their ramifications concerning a complex system of goals and objectives. Maps, in this case, are networks (directed graphs) comprising nodes (constructs/statements) and links (causal arrows). They can be viewed as representations of how an individual or a group interprets a situation and helps them make sense of it before considering action. The method aims to help groups arrive at a negotiated agreement about how to act to resolve the situation. The approach is meant to emphasise both the process and the outcome of the collaboration between participants. Although it can encompass a broad range of system dimensions, its lack of any formal overarching structure can overwhelm participants who may find it too abstract.

A.2.2.4 Storyline approaches

Storylines are defined as a ‘physically self-consistent unfolding of past events, or of plausible future events or pathways (Shepherd et al., 2018). They are not predictive, with emphasis placed on understanding the driving factors involved in change and the plausibility of those factors occurring. Storyline approaches (e.g., Hazeleger et al., 2015), have emerged in recent years in opposition to the limitations of trying to represent the physical aspects of climate change probabilistically. Instead of seeking to quantify probabilities, storyline approaches (also referred to as ‘narratives’ or ‘tales’; Shepherd et al., 2018) seek to develop descriptions of plausible future climates. This family of approaches all share similar characteristics: emphasis is placed on qualitative understanding rather than quantitative precision, and storylines are accepted as not being probabilistic. Typically, more than one storyline is considered to facilitate the exploration of multiple plausible futures.

There a many ways to develop a storyline can be developed. MYRIAD-EU has developed its own approach under Task 6.3, which will be further detailed separately in the project. The proposed approach is presented below in Figure 26.

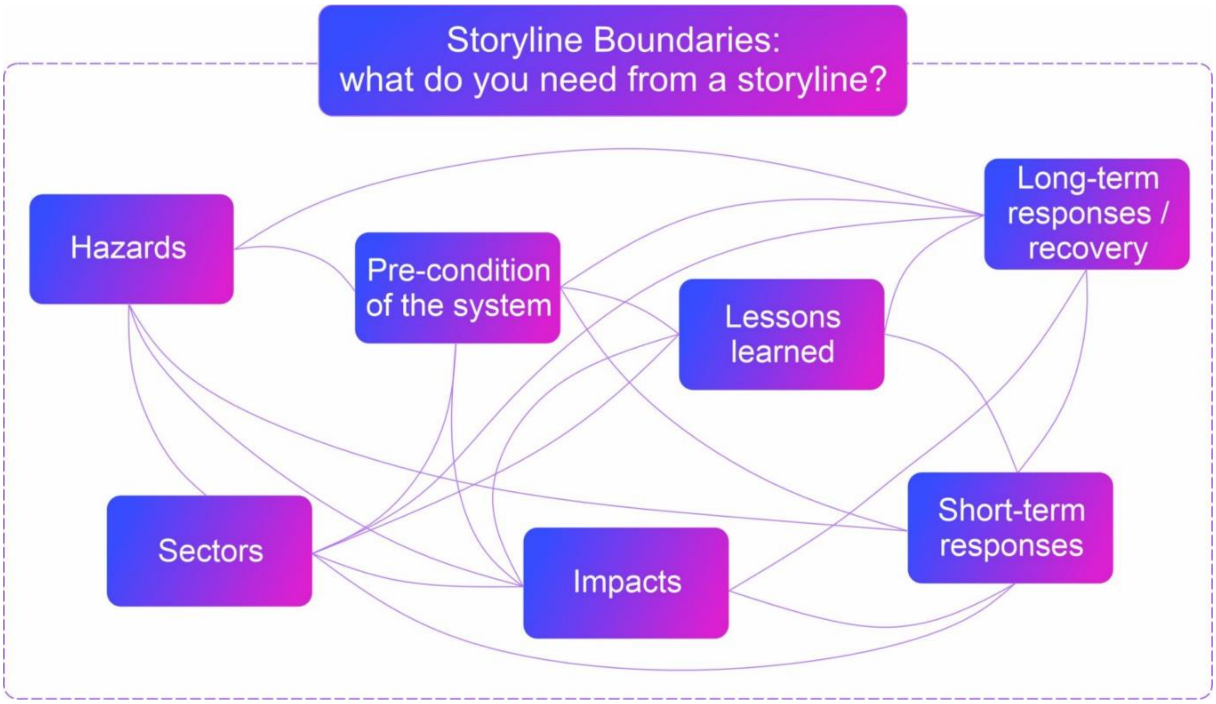

Figure 26: MYRIAD-EU approach to the storyline development

A.2.3 Causal relationships

The second category focuses on the development and visualization of causal relationships within the system. These approaches all do so without providing any form of overarching conceptual framework from which to analyse these, but rather simply represent causality in different ways and levels of complexity, from simple linear chains, through to more complex loops, matrices, networks, or maps (Banitz et al., 2022). As such, they are broadly applicable across a wide range of domains and are particularly well-suited to the analysis of socio-ecological systems. Banitz et al. (2022) identify six challenges of visualising complex causal relationships, which the various types of visualisation are variously able or not to meet. These challenges include:

- Visualising whether a relationship is causal, particularly when multiple factors are involved, and causality is difficult to discern.
- Visualising the characteristics of causality, including positive and negative relationships.
- Visualising reciprocal relationships
- Visualising multiple causes
- Visualising temporal dynamics of causal relationships
- Visualising uncertainty around causal relationships

A.2.3.1 Linear causal chains

These aim to highlight the simple relations that exist within individual parts of the system and typically do not try to represent the system as a whole (Figure 27).

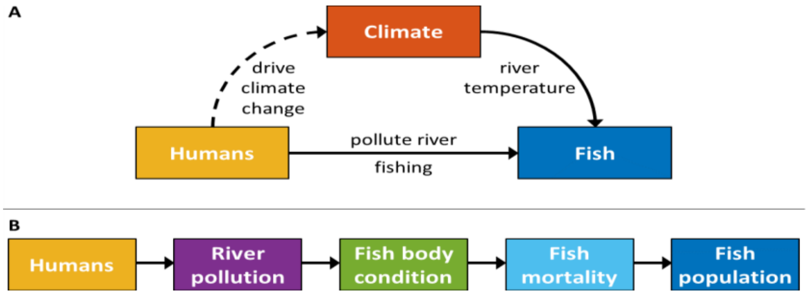

Figure 27: Linear causal chains (Banitz et al., 2022)

A.2.3.2 Dot and arrow diagrams

These aim to represent the system as a series of dots and arrows, where dots represent variables and arrows the inferred causality between them (Figure 28). Here, an additional restriction is placed on the diagram that only unidirectional arrows and no cycles or loops are permitted. Paths can be traced, and common challenges can be easily identified. Backdoor paths are those that lead from a subsequent variable back to a previous one in the chain, becoming a confounder in the relationship. An indirect path is formed by connecting two variables through a third variable, representing a mediator. This amounts to a robust causal diagram suitable for sectoral analysis. The directionality of the arrows is meant to present a certain order in which these events/variables affect one another, if that is uncertain then directionality can be relinquished.

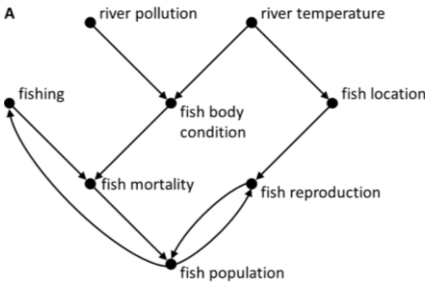

Figure 28: Dot and arrow diagram for inferring causality (Banitz et al., 2022)

A.2.3.3 Causal loop diagrams

Causal loop diagrams (CLDs) are a popular means of visualising causality and have been applied widely in natural resource management domains (e.g. Purwanto et al., 2019). They are a key tool in system dynamics approaches and aim to represent the system as a series of feedback loops involving two or more variables (Figure 29). In CLDs, directional arrows are also assigned a positive (reinforcing) or negative (balancing) relationship. This feature makes CLDs highly suitable for characterising and visualising reciprocal causal relationships. Linking multiple loops can be used to create a more concise understanding of a particular problem and help illuminate the spillover effects from one system to another.

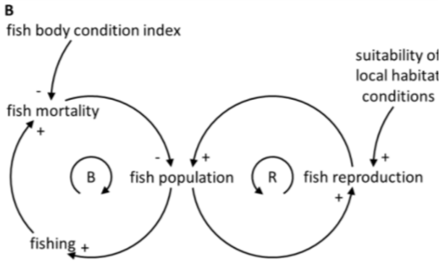

Figure 29: Causal loop diagram (Banitz et al., 2022)

A.2.3.4 Network diagrams

Network diagrams have two types of elements, nodes (objects) and edges (lines that link the objects), these diagrams can be used to describe abstract structural aspects of systems (Figure 30). Nodes usually represent elements of the same category, i.e. individuals, organisations, spatial areas, and events, although this is not an absolute requirement. Meanwhile, edges can represent proximity, flows, interactions, or association between elements, and can be assigned both weights or directionality (or neither). This type of diagram aims to derive causation from the network structure, which is used to identify vulnerabilities and bottlenecks generated by the number and distribution of nodes and edges.

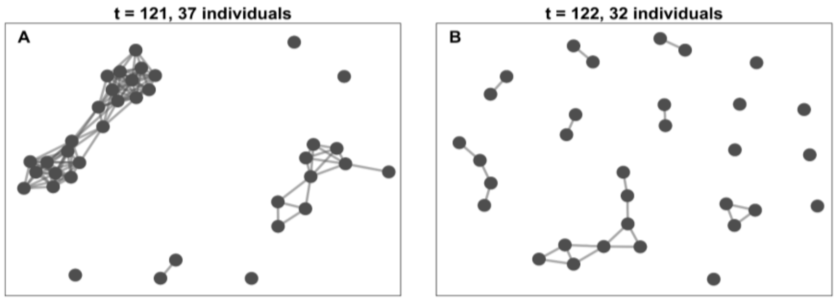

Figure 30: Network diagram (Banitz et al., 2022)

A.2.3.5 Group Model Building

Group model building refers to a participatory method whereby stakeholders are guided to collaboratively develop a conceptual causal loop diagram of their system for the purposes of decision-making. Here the focus is not only on the visualisation of the system, but also on the structured participatory processes behind the development of this model. It aims to generate a shared understanding of a system and its challenges by aligning perceptions (problem framing), elucidating variables, and developing mitigation strategies based on the dynamics present in the system. Originally applied in organisational settings and in combination with system dynamics software simulations (Vennix, 1996), it is now commonly used in natural resource settings as a qualitative modelling tool (e.g. Purwanto et al., 2019) and with a range of quantitative simulation tools.

A.2.4 System interdependencies

The third category of tools focus less on general causal relationships but more on the interdependencies between a specified set of system components, for example, sectors, and actors. processes, hazards. Here the nature of the interdependency is not explicitly captured in the visualisation medium, but simply the existence of the interdependency itself.

A.2.4.1 CIrcle

Critical Infrastructures: Relations and Consequences for Life and Environment (CIrcle, Deltares, 2022) is an online open tool that can be used interactively with stakeholders. It has traditionally been applied in workshop settings to assess the vulnerability of infrastructure to the cascading impacts of flooding events. Is useful for visualising the existence of interactions between system components in data-poor environments (Figure 31), and therefore lacks some of the information needed for an in-depth systems analysis when considered in isolation. Additional complexity must be captured through detailed note-taking of stakeholder discussions as the CIrcle diagram is generated. It is often applied in combination with quantitative physical system (e.g. flooding) simulation models to visualize the impacts of the cascading effects.

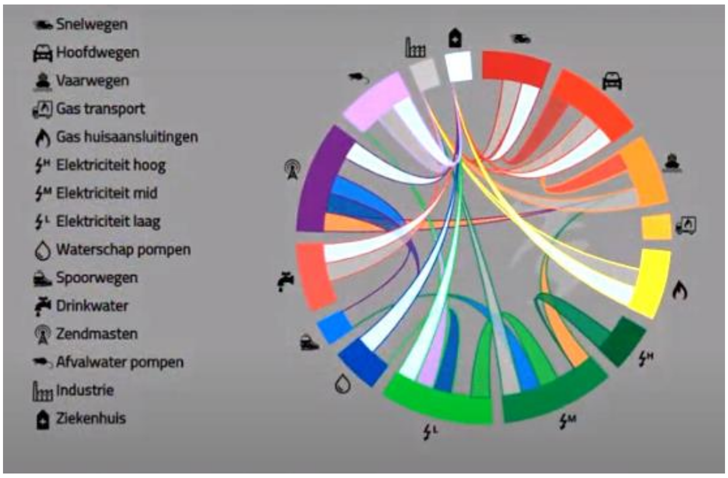

Figure 31: CIrcle diagram (Deltares, 2022)

A.2.4.2 Regional interaction frameworks

Regional interaction frameworks (Gill et al. 2020), can help in understanding the multi-hazard environment of specific spatial events. It aims to determine potential natural hazard interactions and to depict hazard cascades via a matrix form (Figure 32). It is an extensive approach, which integrates gathering evidence from a diverse range of sources, including literature, field observations, interviews, and workshops. It is an easily scalable approach, working at both global, regional, and local scales with information at different resolutions. As with CIrcle, the tool itself does not entail analysis of the nature of the interactions between hazards or any necessary thresholds, but merely the existence of the interaction.

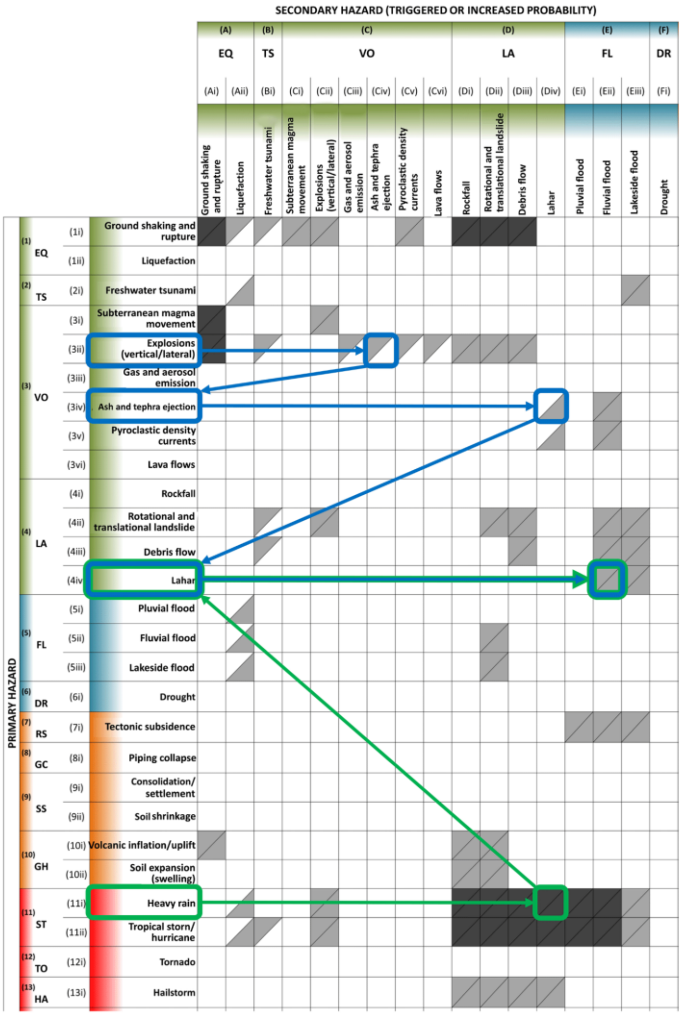

Figure 32: Regional hazard interaction matrix illustrating a hazard cascade (Gill et al., 2020)

A.2.4.3 Interdependency impact matrices

Interdependency impact matrices (Lomba-Fernandez et al., 2019), have been proposed for critical infrastructure systems to explore the interdependencies, and particularly the cascading impacts of failures in one critical infrastructure spreading to others through indirect impacts and cascading effects. These matrices are used to establish the effect of one failure on another via qualitative assessment of their dependencies (e.g., low, medium, and high). An example of such a matrix is provided below in Figure 33.

FAILED CI \ CI AFFECTED BY OTHER FAILED CI	ENERGY	WATER	COMMUNICATIONS	TRANSPORTATION	HEALTH	FOOD	FINANCIAL	ADMINISTRATION	SAFETY AND ORDER
ENERGY		HIGH	HIGH	HIGH	HIGH	HIGH	HIGH	HIGH	HIGH
WATER	LOW		LOW	LOW	HIGH	HIGH	MEDIUM	MEDIUM	MEDIUM
COMMUNICATIONS	HIGH	MEDIUM		HIGH	HIGH	MEDIUM	HIGH	HIGH	HIGH
TRANSPORTATION	HIGH	MEDIUM	MEDIUM		HIGH	MEDIUM	MEDIUM	MEDIUM	LOW
HEALTH	LOW	LOW	LOW	LOW		LOW	LOW	LOW	MEDIUM
FOOD	LOW	LOW	LOW	LOW	LOW		LOW	LOW	MEDIUM
FINANCIAL	MEDIUM	MEDIUM	MEDIUM	MEDIUM	MEDIUM	MEDIUM		MEDIUM	MEDIUM
ADMINISTRATION	MEDIUM	MEDIUM	MEDIUM	MEDIUM	MEDIUM	MEDIUM	MEDIUM		MEDIUM
SAFETY AND ORDER	MEDIUM	MEDIUM	MEDIUM	MEDIUM	MEDIUM	MEDIUM	MEDIUM	MEDIUM	

Figure 33: Interdependency matrix for a sectoral analysis of critical infrastructure in a city (Lomba-Fernandez et al., 2019)

A.2.5 (Online) visualisation tools

The fourth category of tools reflects those that serve as supporting tools to other approaches for systems analysis and assist in the development of system diagrams. There has been an explosion in online digital diagrammatic tools in recent years. These now mean that system diagrams can be easily developed in both remote and face-to-face settings.

A.2.5.1 Digital whiteboards

Simple visualisations can be manually generated using online collaborative whiteboard applications (e.g. Miro, Mural, MS Whiteboard, etc.). These typically share common features such as the ability to place shapes, text boxes, images, and (virtual) post-its on a canvas and join these elements together with lines and arrows. Most importantly, they offer the ability for multiple users to collaborate in real-time in the development of the diagram on the canvas, which is well-suited to collaborative mapping sessions. Most of these collaborative tools, however, require a licence to access or unlock their full feature sets.

A.2.5.2 Digital drawing tools

More sophisticated system diagrams can be created using digital drawing tools (e.g. draw.io, Visio, etc.). These applications are typically focused on generating specific types of diagrams such as organisation charts, flow charts, process diagrams, maps, or networks. In most instances, however, these tools lack the collaboration element, which means their use in participatory settings needs to be mediated by a single user.

A.2.5.3 Collaborative digital drawing tools

A final family of tools (e.g. Kumu, Lucidchart, Creately) seeks to combine the advantages of the preceding two paragraphs. They offer digital visualisation tools to map systems, stakeholders, community assets, concepts, and networks. Multiple users can collaborate in real-time in the development of their system maps or can in some instances generate maps from imported tabulated data. A variety of diagram types can be generated, including stakeholder maps, systems maps, causal loop diagrams, community asset maps, and concept maps. A downside of many of these tools is that they require a licence to either access or unlock the majority of their feature sets.

A.2.6 Additional systems approaches

The final category belongs to a set of approaches that can be combined with systems mapping to enhance understanding of uncertainties in the system elements and the links between them. The following approaches present methods that do not result in systems maps or conceptual models, but rather elaborate on specific issues, such as problem definition, or aim to generate consensus and understand the viewpoints of participating stakeholders. These approaches were not considered for inclusion in the generic collaborative systems analysis approach, but include:

- Q methodology (Stephenson, 1953, Raadgever et al, 2008)
- Soft systems methodology (SSM, Checkland and Scholes, 1990)
- Strategic assumptions and group testing (SAST, Mitroff & Emshoff, 1979)
- Strategic choice approach (Friend, 2011)
- Scenario planning (as presented by Butler et al. 2016)
- Critical scenario method (Cairns et al. 2010)
- Adaptive capacity wheels (Gupta et al. 2010)

A.3 Table of sector stakeholder questions aiming to facilitate investigation of the most relevant drivers of sectoral interdependencies and risk typologies (D1.3, Table 3)

	Functional	Spatial	Financial	Societal
Spill over	*How reliant are my services/machinery on specific critical infrastructure?* *If a particular piece of this infrastructure stopped functioning, how affected would my system's functionality be?*	*How close is my infrastructure to a potential hazard?* *How proximate is my infrastructure to other infrastructure that could inflict damage in a hazard event?* *What other sectors or stakeholders are likely exposed to the same impacts and therefore might be willing partners to cooperate regarding risk reduction measures?*	*How interlinked is my sector with the global financial markets?* *Are fixed prices built into my supply chain contracts to buffer cascading impacts of price spikes? (Carter et al, 2021).* *How likely are consumers to panic buy products in my sector?*	*What potential regions might a failure in my sector reach?* *What actors would be particularly affected and in what capacities?* *In what ways does my disaster risk planning account for potential spill-over effects?* *Is disaster planning adaptable and able to deal with dynamic disasters? i.e., does it use dynamic adaptive pathways?*
Co-dependent	*Are my services highly coupled with other systems, whereby they are mutually dependent on each other's functionality?*	*Are there proximate system services which are highly inter-dependent with each other, which if fail, could threaten the functioning of the system?*	*Are the financial systems of my sector highly coupled with financial wellbeing of another, such that if one experiences financial shock, so would mine?* *With which sectors are mine tightly coupled to?*	*Are there particular groups that are co-dependent for disaster management?*
Interacting intersecting	*Does my sector rely on multiple functions that on failure, intersect to compound the overall impact?*	*Are there sectors operating in the same location and what are their interacting aspects?* *What is the geographical area that could be affected by an incident and are there cross-border impacts?*	*How far does my sector interact and intersect with others financially?*	*What adaptive capacity is there at the interaction location?* *Do we have contingency plans for long-term compounding disasters?*
Independent intersecting	*What sectors do we rely on in terms of their functionality, for ours to also function? (i.e., Do we depend on transport service functionality for our services?)*	*What is the geographical area that could be affected by an incident and what independent sectors could be impacted?*	*What potential impacts in other sectors, when combined could impact the financial security of our sector?*	*What is the adaptive capacity to deal with independent risks coalescing?* *Are there contingency plans for the long-term effects of disasters?*